Impact of different short-term thermal energy storage strategies on the performance of an inverter controlled air-to-water heat pump(IATWHP) in residential buildings in Belgium.

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Abstract

A solar energy assisted heating system is used in combination with electrical and thermal energy storage to cope with the time shift between renewable energy generation and energy demand. This study analyses the autonomy that can be reached for several combinations of photovoltaic solar panels (PV), solar thermal panels (ST), electrical storage (ES), thermal energy storage (TES) and heat pump (HP) capacity for a low energy building. The influence of the different systems sizing on the energy supply autonomy is investigated. The solar fractions of the heating and domestic hot water demand are calculated for a reference building in Belgium for different sizing combinations. The simulations are executed in TRNSYS and Matlab. A 15kWh/m²a building can achieve a solar fraction (SF) of 22% with only solar thermal. A SF of 45% can be attained with only TES and 90% with a combined system of TES and ES or only ES. The autonomy is limited by the available roof surface. A TES increases the solar fraction with 5 to 15%. Doubling the battery capacity in the reference case results in 5 to 7% of solar fraction increment.

1. Introduction

The mitigation of climate change and fossil reserve depletion forces the shift to renewable energy (RE). The intermittent RE sources such as wind, PV and ST do not match with the demand side (Moriarty 2012). Energy storage technologies will have an important contribution to the balancing of energy demand and renewable energy production (Ozdemir 2016). Weitmeyer (2015) studied the necessity for energy storage in Germany as a function of the renewable energy fraction. As long as renewable energy accounts for less than 50% of the installed capacity, curtailment or storage devices are not required, if sufficient flexible power plants are available. Above 80% renewable energy production, seasonal storage is required. In-between, small, highly efficient storage devices should be favoured. Electrical and thermal energy storage on a domestic scale can contribute to a balanced grid (Ozdemir 2016, Child 2016, Articoni 2013).

The renewable energy used in residential buildings are PV and ST. Different energy storage systems are available for residential buildings: ES in batteries, TES in the thermal mass of the building or TES in a storage volume. The incentive for the end-user to invest in energy storage or to attain a certain degree of autonomy can be the price difference between feeding the grid with the surplus of produced solar energy and taking energy from the grid (Speidel 2016), insufficient or no power supply from the grid (Kaldellis 2004) or the target to have an off-grid zero energy building (Marszal 2011). This is not to be confused with net zero energy buildings, where the target is to compensate the yearly energy use from the grid with surplus solar energy supply to the grid (Marszal 2011).

Each subsystem such as the inverter, the battery, the heat pump and the thermal energy storage can be the subject of an optimisation.

Daher (2008) describes the inverter efficiencies and found 90 to 96% inverter efficiency as representative for the available inverters. Rydh (2005) investigated the energy return factors and overall battery efficiencies. Rydh found an overall battery efficiency for an Li-ion battery of 85% to 90%. The renewable energy that is immediately used by the appliances has only the inverter losses. Once the battery is used to delay the energy use, that part has to consider the overall battery efficiency. Khatib (2016) and many others describe the design and efficiency of PV/ES systems (Sauer 2001,Kaldellis 2004). A lithium ion battery is used for the electrical storage as it provides a better performance than NaNiCl and Lead Acid batteries for this application (Zhang 2016).

There are different degradation phenomena which decrease the performance of PV systems, such as:

- degradation of the PV array, magnitude of 1% per year (Jordan 2013)
- battery calendar aging, magnitude of 2% per year
- battery cycle aging, magnitude of 2% per year (Keil 2016, Schmalstieg 2013).

J. Leadbetter mentions that the accumulation of those effects can result in a 20% decrease of the efficiency after 8 years (Leadbetter 2012). TES in combination with a PV/ES system is seldom investigated. Authors who compare the efficiency of PV with ES to the same system extended with ST and TES conclude that the contribution of the ST is low (Good 2015).

Solar thermal assisted heat pump systems are recognized as a significant contribution to the energy performance of low temperature heating systems (Buker 2016). A 5m² solar thermal surface for the production of domestic hot water (DHW) results in a solar fraction of 65% for central Europe (Bertram 2012). The energy use for DHW in low energy buildings becomes as important as the heating demand, with each having a share of approximately 50% of the total heat demand (Thomsen 2005).

Visa (2016) simulated a solar thermal assisted ground coupled heat pump, which resulted in a thermal solar fraction of 20% . Parra (2016) investigated the use of an electrical resistance in the domestic hot water (DHW) tank as TES for the surplus of PV generation. He concluded this combination was the best solution for the UK energy market. Wang (2015) compared ES with cold storage for three locations and concluded that ES gives the highest primary energy savings. The investigated PV system covered 65% of the total electricity use. The negative results for cold storage were caused by the lower efficiency of the cooling system due to the lower working temperatures to make cold storage possible. The disadvantage of a high coverage by PV generation is the excess of renewable energy production during low load periods of the process (Speidel 2016, Kaldellis 2004). Bellos (2016) investigated the full combination option: PV, ES, ST, TES for four heat pump systems. Solar fractions up to 93% were calculated. However, none of the cited authors mention the effect of the size of ES, TES and PV.

