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Autonomy of low energy residential houses in Belgium using photovoltaic panels and energy storage

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ABSTRACT

A building can be considered to be a zero energy building if the energy use of the building is compensated with on-site produced renewable energy on a yearly basis. This paper investigates the possibility of low energy buildings using photovoltaic PV solar panels in combination with energy storage systems to become zero energy or a (partly) autonomous building. A detached residential building with underfloor heating, air to water heat pump and photovoltaic panels PV is considered for this case study. The building is modelled in three energy performance levels, 15, 30 and 60 kWh.m^{-2}.a^{-1}. All three energy performance levels ensure comfort heating. A user profile for domestic hot water is implemented according to Ecodesign. The energy use profile for appliances is taken from field measurements. Maximum autonomy of the three different buildings, using energy storage, results in 73%, 67% and 60% respectively for 100m² PV panel use and the selected boundary conditions of this research.
Keywords: Energy Efficiency, Energy Storage, Heat Pump, Residential Building, Solar Energy.

1. INTRODUCTION

In the European Union (EU), the total final energy use was measured to be equal to approximately 1.084 Mtoe (Bertoldi et al., 2018). The term final energy represents the amount of energy that is actually used by the end consumer. According to statistics, final energy is principally used by four sectors: transport, residential, industry and services. The residential sector accounts for 25.38% of the final total energy use in EU (Bertoldi et al., 2018). On the other hand, residential buildings account for a share of 75% of the total building stock in EU (De Boeck et al., 2015).
Households use energy for different purposes: space and water heating, space cooling, cooking, lighting, electrical appliances. Statistical surveys carried out by the official organization of the EU have shown that the used energy in dwellings is mostly taken by space heating (64.7%) and domestic hot water production (14.5%), while consequential production of energy for covering both of the thermal needs accounts for 79.2% of total final energy use (Eurostat, 2018). The same study has shown that natural gas, fossil fuel, plays an important role in providing energy to satisfy the energy needs for an average dwelling in Europe. In fact, gas is still responsible for providing 43.4% of the heat for space heating, 47.9% for water heating and 33.1% for cooking needs. Present world society has a clear awareness of the transient of the fossil fuel energy sources. As a matter of fact, renewable energy sources are finding an outstanding breakthrough in the market. According to the official statistical data (Eurostat, 2018), renewables cover 22.2% of the energy needs for space heating, 9.6% for hot water production following 4.2% for cooking in EU. The future expectations over energy use in novel as well as in refurbished buildings testify about optimal use of energy and definite implementation of renewable energy sources and accompanying technology.

With each novel directive, European legislation intends to push building stock to near zero or zero energy buildings. A building can be considered to be a zero energy building (ZEB) if the energy use of the building is compensated with on-site produced renewable energy on a yearly basis. As stated by Agostino and Delia (2015) a zero energy building compensates its total energy use for heating, ventilation, domestic hot water and appliances by renewable energy produced on site. In the case of zero energy building, energy demand and energy production are shifted over the seasons. Fig. 1 shows change in energy demand for comfort heating versus electrical energy production using 50 m^2 photovoltaic (PV) solar panel for a full year time. It can clearly be seen that energy demand has completely contradictory behaviour when compared to the energy production at the given moment for all different building energy performances. A 15 $kWh.m^{-2}.a^{-1}$ building has a reduced heating demand during the offseason due to the high passive solar gains but still has a significant energy use during the coldest winter period with low solar radiation, not enough to compensate the heat losses of the building. When no sufficient energy storage is used the electricity grid is utilized as virtual energy storage. To get an autonomous building, energy storage is needed on site to bridge the time shift.

