Solar Energy and Energy Storage in Low Energy Renovation Paves the Way for Urban Energy Island Communities

Chiel Boonstra[1], Dennie Bloem[2]

[1] Trecodome BV, Roosendaal (The Netherlands)

[2] Bloem Engineering Energy, Duiven (The Netherlands)

Abstract

The objective of the research work is to define a replicable demonstration case towards 100% renewable energy in the built environment, by renovating 40 existing apartments from the 1960s in The Netherlands. Side-effect of the approach is to avoid the reinforcement of the electricity grid, whilst achieving conversion from natural gas towards electricity within the margins of the existing residential electricity grid.

High grade insulation, triple glazing and heat recovery ventilation result in a net heat demand below 25 kWh/m2. Maximum application of rooftop PV, application of smart controls, heat pump technology and energy storage increases self-consumption and autarky figures. Technically, the project will demonstrate communal salt batteries for short term storage and innovative hydrogen in metal-hydrides for long term storage.

For tenants the concept results in low predictable energy costs. The costs for purchasing energy shifts towards capital costs or depreciation and maintenance costs.

The high fraction of direct and indirect used solar generation means that only a small portion of the energy has a CO_2-emission factor associated with purchased electricity.

The concept serves as an example for application at the scale of transformer stations for 500 – 1,000 apartments in an urban community.

Keywords: Solar Energy, Built Environment, Salt battery, Hydrogen in Metal-hydrid Seasonal Storage, Net congestion, Self sufficiency

1. Introduction

Buildings move towards NZEB by better insulation, ventilation and the inclusion of solar PV. In Europe the concept of net zero energy renovation has been widely spread, however based on an assessment on a yearly basis: the annual generation of PV on a building compared with the annual energy demand. On a yearly basis the net figure is zero if the renewable supply and demand are equal.

In heating dominated climates in North West Europe, the solar energy supply in winter is not enough to deal with the energy demand in winter. In summer, renewable energy regeneration is much higher than the energy demand. In reality, 25 – 30% of the renewable energy can be used in the building directly, and 70-75% of the generated PV is exported to the grid. In the winter, (non-renewable) energy is imported through the grid (Hall, Geissler, 2017)

Existing buildings in North-West Europe typically have a space heating demand of 100-125 kWh/m2 both theoretically as in reality. Current renovation practices based on insulation, low-E glazing and mechanical exhaust ventilation reduces the demand to 70-90 kWh/m2. However, there is a long track record of higher grades of insulation, the application of triple glazed windows and the use of heat recovery ventilation systems. This typically results in a heating demand of 25 kWh/m2 (Feist, Schnieders, 2009).

10.18086/swc.2025.05.17 Available at http://proceedings.ises.org

The energy transition requires renewable energy supply, electrification of heating (currently natural gas) and electrical mobility (currently fossil). Local electricity networks are designed for household electricity only: max 1 – 1.5 kW of simultaneous power per apartment or house can be handled by the existing electricity grid. The energy transition causes stagnation in various sectors because of net congestion in the existing electricity grid.

Research and demonstration objectives:

- To increase direct and indirect use of renewable energy from buildings to 80% and more.
- To enhance the use of available energy infrastructure.
- To achieve reliable and predictable energy costs.
- To achieve 90% CO_2-emission reduction.

2. Approach

The planned demonstration project is located in a residential area in the social housing sector in The Netherlands. The community mainly has apartment buildings from the 1960s. Several maintenance work have taken place during the last 60 years. The buildings are in need of an upgrade to reach a further life cycle of 30 years. The demonstration project has four two story buildings, each with 10 apartments. The floor plans are 46 m2 per apartment.

Each apartment building has its own communal condensing gas boiler for space heating, and an individual gas boiler for domestic hot water. The apartments are individually vented with mechanical exhaust ventilation. The building envelope is partially insulated and has double glazing. Electricity is provided to the communal plant room and 10 individual apartments.

The research approach contains the following steps:

Step 1. Definition of maximum renewable supply. Maximum Solar PV generation.

Step 2. Demand definition. Energy efficient renovation and use of efficient conversions and demand steering for space heating and hot water production, via a ground source heat pump and individual booster heat pumps for domestic hot water.

Step 3. Meeting supply and demand at annual level.

Step 4. Storage at all levels.

Step 5. Results. Maximum self-consumption of renewable energy, 90% CO2 emission reduction and predictable energy costs.

Step 6. Optimizing economies of scale and energy management.

Step 7. Conclusions.

