Techno-economic evaluation of a thermal-power microgrid in a public building

Maria Teresa Moreira da Cruz Borges de Assunção

teresa.borges.assuncao@gmail.com

Instituto Superior Técnico, Universidade de Lisboa, Portugal
December 2022

ABSTRACT

Buildings represent 30% of final energy consumption worldwide, thus playing an important role in decarbonizing the energy sector. Hence, the European Union (EU) obliged all new public buildings to be nearly Zero Energy Buildings (nZEB) from 2019 and all other building from 2021 onwards. The EU has also been investing in projects that focus on retrofitting of existing buildings. The IMPROVEMENT Project aims to convert existing public buildings into nZEBs, and "improve the implementation of public policies on energy efficiency". The Portuguese pilot is in a public research building in Lisbon, that has been retrofitted to a thermal-power microgrid as energy efficient and renewable-powered as possible. In this work, a techno-economical assessment of that microgrid is presented. A fully detailed characterization of the microgrid is carried out, and improvements in its comfort, thermal and electrical performance are analyzed. The microgrid proved to be nZEB at a monthly scale. New insulation increased comfort in the winter and decreased comfort in the summer. Phase change material (PCM) introduction into a wall increased comfort in the summer, but should show more promising results if combined with natural ventilation at night. Economic gains are assessed (using Net Present Value and Simple Payback Period), to attempt to establish which retrofitting measures are economically viable. Heat pumps are highly efficient heating and cooling systems, and economically viable. PV modules coupled with lead acid batteries for self-consumption are economically viable when the option to sell surplus electricity is available. Replacing older lamps with LED lamps is economically viable even for a relatively low consumption. An evacuated-tube solar collector system did not show, even in an optimistic scenario, to be economically viable. Monitoring is crucial for improvement in energy efficiency, but it is not always economically viable. Finally, user behaviour should also promote energy efficiency.

Keywords: Nearly Zero Energy Building, Public Buildings Energy Efficiency, Thermal and Power Microgrids

1 Introduction

Climate change and environmental degradation are one of the world's most pressing concerns. There is the need to reduce greenhouse gas emissions, caused mostly by fossil fuel-based energy sources. In 2020, buildings represented 30% of final energy consumption worldwide[1], and 40% in European Union (EU) countries. In 2010, the EU Directive 2010/31 introduced the nZEB concept, and obliges all new public buildings from 2019, and all new buildings from 2021 onwards, to be nZEB [2]. As the problem remains for older buildings, the EU has also been investing in projects that focus on tackling energy poverty and low-performing buildings, and renovation of public buildings[3]. The IMPROVEMENT Project is being jointly developed in Portugal, Spain, and France. Its goal is to demonstrate the technical and economic viability of the retrofitting of 2 pilot buildings, one in Portugal in a real public research building, and one in Spain in a laboratorial facility replicating the behaviour of service and commercial buildings. The Portuguese pilot is in National Energy and Geology Laboratory (LNEG, in Portuguese). At earlier stages of the project, the pilot was retrofitted to have its thermal-power system as energy efficient and renewable powered as possible. This thesis is integrated into IMPROVEMENT, and its objective is to perform a techno-economical assessment of the thermal-power microgrid implemented in the Portuguese pilot. This is done by performing 3 main tasks: carry out a fully detailed characterization of the retrofitted pilot system; to validate the pilot energy generation and consumption, as well as improvements in its comfort, thermal and electrical performance; investigate whether the investment on the pilot has a positive return, to eventually serve as basis for energy policies.

2 Literature review

2.1 nZEB examples

The solar estate, built in Germany in 2006, is a plus energy building – generates more energy than it consumes. It has 59 houses, designed with the passive house standards: living room and bedrooms towards south, kitchens, bathrooms and other service areas facing north, high insulation, efficient ventilation with heat recovery, electricity-saving appliances, and appropriate user behaviour. Energy monitoring is performed as a full balance of 50 houses, with heating and electricity on demand side, and solar electricity (from photovoltaic (PV) panels covering the roofs) on the generation side[4].

ÉcoTerra, in Canada, is a single detached home with 2 floors and a semi-basement. It has high thermal insulation materials and air-tight construction, combined with a heat recovery ventilator (HRV), that can recover up to 76% of heat lost through ventilation, insuring both thermal comfort and air quality. On the generation side, the it has a building integrated photovoltaic thermal (BIPV/T) system, that generates PV electricity, and thermal energy by extracting heat from the panel into an air system. Air heated by the BIPV/T is used to dry clothes, to pre-heat water through an air-to-water heat exchanger, and thermal mass heating. Underground, a geothermal heat pump is responsible for space heating and cooling, and assists in water heating. Additionally, the house uses heat released from these machines to supplement space heating by stack effect [5].

The Solar Building XXI, in Lisbon, has PV systems serving as shading for two car parks, and as building façade – creating an air cavity, providing extra ventilation and space heating. This building also has a ground cooling system. It provides incoming pre-cooled air into the building, through an underground tube, using the earth as a cooling source and avoiding the use of an active cooling system. Other energy efficiency measures include natural ventilation and lighting, through windows on both sides and a skylight, thermal mass and venetian blinds for sun shading. It also has thermal solar collectors for water and space heating. [6]

2.2 Retrofitting public buildings

Irulegi et a. analyze the best retrofit strategies for a building of the University of the Basque Country. Monitoring confirmed a reported overheating problem during shoulder months. It was found that the comfort temperature was around 5 °C lower than theoretical results predicted, showing that user preferences are dependent on cultural and climatic characteristics. The implemented strategies were thermal bridge improvement, heat recovery ventilation with air-to-air heat exchangers, replacing the window glazing system in north-facing façades for less heat losses and more solar gains in the winter, and night and daytime (with users in control) natural ventilation in the summer. These induce a large reduction in discomfort hours and heating needs [7].