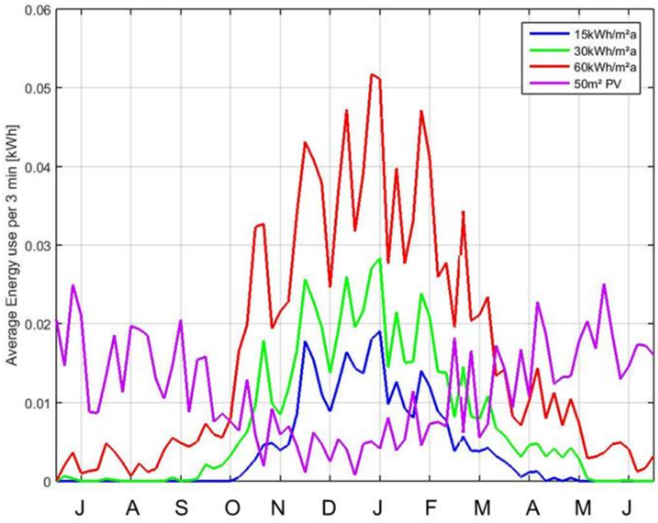

Figure 1: The energy demand of a 15, 30 and 60 $kWh.m^{-2}.a^{-1}$ building and energy production 50m² PV

Weitemeyer et al. (2015) highlighted that energy storage and/or curtailment will be required once the renewable energy ratio surpasses 50% in covering overall energy demand with joint use of flexible power plants. Later research performed by Child et al. (2017) and Child et al. (2018) have confirmed the same share of renewable energy production ratio value.

This paper investigates the possibility of low energy buildings using photovoltaic (PV) solar panels with efficiency of 16% in combination with energy storage systems to become a partly autonomous building. This part of the research focuses on different building envelopes, the needed amount of renewable energy and the needed energy storage to reduce the dependency from the grid. The importance of having a vigorous building envelop resulting in the lower necessity of taking the energy from the grid or to have a higher autonomy intends to be the goal of the research. Non-technical people pretend that a lower energy performance of the building can be compensated by extra renewable energy production on site. This is mathematically correct on a yearly basis if only the total energy use is considered. This paper highlights the incontrovertible advantage of higher building performance.

In the following text, 15 $kWh.m^{-2}.a^{-1}$, 30 $kWh.m^{-2}.a^{-1}$ and 60 $kWh.m^{-2}.a^{-1}$ building levels will be represented as B15, B30, B60 buildings respectively in order to facilitate the understanding of the results.

2. METHODOLOGY

2.1. Observed Case

A detached residential building with underfloor heating, air to water heat pump and photovoltaic panels (PV) is considered for this case study. The building is modelled in three energy performance levels of 15, 30 and 60 kWh.m^{-2}.a^{-1}. All three buildings are assumed to be located in the area of Brussels, Belgium. Therefore, the chosen outdoor boundary conditions are corresponding to the available weather data conditions of Brussels. This study is focussing on one building design with one set of building parameters for each investigated energy performance of the building. However, it is important to mention that a building with the same energy performance but with a different orientation and different window construction will change the energy load profile for heating on a daily basis. Previously, it has been ensured that all three energy performance levels are fulfilling the comfort heating demand with respect to the heat losses. The buildings are assumed to be constantly heated with the indoor set point temperature at 20ºC.

The only difference in the energy use of the investigated buildings is the energy performance of the building envelope. Due to different heating demand, the electrical energy use is 689, 1378 and 2756 kWh.a^{-1} for the 15, 30 and 60 kWh.m^{-2}.a^{-1} building for comfort heating while all three houses have the same demand of 848 kWh.a^{-1} for domestic hot water and 5011 kWh.a^{-1} for the appliances. This brings the total electricity use on 6548, 7237 and 8615 kWh.a^{-1} for each energy performance building level respectively.

2.2. Simulation Tools and Strategy

The buildings and the systems are modelled in software package TRNSYS17 (Solar Energy Laboratory, 2009), using TRNFlow to calculate the ventilation, in- and exfiltration of the buildings. In addition, several MATLAB (2015) scripts were used in order to calculate relations between produced heat by the air to water heat pump and energy stored by the energy storages. Data analysis was also performed using the MATLAB software package. Fig. 2 illustrates the simulation methodology.

