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Effects of Climatic Conditions on Performance of Innovative Prefabricated Movable Buildings for Smart/Co-Working in Small Villages of Southern Italy

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ABSTRACT

Smart/co-working spaces are growing significantly, involving 16 million workers. Many small villages, representing 11 million citizens, are facing depopulation, job opportunities scarcity and services lack. Using prefabricated movable buildings (PMBs) could represent an opportunity to create smart/co-working spaces in a regenerative contest, allowing to save energy, CO_2 emissions, and costs, as well as enhance worker's perception of surroundings, and support the rebirth of small villages with high regenerative potential. In this paper, the performance of an innovative PMB for smart/co-working have been analyzed in 5 small villages of the Campania region (southern Italy) via the software TRNSYS. The PMB accommodates up to six workers and is equipped with smart windows and roof-mounted photovoltaic panels. The produced electricity can be stored in a battery and/or used to operate an electric reversing heat pump (EHP) for heating/cooling purposes. Its dynamic performance have been compared with a conventional PMB, highlighting that the utilization of smart windows reduces the cooling demand (at least by 47.77%) and the EHP electric consumption (at least by 41.26%); the integration of both photovoltaic panels and battery allows to fully cover the energy needs (so that the PMB is totally energy independent thanks to renewable sources).

1. INTRODUCTION

Smart/co-working represents a widespread practice, both in public and private sectors, and is evolving in national and international work landscape. However, it comes with challenges that must be addressed to maximize its potential energy, economic, and environmental benefits. Specifically, dedicated smart/coworking spaces worldwide have experienced a significant growth, increasing from 160 in 2008 up to 19,000 in 2018, with 16 million workers and substantial investments involved [1]. According to predictions, by the end of 2024, there will be 41,975 coworking spaces worldwide [2]. Also, in Italy, smart workers are on the rise, and it is estimated that their number will reach 3.65 million people by 2024 [3]. Many Italian small villages, representing 70% of Italian cities and 11 million citizens, are characterized by a significant regenerative potential, but face various issues related to depopulation, as well as lack of job opportunities and essential services [4, 5]. In particular, villages that exhibit historical, architectural, and naturalistic elements, as well as characteristics of slow life, have the potential to be perfect locations for combining vacation and work applications [6]. The use of prefabricated mobile buildings in urban spaces could represent an opportunity to create smart/coworking spaces in a regenerative context and could contribute to (i) saving energy, CO_2 emissions, and costs; (ii) improving the worker's perception of the surrounding environment; (iii) supporting the rebirth of villages with high regenerative potential.

In this paper, the performance of an innovative modular Prefabricated Movable Building (PMB) have been modelled, simulated and analyzed by means of the dynamic simulation software TRNSYS [7] over a period of 1 year. It accommodates up to six workers, it is equipped with smart windows that can reduce heat input and loss through the building envelope, and it can generate electricity from solar sources to satisfy electricity demands by using roof-mounted photovoltaic panels; the produced electricity can be stored into a battery and/or used to operate an electric reversing heat pump for heating/cooling purposes. The analysis has been performed by considering 5 different case studies consisting of the same building located into 5 different small villages belonging to the 5 different provinces of the Campania region of southern Italy. Specific weather data files obtained from the NASA database (referring to the year 2023) have been developed for each province in order to take into account the influence of meteorological conditions [8]. The performance of the proposed PMB have been assessed from energy, environmental and economic points of view in comparison with a building assumed as reference of the Italian context. The main objective of this work is to evaluate the potential benefits associated with the use of the proposed PMB in terms of energy savings, CO_2 emissions and operating costs compared to the reference scenario and, therefore, to assess the suitability of the proposed solution and support its deployment. This work is one of the outcomes of the research project titled “New movable systems for smart/co-working taking advantage of life quality, sustainability and energy efficiency (RESTANZA)”, funded by the University of Campania L. Vanvitelli and involving the participation of A. Ciervo, A. Rosato, F. Castanò, M.D. Morelli, M. Masullo, R. Marzocchi, and S. Boucherit [9]. Section 2 describes the selected small villages. Section 3 reports the characteristics of the proposed PMB and related simulation models. Section 4 briefly depicts the reference building. Section 5 details the methods of analysis. Section 6 discusses the simulation results.

2. SELECTED 5 SMALL VILLAGES

In this study, 5 different small villages (with less than 5,000 inhabitants [10]), one for each Campania region province have been selected, namely Visciano (Napoli province NA), Dragoni (Caserta province CE), Cerreto Sannita (Benevento province BN), Bisaccia (Avellino province AV), and Serre (Salerno province SA). The above-mentioned small villages have been selected according to the criteria and analyses developed within the activities of the research project titled “New movable systems for smart/co-working taking advantage of life quality, sustainability and energy efficiency (RESTANZA)” [9]. Figure 1 displays the Campania region population density and the geographic locations of the selected villages. In particular, Visciano has a number of inhabitants equal to 4161 with a population density of approximately 378.81 number of people/km², Dragoni has a number of inhabitants equal to 1976 with a population density of approximately 75.17 number of people/km², Cerreto Sannita has a number of inhabitants equal to 3606 with a population density of approximately 107.38 number of people/km², Bisaccia has number of inhabitants equal to 3544 with a population density of approximately 34.83 number of people/km², Serre has a number of inhabitants equal to 3683 with a population density of approximately 54.95 number of people/km² [5].