A study performed on a building of the Polytechnic University of Catalunya includes the possibility of 2nd life Li-ion batteries. Using real data, it proposed solutions to retrofit the energy generation system, not including building energy efficiency measures, as well as try and cut off natural gas consumption at an affordable cost. Optimizing the energy generation system by maximizing Net Present Value (NPV) and minimizing CO_2 emissions, the study concludes that: (a) it is feasible to include 2nd life batteries into the system; (b) PV panels are highly profitable; (c) it is, in this case, possible to cut off natural gas at an affordable cost; (d) the optimized system does not include solar thermal collectors, as they compete with PV panels for roof space. Two optimized systems are proposed, both including PV panels, 2nd life batteries, a biomass boiler, and the existing mechanical chiller. The first, not cutting off natural gas, also includes a gas boiler, a cogeneration module, and an absorption chiller. The second, cutting off natural gas, has instead a heat pump and a thermal energy storage for heating [8].

Cho et al. study a retrofit plan for a century old historic university building in Seoul. The highest heat losses occurred through thermal bridges, and U-values on roofs and walls were much higher than the energy-saving standards in Korea. Eight possible technologies were evaluated, and gains were estimated using an energy simulator. Worth to implement measures, also considering cost, included: the application of extruded polystyrene insulation to interior of roof and walls, replacing window system from clear glazing and aluminum frame to low emissivity double glazing and PVC frame, application of an airtight tape construction, change to LED lighting, and installation of a high-efficiency HVAC system [9].

Another study in Seoul analyzed PCM application as a passive retrofit system on an educational building. The building was retrofitted with a shading system (SS), that prevents overheating in the summer, but may cause an increase in heating consumption. As such, the application of three different PCMs to the SS was simulated and compared to the system both before and after the shading retrofit. The results show a cooling energy consumption reduction by 41% after SS installation, and 44% with PCM, the latter with the additional benefit of a smoother temperature increase due to the time lag effect. PCMs increased heating consumption, however the total energy consumption reduced by 6.7%. A simple payback period (SPBP) is 37.2 years for SS and 34.7 years with PCM, and choice between PCM material is indifferent [10].

2.3 Energy management commercial tools

A building energy management system (BEMS) is the system responsible for monitoring, controlling, optimizing, and reporting on all energy-related systems in a building[11]. The BEMS market is expected to grow in the coming years, lead by Siemens AG, Honeywell, Johnson Controls International PLC, and Schneider Electric[11]. Their BEMS tools integrate and optimize HVAC, lighting, and electrical supply control, as well as controlling ventilation and monitoring air quality in terms of temperature, relative humidity and CO_2 levels. [12–15]. Fire safety and security are some of the non-energy related features included in these BEMS. All four tools have user-friendly dashboards and indicators, as well as an open software architecture. Moreover, these tools are (in theory) highly scalable and implemented in a wide range of building end-uses.

3 System characterization

3.1 Pilot area and energy efficiency measures

As previously mentioned, the Portuguese pilot is part of a building in LNEG, Lisbon. As Figure 1 shows, the pilot area is composed of six contiguous rooms: three individual offices (1049, 1050, 1051), a multiuse room (1052), a meeting room (1054), and a corridor (1048) connecting all other rooms. It is on the ground floor of a large building, and three of its walls – SW, SE and NE directions – are facing the exterior. Being a public research facility, the pilot's energy needs are space heating and cooling, ventilation, lighting, and electrical supply for different appliances, e.g., computers. Between July 2021 and February 2022, the pilot underwent renovations where several energy efficiency measures were applied.

A new insulation layer was installed in all ceiling within the pilot area. Also focusing on thermal comfort, an extra wall layer was added to both walls underneath the windows in Multiuse Room, increasing thermal inertia by imposing an air layer between interior and exterior walls. During the development of this thesis, DuPont Energain PCM panels were inserted into the air layer. These panels are 60% made of paraffin wax, a PCM with a melting temperature of 21.7°C [16]. PCMs absorb great amounts of energy as latent heat while melting, preventing (to a certain extent, when the whole material has melted) room surface temperature to rise above their melting temperature. When surface temperature decreases, the material solidifies, releasing the stored latent heat. Thus, they aim to reduce cooling needs during the summer, which, in the pilot case, are higher than heating needs during winter [17].

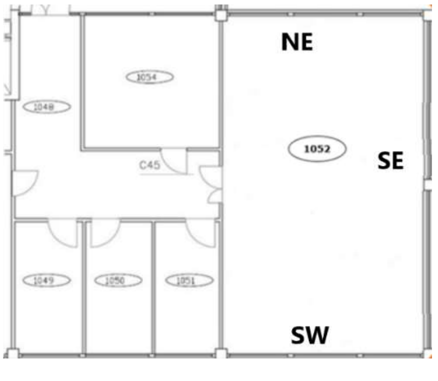

Figure 1. Plant of pilot area [17]

Regarding lighting, old 150 W fluorescent lamps were replaced by 45 W LED panels. These panels allow for intensity regulation, proportional to their consumption (meaning that most of the time they are consuming less than their rated power). Installing a monitoring system (Schneider's EcoStruxure) allows for a continuous improvement in energy efficiency and user behaviour.

