BACHELOR

Performance of the Bunnik campus
Implementation of a battery storage system Sharing energy to a residential area

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Performance of the Bunnik campus

Bachelor final project

Implementation of a battery storage system

Sharing energy to a residential area

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Abstract

The imbalance in the electricity grid is ever-growing and solutions need to be found to reduce the grid imbalance and reduce total electricity consumption. BAM Energy Systems and TROEF have introduced a layered energy system based on sharing energy.

In this research, the potential of using a battery energy storage system on the BAM campus in Bunnik and the potential of sharing energy with a residential community are investigated. For this, a tool is developed in Python with battery management based on the logic that first PV energy is used or stored and then wind energy.

The results are promising with an increase in self-sufficiency and self-consumption and a reduction in total grid imported energy and reduced CO_2 emissions by implementing a battery, but the cost is very high making a battery by itself not financially feasible.

Sharing surplus energy from the utilitarian campus to a residential community shows great potential, with improved self-sufficiency of the community and overall reduced CO_2 emissions on an Internet-of-Energy level.

Contents

List of symbols and abbreviations

Symbol	Name	Description	Unit
BESS	Battery energy storage system		
C	Cost	Total cost of electricity	[€]
D	Consumption	Consumed energy	[kWh]
EPEX	European Power Exchange SE	Electricity exchange market	
f_{CO2}	CO_2 emissions factor		[-]
IoE	Internet of Energy	Highest level in a LES	
$kgCO_2$	Kilogram CO_2	Amount of CO_2 produced	[kg]
KPI	Critical performance indicator	From Dutch: Kritische Performance Indicator	
kW	Kilowatts		[kW]
kWh	Kilowatthours		[kWh]
kWp, Wp	Kilowatt peak and Watt peak	Peak power a PV panel can deliver	[kW], [W]
LES	Layered Energy System		
P	Production	Produced energy	[kWh]
PV	Photovoltaics	Solar panel energy	
SC	Self-consumption		
SS	Self-sufficiency		
U	Energy volume	E.g. imported energy or stored energy	[kWh]
W	Wind	Wind energy	

1 Introduction

The BAM Energy Systems campus in Bunnik is a living lab used for research on a new energy system to speed up the energy transition in the built environment. A layered energy system (LES) as introduced by TROEF (BAM Energy Systems B.V., 2020) is implemented and energy is purchased using forecasting of energy production and consumption.

The goal of this BEP is to evaluate the performance of the campus in Bunnik based on a set of KPIs (Critical performance indicators) as stated below in Table 1, after introducing a battery energy storage system (BESS). The KPIs are introduced by the TROEF consortium and slightly altered for this research.

Furthermore, the potential of combining the utilitarian campus with a residential area are investigated and measured against the KPIs.

Table 1: TROEF Critical performance indicators and goals

Indicator	Goal
$kgCO_2$	CO_2 Reduction of 20% within one building by using insight and introduction of sustainable measures.
	CO_2 Reduction of 50% within one community (with on average 50 connected buildings).
	Improvement of the momentary CO_2 footprint of the energy mix for all connected communities by 70%.
Cost end user (€)	Reducing energy cost per kWh for end-users by 20%

TROEF has three main goals (van Goch, van Prooijen, de Vaal, & de Bruijn, 2022):

1. develop a new energy supply based on the 'Internet of Energy';
2. develop platforms and aids;
3. standardize and make replication possible of Internet of Energy concepts.

The research will consist of a part concerning the usage of a battery on the campus and exploring options of combining a residential part into the utilitarian campus buildings.

2 Research questions

To evaluate the performance of the campus, two research questions are drafted.

1. What is the optimal size of a BESS when all locally produced (surplus) green energy is to be used on the Bunnik campus?
2. What is the value of combining a residential part into the up-to-now utilitarian campus?

3 Literature

In this section, relevant literature and data are presented.

3.1 Performance analysis methods

To analyze the performance of the battery and other energy-saving measures, the KPIs are used, as well as self-sufficiency and self-consumption.

Self-sufficiency and self-consumption
The self-sufficiency (SS) is the percentage of total energy consumed by an energy user (e.g. a building or community) that is produced by on-site sources such as solar, wind, or other renewable energy sources and ranges from 0 % to 100 %. A high SS means that a lot of the consumed energy comes from local green sources. The SS is calculated as follows, where $\sum P_{used}$ is the part of production used on-site and $\sum D_{buildings}$ is the total consumed energy on-site.

$$SS = \frac{\sum P_{used}}{\sum D_{buildings}} * 100\% \tag{1}$$

The self-consumption (SC) is the percentage of energy that is produced by on-site sources that is actually consumed by the energy user, instead of being exported to the grid or elsewhere, and also ranges from 0 % to 100 %. A high SC means that a lot of the produced energy is used on-site. It is calculated as follows, where $\sum P_{used}$ again is the part of production used on-site and $\sum P_{total}$ is the total on-site produced energy.

$$SC = \frac{\sum P_{used}}{\sum P_{total}} * 100\% \tag{2}$$

In the performance analysis, wind energy is also included in the locally produced energy, although the windmill is not physically located on-site.

KPIs

To analyze the performance of an on-campus battery system, critical performance indicators (KPI) are used as set up by TROEF. Due to the complexity of these KPIs, only two will be used that are slightly altered. These are stated below.

- CO_2 emmissions, or $kgCO_2$.
- cost end-user, in euro;

CO_2 emissions
The CO_2 footprint is calculated with a CO_2-emission factor per source f_{CO2} multiplied by the imported energy $\sum U_{meter,gray}$. The PV and wind energy is assumed to have zero CO_2 emissions. An emissions factor of $f_{CO2} = 0.51$ is used, based on the average CO_2 emissions for the Netherlands in the years 2018-2022 (Electricity Maps, n.d.).

$$CO_{2,tot} = \sum U_{meter,gray} * f_{CO2} \tag{3}$$

Cost end-user
The cost C_u is simply calculated by summing all costs for the final user. These costs are the energy cost drawn from the net (gray energy, C_E), the cost from wind energy that is immediately used (C_W), and the battery cost (C_B), both fixed and cost of energy stored in the battery.

The battery cost is built up out of a fixed cost as discussed in subsection 3.3 and the cost of the energy stored in the battery, $C_{B,s}$. This applies to wind energy that is stored in the battery. This cost is not the same as the wind energy that is used immediately but will have the price of the moment it is stored in the battery and is used later.

$$C_u = \sum (C_E + C_W + C_B + C_{B,s}) \tag{4}$$

3.2 Datasets

The data used in this research is made available by BAM Energy Systems.

Bunnik campus
The data available from the Bunnik campus consists of separate data per building, for all buildings (A up to and including H). Available columns are the main meter data and forecast data. The data ranges from 2018 up to and including 2022. The dataset consists of data points every 15 minutes. For the PV panels, a dataset is available for all inverters in building cluster ABCD. This dataset starts on 05-11-2018.

To calculate the energy cost, the EPEX prices for the same years are available, in hourly intervals.

For the windmill production, a smaller dataset ranging from 15-10-2021 up to and including 17-05-2022 is available.

Residential area
For the residential area, a much bigger dataset is available for two neighborhoods in Woerden and Soest. In Soest, main meter data for 69 homes is available, in Woerden this is for 39 homes. Per home the consumed, produced and inverter data is available. Heat pump and boiler data is also present, but not relevant for this research. The data ranges from 2020 up to halfway through 2022 in 5-minute intervals.

3.3 Battery energy storage systems

A battery system on the Bunnik campus would include an initial investment cost and yearly operational costs for the entire lifespan of 15 years of operation. These costs per battery size available are shown in Table 2.

The operating cost is a set value that is spread out over 15 years of operation. The infrastructure and grid cost comes from changes to e.g. the connections, changes to the grid, and infrastructure. The total cost for the 15 years is then divided into a fixed annual cost. This value is used in the analysis.

Table 2: Purchase and operating cost for three battery sizes

Battery pack size [kWh]	Purchase cost (€)	Infrastructure and grid cost (€)	Operational cost for 15 years (€)	Annual operation cost (€)
240	260000	100000	350000	47333
500	400000	100000	350000	56667
1000	630000	100000	350000	72000

3.4 PV panels

In Table 3 below, the number of solar panels mounted on building cluster ABCD is shown.

