Techno-Economic Analysis of a Peltier Heating Unit System Integrated into Ventilated Façade

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Additional information is available at the end of the chapter

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Abstract

This chapter aims to describe the conceptual design and operating mode of an innovative thermoelectric heating unit (THU) prototype in a heating mode. Firstly, the conceptual design of THU system and improvements are described to investigate the effects of design in the thermal performance. Secondly, the THU prototype was compared with a conventional air-conditioning system using the typical economic indicators (investment costs, maintenance costs and operational costs). The results indicate that the overall cost of this project was approximately 84,860 Euros, of which 69.27% of the total investment cost are for the engineering costs. By focused on the investment costs of the THU system, the results reveal that the conventional air-conditioning system is economically viable than a THU system. The analysis shows that the design has a direct effect on the costs. The maintenance costs show that THU v1.2 prototype is more economically viable in maintenance than the conventional air-conditioning system. Likewise, the operational costs show that THU v1.2 had a more stable thermal behaviour than the conventional air-conditioning system. Based on the results, the authors concluded that the THU system could be a viable option for a heating room.

Keywords: Peltier, façade, thermoelectric system, techno-economic analysis

1. Introduction

The thermoelectric generators, sometimes called Peltier modules, are semiconductors based on Peltier effect to pump heat. The advantage of this system is that it can be used in the heating or cooling mode in a simple way. Due to it, the use of the thermoelectric generators is having a growing interest in developing new prototypes in the military, industrial and commercial areas [1–5].

The studies related to the cooling mode have focused their efforts on developing prototypes [6–12] that dissipate the heat in small applications such as in lasers, personal computers, refrigerators, cryogenic prototypes, and so on, while heating modes are being applied mainly in architectural area. The essential concepts of Peltier modules applied in the architecture have been introduced by Khire et al. [13], who proposed an ABE system that uses solar energy to compensate for passive heat losses or gains in a building envelope. The authors discussed the design and optimization of Peltier modules with PV panels in their work. Under this context, Xu et al. [14] developed various ABE prototypes in a heating mode, using commercially available PVs and Peltier cells, and Liu et al. [15] designed an ASTRW system with thermoelectric technology and PV panels. Likewise, Vázquez et al. [16] described the basic principles of a new concept for an active thermal wall that improves the current practice for designing and installing air-conditioning for enclosed spaces. Irshad et al. [17] designed a solar TE-AD system that employs thermoelectric modules (TEMs) inside an air duct to provide thermal comfort. In [18], a solar thermoelectric cooled ceiling is combined with a displacement ventilation system. The prototype was tested in cooling and heating modes. Other interesting studies [19, 20] described the application of Peltier cells in active walls, active building windows and thermoelectric ventilators. Recently, Luo et al. [21–23] proposed a building integrated photovoltaic thermoelectric wall system, which is supported by the co-work of PV module for solar radiation transformation, air gap for thermal dissipation and thermoelectric radiant panel system for active radiant cooling/heating. This study focused on an efficient and accurate system model for the simulation of this system. Wang et al. [24] develop a thermoelectric heating system powered by renewable energy to reduce the CO_2 emission in buildings. According to results, the prototype minimises the energy demands and therefore reduces CO_2 emissions.

The studies related to the economic analysis of HVAC technologies emphasise energy saving in the heating/cooling system [25–27] and the energy demand in buildings [28, 29]. From the engineering point of view, the number of Peltier cells, the heat exchanger design and the auxiliary system (fans, back-up system, control system, etc.) are studied in order to reduce the investment, operational and maintenance costs [30–32]. The purpose of this study is to present the conceptual design of a THU integrated into ventilated façade and analyse its economic viability and its thermal performance. To accomplish this aim, the following items are proposed:

1. describe the conceptual design and the operating mode of an innovative THU prototype;

2. compare the thermal performance of a THU prototype with a conventional air-conditioning system using the typical economic indicators (investment costs, maintenance costs and operational costs).

This work contributes in identifying the key aspect that may increase the efficiency of the HVAC systems in ventilated façades. Also, this research completes the authors' previous work [33–37] about the theoretical design and construction of an active ventilated façade with Peltier modules. The authors are aware that a techno-economic analysis of a THU prototype has not yet been reported.