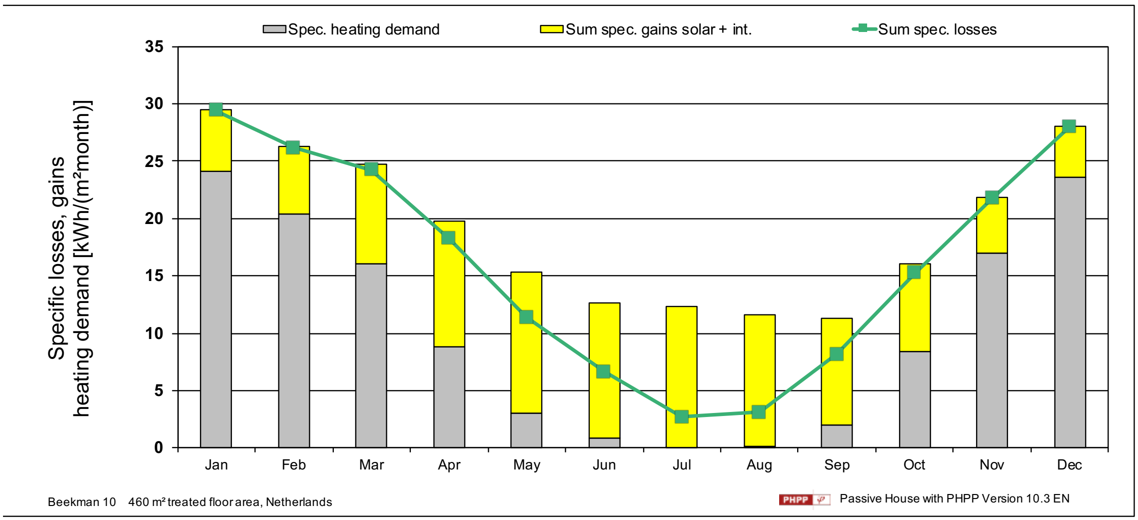
3. Optimizing demand and supply

The first step was to define the maximum rooftop PV solar generation. Different orientations and numbers have been compared. It was concluded that around 35,000 kWh of solar electricity can be generated from the roof of each apartment building of 10 apartment each, i.e. 3,500 kWh/apartment.

For the second step, simulations in PHPP10 and the national building energy simulation software (UNIEC3) have been made with different combinations of measures resulting in multiple options for establishing the net heat demand.

Below simulation in figure 1 shows the monthly heat demand (in grey bars) as a calibration of the existing measured energy consumption in 2022. The yellow bars show additional monthly passive solar contributions, whereas the green line shows the heating losses of the building envelope with its ventilation losses.

Annual heating demand	11101	9385	7387	4058	1375	377	24	42	912	3862	7800	10878	57201	kWh
Spec. heating demand	**24,1**	**20,4**	**16,1**	**8,8**	**3,0**	**0,8**	**0,1**	**0,1**	**2,0**	**8,4**	**17,0**	**23,6**	**124,3**	kWh/m²

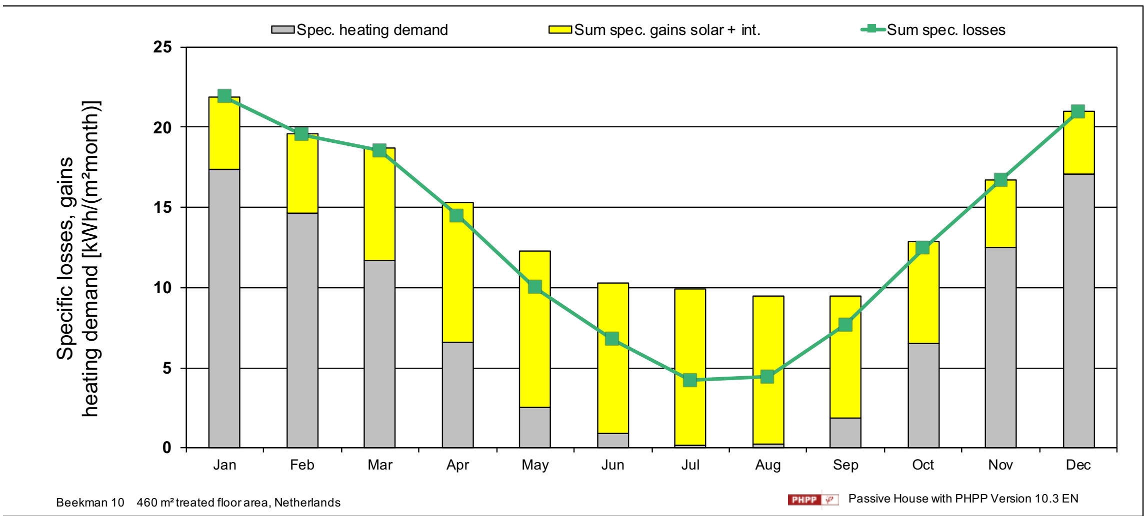


Annual heating demand: Comparison					
Monthly method	('Heating')	**57201**	**kWh/a**	**124,3**	**kWh/(m²a)** reference to treated floor area according to PHPP
Annual method	('Annual heating')	**54658**	**kWh/a**	**118,8**	**kWh/(m²a)** reference to treated floor area according to PHPP

Figure 1: Simulation existing situation, net heat demand 124 kWh/m2

Simulation BWP21 is shown in Figure 2 and shows the monthly heat demand following 'standard' renovation measures in the Dutch renovation market for this particular type of apartment building. The net heat demand results in 92 kWh/m2 for these 46 m2 apartments. Measures include: low-E glazing (U value 1,8 W/m2K), cavity wall insulation (U value 0,7 W/m2K), roof insulation (U value 0,35 W/m2K), floor insulation (U value 0,25 W/m2K) and mechanical exhaust ventilation combined with decentralized heat recovery ventilation.

Annual heating demand	7980	6743	5387	3017	1151	413	81	111	874	3012	5737	7856	42361	kWh
Spec. heating demand	**17,3**	**14,7**	**11,7**	**6,6**	**2,5**	**0,9**	**0,2**	**0,2**	**1,9**	**6,5**	**12,5**	**17,1**	**92,1**	kWh/m²
	19%	16%	13%	7%	3%	1%	0%	0%	2%	7%	14%	19%		