Research description

The total energy use in a residential house is determined by the heating system and the appliances. This research focuses on a detached building that can be supplied with only electrical renewable energy, which means that the heating system has to be provided by a heat pump. To optimize a complete system, the optimal design conditions of each subsystem (PV, TES, battery, heat pump) must be known. This research investigates the design conditions of the heating system.

The aim of this study is to investigate the interaction of the sizing of the ES, TES, PV and ST and the resulting solar fraction. The investigation is executed with TRNSYS simulations over one year for a residential building in Belgium. Three energy performance levels of the building are considered: 15, 30 and 60kWh/m²a. The surface of PV and ST, the capacity of the ES and the volume of the TES are the main variables of the study.

2. Case study

The case study considers a low energy building outfitted with PV, ST, ES and TES. The present section describes the characteristics of the used components.

The heating system is provided with three thermal energy buffers and a battery system. A control system guarantees optimal use of the different energy flows.

Low energy building:

The study is performed on a low energy building. A low energy building is defined as a building with a heating demand lower than 70 kWh/m²a (Feist 1996). The low heating demand is achieved by a high insulation level, air tightness and the use of passive solar gains. The characteristics of the 15kWh/m²a building is presented in table 1.

Table 1: Characteristics of the 15kWh/m²a building

Building typology	Detached house
House levels	3 floors + attic
Orientation	North-South
Net heated surface	143m^2
Air tightness n50	0.3 1/h
Yearly heat demand	2358 kWh/a
Total roof surface	88.51 m^2
Maximum heating load	6 kW

Photovoltaics (PV)

Most commercial products have an efficiency between 12 and 16% (Shukla 2016). A PV module with an efficiency of 16.6% is selected. Since the average yearly solar irradiation in Belgium is approximately 1000kWh/m² (Wauman 2010), the energy generation is 166kWh/m²a. Table 2 presents the characteristics of the PV panels.

Table 2: The PV specifications of the model

Short-circuit current at reference conditions	9.47 A
Open-circuit voltage at reference conditions	39.08 V
Reference temperature	298 K
Reference insolation	1000 W/m^2
Voltage at max power point	31.42 V
Current at max power point	8.91 A
Temperature coefficient of short-circuit current	0.04 A/K
Temperature coefficient of open-circuit voltage	-0.29 V/K
Module temperature at NOCT (Nominal Operating Cell Temperature)	318 K
Ambient temperature at NOCT	293 K
Insulation at NOCT	800 W/m^2

Four different PV areas are evaluated, between 25 and 100 m².

Solar thermal (ST)

The solar thermal panels used in the case study are vacuum tube collectors. Those collectors have the best performance during the coldest outdoor temperatures. (Zambolin 2010) The areas that are considered are 0, 4, 12, 24 and 48 m².

The technical specifications according to standard EN12975-2 (CTSB 2012) are given in Table 3

Table 3: Characteristics of the solar thermal

Surface	3.91 m^2
Test flow	75 l/h.m^2 water
Optical efficiency η_p	0.761
Thermal loss coefficient of first order a_1	1.047

Thermal loss coefficient of second order a_2	0.007

Battery

The battery cycle and calendar aging are not investigated in this research. The investigated capacities of the battery are 6500Wh, 9750Wh and 13000Wh, which are available sizes on the market.

Renewable energy production

The PV area indicated on the different graphs of this paper are surfaces for 100% efficiency of the inverter and the battery system. Dividing the PV surface by the overall efficiency of the PV-Maximum Power Point tracker – inverter – battery system gives the effective PV surface that is needed.

Thermal Energy Storage (TES)

Three different TES units are identified in the heating system. The first TES system is the domestic hot water tank of 400l. Secondly, a tank of 400l is directly connected to the heating system and is heated to the calculated supply water temperature determined by the heating curve. This tank makes immediate use of solar thermal energy on low temperature possible, which increases the efficiency of the solar thermal system. The third TES system stores excess renewable energy as thermal energy on a higher temperature. The heat pump loads this tank to maximum 50°C, the solar thermal system can load it to maximum 80°C. All of these TES systems are evaluated using a stratified water tank model. The thermal losses of the buffers are considered as totally lost and are not contributing to the heating of the building.

- DHW buffer 400 l
- Floor Heating Buffer : 400 l
- TES 1000 to 3000 l

The floor heating buffer (FHB) also serves as a hydraulic separation between heat pump and floor heating, see figure 1.

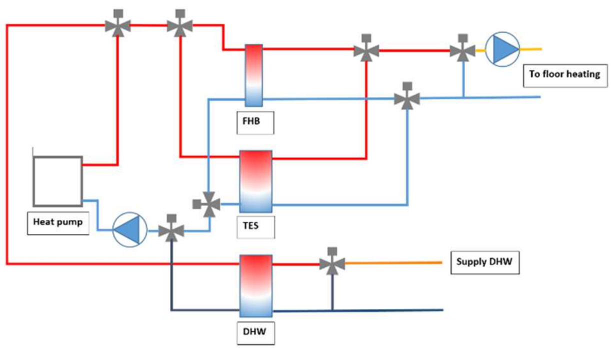

Figure 1: Hydraulic scheme

Heat pump

The air to water heat pump is inverter controlled. The base case has a heating capacity of 150% of the maximum heating load. A heating capacity of 100% and 200% are also evaluated, to assess the impact on the solar fraction. The heating curve is defined by a supply water temperature of 40°C at an outdoor temperature of -10°C and 31°C at an outdoor temperature of 18°C.

