Hirvonen, Janne; Wang, Yangmin; Jokisalo, Juha; Kosonen, Risto

SUREFIT- Sustainable solutions for affordable retrofitting of domestic buildings

Published in:
Proceedings CLIMA 2022 : 14th REHVA HVAC Congress, 22- 25 May 2022, Rotterdam

DOI:
10.34641/clima.2022.210

Published: 27/05/2022

Document Version
Publisher's PDF, also known as Version of record

Surefit - Sustainable solutions for affordable retrofitting of domestic buildings

Janne Hirvonen [a, b], *Yangmin* Wang [a], *Juha* Jokisalo [a, c], *Risto* Kosonen [a, d] .

[a] Department of Mechanical Engineering, Aalto University, Espoo, Finland, janne.p.hirvonen@aalto.fi [b] Faculty of Built Environment, Tampere University, Tampere, Finland

[c] Smart City Center of Excellence, TalTech, Tallinn, Estonia

[d] College of Urban Construction, Nanjing Tech University

Abstract

To reduce greenhouse gas emissions caused by buildings, the EU has declared the Renovation Wave strategy with the goal of retrofitting existing buildings to be more energy efficient. Long-term emission reductions require both speedy and cost-efficient renovation methods. The Surefit project aims to develop practical means for effective building retrofitting. The aim is to reduce emissions and CO_2 emissions by 60%, to reduce installation time by 40% and to demonstrate a payback period of less than 10 years. New modular technologies for improving energy efficiency and indoor conditions will be tested. This study examines three demonstration buildings chosen from three European countries (United Kingdom, Spain and Greece). Each demonstration building was modelled using IDA-ICE and their energy demands simulated to provide the baseline for energy efficiency. Then, various retrofit options were tested using dynamic computer simulations, with the aim of finding out the impact of the different technologies in different climates and under different energy mixes. This study focuses on measures integrated to the building envelope and structure, namely bio-based thermal insulation, solar electric low-energy windows and phase-change materials. Thermal insulation of the building envelope using bio-aerogel reduced CO_2 emissions by 41-43% in continuously heated buildings, but only by 15% in an intermittently heated building. The emission impact of PV glazing was only 3-8%. PV glazing resulted in a slight reduction of overheating in Spain and UK, but increased the temperatures in Greece, because it could not replace the external shading device that was removed when PV glazing was installed. The benefits of PCM were low. A smart ventilation control scheme or a different type of PCM material could help in attaining additional benefits.

Keywords. Surefit, Energy retrofit, Energy efficiency, Emission reduction, Indoor comfort
DOI: https://doi.org/10.34641/clima.2022.210

1. Introduction

Energy use in buildings is the cause about 36% of the CO_2 emissions in the EU [1]. By 2050, most of the current building stock will still be in use, with energy efficiencies much worse than those of new buildings being built now and in the future. The Renovation Wave initiative aims to increase the rate of retrofitting of old buildings to also reduce emissions in the already existing buildings [2].

In this spirit, the Surefit project examines the retrofitting potential of old buildings in various European countries [3]. The goal is to test new energy efficiency technologies and find cost-effective and fast methods for reducing energy use and emissions by 60%. This calls for modular technologies and easy to install packages, which fit typical buildings in each region. In the first stage, the buildings will be modelled and technology impacts will be estimated through dynamic simulation. In the second stage, the retrofits will actually be completed and the new technologies installed in the demo buildings. This is followed by real-time monitoring of energy use and indoor conditions, which will be used to refine the initial simulation models of the buildings.

In this study, we examine some of the technologies and focus on envelope upgrades in three countries: Spain, Greece and the United Kingdom. We also examine the impact of heating schedule on the benefits of thermal insulation.

2. Research methods

2.1 Simulation tool

To obtain the hourly energy demand profiles of the demo buildings, they were modelled and simulated in IDA-ICE 4.8 [4]. IDA-ICE is has been validated for producing accurate results of building energy use and indoor conditions [5] [6].