3.2 Thermal system

The thermal system main components are: two solar collectors of the evacuated-tube type; a 300L solar storage tank, connected to the solar collectors; a reversible air-water heat pump; a 100L buffer tank; a 1000L storage tank; fan coils: in each individual office 1049 and 1050, in Meeting Room, and in Multiuse Room.

In Winter/Summer, the system's purpose is to heat/cool the rooms. This is achieved by running hot/cold water through the fan coils, that then exchange heat with surrounding air, increasing/decreasing room temperature.

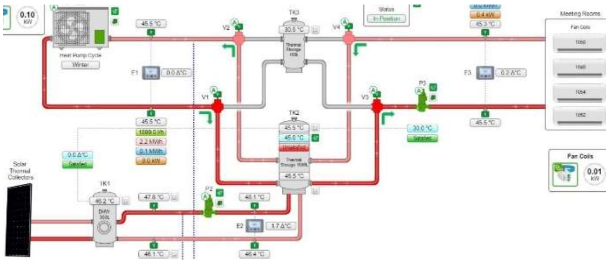

Figure 3. Scheme of thermal system operation

Figure 3 was taken from the BEMS dashboard, in winter mode. In winter, the system prioritizes solar heating over the heat pump. Water is pumped through the STC in a closed circuit, heating water in the solar tank TK1 through a heat exchanger. Another closed-circuit pumps hot water from TK1 to storage tank TK2, heating water in TK2 through a heat exchanger. If the solar system is not enough to keep the temperature in TK2 above a certain temperature, the HP is switched on, and off again when it rises above a maximum value. Pump P3 is responsible for pumping water from TK2 to the fan coils, and back. In Summer mode, the solar thermal system is excluded as only cooling is needed, and the HP provides all cooling power. The process is analogous to the Winter mode. Air renewal is important to maintain comfort inside the rooms. An HVR filters and flows outside air into Multiuse and Meeting rooms, and inside air to the exterior, through different ventilation pipes, transferring heat (or cold) from inside to outside air, recovering some of its energy.

3.3 Electrical system

The electrical system main components are: a PV array with a rated power of 4.05 kWp; a PV inverter; a wind micro-turbine (developed at LNEG for urban applications) with a rated power of 2.5 kW; wind rectifier and wind inverter; lead-acid batteries with 48 V and 660 Ah (C120) of voltage and capacity, respectively; and a hybrid inverter.

On the generation side, PV array and wind turbine, along with their inverters, generate electricity, when irradiance and wind, respectively, are available. On the consumption side, power is consumed in the microgrid in power sockets, lighting and to power the fan coils and heat pump.

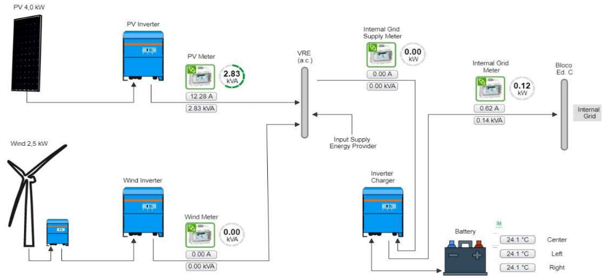

Figure 2. Scheme of electrical system operation

The hybrid inverter is also a rectifier. It receives AC power from PV and wind inverters, or from the grid, and it provides AC power to the microgrid. It also charges and discharges the batteries, providing and receiving DC power. When microgrid generation is higher than its demand, it stores excess energy by charging the batteries, and it discharges them when the opposite happens. When batteries fall below a certain state of charge (SoC), it acts as a bypass while power is drawn from the grid.

3.4 Energy monitoring and management system

In the pilot area, there are 3 relevant sensors measuring room temperature (°C): Office (1050), Multiuse Room, and Meeting Room. There are 3 enthalpy meters: around heat pump P1, around the solar system, and around the fan coils. Regarding electrical energy, there are 6 energy sensors, measuring: total pilot consumption, lighting in Office, a power socket in Office, lighting in Multiuse, total of all four fan coils (two offices, Multiuse, Meeting), and heat pump. There are 4 power meters, measuring: energy supplied by the PV inverter, energy supplied by the wind inverter, energy supplied to the hybrid inverter, and energy supplied by the hybrid inverter. Energy consumed by the HVR, energy monitoring system and management system itself are not being monitored. For simplicity, they are not accounted for in building electricity consumption, even though they belong to the pilot area total load.

4 Experimental analysis

4.1 Indoor temperature

To evaluate whether the renovations had an impact on building insulation, several statistical analyses were performed. Statistics are used as it is not possible to recreate the exact same temperature (and utilization) conditions, as this is a real building and not a laboratory. Excel F-test and t-test were used to check for statistically similar variances and mean, respectively. For both winter and summer, 5 days after renovations (with no room climatization) and 5 days before renovations were gathered, with statistically similar outside temperatures.

Multiuse room is the largest and most exposed to the outside. Graphs of its room temperatures in winter, before and after renovations, are shown below.