Table 3: PV panel count per building

Building	Building part	No. of panels (270 Wp)	Total
A	A1	43	
	A2	77	
	A3	90	210
B	B1	60	
	B2	91	151
C	C1	35	
	C2	28	63
Total			424 = 114 kWp

3.5 Windmill energy

The wind energy that is used comes from an external windmill, it is not located on the campus in Bunnik. The wind energy is direct-sourced to the campus and is all available to be used by the campus. The cost of wind energy consists of the EPEX price plus a premium. For this research, the CO_2 emissions are assumed to be zero for wind energy.

4 Research plan

To find an answer to the research questions, a research plan is set up.

Question one
The first question will be split up into scenarios. For these scenarios, three battery sizes will be investigated that are commercially available. These are 240 kWh, 500 kWh and 1000 kWh. The scenarios are stated below.

1. No use of a battery, to establish a baseline to compare to.
2. Use the locally produced energy optimally, only taking into account the current PV installation, and investigating a 240, 500, and 1000 kWh battery.
3. Expand the above with the energy produced by the windmill.

The results from this will be the following, split in no battery, PV only, PV+W only, PV+battery and PV+W+battery.

- Self-sufficiency and self-consumption.
- Total CO_2 emissions.
- Total cost.

By comparing the results with and without a battery, a result on the performance of a battery on-campus can be found. Furthermore, a number will be put on how big a battery must be to store all locally produced energy.

Question two
To investigate the potential of sharing energy with a residential community, again the KPIs will be investigated, except for the cost. For both communities separately the performance will be analyzed. Then they will be combined and the performance of this Internet-of-Energy (IoE) is investigated.

Similar results will be produced as with question one, but then without a battery involved. A new result is the amount of energy exported to the residential community and to what extent the consumption of that community can be covered by surplus PV and wind energy from campus.

4.1 Method

To research the above questions, the available data will be analyzed using Python (with Pandas and Dask toolboxes) in JupyterLab. This makes the research repeatable in the future and the results can be shown clearly in a single notebook. Because Python is a widely used language, the script can be used in other environments as well.

Data
As explained in subsection 3.2, three datasets are available. The first is the consumption profiles for the Bunnik campus, ranging from 2018 to 2022. The second is the PV production for the panels on the buildings in Bunnik, also ranging from 2018 to 2022. The last is windmill production, ranging from 15-10-2021 to 17-05-2022. For the analysis, one

year of data before the work-from-home advice was given due to COVID-19 (March 2020) is used.

The date range for this single year was chosen to be 15-10-2018 to 15-10-2019. For the first month of this period, no PV production data is available. To overcome this, PV production data from one year later is used and thus shifted exactly one year back.

Because the windmill production data starts in 2021, this data must be shifted back three years to be able to analyze it in the same period as the chosen consumption data in Bunnik. Also, only a shorter period is analyzed, due to the dataset ending on 17-05-2022.

Due to the nature of the production of wind and solar energy being quite unpredictable on a day-to-day basis, shifting the production data should not pose any problems, but is to be kept in mind before analyzing the results. It is important to not move the data to other months, as the production profiles are very different for different months throughout the year.

Calculation
The setup of the script will be such that firstly, the locally produced, free PV energy will be consumed and any surplus stored in the battery. Afterward, the wind energy is used and any surplus is stored. When the consumption of the buildings cannot be satisfied by green energy, firstly the battery will be drained before any grid energy is consumed.

For exchanging energy with a residential community, the calculation is slightly different, as no battery is involved. The basic logic of first using PV energy, then wind energy still applies to the utilitarian campus. Any surplus of energy is then calculated and compared to the consumption of the residential community. If the community has a consumption, the surplus production will be exported to these homes, up to their consumption.

In pseudocode, the battery system will look like Pseudocode 1 on the next page. In this code, the battery size and charging current limits are not included. The consumption parameter reduces throughout the logic. It starts with the original consumption at a step. If at the end of the PV and wind part, there is still consumption, the energy stored in the battery will be subtracted from that leftover consumption and what is left at the end of the loop has to be imported gray from the grid.

Pseudocode 1 Battery control logic

```
if consumption > 0 and PV production < consumption then
    consumption = consumption - PV production
else
    if consumption >= 0 and PV production > consumption then
        consumption = 0
        battery = battery + (PV production - consumption)
    end if
end if

if consumption > 0 and wind production < consumption then
    consumption = consumption - wind production
else
    if consumption >= 0 and wind production > consumption then
        consumption = 0
        battery = battery + (wind production - consumption)
    end if
end if

if consumption > 0 and battery > 0 then
    if consumption <= battery then
        battery = battery - consumption
        consumption = 0
    else
        if consumption > battery then
            consumption = consumption - battery
            battery = 0
        end if
    end if
end if
```

5 Results

In this section, the retrieved results will be shown, per research question or scenario.

5.1 Consumption Bunnik campus

Before implementing a BESS, the consumption profiles of the BAM campus are investigated and the use of PV and wind energy are already implemented. For clarity, only eight days are shown. See Figure 1. The blue line indicates the original consumption for all buildings, red and green are the production of PV and wind respectively and the gray line indicates gray energy imported from the grid as a result of using the green energy on-campus. The wind production has been slightly cut off to have a better visualization but has peaked at around 170 kWh.

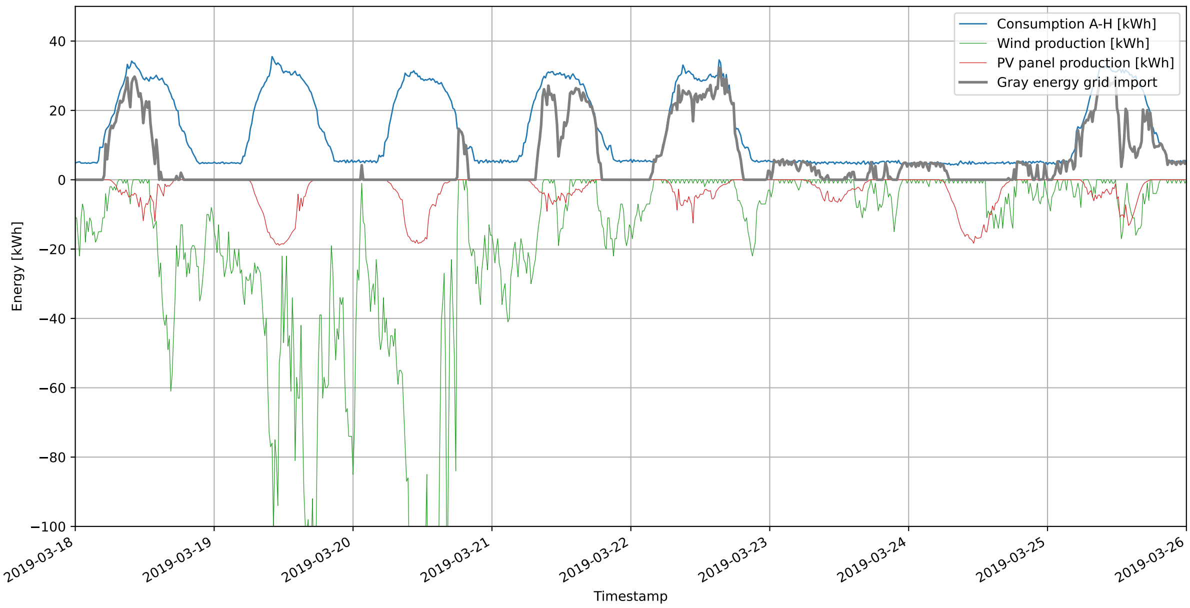

Figure 1: Bunnik consumption and grid import

5.2 Question one: BESS

After running the data through the logic with a battery included, the effect can be seen in a reduction of gray imported grid energy. See Figure 2 on the next page, where a 240 kWh battery is implemented. For clarity, again the production side has been cut in the graph.