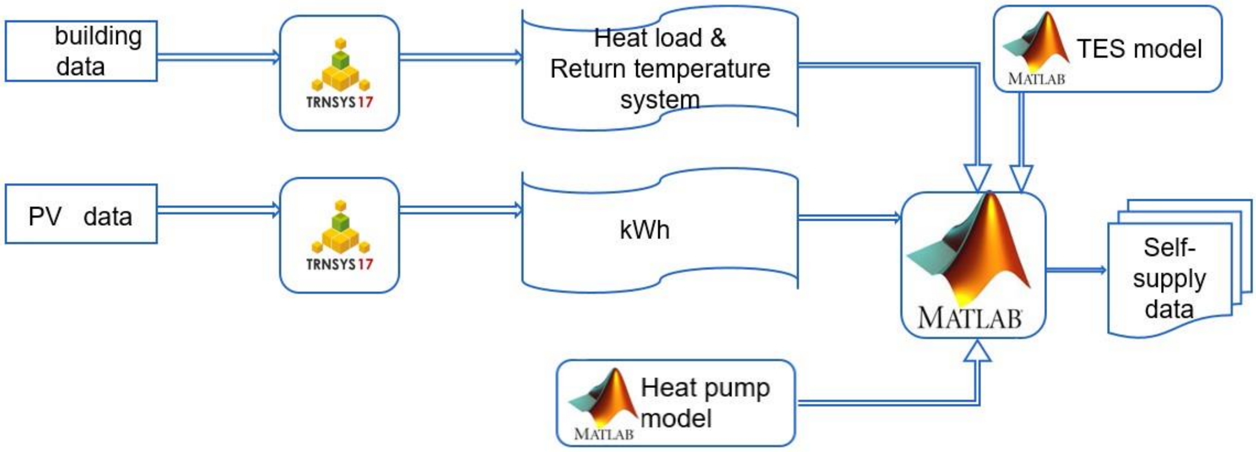

Figure 2: Simulation methodology

Therefore, TRNSYS simulation results are used as input to the storage and the heat pump model, while installation models are developed in a MATLAB script. The calculation of the heating demand and energy supply is thus decoupled from the installation simulation. As a result, the simulation is speeded up sufficiently to evaluate a multitude of energy production and energy storage combinations.

The simulations of the energy performance were done with a time step of 3 minutes. At each time step, the following data were calculated:

- the heating demand of the building
- the return water temperature of the underfloor heating
- the mass flow rate in the underfloor heating
- the thermal power production by the heat pump and energy use of the heat pump
- the solar power production of the photovoltaic solar panels

- the status of the thermal and electrical storage

The energy exchange between the building, the energy buffers and the electrical grid is integrated in the post-processing method using a control strategy which is the same for all analysed cases. The strategy covers the energy balance of the whole building system and it is met at each time step.
The domestic hot water (DHW) production has priority on the heating load of the building. The comfort demand of 40°C DHW at each time step must be guaranteed.

2.3. Used Input Data

A user profile for domestic hot water is implemented according to Ecodesign requirements. The used profile in this study is a medium user profile (3XS) coming from the regulation of the European Commission, (813/2013).
Outdoor conditions are simulated by using the Meteonorm climate data. The data are coming from the official Royal weather station located in Uccle (Belgium). Besides the outdoor temperature, data files are containing as well the information over the solar radiation, the position of the sun, outdoor relative humidity, sky cover etc.
On the other hand, the energy use profile for appliances is taken from field measurements during the Linear project (D'hulst et al., 2015) where the energy use is measured over more than a full year on a time step basis of 15 minutes. The profile of the appliance use is appropriate for a young family with two young children living in a detached house. Both parents are having full-time employment. In the original project, the heating and the DHW production of this case study house were supplied by a gas boiler. For cooking, an electric stove was used. The total electricity use for this case was determined to be 5010 $kWh.a^{-1}$.

2.4. Investigated Energy Storage Systems

As it was shown before, optimum renewable energy production and energy requirement are shifted in time. By introducing energy storages to the system the impact of this phenomenon may be significantly mitigated. Electricity production out of photovoltaic panels has the peak production around noon. On the other hand, air to water heat pumps have their maximum COP at the same time due to maximal daily outdoor temperature. Since the energy demand shows to be disproportionate to the optimum energy production, there is a clear necessity of having energy storage in order to increase the energy autonomy of a dwelling.
In this study, both electrical energy storage (EES) and thermal energy storage (TES) are considered for the purpose of the autonomy analysis. Several different capacities of both EES and TES, as well as their combination with different PV sizes, are considered by the analysis. The charging and discharging losses of the EES are assumed and kept fixed at 10%.The results of the research are given in the next section of the paper.

