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STORY

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Deliverable 7.5
Evaluation of simulation results: Comparing large scale storage simulation results with the STORY demonstration sites

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Authors:
Jernej Zupancic, Andrej Gubina……..University of Ljubljana
Camilla Neumann, Andreas Tuerk…..Joanneum Research
Ariana Ramos………………………….Vlerick Business School

Content

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1 Executive Summary

Large scale simulations for the implementation of storage were performed on an Low Voltage (LV) test network in Suha and an industrial building at the Elektro Gorenjska Headquarters. In this report, the results of the simulations are compared with the resulting indicators from the actual STORY demos. Three main dimensions are compared: technical results, greenhouse gas impact and economic evaluation. The large scale simulations presented in the STORY “D7.4 Report on Environmental and Social Analysis of a Large-Scale Storage Implementation” are compared to the STORY project demonstration results in the instances outlined below.

The comparison of the technical, environmental and economic aspects of energy storage applications is based on the following demonstration projects from the STORY H2020 project that cover a range of applications from industrial to residential settings.

1. **Elektro Gorenjska Suha LV network simulation (Slovenia):** A medium scale lithium-ion battery storage unit (170 kW, 320 kWh) is connected to a MV/LV transformer in Suha, Slovenia, which supplies electricity to 71 households and provides connection for 7 distributed PV plants. An OLTC transformer with rated power of 400 kVA is placed in the transformer substation. The LV network is placed on the countryside, with several farms in the village as well.
2. **Elektro Gorenjska Headquarters simulation (Slovenia):** The DSOs headquarter is an industrial type of end consumer, located in an urban area. Two 630 kVA transformers serve as a connection to MV section of the grid and supply the loads in the compound. The headquarters consist of an office building with a 35 kWp rooftop PV installation and 27 kW electric output CHP plant. The CHP plant serves as a heating source for colder months of the year and in the warm months of the year, an ice bank is responsible for cooling the offices.
3. **Oud-Heverlee residential buildings – heat pump control (Belgium):** Four residential houses which have been equipped with appliances (boiler, heat pump), that have a potential thermal storage capacity.

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4. **Oud-Heverlee Community battery (Belgium):** The neighbourhood battery is a Lithium polymer ABB battery of 80 kWh and 80 kW capacity. The design and implementation of the battery is collaboration of Th!nk-E, ABB, Enervalis, Imtech Belgium and Fluvius, DSO company. The battery's main purpose is to provide voltage support to a rural feeder.
5. **Exkal factory (Spain):** A lithium-ion battery (50 kW, 200 kWh) was installed in addition to the PV plant in Exkal's facility in Navarra, Spain to improve the business case.
6. **Beneens multi-energy grid (Belgium):** Beneens is a wood processing company where a new biomass boiler using waste wood was combined with an Organic Rankine Cycle installation producing electricity. In addition different heat storage tanks were installed.

The technical results show the energy storage systems' impact, according to their characteristics in terms of capacity, rated power, efficiency, and life-cycle. In the STORY project different types and sizes of thermal and electrochemical storage units are installed. The main use cases analysed in this document are demo specific, depending on the technology installed and the controllers in place and comprise: RES use change, self-consumption ratio, reserve provision, peak-to-average demand ratio, relative peak power change, grid energy consumption, voltage control and zero load provision (zero active power flow over MV/LV transformer).

The environmental results show that different factors influence the greenhouse gas (GHG) emissions of network development scenarios with PV and battery storage: The most important factor is the amount of PV power installed in the distribution grid and the ability of the grid to transport the PV-generated electricity. In the investigated scenarios the grid model showed no limitation in technical parameters for the LV grid, so PV generation curtailment was not needed in any of the scenarios. Transporting the electricity to another place in the network ("grid as a storage") leads to fewer losses than storing the electricity in the battery system. Also, additional GHG emissions from the manufacturing of the batteries arise, although the contribution of battery manufacturing on the total GHG emissions of the scenarios was rather low (2-11% of total GHG emissions). These factors lead to the result that the scenarios with batteries have higher GHG emissions compared

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to the scenarios without batteries. The assessments however neglected a change on the power generation mix in case of a high level of injection of fluctuating PV.

The economic results show that storage can reach a positive business case when multiple income streams can be stacked. The potential of storage is in peak shifting, renewable energy utilization, energy bill reduction, voltage control, and reserve market participation. However, the potential service provision by storage is not always adequately remunerated. For example, it is shown in the simulations and in the demonstrations that storage can contribute to voltage control, but this is currently not remunerated by the distribution system operators. Storage has the potential to have a positive grid impact if it will delay the building of new grid infrastructure that might only be needed for a few hours a year.

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2 Introduction

Network development scenarios were investigated through large scale simulations, representing a typical European distribution grid, which could be located anywhere in Europe. Scenarios included different deployment levels of PV in the distribution grid as well as electric vehicles (EVs). In scenarios with a battery, electricity from PV plants is either consumed directly, stored in the battery, or injected behind the meter in the building or from the local LV grid into the MV grid. When surplus electricity from PV plants is injected into the MV power grid it replaces electricity from another energy source e.g. the country specific electricity generation mix or is stored on the high voltage (HV) grid storage, e.g. in a pumped storage power plant. The results presented in this document have been presented to relevant stakeholders during the STORY final event in October 2020. Their feedback has been integrated into the final version.

The main content contributors to this document have been the STORY partners University of Ljubljana and Joanneum Research. The University of Ljubljana has carried out the large scale simulations outlined in sections 4.1 EG Suha simulation, and 4.2 EG Headquarters Simulation. Joanneum Research has provided the technical, greenhouse gas and economic analysis for the demo cases presented. Coordination of the task, document editing, and results comparison has been done by Vlerick. The authors would like to thank the partners who have contributed data from their respective demos: Think-E, Beneens, Exkal and Cener.

3 Assessment methodologies

The first aspect is the technical analysis, where data is directly analysed or used to calculate Key Performance Indicators (KPIs). KPIs further provide insight on the performance of the storage installation and operation in the investigated area or network. Technical aspects are the easiest to observe and evaluate, since most of the data is either known from the system properties or directly measured in the system. In some cases however simulations were used to complement measured data and provide simulated results from additional scenarios.

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The second point of analysis are the greenhouse gas impacts, which evaluates the storage technology installation and operation in the network in terms of GHG emissions. As storage replaces existing network upgrades or is installed as an additional unit in the grid, the GHG emissions of the network are altered. For example, the production of the storage unit causes GHG emissions. On the other hand, storage technologies have a positive impact due to the increased renewable energy sources integration.

Finally the economic dimension was assessed. Storage can lead to energy cost savings e.g. via peak shifting addressing the time- and location-disconnect between generation and consumption of electricity, but can also participate on various electricity markets or provide ancillary services to the network operator, which controls and maintains the stable network condition to deliver energy within required quality boundaries.

3.1 Technical analysis and simulations

Table 1 presents key technical parameters used as Key Performance Indicators in the demonstration monitoring that were analysed in this report. The detailed description of KPIs is provided in STORY report D6.2 Demonstration protocol book.

Table 1. Technical parameters/KPI's

KPIs	OHL part 1	OHL part 2	Exkal	Beneens	Suha	EG
RES use change	✔		✔	✔	✔	✔
Self-consumption ratio	✔	✔	✔	✔	✔	✔
SSR		✔		✔		
Peak-to-average demand ratio			✔		✔	✔
Relative peak power change			✔	✔	✔	✔
Grid energy consumption			✔		✔	✔
Voltage control		✔			✔	✔
Zero Load Provision						✔

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3.2 Economic analysis approach

The methodology for the economic assessment carried out by JR is based on the output of the technical analysis and combined with the economic characteristics of the demo, Figure 2. One reference case without storage is calculated and compared to case with storage implemented. The following economic parameters were considered:

- Cost of the renewable energy unit, Operation and Maintenance costs, BESS costs, Inverter costs
- Lifetime of the technologies
- Discount rate
- Wholesale market price, retail price, day-ahead market prices, prices for tertiary reserve reservation/activation, hours of tertiary reserve activation, gas price
- Nominal increase in electricity price per year

As indicators for the economic feasibility, the net present value (NPV) (1) and the internal rate of return (IRR) are calculated. The internal return describes the discount rate at which the NPV becomes positive. An increase in the electricity price is assumed for each year. Revenues could also be generated by offering services on the tertiary reserve market or through exchange on the day-ahead market. For this reason, historical market data is used as a reference. In the case of heat being used the gas price is considered as an indication in the base case. A representative discount rate for the respected country is chosen to calculate the NPV of the use cases.

$$NPV = \sum_{t=0}^{n} \frac{Rt}{(1+i)^t} \qquad (1)$$

R = net cash in/outflow during t
i = discount rate
t= number of time periods

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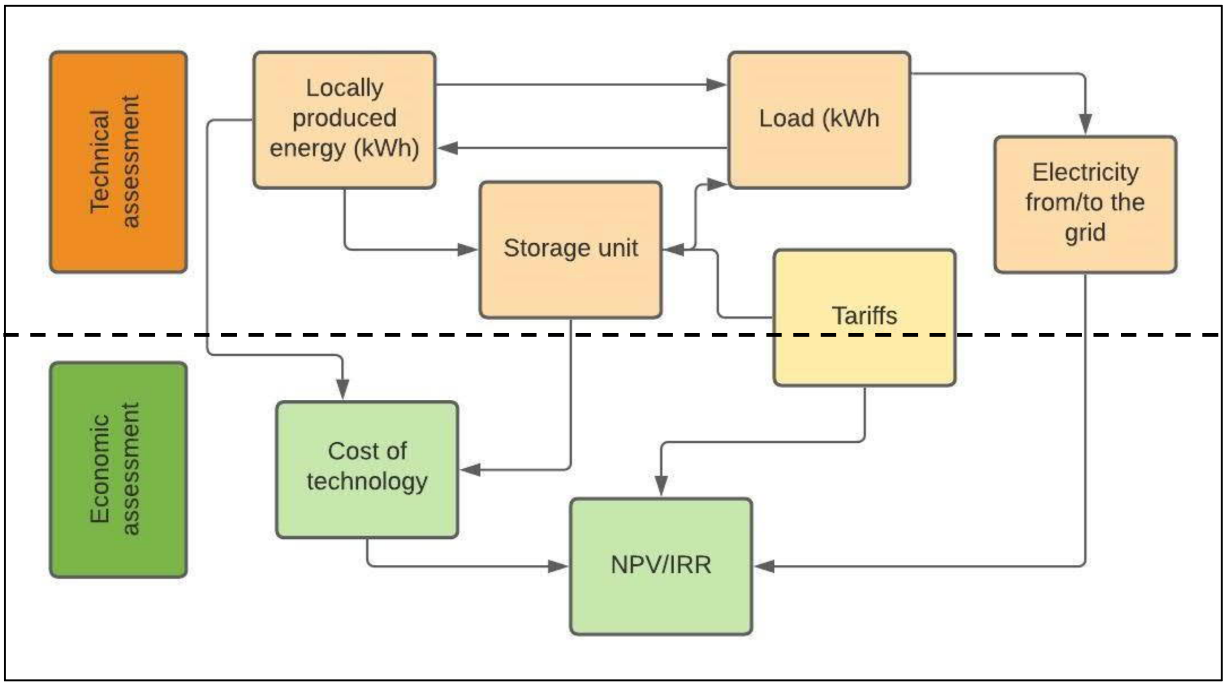

Figure 2: Methodology of the economic assessment

3.3 Greenhouse gas emissions

The analysis on the climate impact of different demonstration cases is based on a life cycle assessment (LCA). According to ISO 14040 LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).

In the LCA we used different data sources: First we used demonstration specific data and results from the technical analysis (e.g. battery size, installed amount of PV plant, electricity demand, electricity generation from PV, electricity needed from grid) . Second data on emissions factors and primary energy demand was taken from the LCA databases GEMIS (IINAS, 2017) and ecoinvent (Wernet et al, 2016) and from literature.

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A detailed description of the LCA methodology used for the investigation of all presented demonstration cases and its results can be found in STORY Deliverable: D7.4 Report on environmental analysis of demo-scale storage implementation.

4 Multidimensional assessment of simulations and STORY demos

This section summarizes the results of the three different assessment dimensions (technical, climate, economic) per demonstration case. The analysis involved different scenario applications and use cases. Scenarios and use cases are described in the first sub-chapter of each demo-section. The following sub-chapters present the results for each assessment dimension. Each demo section ends with a short synthesis bringing together the three dimensions on demo-level.

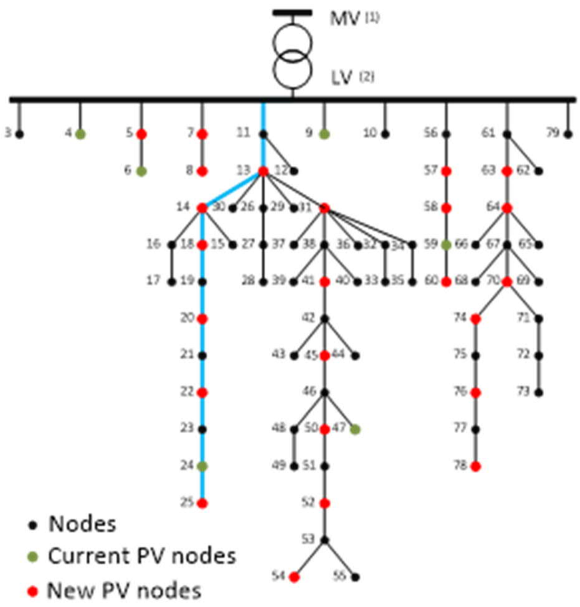

Figure 3: LV Suha network with existing RES location (green), measured loads (orange) and BESS location (blue)

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4.1 EG Suha Simulation

As described in Section 3.2, the demo results and KPIs are based on scenarios and with the base case PV deployment scenario considering measured demo data.

4.1.1 Simulation models for EG Suha network

The technical analysis of the EG Suha network and EG Headquarters is based on simulations carried out by UL. These simulations were performed within the STORY simulation platform, designed in OpenDSS and MATLAB software environment. The simulation platform was updated for the needs of analysis and simulation needed in this task.

With the technical simulations we aim to show how the storage impacts individual network in detail in case of higher PV deployment as opposed to large scale simulations, where the focus was on entire grid sections with massive implementation of PV, EVs and storage technologies. Here, with a smaller section of the network, which resembles the pilot location, additional simulations served as extrapolation of demo setting and testing ground for additional scenarios and technology implementations. This was done in the two Elektro Gorenjska pilot locations, LV residential network Suha and the industrial site of EG headquarters.

The low voltage cable network in this demonstration case model is connected to a MV/LV transformer substation which supplies electricity to 71 households and provides connection for 7 distributed PV plants. OLTC transformer with rated power of 400 kVA is situated in transformer substation. The LV network is located on the countryside, with several farms in the village as well. The network can be observed in Figure 3.

The network is quite specific for several reasons. Due to the cable infrastructure it is quite resilient, while the OLTC is taking care of the voltage regulation. Three of the feeders are quite long and installing additional loads or RES units could have worsened the network operating conditions. The consumer and RES production profiles are mismatching; the load has peaks in the morning and in the evening, while PVs are producing the most during the day. One of the goals of storage implementation in this pilot site was peak

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demand control, where consumption peaks were mitigated with stored energy in a BESS. The BESS was charged with surplus of RES energy in the grid or during the night-time, when low tariff energy prices occur, and the BESS unit can recharge with lower cost option.

4.1.1.1 Simulation inputs

A 12-month period simulation was performed for the technical simulations of the two pilot sites, Suha LV network and EG HQ LV network. Voltage, current, active- and reactive power measurements of both transformers were available and were used to provide load and generation profiles, to calibrate for the models and to run the simulations. All the PV locations in the networks were also available, which was utilized in the scenario application process. Power flow simulations were run for the entire simulation interval in 15 min timestep resolution. The BESS control algorithm reacts based on the local measurement of active power flows, measured at MV/LV transformer substation. Based on the grid topology and power consumption, and production profiles and BESS response, the technical results are calculated in the simulation platform. Through technical parameters, BESS impact can be seen on the chosen key grid parameters, such as voltage levels, loading of the elements and losses in the network. Energy consumption shifts are seen through the transformer power flow profiles. In addition to the input data for simulations, 3 key algorithm functions were included for the technical simulations of EG pilot sites for the BESS implementation use case:

- **BESS Peak demand control algorithm**, which is installed in Suha LV network, through which BESS is preventing reverse power flows of active power to the MV grid and shifting/reducing peak demand values on the MV/LV transformer.
- **BESS two-tariff economic control with peak consumption reduction**, which was used to control BESS in the EG HQ demo.
- **PV unit droop control algorithm,** which curtails PV production based on the droop control function instead of in an on/off fashion. If the PV unit causes voltage rise above certain threshold, the BESS output is decreased to maintain the voltage values within the allowed boundaries.

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Given the current PV penetration at Suha no grid operational issues were observed in the demo. Therefore scenarios representing higher PV shares were created and focused on the integration of the storage operation and RES generation. With increased RES integration, PV production will increase to a level where PV units are causing network voltage violations. To mitigate this negative impact of PV units, the inverters are performing droop control of the PV production. When voltage rises occur due to high PV injection and low demand in the network, the inverter gradually curtails the output of the unit. If this measure is not enough to mitigate the voltage rise sufficiently, the PV units gets completely shut down when voltage limit level of 1.10 p.u. is met. This means that the voltage in the grid increased by 10 % compared to the nominal value. As a result, PV units produce less as network conditions restrict the operation. Less green energy is locally produced, and more favourable sort of control is sought after. With implementation of the PV curtailment algorithm in combination with optimal control of the BESS unit, we store this surplus of energy, which would otherwise be lost, and the BESS provides this green energy back to the grid in time instances when energy is needed, for example in evening demand peak, when PV production is at lower rates.

4.1.1.2 Use case description

Different use cases (UC) were investigated through the technical simulation. Here the impact of PV curtailment control and BESS on the energy flows into the grid are presented. The BESS model parameters are described in Table 2. To investigate RES and BESS impact on Suha LV network, the following scenarios and use cases (UC) were applied to the simulations:

- **Scenario low RES**, where existing 210 kWp RES units were simulated
- **Scenario high RES setting**, where RES amount was increase by 200% to 630 kWp

For both scenarios the following use cases were simulated:

- UC0: No PV control – theoretical potential
- UC1: Droop control of PV units – PV curtailment application
- UC2: BESS unit implementation and droop control

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The parameters of the BESS model used, shown in Table 2, have been supplied by the BESS provider, ABB, and are described in detail in STORY report D7.3 Report on large scale impact simulations.