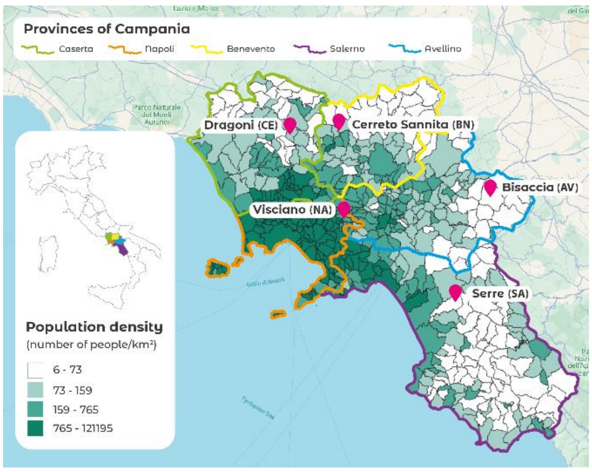

Figure 1. Population density of the Campania region and geographic positions of the selected small villages [5]

All the selected small villages are characterized by the presence of historical, architectural, and natural elements as well as a slow life. In addition, they have been given financial incentives for increasing their digital connectivity, making them an excellent location for hosting smart workers and digital nomads.

Table 1 reports the weather information referred to the year 2023 obtained from the NASA database [8] for each village, namely Italian Climatic Zone (ICZ), minimum/maximum outside temperature and annual horizontal global solar irradiation. Figure 2 shows the monthly horizontal global solar irradiation according to the NASA database [8] as a function of the village.

Table 1. Weather conditions as a function of the village [8]

	Visciano (NA)	Dragoni (CE)	Cerreto Sanita (BN)	Bisaccia (AV)	Serre (SA)
ICZ	D	C	D	E	C
Minimum/maximum outside temperature (°C)					
Annual	-2/39.5	5.3/33.9	-4.5/40.6	-3.6/40.5	-0.6/36.9
Jan	-0.7/16.9	7.8/16.5	-4.2/15.3	-1.4/17.3	2.1/17.6
Feb	-2/16.4	5.3/15.7	-4.5/14.9	-3.6/17.9	-0.6/16.9
Mar	1.6/18.4	8.8/17.8	-1.5/18.5	-1/20.4	3.2/18.6
Apr	2.7/21.3	9/19.4	-1.5/19.5	-0.7/22.7	4.5/20.9
May	9/25.9	15/25.4	6.8/22.8	7.1/26.4	10.4/25.4
June	14.8/35.7	19.3/28.8	10.5/34.9	12.4/35.9	15.1/33.7
Jul	18.4/39.5	22.8/32.7	14.1/40.6	15.4/40.5	18.8/36.9
Aug	16.9/37.7	21.3/33.9	12.6/37.6	14.2/38.9	17.5/36.3
Sept	15.5/34.6	19.5/30.7	10.6/34.1	12.9/35.5	16.5/31.5
Oct	13.6/31.5	17.7/27.8	9.4/30.3	11.1/30.4	15.7/29.9
Nov	2.9/21.4	9.9/22.5	-2.2/18.9	0.2/21.5	3.6/21.1
Dec	2.3/18.3	9.9/19.2	-1.2/15.6	0.5/18.8	5.1/18.4
Annual global horizontal solar irradiation (kWh/m²)					
Annual	1643.48	1566.61	1551.47	1607.18	1572.89

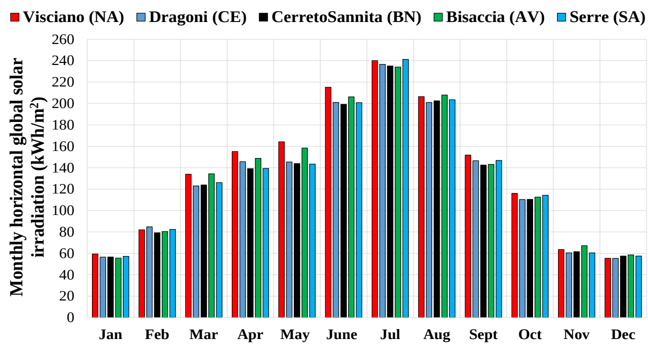

Figure 2. Monthly horizontal global solar irradiation upon varying the small villages [8]

