Carbon Footprint and Social Impact Assessment of Stationary Batteries in Distribution Grids

Johanna Pucker-Singer, Ingrid Kaltenegger, Jernej Zupančič, David Neil Bird, Andrej Gubina, Hannes Schwaiger

JOANNEUM RESEARCH Forschungsgesellschaft mbH, LIFE – Institute for Climate, Energy and Society, Waagner-Biro-Straße 100, 8020 Graz, +43 316 876-7637, johanna.pucker-singer@joanneum.at, www.joanneum.at/life

Univerza v Ljubljani, Laboratory of Energy Policy, Faculty of Electrical Engineering, Tržaška cesta 25, SI-1000 Ljubljana, Slovenija, +386 1 4768 222, Jernej.Zupancic@fe.uni-lj.si, www.fe.uni-lj.si

Abstract: The European project STORY demonstrates and evaluates innovative approaches for energy storage systems in the residential and industrial sectors. To assess the environmental impact of storage systems within the project, a Life Cycle Assessment (LCA) is performed for different storage implementation scenarios. In more detail, network development scenarios with and without battery energy storage are compared. Each scenario provides electricity to households and electric vehicles. The electricity consumption is covered by local PV plants and electricity from the grid. Surplus electricity from PV is injected into the power grid. In this paper, we will show the climate impact (so-called carbon footprint) of the battery-systems for the investigated large-scale and demo-scale scenarios and identify the main factors influencing the results. Similar to LCA, Social Life Cycle Assessment (sLCA) incorporates the traditional LCA methodological steps, while having social impacts as a focus. In addition, from the sLCA, the evaluation of large-scale battery storage implementation using appropriate social indicators (e.g. employment, health and safety, prevention of forced and compulsory labour) is presented.

Keywords: energy, storage, lithium-ion battery, carbon footprint, LCA, sLCA, social hot spots, critical raw materials

1 Introduction

The European project STORY (Added value of STORage in distribution sYstems) demonstrates and evaluates innovative approaches for energy storage systems in the residential and industrial sectors.

The overall objective of STORY is to show the benefit storage can bring for a flexible, secure and sustainable energy system. The project specifically focuses on the added value of energy storage in distribution systems [1]. STORY includes six demonstration sites, which range in size from individual buildings to the district level, and are located in five member states. They include different energy storage types, different renewable energy technologies, and target different project goals (Figure 1). All demonstration activities deliver input on technological performance, stakeholder acceptance and on the overall process of storage integration.