DHW-profile

The daily DHW-profile of the European Directive EU813/2013 is used (Medium user profile) (EU 2013).

Appliances

The energy use for the appliances is not implemented in this study. D'hulst (2015) measured the electricity use for appliances in 186 household during 3 years. The low/medium/high values for one household were 2500/4250/6650kWh/a. The authors of this paper calculated an electricity use for comfort heating and DHW of 3105kWh/a for a 60kWh/m²a building and 1097kWh/a for a 15kWh/m²a building. Heating electricity use accounts for 14 to 55% of the total electricity use in residential buildings. This study focusses on the performance of a heating system with RE to define the impact of electrical and thermal storage on the solar fraction.

3. Methodology

Figure 2 gives a schematic overview of the simulation methodology. The building heating demand, thermal solar and PV production are simulated in TRNSYS. At each time step, the following data is calculated:

- the heating load
- the return water temperature of the floor heating
- the mass flow rate in the floor heating

The solar thermal model generates a file for different inlet water temperatures with:

- the supply water temperature of the solar thermal collector
- the mass flow rate in the solar thermal collector

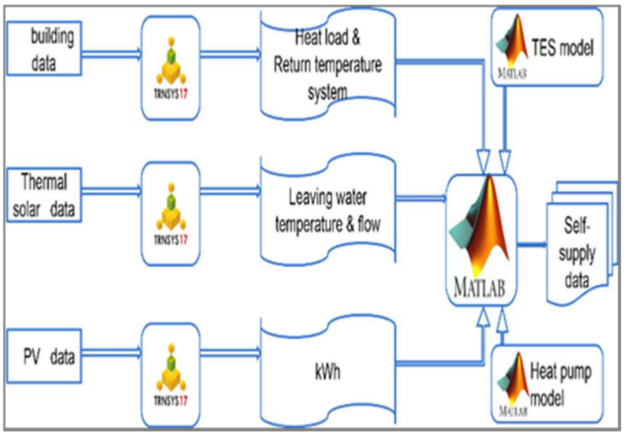

Figure 2: Schematic representation of the simulation methodology.

The PV model calculates the solar power production at each time step.

The TRNSYS results are used as input to the storage and heat pump model. These installation models are implemented in Matlab. The calculation of the heating demand and energy supply is thus decoupled from the installation simulation. As a result, the simulation is speed up sufficiently to evaluate a multitude of PV, ST, ES and TES combinations. All TRNSYS simulations use a time step of 0,05 h.

The rest of the section describes the TRNSYS setttings and the post processing in Matlab.

TRNSYS simulation settings

Building: type 56

The building model type 56 is a multi zone non-geometrical balance model. Each zone is discretized as a single air node.

Room set temperature: 20°C (bathroom 24°C)

Ventilation with heat recovery: type 667

Type 667 uses a "constant effectiveness-minimum capacitance" approach to model an air to air heat recovery device. Minimum capacitance can be determined by the minimum mass flow rate and specific heat for each of the two streams.

Heat loss to the soil: type 49

The model relies on a 3-dimensional finite difference model of the soil and solves the resulting coupled differential equations using a simple iterative analytical method.

Infiltration and exfiltration: TRNflow, type 2260

TRNflow is a multizone air flow model, based on a network model of the building. Mass conservation results in a system of non linear equations. The system is solved for the node pressures and the mass flows between nodes.

Radiant floor heating: TRNbuild active layers

The active layer model is based on an equivalent star network.

Climate: type 15 Uccle, Belgium

Using raw data read from the climate file, type 15 uses solar radiation processing algorithms to calculate detailed weather data.

PV: – type 194

The PV model is based on the five parameter equivalent circuit model that is presented by Duffie and Beckman (1991) .

Solar thermal: type 538

The solar thermal model is based on the Hottel-Whillier equation (Nelson 1998).

Orientation: south

Collector slope: 45°

The simulation is made for inlet water temperatures into the solar collector of 10°C to 99°C in steps of 10°C. The flow of the solar thermal pump is a function of the outlet temperature of the collector. The solar pump control attempts to keep the solar collector outlet at a temperature that is 10°C higher than the inlet temperature. Once the maximum flow rate is reached, the temperature difference between inlet and outlet of the collector rises accordingly above 10°C.

Matlab process simulation.

The post processing method keeps track of the stored thermal and electrical energy, using models for the battery and the thermal energy storage system. Furthermore, the required input energy for the heat pump, given the requirements from the building simulation, is also evaluated at this point. The energy exchange between the building, the energy buffers and the electrical grid is implemented in the post processing method using a control strategy. This strategy is such that it satisfies the requirements of the dynamic building simulation at each time instance.

The installation simulation is performed using Matlab. At each time step the building heating demand has to be met. The PV electricity generation and ST heat production are inputs to the Matlab simulation.