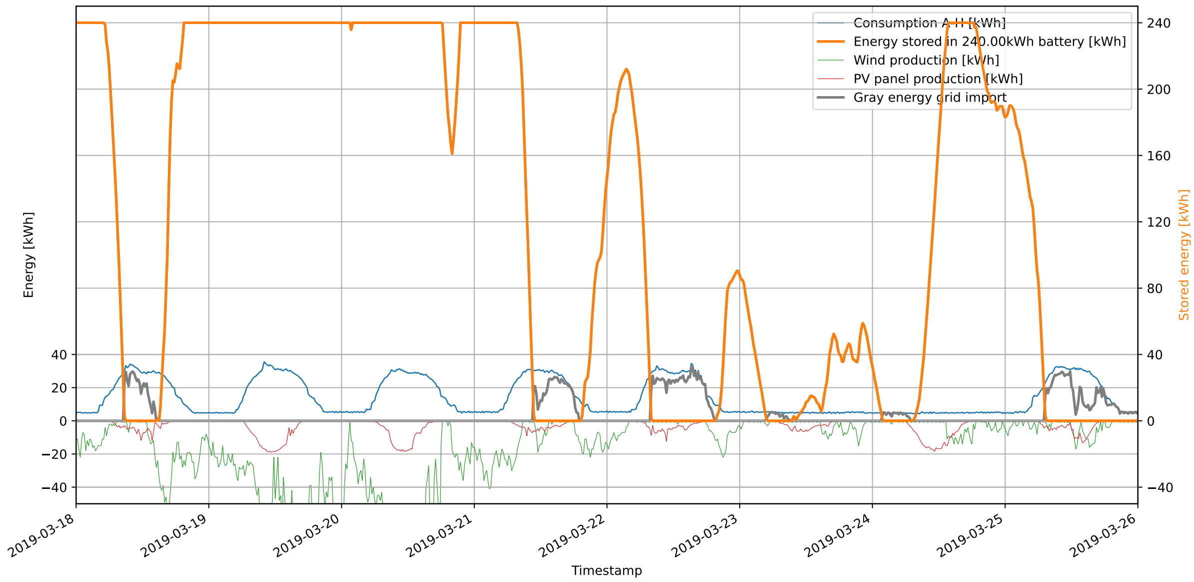

Figure 2: Bunnik consumption with 240 kWh battery and use of both wind and PV energy

What can be seen in the above figure, is that when there is a lot of production, the battery will remain on full charge for an extensive period. If the production stops, the battery is empties very quickly.

If in the same period, no wind energy would have been used or stored, Figure 3 below is the result. The battery is empty for most of the time now because the PV energy is produced during business hours when consumption is also high. Only on a weekend there is surplus PV energy for the week displayed.

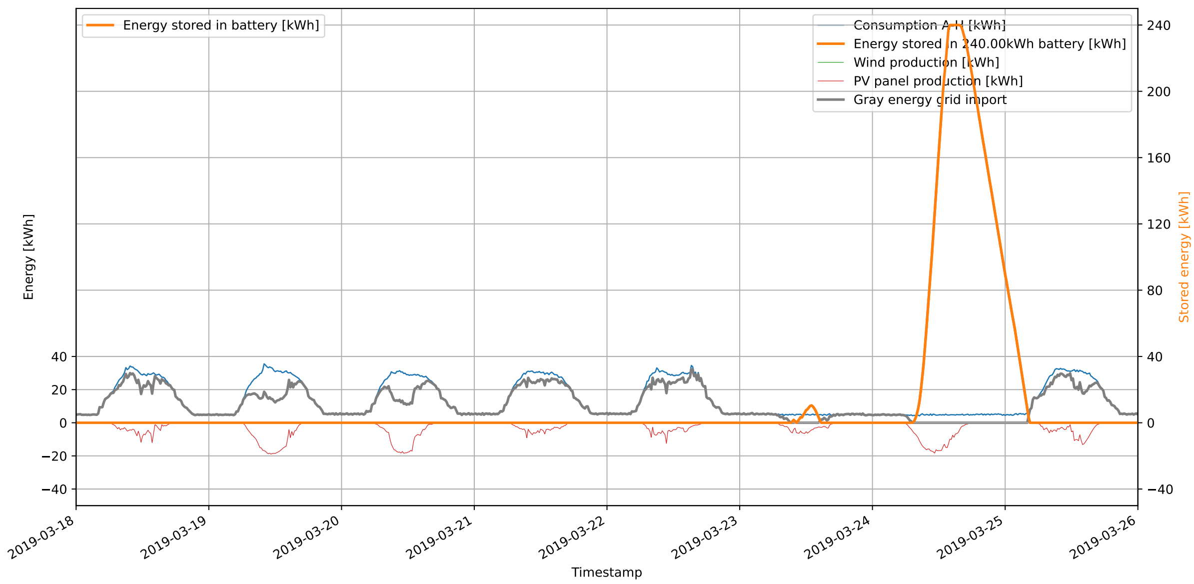

Figure 3: Bunnik consumption with 240 kWh battery using only PV energy

Results

Self-sufficiency and self-consumption - PV only

In Table 4 below, the resulting SS and SC for the first case with only PV and a battery is shown. What becomes very clear is that the PV installation can only take care of a very small part of the total consumption (SS is ranging from 0.19 to 0.22), but due to the nature of the PV production, almost all PV energy can be used on-campus. Especially with the larger battery sizes.

The maximum SS that can be achieved is 21.9 %, which is calculated by dividing the total PV production $\sum PV_{tot}$ by the original consumption $\sum D_{buildings}$. The maximum SC is 100 %. In that case, all locally produced energy is used on-site.

$$SS_{max} = \frac{\sum PV_{tot}}{\sum D_{buildings}} * 100\% = 21.9\% \tag{5}$$

Visually, this is shown in Figure 4.

Table 4: SS and SC and the increase from no battery for PV only

Size [kWh]	**SS [%]**	**Difference**	**SC [%]**	**Difference**
0	19.0	0	86.9	0
240	21.2	2.2	96.8	9.9
500	21.7	2.7	99.1	12.2
1000	21.9	2.9	100	13.1

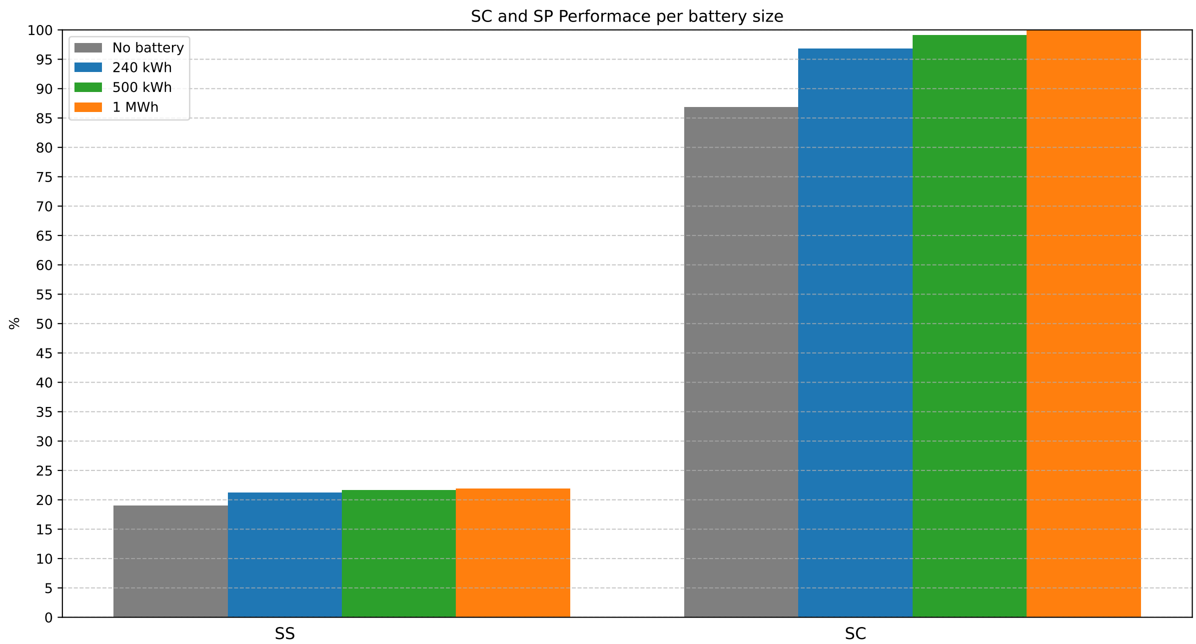

Figure 4: SS and SC visualized for PV only

CO_2 emissions - PV only

In Table 5, the total gray import $\sum U_{meter,grid}$ and stored energy $\sum U_{stored}$ is shown. The total CO_2 emission is calculated using the gray imported energy with the emissions factor $f_{CO2} = 0.51$. As can be seen, the impact of a battery is very little regarding to the total CO_2 emissions, with a maximum reduction of only 3.6 %. In Figure 5 the CO_2 emissions are visualized.