3. PREFABRICATED MOVABLE BUILDING “RES_STANZA”

3.1 Geometry and design

The proposed PMB is named “*RES_stanza”*. Its design has been defined as result of the activities performed within the research project titled “New movable systems for smart/co-working taking advantage of life quality, sustainability and energy efficiency (RESTANZA)” [9]. The design process of the proposed PMB involved a multidisciplinary approach, considering objective (such as indoor thermo-hygrometric conditions) and subjective factors impacting the health, well-being, and productivity of occupants. The PMB comprises six indoor areas: three identical offices (labelled A, B, and C, with a floor area of 9.6 m^2 each), a relaxation area (floor area of 9.6 m^2), a toilets area (ante bathroom, WC1, and WC2, with a total floor area of 14.2 m^2), and a corridor to connect each area. Additionally, the outdoor spaces have a laboratory area, a small garden, and an impluvium for rainwater recovery. Each office is designed for a maximum of two people, for a total occupancy of six individuals in smart/co-working mode. The offices, relaxation area, and toilets vertical external walls are identical; the thickness and materials are selected based on established best practices commonly used for movable buildings in the Italian context [11]. The thermo-physical properties of materials are determined based on data provided by manufacturers or sourced from the scientific literature. Table 2 outlines the layers and the thermo-physical properties of materials used for the "*RES_stanza*" building; specifically, thickness (s), thermal conductivity (λ), specific heat capacity (c_p), and density (ρ) are listed.

Table 2. Walls, ceiling, and floor thermo-physical properties [11, 12]

Layer Material (outside to inside)	s (m)	λ (W/mK)	c_p (kJ/kgK)	ρ (kg/m^3)
Ceiling of the offices, relaxation area and toilets				
Galvanized corrugated sheet	0.0050	52	0.46	7800
Rock wool	0.0400	0.042	0.835	70
Steel sheet	0.0040	52	0.46	7800
Polyurethane resins (PUR)	0.0720	0.02	1.255	39
Steel sheet	0.0040	52	0.46	7800
Fir timber panel	0.0100	0.12	2.72	450
Floor of the offices, relaxation area and toilets				
Galvanized and pre-painted steel profile	0.0015	52	0.46	7800
Galvanized sheet	0.0060	52	0.46	7800
Steel sheet	0.0040	52	0.46	7800
Polyurethane resins (PUR)	0.0720	0.02	1.255	39
Steel sheet	0.0040	52	0.46	7800
Timber panel	0.0180	0.12	2.09	600
Porcelain stoneware	0.0100	2.3	0.835	2300
External vertical walls of the offices, relaxation area and toilets				
Fir timber panel	0.0100	0.12	2.72	450
Steel sheet	0.0040	52	0.46	7800
Polyurethane resins (PUR)	0.0720	0.02	1.255	39
Steel sheet	0.0040	52	0.46	7800
Fir timber panel	0.0100	0.12	2.72	450
Internal vertical walls of the offices, relaxation area and toilets				
Fir timber panel	0.0100	0.12	2.72	450
Steel sheet	0.0040	52	0.46	7800
Polyurethane resins (PUR)	0.0320	0.02	1.255	39
Steel sheet	0.0040	52	0.46	7800
Fir timber panel	0.0100	0.12	2.72	450

In order to improve its energy efficiency, the "*RES_stanza*" building is equipped with 4 electrochromic Smart Windows (SWs) used for the offices and the relaxation area. The SWs are made up of an electronically tintable double-glazing system (model Climaplus Classic) developed and marketed by the company SageGlass [13], featuring four states: clear, intermediate 1, intermediate 2, and dark. Table 3 lists thermal and visible characteristics of the selected SWs provided by the manufacturer as a function of the state, including the type, geometry (layers' thickness), spacing gas, frame area (A_f), glazing area (A_g), thermal transmittance of both the frame (U_f) and the glazing (U_g), Solar Heat Gain Coefficient (SHGC), and visible transmission coefficient (τ_{vis}). Each SW is separately controlled based on the indoor air temperature in the served space, as suggested in the study of Maffei et al. [12]. Table 4 summarizes the indoor air temperature threshold values used to set the state of the SWs.

Photovoltaic (PV) panels, commercialized by TRIENERGIA [14], coupled with electric storages, commercialized by the company TESLA [15], serve the "*RES_stanza*" building. The characteristics of the PV panels are given in Table 5. Following the triangular shape of spaces composing the "*RES_stanza*" building, three PV models (TRI120TM-BB, TRI240TM-BB, TRI380HP-BB) are considered to maximize roof coverage. PV panels are mounted horizontally for a total of about 59.6 m^2.

