VTT Technical Research Centre of Finland

Investigating the energy resilience performance of the energy flexible enabled new and old house integrated with renewable energy in cold climatic conditions

Rehman, Hassam; Reda, Francesco

Published in:
13th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2023)

Accepted/In press: 14/11/2023

Document Version
Publisher's final version

Link to publication

Please cite the original version:
Rehman, H., & Reda, F. (in press). Investigating the energy resilience performance of the energy flexible enabled new and old house integrated with renewable energy in cold climatic conditions. In *13th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2023)*

Investigating the energy resilience performance of the energy flexible enabled new and old house integrated with renewable energy in cold climatic conditions

Hassam Ur Rehman[1,*], Francesco Reda[1]
[1]VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Espoo, Finland
[*]Corresponding author: hassam.rehman@vtt.fi

Abstract

The buildings face two-fold challenges of climate change and energy crisis. To tackle these challenges future proof buildings are needed that are flexible and resilient. The aim of the article is to model and compare the energy performance of the old (1970s) and new (2000s) single family building integrated with the photovoltaic (PV) in cold climatic condition of Finland. The objective is to compare the building's performance in terms of energy flexibility and resilience as both are competing for the same resources. It is found that flexibility factor and energy cost saving is higher in the old building integrated with PV compared to the new building. In terms of energy resilience, the new building showed better robustness against power outage compared to the old building. As the indoor set point temperature increased from 20 ºC to 23 ºC (due to flexibility) the resilience performance increased, however the recovery speed is slow, and the amplitude of failure (AoF) is higher. When PV is added the robustness and habitability duration improved, the AoF reduced, and the recovery speed improved. To tackle the future challenges the buildings, have to be flexible and resilient at the same time. Therefore, both these concepts have to be studied together to provide optimal building design and controls of renewables.

Highlights

- Energy resilience of the new and old buildings are simulated that are situated in Finland.
- Energy flexibility is enabled in the simulated buildings and its impact in terms of resilience is carried out.
- Two resources in the building i.e. thermal mass and photovoltaic, are used to test the energy resilience and flexibility performacne of the buildings in cold climate.
- Energy resilience is also important due to the energy crises, so future researches need to consider this aspect along with energy flexibility as both compete for the same resources.
- Smart integration of renewables and control of the building's heating system is required to be developed and studied so that it can support both the objectives i.e. flexibility and resilience.
- The above outcomes are important as it will provide feasuble, energy flexible, energy resilienct and sustaibale buildings that are aligned with the goals.

Introduction

Climate change is one of the biggest challenges faced by the society. The districts and buildings are one of the largest contributor towards the emissions (Moore, Horne, and Morrissey 2014). To reduce the impact of climate change and to make a sustainable society, the buildings have to energy efficient, energy flexible and able to integrate renewables. To reach these goals the European Union (EU) aims that all the new and old buildings be energy efficient and ultimately reach the zero emissions by 2030 and then carbon neutral by 2050 (European Union Commision 2018). According to the directives the buildings has to be energy efficient and able to integrate renewable sources. In addition to this the buildings have to be smart by allowing energy flexibility and resilience.

The building stock in Finland are old and inefficient. It is found that 43% of the buildings were built before 1980s (Holopainen et al. 2016). Moreover, residential buildings and single-family houses are one of the largest building types in Finland. To reduce the emissions the buildings has to be energy efficient and also energy flexible. With the addition of the energy flexibility and renewables the energy cost can be reduced. It is found that 11% of the energy cost can be reduced by implementing demand response in the building (Yoon, Bladick, and Novoselac 2014). Earlier study also showed that around 400€ can be saved per year in old buildings and 70€ can be saved per year new buildings in Finland by using thermal mass of the building to activate the energy flexibility strategies (Rehman and Hasan 2023). This article discusses about the impact of the energy flexibility on the energy resilience capacity of the simulated old and new detached buildings in cold regions as both are interlinked.

The thermal mass and photovoltaic (PV) can be used together to improve the energy flexibility (Johra, Heiselberg, and Dréau 2019) and energy resilience of the building (Rehman and Hasan 2023). PV can be used to produce heat energy that can be used charge the building thermal mass that can assist in reducing the energy cost. Also, the thermal mass can be charged and discharged based on the price signals. All these integrated components and strategies can assist in reducing the energy cost and improving the energy resilience. This article presents about the use of PV and thermal mass of the building to analyze the energy resilience performance of the simulated buildings.