2. Technical description of the thermoelectric heating units

Since 2009, the authors have been working on alternative HVAC systems for buildings. Based on their previous experience as architects (not engineers) in the area of building services and energy systems [38], the authors have focused on the design of decentralised ventilated heating system for new and rehabilitated building envelopes. The result was the construction of a simplified inhabited housing unit (prefabricated module) with a thermoelectric heating system. A detailed report on this first THU version (v1.1) and its manufacture has been presented by the authors in previous works [33–36]. This section provides a brief description of this first version and presents the improvement of this prototype (THU v1.2). Both prototypes were installed in a prefabricated test room to analyse their performance under real conditions.

2.1. Thermoelectric system of THU version 1.1

Thermoelectric heating unit (THU v1.1) consists of three subsystems: a heating system, a ventilation system and a control system. The heating system was composed of 84 RC12–8 Peltier modules (Marlow Industries, Inc.) with a heat dissipation system. The Peltier modules were placed in groups of two thermoelectric modules, where the Peltier modules were connected in series and the groups were connected in parallel; altogether, they form 42 groups that require a voltage of 50 volts and have a heating capacity of 3 kW (3/4TR heating tonnage). The elements of heat dissipation system are composed of 84 heat pipes, 21 finned heat sinks, two axial fans (fixed on the façade) and two tangential fans (fixed on the internal chamber). A schematic diagram of THU v1.1 prototype is illustrated in **Figure 1**.

The prototype has a control system that supplies electric energy to the system, controls the auxiliary equipment (fans, sensors, actuators, etc.) and regulates the working operations (inside temperature). In addition, a protection equipment was included in case of accidents that basically consists of a PLC, sensors and actuators.

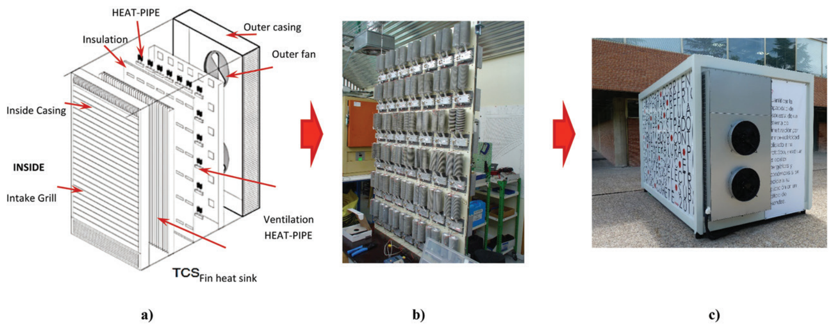

Figure 1. Schematic diagram of THU v1.1: (a) parts of the prototype, (b) heating system (heat pipes with Peltier cells) and (c) external view showing the electrical connection (down) and the ventilation grills (sideways).

2.2. Thermoelectric system of THU version 1.2

Recently, an improved prototype of the THU v1.1 was designed, named THU v1.2. This second version mainly consists of three subsystems: a heating system, a ventilation system and a control system. The heating system is composed of 20 Peltier modules (Marlow Industries, Inc.) with a heat dissipation system. All Peltier modules are connected in parallel, require a voltage of 20 volts and have a heating capacity of 1 kW (1/4TR heating tonnage). The elements of heat dissipation system are composed of 20 finned heat sinks and four tangential fans. This second version has more insulation, better heat dissipation and lower power consumption. **Figure 2** shows the outside and inside views of THU v1.2 prototype.

In order to know the economical and thermal viability of the THU v1.2 prototype, an identical test room was built for a conventional air-conditioning system, as shown in **Figure 3**. The conventional air-conditioning system uses inverter technology to regulate the voltage, current and frequency of an air conditioner so that it consumes only the necessary energy. The used model in this work is the air-conditioning split (1X1 MSZ-HJ35VA Mitsubishi Split) with a heating capacity of 3.6 kW (1TR heating tonnage).

To provide a consistent baseline for comparative analysis, the authors show the technical information for the THU prototype and conventional air-conditioning system (**Table 1**).

2.3. Design and operating principle

The exterior image in this project is based on an opaque ventilated façade with an active mechanism (air grilles) that adapts to different environmental conditions and seeks maximum efficiency at all times. The activation mechanism adjusts the air chamber ventilation of the façade and the heating system. This means that during winter months, the grilles are shut to enhance the accumulation of heat inside a room. However, in the summer months, the grilles are opened to extract the excess heat from the system. It is relevant to mention that the initial configuration of the active ventilated façade is in accordance with the requirements under the regulation of the ventilation of the cavity of the ventilated façade. As is shown in **Table 2**, an enclosure of a light sheet metal, as a light element with low thermal inertia that allows an immediate response to external environmental conditions and a ventilation capacity of 50CFM in the room was selected.

a) b) c)

Figure 2. Integration of the thermoelectric system in THU v1.2: (a) top view, (b) inside view (air inlet and outlet and ceramic surface) and (c) outside view of the prototype with the grills to dissipate the heated/cooled air.