Table 2: BESS models parameters

Parameter	Industrial unit	Household unit
Capacity [kWh]	320	16
Rated power [kWh]	170	15
Efficiency – charging [%]	94 %	76 %
Efficiency - discharging [%]	94 %	88 %
Minimum SoC Level	20 %	35 %
Maximum SoC Level	98 %	99 %
Auxilary power consumption	4 kW constant load when operational	0

The large industrial BESS unit has its own auxiliary consumption for all the subsystems (e.g. inverter, communication, control) and HVAC system which are necessary for stable operation. They are supplied from external source and modelled as a load in the model. In the demo implementation, part of the charge and discharge rate get diverted to those systems, which we implemented in the simulations as well.

Use case UC_0: Theoretical potential

The first use case represents the situation in the grid when no BESS is implemented and PV units can produce at maximum potential, with no regards to their impact on the grid, Figure 4. This results in voltage increase, which would have to be mitigated by other system measures.

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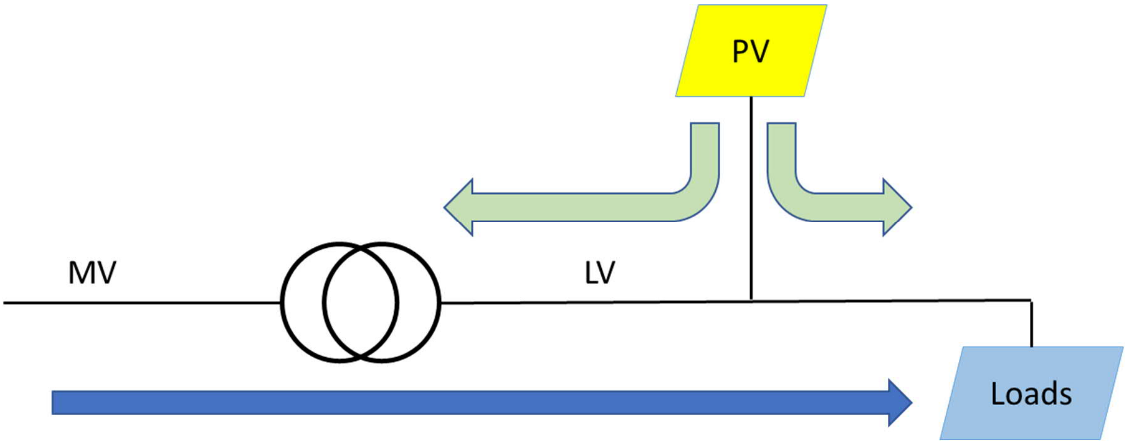

Figure 4. UC_0: unconstrained energy flows

Use case UC_1: PV curtailment application

This use case represents more realistic setting of the PV installations, seen on Figure 4. PV units are controlled by the droop control approach, they can produce power at maximum potential until they are not causing voltage rises in the grid above certain threshold. Their production rate gets limited if they inject too much power and cause too much of a voltage rise. Some of the PV potential is lost due to the reduction of PV injection. PV energy is locally consumed, surplus is still injected in MV grid.

Use case UC_2: BESS implementation

In this use case the central BESS is implemented in the transformer substation, Figure 5. BESS is performing peak shaving; it charges in intervals with high PV production and low network demand intervals (night), and discharges energy back into the grid in intervals with high demand peaks. PV units are still controlled with the droop control algorithm in case they worsen the network condition, but due to the BESS support the curtailment is decreased, more PV energy is produced and consumed locally.

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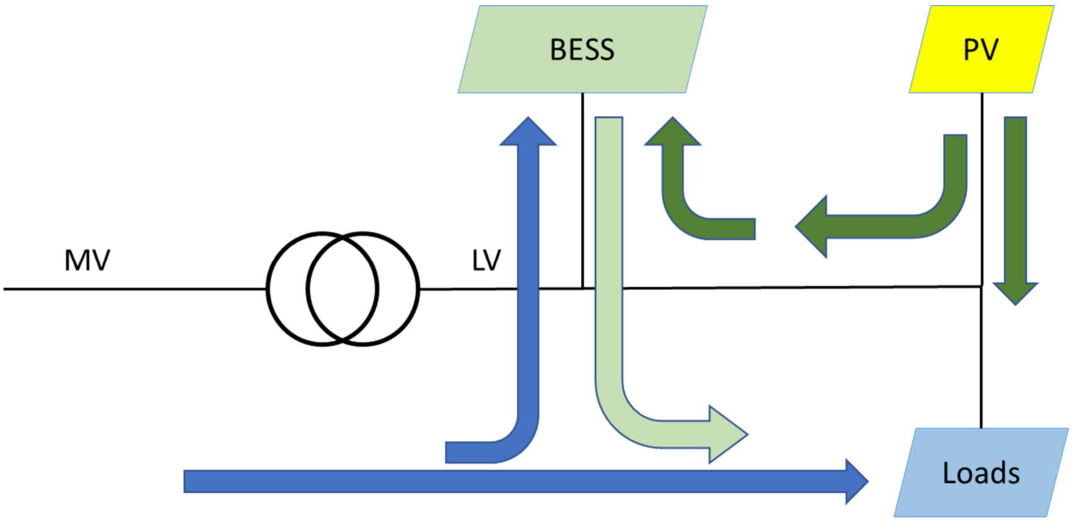

Figure 5. UC_2: energy flows with BESS implemented

4.1.2 Technical analysis

The voltage profile of the end consumers must follow strict boundary conditions. For normal operation of the network, all of the users node voltages are allowed to fluctuate up to 10 % from the nominal value of 230 V. so voltages are allowed within boundaries of 0.9 p.u. to 1.10 p.u.. In Figure 6, we see the values for the load voltage on a yearly span. In blue, we see the initial shape, it overlaps with the scenario with the PV curtailment algorithm (red) and BESS implementation in green. Due to grid resilience we observe only a slight impact of the BESS technology. In general, the BESS operation brings voltage profiles closer to 1 p.u. value with slightly higher amount of those measurements.

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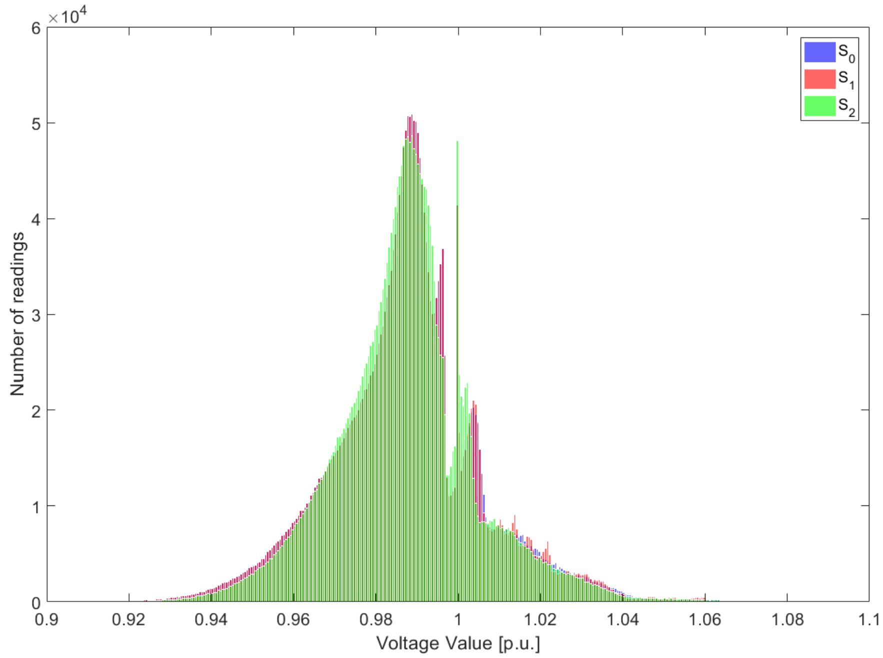

Figure 6: Node voltage measurement histogram comparison

Figure 7 presents the voltage analysis for the High RES setting. In the first scenario, the blue graph, the voltages are impacted by uncontrolled PV production. Voltage in the network rises to 1.15 p.u., which is way above the allowed deviation. In a realistic scenario with PV curtailment control, the element control ensures that the PV unit does not cause voltage raise above 1.10 p.u. This is an effective measure, as voltages are maintained within the allowed boundaries, but PV production is reduced. With BESS implementation, in the green colour, we maintain the voltage within boundaries, defined by the systems standards. A combination of PV droop control and optimal BESS control were effective regarding voltage level control.

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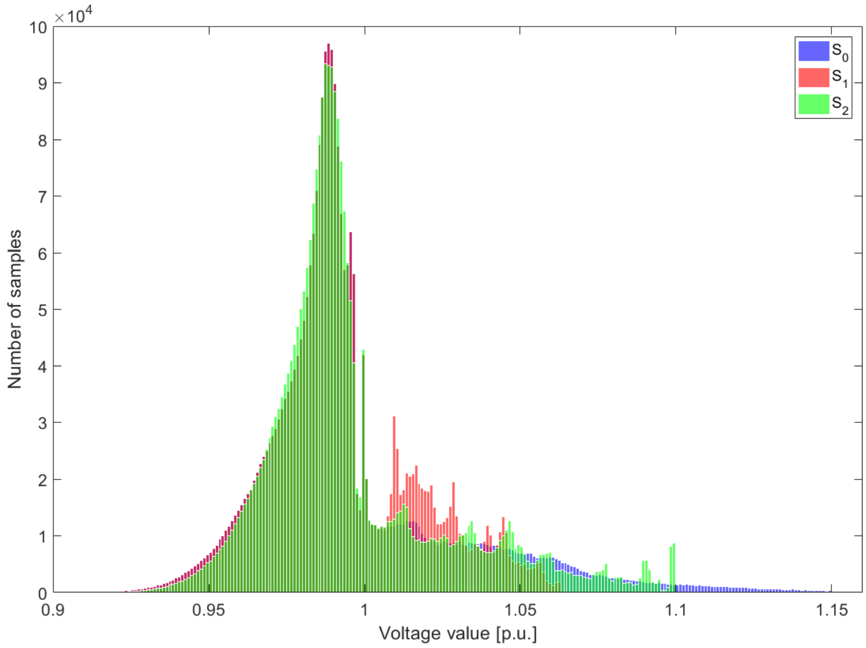

Figure 7: Voltage measurements, high RES scenario

With the implemented control strategy, PV curtailment impacts the PV production, based on the voltage levels on the node, Figure 8. The comparison of PV production by the units can be seen on the figure, where yearly PV production of each unit in the network is compared for all three scenarios. In the high RES scenario, where the effect is mostly present, we can see how much the local control of PV production impacts the individual units, which are installed on the longer feeder sections, where voltage fluctuates with highest rates. PV units 4 and 5 are curtailed up to 50% with the curtailment algorithm. Their connection points experience voltage rise along the feeder due to their own power injection and also due to the injection of other units installed on the feeder closer to the transformer substation.

To enhance PV production of all units in the network, a BESS implementation presents an effective solution. An alternative would be a centralised control mechanism, which would allow more unified PV curtailment of the units in the grid, however, BESS has a positive impact on other network parameters.

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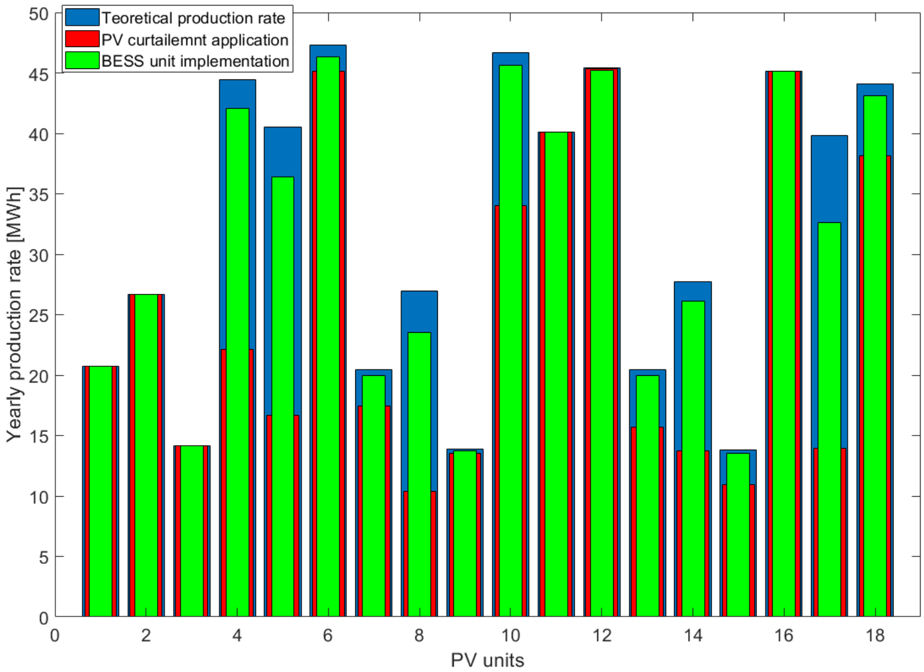

Figure 8:Comparison of individual PV unit production between scenarios

In the following paragraph, the impact in existing and future scenarios is investigated on the transformer substation. The storage operation has an impact on the power flows, loading levels and sequentially the losses of the transformer. In Figure 9 and Figure 10 we see simulated transformer power flow instances (referred to as 'measurements') on the yearly level for low RES and high RES setting, respectively. Figure 9, in the low RES setting, shows that curtailment of the PV inverters has almost no impact on the power flows, while BESS implementation helps to reduce reverse power flows and also reduces the peak consumption, so the transformer is in general loaded to lower levels compared to non-BESS options.

In the high RES scenarios, Figure 10, the unrestricted PV would reach over 400 kW, which is the transformer nominal power ratio. In a realistic scenario, the network mechanisms would be activated to prevent current congestion on the transformer and overvoltage in the network. We observe how PV curtailment reduces PV injections, so it does not exceed negative 200 kW injected from the LV grid to the main MV grid. In all

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figures henceforth, negative power flow denotes the flow from the LV to MV grid. With BESS implementation, we experience some slightly higher rate of the power flows, but the PV production is significantly higher than in the use case with the PV curtailment algorithm activated.

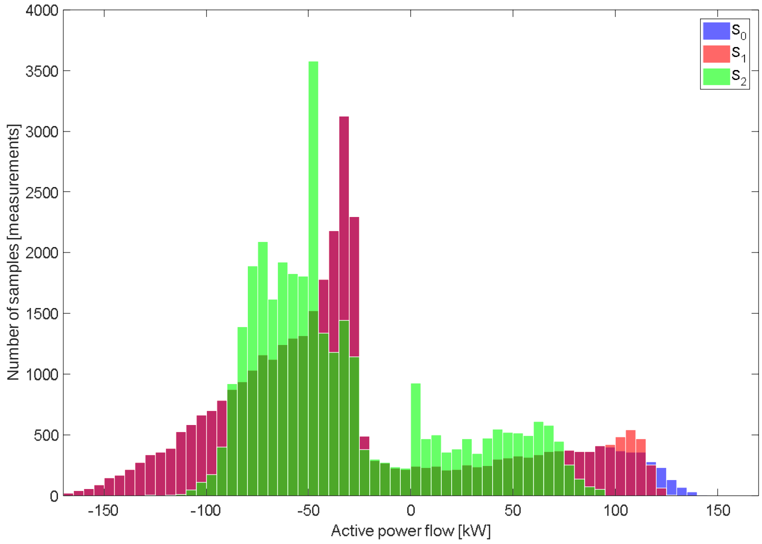

Figure 9: Low RES scenarios histogram comparison

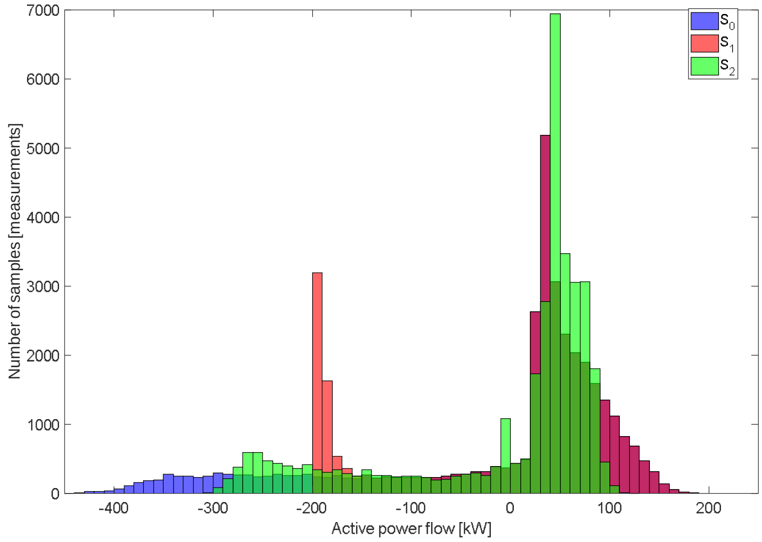

Figure 10: High RES scenarios histogram comparison

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Key findings

Table 3 presents the comparison of energy flows between the use cases. The relative impact on parameters is presented in Table 4, where comparison to theoretical potential is made. The LV network demand remained the same throughout the simulations (0% change) and while it was not subject of the analysis, it serves as a basis for comparison. Losses in the LV grid increase with higher share of PV production in the grid since they cause additional power flows in the grid and out of the grid (increasing active power losses from 16 MWh to 39 MWh p.a.). This effect is mitigated with PV curtailment as seen in comparison of High RES settings with the base line. BESS implementation also decreases losses compared to theoretical situation, down to 23 MWh and 32 MWh respectively. The PV droop control algorithm has negative impact on PV production since it limits the production of the units. The net PV production is curtailed by 134 MWh per year with this measure, while BESS implementation keeps PV production at almost the theoretical rate, only 23 MWh per year is curtailed in High RES setting. Energy consumption from MV grid is reduced only with BESS implementation as it allows storing and shifting the PV produced energy for later use. 44 MWh of energy is less injected from the main grid in low RES scenario and with high RES and BESS implemented we further decrease the active power flow from the MV to the LV grid by 87 MWh per year.
Additionally, BESS helps mitigate reverse power flow injection from the LV into the MV grid with the local storage. 56 MWh are additionally used in LV grid with low RES setting and in high RES setting, additional 85 MWh of energy is annually not injected from the MV grid into the LV grid.