The maximum performance that could be achieved is a CO_2 reduction of at most 3.6 %. The total PV production $\sum PV_{tot}$ is 100499 kWh and the total original consumption $\sum D_{buildings}$ (no PV energy subtracted) is 458335 kWh.

$$CO_{2,tot,min} = (\sum D_{buildings} - \sum PV_{tot}) * f_{CO2} = 182496 \ [kgCO_2] \tag{6}$$

Table 5: CO_2 emissions and the increase from no battery for PV only

Size [kWh]	$\sum U_{meter,grid}$ **[kWh]**	$\sum U_{stored}$ **[kWh]**	$CO_{2,tot}$ **[kgCO$_2$]**	**Dif.**
0	371035	0	189228	0
240	361052	9983	184137	-2.7 %
500	358697	12338	182936	-3.3 %
1000	357836	13199	182496	-3.6 %

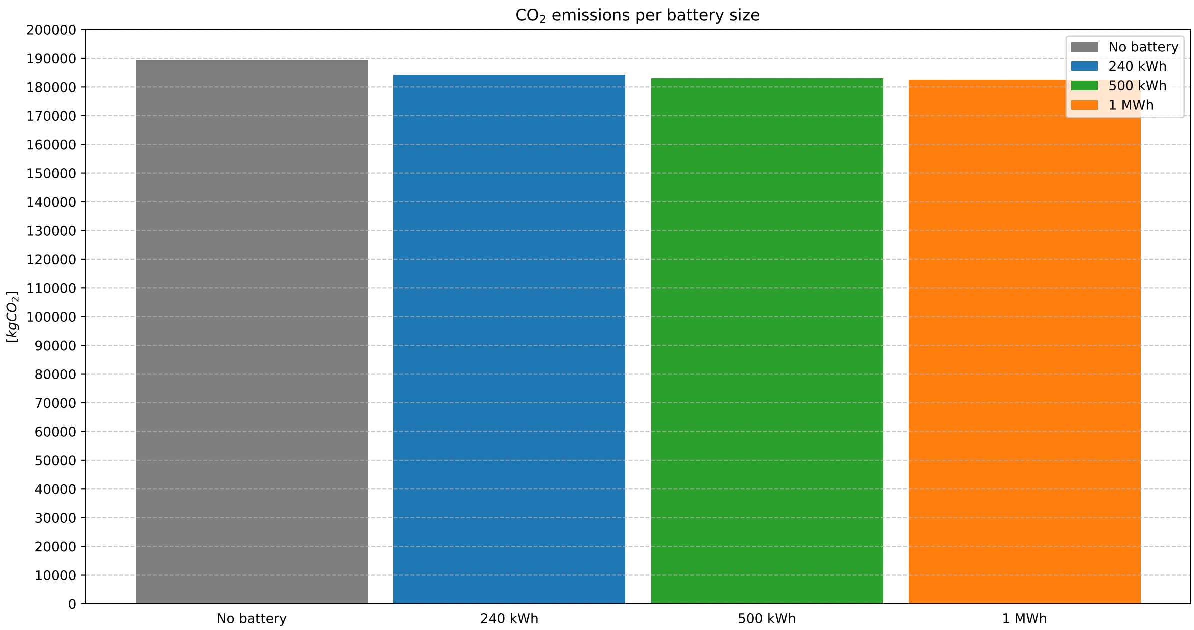

Figure 5: CO_2 emissions visualized for PV energy only

Cost - PV only

Below in Table 6, the increase in cost with implementing a battery storage system can be seen. As the PV energy is locally produced, it is regarded free and thus the cost of stored battery energy is left out here. The biggest cost factor here is the battery system. In Figure 6, the total PV cost is visualized and split in its different sources.

Table 6: Cost and the increase from no battery for PV only

Size [kWh]	**Cost gray energy C_E (€)**	**Fixed cost battery C_B (€)**	**Total cost C_U (€)**	**Dif.**
0	17547	0	17547	0
240	17171	47333	64504	268 %
500	17085	56667	73752	320 %
1000	17052	72000	89052	408 %

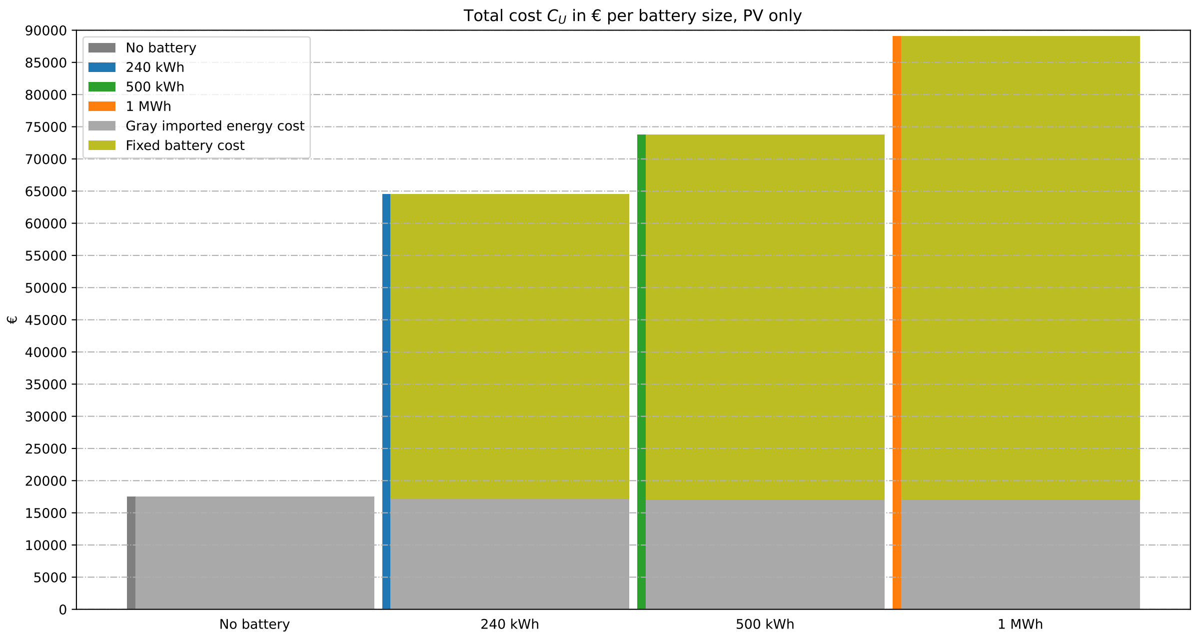

Figure 6: PV total cost split out

Self-sufficiency and self-consumption - PV+Wind
In Table 7 below, again the SS and SC are shown for the case with wind energy also taken into account. The result is drastically different from the previous case. The SS is rather high now because there is a lot of wind energy compared to the demand. This is also the cause of the very low self-consumption. Even with a large 1 MWh battery, not even 20% of the total production can be used on-campus. Again, the result is visualized in Figure 7.

The maximum SS that can be achieved is 486.5 %, which is calculated by dividing the total PV and wind production $\sum P_{tot}$ by the original consumption $\sum D_{buildings}$. Because there is more production than consumption, the theoretical maximum self-consumption is bigger than 100 %. In reality, the maximum would be 100 %. In that case, all consumed energy is covered by local green sources. The maximum SC is also bigger than one, but again the maximum would be 100 % without a battery in the ideal case. With a battery, 100 % SC is achieved at a battery size of 5.4 MWh.

$$SS_{max} = \frac{\sum P_{tot}}{\sum D_{buildings}} * 100\% = 486.5\% \tag{7}$$

Table 7: SS and SC and the increase from no battery for PV and wind

Size [kWh]	**SS [%]**	**Difference**	**SC [%]**	**Difference**
0	74.4	0	15.3	0
240	82.0	7.6	16.9	1.6
500	86.1	11.7	17.7	2.4
1000	90.5	16.1	18.6	3.3