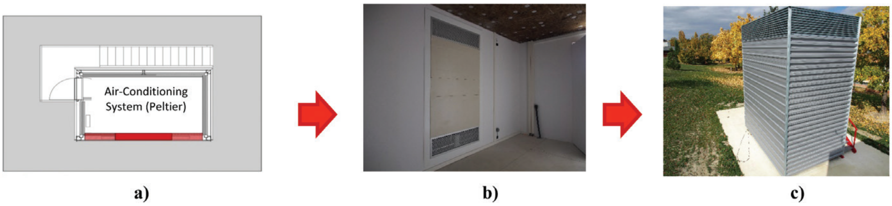

Figure 3. Schematic diagram of conventional system v2.0: (a) top view, (b) inside view and (c) outside view.

Parameter/component	THU v1.0	THU v1.2	Conventional system V2.0
Internal dimension (m)	4.0 × 2.4 × 2.5	3.75 × 2.10 × 2.0	3.75 × 2.1 × 2.0
Façade thickness (mm)	35	160	160
Dimension of chambers (cm)	100 × 10	100 × 10	No
U of the façade ($W/m^2 K$)	0.52	0.21	2.21
Double height	No	Yes	Yes
Roof thickness (mm)	35	127	127
U of the roof ($W/m^2 K$)	0.52	0.21	0.21
Floor thickness (mm)	19	195	195
U of the floor ($W/m^2 K$)	5.26	0.29	0.29

Table 1. Technical parameters of the prototypes.

The internal concept of the THU prototype consists of three layers, two air chamber and a HVAC system (thermoelectric system), as is shown in **Figure 4**. The first layer (external view) is composed of the metallic frame with two fans and a heat dissipation system. The fans allow the entrance of air to the external chamber (chamber connected to the outside environment), it passes through of the heat pipes and leaves external chamber eliminating the excess heat

Material	Thicknesses (mm)	Λ (W/mK)	R (m^2K/W)
Sheet metal	0.8	—	—
Ventilated air chamber/sealed	100	—	0.18
Inner sheet	177.5	0.163	4.62
Semi-rigid rockwool panel	80	0.034	1.91
Sandwich panel	35	0.028	1.25
Rockwool panel	50	0.035	1.40
Plasterboard	12.5	0.25	0.05

Table 2. Technical parameters of the active ventilated façade THU v1.2.

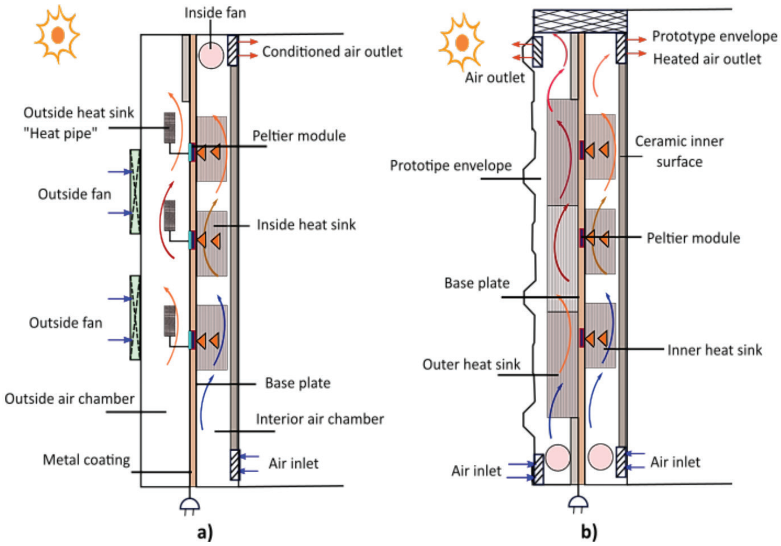

Figure 4. Schematic diagram of the design: (a) THU v1.1 prototype and (b) THU v1.2 prototype.

from the thermoelectric system. A relevant detail in the external view is that for THU v1.1, two axial fans were used, which were placed on the façade, while the second version THU v1.2 used two tangential fans, which were fixed in the lower part of the external chamber. This difference improves aesthetics and heat dissipation in the thermoelectric system.