Table 3. Thermo-physical and visible properties of SWs

State	Clear	Intermediate 1	Intermediate 2	Dark
Window Type	Double glazing			
Layers' Thickness (mm)	9.1/12/4			
Spacing gas	Krypton			
A_f (m^2)	1.6			
A_g (m^2)	9.4			
U_f (W/m^{2}K)	1			
U_g (W/m^{2}K)	1.1			
SHGC (-)	0.4	0.12	0.07	0.05
τ_{vis} (-)	0.6	0.17	0.05	0.01

Table 4. Smart windows control strategies [12]

Driving Variable	Threshold Values	Smart Window State
Indoor air temperature T_i	$T_i \leq 24.5°C$	*Clear*
	$24.5°C < T_i \leq 25°C$	Intermediate 1
	$25°C < T_i \leq 25.5°C$	Intermediate 2
	$T_i > 25.5°C$	*Dark*

The number of batteries is selected to make the proposed system self-sufficient from an energy point of view. In particular, 3 batteries are used in Dragoni (CE) and Cerreto Sannita (BN), while only 2 batteries are adopted in Visciano (NA), Bisaccia (AV) and Serre (SA).

Table 5. Main characteristics of PV panels and electric storages

PV Panels [14]			
Model	TRI120TM-BB	TRI240TM-BB	TRI380HP-BB
Panel typology	Monocrystalline		
Area of a single panel (m^2)	0.68	1.21	1.87
Number of panels	16	14	17
Orientation	horizontal		
Nominal power of single panel (W)	120	240	380
Shape	Triangular	Square	Rectangular
Electric Storage [15]			
Model	Tesla Powerwall		
Usable capacity of a single battery (kWh)	13.5		
Depth of discharge (%) / Efficiency round-trip (%)	100 / 90		
Power of a single battery (kW)	7 (peak) / 5 (continuous)		

3.2 TRNSYS model

The software TRNSYS 18 [7] is utilized to model and assess the energy, environmental, and economic performance of the proposed PMB. TRNSYS is commonly employed in scientific literature to evaluate the effectiveness of building-integrated energy systems [16, 17].

In TRNSYS tool, the walls and windows have been modelled according to the characteristics reported in Table 2 and Table 3, respectively, through the TRNSYS Type 56a. The external and internal convective heat transfer coefficients for both walls and windows have been assumed to be 25 W/m^{2}K and 7.7 W/m^{2}K, respectively. Internal gains or loads, including those from occupants, lighting systems, and electrical appliances (such as laptops, mobile phones, printers, Wi-Fi routers, coffee machines, mini fridges, microwave ovens, and hand dryers) have been accounted via the TRNSYS Type 56a.

The occupancy profiles (the number of individuals present over time, for the offices, toilets, and relaxation area) are depicted in Figure 3 for weekdays. There are no occupants expected during weekends. Throughout weekdays, the total number of occupants within the building, encompassing offices, relaxation area, and toilets, remains constant at 6 individuals from 8:30 am to 6:30 pm. The sensible heat gain/load associated with each occupant has been set to 115 W, following ASHRAE recommendations [18] for seated/very light work activity levels.

Light-emitting diode (LED)-based luminaires (model Liquid Line-A3 manufactured by Lightnet [19]) have been selected as artificial lighting systems serving the building to guarantee visual comfort according to UNI EN Standard 12464 [20]; 16 luminaires are required for each of the offices A, B and C as well as for the relaxation area, while four luminaires are used for each of the toilets WC1 and WC2. Each luminaire is characterized by a nominal electric power of 9.6 W with a corresponding thermal gain/load assumed equal to 7.2 W (equal to 75% of the nominal electric power). The luminaires have been assumed to be switched on only in the case of at least one occupant being inside indoor space, according to the occupancy profiles reported in Figure 3.

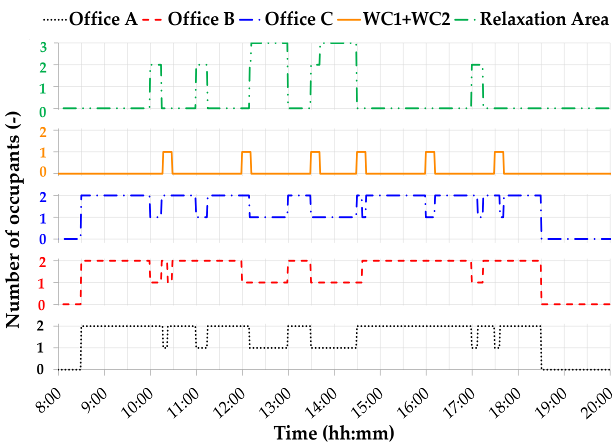

Figure 3. Occupancy profiles during the weekdays of the building

Table 6 presents the count of electric appliances (laptops, mobile phones, printers, Wi-Fi routers, coffee machines, mini fridges, microwave ovens, and hand dryers) categorized by indoor space. This table also specifies the power consumption during standby ($P_{el,Stand\text{-}by}$) and operation ($P_{el,ON}$), as well as the associated sensible thermal gain/load during standby ($P_{th,Stand\text{-}by}$) and operation ($P_{th,ON}$) for each individual electric appliance.

