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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 4b2 Life cycle management of a BESS

Demo site: Chapelle

Developed by
Dr. Dimitri Torregrossa and Julien Furrer,
Aurora's Grid for Romande Energie

[Lausanne, 19.05.2021]

1. Description of deliverable and goal

1.1. Executive summary

Renewable self-consumption, peak-shaving and frequency regulation with the help of renewable power plants can greatly reduce the carbon footprint of these services. With the falling prices of renewable power production and the large penetration of renewable power plants, storage devices can help further to reduce the carbon footprint of the grid. In particular, we saw that for the self-consumption of the building the energy discharged by the battery energy system (BES) allows for an approximate 35% reduction in carbon impact. The carbon footprint of the solar electricity is around 80 gCO2/kWh while the median value of the Swiss electricity is around 210 gCO2/kWh. The impact of manufacturing and recycling the NMC battery is around 311 kgCO2/kWh of storage which distributed over the nominal cycle life of 4500 cycles gives around 70 gCO2/kWh discharged which is close to the impact of the solar electricity.

1.2. Research question

From a C02 footprint point of view, it makes sense to deploy BES for providing self-consumption, peak shaving and ancillary service such as primary frequency control?

How the ageing of the BES impact its C02 footprint?

How the renewable energy content of the main grid impacts the C02 footprint of such services?

1.3. Novelty of the proposed solutions compared to the state-of-art

This deliverable assess the impact the three above services provided by a BES and accounting for ageing of the BES and different renewable ration penetration in the main grid

1.4. Description

[Please provide more background information and technical details on the deliverable]

1.5. Regulatory and legal barriers for implementation

[Please state any necessary regulatory or legal change to implement the proposed solutions in practice]

2. Achievement of deliverable:

2.1. Date

01/01/2021

3. Impact

Carbon footprint assessment of self-consumption, peak-shaving and frequency regulation services, supplied by a battery energy storage systems, a PV system and/or the grid

1. General description

This work aims at assessing the carbon footprint of providing several services to a building or a microgrid with a lithium-ion battery coupled with a photovoltaic system. The analysis includes the energy exchanged between the battery, the PV system and the grid for the three following services: self-consumption, peak-shaving and primary frequency regulation (PCR).

The analysis looks at those three services for three different configurations which differ in the load consumption profile, PV production profile and therefore battery size. Moreover, for each configuration,

a) simulations are performed with two different Energy Management Software (EMS), a standard one and Aurora's Grid EMS which reduces the ageing of the battery system,
b) two charging options with or without the possibility to charge the battery with the grid for the supply of peak-shaving and PCR.

The point b is extremely important to evaluate if it makes sense on a carbon footprint basis to charge the battery with the grid to supply these services.

2. Battery sizing

The sizing of the BES is performed with the help of Aurora's Grid sizing tool with the following data and assumptions.

2.1. Assumptions

Data:

- Building with 102 kWp PV and 63 kWp load (Chapelle-sur-Moudon)
- Building with 80 kWp PV and 47 kWp load (Yverdon)
- Household with 5 kWp PV and 6.5 kWp load (Neuchâtel)

Tariffs for building: RE BT pro faible 2019

- Retail price peak: 0.1795 (CHF/kWh)
- Retail price offpeak: 0.1302 (CHF/kWh)
- Feed in tariff: 0.0816 (CHF/kWh)
- Power cost: 5.299 (CHF/kW/month)

Tariffs for household: RE household 2019

- Retail price peak: 0.2390 (CHF/kWh)
- Retail price offpeak: 0.1515 (CHF/kWh)
- Feed in tariff: 0.0816 (CHF/kWh)
- Power cost: 5.299 (CHF/kW/month)

Battery chemistry: G-NMC
BES price: 500 (CHF/kWh)
BES cycle life: 4500 nominal cycles
Simulation period: 10 years

2.2. Battery size

The optimal battery size was found using Aurora's Grid sizing software in which we provide the power production and load profiles as well as the economic parameters of the services provided by the battery. Such parameters are the peak and off-peak electricity prices, the feed-in tariff, the power price. In this is also required to choose a range of battery sizes that will be simulated, both the capacity and the power converter size are specified. The choice is then based on the size which leads to the highest benefits when the battery is profitable. When the battery is not profitable but a battery must be installed, the choice is based individually depending on the reason of installation.

For the building with 102 kWp PV and 63 kWp load, the resulting size of a previous sizing is considered, which is 40 kWh - 20 kW. As the battery could not be profitable for this scenario, the choice was based on the self-consumption derivative. In Figure 1, we see that 40 kWh is the point with the highest derivative and the highest self-consumption rate.