The thermoelectric system is fixed in the second layer and its function is to separate the two chambers and supply heat to the room. Finally, the third layer connects the internal chamber with the room. This is composed of a group of heat sinks and two tangential fans (fixed in the lower part of the internal chamber). They allow the passage of air into the inner chamber for supplying hot air in the room. In this model, an air exit grill on the top of the wall was placed for extracting the cold air of the room.

2.4. Mathematical model

The Peltier modules consist of two or more elements of n-type- and p-type-doped semiconductor material that are electrically connected in series and thermally connected in parallel. These thermoelectric elements and their electrical interconnects are typically mounted between two ceramic substrates. Applying a voltage to a thermoelectric module creates a temperature difference. This temperature difference can be used to transfer heat from a cold side to a hot side and vice versa. Therefore, Peltier modules can be used to control the climate in rooms: to heat in winter and to cool in summer. In this regard, it is necessary to obtain a better heat transfer between the Peltier cells and the room air for increasing the heat transfer area of the ceramic plates with heat sinks [39, 40]. In this section, a brief overview of the basic equations that influence the functioning of a THU system is presented. The equations that mainly govern the thermoelectric effect are the electric power and the heat flow. The electric power shows the difference between the heat dissipated on the hot side and the heat absorbed at the cold side of the Peltier modules, and this is given by

$$P_{elect} = q_{hot} - q_{cold} = V \cdot I \tag{1}$$

where I is the load current, V is the output voltage, q_h is the heat dissipated on the hot side (W) and q_c is the heat absorbed at the cold side of the Peltier modules (W). The heat conduction from the hot side to the cold side is given by

$$q_{e,com} = K(T - T_o) \tag{2}$$

The heat flow is given by

$$q_1 = \alpha I_g T - \frac{1}{2} I_g^2 R + K(T - T_o) \tag{3}$$

and

$$q_1 = \alpha I_g T + \frac{1}{2} I_g^2 R + K(T - T_o) \tag{4}$$

where α is the total Seebeck coefficient (V/K), $\alpha = m(\alpha_p - \alpha_n)$, the subscripts p and n stand for p-type and n-type semiconductors, m is the number of Peltier cells, R is the total electrical resistance (Ω), $R = m(\rho_p I_p/S_p + \rho_n I_n/S_n)$, ρ is the electrical resistivity, l is the length of the semiconductor arms, S is the cross-sectional area of semiconductor arms, S is the cross-sectional area of semiconductor arms, K is the total thermal conductance, $R = \kappa_p S_p/l_p + \kappa_n S_n/l_n$, κ is the thermal conductivity of the semiconductor materials, I_g is the operational electrical current of a multi-couple Peltier cell.

A key parameter used to measure the performance of any air-conditioning system is the COP, defined as the useful thermal power output per unit of heat power. Its mathematical expression can be given as follows [42]:

$$COP_{(thermal)} = \frac{Useful\ Power\ (kW)}{Input\ Power\ (kW)} \tag{5}$$

The air-conditioned systems can be used in heating and cooling modes. In this work, the heating cycle is only considered, so the COP in heating mode for conventional system is given by [43]

$$COP_{(heat)} = 1 + \frac{T'_a - \Delta T'_{evap}}{T'_{room} - T'_a \Delta T'_{cond} + T'_{evap}} \tag{6}$$

where T'_a is the ambient temperature outside the evaporator in the heating mode $(^\circ K)$, T'_{room} is the room air temperature outside the condenser in the heating mode $(^\circ K)$, T'_{cond} is the temperature difference between refrigerant in condenser and ambient temperature ($^\circ K$) and T'_{evap} is the temperature in the evaporator ($^\circ K$).

In the case of thermoelectric system, the ideal COP in the heating mode is given by [43]

$$COP_{(heat)} = \frac{T_h}{T_h - T_c}\left(1 - 2\frac{1 + Z\,T_{m-1}}{Z\,T_m}\right) \quad (7)$$

where T_h is the hot side temperature at ceramic plate location in a thermoelectric module ($^\circ K$), T_c is the cold side temperature at ceramic plate location in a thermoelectric module ($^\circ K$), Z is the figure of merit of thermocouple and T_m is the arithmetical average temperature of a thermocouple($^\circ K$) .