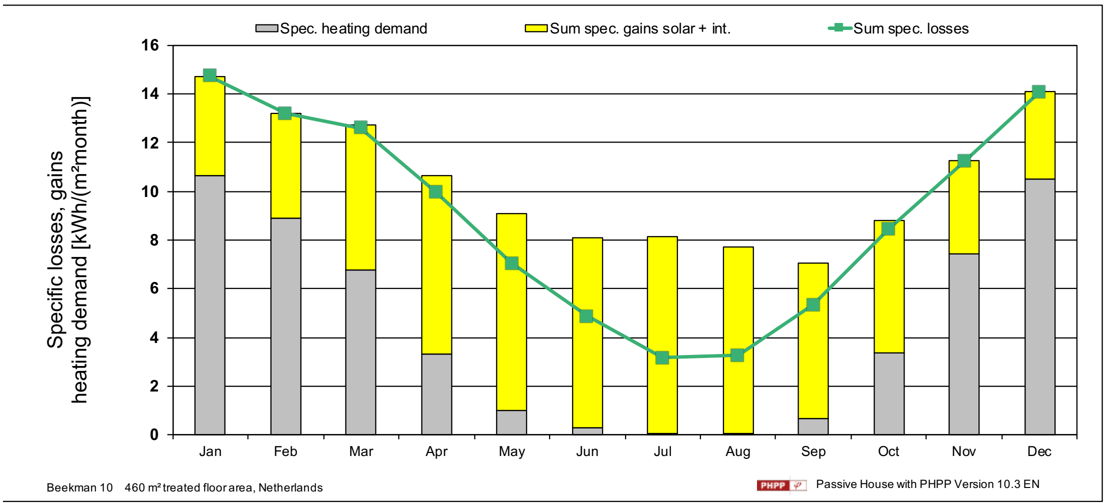


Monthly method	('Heating')	**42361**	**kWh/a**	**92,1**	**kWh/(m²a)** reference to treated floor area according to PHPP
Annual method	('Annual heating')	**40046**	**kWh/a**	**87,1**	**kWh/(m²a)** reference to treated floor area according to PHPP

Figure 2: Simulation BWP21: Standard renovation, net heat demand 92 kWh/m2

Simulation BWP42 is shown in Figure 3 and shows the monthly heat demand following ‘improved’ renovation measures in the Dutch renovation market for this particular type of apartment building. The net heat results in 53 kWh/m2 for these 46 m2 apartments. Measures include: triple glazing (U value 1,0 W/m2K), cavity wall insulation (U value 0,7 W/m2K), roof insulation (U value 0,13 W/m2K), floor insulation (U value 0,25 W/m2K) and mechanical heat recovery ventilation.

Annual heating demand	4896	4092	3105	1536	460	131	19	25	321	1554	3421	4837	24396	kWh
Spec. heating demand	**10,6**	**8,9**	**6,7**	**3,3**	**1,0**	**0,3**	**0,0**	**0,1**	**0,7**	**3,4**	**7,4**	**10,5**	**53,0**	kWh/m²



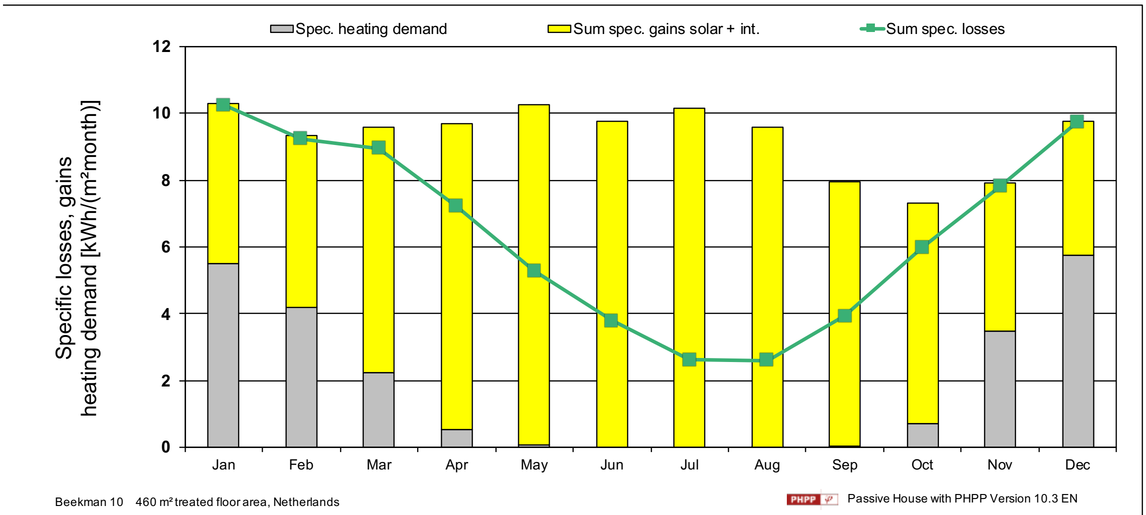
Annual heating demand: Comparison

Monthly method	*('Heating')*	**24396**	**kWh/a**	**53,0**	**kWh/(m²a)** reference to treated floor area according to PHPP
Annual method	*('Annual heating')*	**23745**	**kWh/a**	**51,6**	**kWh/(m²a)** reference to treated floor area according to PHPP

Figure 3: Simulation BWP42: Improved renovation, net heat demand 53 kWh/m2

Simulation BWP62 is hown in Figure 4 and shows the monthly heat demand following ‘PassivHaus’ renovation measures in the Dutch renovation market for this particular type of apartment building. The net heat demand results in 23 kWh/m2 for these 46 m2 apartments. Measures include: triple glazing (U value 1,0 W/m2K), facade insulation (U value 0,13 W/m2K), roof insulation (U value 0,13 W/m2K), floor insulation (U value 0,25 W/m2K) and mechanical heat recovery ventilation.