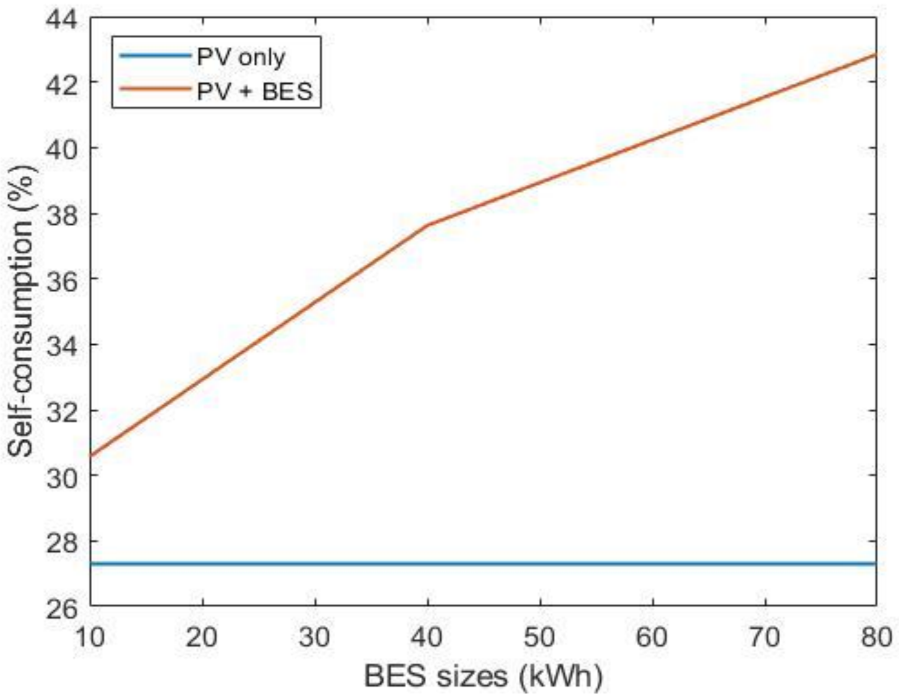

Figure 1: Self-consumption rate vs battery size for the 102 kWp PV and 63 kW load building

For the 80 kWp PV and 47 kW load, the size is already chosen being an existing system. Its size is 100 kWh - 50 kW.

For the smaller building with a 5 kWp PV and 6.5 kW load, the smallest battery is almost profitable as seen in Figure 2. As the battery is almost profitable, it's possible that with electricity prices increasing in the near future, the battery can become profitable. In Figure 3, detailed results are shown and we can see that the smallest battery still adds around 20% of self-consumption which is great for this household. The smallest size is therefore chosen.

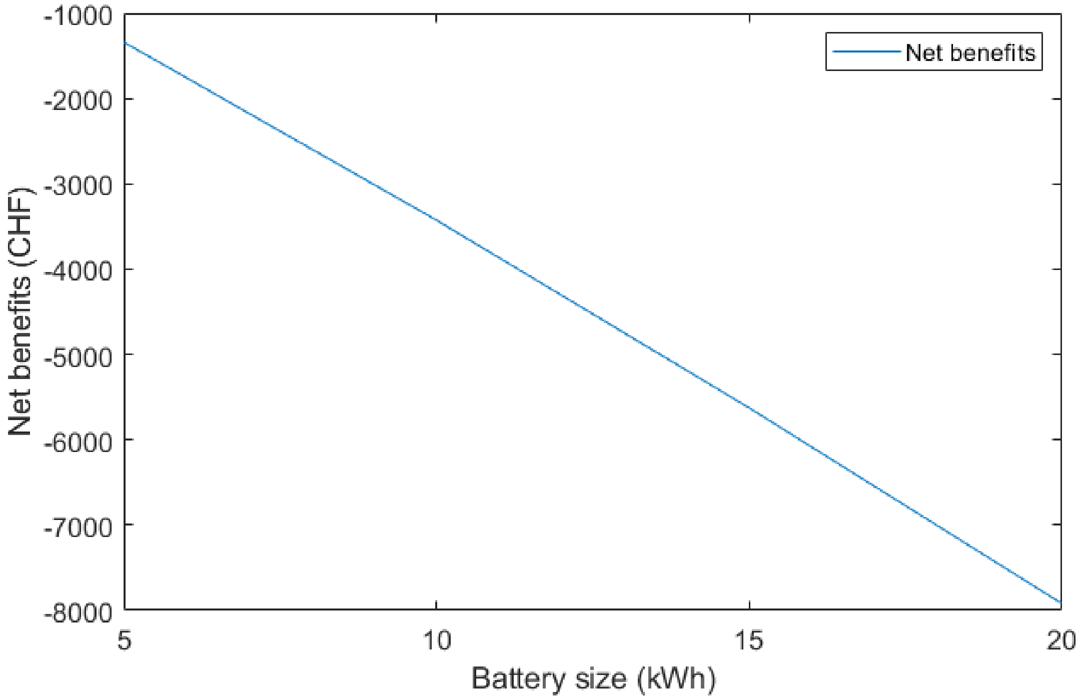

Figure 3: Net benefits vs battery size for the 5 kWp PV and 6.5 kW load building

3. Assessment method

This assessment is a relatively simple life cycle assessment (LCA) because it only looks at a fraction of the entire system for the use phase. Indeed, the focus is the supply of three services (self-consumption, peak-shaving and frequency regulation) by the PV and battery system. Instead of looking at all the energy exchanges, we only look at few of them. An example with providing self-consumption, we assess the carbon footprint of the