3. Techno-economic parameters

3.1. Economic indicators

The economic evaluation is based on investment costs, operational costs and maintenance costs. The investment costs consider the cost of each piece of the prototype, including the electrical equipment, structure, heating system and instrumentation equipment and electrical installation. For the determination of the investment costs, these costs were divided into three categories: engineering costs, supply/handing cost and auxiliary costs. The engineering costs combine design, manufacturing processes, modelling of the pieces, architectural plans and installations. The supply/handing costs involve the material supply. In this case, the prices are quoted for Pamplona, Spain. Finally, the auxiliary costs depend on the finishing touches of the project.

Operational costs refer to the costs for the proper operation of each prototype. These costs mainly depend on the electrical consumption of the prototype subsystems (cooling–heating system, ventilation and control system). The THU v1.2 prototype under investigation was designed with a power nominal consumption of 1 kW, while that the conventional air-conditioning system is of 1.04 kW.

Maintenance costs consider all types of activities related to the repair and replacement of damaged pieces in the prototype subsystems. These costs have been estimated based on the price of the prototype and the maintenance of each subsystem. In the case of the conventional v2.0 system (Split 1x1MSZ-HJ35VA Mitsubishi), these costs are related to the use of special chemicals, checking the pressure, voltage drop, amperage drop, cleaning and blowing the dirty parts. According to [40], the maintenance cost of this system varies from $737 to $2156 Euros each year, depending on the capacity of cooling/heating. It represents between 10 and 20% of the total investment cost of the Split cost. In the case of THU v1.2, the authors have estimated that the maintenance cost could be approximately 6–10% of the heating system cost. This estimation was based on 1.5 years of test with the prototype [36].

3.2. Lifetime of the prototypes

The lifetime of the prototypes reflects the useful life of each system or the prototypes during a determined time. It includes the operational, physical and technological lifetime. In this study, the operational lifetime of thermoelectric device reported by Marlow Industries. Inc. [41] is in the range of 20,000–350,000 h at normal conditions, and Mitsubishi Company guarantees 15 years for inverter air-conditioning [44]. It is estimated that the physical lifetime of the structure is 30–40 years because the structural design combines durability, resistance and anti-corrosive materials. Also, it is assumed that the technological lifetime of the THU system is as long as the lifespan of the building (30–40 years), since it has a digital display that allows controlling the Peltier system and a sophisticated PLC that can be reprogrammed to the user necessities.

3.3. Environmental benefits

In addition to an economic assessment, the THU systems have social benefits that play an important role in taking care of the environment. In other words, the benefits associated with the use of THU systems are mainly related to reducing carbon dioxide emission. THU systems do not emit CO_2 in the operational and maintenance phase as inverter air-conditioning systems, because they do not have a working fluid. Therefore, THU systems are a good option for avoiding greenhouse gas emissions. Their electronic components can also be recycled. Moreover, a photovoltaic system could be added into this system to generate electricity and could reduce the annual operational costs, according to [14, 15].

4. Results and discussion

The investment costs of the THU v1.2 prototype and conventional air-conditioning system are reported in **Table 3**. The results show that the overall cost of this protect was approximately 84,860 Euros. This cost is because the authors considered the architectural and engineering aspects of both prototypes. Also, it can be observed that the highest value was for the engineering costs at 69.27% of the total investment cost, so that it is suggested that the designer has to pay attention for proposing competitive and viable prototypes.

The improvements of THU v1.1 prototype reduced the total investment cost by 30%. This percentage is directed directly related to the design, manufacture process and size of the prototype. On the other hand, **Table 3** shows that the supply/handing cost represented no more than 18.89% of the investment cost and that the auxiliary cost contributed only 14.54%, as it was expected. The above data indicate that the design plays an important role in engineering aspects. This means that the designer should select appropriate construction materials, the number of Peltier cells and the distribution of each system considering their cost. Also, the results indicate that the conventional v2.0 system is more economically viable than THU v1.2 because the THU system is the first product built in a prefabricated module. This prototype would be more viable if a considerable number of THU systems were manufactured.