TES model

The tank model is a one dimensional finite volume model as is commonly used in literature (Nelson 1998, Arteconi 2016), discretized into five cells. Only conductive heat exchange between the cells is taken into account, convective mixing is disregarded. The water is assumed to be incompressible with constant properties. Heat loss to the ambient is estimated using the conductive loss through the tank insulation, neglecting the convective resistances. All these assumptions result in a linear model, which allows for a fast evaluation. The time derivatives are discretized using a first order backwards Euler scheme.

Heat pump

Part load data for 30% to 100% load is available for outdoor temperatures between -18°C and +18°C. The temperature range is representative for the heating season in Belgium. The supply water temperatures range from 30°C to 50°C. An interpolating polynomial model is fitted to the data.

4. Control strategies

A specific control strategy is implemented in the post-processing method. The control strategy is the same for all considered cases.

Control of the domestic hot water

The domestic hot water production has priority on the heating load of the building. The comfort demand of 38°C DHW at each time step must be guaranteed.

Temperature top of the DHW tank<40°C: priority high

Thermal solar energy and heat production of the heat pump goes to DHW buffer. If the PV or the battery cannot supply the needed energy, energy is taken from the grid. The heating of the building is supplied from the FHB buffer or the TES buffer if possible. Not delivered heating energy is shifted to the next time step.

Temperature middle of the DHW tank<40°C: priority low

The solar thermal energy goes to the DHW buffer. The heat pump charges the DHW buffer if enough renewable energy is available and if the heating load of the building is supplied by the FHB buffer or the TES buffer.

Top > 40° C and middle >40° C: no priority DHW

Available solar thermal is transferred to the buffer DHW if the bottom temperature of the buffer DHW is lower than the bottom temperature of the other buffers.

During summer, the operation of the heat pump is delayed until 17h00 in case of the low priority to make optimal use of the thermal solar energy and to reduce the operation hours of the heat pump.

Control of the heating of the building

This control manage the heat supply to the building. If the DHW has no high priority this control decides which buffer will supply the heat demand and if activation of the heat pump is necessary.

If the FHB buffer can supply the heating load, the heat pump is available to charge the DHW buffer or the TES buffer. If the FHB buffer has not enough stored energy and there is enough renewable energy available in the battery, the heat pump will supply heat to the FHB buffer. In case there is not enough renewable energy available and there is enough stored energy in the TES buffer, the last one will supply the heating load. Only if the previous steps did not succeed to supply the heating load, the heat pump will use the left- over of the battery in combination with energy from the grid.

Direct heating with the FHB buffer has priority on loading the TES buffer. That strategy takes care that the heat pump prioritizes heat production with the highest COP. Simultaneously using the TES buffer to supply the heating load and loading the TES buffer would result in a lower COP than using the FHB which always is on a lower temperature.

When the FHB cannot supply the requested heating load, e.g. when no heating capacity of the heat pump is available for the floor heating due to the priority of DHW heating, the requested heating load is delayed to the next time step.

Control of the thermal energy storage

If the heating load could be supplied by the FHB buffer and there is no priority for DHW, the TES buffer is charged with the heat pump if the battery charge is higher than 50%. A minimum load of 50% before charging the TES buffer is chosen to keep renewable energy available for direct heating at a higher COP. Due to the lower temperatures in the FHB buffer, the COP while using the TES buffer is lower than in direct heating mode.

Control of the PV panels

The total amount of produced electricity goes to the batteries until 100% charge is attained. The surplus goes to the grid.

Control of the solar thermal panels

As long as the DHW has either high or low priority, the available solar thermal energy goes to the DHW buffer. In case the DHW has no priority, the available solar thermal energy goes to the buffer with the lowest temperature at the bottom of the tank. During summer, the FHB buffer and the TES buffers are disabled and all energy is transferred to the DHW buffer.

Control limitations

The maximum supply water temperature of the heat pump is 50°C.

The maximum inlet water temperature of the solar thermal is 80°C.

5. Results

The solar fraction is used to measure and compare the autonomy of different installations. It is defined in Equation (1).

$$\%solar\ fraction = \frac{100 \cdot (Q_{solar} + Q_{heat\ pumpRE})}{Q_{DHW} + Q_{building} + Q_{losses\ tanks}} \quad (1)$$

In Equation 1, Q_{solar} is the yearly heat supply from the solar thermal collectors, $Q_{heatpumpRE}$ is the heat output of the heat pump produced with renewable energy, Q_{DHW} is the heat demand DHW, $Q_{building}$ is the heat demand of the building and $Q_{losses\ tanks}$ is the total heat loss of all buffers.

Figure 3 shows the solar fraction as a function of the area of solar thermal panels, for the case without PV and with the largest TES buffer (2000 l). The maximum solar fraction that can be attained only with solar thermal panels is limited to 22%.

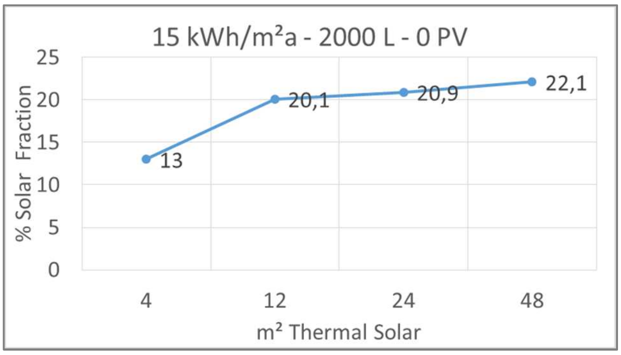

Figure 3: Solar fraction without PV for a building 15kWh/m²a.