Figure 2: Self-consumption rate and revenues for several battery sizes

1 (Best)	5.1	5	PV: 31.5% PV and BES: 53.1%	1.161	95.4%	4.6%
2	5.1	10	PV: 31.5% PV and BES: 62.4%	1.574	94.1%	5.9%
3	5.1	15	PV: 31.5% PV and BES: 65.4%	1.873	87.4%	12.6%
4	5.1	20	PV: 31.5% PV and BES: 67.2%	2.08	83.1%	16.9%

energy supplied by the battery even if this fraction of the energy supplied is not 100% of the energy supplied to the building. The scope and the methodology are explained below. In the results below, two scenarios are presented with a Standard or Aurora's Grid EMS. EMS stands for Energy Management Software (EMS) which is controller of the battery as well as the monitoring unit. It is the EMS which is responsible for choosing how and when to charge and discharge the battery and for which services. It is the core algorithm of the battery system.

3.1. Carbon footprint of electricity

The carbon footprint of electricity from different origin is used in this assessment. Two different origins are indeed needed, the Swiss grid and the PV system.

The Swiss electricity carbon content is based on the work of Didier Vuarnoz from the Building 2050 Research Group of EPFL. who works on the greenhouse gas emissions of the Swiss electricity.

His work aims at improving the inventory used for LCA when studying electricity use supplied by the grid. Most of the time when LCA data of electricity supplied by the grid is used, the carbon footprint of data corresponds to an average annual value and this introduces a very large error when the time resolution of the energy use is not on an annual basis but on a smaller resolution such as hours or smaller. The grid's electricity is made of a mix that varies all the time and this is even more the case today with the increasing portion of renewable energy. This study used an hourly dataset of the Swiss' electricity mix and the carbon footprint value associated with the corresponding sources in order to compute the hourly carbon footprint of the electricity mix. A deeper look at his work can be seen in [1].

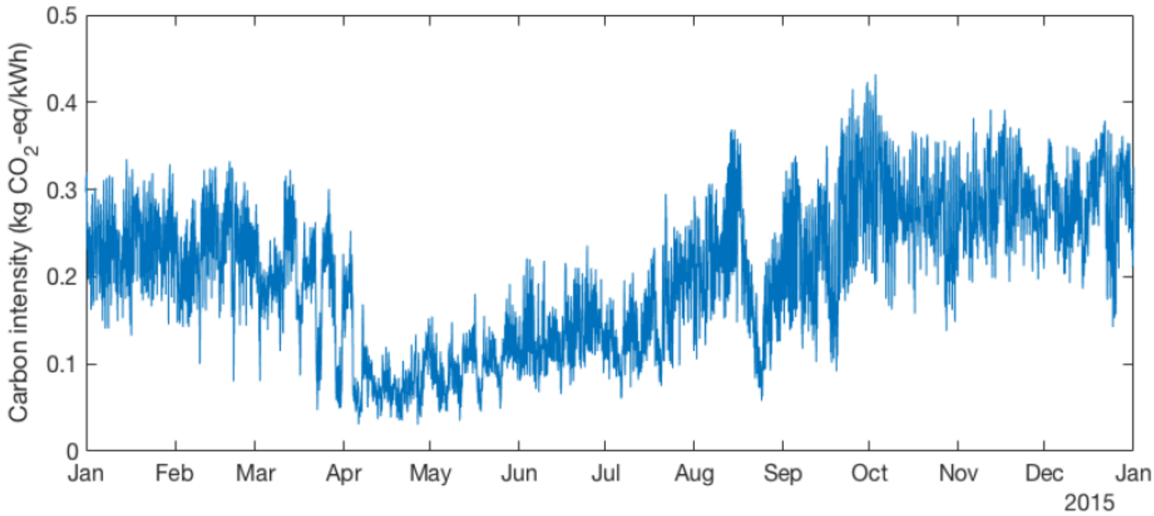

Figure 4: Hourly carbon intensity of the Swiss electricity for the year 2015

The carbon content of electricity coming from PV is assumed as 83.6 kgCO2/kWh, this value comes from the Ecoinvent dataset *PV 3kWp roof installation multi-Si panel [CH]*. It corresponds to the carbon impact of the manufacturing, the use and the recycling, normalized by the nominal energy that can be produced over the panel's lifetime.

3.2. Carbon impact of the battery system

The carbon impact coming from the manufacturing and the recycling of the battery storage system is taken from [2]. In this work, a complete LCA was done for Li-ion batteries, from the manufacturing to the end-of-life (recycling). The functional unit of this study, or the value to quantify to function of the system, was 1 kWh of storage capacity of the battery which is helpful to use as it is normalized. The life cycle inventory, or the data collection, contained manufacturing data of Leclanché SA for both NMC and LTO chemistries and the Ecoinvent database. No LCA software was used and the whole analysis was done in Matlab. The impact characterization method used is the ReCIPe method for midpoint indicators from a hierarchical perspective. The allocation cut-off method is used. ReCIPe from a hierarchical perspective is the most used method in the LCA scientific community, it is a consensus model. The midpoint indicators consist of a list of specific indicators used to characterize the environmental impacts. Finally, the cut-off model specifies that the allocation of the material production goes to the primary user. This means if the material is recycled, the primary user does not get credit for it and the burdens of recycling are allocated to this primary user.