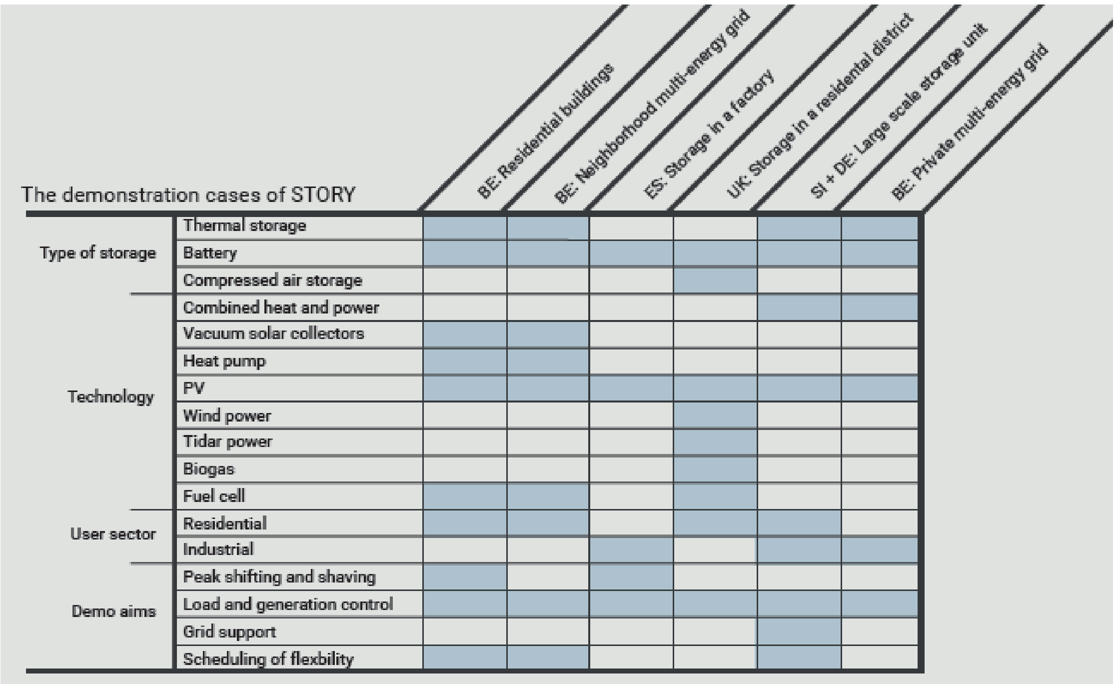

Figure 1: Overview on the STORY demonstration cases [2]

The knowledge gained from the demonstration activities feeds into a business model analysis and a large-scale impact assessment, which are used to evaluate the large-scale integration of small-scale storage units in the European distribution networks. Many benefits are expected to arise from a large-scale integration of storage solutions in the distribution system. Storage integration in combination with appropriate business models empower different actors (e.g. distribution system operators, aggregators, consumers, storage operators) to position new services on the electricity market. These services provide financial, operational and other benefits to the power system and its actors. To measure these benefits in STORY a Value Analysis Framework was defined (Figure 2), also including the evaluation of environmental and social impacts of storage integration.

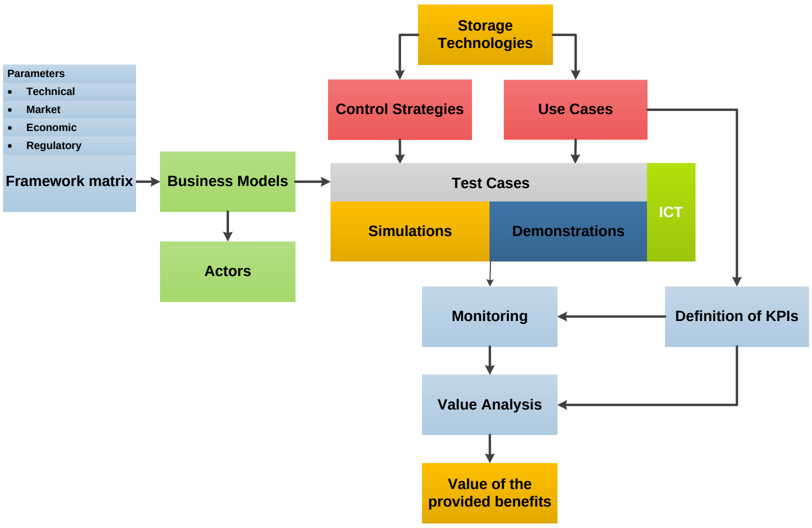

Figure 2: STORY Value Analysis Framework

In this paper, we present selected project results on the climate impact and social impact of storage integration in the distribution grid.

2 Climate impact

2.1 Methodology

To estimate the climate impact of storage integration in the distribution grid a Life Cycle Assessment (LCA) was performed for different storage implementation scenarios.

According to ISO 14040 [3] 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).

Within the STORY project several environmental impacts were investigated (e.g. acidification potential, cumulated primary energy demand). In this paper, we will show the climate impact (so-called carbon footprint [4]) of battery systems in distribution grid networks.

The assessment of the climate impact includes the greenhouse gases (GHG) shown in Table 1. Global Warming Potential on a 100 year time horizon (GWP 100) was used to express the contribution of the listed gases (e.g. CH_4, N_2O, R-14) to global warming, in terms of equivalent amount of CO_2 (CO_2-eq) [5].