Figure 4 shows the results for installations without TES or without ES compared to a combined system for a 60kWh/m²a building.

When no energy storage is used, a 60kWh/m²a building can reach a solar fraction of 20% with 100m² PV (see figure 4). Adding a TES, still without ES, a solar fraction of 45% is attained with 2000 L TES which is close to the result of an ES of 6500Wh. A higher solar fraction than 45% for a 60kWh/m²a building needs extra ES. Although ES without TES reaches a high solar fraction, e.g. 13kWh ES results in 60% SF for 100m² PV, combination of ES and TES can result in better solutions. The solar fraction with a 2000l TES buffer combined with a 6500Wh battery is still better (SF 63%)than the use of a 13000Wh battery without a TES buffer (SF 60%).

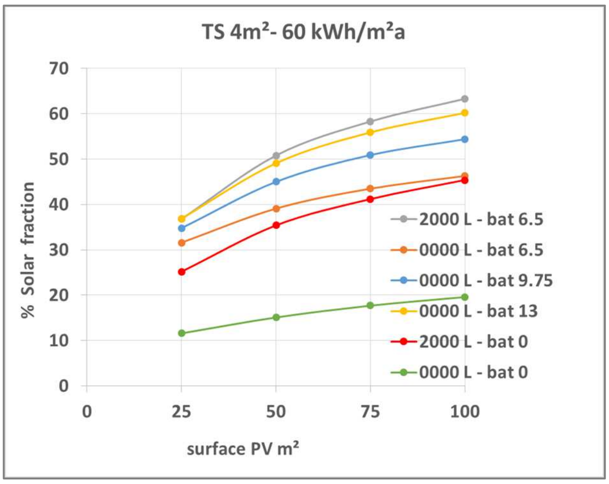

Figure 4: Solar fraction for only TES supported, only ES supported and combined systems.

Figure 5 shows the solar fraction as a function of the size of the thermal energy buffer, for different PV areas and a battery of 6500Wh. The maximum solar fraction is obtained for the maximum TES buffer size and is equal to 86.6% for 50m² of PV panels. The larger the PV area, the higher the solar fraction that can be attained. The larger the TES buffer, the higher the solar fraction for the same PV area. Increasing the TES buffer from 500l to 1000l for the 50m² PV results in an increase of the solar fraction of 2.7%. Increasing the TES from 5000 to 6000l has no significant increase anymore of the solar fraction. The continued increase of the solar fraction is the result of the abundant PV generation during off season that is used to charge the TES buffer. During the coldest winter periods, there is occasionally charging of the TES. RE is immediately used to supply the heating demand.

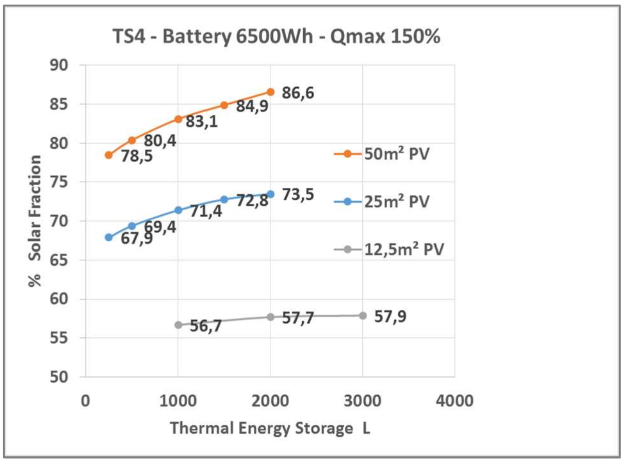

Figure 5: Solar fraction as a function of TES size and PV surface area for 4m² thermal solar with a battery of 6500Wh.

Figure 6 shows that using the same total surface of renewable energy production, but distributing it as 41.5m² solar thermal and 12.5 m² PV only gives a solar fraction of 73.6%. instead of 86.6%. Clearly, for the considered case, it is more advantageous to install photovoltaic panels instead of solar thermal panels.

Although the efficiency of a PV panel (16.6%) is lower than the efficiency of the thermal solar collector (45%) during the winter months. This can seem contradictory with ST higher efficiency (45%) to the PV panels efficiency (16.6%). Since the system employs a heat pump, a nominal amount of electric energy can transfer about 3.3 times the amount thermal energy.

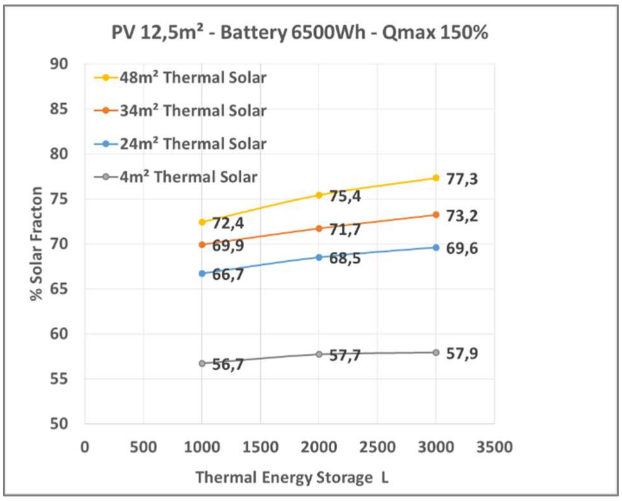

Figure 6: the solar fraction for a solar thermal dominant heating installation : building 15 kWh/m²a.