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Table 3: Comparison between use cases [MWh/year]

Energy (MWh/a)		LV grid energy consumption	Losses in LV grid (incl. TR)		PV generation injected	PV energy consumed in LV grid	Energy injected from MV into LV grid	Energy injected from LV into MV grid
low RES	UC_0	457.62	16.53	10.48	193.89	56.17	411.84	137.72
	UC_1	457.62	16.53	10.48	191.48	55.93	411.84	135.55
	UC_2	457.62	15.50	7.38	193.89	112.52	367.03	81.37
High RES	UC_0	457.62	39.27	32.50	578.40	105.31	376.52	473.09
	UC_1	457.62	22.77	18.82	444.02	95.27	376.52	348.75
	UC_2	457.62	32.44	22.63	555.11	167.15	324.78	387.96

Table 4: Comparison between use cases [%]

Energy (MWh/a)		LV grid energy consump-tion	Losses in LV grid (incl. TR)		PV generatio n injected	PV energy consum ed in LV grid	Energy injected from MV into LV grid	Energy injected from LV into MV grid
low RES	UC_0	0%	0%	0%	0%	0%	0%	0%
	UC_1	0%	0%	0%	0%	-1%	0%	0%
	UC_2	0%	0%	-6%	-30%	0%	100%	-11%
High RES	UC_0	0%	0%	0%	0%	0%	0%	0%
	UC_1	0%	0%	-42%	-42%	-23%	-10%	0%
	UC_2	0%	0%	-17%	-30%	-4%	59%	-14%

Table 5 presents the BESS energy flow. BESS stores 56.5 MWh and 63 MWh of PV energy per year in low and high RES setting, respectively. In low RES setting the BESS charges more often during the night interval so the power from MV grid is used to charge the BESS. The amount of energy charged to the BESS during one year amounted to 45 MWh, while overall MV grid consumption was decreased by 44 MWh. The charging of the

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BESS from MV grid occurs during the night interval, when the energy price is lower and network load rates are lower. The battery operation times are different for low RES and high RES. In the latter, it has charged fasted, so the BAT own consumption is lower.

Table 5: Battery energy flows

Energy (MWh/a)	Energy stored in BAT from PV	Energy stored in BAT from MV grid	Energy injected from BAT into LV grid	Energy injected from BAT into MV grid	BAT own consumption
Low RES	56.50	45.25	86.10	4.11	23.22
High RES	63.01	34.77	82.13	4.56	20.20

Simulations showed that BESS implementation enhances local RES use by 101 % in low RES setting and 59 % in high RES setting. Self-consumption increases by 23 % and 8 % in respective scenarios, while self-sufficiency is increased by 17 % in low RES setting and 13% in high RES setting. The BESS is able to reduce demand peak almost to 40 % on yearly average. In the low RES scenario it halves the production peak, while in High RES scenario it reduces the production peak only by 4 % on yearly average, while enabling PV units to produce significantly higher amount of energy. This can be seen in the energy flows of Suha analysis in Table 3, where BESS increases PV production from 444 MWh to 555 MWh in the grid. Grid losses are reduced by 7% in the low RES and by 21% in the high RES scenario.

Table 6. Technical results

	Low RES	High RES
Increased RES use	100.75%	58.72%
Self-consumption level	23.18%	8.02%
Self-sufficiency level	17.08%	12.99%
Relative peak power change	41.87% positive, 49.38% negative	44.87% positive, 34.47% negative
Reduction of grid losses	6.97%	20.53%

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4.1.3 Greenhouse gas impact

The Greenhouse gas impacts of the EG Suha demonstration was investigated using LCA. The electricity demand from the households in the residential grid is covered by local PV plants and electricity from the grid. Surplus electricity from the PV plants is injected into the power grid and/or stored in the battery system.

The LCA was performed for two use cases which differ in the included components and the way PV electricity is handled:

- UC1: PV curtailment application
- UC2: BESS implementation

The climate impact of both UC1 and UC2 was investigated for two different amounts of PV units installed in the grid: 210 kWp (low RES scenario) and 630 kWp (high RES scenario) installed peak power. Main input data for the LCA were results from the technical analysis on the energy flows of the UCs (see Table 3 and Table 4).

Figure 11 presents the annual GHG emissions for RES scenarios with 210 kWp PV and 630 kWp PV. The figure shows the total annual GHG emissions and contributions from PV plant manufacturing, battery manufacturing, electricity from grid, electricity into grid. If the PV generation level covers all demand in the grid and the surplus energy can neither be consumed nor stored it is injected into the MV grid. This energy flow affects the electricity generation in the network and electricity generation by other power plants can be replaced. Therefore, the GHG emissions for electricity supplied to the grid are negative. In Figure 11 the hourly Slovenian electricity mix of 2018 was used for consumed and replaced grid electricity.

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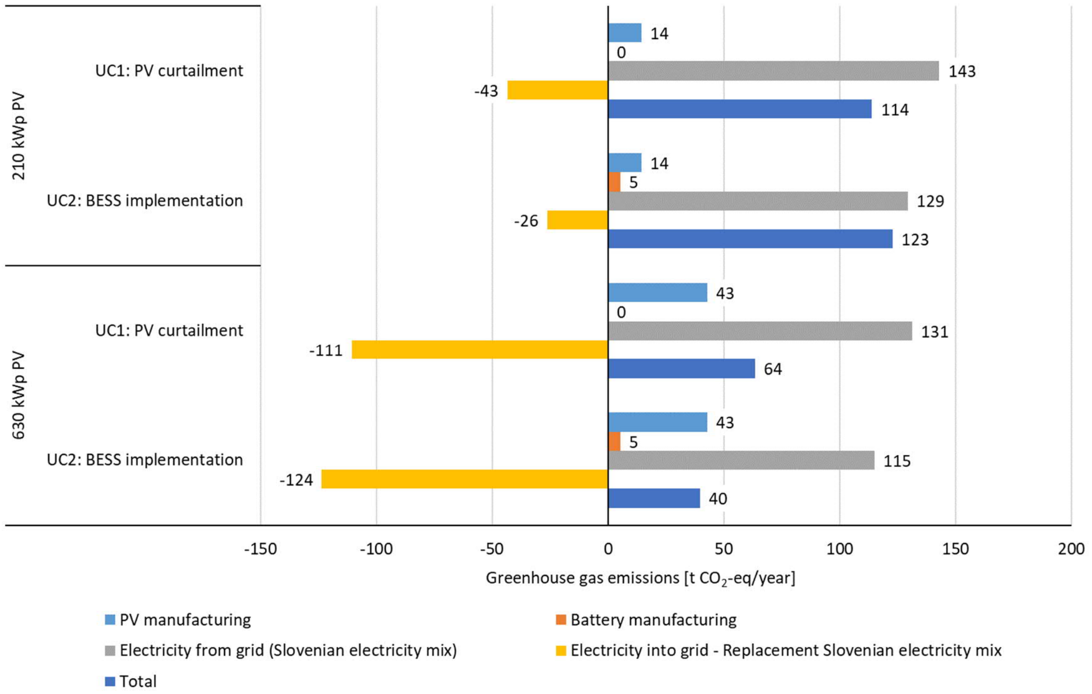

Figure 11: Annual greenhouse gas emissions for “UC1: PV curtailment” and “UC2: BESS implementation” (Slovenian grid mix for consumed and replaced grid electricity)

In the scenario with 210 kWp PV power the “UC2: BESS implementation” has slightly higher GHG emissions (123 t CO_2-eq/year) than the “UC1: PV curtailment” (114 t CO_2-eq/year). The advantage of less GHG emissions for grid electricity consumption does not compensate for the lower amount of saved GHG emissions and the additional GHG emissions for battery manufacturing. With 210 kWp, PV power curtailment of the PV plants is practically not needed. In both use cases, PV plants can use the grid almost unlimited. The situation changes in the second scenario, where 630 kWp PV are installed. Here, the grid model showed grid limitations and, in both use cases, curtailment is needed. However, in use case “UC2: BESS implementation” less curtailment is needed when using the battery for peak shaving. Therefore, GHG emissions for consumed grid electricity are lower in use case “UC2: BESS implementation”, but also saved GHG

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emissions are higher as the amount of PV electricity injected into the MV grid level is higher.

Figure 12 shows the specific GHG emissions per MWh electricity demand. With 210 kWp PV power the specific GHG emissions of the investigated use cases “UC1: PV curtailment” and “UC2: BESS implementation” are in same range with approximately 250 kg CO_2-eq/MWh. With 630 kWp PV power the specific GHG emissions of use case “UC2: BESS implementation” (~ 90 kg CO_2-eq/MWh) are clearly lower than the specific GHG emissions of “UC1: PV curtailment” (~ 140 kg CO_2-eq/MWh).

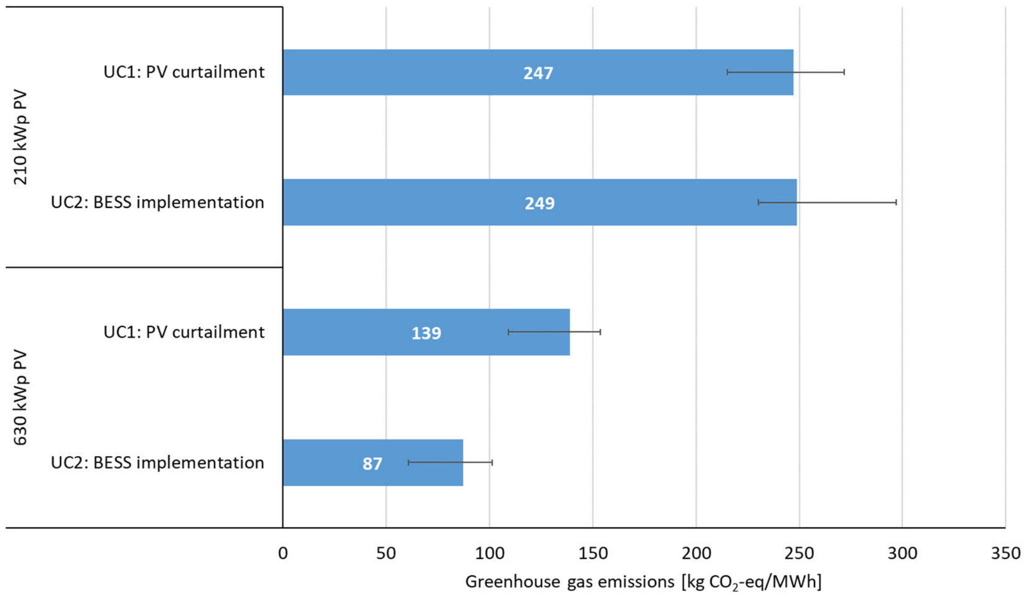

Figure 12. Specific greenhouse gas emissions for “UC1: PV curtailment” and “UC2: BESS implementation” (Slovenian grid mix for consumed and replaced grid electricity)

4.1.4 Economic impact

The battery in Suha has a nominal capacity of 550 kWh and 170 kW. Due to the specific set-up characteristics, only 320 kWh of the battery can effectively be used. This

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assessment considers therefore a battery of 320 kWh and 170 kW with a lifetime of 15 years.

The “scenario low RES setting“ and the “scenario high RES setting” as mentioned above are examined in this analysis. For both scenarios UC2, BESS implementation is analysed. In “UC2- A” the battery is used to minimize demand in high tariff times and reduce demand during peak hours. The battery is charged from PV or in lower price periods from the grid. In the High RES scenario, energy PV generation has to be curtailed due to network restrictions. In this case, the battery is also used to minimize curtailment. The profit is avoided curtailment of energy times the feed-in tariff.

“UC2 – R” analyses the economic feasibility of using the entire (low RES scenario)/ part of the (high RES scenario) storage (170 kW) on the mFRR market for a reservation price of 4.43€/MWh and an activation price of 249.5 €/MWh (ELES, 2018). In the high RES scenario part of the battery is reserved for minimizing curtailment. 60% of the total storage capacity is used on the tertiary market in winter, 0% in spring, 40% in summer, and 50% in fall while the remaining capacity is used for curtailment. It is assumed that the reserve capacity is activated 21 times in one year under the assumption that there is no minimum capacity threshold for market participation. The price for recharging the battery is 30 €/MWh. Storage system costs add up to 500 €/kWh and a feed-in tariff of 0,0462€/kWh is assumed.

The results show that in UC2–A, arbitrage and self-consumption, the battery is not profitable. If the battery is only used on the reserve market the business case is drastically improved (IRR = -6%). For the second scenario, the avoided curtailment of energy creates value which leads to an IRR = -4.9%. A combination of the use for mFRR and to prevent curtailment leads to the best business case (IRR = -3.2%). Note that the result importantly depends of the assumption on the frequency of the reserve activation and the reserve prices.

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Table 7. Results of the economic analysis for SUHA

PV capacity	Use case	Market mechanisms	NPV €	IRR
Scenario low RES setting	UC2 - A	Arbitrage, self-consumption	-134,870	-18%
	UC2 - R	Reserve market	-81,470	-6%
Scenario high RES setting	UC2 – A	Arbitrage, self-consumption, curtailment	-79,079	-4,9%
	UC2 - R	Reserve market, curtailment, arbitrage, self-consumption	-67,859	-3,2%

Figure 13 presents the influence of the storage costs on the IRR. In the low RES scenario in UC2 - A no break-even can be reached, UC2 -R and in the high RES scenario UC2 -A provide a business case (WACC of 5%) if the cost for the storage system drop to approximately 265 €/kWh. For UC2 –R a cost decrease to 300 €/kWh would make the set-up economically feasible.

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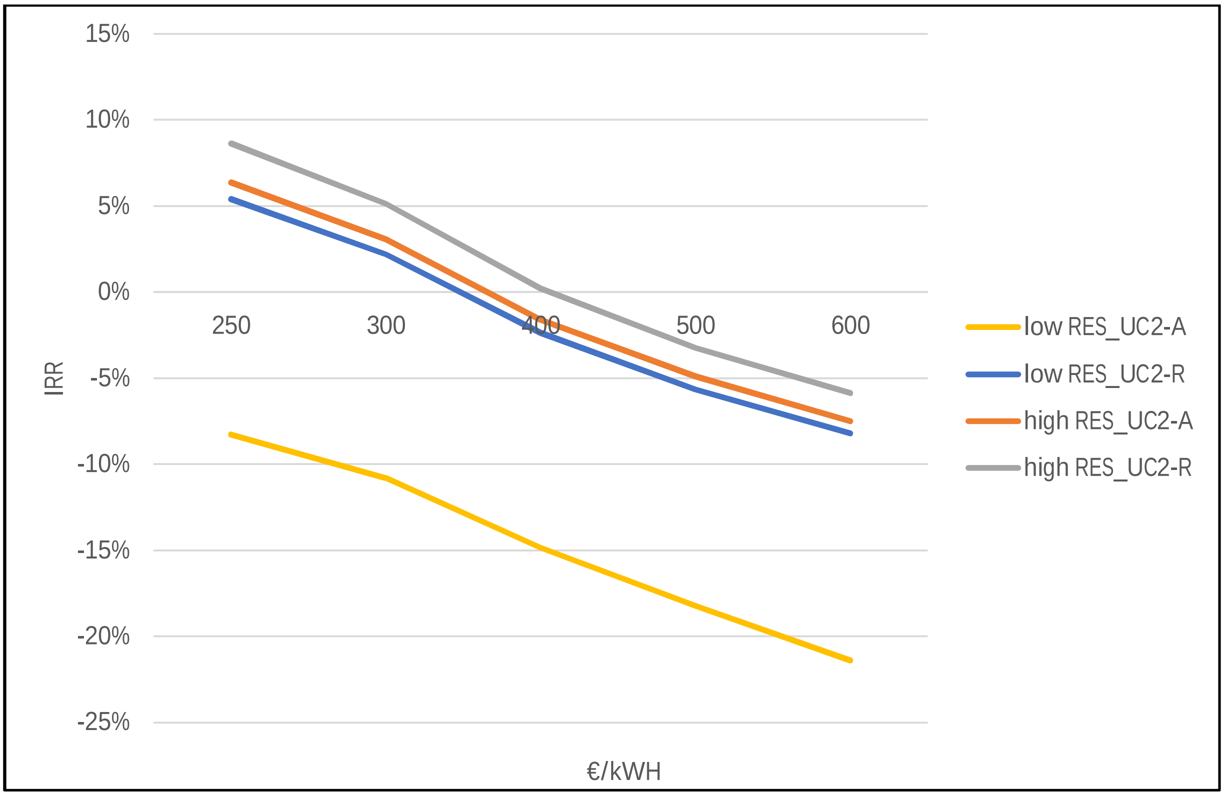

Figure 13. Influence of storage costs on the IRR

4.1.5 Synthesis

The implementation of a medium sized battery in a neighbourhood in the case of high PV penetration, as shown in the Suha demonstration in Slovenia, can reduce PV generation curtailement up to 25%. The BESS also increases local use of the PV-generated energy by 75%. Since there is a small net decrease of 3% in the total energy exchanged with the grid, this could lead to deferred grid investment. Overall, the use of the battery increased the use of local renewable energy in a simulated case of high PV penetration.

This demonstration highlights important technical benefits to the DSO, such as peak demand reduction, reduction of losses and increased local RES generation. A possible positive business case with revenues from the tertiary reserve market and by minimizing

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RES curtailment is shown to be possible. Mitigating RES curtailment presents also a use case where the implementation of a storage unit decreases GHG emissions in comparison to a case without a battery, improving the business case and the perceived usefulness of BESS.

4.2 EG Headquarters Simulation

The second EG pilot site location is EG Headquarters, an industrial type of end consumer, located in an urban area. Two 630 kVA MV/LV transformers serve as a connection of the local LV grid to the MV grid and supply the loads in the industrial compound. The EG headquarters consist of an office building with its consumption, a 35 kWp rooftop PV installation and a 27 kW (electric) CHP plant. The CHP plant serves as a heating source for colder months of the year and in the warm months of the year, the chiller combined with an ice bank is responsible for cooling the offices. The BESS was to be connected within the internal LV network of the building, and its control strategy was to optimize the BESS operation with the active distributed RES generation devices and flexible consumption devices currently existing in the grid.

The aim of the EG Headquarters simulations was to present the economic potential of the BESS for an industrial user with local LV network peak demand control. By storing the energy withdrawn from the grid and reinjecting it later, BESS shifts the load from high tariff time intervals into the intervals with low energy cost and flattens the overall consumption profile. Peak tariff time interval consumption, which is present during the weekdays is reduced with BESS-provided energy, which charges during the off-peak tariff period. With this measure, high-tariff time interval energy consumption of the industrial consumer gets partially covered by the stored energy in BESS, stored during the low-tariff time interval, thus lowering the energy costs of the industrial end consumer.

Since the BESS has not been deployed to the EG Headquarters, we only present simulation results.

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Here the BESS unit provides 2 important benefits to the demo setting:

- The compressors of the chillers, which are cooling the ice bank, present load spikes in the consumption profile, and with storage we aim to shave those spikes as much as possible to limit the stress on the network elements.
- Additionally, office consumption which is present during the weekdays will be lowered with BESS-provided energy, which will charge during the off-peak tariff periods, at night and during weekends. With this measure, peak tariff energy consumption gets partially covered by the stored energy from the off-peak tariff price period, thus lowering the energy costs of the EG headquarters as an end consumer.