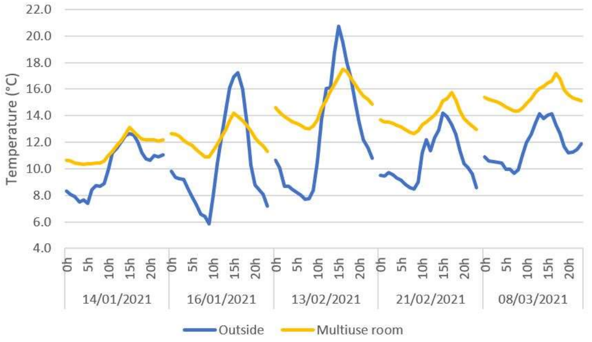

Figure 4. Winter Multiuse room temperature before renovations

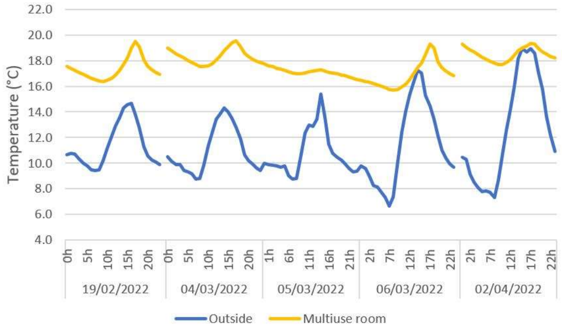

Figure 5. Winter Multiuse room temperature after renovations

One can clearly see that room temperatures are different in 2021 and 2022. F-test and t-test prove that both their mean temperature and variance are different, while for the outside temperature the tests consider no difference. The average outside mean temperature and (pooled) variance are, respectively, 11.2 °C and 8.03 °C^2. Mean room temperature was 13.6 °C in 2021 and 17.6 °C in 2022, meaning that now the room has potentially much lesser heating needs as it is closer to the comfort temperature. Moreover, the variance is considerably less after renovations (3.32 °C to 0.93 °C), meaning that the new insulation makes the room more thermally stable.

A complementary analysis of each wall's temperature was also made. It concluded that all wall temperatures are higher and vary less (except for the SW wall) after renovations, demonstrating that the room has a better insulation. The SW wall, even though warmer on average, maintains its variance throughout the day. This happens because this wall is not only the most exposed to sunlight (and thus solar gains), but also because its construction has a lower thermal resistance – resulting in a lower thermal inertia and thus "follows" closer the variations of outside temperature.

Similarly to Multiuse room, mean temperatures in Office and Meeting room are higher after renovations, and variances lower, which again shows a better insulation and potentially lower heating needs. When comparing all rooms, Meeting room is where temperature is the most stable, followed by Office, and Multiuse. This makes sense as Meeting room is the one least exposed to outside conditions – it has no direct contact with it. Multiuse room is the largest one, with large windows that exchange heat with the outside, so it is expected that it has the largest temperature variation.

Figures 6 and 7 show Multiuse room temperatures in summer, before and after renovations. As in winter, one can easily see that room temperature behaves differently before and after renovations. The average outside mean temperature and (pooled) variance are, respectively, 24.9°C and 27.1 °C^2 – a much higher variance than in Winter, as expected in Lisbon Summer, with hot days and chilly nights. Variance of room temperature is lower after the renovations (2.41 °C to 1.13 °C), confirming a more thermally stable room. However, the mean room temperature increased from 25.5 °C in 2021 to 26.7 °C in 2022. This slight decrease is undesirable in the Summer, because it means higher cooling needs.

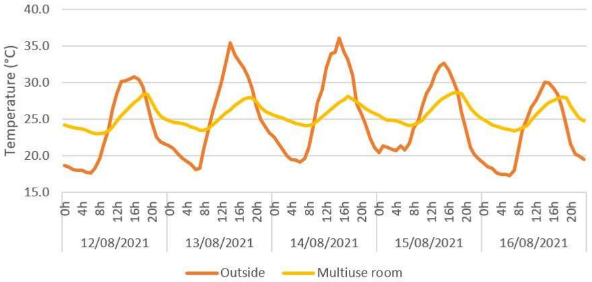

Figure 6. Summer Multiuse room temperature before renovations

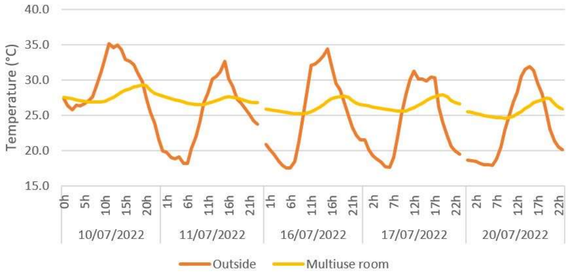

Figure 7. Summer Multiuse room temperature after renovations

In all rooms, the indoor temperature, after renovations, never falls below 23 °C (in the contemplated period), even when outside temperature during the night reaches 17 °C. This indicates that they could all benefit from natural ventilation at night, to decrease indoor temperature and, potentially, its cooling needs.

4.2 PCM improvement

Four rows of PCM panels were inserted into the SW wall. Similarly to 4.1, 5 Summer days after PCM placing were found, whose temperatures are statistically identical to the 5 Summer days before PCM placing. Statistically, temperature variation remains the same, and mean room temperature sees a 0.5°C decrease (without natural ventilation at night). To evaluate whether that desirable temperature decrease is due to PCM latent heat absorption, PCM panel temperatures must be analyzed. In Figure 8, T2-T5 represent PCM panels, in ascending order outside in.