3. RESULTS

Autonomy for three different energy performing buildings was analysed for several different energy storages and PV surface sizes. Electrical energy storage is evaluated for 0, 2000, 4000 and 8000 Wh. On the other hand, thermal storage is evaluated for 0, 500, 1000 and 2000 litre of volume. All sizes used for evaluation of impact to building autonomy are realistic and taken as standardized capacities provided by relevant manufacturers of the equipment.
In real use, a different combination of EES and TES sizes are possible. Depending on the energy need and principally on investment costs, different solutions are to be found in modern households. Different energy storage systems will be compared to the basic system without energy storage and without renewable energy production. The last baseline has per definition an autonomy of 0% which means that all needed energy has to be supplied by the grid. Autonomy stands for the independence from the grid or fraction of the load covered by on-site generation. In this study, the autonomy of different dwellings is evaluated based on the solar fraction. As shown on the Eq. (1) and based on the research performed by Widen et al. (2009), the solar fraction is defined as the ratio between energy supplied from the grid and total electricity demand:

$$solar\ fraction = 100 - \frac{energy\ supply\ grid}{total\ electricity\ demand} \qquad \text{Eq. (1)}$$

3.1. Autonomy of the 15, 30, 60 kWh.m^{-2}.a^{-1} Energy Performance Level Building in Belgium

Fig. 3, Fig. 4 and Fig. 5 illustrate which solar fractions can be realized with PV areas up to 100m² combined with different sizes of electrical and thermal energy storage for all three energy performance levels. Small thermal storage has always a significant improvement on the solar fraction. However, the increment of the size of the TES without an introduction of the EES does not give further notable improvement except for the least energy efficient building. Nevertheless, EES brings higher grid independency even for the smallest battery capacity. In fact, the impact of using the small scale electrical battery brings higher solar fraction than the use of the biggest TES for B15 and B30 building cases. The higher impact of EES is due to the fact that the thermal energy storage is only used during the heating season and the EES is used during the entire year.
Fig. 3 shows autonomy results of the B15 building. The B15 building has an autonomy of 30% (solar fraction) in the absence of any energy storage and use of 100m^2 PV solar panels. Without energy storage and 50m² PV, a solar fraction of 25% is achieved (remaining energy requirement is 4911 kWh.a^{-1}). Using the same PV area and introducing a thermal energy storage of 2000l increases the solar fraction up to 31%, leaving the remaining energy requirement to be 4812 kWh.a^{-1}.

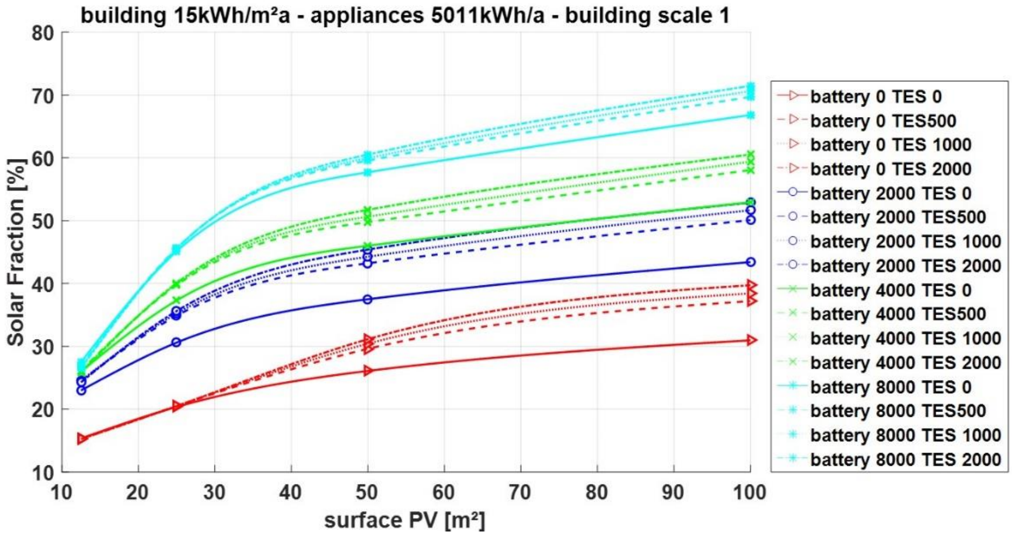

Figure 3: Solar fraction for 15 kWh.m^{-2}.a^{-1} building, appliances 5011 kWh.a^{-1}