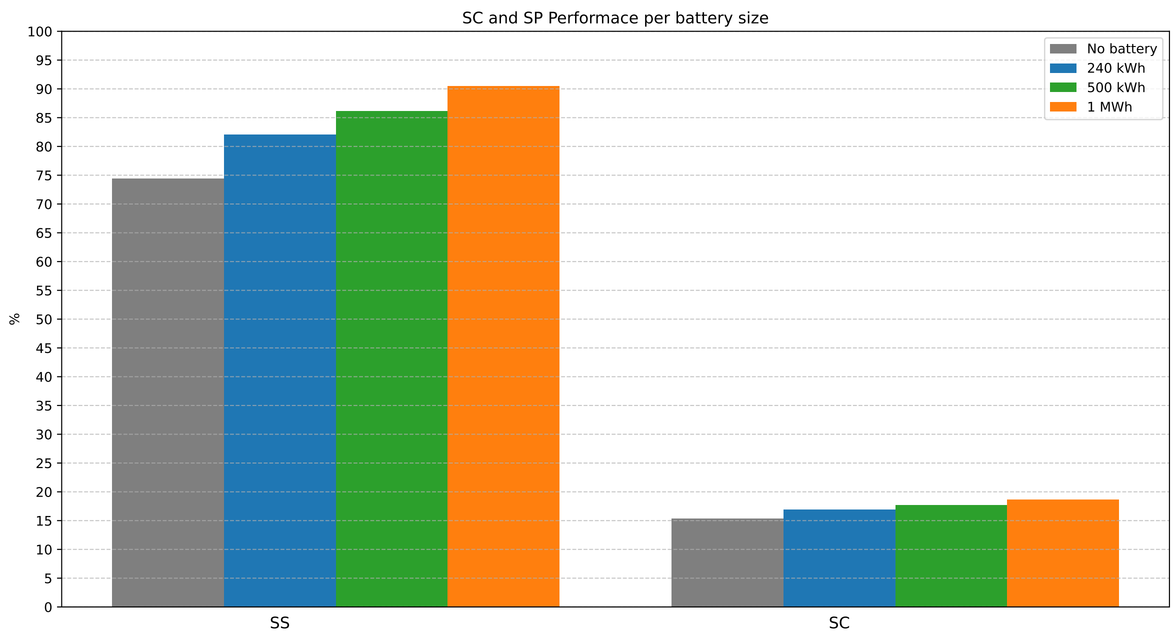

Figure 7: SS and SC visualized for PV and wind

CO_2 emissions - PV+Wind

In Table 5, the total gray import $\sum U_{meter,grid}$ and stored energy $\sum U_{stored}$ is shown. The total CO_2 emission is calculated using the gray imported energy with the emissions factor $f_{CO2} = 0.51$. Compared to the case with only PV energy, the impact of a battery is much larger on the total CO_2 emission. With a small 240 kWh battery, already 29.7% reduction can be achieved. In Figure 8 the CO_2 emissions are visualized.

The maximum performance that can be achieved is a CO_2 reduction of 100%. The total production $\sum P_{tot}$ is 1136073 kWh and the total original consumption $\sum D_{buildings}$ (no PV energy subtracted) is 233536 kWh. There is much more production than consumption. If all consumption would be covered by green produced energy, all CO_2 emissions would be removed. For this, a 5.4 MWh battery would be needed, but this battery size is not further investigated in this research.

Table 8: CO_2 emissions and the increase from no battery for PV + Wind

Size [kWh]	$\sum U_{meter,}$ **[kWh]**	$\sum U_{stored}$ **[kWh]**	$CO_{2,tot}$ **[kgCO$_2$]**	**Dif.**
0	59712	0	30453	0
240	41980	17844	21410	-29.7 %
500	32382	27442	16515	-45.8 %
1000	22249	37659	11347	-62.7 %

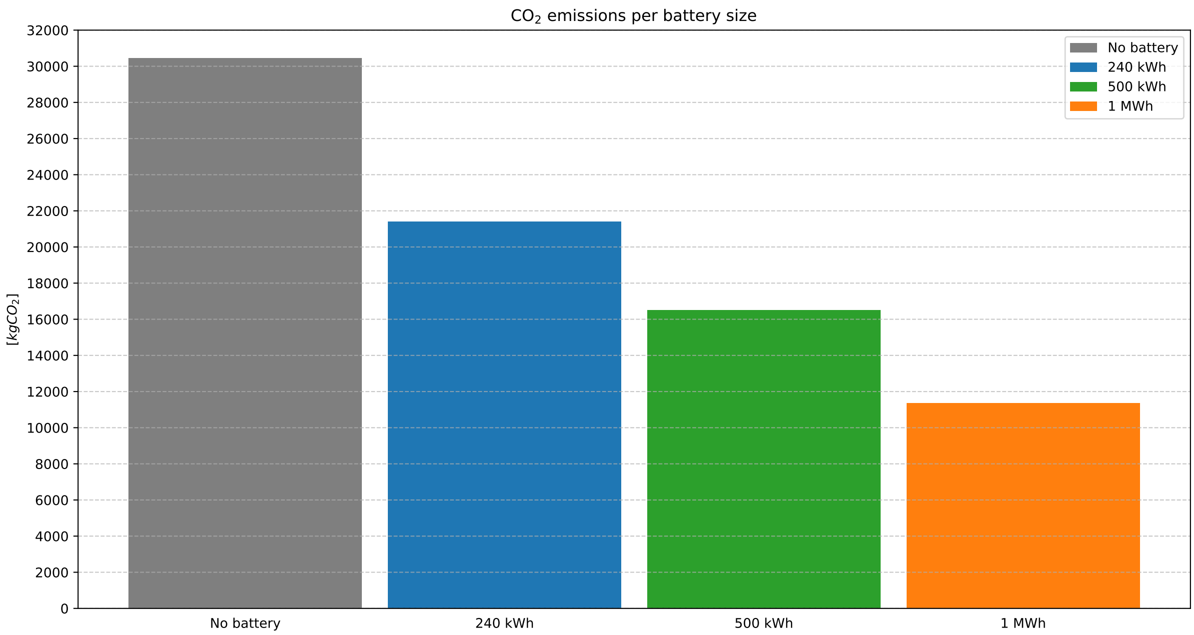

Figure 8: CO_2 emissions visualized for PV+wind energy

Cost - PV+Wind

Below in Table 6, the increase in cost with implementing a battery storage system can be seen. As the PV energy is locally produced, it is regarded as free. The cost of wind energy C_W remains constant, as the immediately used wind energy remains the same. The cost of stored wind energy which is used later is $C_{B,s}$. The biggest cost factor here is again the battery system fixed cost C_B. In Figure 9 the cost buildup is visualized.

Table 9: Cost and the increase from no battery for PV and Wind

Size [kWh]	**Cost gray energy C_E (€)**	**Cost wind energy C_W (€)**	**Fixed cost battery C_B (€)**	**Cost stored battery energy $C_{B,s}$ (€)**	**Total cost C_U (€)**	**Dif.**
0	3287	7753	0	0	11040	0
240	2320	7753	27881	904	38858	252 %
500	1780	7753	33379	1380	44292	301 %
1000	1225	7753	42411	1883	53272	383 %

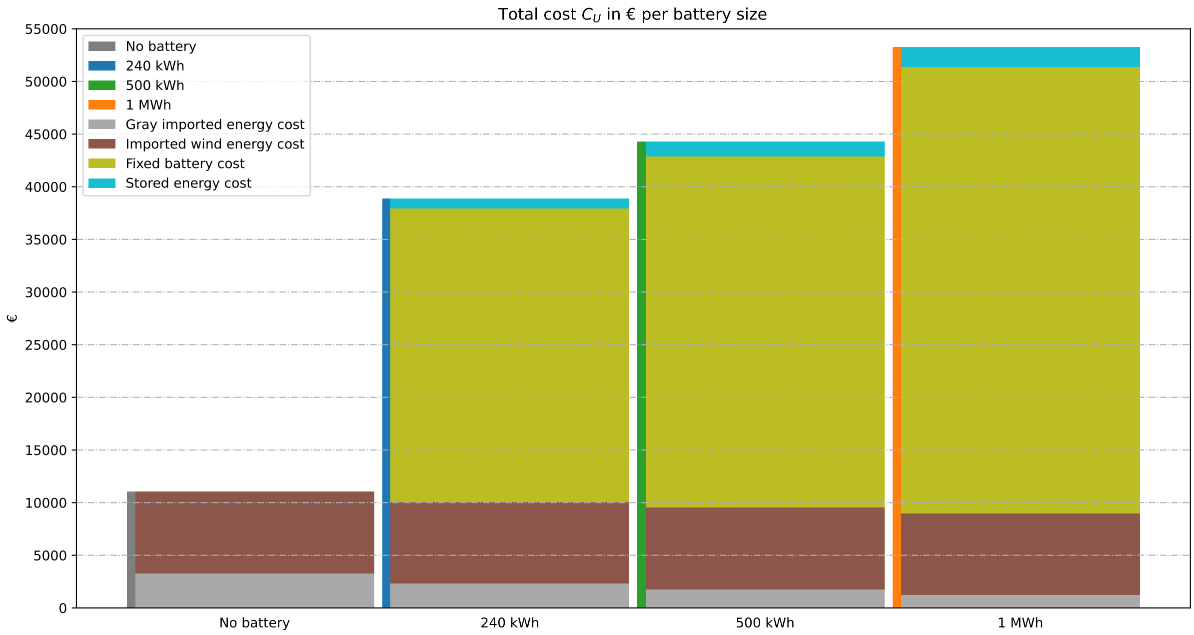

Figure 9: PV and wind total cost split out

Final result

Combining all the above results gives a clear overview of the impact of implementing the battery and what it may have to offer.