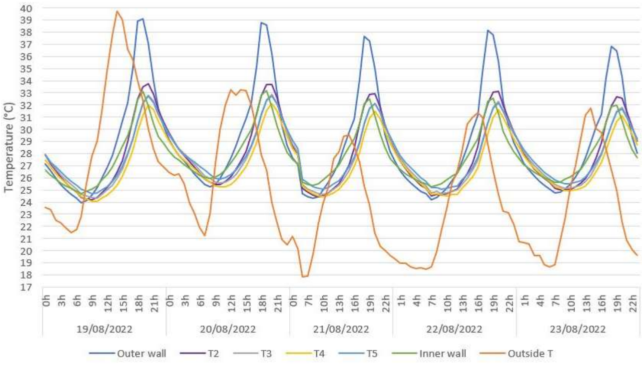

Figure 8. PCM panel temperatures (no night natural ventilation)

All measured surfaces follow the outside temperature, with a certain delay. The outer wall stands out, by increasing its temperature much more than PCM panels and the inner wall. A more important conclusion is that PCM panel minimum temperature is around 24°C, never reaching their melting temperature of 21.7°C. This means that the PCM is not solidifying and releasing latent heat during the night, to be ready to melt and absorb latent heat again on the next day, which is its purpose. The observed decrease in room temperature is then a consequence of adding another insulation layer to the air gap, but it is not taking advantage of PCM potential. As such, considering that outside temperatures in Lisbon Summer nights reach 18°C, natural ventilation at night should be combined with PCM placing. This measure should decrease even more mean room temperature in summer, and cooling needs.

4.3 Heat pump COP and EER

Coefficient of Performance (COP) and Energy Efficiency Ratio (EER) parameters are obtained through:

$$COP/EER = \frac{Heating/cooling\ power\ given\ by\ HP\ (kW)}{Electrical\ power\ from\ the\ grid\ (kW)}$$

The measured values and the manufacturer's data sheet values COP and EER (which are a seasonal average) were statistically compared. The COP datasheet value is 3.3, and the mean measured value is 3.9, with a standard deviation of 0.61 and a Mean Absolute Percentage Error (MAPE) of 23%. For EER, the datasheet value is 3.1, mean measured value 4.3, with a standard deviation of 0.81 and a MAPE of 38%. Scatter maps relating COP/EER and outside temperature were plotted (Fig. X shows EER plot as an example), finding a clear relation between them, positive for COP and negative for EER. This happens because the higher the initial water temperature, the less (COP)/more (EER) energy the HP needs to spend to bring it to setpoint temperature. The most reasonable explanation for such large differences between measured and manufacturer's values is that the temperature conditions used by the manufacturer in defining COP/EER are much stricter than reality in Lisbon.

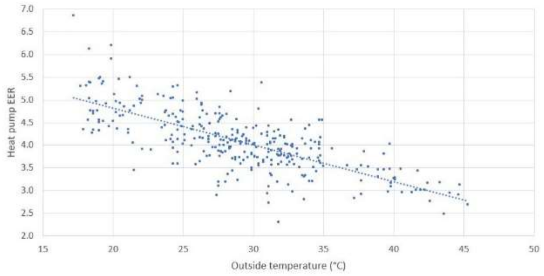

Figure 9. Correlation between EER and outside temperature

4.4 Electricity generation and consumption

Figure 10 shows the daily generation and consumption. On most days (87%), electricity generation is much larger than consumption. Not only so, but the average daily surplus is 14.5 kWh, while the average daily shortage is 5.5 kWh, only around 40% that number.

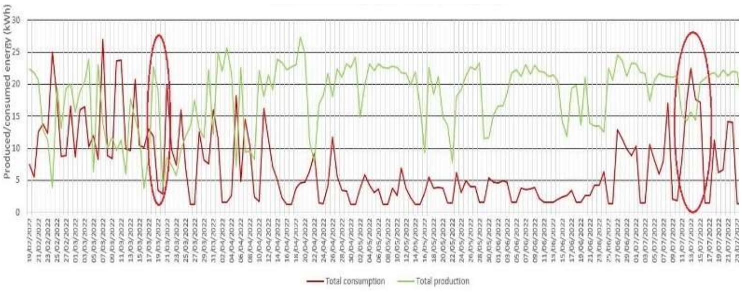

Figure 10. Daily generation and consumption, February to July 2022

The HP was kept on during the night until March 18th 2022, rising consumption to abnormally high values. From then onwards, shortage days in Winter (March and April) happened due to high fan coil consumption combined with little solar collector system contribution, low PV production, or both The only shortage summer days happened on the hottest days of the season (reaching 45 °C), when fan coils and HP were on all day, and PV production was lower than most summer days, probably due to the high temperature.

It was also confirmed that, in monthly periods, the microgrid under study is energy positive. In 5.5 months, the total microgrid generation is 3.1 MWh, from which 99.5% is PV. Thus, wind generation is negligible. The total microgrid consumption was 1.2 MWh, divided as:

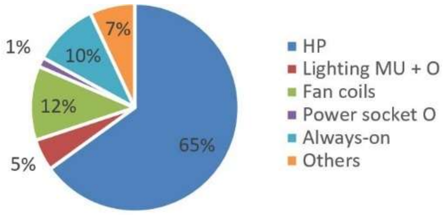

Figure 11. Consumption share. Mid-February to July 2022

HP has the largest share, followed by fan coils, together making heating/cooling services be 77% of total consumption, which is in line with other public buildings. The microgrid has a constant 30 W consumption, resultant from electronic devices (HP and fan coil controllers, gateway sensors, switches, etc) within the pilot area that are never switched off. In a month that amounts to 21.6 kWh, representing a considerable 10% of total consumption.

4.5 System operation optimization through monitoring

Two issues were found and fixed during the months following renovations, easily identified due to the monitoring system. From the start, the HP was on at night, spending much more energy than needed. On March 19th that was noticed, and HP programmed to only be available to work from 7h to 20h on weekdays. In the summer, it was noticed that the solar tank was rising to very high temperatures, that might damage the system, not being able to decrease during the night. As such, the collectors were covered with a shading net, the valves connecting both tanks were closed, and the controller was turned off. The (achieved) goal was for temperature not to rise as much during the day, and to slowly decrease at night.