Annual heating demand	2537	1928	1026	250	34	6	1	1	21	327	1610	2643	10383	kWh
Spec. heating demand	**5,5**	**4,2**	**2,2**	**0,5**	**0,1**	**0,0**	**0,0**	**0,0**	**0,0**	**0,7**	**3,5**	**5,7**	**22,6**	kWh/m²
	24%	19%	10%	2%	0%	0%	0%	0%	0%	3%	16%	25%		
	5,5	4,2	2,2	0,5	0,1	0,0	0,0	0,0	0,0	0,7	3,5	5,7	22,6	
	4,8	5,1	7,4	9,1	10,2	9,8	10,1	9,6	7,9	6,6	4,4	4,0	89,0	
	10,3	9,3	9,6	9,7	10,3	9,8	10,1	9,6	7,9	7,3	7,9	9,8	111,5	



Monthly method	*('Heating')*	**10383**	**kWh/a**	**22,6**	**kWh/(m²a)** reference to treated floor area according to PHPP
Annual method	*('Annual heating')*	**9927**	**kWh/a**	**21,6**	**kWh/(m²a)** reference to treated floor area according to PHPP

Figure 4: Simulation PassivHaus renovation, net heat demand 23 kWh/m2

Each apartment building of 10 apartments will shift from a communal gas boiler to a communal ground source heat pump. Every apartment will shift from a gas-fired DHW boiler to a booster heat pump which uses the buildings heat network as its heat source. The system lay-out will offer the opportunity to steer the demand for space heating and the demand of the individual heat pumps for domestic hot water on a daily basis.

The monthly heat demand profiles have been disaggregated into hourly figures and combined with hourly profiles for domestic hot water and all household electricity uses. The PV generation has been simulated on an hourly basis as well. For readability Figure 5 – 8 have been reported in kWh/month for an average apartment in this project.

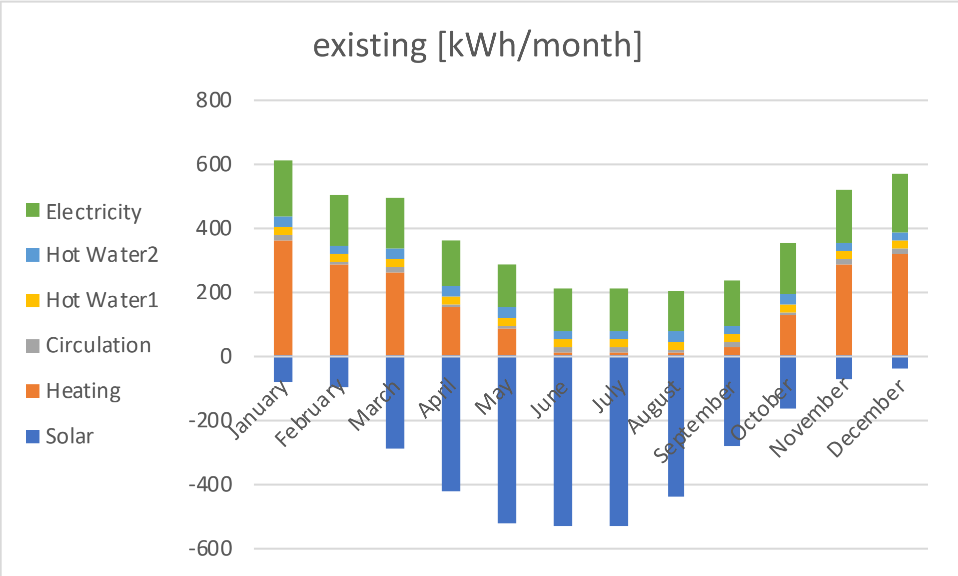


Figure 5: Existing situation; Electricity for Space Heating+ DHW + household e + Solar PV

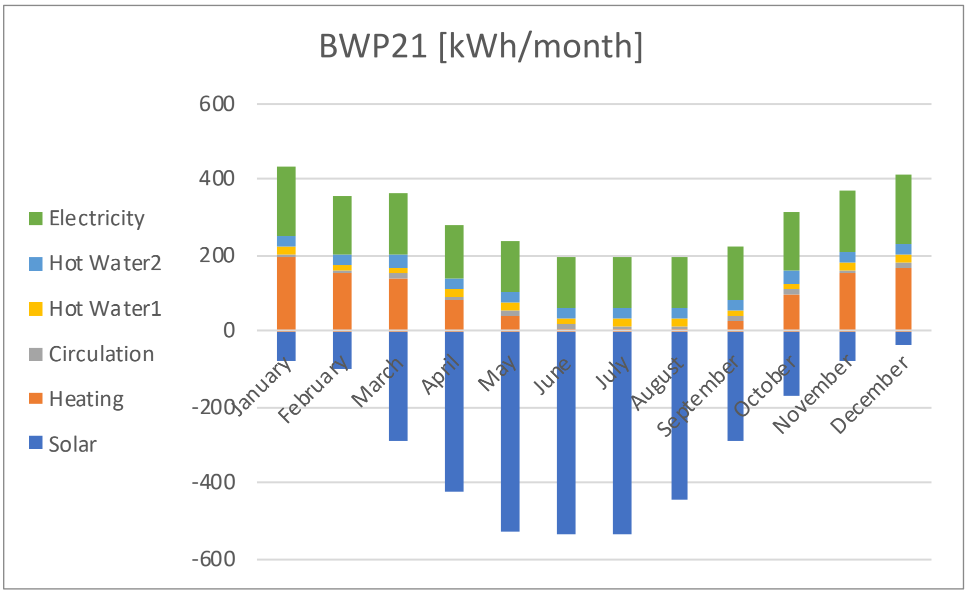


Figure 6: Standard renovation; Electricity for Space Heating+ DHW + household e + Solar PV