4.2.1 Scenario and use case definition

For the EG Headquarters, three different PV setting scenarios and two different use cases were investigated:

- **Base case setting**, a 35 kWp PV unit is installed
  - UC1: no BESS installed
  - UC2: BESS installed
- **+100% PV setting**, a 70 kWp PV unit is installed
  - UC1: No BESS installed
  - UC2: BESS installed
- **+200 PV setting,** 105 kWp PV unit is installed
  - UC1: No BESS installed
  - UC2: BESS installed

For the EG headquarters, the PV curtailment option was not applied due to several reasons. Even a 200 % increase of existing PV installation (105 kWp total) wouldn't pose operational problems at the demo site location as no surplus of PV production would occur. Additionally 2 x 630 kVA transformers present a very strong connection point, so it is more reasonable to look into the impact of storage operation alone, instead of including PV curtailment option as well.

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4.2.2 Technical results

The focus of the technical analysis results is the energy consumption of the EG HQ demo site. The aim of use cases investigated was to shift consumption from the peak tariff time interval into the off-peak tariff time interval and thus lower the energy consumption cost. Additionally, the overall consumption profile was flattened and peaks were reduced.

In Table 8, the energy consumption of EG Headquarters is presented. With the BESS implementation, high tariff time interval consumption is decreased by 50 MWh per year, while low tariff time interval consumption is increased by 70 MWh per year, due to increased consumption of BESS (auxiliary energy consumption and round-trip efficiency losses). The values for the three scenarios (Low RES, 100 % RES increase and 200 % RES increase) are presented also in Figure 14.

Table 8: Energy consumption comparison [MWh/year]

	Low RES		100 % RES increase		200 % RES increase	
Interval	Original	BESS	No BESSll	BESS	No BESS	BESS
Off-peak Tariff	208.0	279.5	198.3	265.6	188.6	253.5
Peak Tariff	230.1	181.6	205.5	158.5	181.1	135.0
Total	438.0	461.1	403.8	424.1	369.7	388.4

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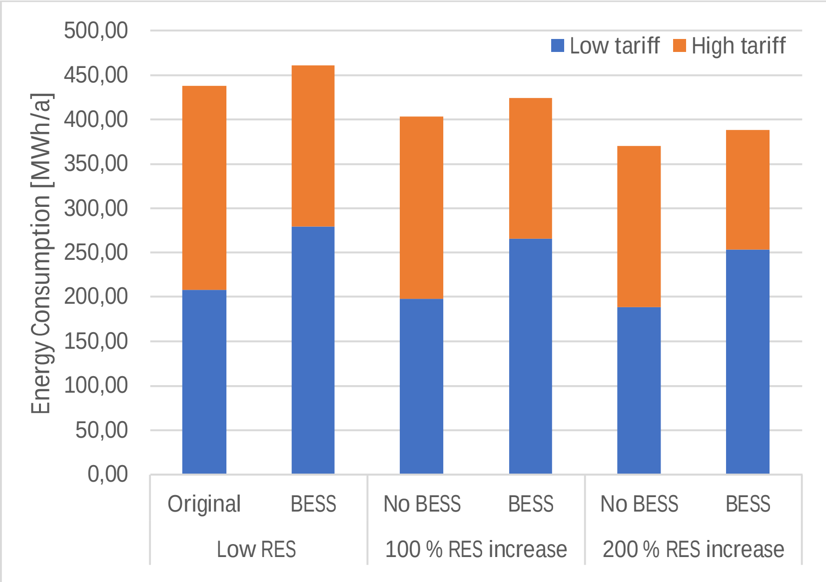

Figure 14: Yearly energy consumption comparison

On Figure 15 and Figure 16 the BESS impact on the transformer loading levels for each tariff interval is presented. In the low tariff interval, the loading levels increase due to BESS charging, a 120-kW threshold of charging is clearly seen on the graph. Similarly, in high tariff instances, the lowest discharging point is 20 kW, where a spike in the number of samples occurs as well. In high tariff consumption we see a reverse trend, where consumption values are lowered compared to the original power flow.

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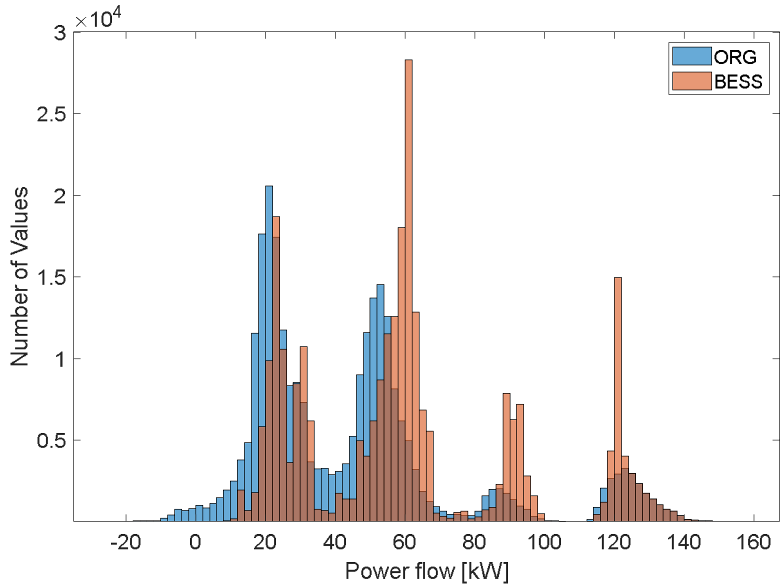

Figure 15: Impact of BESS on off-peak Tariff power flows

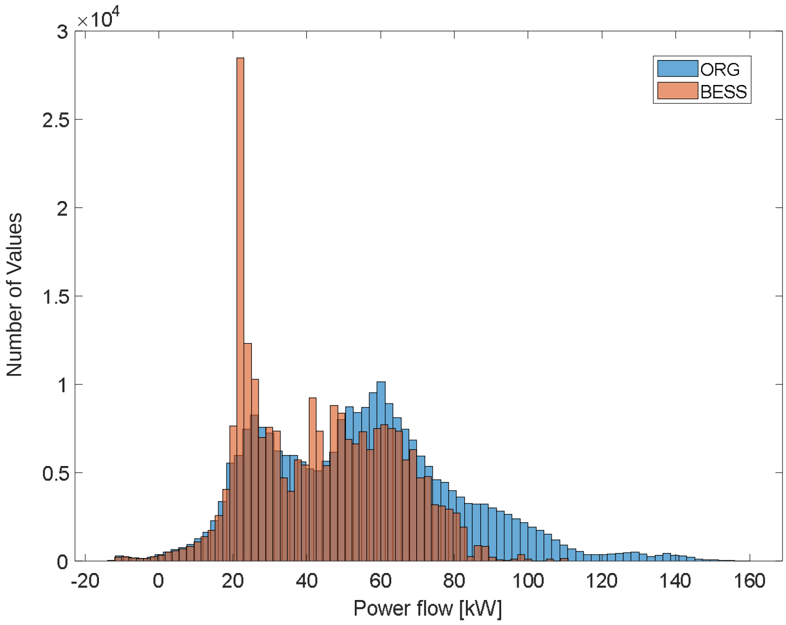

Figure 16: Peak Tariff power flow BESS impact

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4.2.3 Greenhouse gas impact

The climate impact of the EG Headquarters demonstration was investigated using LCA. The electricity demand of the EG Headquarters is covered by a PV plant, a natural gas driven CHP unit and electricity from the grid. The CHP unit is operated based on the heat demand and provides the same amount of electricity in all investigated scenarios and use cases. The total GHG emissions of the CHP unit were allocated to the electricity output based on the electricity heat ratio (250 MWh/a heat, 120 MWh/a electricity).

The LCA was performed for three different PV scenarios (35 kWp – base case, 70 kWp, 105 kWp) and two use cases with (UC2) and without BESS (UC1). The main input data for the LCA calculation are results from the technical analysis on the electricity flows from PV, from the CHP unit, from the grid and into the grid.

Figure 17 presents the annual GHG emissions for the PV scenarios with 35, 70 and 105 kWp PV. The figure shows the total annual GHG emissions and contributions from PV plant manufacturing, battery manufacturing, electricity from the CHP unit, electricity withdrawn from the grid and electricity injected into the grid.

If the PV generation level covers all demand in the grid and the surplus energy can nether be consumed nor stored, it is injected into the grid. This energy flow affects the electricity generation in the network and electricity generation by other power plants can be replaced. Therefore, the GHG emissions for electricity supplied to the grid are negative. However, this happens only to a small extent in the EG Headquarters demonstration case, as most of the PV electricity is consumed directly by the local demand.

In all investigated settings the main contribution to the total GHG emissions is the electricity consumed from the grid (76 % – 81 %). In “UC2: BESS implementation” the electricity demand from the grid is increased due to storage losses and additional auxiliary energy demand for heating and cooling of the battery. Therefore, the GHG emissions of the use cases with BESS are 8 to 10% higher compared to the GHG emissions of UC1, where no battery is installed.

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Figure 18 shows the specific GHG emissions per MWh electricity demand. Increasing the installed amount of PV power decreases the GHG emissions of the system. For example, the specific GHG emissions of “UC1: No BESS” are 301 kg CO_2-eq/MWh in the Base case with 35 kWp PV. Adding 200 % PV installation would lead to 270 kg CO_2-eq/MWh, representing a GHG emission savings of 10 %. Concerning the implementation of a BESS the specific GHG emissions show the same results as the annual GHG emissions before: in use cases with BESS the specific GHG emission increase by 16 to 19 kg CO_2-eq/MWh.

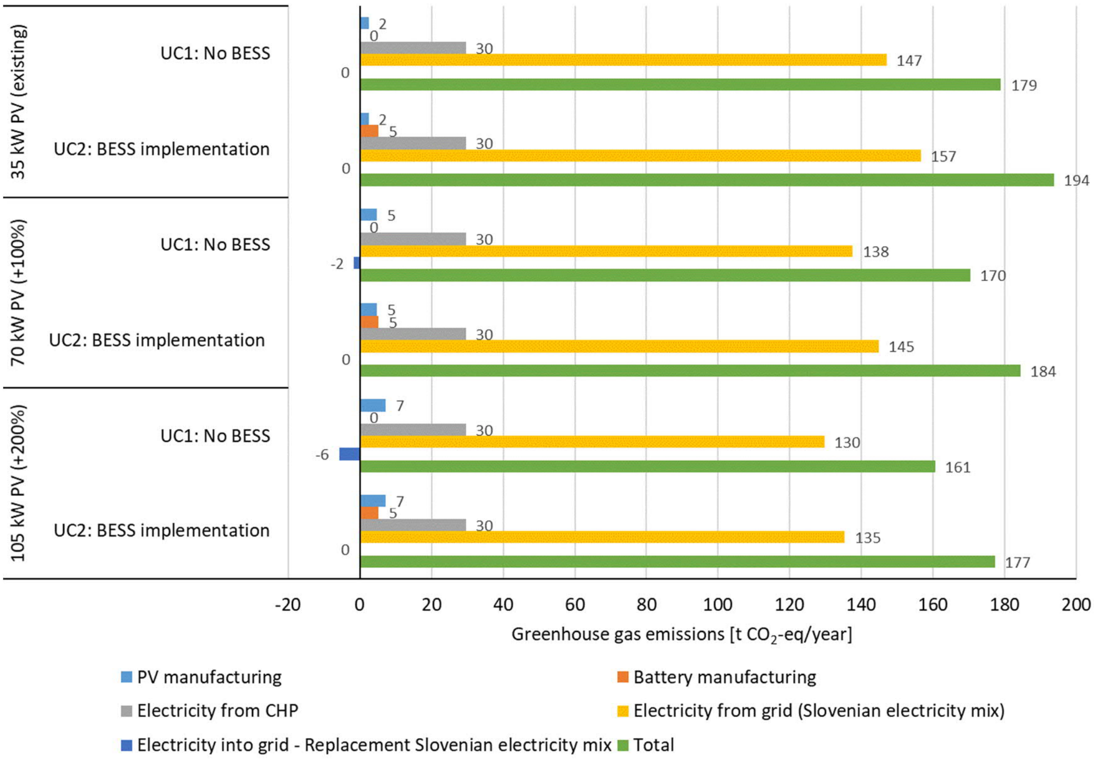

Figure 17: Annual GHG emissions of the EQ Headquarters demonstration case, using the 2018 Slovenian hourly electricity mix for consumed and replaced grid electricity

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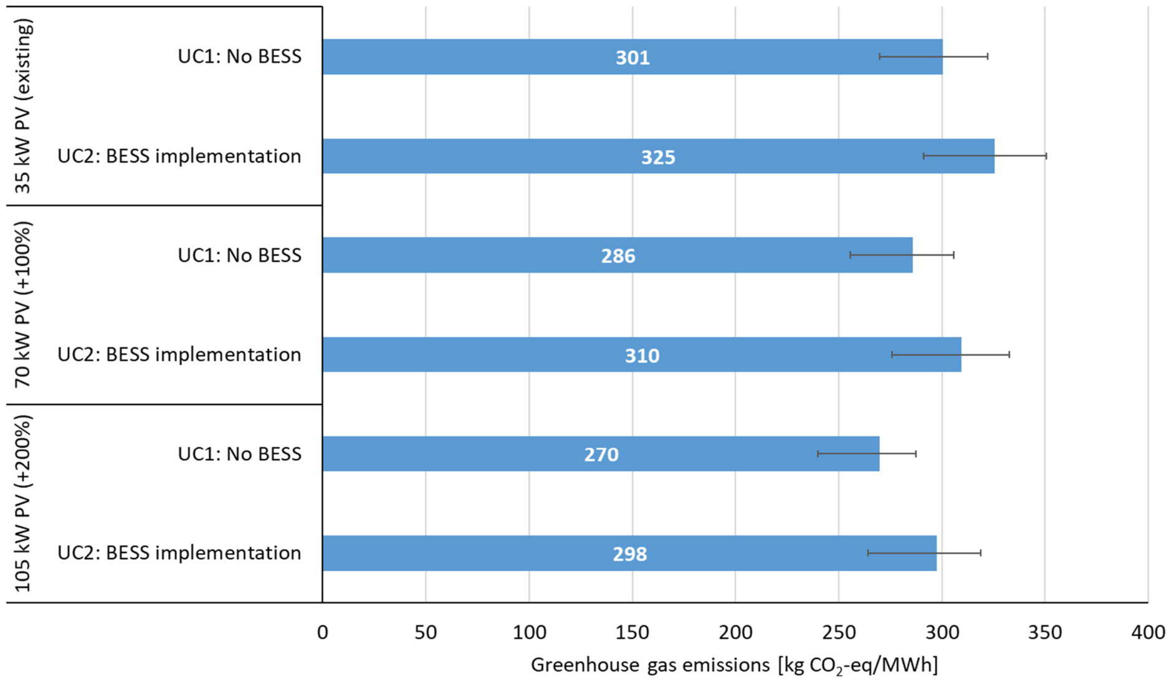

Figure 18: Specific GHG emissions of the EG Headquarters demonstration case, using the Slovenian electricity mix for consumed and replaced grid electricity

4.2.4 Economic evaluation

For the economic evaluation, the energy shift was evaluated with the Slovenian high and low industrial tariff energy prices. The assumed high tariff energy price was 0.08534 €/kWh and the low tariff price was 0.05606 €/kWh, which results in 0.02928 €/kWh price difference between the intervals.

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Table 9: BESS impact on Energy consumption cost [€]

Scenario	Low RES		100 % RES increase		200 % RES increase	
Costs [€]	Original	BESS	Original	BESS	Original	BESS
Off-Peak Tariff	11658.3	15667.3	11114.1	14888.1	10571.8	14209.7
Peak Tariff	19634.0	15498.2	17540.0	13524.4	15453.4	11517.2
Total cost	31292.2	31165.4	28654.1	28412.5	26025.2	25726.9
Profit [€/year]	126.8		241.6		298.4	

As the results in Table 9 show, the BESS impact on the yearly energy cost is very small. This is a result of several factors, both technical and economic. BESS efficiency factors are highly impacted by the auxiliary power consumption of the unit for the needs of an HVAC system. In addition to charging and discharging round-trip efficiencies, auxiliary consumption was also considered in the technical simulations. If BESS could achieve a higher overall efficiency ratio, the energy difference between high and low tariff time intervals would increase together with the economic profit of the operation. The second option, which would enhance the BESS impact on the overall economic situation is market-specific, namely the price difference.

Figure 19 presents sensitivity analysis results. The increased price difference of only 0.015 €/kWh from existing prices would result in 1000 €/year energy cost reduction.

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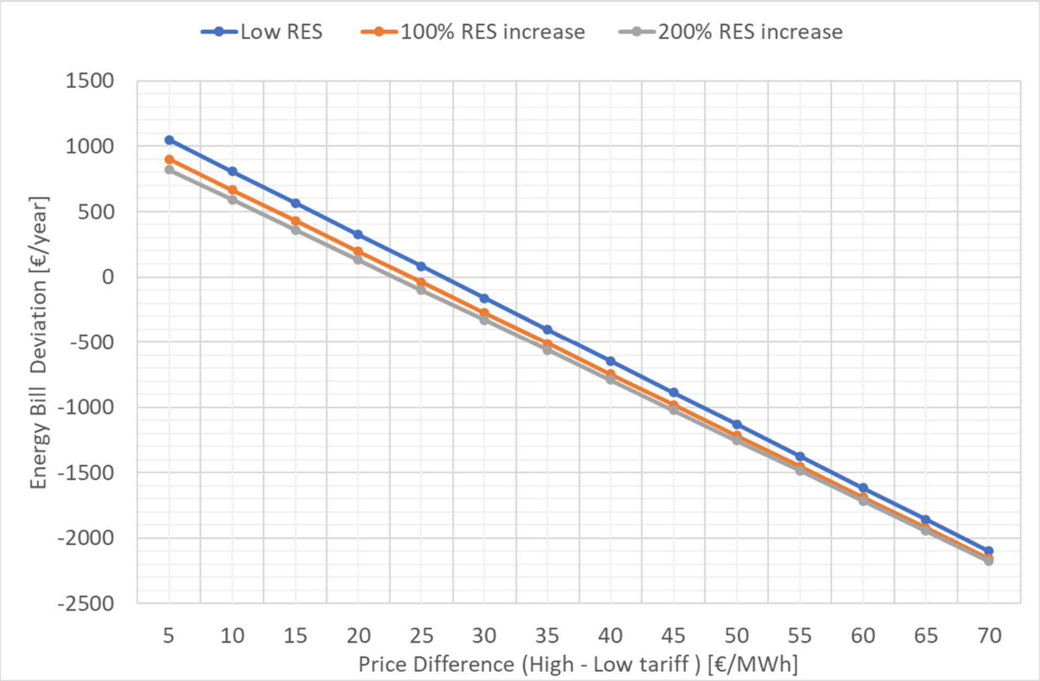

Figure 19: Energy Cost deviation due to BESS load shift and price difference

Since the existing end user energy prices do not present favourable situation for BESS investment to use it for energy shifting no further economic evaluation for this demo was investigated (IRR and NPV as in other demos)

4.2.5 Synthesis

The EG HQ BESS implementation aimed to utilize the BESS flexibility as a load shifting mechanism for the daily load profile which benefits from price differences of a two-tariff price system of an industrial user. The main assumption was that the profit is generated by price arbitrage between the two price levels. With the assumed realistic price levels of the two tariffs in Slovenia, BESS could be generating very small profit this way. The profits could be increased either if the BESS system achieved higher round-trip efficiency rates or if the electricity market conditions became more favourable with a higher price difference between high and low tariffs. An already existing alternative would also be an operation on other markets where energy stored in BESS could be sold at a better price,

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e.g. ancillary services – especially secondary and tertiary reserve market, where annual income of the owner increases, as already presented in the economic analysis of Suha demo in Chapter 4.1.4

4.3 Oud-Heverlee residential buildings – heat pump control

The demonstration setup consists of 4 residential buildings at Oud-Heverlee, Belgium. These houses have been equipped with smart appliances, which offer the potential to use thermal storage capacity of the buildings (boiler, heat pump). Table 10 gives an overview of the demo use cases. In this section, results from the demonstration will be presented.