5 Economic analysis

This section aims at answering whether such a project is financially viable. The energy gains achieved in each of the system's separable components are estimated, along with their NVP and SPBP.

5.1 Methodology

NPV of project P determines the current value of all future cash flows generated by P: a positive/negative NPV renders investment in P worth it/not worth it. NPV calculation is shown below, where I_0 is initial investment, Cf_j cash flow in year j, N number of years the project lasts, and i the discount rate.

$$5.5 NPV[€] = -I_0[€] + \sum_{j=1}^{N} \frac{Cf_j[€]}{(1+i)^j}$$

The European Central Bank risk-free rate is the euro short-term rate, that has been oscillating around 0%[18]. Yearly cash flows are estimated yearly savings of each investment, minus yearly operation and maintenance (O&M) costs, assumed in most cases as 5% of initial investment. The SPBP ascertains how long it requires to recover the investment, and is computed as:

$$SPBP\ [years] = \frac{Initial\ investment\ [€]}{Yearly\ savings\ [€]}$$

Savings are computed using electricity consumption, electricity price, peak power consumption and peak power price. LNEG has a medium voltage electricity supply, with its electricity tariff divided into four daily periods: peak, shoulder, off-peak and super-off peak. For this analysis, the electricity price considered is 0.2296 €/kWh [19]. This price is independent of the time when electricity is consumed, which is a simplification. Power at peak (PP) hours (different in winter- and summertime) are computed as the average power consumed during peak hours within a month. PP price in 2022 is 0.2198 €/(kW.day) [20]. Yearly electricity and PP gains are estimated from the observed period using the rule of three. Regarding costs, HP cost is the real cost paid by LNEG. All other values are estimations, as the components either already belonged to LNEG, were offered by a partner, or were part of a larger bill.

5.2 HP gains

To estimate HP gains, its installation is compared with the fictitious installation of a gas boiler (GB). The heating days in April (only available data) were used as typical heating days. Natural gas price is assumed 0.0735 €/kWh[21].

Table 1. NPV of HP over GB

	Initial assumptions		**2nd scenario**	
	Gas boiler	**HP**	**Gas boiler**	**HP**
Investment cost	1 100 €	6 000 €	1 100 €	6 000 €
Service life (years)	12.5	20	12.5	20
Heating needs (kWht)	3560		8135	
Efficiency/COP	0.881	3.9	0.881	3.9
Energy price (€/kWh)	0.0735	0.2296	0.1018	0.1433
Energy yearly cost	297 €	131 €	940 €	299 €
NPV: HP over GB	-4 612 €		742 €	
SPBP: HP over GB (y)	48.5		17.0	

With initial assumptions, yearly heating cost with a HP being less than half of that with a GB still does not compensate for the difference in investment cost. The NPV of installing HP instead of a GB is negative, and SPBP is 25.5 years, which is longer than the expected 20 years of service life. However, there are two considerations worth making, that lead us to another scenario. Firstly, these heating needs are the measured ones, not the ones an office with a typical utilization would have (explained in 5.3). Considering a typical utilization, the ratio typical/measured heating needs was assumed 2.29, equal to the same ratio for electrical needs (without HP consumption), computed in 5.3. Secondly, natural gas price is rising, and it is expected to remain high. As such, the ratio natural gas price in 2024/in 2022 for Portugal is assumed to be 1.39, the same as for Europe [22], and that is the considered price.

With these new assumptions (Table 1), yearly heating cost with a HP becomes less than 3 times lower than with a GB. NPV of installing a HP instead of a GB is positive, and SPBP is 17 years. Two other aspects favour HP installation. The first is that there are also cooling needs during summertime, and the need for a cooling system, and the HP does both very energy efficiently. Another aspect is the current geopolitical uncertainty that makes natural gas supply and prices volatile. This incentivizes an EU shift from natural gas to electricity as its preferred energy carrier.

5.3 Self-consumption gains

From February to July, the microgrid real energy generation and consumption was used to check whether batteries were charging or discharging, and whether electricity was being drawn (and bought) or injected (and sold) into the grid. The selling electricity price considered is 90% of the average wholesale price[23].

Batteries SoC over time is displayed in Figure 12. Batteries were mostly required on days when generation does not meet consumption (Figure 10). On the remaining days, there is discharge at night, when always-on equipment needs energy but there is no PV generation, but that energy is replaced during the day.

Figure 12. Batteries SoC (%). Mid-February to July 2022

Because real consumption data is much lower than a typical office's (occupation was scarce during these post-COVID months), it is interesting to perform the same analysis with typical office profiles, concerning lighting and power socket utilization [17]. As the heating/cooling system is complex, HP and fan coil consumption used in this analysis are the measured values. However, a typical office would have higher needs and, therefore, consumption. Wind electricity generation is so little that it is not considered for a typical office. Table 2 summarizes the results. As expected, the typical profile has more consumption, a slightly lower generation (due to lack of wind generation), more energy taken and less energy injected into the grid, and a higher PP.

Self-consumption is obviously higher, in both profiles, when the option to sell electricity is available. Without the option to sell electricity, self-consumption is higher (32%) for the typical profile because consumption is higher. With the option to sell electricity, gains for the typical profile are still higher, even if by a smaller margin (4%), because buying electricity price is 62% higher than selling electricity price, and self-consumption is rewarded.