2.2 Demo building descriptions

The UK demo building is one half of a semi-detached house. Space heating is provided by a gas boiler and hot water heating by a direct electric heater. An additional electric radiator is also utilized in the living room. The building is located in Nottingham, United Kingdom. The region has a temperate oceanic climate with mild summers, cool winters and abundant rain (Köppen climate classification Cfb).

The Spanish building is a terraced house of four apartments. Each apartment has two storeys of living area plus an unheated basement. Space and hot water heating is provided by a gas boiler. The building is located in Valladolid, Spain. It is a region with hot summers and relatively cold winters, with large temperature shifts between night and day (Csb).

The Greek demo building is a small apartment building with two apartments, connected on two sides to neighbouring buildings. Space heating is provided by an oil boiler and hot water by a solar boiler. Cooling is provided by electric air-conditioners. The Greek demo building is located in Athens, Greece. This area has a warm climate with hot summers and mild winters (Csa).

Figure 1. Photographs of the demo buildings. From left to right: UK, Spain, Greece.

Table 1 shows the properties of the building envelope in each demo building before retrofit measures. Some of the data was provided by building owners. Some values were not known, so these data points were obtained from building archetypes shown in the literature. Literature values were used for estimating the envelope U-values for the Spanish demo building and the infiltration value for the Spanish and Greek demo buildings.

Table 1. Properties of the building envelope in the demo buildings before retrofit measures.

	Wall	Roof	Windows	Infiltration
	(W/(m²K))			n_{50} (ACH)
UK	2.1	0.22	2.4 / 2.5	16.1
Spain	1.7 [a]	1.6 [a]	2.8 / 5.7	6.7 [b]
Greece	1.0	3.9	3.5 / 5.9	6.7 [b]

[a] TABULA WebTool [7]
[b] Feijó-Muñoz et al. (2019)[8]

In Mediterranean countries, it is typical to only heat the building intermittently, at certain hours of the day. In regions like the UK, continuous heating is used instead.

The UK demo building was heated continuously to provide 20 °C indoor temperature. The Spanish demo building was heated using a varying setpoint, 18 or 20 °C during the day (hours 14-23) and 17 °C during the night and morning. The Greek building was heated only intermittently, 2 hours in the morning (7-9) and 3 hours in the evening (19-22). This intermittent heating has a big impact on indoor temperatures and energy use. To improve comparability, the building was also simulated using a continuous heating schedule, which always keeps the building at 20 °C during the heating season.

2.3 Model validation

Measured data of building energy use was available, but of varying quality. Monthly consumption was available for the UK demo building. The reference building model was validated by normalizing the measured consumption using monthly heating degree days and comparing the results to the simulations. Simulated energy demand was within 5% of the measured value.

For the Spanish demo building, bi-monthly energy use data split between 2019-2020 was available for only one of the four apartments. Hot water use according to statistics was removed to obtain the space heating demand. Monthly heating degree days for Valladolid were used to split the bi-monthly energy use data to monthly values and to normalize it to make it comparable to the simulated energy use. The simulated demand was within 12% of the measurements, which was deemed acceptable, considering the uncertainties in both the building envelope properties and energy use data. The monthly comparison is shown in **Figure 2**.

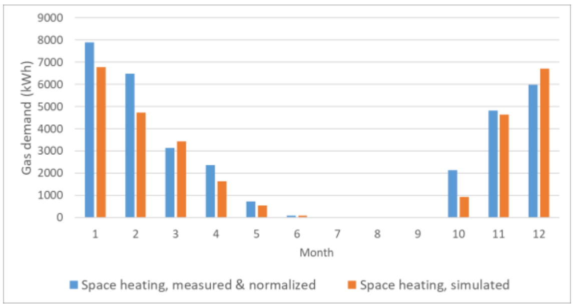

Figure 2. *Measured and simulated space heating fuel use in the Spanish demo building.*

For the Greek demo building only average annual energy use data was available and only for one apartment. Detailed validation was not done due to lack of data. **Table 2** shows the measured and simulated total heating energy use (space heating and domestic hot water) of all demo buildings on an annual level.