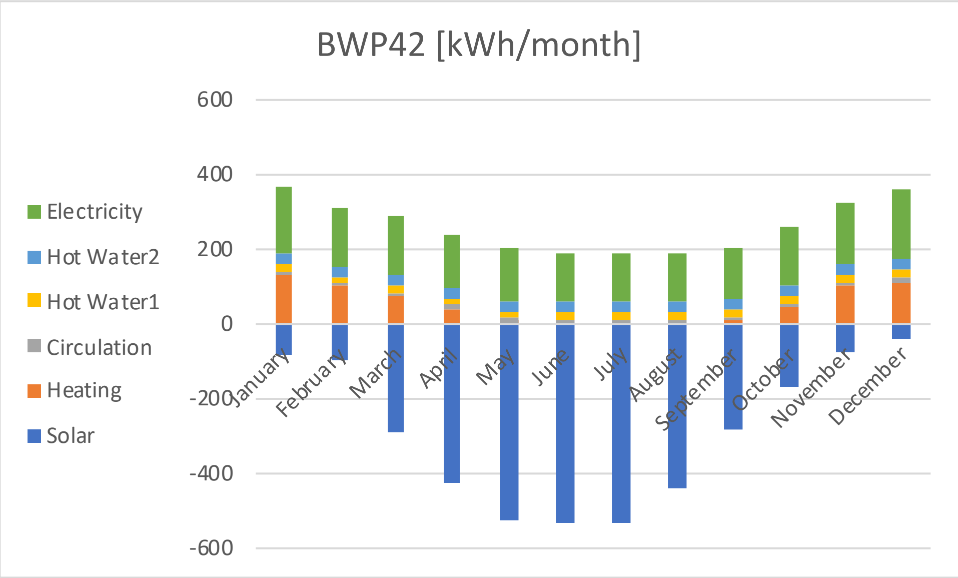


Figure 7: Improved renovation; Electricity for Space Heating + DHW + household e + Solar PV

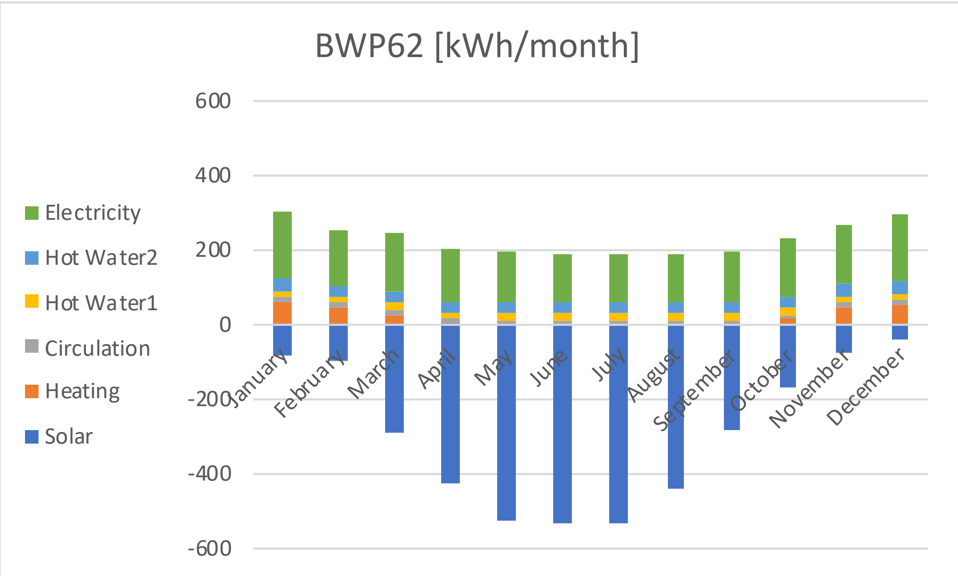


Figure 8: PassivHaus renovation: Electricity for Space Heating + DHW + household e + Solar PV

The conclusion is that after a renovation down to 23 kWh/m2, PV can generate more electricity than needed on a yearly basis for the heat demand, domestic hot water, and household electricity. In case of a standard renovation to 92 kWh/m2 the energy demand can only partially be met. Therefore, it was concluded that low energy renovation is the first prerequisite for achieving higher autarky levels.

4. Thermal, Battery and hydrogen storage

Batteries and heat storage are the most adapted and most affordable technologies for the built environment to store energy. These technologies offer great advantages in improving the self-use of solar and/or wind energy and autarky and benefit the path towards a 100% renewable energy system in a reliable manner. These technologies have been proven, have a high level of efficiency, can response quickly to fulfill demand and are scalable. However, for storing large amounts of energy for long periods of time, these technologies are less suitable due to volume and costs when storing large quantities.

An alternative can be found in hydrogen storage. Through water electrolysis excessive renewable energy can be converted into hydrogen, stored, and converted back into electricity and heat by using fuel cells. A big benefit of hydrogen storage is the possibility of storing energy in large amounts for months of time without losses. It can be stored in a wide variety of systems such as pressurised storage, metal powders or metal hydrides. The latter offers a great benefit in terms of safety when comparing with pressurized storage and it is commercially available. The conversion losses in the hydrogen process and the high costs of the electrolysers and fuel cells are current barriers for implementing this technology on a large scale.

5. Hybrid systems: the future of energy storage and the path towards 100% renewable energy

Technologies can be combined to maximize self-sufficiency and minimize dependency of the electricity grid. Batteries offer daily storage at a high efficiency while hydrogen handles the fluctuations between seasons. Adding heat storage to the mix minimizes the need for electricity storage and allows the recovery of waste heat of hydrogen components. A balance needs to be found between costs and volume, and a smart control system needs to be implemented for the interaction between the different types of storage. This hybridized approach makes the path towards 100% renewable energy feasible for the built environment, and it is time to demonstrate the potential of these kinds of combinations.