Table 1: Investigated GHGs and their CO_2-equivalent factors (including Climate Carbon Feedback) [5]

Category	GHG	CO_2-equivalent
	CO_2	1
	CH_4	34
	N_2O	298
Chloro-fluorocarbon (CFC)	CFC-113	6 586
	CFC-114	9 615
	CFC-115	7 370
	CFC-13	15 451
	CFC-12	11 547
	CFC-11	5 352
Hydrochloro-fluorocarbons (HCFC)	HCFC-141b	938
	HCFC-142b	2 345
	HCFC-123	96
	HCFC-124	635
	HCFC-22	2 106
	HCFC-21	179
Organ-chloride	HCC-30	11
	R-10	2 019
	R-40	15

Category	GHG	CO_2-equivalent
Hydrofluorocarbon (HFC)	HFC-134a	1 549
	HFC-143a	5 508
	HFC-152a	167
	HFC-116	12 200
	HFC-125	3 691
	HFC-32	817
	R-14	7 390
	HFC-23	13 856
	HFC-43-100mee	1 952
	HFC-227ea	3 860
	HFC-236fa	8 998
	HFC-245fa	1 032
	PFC-318	10 592
	PFC-5-1-14	9 300
	PFC-218	9 878
	PFC-3-1-10	10 213
	PFC-4-1-12	9 484

2.2 Investigated scenarios

The goal of the LCA is to investigate the climate impact of storage integration in the distribution grid. Therefore, we compare network development scenarios with and without batteries, to assess the changes occurring from the battery integration.

First, the grid model and the network development scenarios were investigated in a technical impact simulation. This impact simulation is performed for two scales: (1) for large-scale storage integration and (2) on demonstration scale, more closely simulating the demonstration environment.

Details on the technical impact simulation are described in [6]. In the following section, the most important aspects for the LCA are described.

2.2.1 Large-scale storage implementation

For large-scale storage implementation, different network development scenarios are assessed. They are characterised by:

- the installed power from renewable energy sources (PV power plants in the distribution grid),
- the installed capacity of electric vehicles (EV), and
- the installed storage capacity and the storage unit type (lithium ion battery installed in households or a community size lithium ion battery system connected at the MV/LV transformer station supplying the LV network)

To investigate technical effects of these scenarios on the distribution grid a simulation platform was developed with proposed grid model implemented in the platform [6]. The grid model covers all the important parts of the distribution system. Medium- and low voltage (MV and LV) networks are supplied from high voltage connection point (Figure 3). The network model covers a rural and urban grid configuration on the medium and the low voltage level. Detailed model includes three-phase models of consumption, generation and storage as new emerging connected devices. Data based on yearly measurements was used as the simulation input. Household consumption profiles, renewable generation from PV, electric vehicle model and charging strategy were important network parameters in addition to electric energy storage as the main focus of the simulations.

For the LCA, we selected eight network development scenarios (Table 2). The percentage-values in Table 2 refer to 30 MVA nominal power of the HV/HV transformer (Example: 110% RES means 33 MW installed power of RES units). Figure 4 shows a simplified scheme of the scenarios including the system components and energy flows most relevant for the LCA. Each scenario provides electricity to households and electric vehicles. The electricity consumption is covered by local PV plants and the main grid. Surplus electricity from PV, when it is available, is injected into the power grid

Table 2: Network development scenarios investigated using LCA (percentage values refer to 30 MVA nominal power of HV/MV transformer)

Scenario - Short Name	RES installed power	EV installed capacity	Storage installed capacity (Unit type)	Group
1_40%RES_5%EV_0%Batt	40%	5%	0%	"Low PV, low EV"
2_40%RES_5%EV_15%Batt(Household)	40%	5%	15% (Household)	
4_40%RES_5%EV_30%Batt(Household)	40%	5%	30% (Household)	
6_110%RES_40%EV_0%Batt	110%	40%	0%	"High PV, high EV"
3_110%RES_40%EV_15%(Grid)	110%	40%	15% (Grid)	
7_110%RES_40%EV_30%(Household)	110%	40%	30% (Household)	
9_110%RES_40%EV_80%(Household)	110%	40%	80% (Household)	
10_110%RES_40%EV_80%(Grid)	110%	40%	80% (Grid)	