In is important that the sustainable buildings should address the challenge of energy crises. The energy efficient buildings should be made energy resilience to address the energy crisis challenge. This can be done by providing energy resilient buildings. The energy resilient building is a novel concept that is still under developing and it is becoming important in view of the approaching energy crises(Alfraidi and Boussabaine 2015). Due to increase in the extreme climatic events (storms, rain, extreme temperature etc.), economic and political situations (war etc.) there is high probability of black outs and power loss(Nik, Perera, and Chen 2021). These crises can indirectly impact the energy performance of the building and habitable conditions inside the building. Hence the future and renovated buildings should be developed that can provide reliable minimum performance that can provide end user comfort. The minimum performance of the building can be provided by the energy resilient buildings. It can be defined as the building that has the ability that can provide and maintain minimum level of the comfort and habitability during the power loss that prevents the normal operation of the building (Homaei and Hamdy 2021). The 'habitability' here refers to the ability of the building to maintain habitable thermal conditions during and after the power loss. This can be done by reducing the heat loss and ventilation etc. (Schoeman 2019). Few research is done at the urban scale at the international level (Nik, Perera, and Chen 2021), (Kopányi, Poczobutt, and Pallagi 2020), (Breesch and Janssens 2010). More research has been carried out in warm and mild climatic conditions at the urban and building level (Homaei and Hamdy 2021), (Attia et al. 2021). However extreme cold climatic conditions is a challenge in Finland. Methods to analyze and improve the performance of the building energy system under grid power loss needs to be investigated in Finland. Moreover, research is seldom in which the aim is to investigate energy resilience at the building level in Finland. Hence research is needed that analyze the energy resilience performance of the new and old buildings in cold conditions. Furthermore, methods to improve the energy resilience of the buildings have to be analyzed with and without the integration of onsite photovoltaic (PV) along with energy flexibility.

The article published earlier (Rehman and Hasan 2023) discussed and focused on the energy flexibility of the buildings in Finland. In the earlier article only the thermal mass of the building is used as energy resilience and flexibility source (Rehman and Hasan 2023). This article is an extension of the earlier study and presents a quantitative analysis of the two buildings that aims to reach the objective of energy resilience together with energy flexibility as both are competing with the same resources i.e. thermal mass and onsite PV. The focus in this article is on the energy resilience of the same buildings (old and new buildings) integrated with PV and that has the ability of activating the energy flexibility strategy. The novelty lies in the close comparison between the performance of an old and new building in terms of resilience with and without integration of PV and also using thermal mass situated in cold region. The intent is to evaluate the habitability threshold periods, impact of the failure and recovery performance of the old and new buildings that are performing energy resilience together with flexibility. The focus is on the heating energy of the building. Various heating indoor set points are analyzed due to energy flexibility and the impact of these different set points on energy resilience of the buildings. This is needed as no regulations or policy exist about the energy resilience therefore this research is needed to guide the stakeholders.

Methodology

Design of the study

The work is divided into two sections. The first section briefly discusses about the energy flexibility potential of the new and old building in Southern Finland. The second part discuss about the energy resilience performance of the same buildings. In first section the energy flexibility discussion is based on the initial findings in the earlier published paper (Rehman and Hasan 2023). As an extension of the earlier study onsite PV is integrated with the building as a source for energy flexibility along with the optimal activation control of the mass of the building. Heating demand and indoor set point temperature is used for energy flexibility. The economic analysis is carried out using energy price to evaluate the cost saving potential in the new and old buildings using the PV and thermal mass activation strategy. In the second section, the energy resilience performance of the buildings in terms of heating is carried out under 30hr power outage. Various indoor set point temperatures are used to analyze the impact of these set points temperature on the energy resilience of the buildings. This is done due to the energy flexibility activation strategies that may vary the indoor temperature to save the energy cost. Similar to the energy flexibility analyses both the thermal mass of the building and PV is used as a passive and active source respectively to improve the energy resilience of the buildings in cold climate.

Figure 1 shows the old and new buildings that are simulated in TRNSYS (University of Wisconsin 2017). The grid and PV are integrated with the building to provide heating energy to the building. The PV size (48, 72, 98 m2) is used as a design parameter in the article to analyze the impact of size on the energy flexibility. For energy resilience the PV size is assumed to be 140 m^2 due to the roof area limitation. It is assumed that building is heated using radiator and direct electricity to generate heat. The heater is sized to maintain indoor set point temperature as 21.5±0.5 ºC inside the building zone during winters. Cooling energy is not considered. No electrical or heat storage is used as a component to improve the flexibility and resilience.

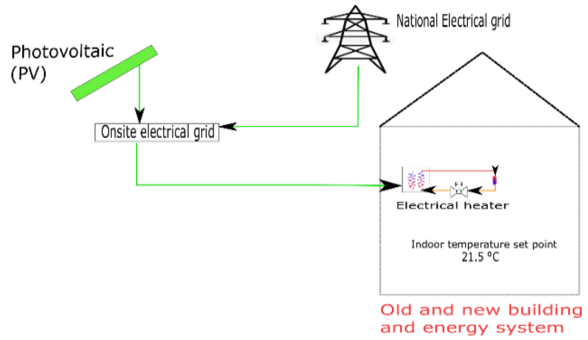

Figure 1: The design of the new and old building and its energy system in Finland.

Building design and software

The simulated single family old and new building is situated in Southern Finland, Helsinki. The old building is constructed in 1980s (Hirvonen et al. 2019) and the new building is constructed in 2020s 2000s (Ala-Juusela et al. 2020). The building has the heated floor area of 140 m2. Both the building are designed and modelled based on the typical building archetype (Hirvonen et al. 2019) and Finnish regulations (Ministry of the Environment 2017). The design parameter of the modelled old and new buildings are shown in Table 1. The heating demand is considered in the study as heating energy is the dominant demand in cold region, while cooling demand is not considered. The ventilation rate is 0.55 1/h for the buildings.