Table 6. Electric appliances

Type of Appliance	Numbers of Appliances						
	Office A	Office B	Office C	Relaxation Area	Toilets	$P_{el,ON}$/ $P_{el,Stand\text{-}by}$ (W)	$P_{th,ON}$/ $P_{th,Stand\text{-}by}$ (W)
Laptop [21]	2	2	2	0	0	59/0	53/0
Mobile phone [21]	2	2	2	0	0	5/0	5/0
Printer [22]	1	1	1	0	0	351/4	101/1.2
Wi-fi router [23]	0	0	0	1	0	7/0	7/0
Coffee machine [21]	0	0	0	1	0	1400/0	385/0
Mini fridge [21]	0	0	0	1	0	130/0	125/0
Microwave oven [21]	0	0	0	1	0	1000/0	713/0
Electric hand dryer [24]	0	0	0	1	0	900/0	900/0
Lighting appliances [19]	16	16	16	16	4	9.6/0	7.2/0

Figure 4 displays the utilization time of electric appliances (printers, coffee machine, microwave oven, hand dryer, mini fridge) across weekdays, segmented into operating states: OFF, stand-by, and ON. Laptops, mobile phones, and Wi-Fi routers remain operational throughout the entire weekday period from 8:30 am to 6:30 pm; during weekends, all electric appliances are turned off.

The air change of infiltration has been set as a constant value of 0.5 h^{-1}, based on the value suggested by Ye et al. [25].

The building is served by energy systems that can control indoor air temperature in both the offices and the relaxation area (while it is not controlled in the toilets) during heating and cooling periods.

The heating period starts on November 15th and ends on March 31st in the cases of Dragoni and Serre (Italian climatic zone C); for Visciano and Cerreto Sannita (Italian climatic zone D), it covers a different period, starting on November 1st and ending on April 15th.

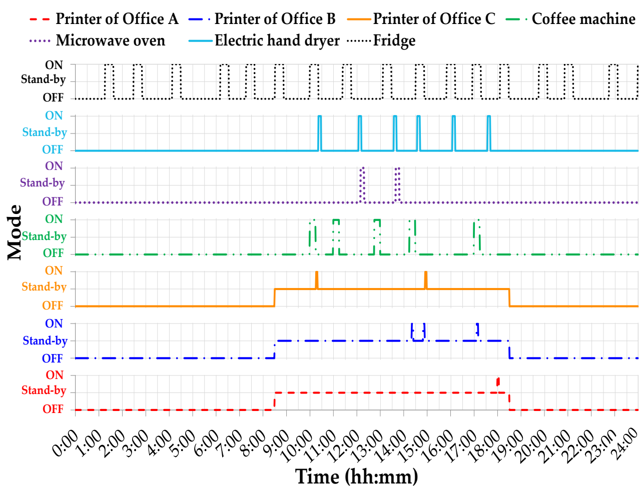

Figure 4. Operating schedules of electric appliances

For Bisaccia (Italian climatic zone E), the heating period begins on October 15th and ends on April 15th. The cooling season covers the remaining part of the simulation year, whatever the city is. During the heating season, the target temperature is established at 20 °C, with a deadband of ±1°C, while during the cooling season it is set to 26°C, also with a deadband of ±1°C [12, 26]. These target temperatures are maintained when at least one occupant is present in the offices and/or relaxation area; otherwise, the indoor air temperature is left unregulated. An air-to-air vapor-compression electric reversing heat pump (EHP) has been employed to maintain the desired levels of indoor air temperature. Four identical mono-split EHPs [12] (Bluevolution FTXJ+RXJ model manufactured by DAIKIN [27]) have been chosen to cover the heating and cooling requirements of each indoor area. Each unit is characterized by a nominal heating capacity of 2.5 kW (with a Coefficient of Performance COP of 5.0) and a nominal cooling capacity of 2.0 kW (with an Energy Efficiency Ratio EER of 4.7) [27]. The EHPs have been modelled and simulated by using the TRNSYS Type 786, which utilizes performance data files provided by the manufacturer. These files contain normalized capacity and coefficient of performance ratios, which vary based on the normalized return air flow rate, return air temperature, and outdoor air temperature [12, 27].

The PV panels have been characterized via the TRNSYS Type 190. This component determines the electrical performance of a photovoltaic array. The model of the PV panels is described by De Soto et al. [28].