Both batteries, heat storage and hydrogen will fulfil their role in the energy system of the future (Esposito, et al, 2024). Batteries and heat storage are already very cost competitive and available at a large scale and there is still room for further improvement, both at cost and technological level. Hydrogen technologies have not seen their upscaling potential yet and the markets still need to evolve to reach their maximum potential. As all three technologies are being further developed, costs will drop, and they will play a larger role in realizing an energy system based on 100% clean and renewable energy.

Step 4. Storage at all levels

Thermal storage *In the ground*

With a heat pump the heat in the ground can be used as a source to feed the heat pump. The temperature in the ground is approximately 10 - 20°C. Using this heat as a source boosts the efficiency of the heat pump. The heat can be extracted via a closed loop system which is common for smaller heat pump systems up to 100 kW of heating power. Above 100 kW an open-source system becomes more attractive. Using a ground source heat pump boosts the coefficient of performance (COP) of the heat pump towards 6, even in wintertime when the outside temperature is sub-zero. In comparison, the COP of an air to water heat pump can drop below 2 in sub-zero temperatures. Besides the advantages in heating efficiency, also cooling becomes much more efficient because the temperature in the ground is cold enough to cool the building directly. This is called passive cooling which means the heat pump is not actively working to supply cooling. Extracting heat in the winter means there is cold available during the summer and vice versa, offering a balance between the cooling and heating seasons. Additional heat can be added to the ground, if necessary, which allows for the use of waste heat even in summertime.

The choice is made for one communal ground source heat pump for a building of 10 apartments with a closed loop system as a source. This decreases the required power which helps to reduce the load on the electricity grid. It also decreases the amount of electricity required for the heat pump which is critical to reduce the required amount of storage capacity.

Thermal storage *in the building or plant rooms*

High temperature heat storage can be accommodated with storage tanks. These types of tanks come in different forms and sizes. A storage tank connected to a heat pump helps to reduce the power output of the heat pump: the heat pump can run at a moderate power whilst filling the storage tank with heat. At peak moments in heating demand the storage tank can be emptied to fulfil this demand. With regards to domestic hot water, thermal storage can be applied at the building level or individual per apartment. Applying an individual storage tank per apartment of approximately 120 liters, decreases the losses in distributing the domestic hot water.

In this project, individual storage tanks are applied per apartment. Because the communal heat pump delivers a temperature that is too low for domestic hot water, individual booster heat pumps will be used to boost the temperature from 40°C to above 60°C. The booster heat pumps on their turn use the heat from the communal heat pump as a source. The booster heat pumps heat up the storage tanks during the day and thus increases the amount of solar PV that can be used directly when the sun shines. During times of little solar production, mainly in wintertime, the storage tanks can be filled when there is a small demand in the electricity grid helping to reduce the load and reducing the costs for electricity.

Both above thermal storage techniques help to increase the amount of solar production that can be used directly when it is being produced whilst reducing the power load on the electricity grip during critical moments.

Daily storage *in batteries at block level*

After maximizing the potential of thermal storage, electricity storage can be applied. Solar production still has a large load on the grid and the same goes for peaks in demand. Applying a communal battery at the building level makes it possible to absorb the peaks of solar production. At nighttime when the sun does not shine, the battery can deliver electricity towards the transformer at a moderate power level. This way, PV panels can be added on the whole roof of the apartment building and keep the transportation of electricity within the threshold of 1 kW per apartment.

A battery of 40 kWh useable storage capacity is required for the building of 10 apartments to accommodate this concept and maximize the use of local PV-production, and the level of autarky is boosted to a higher level. It makes it possible to electrify heating, domestic hot water and cooking and thereby go all-electric without the need for reinforcement to the existing electricity grid. It also makes it possible to add the maximum number of PV-panels that can be added to a house or building whilst staying within the threshold of 1 kW of transportable power through existing electricity grids. It is a concept that can be repeated and scaled to almost every type of building or house.

Seasonal Storage *in metal hydrides at community level*

A solution for seasonal electricity storage is found in hydrogen. Hydrogen is made from renewable electricity from an abundance of solar energy, mostly during summertime. A common way to store hydrogen is in pressurized tanks bringing great challenges with aspect to safety. An alternative is found in storing hydrogen in solid form by binding it to a metal alloy. This type of hydrogen storage is called metal hydrides. Metal hydrides offer the potential of storing thousands of kilograms of hydrogen in an ultrasafe manner. The stored hydrogen can later be used when there is no solar energy, mostly in wintertime.

Step 5. Maximizing self-consumption of renewable energy; staying within the current limits of the local electricity grid; CO2 emission reduction; achieving a business case

Lowering heating demands by isolation and ventilation, the combination of thermal storage in the ground and in tanks, daily electrical storage in batteries and seasonal storage in metal hydrides at the community level, pave the way for urban energy island communities. It opens a path towards areas that run on 100% renewable and locally produced electricity without using natural gas or other fossil fuels. It allows for the electrification of central heating, domestic hot water and transportation. Buildings and houses can be equipped with a maximum number of solar panels. All of which can be done within the limits of existing electricity grids without the need for reinforcement to the grid.