The analysis for the manufacturing of the battery packs started from the analysis of the battery cell with all of its components and their production. Then the battery module was assessed with the correct number of battery cells and the numerous other components. The same logic was used for the battery pack. Transport for the modules and packs were also considered. The components of the battery can be seen in Figure 5.

Configuration	Content	Storage capacity (kWh)
Graphite/NMC battery rack	10 modules	96
Graphite/NMC battery module	60 cells	9.6
Graphite/NMC battery cell	Miscellaneous	0.160

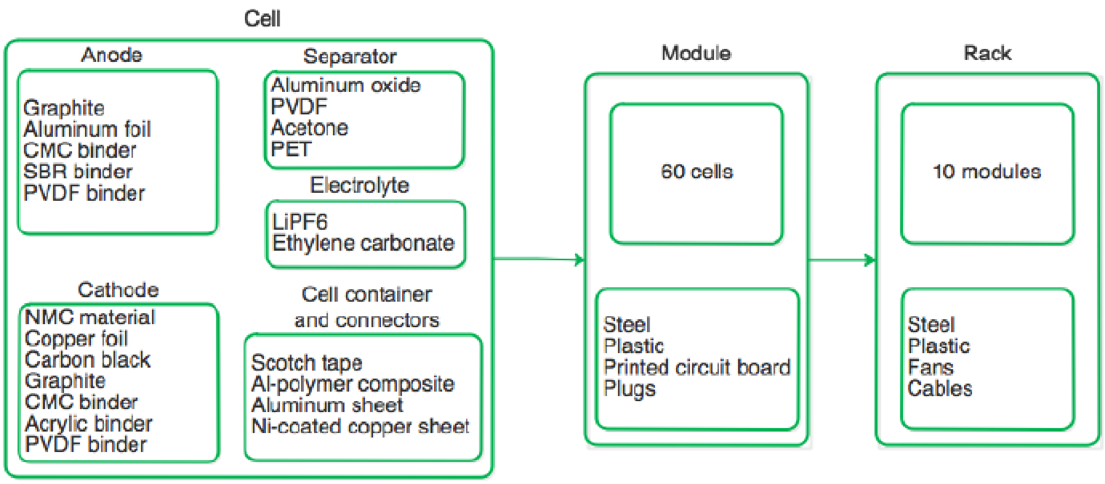

Figure 5: Graphite/NMC battery composition [2]

Numerous assumptions were made such as the chemistry and manufacturing data which come from Leclanché SA. Each battery chemistry and manufacturing are slightly different but having access to an almost complete list of battery components is very hard [3] to find meaning that this analysis had many details on this data collection side. Data on the manufacturing processes were not very precise so approximations on the processes were made. A further and more detailed analysis on the cell manufacturing operations would be beneficial. Indeed, as seen in Figure 6, the cell manufacturing has the highest contributions in most of the environmental impacts, representing around 70% for the carbon footprint (GWP100 in the figure).

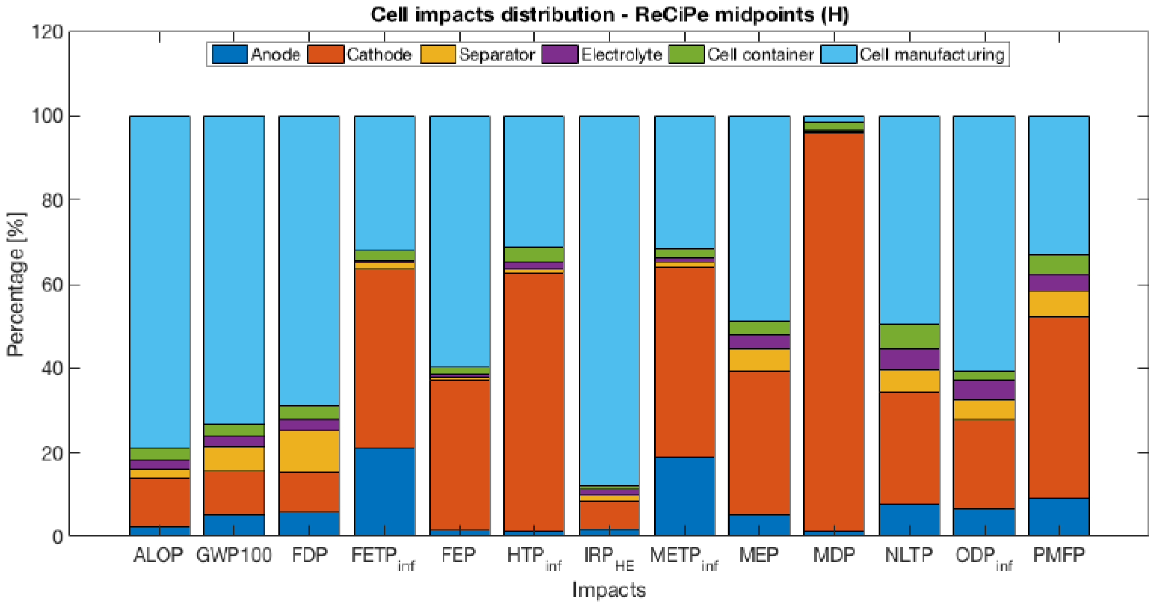

Figure 6: : Impacts distribution for a Graphite/NMC cell [2]