Concerning manufacturing process of heating system, it was noted that investment costs are directly influenced by the size and number of Peltier modules, that is, an increase of Peltier modules increases the number of finned heat sinks, so that the investment costs increase. Also, the use of heat pipe sinks increases the investment costs by 30%. Although the heat pipe sinks offer better performance in terms of heat dissipation, the manufacturing process of a finned heat sink is less complicated than that of a heat pipe sink, so that the finned heat sink

Description	Costs (€)
Engineering costs	**68.88%**
-Construction of sills, general electricity networks, water and fibre optic installation	18,115.38
-Gardening work	
-Manufacture of the heat exchange module based on the Peltier cells	38,829.71
-Design, installation and start-up of equipment for measurement and control	
Supply/handing costs	**15.22%**
-Supply of the materials for the manufacture of the outside coating façade and the finishes of the test modules	2523.90
-Supply of insulation: blankets and insulation plates allocated to cover façades, roofs and floors (inside and outside)	2381.40
-Supply of materials for the interior walls and flooring of the modules: substructures and plasterboard plate	1095.96
-Transfer of Rockwool materials	
-Supply of four motorised doors to control the ventilated camera	632.80
-Supply and assembly of structures and enclosures	5993.00
-Split 1x1MSZ-HJ35VA 3.15 W cool-3.5 W heat MITSUBISHI and miscellaneous accessories	1332.07
Auxiliary cost	**15.90%**
-Installing the insulation (inside and outside) and coating the walls and floors with plasterboards	1769.68
-Placing metallic elements on the façades	10,829.71
-Constructing and installing the stairs	
-Painting	513.60
-Installing the Split 1x1MSZ-HJ35VA	860.53
Total Cost	**84,860.10**

Table 3. Investment costs of the prototypes v2.0 and conventional air-conditioning system.

is more economic. Moreover, it was seen that an increase in insulation level is beneficial in reducing heating demand. In the supply cost can be see that represent no more that 16% of the investment costs. According to the authors' experiences, these costs can be increased or reduced depending on the location of the supplier. Also, **Table 3** shows that the conventional air-conditioning system is more economically viable than THU v1.2, due to the manufacturing cost.

In regard to the operational costs, two 24-h thermal performance tests in January, from 13:30 to 13:30 h, were carried out in both prototypes, see **Figures 5** and **6**. Firstly, it was noted that after 30 min, the internal temperature of the room in the THU v1.2 reached 21°C, while in conventional system it was 26°C. In both tests, it was observed that there was a difference of 5°C in the internal temperature of the room. This means that THU v1.2 prototype could not reach 26°C in the room. It is because the THU v1.2 prototype was designed with 1/4TR of heating tonnage

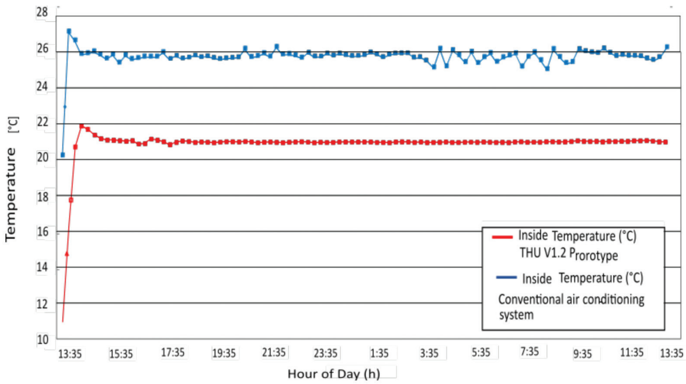

Figure 5. The inside temperature of the room in THU v1.2 and conventional v2.0 system, from January 12 (13:30 h) to 13 (13:30 h) in Pamplona, Spain.

and conventional v2.0 system is about 1TR of heating tonnage. To increase the temperature in the room, an increase of Peltier modules is needed. Therefore, it was deduced that the number of Peltier modules have an important impact on the thermal performance of the prototype.

The results showed that THU v1.2 had a more stable thermal behaviour than the conventional air-conditioning system, despite variation in the outside temperature, see **Figures 7** and **8**. It can be claimed that the active mechanism may be a key parameter in the efficiency.