Table 2*. Measured and simulated energy demand.*

Heat demand, SH + DHW	UK	Spain	Greece
(kWh/m2)	Monthly	Bi-monthly	Annual
Measured, original	181.5	113.4	36.4
Measured, HDD-corrected	191.3	125	-
Simulated	182.3	115	42.6

2.4 Emissions and primary energy

Each country has a different energy generation mix, which impacts the primary energy and CO_2 emission factors of energy generation. These are shown in **Table 3**.

Table 3. *Emission and primary energy factors.*

	Emission factors (kg-CO_2/MWh)		Primary energy factors (kWh/kWh)	
	Heat	Electricity	Heat	Electricity
UK	203	231	1.13	1.5
Spain	199	190	1.07	1.51
Greece	264	572	1.1	2.9

2.5 Retrofit plan

The envelope retrofit package includes three technologies: bio-aerogel thermal insulation, PV-glazed low U-value windows and phase-change material (PCM). These were applied in sequence to see their impact on building energy efficiency and indoor conditions.

Table 4*. Retrofit measures applied to the buildings.*

-	Installed amount (m^2)		
Technology	UK	Spain	Greece
Bio-aerogel, 5cm on all external walls	81	282	412
Bio-aerogel, 5cm on roof	73	112	108
PV-glazing, on south-facing windows	13	20	11
PCM, 3.2cm on living area ceilings	67	198	154

The bio aerogel was installed on the external walls and roof in a 5 cm layer in each building.

The PV glazing was only installed on the south face of the building exposed significantly to the sun. These windows provide thermal insulation, solar shading and solar electricity generation (though at a low efficiency). There is no such integrated component in IDA-ICE, so the integrated solar electric capacity was modelled as a separate PV system, installed in a vertical position.

The PCM was installed on the ceiling of each room in 3.2 cm layers. The purpose of PCM is to serve as passive energy storage and cooling measure, which absorbs excess heat during the day and releases it during the night. While the salt hydrate product has a nominal melting point of 22 °C, experimental results by the PCM manufacturer show that the phase change happens over a wide range of temperatures. The PCM was modelled in IDA-ICE using the enthalpy method, such that the temperature range of phase change was divided to sections of varying partial enthalpy values (**Figure *3***). Higher enthalpy values indicate a better capacity for absorbing heat at that temperature value. For solidification, the melting curve was shifted by 2 °C.

Properties of the technologies

Bio-aerogel:

k = 0.024 W/(mK), ρ = 430 kg/m³, c_p = 2260 J/(kgK)

PV glazing:

Window U-value = 0.6 W/(m²K), g-value = 0.53, electricity generation efficiency η_{PV} = 3.5%

PCM:

rho = 1530 kg/m³, c = 2200 J/(kgK),

k = 0.54 W/(mK),

$h_{f,ave}$ = 200 kJ/kg.

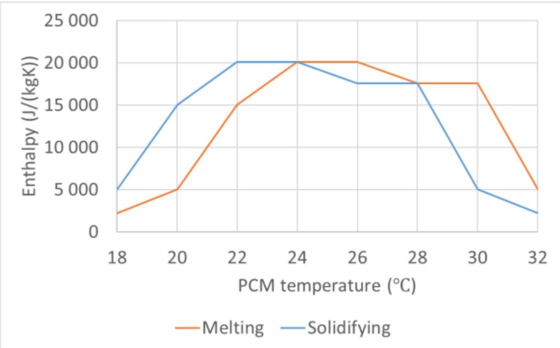

Figure 3. PCM enthalpies used in the simulation.

3. Results and discussion

3.1 Energy use

Figure 4 shows an overview of the emission impacts of the retrofit actions. A more detailed account can be seen in **Table 5**, which shows the fuel, electricity and primary energy use as well as the CO_2 emissions in the examined buildings. Primary energy demand was reduced significantly in the Spanish (-40...-47%) and UK cases (-40...-44%). In the Greek cases utilizing the default intermittent heating, the reduction in primary energy use was much smaller (-15...-25%).

This difference is explained by the intermittent heating pattern used in the Greek building. Since space heating was turned on for only 25% of the heating season, the share of space heating vs. domestic hot water was smaller than in continuously heated buildings. Therefore, measures that reduce space heating demand (thermal insulation and window upgrades) had a smaller impact.