Table 2. Self-consumption gains, NPV and SPBP

	Initial assumptions		**2nd scena**
	Measured	**Typical**	**Typical**
Electricity (kWh) in 5.5 months			
Balance to/from grid	1790	1248	1253
Injected into grid	1854	1409	1558
Taken from grid	64	161	304
Consumed	1166	1693	1693
Generated	2963	2948	2948
Peak power (kW.month) in 5.5 months			
Without PV + battery	2.0	3.4	3.4
With PV + battery	0.1	0.2	0.5
Yearly self-consumption gains (€)			
Electricity: not selling	580	767	434
Electricity: selling	1153	1203	915
Peak power	28	45	41
PV + batteries (selling electricity)			
Initial investment (€)	21741		12026
Service life (years)	20		20
NPV (€)	-8980	-7648	1085
SPBP (years)	34.1	30.9	18.3

PP is greatly reduced with PV and battery installation. However, yearly PP gains represent 5% of total yearly gains, meaning that electricity has indeed the most relevant share in gains. This is partly since PP without PV and batteries is not so high to begin with. On evening peak periods and weekends there is little utilization, and as PP is an average value, even if there is great utilization on morning periods, its monthly value cannot be very high.

NPV is computed considering the option to sell the electricity, as that is the desirable scenario. It is negative, with SPBP of 34 years and 31 years for measured values and typical profile, respectively. With yearly gains over €1000 (from where yearly O&M must be deducted), the main reason for such an outcome is the fact that battery capacity is too high for these electrical needs (they were reused from previous projects, and not acquired for this microgrid). Considering that batteries last half of the system service life, they comprise 60% of initial investment. On the other hand, Figure 12 shows that it hardly ever uses its full discharging capacity, and it is full most of the time.

Table 2 shows the same results for the typical profile if battery capacity is reduced to 25% of its current capacity. Electricity taken from the grid increases by 88%, but yearly gains reduce only by 24%. Batteries now use their full charging/discharging capacity, staying shorter at their maximum/minimum capacity. The NPV is positive, with a SPBP of 18 years. The NPV would be even higher (and SPBP lower) if inverters and PV modules were also adjusted to the electrical needs of the building – which are higher than estimated, remembering that HP and fan coil consumption were not adjusted to the typical profile.

5.4 Gains from solar thermal system

To estimate the electrical (from HP use) and financial gains obtained with the STC system, two statistically identical Winter days after renovations were chosen, one when the STC was heating the storage tank, and one when it was turned off. Assuming that: (a) the chosen days are typical Winter days, (b) Winter lasts 4 months, each with 5 working days with heating needs, and (c) only 50% of those days have enough solar radiation to provide heating power, economic gains, NPV and SPBP were computed.

Table 3. Electricity, PP, NPV and SPBP of STC and tank

	Initial assumptions		**2nd scenario**	
	No STC	**STC**	**No STC**	**STC**
Daily fan coil consump. (kWh)	2.9	4.5	4.5	
Daily HP consumption (kWh)	14.0	6.2	21.7	6.2
Daily PP (kW)	0.74	0.60	0.74	0.60
Yearly electricity gains (kWh)	334.0		2057	
Yearly electricity gains (€)	76.7		472.4	
Yearly PP gains (€)	1.3		2.6	
STC initial investment	7 316 €			
STC service life (years)	20			
STC NPV	-12 784 €		-5 242 €	
STC SPBP (years)			67.0	

On STC day, fan coils were on for roughly 2 hours longer than on non-STC day, consuming 55% (1.6 kWh) more. Even so, there are electrical HP savings of 7.8 kWh. As yearly electrical gains (78€) are only 1% of investment (7316€), they are not enough to overcome O&M costs. As such, there are no yearly savings, but a monetary loss – NPV is negative, and it is pointless to compute SPBP.

However, initial assumptions are conservative. Table 3 also shows the results of a more optimist scenario, assuming that: (a) HP consumption on non-STC day is increased by a rule of three, eliminating the difference in fan coil consumption; (b) Winter lasts 5 months; (c) 80% of Winter days have enough solar radiation to provide heating power. Even in this scenario, NPV is negative and SPBP is 67 years. It is not economically viable to install this STC and tank in these conditions. This is, however, a preliminary analysis done with only two experimental days, and the STC were not designed to the building's specific needs.

5.5 Lighting gains

Lighting gains calculations are made as a rule of three, comparing how much was consumed after renovations against how much would have been spent had the lamps not been replaced. Table 4 summarizes the results.

Yearly electricity savings are 26 kWh and 6€ for measured values, adding to 2.1€ of PP savings. Even with such small numbers, the investment is worth it – positive NPV –, with a very low SPBP of around 5 months. This is because initial investment is nearly the same. Even though fluorescent lamps are already in place, the fact that their service life is half of the LED's (and discount rate is 0%) evens their investment cost. As such, because LED lamps spend 30% of the fluorescent to provide the same service, that small difference in investment is rapidly recovered.