Simulations

The solar production and the electrical demand after electrifying heating, domestic hot water and cooking, are simulated at an hourly base over a year. Below graphs show the results. Figure 9 shows the electrical demand and solar production and in Figure 10 the profile is shown when solar production is directly being used without any type of storage. In Figure 11, the battery is added to the mix. The battery absorbs solar energy during the day and transports the electricity towards the transformer station when there is no sunshine, mostly during nighttime. In the last graph, Figure 12, seasonal storage is added. The storage is sufficient to overcome the most critical days in wintertime, but it is not enough to be fully self-sufficient. The remaining demand, however, can be drawn from the grid during off-peak hours when costs are low. The results of the simulations are summed up in Table 1.

Table 1: Results of autarky and self-use, simulations of 40 apartments

40 apartments results	kWh	%
Demand	110540	0% autarky
Solar production	140113	0% Self-use
Demand after direct use	60942	45% Autarky
Solar production after direct use	90515	35% Self-use
Demand after battery	34336	69% Autarky
Solar production after battery	53345	62% Self-use
Demand after seasonal storage	15633	86% autarky
Solar production after seasonal storage	10969	92% Self-use

Profile without electrical storage:

In the demand profile below, domestic hot water is shifted towards daytime via a booster heat pumps with a storage tank of approximately 120 liters per apartment. The green line shows the maximum power that can be handled in the electricity grid at street level.

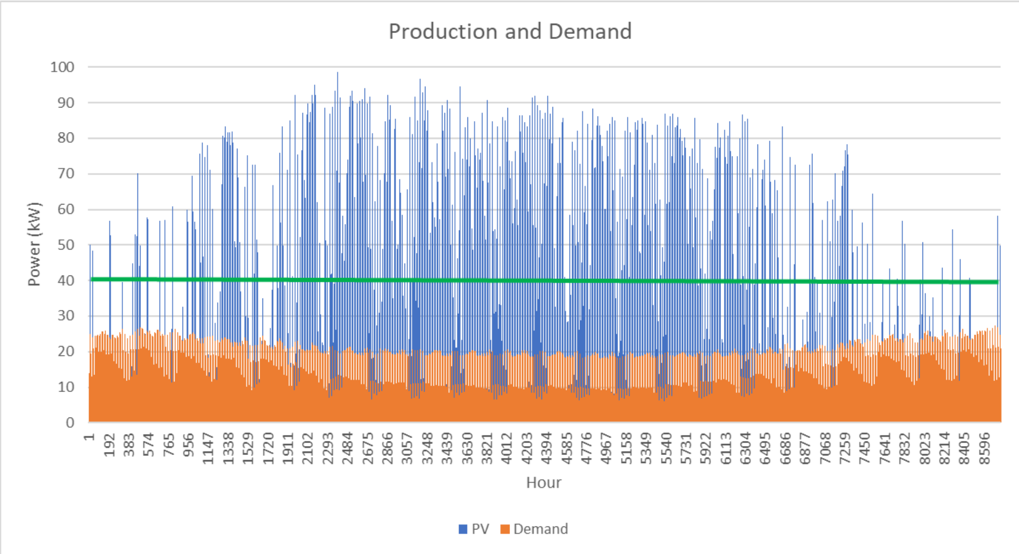


Figure 9: Production and demand 40 apartments

Profile after direct use:

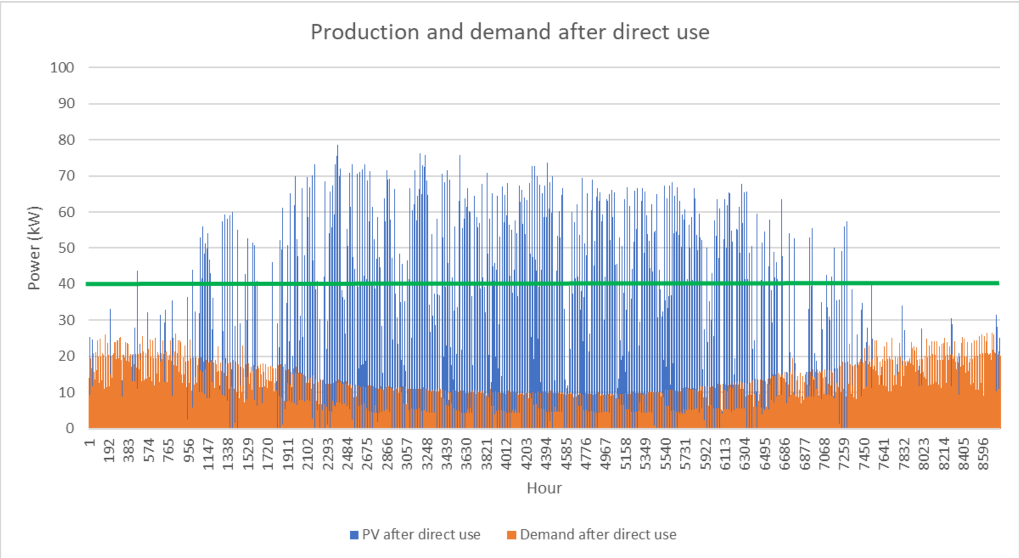


Figure 10: Production and demand 40 apartments after direct use of solar energy

Profile after battery storage:

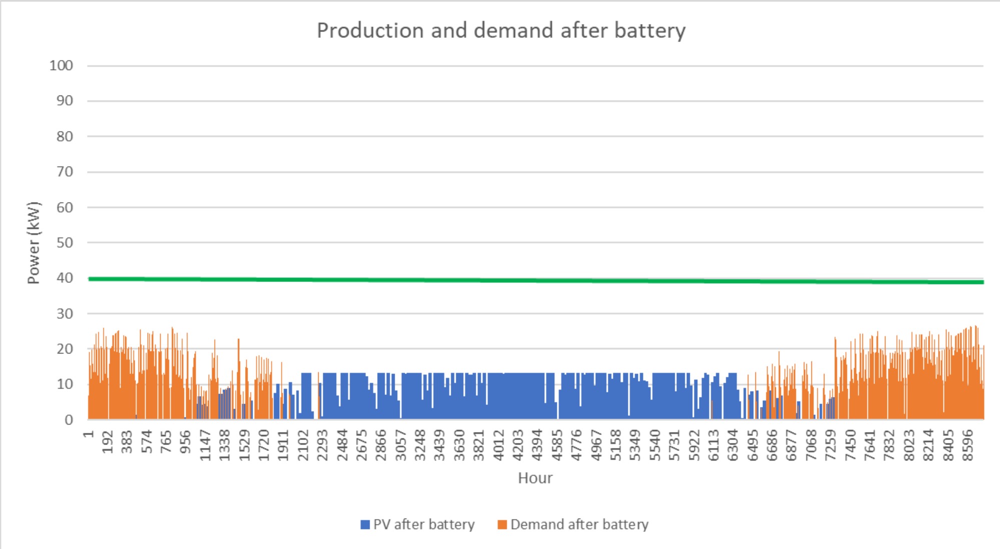


Figure 11: Production and demand 40 apartments after use of a battery per building

Profile after seasonal storage:

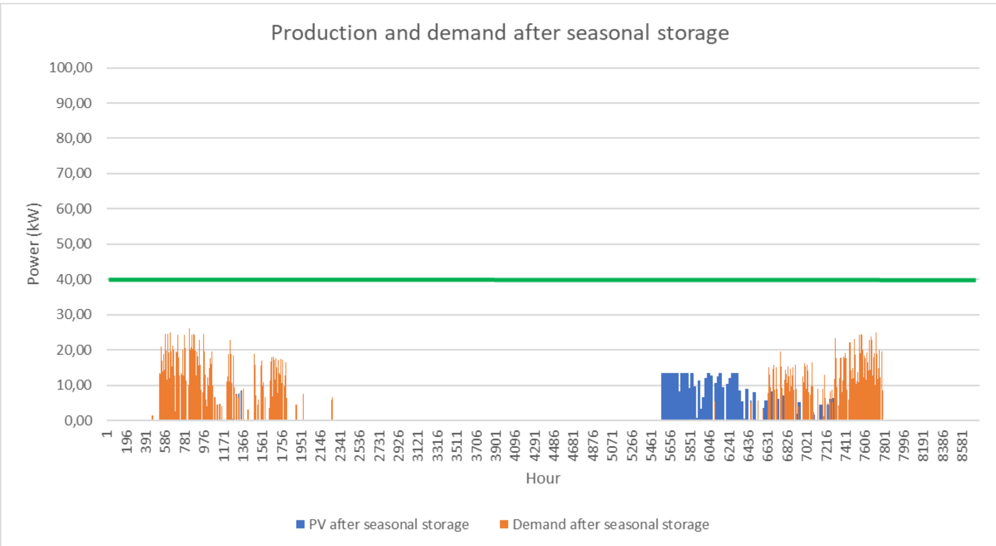


Figure 12: Production and demand 40 apartments after seasonal storage

Step 6. Optimizing economies of scale and outlook

Seasonal Storage is a big challenge when moving towards 100% renewable energy. Technology wise, systems can be built to store electricity over the seasons but from an economic point of view, seasonal storage is not feasible yet. Where batteries and PV-panels have achieved significant cost reductions because of scaling up production, seasonal storage has not seen the same upscaling development yet. Besides upscaling production, it is equally important to implement projects of the right magnitude. The smaller the storage system, the higher the price per kilowatt-hour. Individual seasonal storage systems for each building or home therefore is not logical and it makes more sense to implement larger scale storage systems. An ideal scale is found in offering seasonal storage at the community level for approximately 500 – 1,000 houses or apartments. This corresponds to the load of a transformer station offering seasonal storage to a neighborhood. Typically, this requires an electrical power load of 500 kW.

Step 7. Conclusions

The future demonstration project Urban Energy Island shows that it is feasible to use up to 90% of the generated PV when using highly renovated buildings, efficient energy conversion processes, such as heat pumps, and the deployment of batteries for short term storage and H2 in metal hydrides for long term storage.

The project addresses all energy flows in and around apartment blocks: heating, cooling, ventilation and household electricity. In addition to on-site use of renewable electricity over the year, the project will also demonstrate how electric mobility can benefit from local renewable energy sources and using storage to interact with the electricity grid.

The renewable energy is distributed over the days without generating peak-loads in the local grid.

By implementing more projects based on hydrogen technologies, future investment costs can drop the same way as seen with solar panels and batteries.

The combination of renewable energy generation in the built environment, renovating buildings towards a low energy demand and a hybrid solution of short- and long-term energy storage opens the door for predictable and manageable energy communities based on the principles of 100% renewable energy.

Socially the approach hints at achieving predictable and stable energy costs for social housing tenants.

6. Acknowledgments

Wim Wijnhoud, innovation manager at deltaWonen, must be thanked for his continuous motivation to support research work aimed at real demonstration during the past three years.

7. References

Feist, W. Schnieders, J. 2009. Energy Efficiency – A key to Sustainable Housing. The European Physical Journal Special Topics. 176(1). 141-153.

Hall, M., Geissler, A., 2017. Different balancing methods for Net Zero Energy Buildings - Impact of time steps, grid interaction and weighting factors. Energy Procedia 122. 379 – 384.

Esposito, L., Wiel van der, M., Acar, C., 2024. Hydrogen storage solutions for residential heating: A thermodynamic and economic analysis with scale-up potential. International Journal of Hydrogen Energy. Volume 79. 579 – 59