At the end of the analysis, the results were normalized by the size of the battery studied in order to get a result that is easy to use in order analysis. The obtained result is the carbon footprint per kWh of capacity (kgCO2 / kWh capacity).
In the end, the result of the battery impact was 311 kgCO2 /kWh capacity which includes the recycling. The total impact of manufacturing and recycling has to be normalized by the nominal cycle life in order to distribute the impact on the usage of the battery.
At that time and still today, second-life batteries are not very common and it is therefore really difficult to have precise data on the reconditioning of first-life battery packs into second-life battery packs. The reconditioning impact were assumed following a slingshot assumption of 30% of the manufacturing impact. This would mean the impact of a reconditioned battery pack is around 93.3 kgCO2/kWh capacity, including the later recycling.
Further work could include an updated list of components and processes and a report of the electricity's origin used in the factories in order to get more accurate results on the process side of manufacturing. Moreover, getting data on the reconditioning operations for a second-life battery pack would be highly beneficial in order to assess precisely the impact of this kind of system.
The nominal cycle life of the battery is assumed as 4500 cycles, which means each cycle of 1 kWh (100% DOD, charge + discharge 1C) consumes approximately 0.069 kgCO2 (311 kgCO2/kWh capacity / 4500 cycles of nominal capacity).

3.3. Carbon footprint of self-consumption

The first service is the self-consumption and, in that case, we look at the impact of supplying this service with energy coming from the BES (and therefore from the PV system) compared to consuming directly from the grid.
When the electricity comes from the battery, its impact is the carbon content of the PV electricity which is constant. However, when electricity is coming from the grid, it's necessary to look at the time because the carbon content of the grid is constantly changing. The energy supplied by the grid corresponds to the energy discharged by the battery but its CO2 impact is different.

3.4. Carbon footprint of peak-shaving

The second service is peak-shaving and the two options are either to supply completely the service with the battery charged with solar energy, either charging the battery with the grid in order to create dedicated reserves.

The impact of this service is assessed by computing the energy reserves required based on the power profiles of each configuration and by multiplying these reserves by the electricity carbon content for both electricity origins, PV and the grid. Moreover, for the electricity charged with the grid, it's necessary to take the carbon content at the time of the charge, which is set at 12 hours before the peaks. Indeed, the battery has to be charged sometime in advance and we assume that the forecast of the peak is done at least 12 hours before the peaks.

$$I_{peak(i),grid} = energy\_reserve_{peak(i)} \cdot mean(I_{grid}(t_{peak(i)} - 12\ hours : t_{peak(i)} - 12\ hours + charge\_time)$$

$$I_{peak(i),PV} = energy\_reserve_{peak(i)} \cdot I_{PV}$$

where:

$I_{peak(i),m}$: Impact of peak number i supplied by system m (grid, PV) (kgCO2);

$energy\_reserve_{peak(i)}$: Energy reserve required to supply peak i (kWh);

$I_{grid}(t)$: CO2 impact of the grid's electricity at time t (kgCO2/kWh);

I_{PV}: CO2 impact of PV electricity (kgCO2/kWh).

3.5. Carbon footprint of PCR

The third and last service is frequency regulation (PCR) and because of the complexity to differentiate the electricity's origin when this service is enabled, simplifications are made to assess the carbon footprint of providing this service.

The energy exchanges considered are the energy going from the PV system to the PCR demand and the energy from the battery going to the PCR demand. In the first option, the energy going from the battery has been charged with the PV production only. In the second option, we assume that 75% of the energy supplied by battery to the PCR comes from PV generation, while 25% is charged with the grid. The latter percentage of energy is therefore charged with the grid's carbon content based on the time of the charge. The value of 25% comes from previous simulations where we noticed that on average this fraction of the energy exchanged with PCR could not be supplied due to the battery being at the limit SOC.

3.6. Carbon footprint of the battery usage

The battery usage implies a carbon impact which corresponds to the portion of the total impact, caused by manufacturing and recycling, based on the number of kWh charged and discharged compared to the lifetime of the system.

The carbon impact is simply the impact of manufacturing and recycling, divided by the nominal cycle life and multiplied by the number of kWh discharged.

$$I_{BES\ use} = I_{BES\ production} \cdot BES_{capacity} \cdot \frac{energy\_discharged}{BES_{capacity} \cdot nominal\ cycles}$$

$$I_{BES\ use} = I_{BES\ production} \cdot BES_{capacity} \cdot \frac{energy\_discharged}{BES_{capacity} \cdot nominal\ cycles}$$

where:

$I_{BES\ use}$: Carbon impact of the BES usage (kgCO2);

$I_{BES\ production}$: Manufacturing and recycling footprint of the BES (kgCO2/kWh);

$BES_{capacity}$: Storage capacity (kWh);

$nominal\ cycles$: Cycle life of the BES (cycles);

$energy\_discharged$: Energy discharged by the BES (kWh).