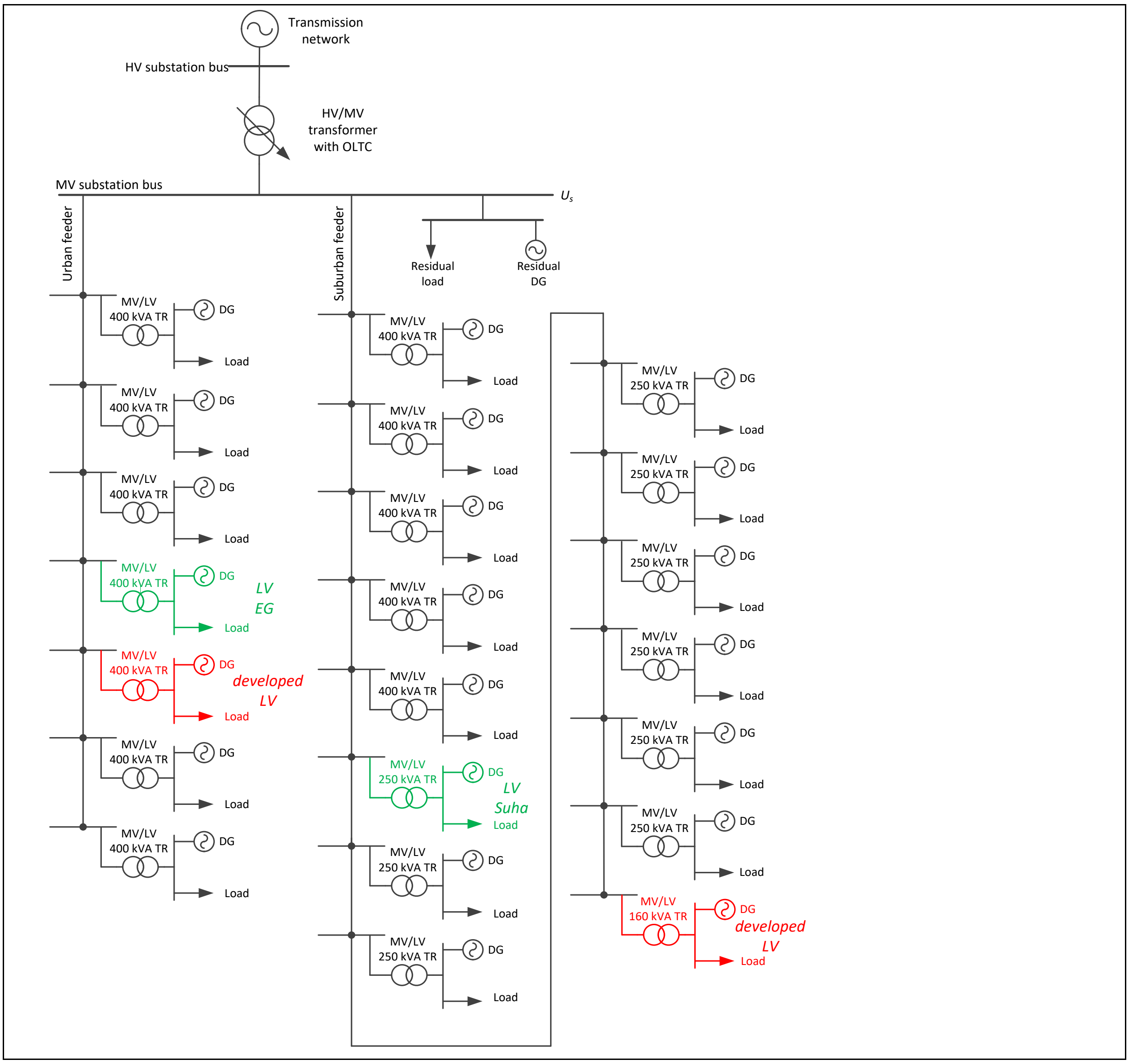

Figure 3: Simulated network structure - Single-line MV distribution network scheme with two feeders. Location of fully modelled synthetic LV networks (red) and real networks (green) are also shown [6].