Table 1: The design parameters for the simulated old and new buildings.

Building type	**Air tightness ($m^3/h\ m^2$)**	**U-value ($W/m^2\ K$)**			
		Ext. Walls	**Roof**	**Windows**	**Floor**
Old building	6	0.5	0.27	2.5	0.38
New building	2	0.17	0.09	1	0.16

As mentioned, TRNSYS software is used to simulate the building and its energy system. Building (Type 56), PV module (TYPE 194), controller (TYPE 2b), temperature control (TYPE 11f), and weather data (TYPE 15) is used to model the building and its system (Rehman 2018).

Building's heating system control for energy flexibility

The PV along with the thermal mass of the building is used as energy flexibility sources in the building. The energy conservation and storage activation methods are used to save the energy cost and minimize the energy consumption. 21.5±0.5 °C is used as a reference indoor temperature for the space heating, which is according to the recommendation of the Finnish Society of indoor air quality and climate (Ahola, Säteri, and Sariola 2019). This set point temperature is varied to activate the energy conservation and storage controls strategies. In earlier study in energy conservation mode without PV, the reference indoor set point temperature is reduced by 1.5 °C to activate the thermal mass of the building (Rehman and Hasan 2023). Similarly in the earlier study in energy storage without PV, the reference indoor set point temperature is increased by 1.5 °C to activate the thermal mass of the building (Rehman and Hasan 2023). The activation method used in this study with the PV is defined as follows:

- Energy conservation and storage with PV: This is also used as flexibility option in addition to the building's thermal mass activation. If the PV generation is available, the indoor air set temperature is increased by 1.5 °C to 23 °C or kept at 21.5 °C regardless of the electricity price signal. If the PV is not available and the energy price is high, then the set point is reduced to 20 °C. If PV generation is not available and the energy price is low, then the set point is increased to 21.5 °C. is not available Different PV areas are simulated to analyse the impact of the PV on the energy flexibility and resilience.

In all above three methods, 1 h is used as activation hour for the thermal mass as this is found to perform better compared to longer activation hours (Rehman and Hasan 2023), (Le Dréau and Heiselberg 2016). The high and low energy price discussed is defined in the following section 'Weather and energy cost'.

Weather and energy cost

For weather data year 2016 is used so the weather and electricity data are of same year. The energy conservation and storage activation of the building's thermal mass is carried out based on the price signal and availability of the solar energy. In this study, electricity price of 2016 is used for price signals. The price data is from Nordpool (Nord Pool As 2016) and it includes the distribution and tax cost. The objective is to minimize the operational i.e. energy cost of the building for heating. The electricity price is defined based on the percentile. For the electricity price above 80% percentile is classified as high price. On the other hand, for the electricity price below 20% percentile is classified as low price. Any price between these percentiles are classified as normal price. The time window of 12 h is used at each time step for analyzing and marking present time as high or low pricing signals. Same approach is used in (Rehman and Hasan 2023). This window moves one hour at each time step. In other words, at each time step of 1 h the price is analyzed for classification as high or low price against within the time window of 12 h. The investment cost and export from PV is not considered in the study.

Energy flexibility computation

The indicator used for calculating the techno-economic performance for flexibility are as follows: (Rehman and Hasan 2023), (Le Dréau and Heiselberg 2016):

$$Flexibility\ factor = \frac{\sum_{low\ price} Heat_Q - \sum_{high\ price} Heat_Q}{\sum_{low\ price} Heat_Q + \sum_{high\ price} Heat_Q} \quad (1)$$

Equation 1 defines the performance of the building in terms of flexibility. When additional heat is added to the building to rise the indoor air temperature (in case of low price), then it is called "low price $Heat_Q$". When heat is decreased in the building to reduce the indoor air temperature (in case of high price), then it is called “high price Heat_Q”.

Energy resilience computation

Different performance indicators are used to estimate the energy resilience performance and behavior of the energy flexible old and new buildings during power outage in cold conditions. These indicators are needed to evaluate the pre-disturbance, disturbance, and post disturbance phases during a power outage. Due to the energy flexibility option in the pre-disturbance phase, the indoor air set point temperature is 20, 21.5 and 23 °C. During the disturbance and post disturbance phase the following indicators are defined and calculated to evaluate the performance (Homaei and Hamdy 2021):

- Robustness period (RP): It is defined as the time duration until when the indoor room temperature of the building can be maintained above the robustness threshold after the power outage.
- The robustness threshold (RT): It is the minimum temperature above which the performance can be called as robust performance. Minimum robustness threshold is 18 °C for the old and new buildings.
- Habitability threshold (HT): It is assumed that 15 °C is the lowest minimum habitability threshold. Below this point, the building is not able to provide comfort to the end users during power outage.
- Amplitude of failure (AoF): It represent the impact of failure (i.e. it shows the minimum indoor temperature that is reached during outage). Less the AoF, better the building is to sustain the impact and adapt to the power failure.
- Recovery pace (RP): It demonstrates how fast the indoor temperature is able to accomplish the target indoor set point (20, 21.5 and 23 °C) after reinstatement of the power.