Figure 7 shows the solar fraction for three energy performances of the building with 4m² solar thermal, a

6500Wh battery and a TES buffer of 2000l. The solar fraction for the 15kWh/m²a building goes up to 93.3% as a function of the PV surface. The same installation in a 60kWh/m²a building only attains a solar fraction of 63.3%. (Fig.7) The solar fraction of 93% for the 15kWh/m²a building is equal to 3978kWh. The solar fraction of 63.3% for the 60kWh/m²a building is equal to 6871kWh. The higher renewable energy supply for the 60kWh/m²a building with the same PV and TES is due to the heating demand of the 60kWh/m²a building during off season when more solar energy is available and when the 15kWh/m²a building has no heating demand anymore due to the better insulation and more use of passive solar gains of the building.

Table 4: total yearly energy use ration of a 15 and a 60kWh/m²a building

Building performance	Heated surface	Heated building	DHW kWh	DHW + building	Ratio
kWh/m^2	m^2	kWh	kWh	kWh	%
15	143	2145	2133	4278	100
60	143	8580	2133	10713	2.5

The reference building has a total roof surface of 88.5m². If only the roof surface is available for PV panels, attaining a solar fraction above 90 % is only possible for very low energy buildings. Coincidentally the heat demand for DHW is for the reference building also 15kWh/m²a. That results in a total heat demand (total of comfort heating and DHW) of 30, 45 and 75kWh/m²a for the three building types., or a ratio of 1, 1.5 and 2.5. The needed PV surface to get the same solar fraction is not directly proportional to the total heat demand.

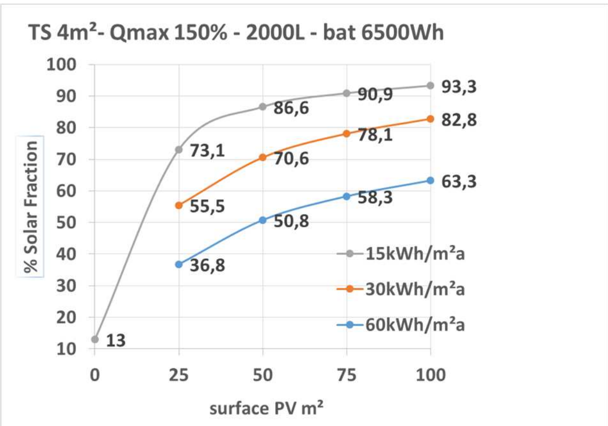

Figure 7: Solar fraction of the same installation in buildings with different energy performance: 4m² thermal solar with PV for different energy levels of the building – buffer 2000 l – battery 6500 Wh

A solar fraction of 70% needs 22.5m² for a 15kWh/m²a building, 50m² for a 30kWh/m²a building and 137.5m² for a 60kWh/m²a building.

Figure 8 illustrates the relationship between TES, ES and PV surface for three TES volumes and two ES capacities.

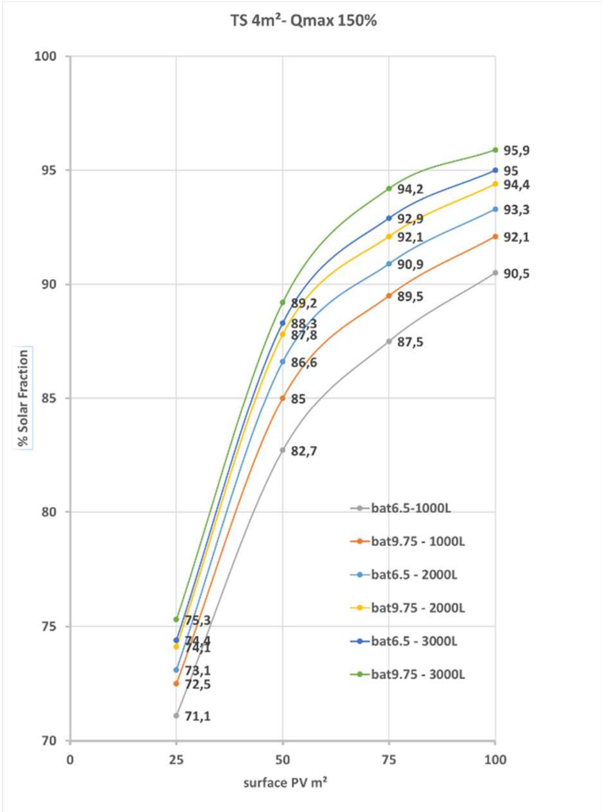

Figure 8: The solar fraction for different TES volumes and different battery sizes, 15 kWh/m²a building.