4. Results

The following tables present the results of the carbon footprint assessment for the supply of self-consumption, peak-shaving and PCR with a battery coupled to a PV system. Two cases are presented each time with two different Energy Management Softwares, a standard one and Aurora's Grid EMS.

4.1. Building with 102 kWp PV and 63 kWp load

Self-consumption

In this configuration, Aurora's Grid EMS allows a decrease in the carbon footprint impact of the self-consumption. However, this decrease is due to the more restrictive limits set by the EMS in order to reduce the ageing, meaning that more energy has to be bought from the grid to supply the consumption. We can see in Table 1 that self-consuming energy coming from PV has a much smaller footprint than consuming only electricity from the grid (13723.07 versus 21718.74 kgCO2, a 36.82% reduction).

Table 1: Carbon impact - Building 102 kWp PV & 63 kW load - Self-consumption

EMS	Charge	Self-consumption (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	7512.20	7512.20	12440	6210.87	13723.07
	Grid	21718.74	21718.74		0	21718.74
Aurora's Grid	PV	7234.11	7234.11		5980.95	13215.06
	Grid	20934.39	20934.39		0	20934.39

Self-consumption & peak-shaving

When it comes to peak-shaving, as the energy reserves are entirely coming from the PV or the grid, we see in Table 2 that the difference is even bigger, from 86.72 kgCO2 to 246.72 kgCO2, which is a 185% increase, without counting the usage of the battery. It does not make sense environmentally to charge the battery with the grid to supply this service. We also see that the impact of using the battery for peak-shaving is very small compared to the usage of the battery for self-consumption.

Table 2: Carbon impact - Building 102 kWp PV & 63 kW load - Self-consumption & peak-shaving

EMS	Charge	Self-consumption (kgCO2)	Peak-shaving (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	7512.20	86.72	7512.20	12440	6282.56	13795.76
	Grid	21718.74	246.72	21718.74		71.69	21790.43
Aurora's Grid	PV	7234.11	86.72	7234.11		6052.64	13286.75
	Grid	20934.39	246.72	20934.39		71.69	21006.08

Self-consumption & PCR

The results for PCR show a higher carbon footprint because in the case where the battery is charged by PV and the grid, the electricity charged by the grid has a higher carbon footprint that the electricity coming from the PV. The increase of CO2 impact is approximately 23%. By comparing the results with the standard EMS and Aurora's Grid EMS, we can see that the impact is slightly higher with Aurora's Grid EMS and this is due to the dynamic limitations of the battery use which cause the battery to be a little less charged with PV, and therefore the grid is used a bit more.

Table 3: Carbon impact - Building 102 kWp PV & 63 kW load - Self-consumption & PCR

EMS	Charge	Self-consumption (kgCO2)	PCR (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	8024.47	1507.44	9531.91	12440	7421.99	16953.9
	PV, grid	23138.95	1855.95	24994.9		787.6	25782.5
Aurora's Grid	PV	7741.37	1516.27	9257.64		7201.63	16459.27
	PV, grid	22337.79	1870.84	24208.63		801.28	25009.86

4.2. Building with 80 kWp PV and 47 kWp load

The results for the case of the second building show the same trend and therefore, explanation of the results of the first building are valid for these results.

Self-consumption

Table 4: Carbon impact - Building 80 kWp PV & 47 kW load - Self-consumption

EMS	Charge	Self-consumption (kgCO2)	Total (services)	BES production & recycling	BES usage (kgCO2)	Total (kgCO2)

			(kgCO2)	(kgCO2)		
Standard	PV	12334.64	12334.64	31100	10197.92	22532.56
	Grid	35349.28	35349.28		0	35349.28
Aurora's Grid	PV	12083.51	12083.51		9990.29	22073.8
	Grid	34676.69	34676.69		0	34676.69

Self-consumption & peak-shaving

Table 5: Carbon impact - Building 80 kWp PV & 47 kW load - Self-consumption & peak-shaving

EMS	Charge	Self-consumption (kgCO2)	Peak-shaving (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	12334.64	296.96	12631.60	31100	10443.44	23075.04
	Grid	35349.28	857.29	36206.57		245.52	36452.09
Aurora's Grid	PV	12083.51	296.96	12380.47		10235.81	22616.28
	Grid	34676.69	857.29	35533.98		2455.21	37989.19

Self-consumption & PCR

Table 6: Carbon impact - Building 80 kWp PV & 47 kW load - Self-consumption & PCR

EMS	Charge	Self-consumption (kgCO2)	PCR (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	14762.74	3270.43	18033.17	31100	14227.57	32260.74
	PV, grid	42346.64	4165.23	46511.87		2022.17	48534.04
Aurora's Grid	PV	14612.26	3271.44	17883.70		14105.09	31988.79
	PV, grid	41938.75	4167.09	46105.84		2024.10	48129.94

4.3. Household with 5 kWp PV and 6.5 kWp load

The results for the case of the second building show the same trend and therefore, explanation of the results of the first building are valid for these results.