Table 10. Overview of the technical characteristics of the demo

Model	State variable	Storage capacity	Boundaries
HP - house 4, 3 & 2	Inside temperature	Building thermal mass	Temperature comfort
Boiler - house 4	Water temperature	Thermal mass	Temperature comfort

Scenario and use case definition

The aim of this demo is to test the impact of dynamic pricing, i.e. the response of appliances to hourly day-ahead market price of Belgium. Control devices are installed to influence their state (e.g., ON or OFF) and allow for remote control. An optimisation algorithm has been designed to shift consumption to hours with low energy costs. In order to compare the behaviour of the houses under the control (Control case) to days without control (Base Case), 5 periods with days with similar characteristics have been defined (Period 1/3/5 – 20 days, Period 2/4 – 8 days).

Table 11: Control and base period definition

Period	House	Storage	Optimized load
1 & 2	4	Boiler	Electric water boiler
3 & 4		House	Heat pump
5	3	House	Heat pump

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4.3.1 Technical results

Table 12 presents the results of the demonstration set up regarding the energy shift. The boiler shifts 40% on average of the daily consumption. The heat pump of house four is shifted 10% and house 3 is shifted 14% on average of the daily consumption. Shifts occur mostly in the morning before 6 am for all periods.

Table 12: Energy shift results

Period 1 & 2	Boiler	40 %	Shifted mostly in the early morning (<6 am) except after water draws
Period 3 & 4	Heat pump	10%	Partly in the morning (<6 am) – 5%, partly in the late evening (>8 pm) – 5%
Period 5	Heat pump	14 %	Shifted mostly in the early morning (<6 am)

Figure 20,Figure 21 and Figure 22 show the daily energy consumption for the control and the base case for the different periods.

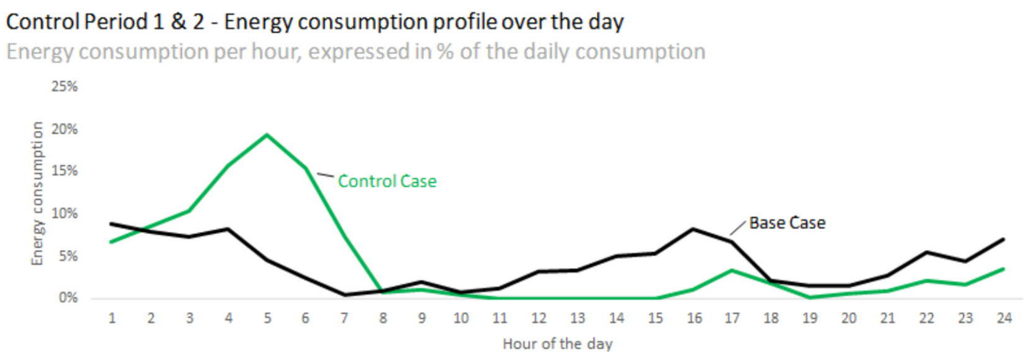

Figure 20: Daily energy consumption for control period 1 and 2 (water boiler)

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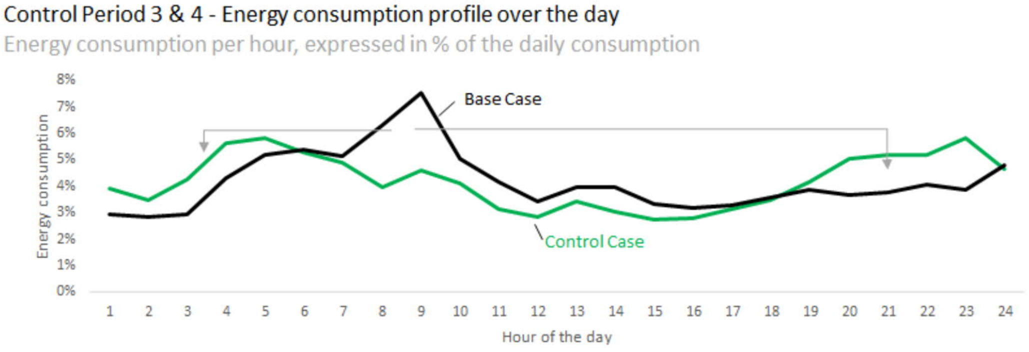

Figure 21: Daily energy consumption for control period 3 and 4 (heat pump)

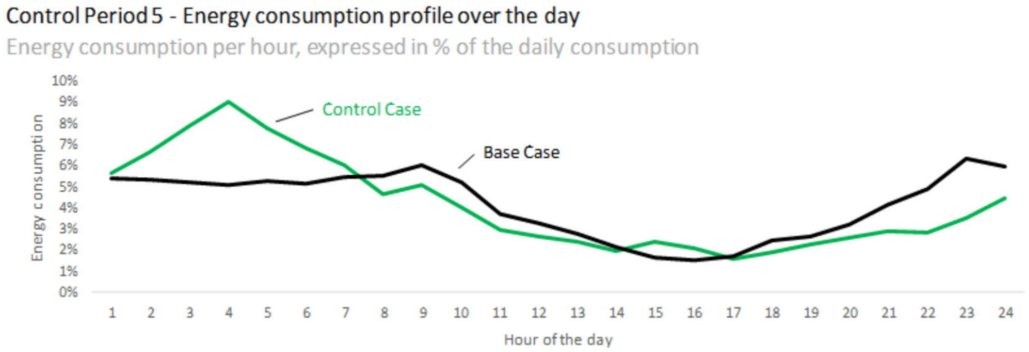

Figure 22: Daily energy consumption for control period 3 and 4 (heat pump)

These shifts also entail a change in the water/room temperature. The water boiler shows a reduction of temperature from 54 °C to 44°C on average. The room temperature in the control periods 2-4 shows an increase of 0.5 °C in the control case. The temperature in Period 5 does not change.

The self-consumption level (SCL) and self-sufficiency level (SSL) are assessed for house 3, which is the only house with PV production, referring to how much energy the house can self-supply. Figure 23 presents the SCL and the SSL for the base and the control case. In both a small relative improvement is visible, SCL +1.21%, SSL +4.17%. The reason for that is that even though energy consumption is mostly shifted to the early morning without PV production, the PV still covers part of the load during the day. For

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example, the energy is sourced from hours before 11:00 or after 20:00 where there is little PV generation. Furthermore, consumption tends to increase from 13:00-17:00 where PV generation is high.

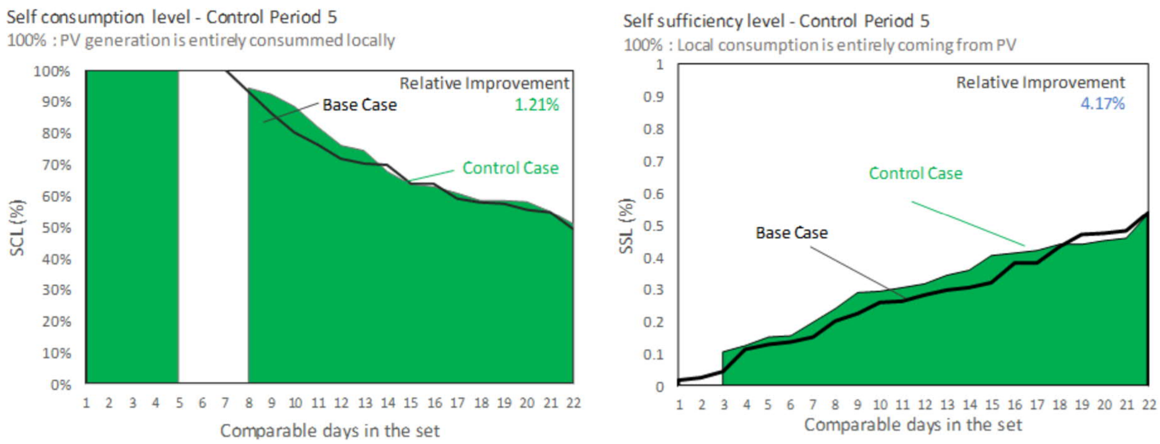

Figure 23: Self-consumption and self-sufficiency level in the control and the base case

4.3.2 Greenhouse gas impact

The calculation of the climate impact is based on a comparison of the CO_{2eq} emissions of the baseload emission and the actual CO_{2eq} emissions/kWh. The CO2eq emissions of the Belgian electricity system are modelled based on publicly available data of production per fuel (largest units)[1] as well as some typical CO2eq. emissions per generation technology.[2] The relative reduction is caused by the hourly variation in CO2eq. emission factors of the generation mix and the potential increase of locally used PV energy.

[1] http://www.elia.be/en/grid-data/power-generation

[2] Source : Tranberg, B., Corradi, O., Lajoie, B., Gibon, T., Staffell, I. and Andresen, G.B., 2018.

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Table 13: Change of emissions for different periods.

Period	Base case	Control case	Relative change
1-2	96%	92%	-4%
3	102%	101%	-0.93%
4	98%	96%	-2.35 %
5	99%	96%	-2.41%

The results show reduced emissions for all periods. Reductions are higher for periods with higher control capability (1,2 and 5). The driver for the reduction of emission is the Belgian fuel mix, which is in general less carbon-intensive at night due to the use of nuclear power.

4.3.3 Economic impact

Table 14 presents the cost reduction, which can be attributed to the control for the 5 periods. The results are in a range from 1% to 15%. The current price and taxation scheme in Belgium lead to insufficient revenues to create a viable business case at the household level. The energy price for residential consumers consists of two tariffs, peak and off peak and does not currently reflect the variations in electricity market prices. Furthermore, the energy price comprises a small part of the total cost for electricity, where taxation and fixed costs represent over 70% of the total expense. Therefore the economic impact of peak shifting at a residential level is limited in cases where it is not aggregated.

Table 14: Cost reduction in the different periods

Period	Cost reduction
1	14.5%
2	2.6%
3	4.3%
4	0.9%
5	6.3%

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4.3.4 Synthesis

The demo shows a potential to shift energy consumption from peak periods to off-peak periods. The potential to shift consumption to hours when there is PV generation leads to a modest decrease in emissions due to electricity fuel replacement. Economically, the demo creates value for the storage owner by reducing the energy bill due to shifting from peak price periods to off-peak periods.

4.4 Oud-Heverlee Community battery

In this case a community battery was installed to stabilize the voltage in the neighbourhood. The neighbourhood battery is a Lithium polimer ABB battery of 80 kWh and 80 kW capacity. The design and implementation of the battery is collaboration of Th!nk E, ABB, Enervalis, Imtech Belgium and Fluvius, (DSO). Due to lengthy preparatory procedure, the conditions for the neighbourhood battery were only met at the end of 2019. The neighbourhood battery was installed and started operation in March 2020. The neighbourhood battery aims to control voltage variations and improve power quality. To assure the safe functioning of the battery in the distribution network safety relay and power quality meter are installed.

The concept of the neighbourhood battery has been discussed and analysed from a technical and economic perspective over the past few years. However, this installation represents the first installed neighbourhood battery in Belgium. Implementation of this installation represented a learning process for all involved stakeholders. Due to this, significant amount of time and effort was spent on raising awareness, discussion and knowledge transfer with various Flemish institutions. The implementation of the neighbourhood battery involved challenges with land use regulation, permitting process, defining electrical connection as well as appropriate electricity pricing.

In order to define optimal operation and electrical connection, good collaboration with distribution system operator (DSO) was needed. Being the first of such installations, the default procedure would have been to connect the battery as any other consumer. However, such connection would limit the potential benefits from the battery installation.

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The focus with the DSO was on the balance of encouraging a grid-supporting behaviour on one hand and restricting potential actions with unintended impact on the other hand. Due to the fact that the distribution line in Oud Heverlee neighbourhood has already been used to the maximum of its capacity, measured voltage variations could be used as a good indication of the actual load or injection on the line. The battery is to compensate for low voltages with discharging and for high voltages with charging. The DSO therefore developed a clear and logical addendum to the connection contract, emphasizing the need for grid-support in the operation of the neighbourhood battery.

4.4.1 Technical results

4.4.1.1 Battery Operation

Figure 24 shows the battery power profile (top) from March to October 2020 and the battery phase voltage (bottom) for the same period. The battery operated mostly normally from March to June, suffered some difficulties over the summer, and resumed normal operation in October.

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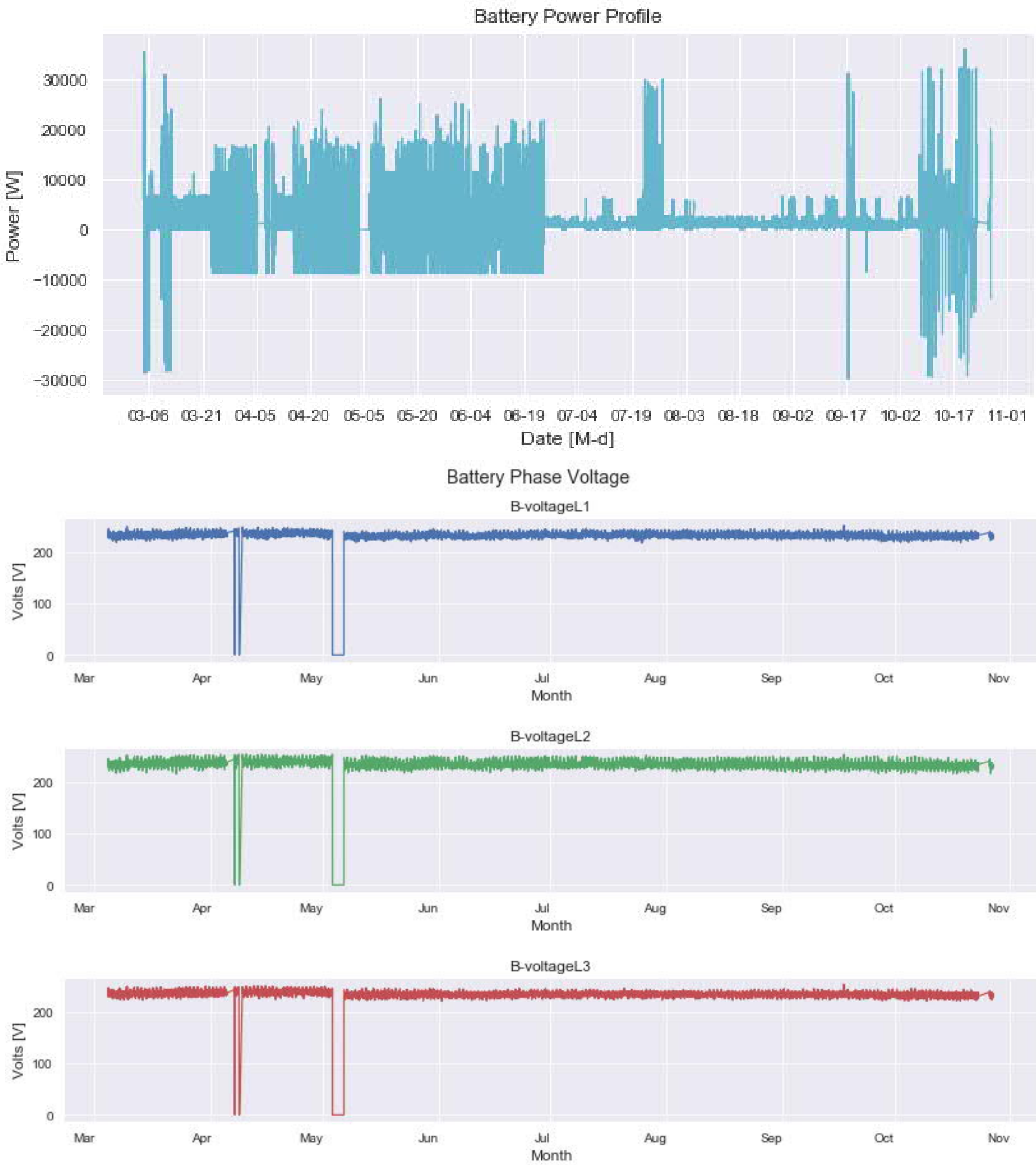

Figure 24: Battery power profile and phase voltage from March to October 2020

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4.4.1.2 Voltage Control

To assure power quality of the distribution line is maintained using the neighbourhood battery, EN 50160 Standard on Voltage Characteristics in Public Distribution Systems was followed. Therefore the battery control had to respect the voltage requirements given in Table 1.

Table 1. Voltage requirements based on EN 50160

Voltage magnitude variations		
Mean 10 min rms values	± 10 %	95% of time
Mean 10 min rms values	85.0% ≤ x ≤ 110.0%	100% of time
Voltage unbalance		
Mean 10 min rms values	x ≤ 2.0%	95% of time
Flicker severity		
Flicker Plt mean for 2h	x ≤ 1	95% of time
Total harmonic distortions		
Mean 10 min THD	x ≤ 8.0%	95% of time

To assure these requirements are respected, the following controls are implemented:

- No injection with high voltages
    - 230 V + 7% or 246 V
- No consumption with low voltages
    - 230 V – 7% or 214 V
- If approaching the limit of 93%-107% mean 10 minute rms values, the load is kept the same and not suddenly changed.
- When the values of voltage on the grid change, the load will be adapted slowly.