Summary result PV only
In Table 10 all the above results for the campus with only PV panels is summarized. What is very clear is that the difference in cost is much higher than the difference in SS, SC and CO_2 emissions. Again note that this data is for an entire year.

Table 10: Summary of all results for PV only

Size [kWh]	**Total cost** C_U (€)	**Dif.**	**SS** [%]	**Dif.**	**SC** [%]	**Dif.**	$CO_{2,tot}$ [kgCO$_2$]	**Dif.**
0	17547	0	19.0	0	86.9	0	189228	0
240	64504	268 %	21.2	2.2	96.8	9.9	184137	-2.7 %
500	73752	320 %	21.7	2.7	99.1	12.2	182936	-3.3 %
1000	89052	408 %	21.9	2.9	100	13.1	182497	-3.6 %

Summary result PV and wind
In the case with wind, it is a much different result. The gain in cost is similar, but the gain in CO_2 emissions is much higher. The SS and SC are very different. The SS is much higher and the SC is much lower. This can be explained by the fact that without wind, almost all PV energy can be consumed locally, but it only covers a little of the total consumption. Including wind energy it is the other way around, a big portion of the consumption can be covered by green wind and PV energy, but only a small part can be actually consumed.

Note that this data is only for 7 months, from October to May.

Table 11: Summary of all results for PV and wind

Size [kWh]	**Total cost** C_U (€)	**Dif.**	**SS** [%]	**Dif.**	**SC** [%]	**Dif.**	$CO_{2,tot}$ [kgCO$_2$]	**Dif.**
0	11040	0	74.4	0	15.3	0	30453	0
240	38858	252 %	82.0	7.6	16.9	1.6	21410	-29.7 %
500	44292	301 %	86.1	11.7	17.7	2.4	16515	-45.8 %
1000	53272	383 %	90.5	16.1	18.6	3.3	11347	-62.7 %

Final scoring table

Below in Table 12, a relative gain score is defined to find the optimal size of battery for the two cases. This relative gain score is determined by dividing the % cost gain by the performance gain (difference column). The lower the score, the better. The table does not compare to having no battery installed, this comparison is done above. It determines the best battery if a battery were to be installed.

The score €/kWh stored energy is determined by dividing the total cost of energy including battery cost by the total volume stored energy in the battery over the entire analysis. This indicates how much a kWh of energy will cost when stored in the battery.

The best scores are highlighted in bold text. For the PV energy only case, the 500 kWh battery turns out to be the best scoring battery. For the PV and wind energy case, the 1 MWh battery is the best choice.

Table 12: Scoring table with relative gains for every battery size and two cases

Size [kWh] and scenario	SS	SC	€/kWh stored
240, PV only	122	27	6.46
500, PV only	**119**	**26**	**5.98**
1000, PV only	141	31	6.75
240, PV+wind	33	158	2.18
500, PV+wind	26	125	1.61
1000, PV+wind	**24**	**116**	**1.41**

5.3 Question two: Combining with a residential community

Again, the logic starts with the consumption from the campus and production from PV panels and wind. This is the same dataset as before. Now also the consumption from the residential community is included. The houses have PV panels, thus the main meter data from these homes is taken to match the surplus of energy. The consumption and Bunnik surplus profiles are shown in Figure 10. Notice that a different date range is used here than before in the plots. The surplus is taken positively, whereas the production before was negative. This is done to make the matching better visible in the next step. Also, in this figure, the total surplus (PV and wind energy together) is shown. The PV panel surplus is much smaller than the wind surplus.

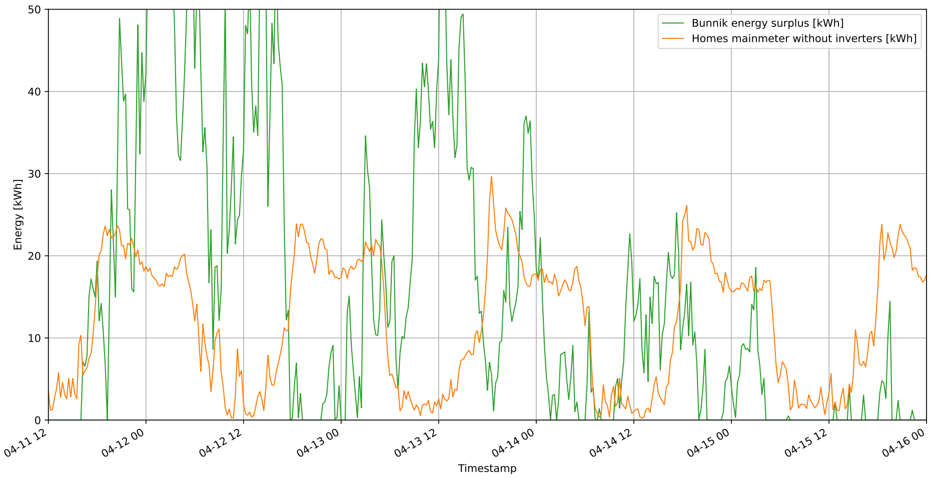

Figure 10: Bunnik surplus and residential mainmeter profiles

From this, with the logic applied, first only the surplus PV energy is exported to the residential community, giving the following result. See Figure 11. Exporting only PV energy has little effect, especially in this small data section. This will be made clear further on in the performance analysis.

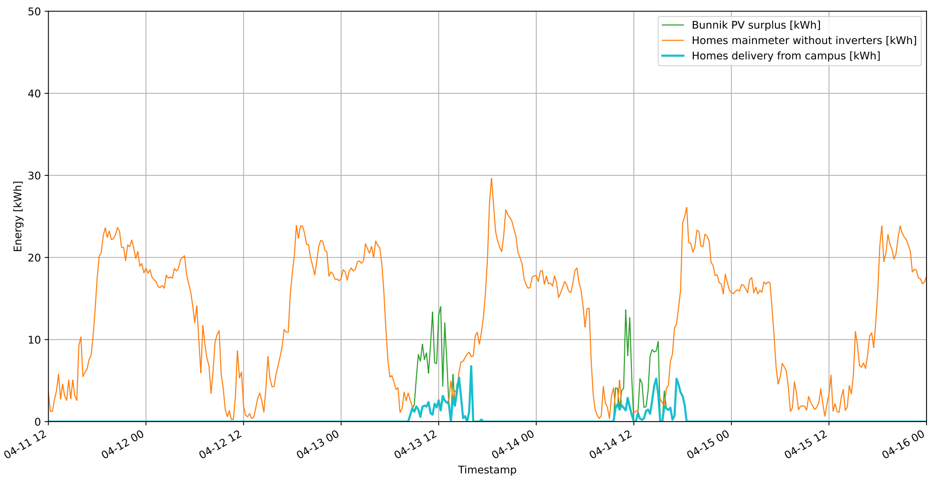

Figure 11: PV export and new consumption

If also surplus wind energy would be exported, the following result shown in Figure 12 is achieved. A large amount of energy is exported, indicated by the cyan line.