Increasing the TES buffer from 1000 to 3000l results in 5.6% extra solar fraction (PV surface 50m²) for the 6500Wh battery. Increasing the battery from 6500Wh to 9750Wh results in 2.3% extra solar fraction for a TES buffer of 1000l. Increasing the TES buffer from 1000l to 3000l and the battery from 6500Wh to 9750Wh results in an extra solar fraction of 6.5% which is lower than the sum of the separate actions. The impact of the TES buffer volume depends on the size of the battery and vice versa. To reach a pre-defined solar fraction a combination can be selected for the PV surface, storage volume and the battery capacity. Table 5 gives the needed PV surface to attain a 90% solar fraction for two ES capacities. The required PV surface to attain a solar fraction of 90 % can be decreased by 40 % by adding 3.25 kWh extra battery capacity and 2000 l more TES.

Table 5: needed surface PV to get a solar fraction of 90% for a 15kWh/m²a building

m^2 PV	Battery kWh	
Storage L	6.5	9.75
1000	86	73
2000	64	57
3000	55	52

Table 6 illustrates the impact on the investment. The extra cost for the 9.75 kWh is mainly compensated by the reduction in PV surface. The cost in 2017 of 2000 l extra storage is 20% cheaper than having more PV and a storage volume of 1000 l.

Table 6: Investment for PV panels, buffer and battery for a solar fraction of 90%.

€	Battery kWh	
Storage L	6,5	9,75
1000	23497	22526
2000	20019	20362
3000	18728	19847
%	Battery kWh	
Storage L	6,5	9,75
1000	100	96
2000	85	87
3000	80	84

For the 15kWh/m²a building, a PV surface until 50m² gives a linear increase of the solar fraction. Above a surface of 50m² the extra solar fraction per extra m² PV becomes smaller. The first 50m² covers the total needed energy during begin and end of the heating season as well as a partly coverage during the coldest period of the winter. Extra m² PV do not contribute anymore to the energy demand during the begin and end of the heating season but results during that part of the season in extra supply to the grid. The coldest period of the heating season is also the period with the lowest solar radiation and needs a lot of extra solar to get full coverage.

Other parameters are investigated such as a larger volume for the DHW and FHB and different heat pump capacities. Those changes give no significant influence on the solar fraction.

Simulations are performed for a heat pump with a design capacity equal to 100%, 150% and 200% of the maximum heating load (Qmax) of the building (6kW) without addition of capacity for the DHW production The difference in solar fraction was not significant. Increasing the maximum capacity of the heat pump does not affect the solar fraction that can be provided. During the coldest period of the year the maximum load occurs just after sunrise. That period is also the period with shortage of solar radiation and grid supply is needed. The rest of that day, the heat pump has operation time available to use the available renewable energy to charge the TES buffer.

6. Conclusion

Different combinations of photovoltaics, thermal solar panels, batteries, heat pump and thermal energy storage were simulated in TRNSYS for a 15kWh/m²a and a 60kWh/m²a detached building with radiant floor heating in Belgium. The sizing of PV, TS, ES and TES are evaluated.

The solar fraction that can be attained only with thermal solar panels in Belgium, is limited to 22%.

The larger the TES buffer the higher the solar fraction for the same PV area. It is more advantageous to install photovoltaic panels instead of solar thermal panels if a heat pump is used. The maximum achievable solar fraction with the available roof surface increases in proportion to a better energy performance of the building. Increasing the capacity of the heat pump beyond the maximum heating load of the building does not increase the solar fraction. The solar fraction increases in proportion to the installed PV. Above a solar fraction of 80 à 90%, the additional increase of the solar fraction is gradually decreasing with extra PV surface (15kWh/m²a building). A solar fraction of 100% cannot be achieved in Belgium, not even for a 15kWh/m²a building, when only the roof surface is used.

The impact of the TES buffer volume on the solar fraction depends on the size of the battery and vice versa. A TES buffer has a positive contribution to increase the solar fraction and to limit the maximum capacity of the battery system.

Extra TES is a more economical strategy to increase the solar fraction compared to extra ES for the investigated cases. Increasing TES and ES results in a smaller PV surface for the same solar fraction.

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References

Arteconi, A. and N.J. Hewitt, F. Polonara (2013). Domestic demand-side management: Role of heat pumps and thermal energy storage systems. Applied Thermal Engineering 51,155-165.

Arteconi, A. and Eleonora Ciarrocchi, Quanwen Pan, Francesco Carducci, Gabriele Comodi, Fabio Polonara, Ruzhu Wang (2016). Thermal energy storage coupled with PV panels for demand side management of industrial building cooling loads. Applied Energy.

Bellos, E. and C. Tzivanidis, K. Moschos, K.A. Antonopoulos, (2016). Energetic and financial evaluation of solar assisted heat pump space heating systems. Energy Conversion and Management 120, 306-319

Bertram, E. and P. Pärisch, R. Tepe,(2012) Impact of solar heat pump system concepts on seasonal performance – Simulation studies. EuroSun Conference 2012.

Buker, M.S. and Saffa B. Riffat (2016). Solar assisted heat pump systems for low temperature water heating applications: A systematic review. Renewable and Sustainable Energy Reviews 55, 399-413.