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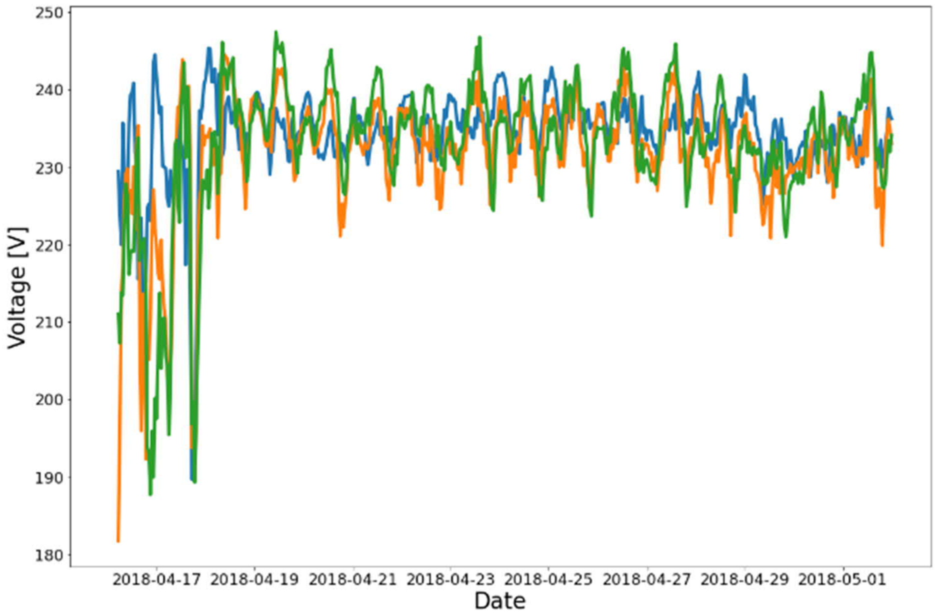

Figure 25: Example of voltage variations on three phases (blue, green, orange) of the distribution line in Oud Heverlee in April 2018

The neighbourhood battery has been installed in March 2020 in Oud Heverlee. Implementing the low level control based on the voltage measurements has been shown to be successful in improving the power quality of the distribution line.

While, through the STORY project there are measurements of the line voltage in the Oud Heverlee neighbourhood for the period from 2017 to mid 2019, it is important to mention that the time resolution of these measurements is on hourly basis and with time interruptions for the mentioned period.

In order to show the difference in the distribution line power quality before and after the neighbourhood battery is installed, voltage measurements of the three phases for April 2018 are presented in Figure 25. Analysis of the voltage variations show that due to the use of multiple high loads (EV charging at the same time), there is a decrease in the line voltage below the allowed deviation of 10 % from nominal level. Such situations could lead to power supply interruptions for the neighbourhood.

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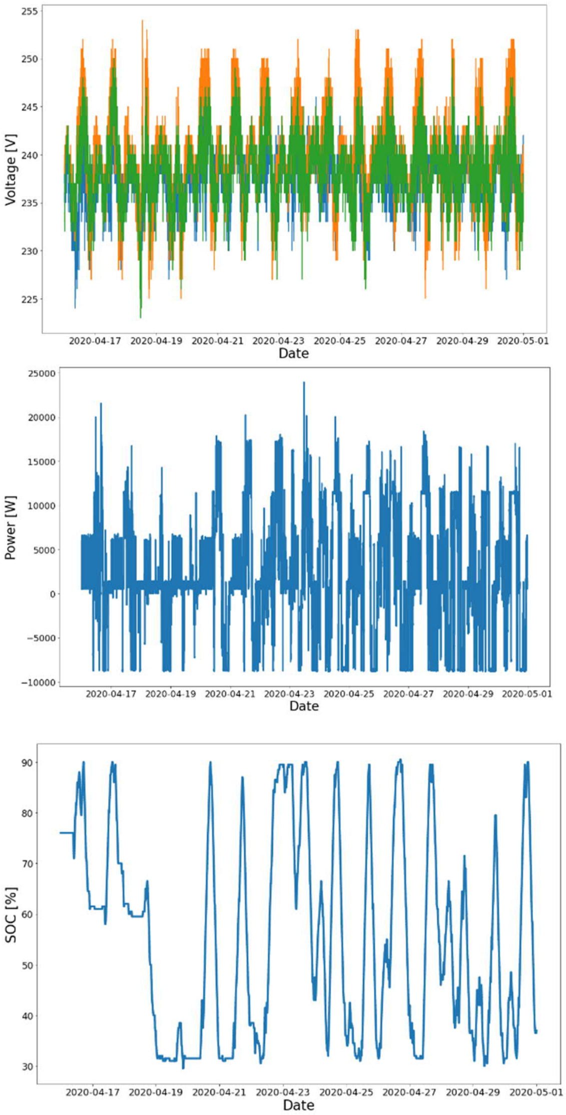
Installation of the neighbourhood battery improved the power quality of the line, as can be seen from example voltage variation for three phases for April 2020, Figure 26.



a)

b)

c)

Figure 26. Voltage variations on three phases (blue, green, orange) of the distribution line in Oud Heverlee, b) neighbourhood battery charging and discharging behavior and c) battery state of charge in April 2020, after the neighbourhood battery has been installed.

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As can be seen from Figure 26 a) the implemented control keeps the line voltage within 10 % variation from 230 V. In cases when the voltage decreases to – 7% the battery is activated to discharge Figure 26 b) and SOC decreases (Figure 26 c). On the other hand as the line voltage increases to + 7 % of 230 V, or to 246 V, the battery is used for charging and SOC increases. Based on the variation in the state of charge it can be seen that the sizing of the neighbourhood battery is optimal for the Oud Heverlee application.

4.4.2 Economic impact

The main contribution of the battery to the network is in terms of voltage control. This however, is as yet a non-remunerated service. A standard low voltage connection with over 10 kW injection power has a separate supply and injection tariff. The supply tariff includes the price for energy used, DSO and TSO grid costs and all charges and taxes (including societal contributions). In contrary to this, the injection tariff includes only what the electricity supplier is willing to pay for the energy that is injected in the grid. In practice, this implies that around 0.28€ is to be paid for every kWh that the battery takes from the grid, while only about 0.04 € is received for every kWh injected back into the grid.

Services that the Neighbourhood battery can offer to the grid are not yet remunerated. The European Clean Energy Package foresees such services and market to be established. With such markets there are possibilities for price signals based on the local grid needs.

Figure 27 shows the energy injections and withdrawals made by the battery (top) and the corresponding injection income and withdrawal cost per month. It is worth noting, that much of the energy injection made by the battery is done in short duration bursts that are noticeable on the power measurements in watts, but are not visible once the energy calculations in kWh are performed. The income is based on measured kWh, which is an average of the power measurements per hour. Injection of energy into the grid occurs, but is not always visible in terms of energy and therefore not remunerated.

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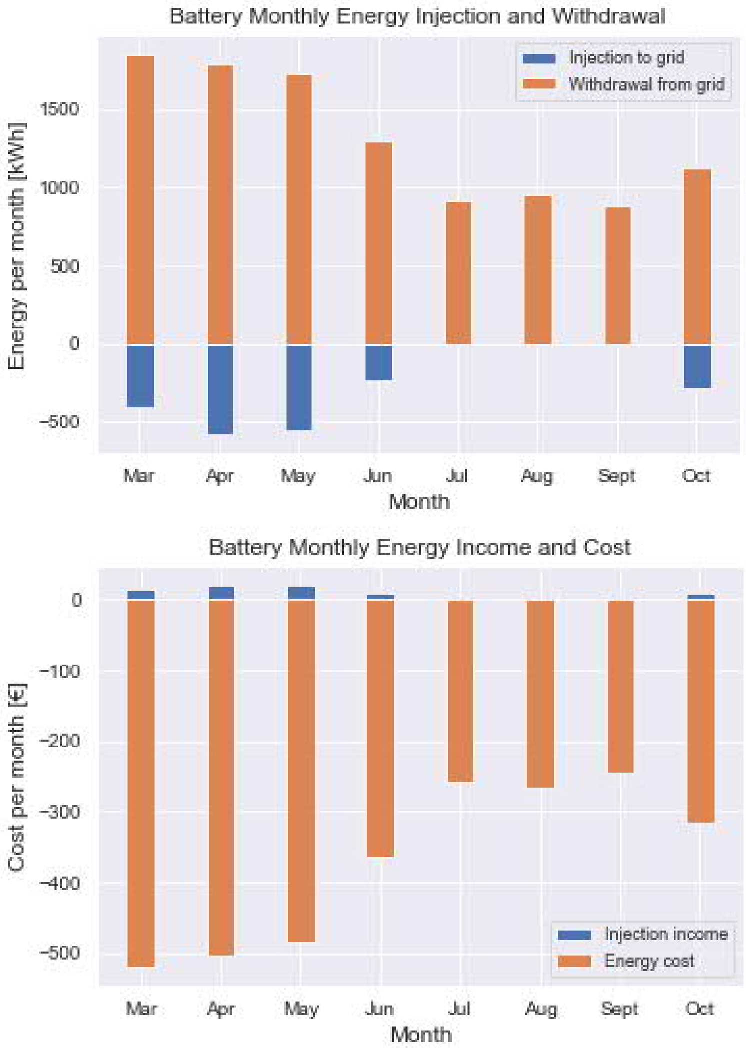

Figure 27: Battery Energy injection and withdrawal (top) and battery energy in revenue and cost (bottom).

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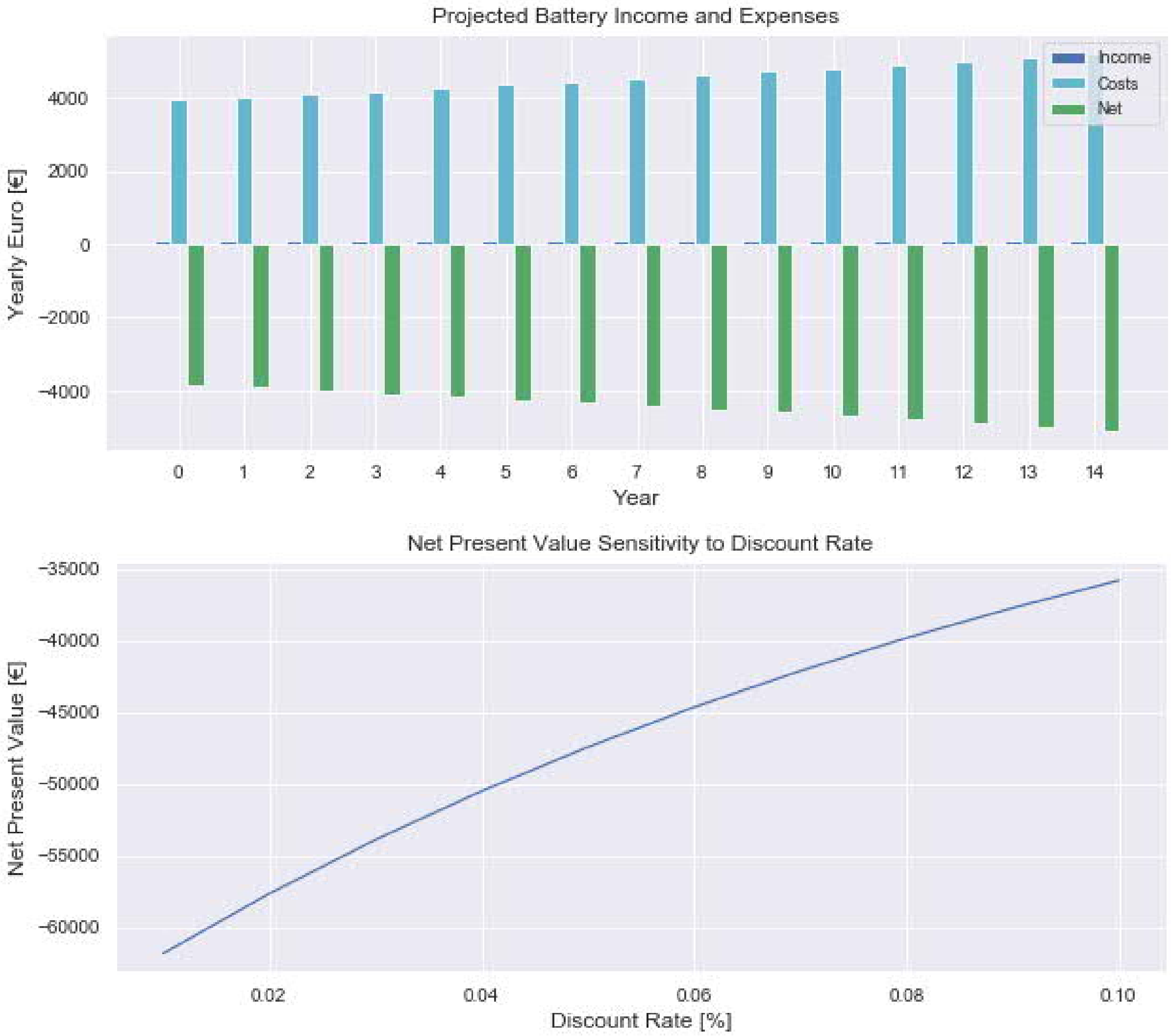

Figure 28: Projected Cashflow [top] and Net Present Value sensitivity to discount rates.

Figure 28 [top] outlines the projected cashflow assuming a 2% increase in energy costs and income over the 15 year lifetime of the battery. The bottom part of the figure presents the net present value sensitivity to different discount rates.

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The overall result is negative due to two main reasons: 1/ the main service that the battery can provide is voltage control which is not remunerated at the moment; 2/ The revenue that can be received for injection is fixed, and most often below the energy market price. If the energy sold by the battery had access to the electricity market, and could be used for market arbitrage through bidding strategies, perhaps the income could be positive.

4.4.3 Synthesis

The complex installation procedure as well as the comparison of the price of the battery to the distribution line improvement makes for a non-optimal busines case. Oud Heverlee neighbourhood presented here is an ideal case of weak distribution line where installation of the Neighbourhood battery can lead to improved end of line power quality and potential for increase in flexible technology installation (renewable energy, EVs etc.). DSOs need to evaluate whether procuring voltage services from storage during a few hours a year is a good alternative to building permanent line infrastructure.

4.5 Exkal factory

In the EXKAL demonstration a lithium-ion battery (200 kWh/50kW) has been installed in addition to the already existing PV panels on the roof of the factory (113 kWp). The tariff structure in Spain includes a significant capacity charge (euro/kW) and therefore the initial aim was to use the battery to decrease the peak power of the factory. Secondly the goal was to reduce the electricity bill by optimizing the PV consumption in the highest tariff hours. To achieve the aforementioned goals the following strategy has been implemented.

Generated electricity is primarily used to cover the current load. If the load is covered, excess electricity is fed into the battery until the SOC_{max} is reached. If regulations allow the battery can also be charged from the grid in low tariff hours. If production cannot cover the load, electricity is discharged from the battery or the grid depending on the SOC and the tariff period. Losses of the battery are included in the efficiency.

Due to the Spanish legislative framework it was only made possible throughout the project to exchange electricity from the battery with the grid. For this reason the analysis is based

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on available data for the year of 2019, as it was already allowed to exchange energy with the grid. Data regarding the PV production and the load of the factory was used in hourly resolution.

Scenario and use case definition

To assess the technical, economic and the climate impact of the EXKAL demonstration case we defined four different use cases:

- **UC0: no PV, no battery**: In this use case the electricity demand of the EXKAL factory is covered by electricity from the medium voltage grid only. It is a reference case showing the situation without the existing PV panels and battery.
- **UC1: PV**: In this use case the electricity demand of the EXKAL factory is partly covered by PV panels installed on the buildings of the factory. Surplus electricity from the PV panels is injected into MV grid. The remaining electricity demand from the factory is covered from the MV grid. It shows the situation before the implementation of the battery on the demonstration site.
- **UC2: PV+battery (no charging from grid)**: In this use case the electricity demand of the EXKAL factory is partly covered by PV panels. Surplus electricity from the PV panels is stored in a battery and used at peak times and at times with high grid electricity costs. If the battery is fully charged surplus PV electricity is injected into the grid. The remaining electricity demand is covered from the MV grid. In this scenario the battery is only charged with PV electricity. Charging of the battery with grid electricity is not possible. This reflects the legal situation at the demonstration site during the first operation phase of the battery.
- **UC3: PV+battery (charging from grid)**: This use case is very similar to use case 2. The only difference is that in this use case it is possible to charge the battery with grid electricity. It reflects the situation at the demonstration during the second operation phase of the battery, after a change in legislation.

4.5.1 Technical results

Table 15 presents energy flows for the three use cases. The total energy consumption is 485 MWh/a and the PV production is 171 MWh/a for each use case. It is shown that a battery allows to locally consume a higher share of PV energy and therefore to reduce

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the need for grid exchange. If the battery cannot charge from the grid (UC2) more PV energy can be stored within the battery than in UC3 where part of the battery capacity charged from the grid. In UC2 and UC3 the battery is used infrequently, only for peak shaving, and therefore the impact on the overall grid consumption is relatively low.

Table 15. EXKAL energy flows

Energy (MWh/a)	PV energy locally consumed	Energy from MV grid	Local energy injected into MV grid	Energy stored in battery from PV	Energy stored in bat. from MV grid	Energy injected from bat. into LV grid	Bat own con-sump-tion
UC0: no PV, no battery	-	485	-	-	-	-	-
UC1: PV	138.7	346.2	32.3	-	-	-	-
UC2: PV + battery (no charging from grid)	149.2	341.5	21.9	28.8	-	23.3	5.6
UC3: PV+battery (charging from grid)	148.9	340.5	22	10.2	13.6	19.2	4.6

4.5.2 Greenhouse gas impact

Using a Life Cycle Assessment (LCA) we investigated the climate impact of four use cases for the EXKAL demonstration case. Figure 29 shows the annual GHG emissions for the four investigated use cases for the EXKAL demonstration case. The figure includes the total annual GHG emissions, GHG emissions from PV plant manufacturing, battery manufacturing, electricity consumed from the grid and electricity supplied to the grid.
If the PV generation level on site covers all demand and the surplus energy can neither be consumed nor stored it is injected into the grid. This energy flow affects the electricity generation in the network and electricity generation by other power plants can be

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replaced. Therefore, the GHG emissions for electricity supplied to the grid are negative. In Figure 29 the Spanish electricity mix was used for consumed and replaced grid electricity.

The highest GHG emissions are in UC0, where the total electricity demand is covered by the grid. By adding the PV plant in UC1 the annual GHG emissions are reduced from 104 to 76 t CO_2-eq. Adding a battery to the system (UC 2 and 3) slightly increases the annual GHG emissions to 79 t CO_2-eq. The battery leads to a small decrease in GHG emissions for consumed grid electricity. But it also reduces the replaced GHG emissions from surplus PV injected into the grid and adds GHG emissions from battery manufacturing.
We could not find a difference in GHG emissions, whether the battery is only charged by PV or also by the grid. UC2 and 3 are very similar in the amounts of electricity consumed from the grid and electricity injected into the grid. However, times of consumption and injection are different and were included in the assessment by using hourly emission factors (EF) for grid electricity. However, the influence of these hourly EF is too small to be reflected in the results. Overall, the battery changes the energy flows of the system only to a very small degree and therefore the GHG emissions of UC1, UC2 and UC3 are very similar.