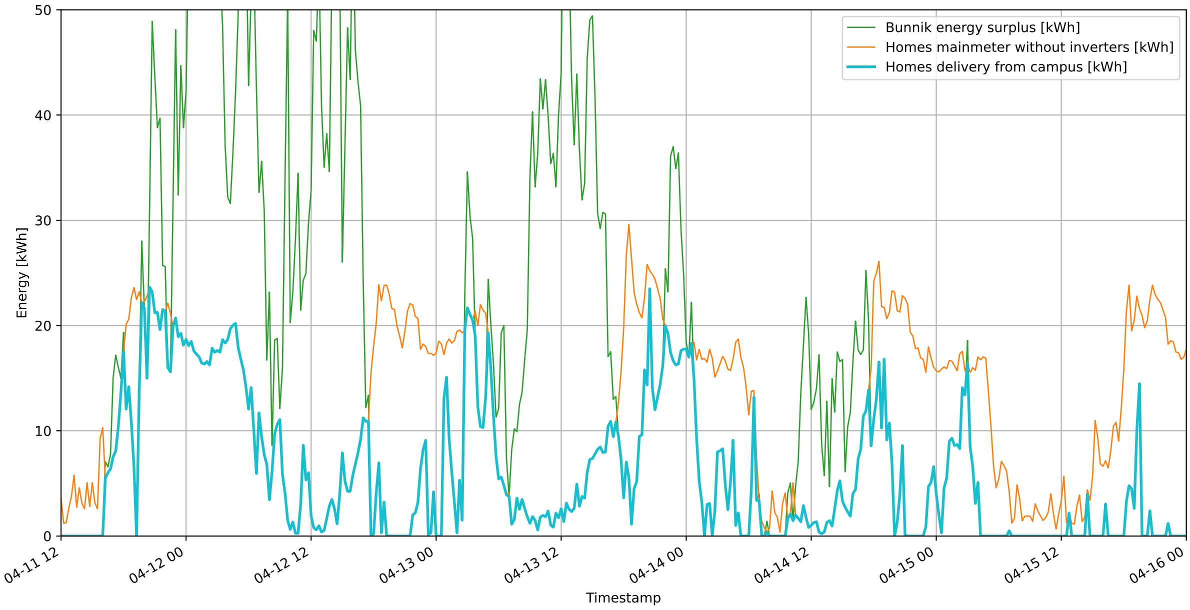

Figure 12: PV and wind export with new consumption

Performance with exported energy

The impact of exporting energy is analyzed in this subsection. A split will be made between exporting only PV energy and also wind energy.

Exported energy volume

The total main meter consumption of the residential area in the length of the dataset with only PV export is 451882 kWh (one year, 15-10-2018 to 15-10-2019). With wind energy, the total consumption is 330735 kWh (length of dataset only 15-10-2018 to 17-05-2019). The volume of exported energy and fraction that can be covered by the export of energy of the total residential consumption is shown in Table 13. If only PV energy is exported, 0.9 % of the total residential consumption can be covered by surplus energy from campus. However, if also surplus wind energy is exported, an enormous 64.1 % can be covered using green wind energy.

Table 13: Performance exported energy volume

Performance	PV export only	PV+Wind export
Exported energy [kWh]	3489	200002
Fraction of residential consumption covered by exported energy	0.9 %	64.1 %

Performance SS, SC, and $CO_{2,tot}$

In Table 14 below, the performance indicators SS, SC, and $CO_{2,tot}$ are displayed, with the percentage reductions in CO_2 emissions for the community in the bottom row.

In the top two rows, the performance of only Bunnik and only the residential area with PV and PV+wind energy are displayed. The performance for Bunnik has been discussed in the previous subsection, the performance for the residential area does not change for the case with wind, as there is no windmill energy allocated to the neighborhoods.

The row "Residential with delivery" shows what the score of the residential community is when surplus energy is delivered to the neighborhoods. The self-consumption does not change, which is logical as there is no increase in its own PV production. The self-sufficiency does improve, as less grid energy has to be imported. There is a very significant improvement in the total CO_2 emissions because of the same reason.

In the bottom row, the performance of the IoE that consists of the Bunnik campus and residential community with delivery from Bunnik is shown, with the total CO_2 emissions with and without delivery from the campus. As can be seen, the gains in total emissions can be very large if wind energy is shared. Delivery from the residential area back to Bunnik is not taken into account in this research.

Table 14: SS, SC and $CO_{2,tot}$ with exported energy

Case	**PV only**	**PV+Wind**
Only Bunnik	SS = 19.0 % SC = 86.9 % $CO_{2,tot} = 189228$ $[kgCO_2]$	SS = 74.4 % SC = 15.3 % $CO_{2,tot} = 30453$ $[kgCO_2]$
Only residential	SS = 11.7 % (max 100 %) SC = 10.7 % $CO_{2,tot} = 230429$ $[kgCO_2]$	SS = 5.6 % (max 53.9 %) SC = 10.4 % $CO_{2,tot} = 168675$ $[kgCO_2]$
Residential with delivery from Bunnik campus	SS = 12.5 % (+0.8, max 100 %) SC = 10.7 % $CO_{2,tot} = 228680$ $[kgCO_2]$	SS = 66.1 % (+60.5, max 100 %) SC = 10.4 % $CO_{2,tot} = 57172$ $[kgCO_2]$
Internet of energy (IoE) Residential and (utilitarian combined with delivery to residential)	SS = 15.8 % (max 65.3 %) SC = 24.2 % No delivery: $CO_{2,tot} = 419657$ $[kgCO_2]$ With delivery: $CO_{2,tot} = 417908$ $[kgCO_2]$ (-0.4 %)	SS = 69.5 % (max 100 %) SC = 29.9 % No delivery: $CO_{2,tot} = 199128$ $[kgCO_2]$ With delivery: $CO_{2,tot} = 87633$ $[kgCO_2]$ (-56 %)

In Figure 13 and Figure 14, the SS and SC are visualized for all cases and for both scenarios. What becomes very clear here is that the Bunnik campus performs very well compared to the residential community or the IoE with delivery. There is a slight improvement in SS for the residential community with delivery. This improvement is much more substantial if also surplus wind energy from Bunnik is consumed by the homes. The performance of the IoE lies between that of the residential community and Bunnik.