Representation of the autonomy for all three building performances allows determination of the needed renewable energy and energy storage to get to the same energy supply from the grid.
The B15 building has a total energy demand of 6548 kWh.a^{-1}. A PV surface of 5m² is needed for the B30 and 30m² PV for the B60 to get the same electricity demand as the B15 on yearly basis using the grid as storage. In case the same supply from the grid is targeted as the B15, without using the grid as a storage system, the B30 needs 9,52% solar fraction. This can be reached by means of 5m² PV panel. However, the B60 building would require a 24% solar fraction which needs 83m² PV or 30m²PV and 2000l TES or 25m² PV and 2000 Wh battery.

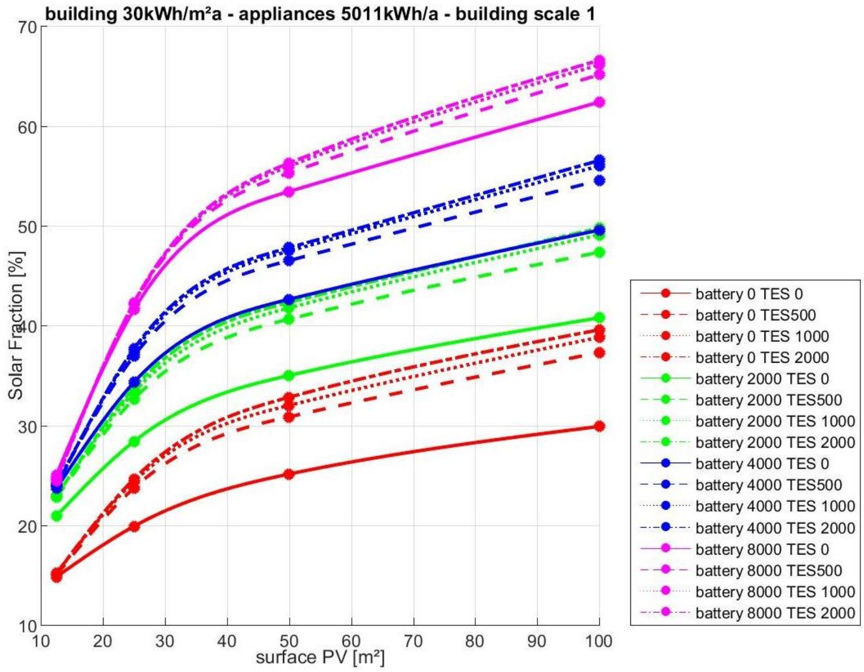

Figure 4: Solar fraction for 30 $kWh.m^{-2}.a^{-1}$ building, appliances 5011 $kWh.a^{-1}$

According to the first definition of zero energy building (ZEB), in order to make all three buildings ZEB, a PV area of 44, 49 and 58m² is needed. This results in the autonomy of 26%, 25% and 22% for the B15, B30 and B60 and leading the supply from the grid as energy storage to become 4845, 5428 and 6720 Wh. To bring all buildings on the same energy supply from the grid of 4845 Wh, the B30 building needs a solar fraction of 33% which includes 50m² PV with 2000l TES or 24m² PV with a 4000 Wh battery or 100m² PV with 700l TES.
The B60 building, however, needs, in this case, a solar fraction of 44% which opens four possibilities. The first is to have a 60m² PV solar panel with a 4000 Wh battery. Then, the second could be to have a 2000l TES and 2000 Wh battery or 28m² PV with an 8000 Wh battery. The last option requires a 100m² PV solar panel with 1000l TES with an 2000 Wh battery. The lower the energy performance of the building, the bigger PV solar panel surface and energy storage is needed to get the same energy supply from the grid.