The electric storage has been modelled and simulated by means of the TRNSYS Type 47a [7] (calibrated according to manufacturer information [15]), while the inverter/charge controller has been characterized via the TRNSYS Type 48b [7]. The inverter/charger controller gets the electric energy generated by the PV panels, prioritizing the satisfaction of electric demands. When the electric generation is larger than the total electric demand, the surplus is directed towards charging the electric storage if its charge level is below 100%; otherwise, the excess energy is sold to the main grid. Electric storage is discharged only when its charge level exceeds 10%; discharging stops when it drops below 10%. Additionally, the central grid supplements peak demands if the electricity from PV panels falls short of meeting the entire electric requirement.

4. BASELINE BUILDING

The baseline building has been modelled and simulated while operating into the 5 selected small villages to be used as a benchmark for the proposed "*RES_stanza*" building. The baseline building has the same geometry, materials, number of occupants, occupancy profiles, electric appliances and operating schedules as the "*RES_stanza*" building. It is not equipped with smart windows, PV panels and electric storage. Conventional windows used in the baseline building have the same characteristics as the smart windows in the clear state. As in the proposed case, four identical air-to-air vapor-compression electric reversing heat pumps (EHPs) have been employed to control indoor air temperature for the offices and relaxation area of the baseline building. The electrical load is covered by purchasing electricity from the electric central grid.

5. METHODS OF ANALYSIS

The simulation outputs representing the operation of the proposed "*RES_stanza*" building (PS) have been analysed and, then, compared with those corresponding to the operation of the baseline building (BB) from energy, environmental and economic points of view. In particular, the Percentage Heating Demand Saving (PHDS) has been determined by using the Eq. (1):

$$\mathrm{PHDS} = \frac{E_{\mathrm{HD}}^{\mathrm{BB}} - \mathrm{E}_{\mathrm{HD}}^{\mathrm{PS}}}{E_{\mathrm{HD}}^{\mathrm{BB}}} \tag{1}$$

where, $E_{\mathrm{HD}}^{\mathrm{BB}}$ is the annual heating demand of the baseline building and $E_{\mathrm{HD}}^{\mathrm{PS}}$ is the annual heating demand of the "*RES_stanza*" building.

The Percentage Cooling Demand Saving (PCDS) has been determined by means of the Eq. (2):

$$\mathrm{PCDS} = \frac{E_{\mathrm{CD}}^{\mathrm{BB}} - \mathrm{E}_{\mathrm{CD}}^{\mathrm{PS}}}{E_{\mathrm{CD}}^{\mathrm{BB}}} \tag{2}$$

where, $E_{\mathrm{CD}}^{\mathrm{BB}}$ is the annual cooling demand of the baseline building and $E_{\mathrm{CD}}^{\mathrm{PS}}$ is the annual cooling demand of the "*RES_stanza*" building.

The Percentage Electric Energy Demand Saving for EHPs ($\mathrm{PEEDS_{EHPs}}$) has been determined via the Eq. (3):

$$\mathrm{PEEDS_{EHPs}} = \frac{E_{\mathrm{EHPs}}^{\mathrm{BB}} - \mathrm{E}_{\mathrm{EHPs}}^{\mathrm{PS}}}{E_{\mathrm{EHPs}}^{\mathrm{BB}}} \tag{3}$$

where, $E_{\mathrm{EHPs}}^{\mathrm{BB}}$ is the annual electric energy consumption of the EHPs serving the baseline building and $E_{\mathrm{EHPs}}^{\mathrm{PS}}$ is the annual electric energy consumption of the EHPs serving the "*RES_stanza*" building.

The Primary Energy Saving (PES) has been computed based on simulation data via the Eq. (4):

$$\mathrm{PES} = \frac{E_p^{\mathrm{BB}} - \mathrm{E}_p^{\mathrm{PS}}}{E_p^{\mathrm{BB}}} \tag{4}$$

where, E_p^{BB} is the annual primary energy consumption of the baseline building and E_p^{PS} is the annual primary energy consumption of the "*RES_stanza*" building [12].

The CO_2 equivalent emissions of the baseline and alternative configurations of the building have been compared by means of the following parameter ΔCO_2:

$$\Delta\mathrm{CO_2} = \frac{m_{\mathrm{CO_2}}^{\mathrm{BB}} - \mathrm{m}_{\mathrm{CO_2}}^{\mathrm{PS}}}{m_{\mathrm{CO_2}}^{\mathrm{BB}}} \tag{5}$$

where, $m_{\mathrm{CO_2}}^{\mathrm{PS}}$ is the mass of CO_2 equivalent emissions associated to the "*RES_stanza*" building and $m_{\mathrm{CO_2}}^{\mathrm{BB}}$ is the mass of CO_2 equivalent emissions associated to the baseline building [12, 29]. The assessment of the pollutant emissions has been performed in this study through the energy output-based emission factor approach suggested by Chicco and Mancarella [30]. According to this approach, the values of $m_{\mathrm{CO_2}}^{\mathrm{PS}}$ and $m_{\mathrm{CO_2}}^{\mathrm{BB}}$ used in the Eq. (5) have been computed as reported below according to the Eqs. (6) and (7):

$$m_{CO_2}^{PS} = \alpha \cdot E_{el,import} \quad (6)$$

$$m_{CO_2}^{BB} = \alpha \cdot \left(E_{el,lighting} + E_{el,appliances} + E_{el,EHPs}\right) \quad (7)$$

where, α represents the CO_2 equivalent emission factor associated to the electricity generation. In particular, α is set equal to 0.314 g_{CO2}/kWh_{el}, according to the data indicated in the study of Maffei et al. [12] for the Italian scenario.