Results and discussion

Energy flexibility in old building

The earlier published article showed that the energy conservation activation method of the thermal mass of the building is beneficial in terms of cost saving and flexibility factor (Rehman and Hasan 2023). With the integration of various sizes of the PV on the roof the earlier study is extended to analyze the impact of PV and thermal mass together on the energy flexibility potential of the buildings. Various activation methods are applied by varying the indoor set point temperature to improve the flexibility factor and reduce the energy cost. In the old building with the PV, the set point temperature is kept at 21.5 °C when the PV generation is available and it is reduced to 20 °C when the PV generation is not available and the price is high, i.e. above 80% percentile at each time step (in 12 h window). When the price is below 80% percentile and the PV generation is not available, then the set point temperature is increased to 21.5 °C.

The PV size is varied to evaluate the impact of the PV size with the thermal mass on flexibility factor and energy cost. Figure 2 presents the flexibility factor (orange bar), energy cost (blue bar) with respect to the PV size. It is observed that when the PV size is varied i.e. it increased from 48 m^2 to 98 m^2 the flexibility factor increased to 85%. On the other hand, the energy cost is reduced from 6001 € (reference cost) to 5600 €. It presents that as the PV size increases with the activation of the thermal mass by varying the indoor set point temperature the energy cost reduced and the flexibility factor increased.

It is also found that if the set point temperature is increased to 23 °C when solar energy is available instead of 21.5 °C, the energy cost is reduced from reference cost of 6001 € to 5961 € when PV size is 48 m^2. This is smaller reduction in the energy cost compared to the case when solar energy is available and the set point is kept at 21.5 °C. This is due to the limited PV area and higher heating demand due to high set point. So it is recommended to use indoor set point temperature as 21.5 °C in the old building when solar energy is available.

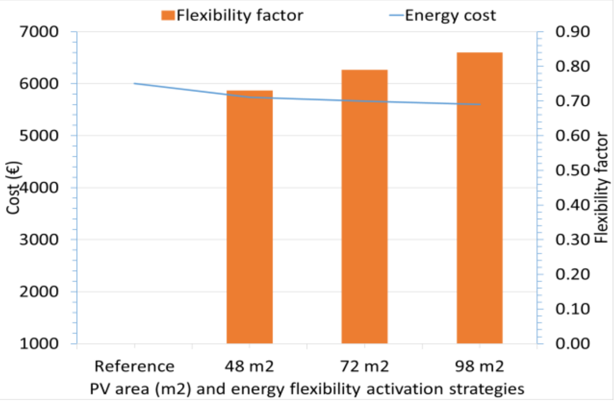

Figure 2: The energy cost and flexibility factor of the old building using various PV sizes and flexibility activation method.

Energy flexibility in new building

In the new building and using the PV, the set point temperature is increased to 23 °C when the PV generation is available and it is reduced to 20 °C when the PV generation is not available and the price is high, i.e. above 80% percentile at each time step (in 12 h window). When the price is below 80% percentile and the PV generation is not available, then the set point temperature is increased to 21.5 °C.

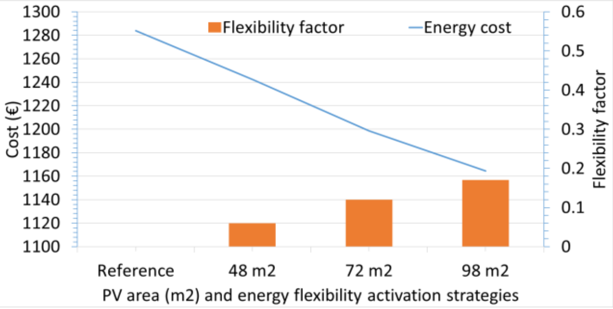

Figure 3: The energy cost and flexibility factor of the new building using various PV sizes and flexibility activation method.

The PV size is varied to evaluate the impact of the PV size with the thermal mass on flexibility factor and energy cost. Figure 3 presents the flexibility factor (orange bar), energy cost (blue bar) with respect to the PV size. It is observed that when the PV size is varied i.e. it increased from 48 m^2 to 98 m^2 the flexibility factor increased to 18%. On the other hand, the energy cost is reduced from 1283 € (reference cost) to 1165 €. Compared to the old building, the new building had lower energy cost saving and flexibility potential. This is due to smaller amount of heating demand is needed in the new building compared to the old building as new building had higher energy efficiency resulting in low flexibility factor and energy cost savings potential.