When the Greek demo building was operated under a continuous heating schedule, the reference energy demand was tripled from 37 kWh/m² to 109 kWh/m². As space heating use was more extensive, the energy efficiency measures became more impactful and primary energy demand was reduced by 43 to 51%. This is similar to both the Spanish and British buildings, despite the differences in climate and starting insulation levels.

Table 5. *Specific energy demand and emissions in the buildings before and after retrofitting.*

	Fuel (kWh /m²)	Elec (kWh /m²)	Primary energy (kWh /m²)	Emissions (kg-CO_2 /m²)
UK				
Original	182.3	24.5	242.7	42.7
Bio-aerogel	98.5	22.3	144.8	25.1
Bio-aerogel + PV glazing	93.9	20.0	136.1	23.7
Bio-aerogel + PV glazing PCM	93.1	20.0	135.2	23.5
Spain				
Original	115.0	19,4	152.4	26.6
Bio-aerogel	58.0	19.3	91.1	15.2
Bio-aerogel + PV glazing	51.1	18.2	82.1	13.6
Bio-aerogel + PV glazing + PCM	50.2	18.2	81.2	13.4
Greece, intermittent				
Original	36.8	14.8	67.0	18.2
Bio-aerogel	30.6	13	56.9	15.5
Bio-aerogel + PV glazing	27.9	11.7	51.6	14.1
Bio-aerogel + PV glazing + PCM	27.2	11.5	50.5	13.8
Greece, continuous				
Original	109.3	18.5	152.8	39.3
Bio-aerogel	56.5	14.3	87.7	23.1
Bio-aerogel + PV glazing	46.6	13.4	75.2	20.0
Bio-aerogel + PV glazing + PCM	45.9	13.4	74.5	19.8

The biggest impact on heating energy use came from the thermal insulation of walls. The window upgrades also had a noticeable impact, but the area covered by them was much smaller and limited the potential. The utilizable solar electricity produced by the PV glazing was small in all cases: 2.3 kWh/m² in the UK case, 1.1 kWh/m² in the Spanish case and 1.7 kWh/m² in the Greek case. This reduced purchased electricity consumption by 10%, 6% and 13% in UK, Spain and Greece, respectively.

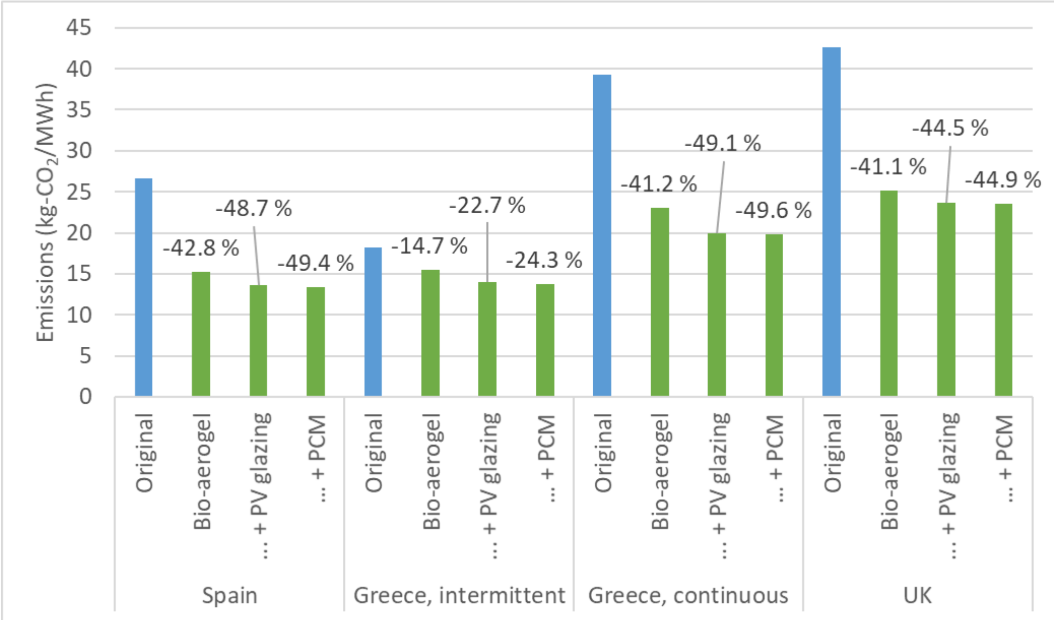

Figure 4. *CO_2 emissions and relative reduction in each demo building before and after retrofitting.*