The conducted tests showed that the nominal consumption of the Peltier equipment, with a set point of 22°C, is approximately 0.45 kW, while the conventional v2.0 system has a consumption of 0.15 kW, with a set point of 26°C. This affirms that the THU v1.2 design should improve the physical model of THU v1.2 prototype, and the annual maintenance cost is between 6 and 10% of the total investment cost of the system. Compared with the conventional air-conditioning system,

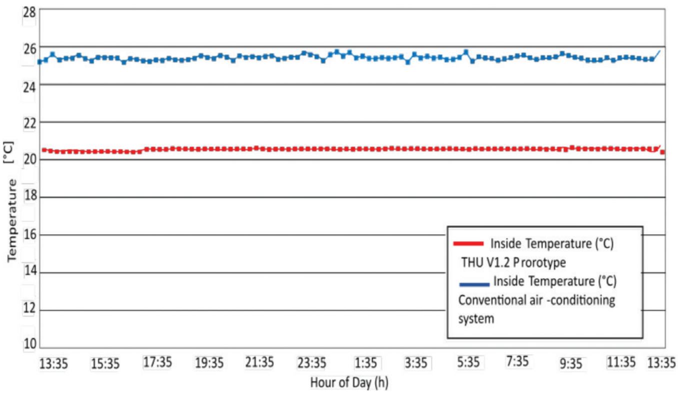

Figure 6. The inside temperature of the room in THU v1.2 and conventional v2.0 system, from January 13 (13:30 h) to 14 (13:30 h) in Pamplona, Spain.

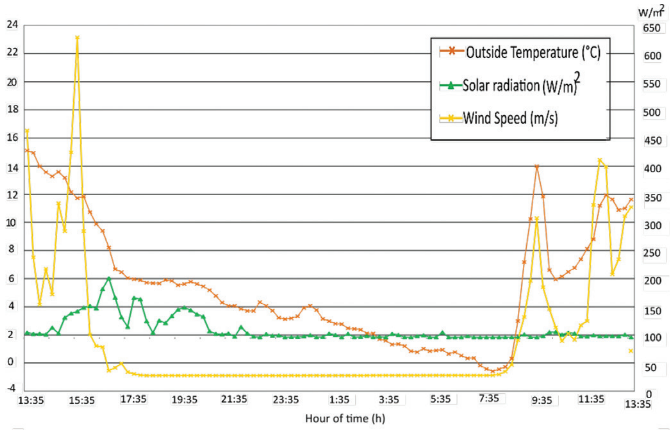

Figure 7. The variations of solar radiation, wind speed and outside temperature from January 12 (13:30 h) to 13 (13:30 h) in Pamplona, Spain.

THU v1.2 prototype is more economically viable in maintenance, so that the conventional air-conditioning system frequently needs maintenance and the replacement of parts.

The indicator associated with COP heat of the conventional air-conditioning system showed that it is in a range of 2.6–3, while the THU v1.2 prototype is between 0.46 and 1.07, as is illustrated in **Figure 9**. Considering the annual experimental data, the COP Carnot in a heating mode for THU v1.2 prototype is between 5 and 18%. Comparing the results of [43], it could be deduced that the conventional air-conditioning system has a COP of 30%. Thus, it can be noted that the conventional air-conditioning system is more efficient than the THU v1.2 prototype.

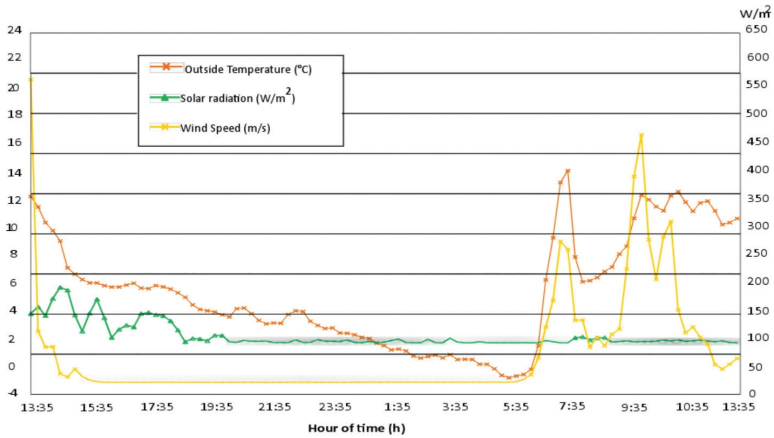

Figure 8. The variations of solar radiation, wind speed and outside temperature from January 13 (13:30 h) to 14 (13:30 h) in Pamplona, Spain.

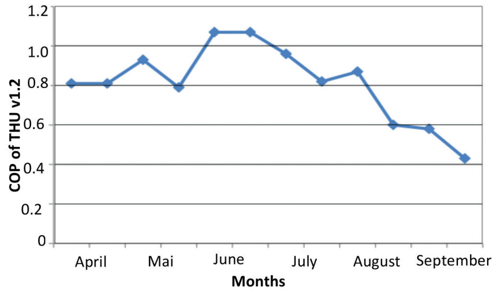

Figure 9. Experimental measurement COP of THU v1.2 prototype versus the months.