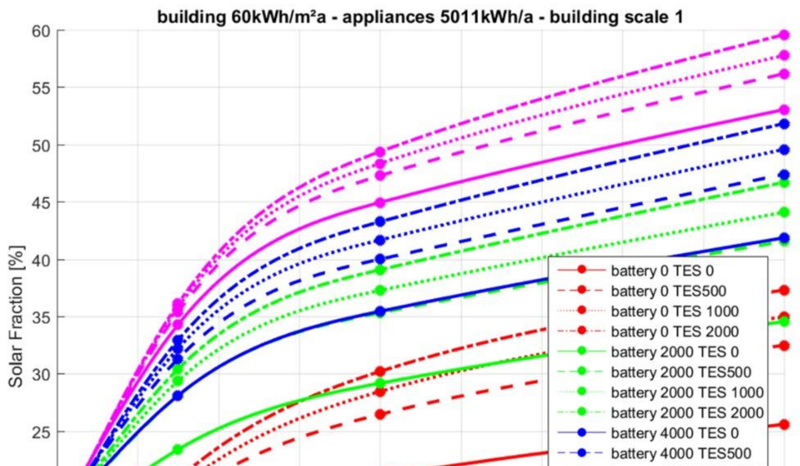

Figure 5: Solar fraction for 60 $kWh.m^{-2}.a^{-1}$ building, appliances 5011 $kWh.a^{-1}$

The highest autonomy for maximal battery and thermal storage capacity and PV surface area of 100m^2 proves to be 72%, 67% and 60% for B15, B30 and B60. Therefore, for the boundary conditions used in this study, it is determined to be impossible to achieve 100% grid independence for neither of the analysed building envelops using the roof as available PV area.

3.2. The Remaining Energy Requirement for the three Buildings with Different Battery Use

Since every different building has different energy requirements due to heat demand, it becomes clear that one size of battery will have a different impact to the remaining energy needs that have to be taken from the grid. Fig. 6 illustrates the remaining energy supply from the grid for different battery sizes for the three levels of building energy performance. Following the result on Fig. 6 it becomes evident that for using e.g. 2000 kWh.a^{-1} from the grid, a 15 kWh.m^{-2}.a^{-1} building will require a battery size of 7500 Wh, while the 30 kWh.m^{-2}.a^{-1} needs to have a double-sized battery of 15000 Wh. The 60 kWh.m^{-2}.a^{-1} building cannot reach the example chosen level of limited energy supply.