Finally, the operating costs of the baseline and alternative configurations of the building have been determined via the parameter ΔOC calculated by means of the following formula:

$$\Delta OC = \frac{OC^{BB} - OC^{PS}}{OC^{BB}} \quad (8)$$

where, OC^{PS} represents the operating costs associated to the "*RES_stanza*" building and OC^{BB} represents the operating costs associated to the baseline building [12]. The following formulas have been used for calculating the values of OC^{PS} and OC^{BB}:

$$OC^{PS} = UC_{el} \cdot E_{el,import} \quad (9)$$

$$OC^{BB} = \left(UC_{el} + UC_{NS,t}\right) \cdot \begin{pmatrix} E_{el,lighting} + \\ + E_{el,appliances} + \\ + E_{el,EHPs} \end{pmatrix} + C_{NS} \quad (10)$$

where, UC_{el} is the unit cost of electricity purchased from the central grid, $UC_{NS,t}$ is the unit cost related to the electricity transmission network and C_{NS} is the cost related to network services (distribution and measurement). Table 7 reports the monthly average values of UC_{el} as a function of the daily time slots F1, F2 and F3 (F1: 8:00-19:00 from Monday to Friday; F2: 7:00-8:00 and 19:00-23:00 from Monday to Friday, 19:00 - 23:00 during Saturday; F3: 0:00-7:00 and 23:00 - 24:00 from Monday to Saturday, 0:00-24:00 during Sunday and non-working days) as well as the month. The values reported in this table have been estimated in accordance with [31], by taking into account the data related to the 3-year period 2020-2022. The value of $UC_{NS,t}$ has been assumed equal to 0.00778 €/kWh, while the value of C_{NS} has been considered equal to 20.12 €/N_{POD} + 20.8 €/kW·$P_{el,PODmax}$ (where N_{POD} is the withdrawal point, $P_{el,PODmax}$ is the maximum electric power to withdrawal point) [32] by considering the data associated to the 3-year period 2020-2022.

Table 7. Monthly values of UC_{el} [31]

	Monthly Average Values of UC_{el} (2020-2022) (€/MWh)					
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**
F1	128.6	111.7	139.2	118.5	111.5	139.5
F2	119.3	110.6	145.3	124.4	119.2	138.8
F3	96.2	90.9	122.2	104.2	98.0	114.1
	July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
F1	216.3	238.1	227.8	174.7	199.2	252.2
F2	207.7	257.0	231.1	175.5	175.3	221.7
F3	170.4	214.3	189.5	135.3	138.0	176.5

6. RESULTS

The performance associated with the "*RES_stanza*" building is analyzed and compared with respect to baseline building by using the metrics reported in Section 5.

Table 8 reports the annual electric energy demand of lighting and appliances, the building annual heating and cooling demand, the annual electric energy demand of EHPs, the primary energy consumption, the mass of equivalent CO_2 emissions, and the operating costs associated to baseline building upon varying the location. This table highlights that Dragoni (CE) is characterized by the largest annual cooling demand (4.68 MWh), primary energy consumption (9.29 MWh), CO_2 equivalent emissions (1.44 $MgCO_2$), and operating costs (1.18 k€). The annual electric energy demand for lighting systems and appliances is considered constant, but the annual heating and cooling demand varies according to the meteorological data of the selected small villages.

Figure 5 reports the values of PHDS, PCDS, and $PEEDS_{EHPs}$ at different locations. This figure demonstrates that, compared to traditional windows, using the SWs (controlled according to the indoor air temperature as reported in Table 4):

a) causes a slight increase in heating demand in four out of five small villages during the heating season. The maximum variation is recorded in Visciano (PHDS equal to -7.32%) and it attributable to a reduction in solar gains (the variation is negligible in the case of Serre).
b) allows to obtain a cooling demand reduction, regardless of the village, during the cooling season. In particular, PCDS values vary between 47.77% and 50.43%. This decrease is attributable to the thermal load reduction.
c) enables, in all five small villages, a reduction of the annual EHPs electric energy consumption, with values of $PEEDS_{EHPs}$ ranging between 41.26% and 50.43% (thanks to the cooling load reduction).