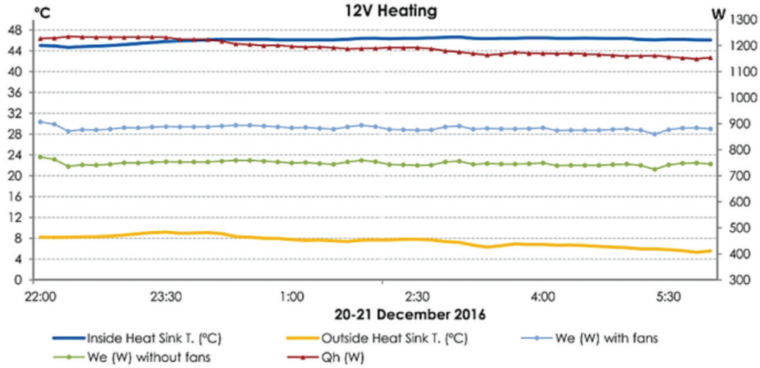

Figure 10. Graphic of the TCHU v1.1 with 12 V in heating.

Moreover, other tests have been published in [45, 46], where it is seen that the power consumption has higher values in Peltier systems, which is associated with the behaviour of Peltier in relation with the weather. As shown in **Figure 10**, the THU version 1.1 system consumes approximately 1.2 kW of power, while the THU version 1.2 system consumes approximately 1 kW. Therefore, the THU version 1.2 THU system has a great economic advantage on the THU version 1.1 prototype.

In summary, the techno-economic analysis gives rise to several interesting ideas for future research, such as the inclusion of photovoltaic panels and batteries in the prototypes, which will create an autonomous and efficient system.

5. Conclusions

The goal of this study was to describe the conceptual design and the operating mode of an innovative thermoelectric heating unit (THU) prototype and compare the thermal performance of a THU prototype with a conventional air-conditioning system. The analysis of investment costs, maintenance costs and operational costs was used as a reference point in the comparison. We found that the overall cost of this project was approximately 84,860 Euros.

By focusing on the investment costs of the THU system, the results reveal that THU v1.2 prototype design is 30% more economical than THU v1.1 design, due to a better design strategy in the manufacture process and the dissipation systems. By considering only dissipation systems, it was noted that the use of heat pipe sinks increase by 30% the investment costs. Although the heat pipe sinks offer better performance in terms of heat dissipation, the manufacturing process of a finned heat sink is less complicated than that of a heat pipe sink, so that the finned heat sink system is more economic.

From a comparative point of view, the results show that the conventional air-conditioning system is economically viable than a THU system; therefore, if THU was to enter the market, it is necessary to implement a strategy that reduces costs. Regarding the thermal performance, the results demonstrate that THU v1.2 had a more stable thermal behaviour than the conventional air-conditioning system. The maintenance costs indicated that THU v1.2 prototype is more economically viable in maintenance than the conventional air-conditioning system. Moreover, verifying the environmental benefits between the studied systems, it was found that the maintenance of a conventional air-conditioning system has a greater environmental impact than the THU v1.2 system. The authors recommended a life cycle analysis (LCA) of both prototypes, in order to know the pros and cons of the environment.

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Conflict of interest

There is no conflict of interest.

Nomenclature

ABE	active building envelope
ASTRW	active solar thermoelectric radiant wall
CFM	cubic foot per minute
COP	coefficient of performance

HVAC	heating ventilating and air conditioning
I	load current (A)
K	total thermal conductance (W/K)
l	length of the semiconductors (m2)
m	number of Peltier cells
PLC	programmable logic controller
PV	photovoltaic
q	heat dissipated
R	resistance (Ω)
S	cross-sectional area of semiconductor arms (m)
TE-AD	thermoelectric air duct
TEM	thermoelectric modules
THU	thermoelectric heating unit
TR	refrigeration tons
V	voltage
V1.1	version 1.1
v1.2	version 1.2

Greek letters

α	total Seebeck coefficient
κ	thermal conductivity of the semiconductor materials
ρ	electrical resistivity

Subscripts

a	ambient
c	cold side
cond	conductivity
eva	evaporator
H	hot side
n	n-type semiconductors
p	p-type semiconductors

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