Self-consumption

Table 7: Carbon impact - Household 5 kWp PV & 6.5 kW load - Self-consumption

EMS	Charge	Self-consumption (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	864.30	864.30	1555	714.57	1578.87

	Grid	2475.79	2475.79		0	2475.79
Aurora's Grid	PV	822.15	822.15		679.73	1501.88
	Grid	2355.65	2355.65		0	2355.65

Self-consumption & peak-shaving

Table 8: Carbon impact - Household 5 kWp PV & 6.5 kW load - Self-consumption & peak-shaving

EMS	Charge	Self-consumption (kgCO2)	Peak-shaving (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	864.30	5.60	869.90	1555	719.21	1589.11
	Grid	2475.79	15.71	2491.50		4.63	2496.13
Aurora's Grid	PV	822.15	5.60	827.76		684.37	1512.13
	Grid	2355.65	15.41	2371.37		4.63	2376

Self-consumption & PCR

Table 9: Carbon impact - Household 5 kWp PV & 6.5 kW load - Self-consumption & PCR

EMS	Charge	Self-consumption (kgCO2)	PCR (kgCO2)	Total (services) (kgCO2)	BES production & recycling (kgCO2)	BES usage (kgCO2)	Total (kgCO2)
Standard	PV	913.34	215.25	1128.59	1555	887.64	2016.23
	PV, grid	2615.80	273.89	2889.73		135.52	3025.25
Aurora's Grid	PV	879.13	215.61	1094.74		859.87	1954.61
	PV, grid	2517.79	274.48	2792.27		133.03	2925.3

5. Sensitivity analysis

The carbon footprint of PCR is assessed with the assumption that 75% of the energy supplied to PCR comes from the PV system and 25% is charged with the grid. In order to see the variations in carbon footprint associated with these fractions, a sensitivity analysis is done with the fraction of energy supplied coming from the PV system going from 60 to 90% and the fraction of energy charged with the grid going from 10 to 40%.

5.1. Building with 102 kWp PV and 63 kWp load

Table 10: Sensitivity analysis - Fractions of energy charged by (PV - the grid) - Building 102 kWp PV & 63 kW load

EMS\fractions	90-10	85-15	80-20	75-25	70-30	65-35	60-50
S – PV	1507						
S – PV & grid	1647	1717	1786	1856	1926	1995	2065

AG - PV	1516						
AG – PV & grid	1658	1729	1800	1871	1942	2013	2084

All results are in (kgCO2)
S: Standard EMS
AG: Aurora's Grid EMS
PV: Charge with PV only
PV & grid: Charge with PV and grid

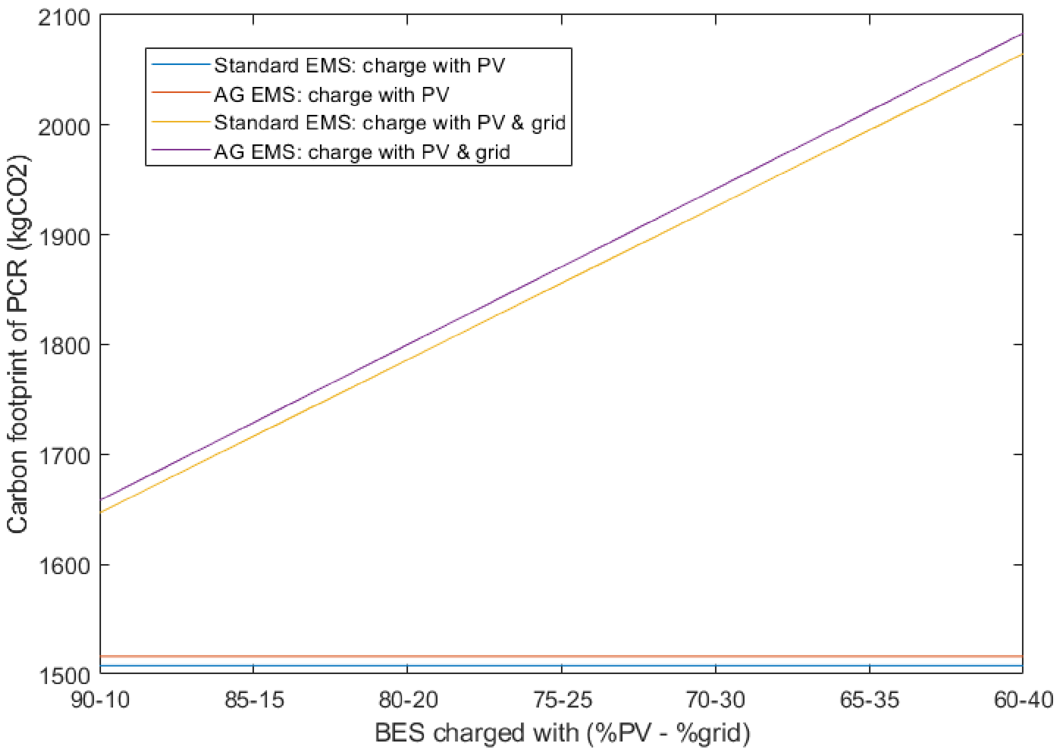

Figure 7: Effect of electricity origin for PCR supply - Building 102 kWp PV & 63 kW load