Energy resilience in old building

The hour selected for simulating and testing the power outage is between 1971 h to 2041 h for the old and new buildings cases when the minimum ambient temperature is around -10 °C and solar radiation is available. The power outage is assumed to start at 1996 h and the duration is 30 h when no electricity is available for heating power. It is done to study the impact of power outage on the building's energy resilience performance without PV and with 140 m^2 PV. In Figure 4, it is found that without PV (orange line) in old building and with the indoor set point temperature at 20 °C the temperature drops below 18 °C (robustness threshold) and below 15 °C in 1 h i.e. below habitability threshold, after this the building is not thermally resilient. The AoF is 9.6 °C in the old building without PV. The recovery speed is around 2.3 °C/hr. Figure 4, also shows that with PV (blue line) in old building the temperature drops around 15 °C but due to the PV generation the indoor set point increased to 18 °C (robustness threshold) and PV is able to maintain the indoor set point for 13 h. As the power outage continue the temperature reached to the habitability threshold of 15 °C in 7 h after crossing the robustness threshold. The AoF is 8.9 °C in the old building with PV. This shows that the impact of power outage is lower with the PV. The recovery speed is around 4.4 °C/hr. This shows that the recovery is faster with the PV as well compared to the case without PV.

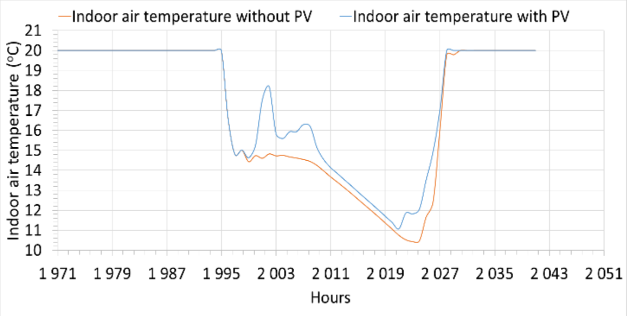

Figure 4: Energy resilience performance of the old building (set point indoor temperature as 20 °C) with and without PV in cold climate during power outage.

In Figure 5, it is found that without PV and with the indoor set point temperature at 21.5 °C the temperature drops below 18 °C (robustness threshold) in 2 h. As the power outage continues the temperature drops below 15 °C (habitability threshold) in 13 h and after this the building is not thermally resilient. The AoF is 10.02 °C in the old building without PV. The recovery speed is around 2.05 °C/hr. Figure 5, also shows that with PV the temperature drops around 16.5 °C but due to the PV generation the indoor set point increased to 18.5 °C (robustness threshold) and it is able to maintain the indoor set point for 8 h. As the power outage continue the temperature reached to the habitability threshold of 15 °C in 10 h after crossing the robustness threshold. The AoF is 9.5 °C in the old building with PV. This shows that the impact of power outage is lower with the PV. The recovery speed is around 3.2 °C/hr.

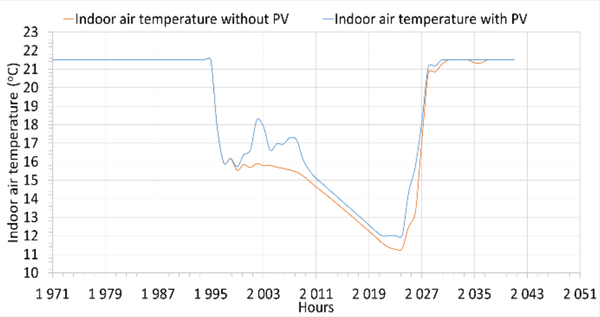

Figure 5: Energy resilience performance of the old building (set point indoor temperature as 21.5 °C) with and without PV in cold climate during power outage.

In Figure 6, similar behavior is observed it is found that with the indoor set point temperature at 23 °C and without PV the temperature drops below 18 °C (robustness threshold) in 2 h. As the power outage continues the temperature drops below 15 °C (habitability threshold) in 19 h. The AoF is 11 °C in the old building without PV. The recovery speed is around 1.82 °C/hr. Figure 6, also shows that with PV the temperature drops around 17.5 °C but due to the PV generation the indoor set point increased to 18.5 °C (robustness threshold) and it can maintain the indoor set point for 13 h. As the power outage continue the temperature reached to the habitability threshold of 15 °C in 7 h after crossing the robustness threshold. The AoF is 10.05 °C in the old building with PV. This shows that the impact of power outage is lower with the PV. The recovery speed is around 2.63 °C/hr.

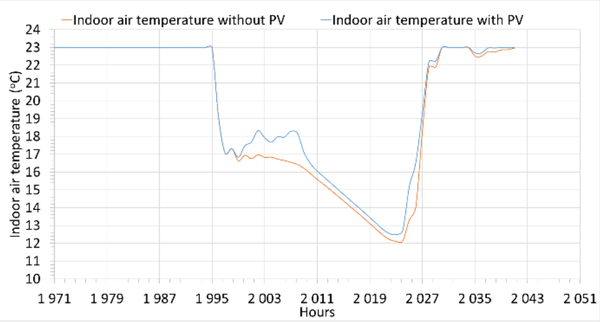

Figure 6: Energy resilience performance of the old building (set point indoor temperature as 23 °C) with and without PV in cold climate during power outage.