This can also be seen in Figure 30, where the specific GHG emission per MWh electricity demand of the demonstration site are displayed. UC0 has the highest specific GHG emissions with 214 kg CO_2-eq/MWh. UC1, with PV electricity has lower specific GHG emissions with 156 kg CO_2-eq/MWh. Adding the battery to the system increases the specific GHG emission to 162 kg CO2-eq/MWh in UC2 and UC3.

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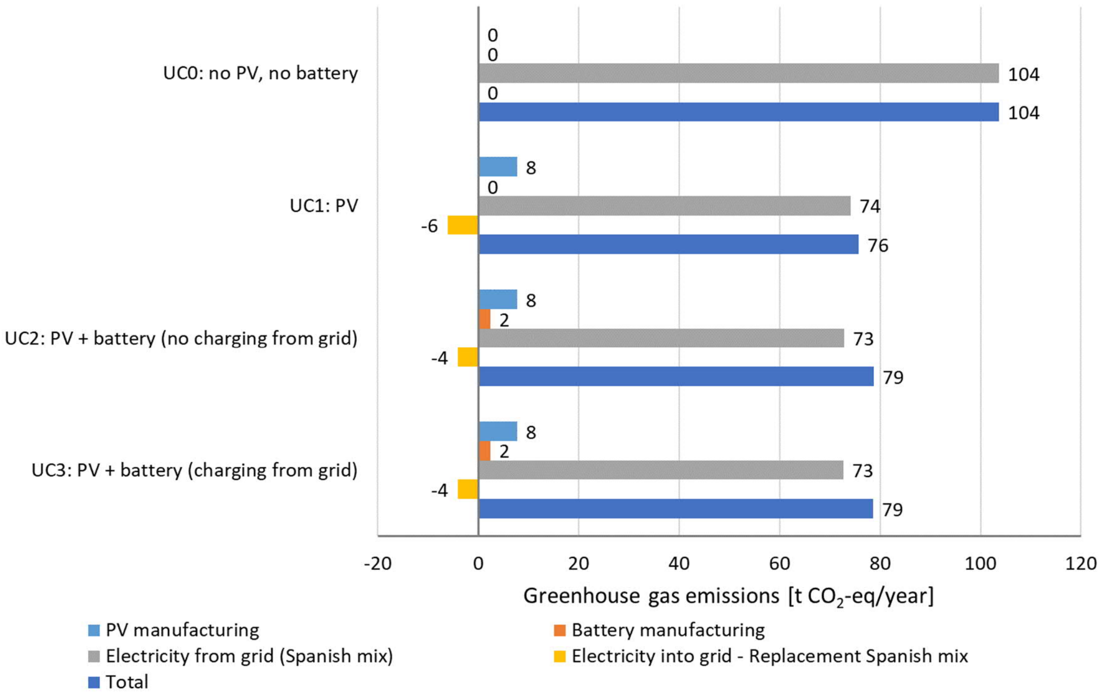

Figure 29: Annual greenhouse gas emissions for 4 use cases for the Exkal demo case (Spanish grid mix for consumed and replaced grid electricity)

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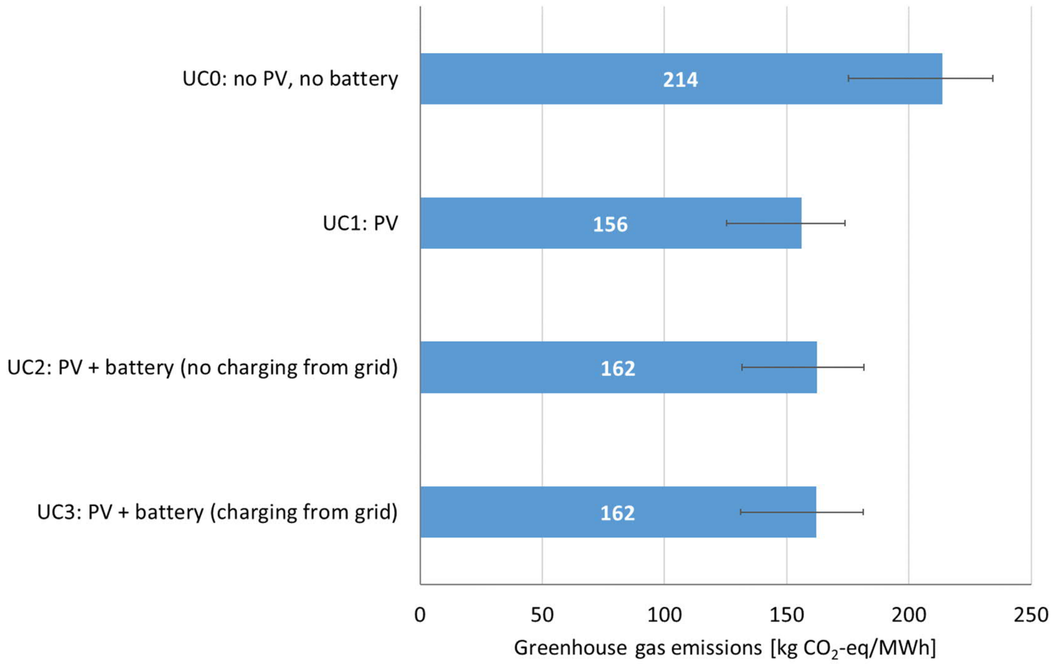

Figure 30: Specific greenhouse gas emissions for 4 use cases for the Exkal demo case (Spanish grid mix for consumed and replaced grid electricity)

4.5.3 Economic impact

The economic assessment focusses on the main aim of this demonstration: peak demand charge reduction. Table 16 presents the results for the three different use cases. It is shown, that in the winter months, solely PV implementation does not decrease the peak power demand charge. This is due to the time of the high tariff period, which starts at 17:00 and does therefore not coincide with PV production. The addition of a battery allows to store the surplus electricity from midday and use it later during the high tariff period and therefore enables a 6% reduction in the maximum power and also in the costs. In the summer/fall two different behaviours are visible. Until the end of October the high tariff period is from 10:00 to 16:00 and can hence be covered quite well by PV production. In this case battery implementation stores electricity from PV to use it later during the off-peak periods, which decreases electricity costs.

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Table 16: Demand charge reduction in the different use cases

Demand charge reduction	Jan	Feb	Mar	Average reduction	Sept	Oct	Nov	Average reduction
UC 0(€)	384.44	367.34	429.87		365.00	447.13	486.00	
UC 1 (€)	384.44	365.56	428.77	-0.24%	264.47	353.26	488.34	-14.80%
UV2 (€)	355.95	357.45	398.91	-5.87%	316.13	359.10	488.34	-10.37%

Figure 31 presents the total energy costs for the three use cases, The blue bar represents the case without a PV system and without a battery. It is visible that PV implementation (orange bar) decrease the energy costs significantly, especially in the summer months the impact of PV implementation is much higher than the impact of storage, which is mostly beneficial in months where PV production and the high tariff period do not coincide. It should be noted however that the impact of the battery has been drastically penalised by the low availability suffered due to technical difficulties with the battery system and slow response times of the technology provider.

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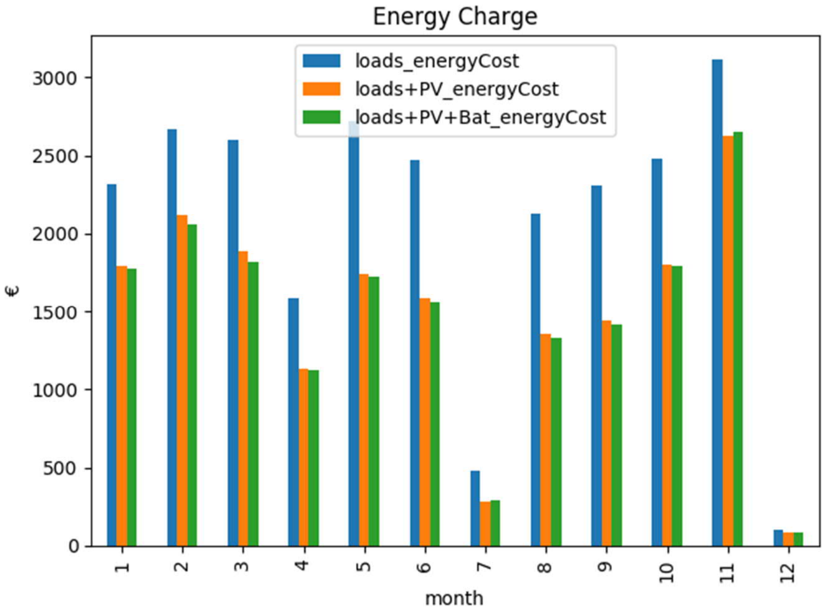

Figure 31: Total Energy costs over one year for the three use cases

4.5.4 Synthesis

It is shown that the demand charge is significantly reduced by PV implementation, while storage is mostly useful in winter to shift excess PV energy to high tariff times. However, this use case does not yet provide a positive business case. A similar picture is painted in regard to GHG emissions which increase to a small extend as well compared to only injecting PV into the grid.

4.6 Beneens multi-energy grid

At Beneens factory a 1.6 MW_{th} wood-fired boiler in combination with a 90 kW_e Organic Rankine Cycle was installed (ORC). Furthermore a large storage vessel of 50 m^3 for the medium temperature circuit as well as a 20m^3 storage vessel for low temperature heat was set up. The high-temperature heat (145 ℃) produced by the boiler is used in two ways: on the one hand to produce electricity by the ORC; and on the other hand, this high-temperature heat is transferred to the medium temperature circuit (90 ℃) via a heat exchanger and stored at the medium temperature storage tank for further use for space

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heating (offices and the workshop) and for industrial processes in the painting and drying cabinets. Additionally, low-temperature (45 ℃) heat available from the ORC condenser can be stored in the low temperature storage tank and further used on site for space heating. Moreover, excess low-temperature heat is stored in a low temperature storage tank cooled off using a cooler. The electricity produced is either used directly on site or stored in batteries for later use. Any surplus is sold back to the grid.

The demonstration focusses on the efficiency enhancement and active control of the ORC though the use of thermal storage, energy consumption cost reduction, a reduced peak power demand. The system allows for heat of the wood boiler to be used mainly for the ORC to produce electricity when the tariffs are high. In periods of low tariffs, the heat can be shifted to the high temperature circuit and the storage tank.

4.6.1 Technical results

The technical results examine the increased RES use, increased self-consumption, relative peak power change and the heat coverage due to storage implementation. Table 17 presents the technical results for the demonstration case with a storage unit. Storage implementation does not have significant impact on most of the technical parameters if only the Beneens site is considered. The use of low temperature heating however led to a reduction of 24% in the distribution heat losses. These results show that with the current installation, an extra thermal consumption up to three times the current consumption, with a similar profile, can be added without the need to upgrade the installation increasing the RES use of the industrial site in case a district heating network to nearby companies is installed.

Table 17: Technical results for the demonstration case in comparison to a base case without storage

Increased RES use	+0,59%
Self-consumption level	+0,45%
Self-sufficiency level	-0,85%
Relative peak power change	1,8%
Heat coverage increase	+0,6%
Distribution heat losses	-24%

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4.6.2 Greenhouse gas impact

To assess the climate impact of the Beneens demonstration case, it is compared to two reference cases, one case producing heat with a natural gas boiler and another reference with a wood boiler. As the demonstration case and the reference case must have the same output, the additional heat and electricity, which is generated in the waste CHP plant in the reference system, also needs to be considered in the demonstration case. For the electricity, we assume that it is supplied by the power grid and for the heat that it is provided by a natural gas heating plant.

Figure 32 shows the annual GHG emissions of the demonstration case in comparison to the reference system with a natural gas boiler. The annual GHG emissions of the demonstration case are 1.5 kt CO_2-eq. of which only 0.1 kt are linked to the actual energy supply (electricity and heat) of the demo site. The remaining GHG emissions are from a natural gas heating plant and additional grid electricity to cover a comparable amount of heat and electricity as the references system using the waste wood. Reference system 1 has higher emissions related to the actual energy supply (grid electricity + natural gas boiler) but lower total GHG emissions due to lower emissions for the reference use waste wood, as the waste wood is used more efficiently in the large-scale waste CHP plant compared to the small-scale ORC unit. Here, especially the higher heat use in the waste CHP plant leads to these results.

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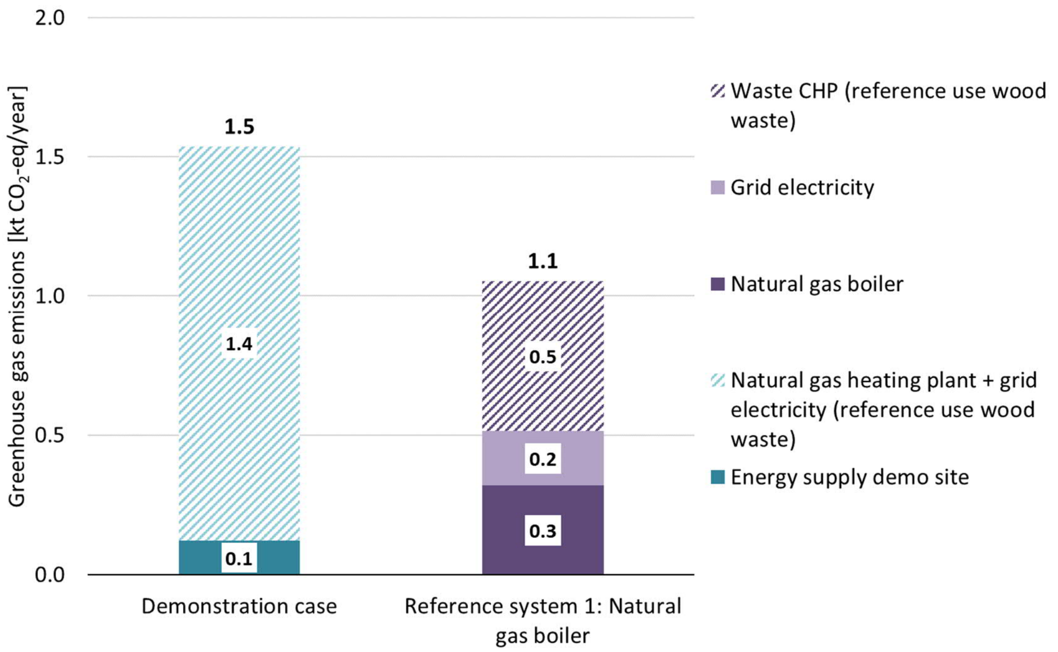

Figure 32: GHG emissions of the “Demonstration case” in comparison to the “Reference system 1: Natural gas boiler”

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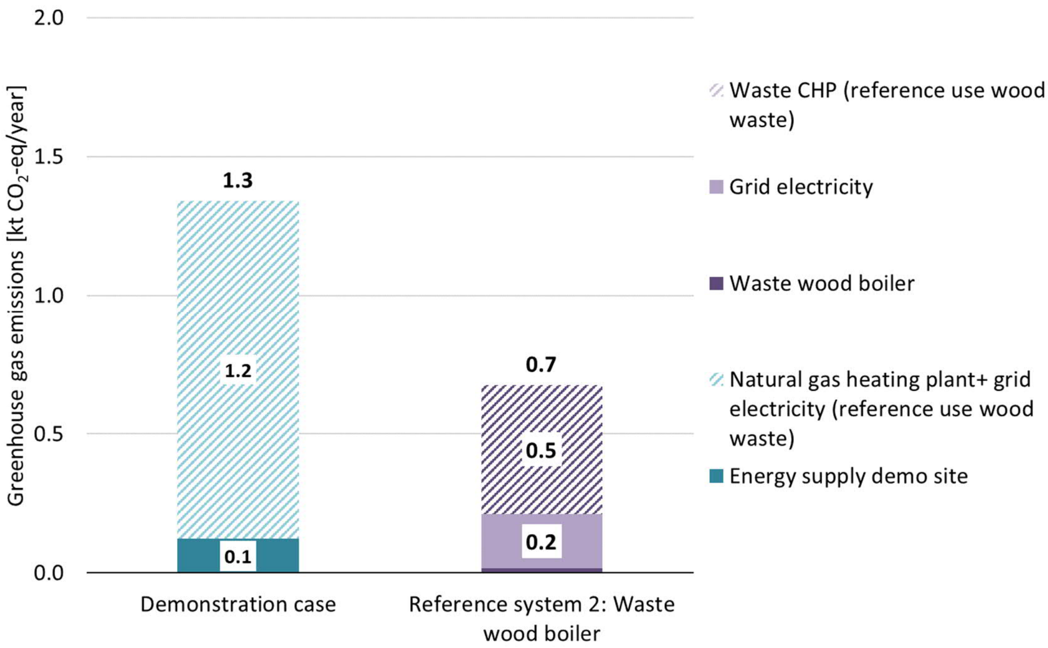

Figure 33: GHG emissions of the “Demonstration case” in comparison to the “Reference system 2: Waste wood boiler”

As the results in Figure 32 and Figure 33 show that the higher heat use in the reference system significantly influences the results, we performed a sensitivity analysis to investigate the influence of a higher heat usage in the demonstration case.

In the demonstration case the electricity production on site with the ORC leads to a high amount of low temperature heat, which is not used at the moment. There are plans for the future to expand the existing low temperature heating grid and to connect additional heat consumers. This will lead to a higher heat usage on the demonstration site.

The results of the sensitivity analysis are shown in Figure 34. The GHG emissions in the “Reference system 1: Natural gas boiler” raise, as more heat needs to be supplied by natural gas. It is expected that in the near future 527 MWh additional heat use is possible at the demonstration site due to the connection of new heat customers. At this point the

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“Demonstration case” has higher GHG emissions compared to the Reference system 1. However, the gap between the Demonstration case and Reference system 1 becomes smaller. At the point of 1 500 MWh/year additional heat use the “Demonstration case” and the “Reference system 1” have the same GHG emissions. If more than 1 500 MWh/year can be used, the GHG emissions of “Reference system 1” exceed the GHG emissions of the Demonstration case.