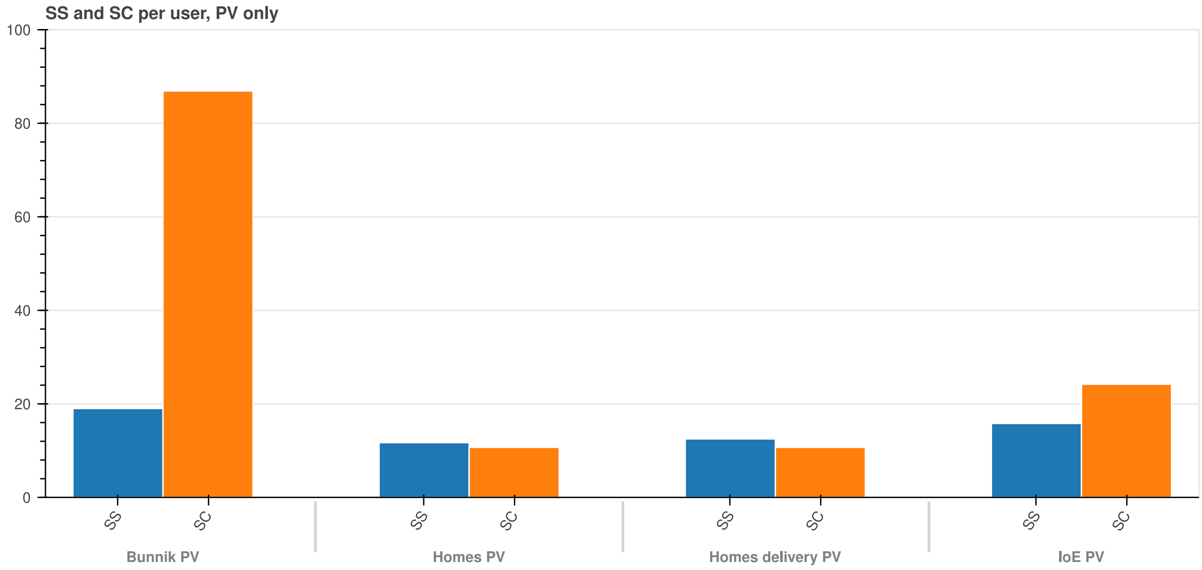

Figure 13: SS and SC for all users with only PV use

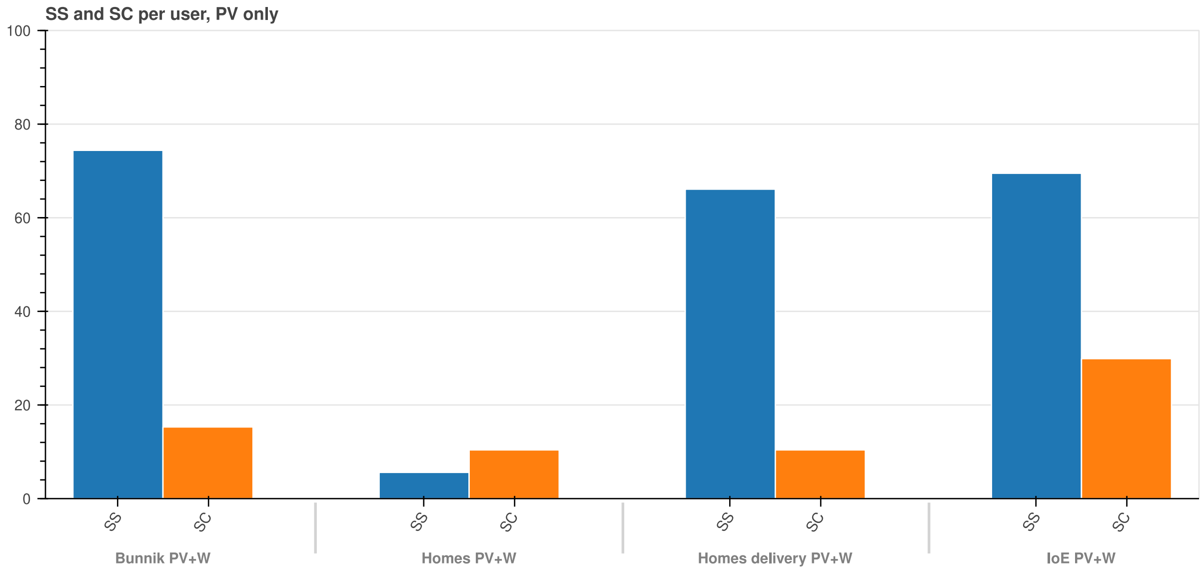

Figure 14: SS and SC for all users with PV and wind usage and sharing

6 Conclusion

In this section, the results will be concluded.

The goal of the first question was to find the optimal size of an on-campus battery, in order to use all locally produced green energy on campus. For this multiple scenarios were set up. Also, the cost is taken into account. Three off-the-shelf battery sizes (240 kWh, 500 kWh, and 1000 kWh) are investigated.

The goal of the second question was to find out what the gain is of sharing energy with a neighboring residential area in order to improve the performance of both the utilitarian campus, the residential neighborhood, and the IoE they form.

6.1 Question one: Battery

The impact of the battery on the total gray energy import is very significant. For the case where only the local PV panels are investigated, a battery can increase the self-consumption to one, which means all locally produced PV energy is consumed on the campus. However, the self-sufficiency remains rather small. Overall, the gains are between 11.4 and 15.3%.

With regard to CO_2 emissions, the gain is marginal at a maximum of 3.6%. This can be explained by the very high self-consumption. Very little energy is left to store and thus to reduce the total CO_2 emissions.

If the energy produced by the windmill is taken into account, the results for self-sufficiency and self-consumption are more or less flipped. The SS is very high and becomes even higher with a battery storage system, due to the big amount of energy that the windmill produces. Because the windmill production is more or less random and not as ideally spread out as that of the PV energy, a battery can have quite a big benefit, with an increase in SS of 21.6% with a 1 MWh battery.

However, the self-consumption becomes very low, again due to the sheer amount of wind energy produced. Still, there is a 21.6% gain with a 1 MWh battery.

The largest gain is in the reduction of CO_2 emissions, with already 29.7% gain at the smallest battery size, all the way up to 62.7% at a 1 MWh battery. The total gray imported grid energy reduces a lot with implementing a battery, which in turn means a big reduction in total CO_2 emissions.

There is one big however, and that is cost. The cost of installing and maintaining a battery storage system is so high, that the total cost of energy increases already more than 250% for the smallest battery, up more than 400%, so four times the cost, for a 1 MWh battery.

This makes the conclusion very simple: implementing <u>only</u> a battery storage system is not financially feasible at this time.

To still decide which battery size would be best, the scoring table is used. This results in the lowest €/kWh price at 500 kWh with PV only and 1 MWh with wind energy. Looking at SS and SC, 500 kWh also has the advantage with only PV and again a 1 MWh battery is the best option when wind energy is taken into account.

If the entire consumption of the Bunnik campus has to come from green sources by using a battery storage system, a 5.4 MWh battery would be needed. In that case, no more grid energy has to be imported and the CO_2 emissions will be zero.

6.2 Question two: Combining with a residential community

The impact of sharing energy between a utilitarian user (the Bunnik campus) and a residential community (Woerden and Soest neighborhoods) is beneficial. Although sharing only the PV energy from Bunnik has very little gains (6.9% reduction in total CO_2), also sharing wind energy shows huge potential for the entire community. A CO_2 reduction of 56% can be achieved.

It can be concluded that the neighborhoods see an improvement in their self-sufficiency from receiving green energy, which again is much larger if also wind energy is shared.

Sharing energy between a utilitarian campus and a residential area shows to be a very promising concept, with small gains for sharing only PV panel energy and large gains if also wind energy is shared.

7 Discussion and recommendations

In this section, the conclusion is expanded with possible options to improve the obtained results and possible further research is explored.

7.1 Question one: Battery

As mentioned before, implementing only a battery storage system is not financially feasible, the increase in cost is too high compared to the increase in performance.

In order to make a battery system feasible, multiple measures should be combined. For example, if energy is bought when it is cheapest and stored in the battery and then consumed when energy is most expensive. This strategy could be implemented when the battery is not or little used (e.g. in periods with little wind or solar energy).

This smart buying of energy can be implemented in a revised version of the battery control logic.

If forecasting of the consumption would be considered, charging the battery with (expensive) wind energy could be paused if a surplus of solar energy is expected. Leaving some overhead in the battery for this surplus would reduce the cost of stored windmill energy. Similar forecasting can also be implemented in the smart buying of energy.

Another way to use the battery is to export and sell part of the stored energy to other users or communities that need energy when the demand in Bunnik is already satisfied. Selling part of the energy in the battery would pay for the battery. Not only stored energy can be sold, but also surplus wind and PV energy can be sold to the market.

Sharing the battery with other members inside a community can introduce benefits to assist with different usage profiles between different users and thus reduce the grid imbalance.

Furthermore, the wind energy that is used right now costs the EPEX price plus a premium. If the windmill would be on-site and would not cost the EPEX price per kWh, the increase in cost can be slightly reduced, just like with the ”free” PV energy. The difference is that a windmill can produce much more energy than the PV panels now available. The drawback is that a windmill has a very high installation cost.

7.2 Question two: Combining with a residential community

As discussed in the conclusion, sharing energy shows to be very beneficial if also wind energy is shared. Sharing surplus energy from the residential community back to the campus has the potential to further reduce the grid import and total CO_2 emissions. The self-sufficiency and self-consumption of the Internet-of-Energy with these two communities will improve.

If a battery is implemented on the Bunnik campus, stored energy might also be shared. If it is expected that there is enough production when energy is needed again and to also charge the battery, stored energy (expected to be surplus) could be exported to another community.

Also, it might be smart to also allocate wind energy directly to the residential community.

7.3 Next steps

Things that can be done in further research on this topic are mentioned above, but the most important ones are implementing multiple measures and then investigating the performance of the campus to see if a battery storage system could be made feasible. For example forecasting and smart buying and selling energy. This can be implemented in a revised battery control logic.

In the future, energy prices might rise even more due to worldwide shortages and ever-increasing consumption. Exploring the same research with increased energy prices could possibly make using a battery more logical.

Furthermore, the potential of sharing energy from a residential community back to Bunnik and sharing a BESS between a residential and utilitarian community can be investigated. If a BESS is shared in the IoE, potentially a bigger battery size could be necessary and useful to investigate.

Lastly, the financial side of sharing energy can be explored to also put a performance indicator on cost in this part of the research. This includes putting a price per kWh shared energy.

7.4 Reflection on the research

With regard to this research, there are some elements that could have been improved upon.

First of all, the data range for the windmill energy is limited to the fall, winter, and spring months, the summer months are not included. This also means that the months where there is the most solar energy production are not taken into account in these analyses. For the case with only PV panel production, also including the summer months had a noticeable influence.

Next, the research could have been expanded to the period after the COVID-19 pandemic, where working partly from home has become more normalized and see if this has an influence on the results.

Lastly, more performance indicators could have been included from the start to improve the decision-making for the optimal battery size. Also, battery efficiency could have been taken into account, as there are always losses involved in storing energy.

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