When comparing energy resilience performance of the old building with different indoor set point temperature (20, 21.5 and 23 °C) it is found that the case with higher indoor temperature has better robustness and habitability duration. The AoF is higher when the indoor set point temperature is higher, this is due to higher temperature difference between the maximum and minimum temperatures before and during the power outage. The recovery speed is also fast with lower indoor set point temperature. Finally, the performance of the resilience is improved with the integration of PV, the building performance is better during the power outage and the recovery speed is also faster.

Energy resilience in new building

Similar hours are used for testing the power outage performance i.e. between 1971 h to 2041 h. The power outage is assumed to start at 1996 h and the duration is 30 h when no electricity is available for heating power. The energy resilience is tested for the new building with and without PV. In Figure 7, without PV (blue line) it can be found that indoor air temperature drops from 21.5 ºC to 18 ºC (robustness threshold) in 13 h. Therefore, the robustness period is longer for the new building compared to the old building (Figure 4). As the power outage continues, the indoor set point temperature remains above the habitability threshold i.e. about 15 ºC during the power outage. The minimum temperature reached during the outage is 16.4 ºC. This shows that building can remain habitable. The AoF is 3.62 ºC without PV in the new building. The recovery speed is around 1.8 ºC/hr. With the PV (Figure 7, orange line) the robustness period increased to 19 h, i.e. the indoor temperature is above 18 ºC (robustness threshold) as the PV is able to sustain the indoor temperature longer compared to the scenario without PV. The AoF is 3 ºC with PV in the new building. This shows that the amplitude of failure is smaller in the building with PV. The recovery speed is around 3.08 ºC/hr.

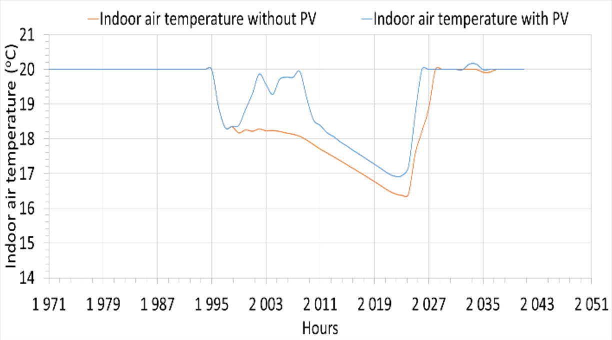

Figure 7: Energy resilience performance of the new building (set point indoor temperature as 20 ºC) with and without PV in cold climate during power outage.

Figure 8 shows that without PV and with the indoor set point temperature at 21.5 ºC the temperature drops around 18 ºC (robustness threshold) in 25 h during the power outage. As the power outage continue, the indoor temperature remains above the habitability threshold of 15 ºC. In this case the AoF is 4 ºC in the new building without PV. The recovery speed is around 1.35 ºC/hr. With PV in Figure 8, the temperature drops around to 18.1 ºC (robustness threshold) and it is able to maintain the indoor set point for 31 h. Moreover, with the PV the building is able to sustain the robustness threshold during the whole power outage and recovery phase. The AoF is 3.42 ºC and the recovery speed is 1.7 ºC/hr in the new building with PV.

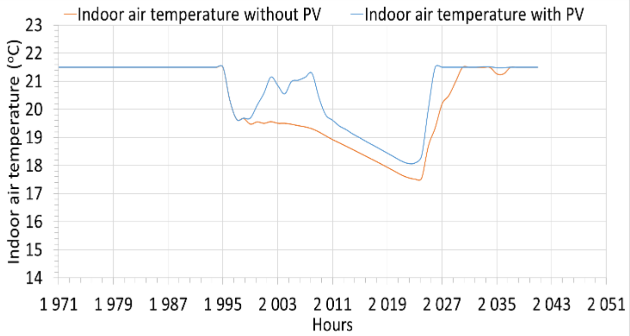

Figure 8: Energy resilience performance of the new building (set point indoor temperature as 21.5 ºC) with and without PV in cold climate during power outage.

In Figure 9, similar behavior is observed it is found that with the indoor set point temperature at 23 ºC and without PV the temperature drops below 18 ºC (robustness threshold) in 31 h during the power outage. The AoF is 5.1 ºC in the new building without PV. The recovery speed is around 1.02 ºC/hr. Figure 9, also shows that with PV the temperature drops around 19.2 ºC in 31 h and remains above the robustness threshold temperature of 18 ºC. The AoF is 3.7 ºC in the new building with PV. This shows that the impact of power outage is lower with the PV. The recovery speed is around 1.26 ºC/hr. The new building with higher indoor set point temperature with and without PV remains robust during the power outage.