As seen in Figure 7, the carbon impact of PCR linearly depends on the fraction of the energy charged by the PV system or the grid. As a reminder, the grid's carbon content for the electricity charged with the grid is an annual average as the model doesn't include further details as explained in the possible improvements.
The increase of carbon footprint for this service is a bit less than one percent per unit decrease of the PV fraction.

5.2. Building with 80 kWp PV and 47 kWp load

Table 11: Sensitivity analysis - Fractions of energy charged by (PV - the grid) - Building 80 kWp PV & 47 kW load

EMS\fractions	90-10	85-15	80-20	75-25	70-30	65-35	60-50
S – PV	3270						
S – PV & grid	3628	3807	3986	4165	4344	4523	4702

AG - PV	3271						
AG – PV & grid	3630	3809	3988	4167	4346	4525	4704

All results are in (kgCO2)
S: Standard EMS
AG: Aurora's Grid EMS
PV: Charge with PV only
PV & grid: Charge with PV and grid

The increase of carbon footprint for this service is around one percent per unit decrease of the PV fraction.

5.3. Building with 5 kWp PV and 6.5 kWp load

Table 12: Sensitivity analysis - Fractions of energy charged by (PV - the grid) - Building 5 kWp PV & 6.5 kW load

EMS\fractions	90-10	85-15	80-20	75-25	70-30	65-35	60-50
S – PV	215						
S – PV & grid	239	250	262	274	286	297	309
AG - PV	216						
AG – PV & grid	239	251	263	274	286	298	310

All results are in (kgCO2)
S: Standard EMS
AG: Aurora's Grid EMS
PV: Charge with PV only
PV & grid: Charge with PV and grid

The increase of carbon footprint for this service is around one percent per unit decrease of the PV fraction.

6. Conclusion

From the results shown, it is safe to say that providing self-consumption, peak-shaving and frequency regulation with the help of renewable power plants can greatly reduce the carbon footprint of these services. With the falling prices of renewable power production and the large penetration of renewable power plants, storage devices can help further to reduce the carbon footprint of the grid.
In particular, we saw that for the self-consumption of the building the energy discharged by the battery system allows for an approximate 35% reduction in carbon impact. The carbon footprint of the solar electricity is around 80 gCO2/kWh while the median value

of the Swiss electricity is around 210 gCO2/kWh. The impact of manufacturing and recycling the NMC battery is around 311 kgCO2/kWh of storage which distributed over the nominal cycle life of 4500 cycles gives around 70 gCO2/kWh discharged which is close to the impact of the solar electricity.

We also saw that charging a battery with the grid in order to provide peak-shaving increases by almost 200% the impact for this service. However, in terms of energy this service does not require as much energy as one could imagine. Therefore, the impact of this service is relatively small compared to the self-consumption.

Finally, we showed that charging the battery with the grid in order to be able to provide PCR can increase the carbon footprint of providing this service by almost 25% in comparison of being able to provide this service only with our renewable power source. By looking at Figure 4, one can notice that the carbon content of the electricity varies a lot and not only on a seasonal basis but also on a daily basis. From that point, power reserves charged from the grid can also contribute to reduce the carbon content of the grid by acting as a green reserve.

To conclude, it is important to remember that the battery's cycle life was assumed as 4500 cycles as specified by the manufacturer. However, this doesn't mean that the battery can't be used beyond this number of cycles as this limit highlights the standard use leading to a capacity degradation of 20%. From this point, the battery can still be used many more years. Moreover, batteries coming from mobility applications can be reused in stationary applications for a so-called second-life [7][8] which greatly prolongs the life of the system and therefore allows a smaller footprint. Indeed, expanding the lifetime of a system allows a wider distribution of the environmental burden over time and also to postpone the need of a new system. This is the goal of an ageing-aware EMS which extend the life of the system.

7. Further improvements

Improvements can be implemented in this LCA model in order to assess more precisely the carbon impact of providing these different services with a battery charged by a PV installation or by both a PV installation and the grid.

The improvement that would be the most important to do is about providing PCR with energy charged from the grid. In the above simplified model, we do not know the origin of the electricity supplied to the PCR, therefore an assumption of 25% is made. However, to be precise, the time and origin of the energy charged should be monitored precisely. After what, some assumptions with respect to the discharge should be considered because it's not possible to physically know if the energy discharged at a certain time was charged by the grid or the PV. Once in the battery, the information about the origin of the energy is lost. Those modifications would allow already a better carbon footprint assessment for the supply of PCR by the system.

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