Child, M. and C. Breyer (2016). The role of energy storage solutions in a 100% renewable Finnish energy system. Energy Procedia 99,25-34

CTSB , Technical report 14/14-1985 (2012)

Daher, S. and J. Schmid, F. Antunes (2008). Multilevel inverter topologies for stand-alone PV systems. IEEE Transactions on industrial electronics, vol.55, issue 7, 2703-2712

D'hulst, R., et al. (2015). "Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium." Applied Energy 155: 79-90.

EU, Commission Regulation No 813/2013 (2013)

Feist, W. (1996). Life-cycle energy balances compared: low-energy house, passive house, self-sufficient house, in: Proceedings of the International Symposium of CIB W67, Vienna, Austria, 183–190

Good C. and I. Andresen, A.G. Hestnes (2015) Solar energy for net zero energy buildings – A comparison between solar thermal, PV and photovoltaic-thermal systems. Solar Energy, Volume 122, December 2015, 986-996

Jordan, D. and S. Kurtz (2013). Photovoltaic Degradation Rates - An analytical Review. Prog. Photovolt: Res. Appl., vol. 21, 12-29.

Kaldellis, J.K. and P. Koronakis, K. Kavadias(2004) Energy balance analysis of a stand-alone photovoltaic system, including variable system reliability impact. Renewable Energy volume 29, issue 7 , 1161-1180

Kaldellis, J.K. (2004). Optimum technoeconomic energy autonomous photovoltaic solution for remote consumers throughout Greece. Energy Conversion and Management 45,2745-2760

Keil, P. and S. F. Schuster, J. Wilhelm, J. Travi, A. Hauser, R. C. Karl, and A. Jossen (2016). Calendar Aging of Lithium-Ion Batteries. Journal of The Electrochemical Society, vol. 163, no. 9, A1872-A1880

Khatib, T. and I.A. Ibrahim, Azah Mohammed (2016). A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system. Energy Conversion and Management 120, 430-448

Leadbetter, J. and L. Swan (2012). Battery storage system for residential electricity peak demand shaving. Energy and Buildings, vol. 55, 685-692

Marszal, A.J. and P.Heiselberg, J.S. Bourelle, E. Musall, K.Voss, I.Sartoni, A.Napolitano (2011). Zero Energy Building - A review of definitions and calculaton methodologies. Energy and Buildings 43, 971-979

Moriarty, P. and Damon Honnery (2012). What is the global potential for renewable energy? Renewable and Sustainable Energy Reviews, vol.16, issue 1, 244-252.

Nelson, J.E.B. and A.R. Balakrishnan, S. Srinivasa Murthy(1998).Transient analysis of energy storage in a thermally stratified water tank. Int J Energy Res, 22 (10), 867–883.

Ozdemir, E. and S. Ozdemir, K. Erhan, A. Aktas (2016). Energy storage technologies opportunities and challenges in smart grids. 3rd Int.Smart Grid Workshop and Certificate Program

Parra, D. and G.S. Walker, M. Gillott (2016). Are batteries the optimum PV-coupled energy storage for dwellings?Techno-economic comparison with hot water tanks in the UK. Energy and Buildings 116, 614-621

Rydh, C. and B.A. Sandén (2005). Energy analysis of batteries in photovoltaic systems. Part II: energy return factors and overall battery efficiencies. Energy conversion and management 46, 1980-2000

Sauer, D.U. and J. Garche (2001). Optimum battery design for applications in photovoltaic systems - theoretical considerations. Journal of Power Sources 95, 130-134

Schmalstieg, J. and K. Stefan, M. Ecker, and D. U. Sauer, (2013). From Accelerated Aging Tests to a Lifetime Prediction Model : Analyzing Lithium-Ion Batteries. Electric Vehicle Symposium 27.

Shukla, A.K. and K. Sudhakar, Prashant Baredar (2016). A comprehensive review on design of building integrated photovoltaic system. Energy and Buildings, Volume 128, 99-110.

Speidel, S. and T.Bräunl (2016). Leaving the grid The effect of combining home energy storage with renewable energy generation. Renewable and Sustainable Energy Reviews 60,1213-1224

Thomsen, K.E. and JM Schultz, B.Poel (2005). Measured performance of 12 demonstration projects – IEA Task 13"advanced solar low energy buildings". Energy and Buildings 37, 111-119.Visa, I. and A. Duta (2016). Innovative solutions for solar thermal systems implemented in buildings. Energy Procedia 85, 594-602

Wang, D. and M. Dennis (2015). Influencing factors on the energy saving performance of battery storage and phase change cold storage in a PV cooling system. Energy and Buildings 170,84-92

Wauman, B. and D. Saelens, H. Breesch, (2010).Determination of boundary conditions for passive schools: impact on net energy demand for heating and cooling.1stCentral European Symposium on building physics, 455-462

Weitmeyer, S. and D. Kleinhans, T. Voght, C. Agert (2015). Integration of renewable energy sources in future power systems: the role of storage. Renewable Energy 75,14-20

Zambolin, E. and D. Del Col (2010) Experimental analysis of thermal performance of plat plate and evacuated tube solar collectors in stationary standard and daily conditions. Solar Energy, Volume 84, issue 8, 1382-1396

Zhang, Y. and A. Lundblad, P.E. Campana, J. Yan, (2016). Employing battery storage to increase photovoltaic self-sufficiency in a residential building of Sweden. Energy Procedia 88,455-461