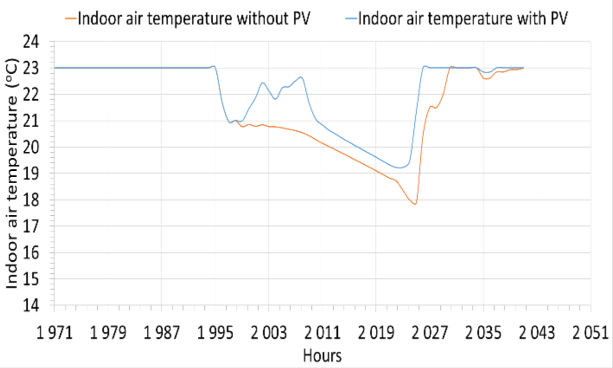

Figure 9: Energy resilience performance of the new building (set point indoor temperature as 23 ºC) with and without PV in cold climate during power outage.

When comparing the energy resilience of the old and new building it is observed that PV is able to provide longer resilience duration compared to the case without the PV. The new building performed better in terms of resilience as the indoor temperature of the new building with varying indoor set point temperature remains above 15 ºC i.e. above the minimum habitability threshold. Hence, the new building can be habitat even during power outage and can remain resilient for longer period compared to the old building. Moreover, the impact of the failure caused by the power outage i.e. the AoF is highest in the old building compared to the new building. This shows that under power outage event, the old building will perform worst with and without PV compared to the new building as the indoor temperature of the old building reaches lowest level.

Conclusion

The energy resilience and flexibility performance of the old and new building in the cold climatic condition of Finland is carried out. It is assumed that the buildings are situated in Southern Finland. Both the building had thermal mass and PV as the activation resources to improve the energy resilience and flexibility. The building has energy conservation and storage activation strategy to activate the thermal mass and PV to save the energy cost and improve the flexibility factor. The main key points on energy flexibility:

- The energy cost reduced from 6001 € to 5600 € and the flexibility factor increased to 85% for the old building integrated with PV and using thermal mass activation strategy.
- The energy cost reduced from 1283 € to 1165 € and the flexibility factor increased to 18% for the new building integrated with PV and using thermal mass activation strategy.
- The energy cost saving and flexibility factor potential is higher for the old building. This is due to higher heating demand and the prospect to save the energy and the cost is higher in the old building in cold regions.

The key findings in terms of energy resilience are as follows:

- For the old building, it is observed that without PV, the roubustness duration increased with higher indoor set point temperature 20, 21.5 and 23 °C as it increased from 1 h to 3 h and the habitability duration increased from 1 h to 19 h. The amplitude of failure (AoF) increased from 9.6 °C to 11 °C as the indoor temprature increased. Moreover, the recovery speed decreased from 2.3 °C/hr to 1.86 °C/hr as the indoor temperature increased. With higher indoor temperature the resilience is better however the recovery speed is slow and the AoF is higher.
- For the old building, it is observed that with PV, the roubustness and habitability duration increased compared to the case without PV. The robustness duration increased to 13 h depending on the indoor temperature. Moreover, the amplitude of failure (AoF) is lower compared to the case without PV as it varied from 8.9 °C to 10.02 °C depending on the indoor temperature set point. The recovery speed improved compared to the case without PV as it varied between 4.4 °C/hr to 2.63 °C/hr as the indoor temperature increased.
- For the new building, it is observed that without PV, the roubustness duration increased with higher indoor set point temperature 13 h, 25 h and 30 h as the indoor setpoint temperature increased from 20, 21.5 and 23 °C respectively. Moreover, the building remaind habitable during the power outage. The amplitude of failure (AoF) increased from 3.62 °C to 5.1 °C as the indoor temprature increased. Moreover, the recovery speed decreased from 1.8 °C/hr to 1.02 °C/hr as the indoor temperature increased. Compared to the old building the new bulding is better in terms of providing longer roubtness period, lower AoF and lower speed of recovery. With lower AoF and lower recovery spped the new building has lower impact during the outage and after the outage (recovery period).
- It is observed that with PV, the roubustness and habitability duration increased compared to the case without PV. The robustness duration increased between 19 h to 31 h depending on the indoor temperature. Moreover, the amplitude of failure (AoF) is lower compared to the case without PV as it varied from 3 °C to 3.7 °C depending on the indoor temperature set point. The recovery speed improved compared to the case without PV as it varied between 3.08 °C/hr to 1.26 °C/hr.

The energy resilience and flexibility are key concept for the building and its energy system. Overall the new building performed building compared to the old building in terms of resilience, while the flexibility is better for the old building. The integration of PV assisted in improving the resilience and flexibility performance. In order to include resilience concept and indicators in the building performance analysis the building regulation needed to be upgraded that aims to provide sustainable and resilient society to meet future challenges.

Acknowledgement

The work was funded and supported by the Research Council of Finland (Suomen Akatemia), under the project name Research Council of Finland project "Energy Resilience in Buildings in Extreme Cold Weather Conditions in Finland 2022-2025 (FinERB) [Grant number: 348060]", Research Council of Finland project "Integration of Building Flexibility into Future Energy Systems 2020-2024 (FlexiB) [Decision number: 333364]". The authors also acknowledges IEA EBC Annex 83 Positive Energy Districts. The funding bodies had no such involvement in preparing the manuscript, methods and results etc

References

Ahola, Mervi, Jorma Säteri, and Laura Sariola. 2019. "Revised Finnish Classification of Indoor Climate 2018." *E3S Web of Conferences* 111: 02017. https://www.e3s-conferences.org/articles/e3sconf/abs/2019/37/e3sconf_clima2019_02017/e3sconf_clima2019_02017.html (October 23, 2022).