Table 8. Annual performance of the baseline building upon varying the location

	Visciano (NA)	**Dragoni (CE)**	**Cerreto Sannita (BN)**	**Bisaccia (AV)**	**Serre (SA)**
Annual electric energy demand of lighting systems and appliances (MWh/year)	3.39	3.39	3.39	3.39	3.39
Annual heating demand (MWh/year)	0.41	0.14	0.78	0.61	0.34
Annual cooling demand (MWh/year)	4.04	4.68	3.44	3.58	4.21
Annual electric energy demand of EHPs (MWh/year)	1.10	1.21	1.04	1.03	1.13
Primary energy consumption (MWh)	9.08	9.29	8.94	8.94	9.14
Mass of equivalent CO_2 emissions ($MgCO_2$)	1.41	1.44	1.39	1.39	1.42
Operating cost (k€)	1.16	1.18	1.14	1.14	1.16

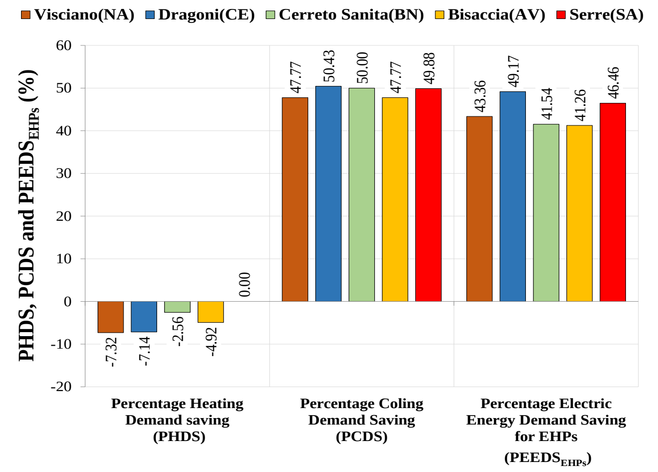

Figure 5. Energy savings achievable by using SWs upon varying the location

Figure 6 describes the annual electric energy flows of the "*RES_stanza*" building (electric energy produced by the PV panels, electric energy discharged from the battery, electric energy sold by the network, and the electric energy purchased from the network) depending on the selected small villages, underlining that:

a) the values of the electrical energy produced by the PV panels (characterized by the same number, type and orientation for the five location) are different, ranging from 13,846.5 kWh (in the case of Cerreto Sannita) up to 14,733.1 kWh (in the case of Visciano);
b) the value of electric energy discharged from the battery and used to satisfy the energy demands of the building is almost constant upon varying the five locations, with values ranging from 722.1 kWh (Visciano) up to 778.8 kWh (Serre);
c) the electric energy sold to the network is more than double the amount required by the building, whatever the village is;
d) the electric energy purchased from the network is zero for all five cases. This means that the PMB is totally energy independent thanks to the utilization of renewable sources.

Considering that the "*RES_stanza*" building achieves energy self-sufficiency, it can be underlined that the values of PES, ΔCO_2, and ΔOC are consistently at 100% across all analyzed scenarios.

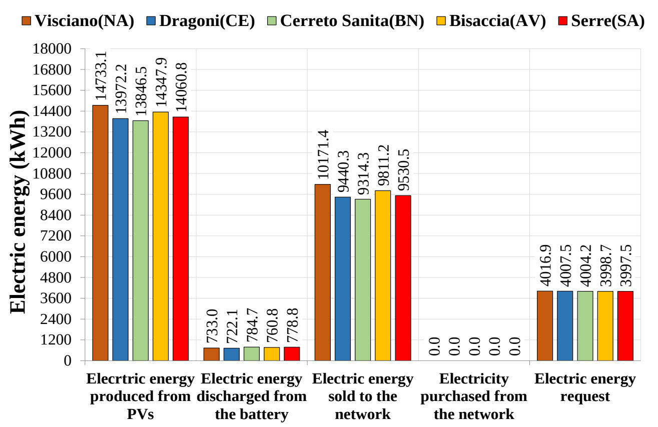

Figure 6. Annual energy flows the "*RES_stanza*" building of the upon the city

7. CONCLUSIONS

The performance of an innovation prefabricated moveable building equipped with smart windows and PV panels coupled with electrical storages have been simulated and assessed for smart/co-working applications in comparison with conventional prefabricated buildings upon varying weather conditions of Campania region (south of Italy). This work is one of the outcomes of the research project titled "New movable systems for smart/co-working taking advantage of life quality, sustainability and energy efficiency (RESTANZA)" [9]. The simulations highlighted that using smart windows controlled based on the indoor air temperature can reduce the cooling demand, regardless of the village, during the cooling season (from 47.77% up to 50.43%) and the annual EHPs electric energy consumption (from 41.26% up to 50.43%). The integration of PV panels and batteries allows to fully cover the electric demands of the proposed building via renewable sources, so that it becomes totally self-sufficient from an energy point of view.

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