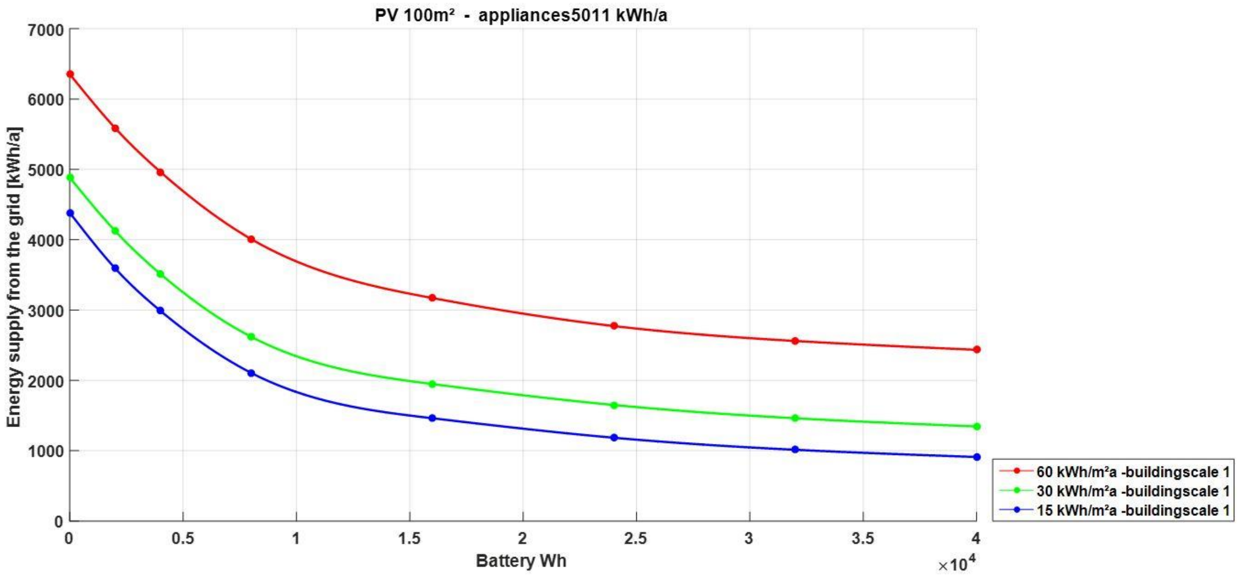

Figure 6: The capacity of EES in order to have the same remaining energy requirement for all three buildings for 100m^2 PV panel area and 5011 kWh.a^{-1} electricity use

The lower the energy performance of the building the more difficult it is to compensate the lower building performance with extra energy storage.

3.3. Financial Aspect

In this chapter, an order of magnitude of the financial impact will be given through a partial financial evaluation on the electrical energy storages (batteries). As part of the study, different battery capacitates are adopted to evaluate the level of the buildings autonomy to the grid that can be achieved.

In 2017, the cost of a battery was approximately 1000€ per kWh capacity. The price corresponds to the average price of the Li-Ion batteries that can be applied to the entire capacity range used in this research. Assuming a lifecycle of the building of 30 years means that the battery has to be replaced two times during the mentioned period. This also means that the magnitude of the extra investment is 15000€ for the case of 15 kWh.m^{-2}.a^{-1} building and 30000€ for the 30 kWh.m^{-2}.a^{-1} building.

Another interesting aspect is the ageing of the equipment. The storage capacity of a battery decreases due to cycling ageing and calendar ageing. In the scientific literature, many studies have been addressing the life cycles of the batteries for the application in the electric vehicles. Compared to the batteries of the electric vehicles, the batteries in buildings application have significantly more stable working conditions. The changing of the battery is spread over a range of 12 hours while only the overshoot of the produced energy is actually stored in the batteries. The ageing of the EES is not considered in this research. Several experimental studies have shown that batteries in buildings application will have a much longer life cycle when compared to others. However, further research over the matter is certainly needed in the close future. Improving the energy performance of the building envelop and building system should be the first step before considering using energy storage.

4. CONCLUSIONS

Long-term targets set out in European Union Roadmap-2050 request emissions from the building stock, with the largest share of housing stock, to be cut by around 90% till the year 2050. Both energy efficiency measures and the transit from fossil fuels to decarbonized electricity, e.g. by using heat pumps merged with renewable energy are indispensable for reaching those ambitious targets. Balancing intermittent renewable energy supply through pro-active demand-side management and energy storage will serve as leading instruments in order to reduce the energy use of residential buildings.

In this research, using simulation tools, several aspects of different energy efficiency level buildings have been analysed. Using realistic sizing of building integrated systems including electrical and thermal energy storage as well as photovoltaic panels results in significant reductions of energy supply from the grid. For the boundary conditions used in this research, results show the impossible reach of energy independence from the grid in Belgium. The maximum obtained autonomy was shown to be 72% for the 15 $kWh.m^{-2}.a^{-1}$ with EES of 8000 Wh, TES of 2000l and PV panel surface of $100m^2$, while the maximum autonomy for the 30 and 60 $kWh.m^{-2}.a^{-1}$ buildings results in 67% and 60% respectively. On the other hand, if the area for using the PV solar panels is limited to $52m^2$, maximum autonomy of the three different building energy levels results in 61%, 57% and 50% respectively.

Local energy storage can significantly increase the autonomy of buildings using on-site produced renewable energy. However, the high investment of energy storage and the limited life cycle of the equipment is still a threshold.

Without a proper design of the building envelop in order to significantly reduce the energy demand, large investments in renewable energy production and storage equipment cannot make a typical residential building in Belgium autonomous. To contribute to the aspirations of the EU, refurbishment of existing buildings and construction of new ones in order to meet high energy performance of the building envelop and the building systems will be inevitable.

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