3.2. Indoor conditions

In each demo building, the envelope upgrades influenced the indoor temperature conditions. The conditions are shown in **Figure 5**. The results show the fraction of time during the whole year that the temperature is above or below the presented limit. It also shows the annual maximum temperature obtained in the simulation.

Less time was spent below the heating setpoint due to the thermal insulation and low U-value windows. Similarly, the low g-value in the windows slightly reduced overheated hours in the UK and Spanish cases. However, in the intermittently heated Greek building, the new windows actually increased overheating by raising the maximum temperature and increasing the time spent above 25 °C. This happened, because an external shading device that covered the balcony in the reference case was removed to see the impact of the PV glazing on preventing overheating. The solar protection effect of the PV glazing was not enough to compensate for the lack of external shading.

Due to intermittent heating, the Greek building was significantly cooled down between the heating periods. This increased the heating power demand when heating was turned on again. Often, the short heating period was not enough to reach the heating setpoint, pointing to a capacity problem. However, improved thermal insulation reduced the time spent below the heating setpoint by 4%-points in the intermittently heated case. The Spanish case was also slightly below setpoint for 5% of the time, but this was reduced to zero by thermal insulation.

The PCM caused a very small reduction (0.4 – 1.9%) of heating demand in the demo buildings. It's main purpose was to reduce overheating, but it only resulted in a 0.4 – 0.6% reduction in the UK and Spanish cases and actually increased overheating in the Greek case with intermittent heating.

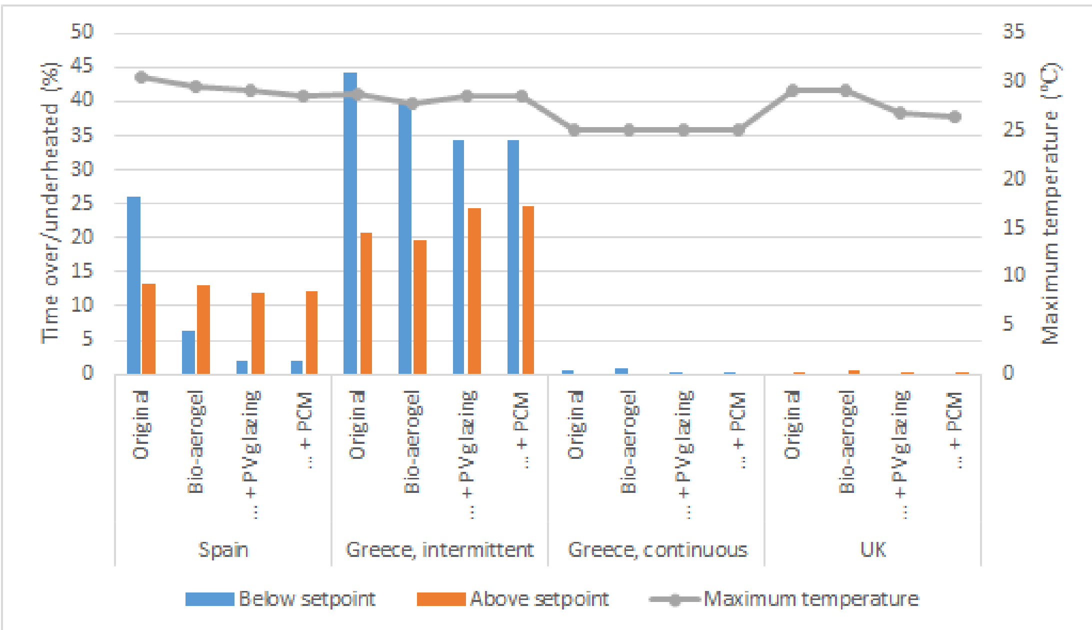

Figure 5. *Indoor conditions in all demo building before and after retrofitting.*

3.3 Discussion

Validation of the specific simulation models was challenging, due to many uncertainties in the data. For example, energy use levels for a whole building had to estimated from measurement data of a single apartment. Some consumption data was given on an annual or bimonthly level, which prevented accurate monthly matching. In addition, infiltration and thermal conduction values of some structural components were uncertain, requiring the use of typical values from statistics.