Ala-Juusela, Mia et al. 2020. *EXCESS | Deliverable 1.1: PEB as Enabler for Consumer Centred Clean Energy Transition: Shared Definition and Concept*. Espoo. https://positive-energy-buildings.eu/ (June 22, 2020).

Alfraidi, Yahya, and Abdel Halim Boussabaine. 2015. "Design Resilient Building Strategies in Face of Climate Change." *International Journal of*

Architectural and Environmental Engineering 9(1): 23–28. www.climatecro.org/content/ (March 26, 2023).

Attia, Shady et al. 2021. "Resilient Cooling of Buildings to Protect against Heat Waves and Power Outages: Key Concepts and Definition." *Energy and Buildings* 239: 110869.

Breesch, H., and A. Janssens. 2010. "Performance Evaluation of Passive Cooling in Office Buildings Based on Uncertainty and Sensitivity Analysis." *Solar Energy* 84(8): 1453–67.

Le Dréau, J., and P. Heiselberg. 2016. "Energy Flexibility of Residential Buildings Using Short Term Heat Storage in the Thermal Mass." *Energy* 111: 991–1002.

European Union Commision. 2018. "DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency." https://eur-lex.europa.eu/eli/dir/2018/844/oj (April 12, 2020).

Hirvonen, Janne, Juha Jokisalo, Juhani Heljo, and Risto Kosonen. 2019. "Towards the EU Emission Targets of 2050: Cost-Effective Emission Reduction in Finnish Detached Houses." *Energies* 12(22): 4395. https://www.mdpi.com/1996-1073/12/22/4395 (November 5, 2020).

Holopainen, Riikka, Adriana Milandru, Hannele Ahvenniemi, and Tarja Häkkinen. 2016. "Feasibility Studies of Energy Retrofits - Case Studies of Nearly Zero-Energy Building Renovation." In *Energy Procedia*, Elsevier Ltd, 146–57.

Homaei, Shabnam, and Mohamed Hamdy. 2021. "Thermal Resilient Buildings: How to Be Quantified? A Novel Benchmarking Framework and Labelling Metric." *Building and Environment* 201: 108022.

Johra, Hicham, Per Heiselberg, and Jérôme Le Dréau. 2019. "Influence of Envelope, Structural Thermal Mass and Indoor Content on the Building Heating Energy Flexibility." *Energy and Buildings* 183: 325–39.

Kopányi, Attila, Karolina Poczobutt, and Lajos Ádám Pallagi. 2020. "Resilient Cooling-Case Study of a Residential Building in Ry (Denmark)." Aalborg University. https://projekter.aau.dk/projekter/files/320838562/Master_Thesis_Group1.307_2_BED.pdf (September 1, 2021).

Ministry of the Environment, Finland. 2017. "The National Building Code of Finland - Ympäristöministeriö." *Energy efficiency of buildings*. https://ym.fi/en/the-national-building-code-of-finland (June 10, 2021).

Moore, Trivess, Ralph Horne, and John Morrissey. 2014. "Zero Emission Housing: Policy Development in Australia and Comparisons with the EU, UK, USA and California." *Environmental Innovation and Societal Transitions* 11: 25–45.

Nik, Vahid M, A T D Perera, and Deliang Chen. 2021. "Towards Climate Resilient Urban Energy Systems: A Review." *National Science Review* 8(3): 2021. https://academic.oup.com/nsr/article/8/3/nwaa134/5857668 (August 17, 2021).

Nord Pool As. 2016. "Historical Market Data (Finland)." https://www.nordpoolgroup.com/historical-market-data/ (November 22, 2020).

Rehman, Hassam ur. 2018. "Techno-Economic Performance of Community Sized Solar Heating Systems in Nordic Conditions." https://aaltodoc.aalto.fi/handle/123456789/34808 (November 4, 2019).

Rehman, Hassam ur, and Ala Hasan. 2023. "Energy Flexibility and towards Resilience in New and Old Residential Houses in Cold Climates: A Techno-Economic Analysis." *Energies 2023, Vol. 16, Page 5506* 16(14): 5506. https://www.mdpi.com/1996-1073/16/14/5506/htm (July 21, 2023).

Schoeman, Laurie. 2019. "What Is Passive Habitability." *Enterprise community*. https://www.tsahc.org/public/upload/files/general/2019-06-26_HEART_Webinar_Passive_Habitability.pdf (August 22, 2021).

University of Wisconsin. 2017. "TRNSYS A TRaNsient SYstems Simulation Program." https://sel.me.wisc.edu/trnsys/ (September 5, 2020).

Yoon, Ji Hoon, Ross Bladick, and Atila Novoselac. 2014. "Demand Response for Residential Buildings Based on Dynamic Price of Electricity." *Energy and Buildings* 80: 531–41.