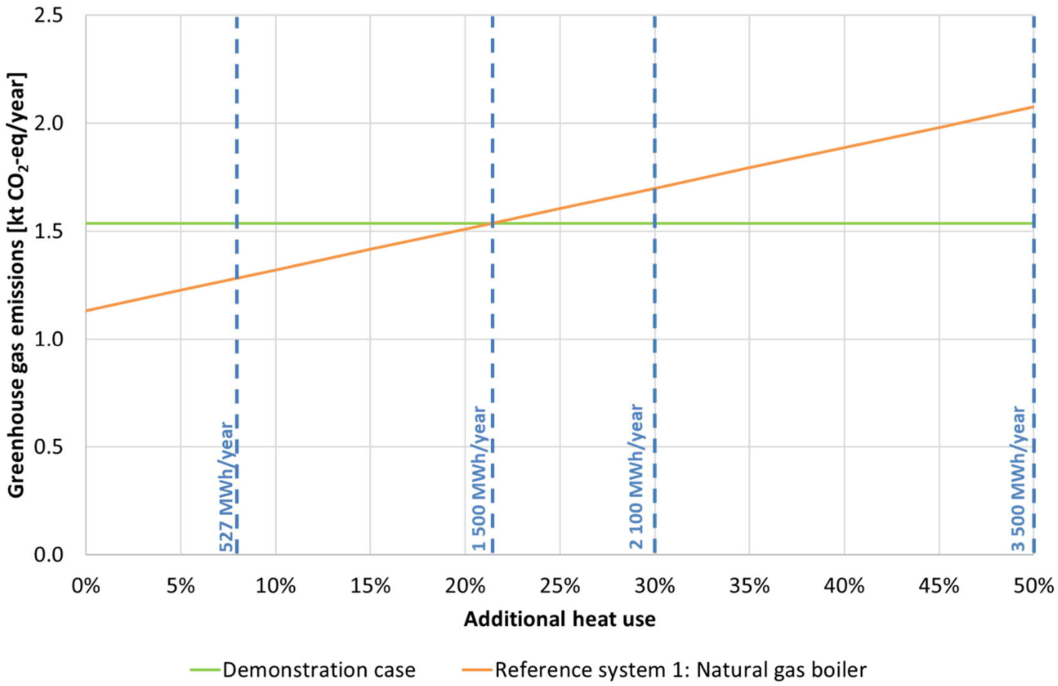

Figure 34. GHG emissions of the “Demonstration case” in comparison to the “Reference system 1: Natural gas boiler” for different amounts of additional heat use

4.6.3 Economic impact

The ORC investment was about 860 000€ and the extra cost for a compatible boiler for the ORC is 125 000€. O&M costs of 1% of the CAPEX were assumed. A WACC of 5% was chosen. Electricity is fed into the grid for market prices (0.0352€/kWh). There is the possibility to sell waste heat to neighbouring companies (approximately 527 MWh/year

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could be used) for which we assumed the gas price (0,036€). The thermal microgrid costs add up to 95 000€. This option is analysed as a sensitivity to the current demonstration set-up as this impacts the economic feasibility. The savings of the storage compared to a set up without storage is 92€/year[3], because heat can be produced during off-peak hours when heat and electrical demands are low, and then stored in the thermal storage to be used during peak hours. Therefore, more heat of the boiler can be directed to the ORC in high tariff hours to produce electricity that is locally consumed reducing electricity costs. Table 18 presents the net present value (NPV) and the internal rate of return (IRR) for the demonstration case. S1 considers the current demonstration case, in S2 a thermal microgrid is included where waste heat can be sold to neighbours. S3 and S4 look at the same scenarios but under the assumption that elec. can also be shared with neighbours for a price of 0,10€/kWh (this case is not allowed at the moment).

Table 18. Results of the economic analysis for Beneens

	NPV	IRR
S1 – current use case	-40 144 €	4.6 %
S2 – heat to neighbours	134 699 €	6.3%
S3 – electricity to neighbours	419 811 €	9.1%
S4 – heat and elec. to neighbours	594 656 €	10.3 %

The current NPV is negative, however, a small reduction in system costs (<5% of the total costs) would make this use case already economically feasible. The maximum heat that can be sold to neighbouring companies is 527 MWh/year, which would lead to an IRR of 6.3%. If all the waste heat could be sold the IRR would be 37.4%. If electricity could also be sold to neighbours the business case increases to and IRR of 9.1% for S3 and to 10.3% for S4.

[3] VITO: D6.1- Report Chapter on Private Multi-Energy Grid in Belgium Performance evaluation

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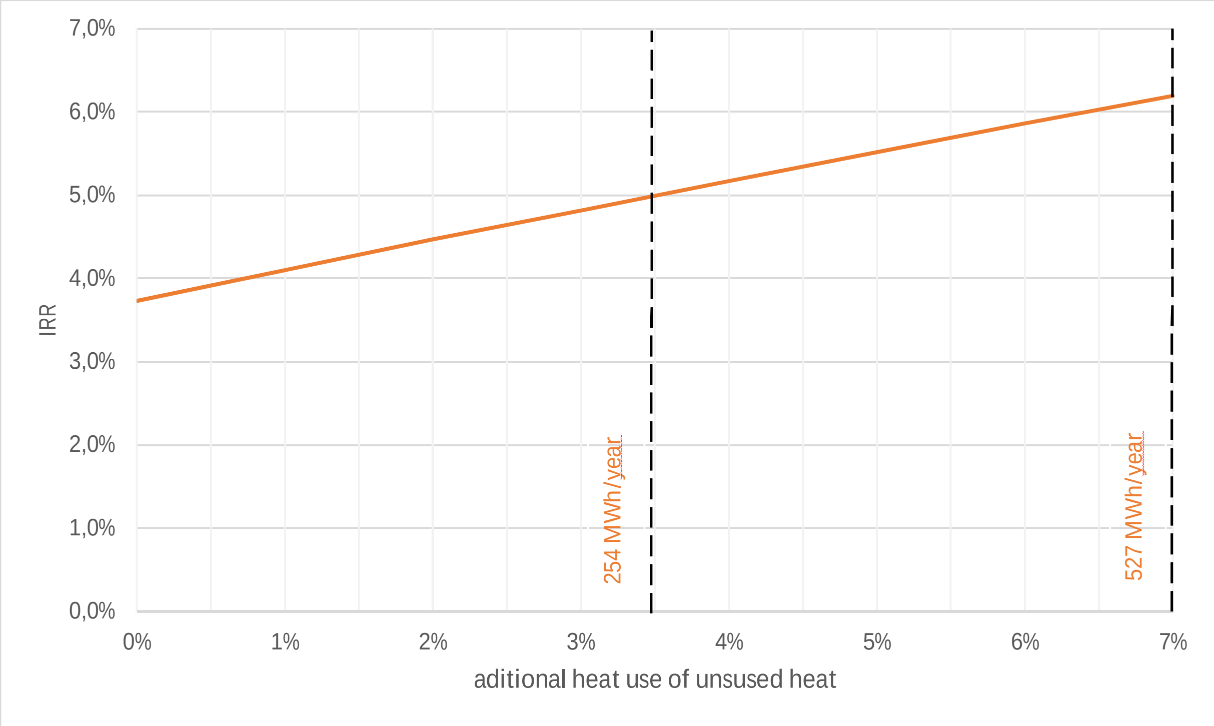

Figure 35: Sensitivity of additional heat use on the IRR S1/S2

4.6.4 Synthesis

The results of the environmental and the economic assessment show that only in case waste heat is used by neighbouring companies the system is better compared to the reference case from an environmental as well as from an economic point of view. Decreasing the amount of waste heat used from the CHP or decreasing the system cost of the demonstration set up improve the demonstration case, however, do not have an impact on the environmental nor the economic perspective.

A key parameter influencing both results is the possibility to further use the currently unused heat in the demonstration case. This is visualized in Figure 35. From an economic point of view 3% or 254 MWh/year of additional heat used, are sufficient to create a business case. Reasonably, 527 MWh/year could be sold to neighbours via implementation of a local heating network. This underlines the economic feasibility of the

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mentioned case. As for the environmental analysis, 1500 MWh/year of additional heat need to be further used to outperform the reference system. With this amount of heat being sold the IRR of the demonstration would increase to 11%. Therefore it is important to consider the overall benefits of a demonstration set-up, as otherwise there is a risk to create a business case that doesn't lead to decarbonisation.

It is further shown that the environmental assessment needs to consider entire energy system for viable results. If system boundaries were set on the demo level, the demo alone seems to be environmentally beneficial.

5 Evaluation and comparison of results

5.1 Technical Characteristics and results comparison

This section summarizes technical characteristics of the technology installed and the main technical outcomes of each demonstration of the STORY project. The information is presented based on availability, and is therefore more complete in some cases than others. Energy storage systems can be compared according to their characteristics in terms of capacity, rated power, efficiency, and life-cycle. In the STORY project different types and sizes of thermal and electrochemical storage units are installed. Table 19 presents an overview of the installed technologies in each of the STORY demonstration sites and their key characteristics in terms of capacity, rated power, efficiency and life cycle.

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Table 19: Technology characteristics installed in each demonstration in the STORY project

Demo	Installed technology	Capacity	Rated Power	Charging/discharging efficiency	Life cycle
OH Building	4 houses – boiler, heat pump				
OH Battery	Community battery	80 kW/80 kWh	80kW		
Olen	Organic Rankine Cycle		90 kWe,	90%	
	Wood boiler		1.6MW	86%	
	Storage vessel 50 m3 and 20 m3			75%	
Exkal	Battery	200 kWh	50 KW	80%	
	PV		113 kWp		
Suha	Industrial battery	320 kWh	170 KW	94% / 94%	
EG HQ	Industrial battery	320 kWh	170 KW	94% / 94%	

The technical results describe the outcome of each demonstration. They relate to the main findings as compared to a case where storage technologies were not installed using predefined KPIs (see Table 20). This section highlights the value for society of using storage in terms of allowing more renewable energy to be used by the system, a better use of the local distribution network and the potential for grid investment deferral created by the demos.

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Table 20. Technical results comparison

KPIs	OH Building	OH Battery	Exkal	Beneens	Suha			EG
					winter	summer	High RES scenario	
RES use change	✔	✔	✔	+0,59%			+75%	✔
Self-consumption change	+1,21%		+1,9%	+0,45%	98%	64%		✔
SSR	+4,17%			-0,85%	11%	44%		
Peak-to-average demand ratio			✔		8% + 83% -	55% + 55%-		✔
Relative peak power change			-5,5% winter +4,5% summer	+1,79%	3% + 82 %-	40% + 41% -		✔
Grid energy consumption			✔		-27,48%		-14%	✔
Voltage control		Voltage deviations limited to +/- 10% in the rural feeder.			50% reduction			✔
Zero Load Provision								✔

Table 20 presents a summary of the change in RES use, the change in grid power and the potential in grid investment deferral across some of the demonstrators. There have

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been other technical results such as valuable lessons learned. For example, how to integrate a multitude of components to create a smart responsive system, and the fact that the value created by the demonstrations cannot always be monetized. These results, however, are not part of the current analysis.

In the **Suha** demonstrator in Slovenia, it is estimated that in the case of high PV penetration, the use of a medium sized battery in a neighbourhood can increase the use of PV generation up to 25%. The battery also promotes local use of the PV generated, increasing the local energy consumption by 75%. There is a small net decrease of 3% in the total energy exchanged with the grid. Overall the use of the battery increased the use of local renewable energy in a simulated case of relatively high PV penetration.

5.2 Economic Results Comparison

The economic outcome of each demonstration depends on the income streams as outlined in the business cases related in Chapter 4. Internal rate of return and net present value are used as a methodology to compare the monetary value created by each demo in cases where the it made sense to calculate them, in some cases the monetary income was too small compared to investment and it was evident that the business case was not profitable. Table 21 presents a summary of the investment costs, IRR, NPV, savings and business model where available.

In the demonstration at the **Beneens** industrial site, a positive IRR of 6.3% can be achieved in the scenario where excess electricity is fed into the grid at market prices, and excess heat is sold to neighbouring companies. The possibility to sell heat to neighbours is the deciding factor in this demo to create a profitable business case.

The demo at **Suha** presents a negative result with an IRR of -3.2%, the investment is higher than the expected income streams. The business case is calculated contemplating participation in the Slovenian reserves market and minimizing curtailment. The revenues of these are however not high enough to compensate the cost of the battery and its operation. A drop in storage costs to approximately 300 €/kWh would make the set-up economically feasible. At the moment, other values generated by the battery, such as voltage control, grid investment deferral and an improvement in the local use of RES and

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the network are not monetizable. For the other demos small financial benefits are visible, however none create a business case. In the **Oud-Heverlee residential buildings demo,** savings of 1-15% occur, however the current price and taxation scheme in Belgium lead to insufficient revenues to create a viable business case at the household level. For the **EG HQ demo** savings due to arbitrage are only 127 €/year due to a low efficiency and auxiliary energy consumption. The electricity cost in the **EXKAL demo** can be reduced in winter months due to storage implementation (5%), however it is increased in summer months and does therefore not lead to significant savings.

The results generally show that the implementation of storage for arbitrage does not lead to a business case as storage costs are still quite high and current market does not provide enough revenues.

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Table 21. Economic summary of demonstrations[4]

Demo	Investment costs	IRR	NPV	Savings	Business Model
OH Residential Building				Cost reduction between 1% and 15%.	Demand shift
Beneens[5]	ORC: 860,000 € Boiler 125,000 € Heat microgrid: 95,000 €	6.3%	134,699		Excess electricity sold to grid. Excess heat sold to neighbours
Exkal				-5% in winter, slight increase in summer	Demand charge reduction
Suha [6]	Storage: 500€/ kWh	- 3,2%	-67,859		Reserve market, curtailment, arbitrage and self-consumption with 630 kWp PV assumption.
EG HQ				-127 €/year	Arbitrage

[4] There is not enough data available to compare the results of the OHD Community Battery, therefore it is left out of this table. The table is filled based on data availability for each case.
[5] WACC of 5% is assumed. Electricity is fed into the grid for market price of 0.0352€/ kWh CHECK, waste heat sale at assumed gas price of 0,036€
[6] Reserve market price for mFRR assumed at 4.34€/MWh reservation price and an activation price of 249.5 € / MWh, a feed-in tariff of 0, 0462 € / kWh is assumed.

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5.3 Greenhouse Gas Impact Comparison

The environmental results are summarized in Table 22. It can be seen that the result of the life cycle analysis for storage implementation yields an increase in greenhouse gas emissions in almost every case. This is because of the contaminant effect of battery production and disposal as well as operational losses, charge/discharge efficiencies, etc.

Table 22: Environmental Results Comparison

Demo	CO_2 eq. without battery	CO_2 eq. with battery	% Change
OH Residential Building ($kgCO_2eq/kWh$)			Between **-1%** and **-4%**
Beneens ($kg\ CO_2eq/year$)	1.1	1.5	+27%
Exkal ($kg\ CO_2eq/MWh$)	156	161	+3%
Suha ($kg\ CO_2eq/MWh$)	210 kWp: **247** 630 kWp: **139**	210 kWp: **249** 630 kWp: **87**	210 kWp**: +1%** 630 kWP: **-37%**
EG HQ ($kg\ CO_2eq/MWh$)	35 kW PV: **301** 70 kW PV: **286** 105 kW PV: **270**	35 kW PV: **325** 70 kW PV: **310** 105 kW PV: **298**	35 kW PV: **+7%** 70 kW PV: **+8%** 105 kW PV: **+9%**

6 Trade-offs and Conclusions

The main benefits and trade-offs in each of the study cases is presented in Table 23. Five dimensions are compared: Increased use of local RES, economic return, grid value, smart system integration and environmental results. Each dimension is qualitatively rated from best (++), good (+), neutral, slightly negative (-), to very negative (--).

It can be observed at a glance in the table that all the cases present a best or good **increase in the use of renewable energy**; which is the core goal of integrating storage into the system. On the **economic return dimension** only two of the cases present a possible positive outcome, both are the storage installed in an industrial site, showing that volume matters and that the main value stream is electricity cost reduction. From the **grid**

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value point of view it has been demonstrated that storage has a potential to manage voltage deviations and possibly defer grid investments. However, there was no grid value investigated in the industrial cases in Beneens and Exkal where the storage system is connected behind the meter at an industrial compound. **Smart system integration** and interoperability challenges were significant in the STORY project demonstrators. Valuable lessons were learned from a technical point of view during the implementation of the project. The STORY project has produced know-how on how to install storage systems and how to integrate them to work together with the existing infrastructure. The **environmental results** measure the change in greenhouse gases. The result is mainly an increase in greenhouse gas emissions due to the life cycle of batteries. The only positive case studied is the simulation of a large battery system with high RES penetration. This result demonstrates, once again, that volume is key for the exploitation of storage coupled with higher integration of renewable energy.

Table 23: Benefits and trade-offs in each study case

Demo	Increased use of local RES	Economic return	Grid value	Smart system integration	Environmental results
Beneens (heat to neighbours)	++	++	Neutral	-	--
Exkal	+	++	Neutral	-	-
Suha (high RES)	++	-	++	-	++
SUHA EG	++	--	+	Neutral	-
OH 1	+	--	+	++	-
OH 2	+	--	+	++	-

Rankings key:

++	+	Neutral	-	--

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This deliverable demonstrates the technical, environmental and economic features of storage implementation. It is highlighted that storage needs to be tailored to a specific purpose such as mitigating curtailment to outweigh potential negative GHG impacts that might occur in case of a roll-out. The implementation of storage comes with fixed emissions due to the manufacturing of the battery, however "saved emissions" are extremely sensible to the actual use case of the battery.

Storage can have an important role to facilitate RES deployment by delaying infrastructure reinforcement or improving power quality. However break-even points from an economic and an environmental perspective might differ and therefore both should deliberately be considered, so one's benefit does not compromise the others.

If the battery operation only changes the parameters "PV to grid" and "Electricity from grid" (which is the case in most of the scenarios), only small differences in the total GHG emissions of the scenarios occur. The reason for this is that we included the replacement of other types of electricity generation if PV electricity is transformed to the next grid level. Even including hourly emission factors for the electricity mix does not lead to big changes in the total GHG emissions of the scenarios. PV generation is the most influential factor on the lifecycle assessment. If the battery impacts the PV generation significantly, the result differ strongly.

This also means that the energy system boundaries have to be well-defined e.g. we looked from the viewpoint of the demos and did not consider the entire electricity network. The analysis showed that as long as the grid can be used as storage, which entails a higher efficiency factor than a storage solution, it is an environmentally more sound solution in case we don't consider a change in the generation system due to an increasing injection of fluctuating renewables. If the grid is no longer able to deal with PV injection and curtailment occurs, a storage system is reasonable.

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8 Abbreviations

LV	Low Voltage
MV	Medium Voltage
OLTC	On load tap changer
CHP	Combined Heat and Power
BESS	Battery Energy Storage System
EG	Elektro Gorenjska (Slovenian DSO)
EF	Emission factor
mFRR	Frequency restoration via manual activation
RES	Renewable Energy Sources
KPI	Key Performance Indicator
DSO	Distribution system operator
TSO	Transmission system operator

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