PCM proved to be of little benefit. In some cases it reduced peak temperatures while in others it raised them, but the impact was only 1 °C or less. The Spanish case had theoretical potential to benefit from the PCM, as even in summer, the outdoor temperatures are reduced significantly during the nights. However, while windows were opened during nights, this was not enough to cool the building and solidify the PCM for significant additional heat absorption. For example, an active blower system might be necessary to benefit from the ambient cooling capacity for both direct space cooling and for PCM regeneration. The wide temperature range for phase change also means that the whole heat capacity cannot be utilized when the temperature remains high for a long time.

In the second stage of the project, the retrofit measures determined to be the most effective by simulations will be installed into the demonstration buildings. Real-time monitoring will be used to assess the accuracy of the simulations and to improve the operational performance through advanced control algorithms. The measurements will be used for validation and further model development.

4. Conclusions

Additional thermal insulation of external walls and roof was very effective for reducing heating energy use. The bio-aerogel insulation reduced CO_2 emissions by 41 to 43% in all demo buildings. Despite the large differences in the initial thermal insulation levels, all buildings received very similar benefits from additional insulation. However, using an intermittent heating profile reduced the impact of insulation on energy use to 15% in the Greek case. Using a continuous heating profile increased the benefit of thermal insulation, because the share of space heating out of the total energy use was higher. This will be important in the cost evaluation phase, as the capital costs of retrofitting will be the same, regardless of the heating strategy. Intermittent heating reduces energy use at the cost of thermal comfort. Continuous heating improves thermal comfort and the potential benefits of energy saving measures, but raises the absolute energy use.

PV glazing provided small additional emission cuts, reducing CO_2 emissions by 3% in the UK, by 6% in Spain and by 8% in Greece. This was mainly due to lower thermal conductivity, with the solar electric generation playing a smaller role. The PV glazing could not replace external solar shading as overheating protection.

The benefit of PCM for passive cooling was questionable. Active night-time ventilation might be necessary to regenerate the PCM for the next day. A material with a more discrete melting temperature range would also help.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 894511. The study received further funding from the FINEST Twins project, that is co-funded by the European Union (Horizon 2020 programme, grant number 856602) and the Estonian government. The authors would also like to thank the partners of the Surefit project, AMSolutions, Faculdade Santa Maria, ISQ Group, PCM Products and the University of Notthingham.

References

[1] European Parliament, "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings." 2010.

[2] European Commission, "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives." European Commission, 14-Oct-2020.

[3] Surefit, "Surefit Project," 01-Jan-2021. [Online]. Available: https://surefitproject.eu/.

[4] EQUA Simulation AB, "IDA ICE - Simulation Software," 2019. [Online]. Available: https://www.equa.se/en/ida-ice. [Accessed: 08-Aug-2019].

[5] EQUA Simulation AB, "Validation of IDA indoor climate and energy 4.0 with respect to CEN standards EN 15255-2007 and EN 15265-2007," May 2010.

[6] P. Loutzenhiser, H. Manz, and G. Maxwell, "Empirical validations of shading/daylighting/load interactions in building energy simulation tools," IEA - International Energy Agency, 2007.

[7] T. Loga, J. Calisti, B. Stein, L. Ortega, and B. Serrano, "TABULA WebTool," *TABULA WebTool, building energy efficiency database*, 11-Jun-2017. [Online]. Available: https://webtool.building-typology.eu/#bm. [Accessed: 05-Jan-2022].

[8] J. Feijó-Muñoz, R. A. González-Lezcano, I. Poza-Casado, M. Á. Padilla-Marcos, and A. Meiss, "Airtightness of residential buildings in the Continental area of Spain," *Building and Environment*, vol. 148, pp. 299–308, Jan. 2019.