Table 4. LED over fluorescent lamps - energy, PP, NPV and SPBP

	Measured		**Typical**	
	LEDS	**Fluor.**	**LEDS**	**Fluor.**
Yearly energy (kWh)	11	37	62	208
Yearly energy cost (€)	2.6	8.5	14.3	47.8
PP (kW.month)	0.13	0.45	1.7	5.7
Yearly PP cost (€)	0.9	3.0	11.3	37.8
Investment cost (€)	1080	1050	1080	1050
Service life (years)	24	12	24	12
NPV: LED over Fluor. (€)	2541		14418	
SPBP: LED over Fluor. (y)	0.4		0.1	

6 Conclusions and future work

New insulation increased room temperature in winter closer to a comfort level (potentially reducing heating needs), and increased it in summer further from a comfort level (potentially augmenting cooling needs). As such, the extent to which insulation increased or reduced total thermal energy needs must be studied and economically assessed. PCM panel introduction into the SW wall showed a desirable reduction of the indoor temperature in the summer. However, they did not fulfill their potential of latent heat storage. PCM gains in the summer, with and without ventilation, and in the winter, should be assessed.

Renewable energy generation was, at a monthly scale, much higher than pilot consumption. This means that the microgrid achieved the nZEB goal.

Regarding the economic analysis, the only investment clearly worth making is to replace old fluorescent lamps by LED ones, regardless of utilization or building size. It is crucial that acquired equipment is carefully chosen according to the building's needs, to minimize cost and become profitable. HP installation is the best available alternative to satisfy a building's thermal needs, because it provides both heating and cooling power, and it is very efficient. Installation of PV modules with lead acid batteries can be profitable if the option to sell electricity to the grid is available. STC and tank, with the current capacity and for this building, are not worth the investment.

Monitoring is crucial for improvement in energy efficiency, and its gains should also be estimated – even though it is a hard task – to calculate its NPV. As its cost is little dependent on building size and consumption, the higher those values, the higher NPV will be.

Two other measures are worth taking to reduce energy consumption. Natural ventilation at night in the summer should be implemented whenever possible, to lower indoor temperature, and potentially its cooling needs.

Moreover, it has the potential to decrease PCM panels temperature to their melting temperature, reducing (as previously explained) cooling needs in the room. Training building also promotes energy efficiency through a conscious user behaviour, such as shifting consumption from peak to off-peak periods.

References

1. United Nations. *2021 Global Status Report for Buildings and Construction*. www.globalabc.org. (2021).

2. European Comission. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*.

3. European Commision. Renovation Wave. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en.

4. Heinze, M. & Voss, K. Goal: Zero energy building: Exemplary experience based on the solar estate solarsiedlung freiburg am schlierberg, Germany. *Journal of Green Building* **4**, 93–100 (2009).

5. Noguchi, M., Athienitis, A., Delisle, V., Ayoub, J. & Berneche, B. *Net Zero Energy Homes of the Future: A Case Study of the ÉcoTerra House in Canada*. (2008).

6. Aelenei, L. & Gonçalves, H. From solar building design to Net Zero Energy Buildings: Performance insights of an office building. in *Energy Procedia* vol. 48 1236–1243 (Elsevier Ltd, 2014).

7. Irulegi, O., Ruiz-Pardo, A., Serra, A., Salmerón, J. M. & Vega, R. Retrofit strategies towards Net Zero Energy Educational Buildings: A case study at the University of the Basque Country. *Energy Build* **144**, 387–400 (2017).

8. Pinto, E. S. & Amante, B. Polygeneration system optimization for building energy system retrofit: A case of study for TR5 building of UPC-Terrassa. *Energy Build* **273**, 112375 (2022).

9. Cho, H. M., Yun, B. Y., Kim, Y. U., Yuk, H. & Kim, S. Integrated retrofit solutions for improving the energy performance of historic buildings through energy technology suitability analyses: Retrofit plan of wooden truss and masonry composite structure in Korea in the 1920s. *Renewable and Sustainable Energy Reviews* **168**, 112800 (2022).

10. Park, J. H. *et al.* Impact of a passive retrofit shading system on educational building to improve thermal comfort and energy consumption. *Energy Build* **216**, 109930 (2020).

11. Daedal Research. *Global Building Energy Management System (BEMS) Market: Size, Trends & Forecasts (2021-2025)*. (2021).

12. Siemens Global. Building Technology. https://new.siemens.com/global/en/products/buildings.html.

13. Honeywell. BMS. https://buildings.honeywell.com/us/en/brands/our-brands/bms.

14. Johnson Controls. Smart Building Automation Integrates Systems. https://www.johnsoncontrols.com/building-automation-and-controls.

15. Schneider Electric Global. Smart Buildings, EcoStruxure Building. https://www.se.com/ww/en/work/campaign/innovation/buildings.jsp.

16. de Abreu, D. D., Neto, R. C., Aelenei, L. & Silva, C. A. S. Modelling and experimenting thermal energy storage through the use of PCM in low thermal inertia office. in 1–8 (IEEE, 2019).

17. Ferreira, G. *Soluções integradas de eficiência energética, energia renovável e micro-rede num edifício público na perspetiva NZEB*. (2021).

18. European Central Bank. Euro short-term rate (€STR). Euro short-term rate (€STR).

19. Eurostat. Electricity prices for non-household consumers - bi-annual data (from 2007 onwards). https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table?lang=en.

20. ERSE. Tarifas e preços - eletricidade. https://www.erse.pt/atividade/regulacao/tarifas-e-precos-eletricidade/ (2022).

21. Eurostat. Gas prices for non-household consumers - bi-annual data (from 2007 onwards). https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203/default/table?lang=en (2022).

22. Statista. Natural gas commodity prices in selected markets in 2020 and 2021, with a forecast until 2024. https://www.statista.com/statistics/444286/natural-gas-price-forecast-by-region/ (2022).

23. Statista. Average monthly electricity wholesale price in Portugal from January 2019 to August 2022. https://www.statista.com/statistics/1281464/portugal-monthly-wholesale-electricity-price/ (2022).