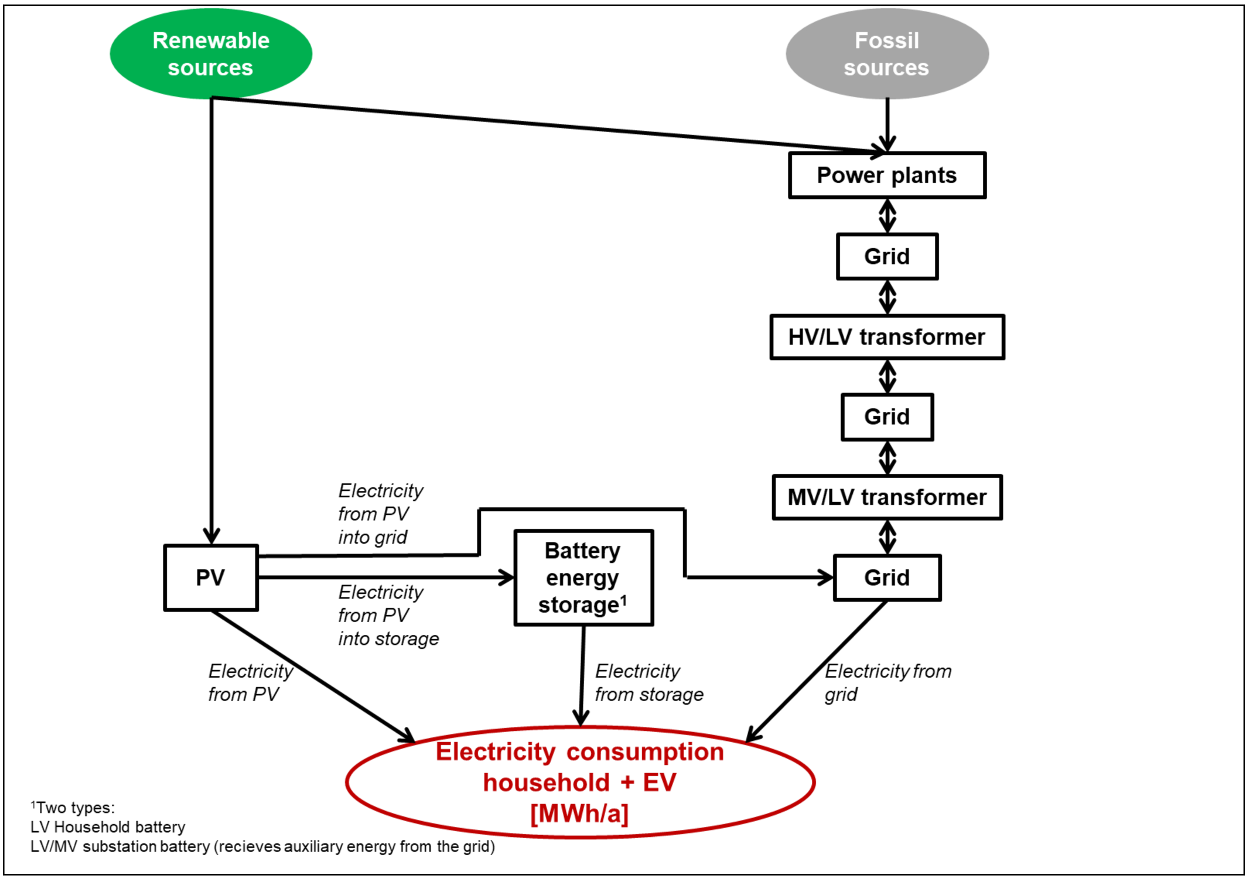

Figure 4: A simplified scheme of the investigated scenarios showing energy flows and system components most relevant for the LCA

Table 3 shows the annual energy balance for the investigated scenarios including the electricity consumption in the household and by the EV. The annual energy balances are calculated using daily profiles generated for the four seasons by the simulations. The energy balances display some of the main differences in the scenario:

- Scenarios with low PV penetration (40% RES) produce approximately half of electricity with PV compared to scenarios with high PV penetration (110% RES).
- Scenarios with low EV (5% EV) have a lower electricity consumption compared to scenarios with high EV (40% EV).
- Electricity from PV injected into the power grid is higher for scenarios without battery systems
- Losses are higher for system with battery systems due to storage losses. Systems with LV/MV substation batteries (Grid) have the highest losses. These systems need auxiliary energy (heating in winter, cooling in summer), which are included in the category “Losses”.

Table 4 shows the (1) share of local PV electricity injected in the power grid in generated electricity, (2) share of losses in consumed electricity, and (3) share of electricity generated with local PV in consumed electricity.

Table 3: Annual energy balance for the investigated large-scale scenarios

Scenario	PV generation	PV into HV grid	Grid	Losses (Grid, TR, Storage)	Consumption (Household + EV)
			[MWh/year]		
1_40%RES_5%EV_0%Batt	20 527	1 459	50 993	1 707	68 354
2_40%RES_5%EV_15%Batt(Household)	20 527	1 113	51 260	2 320	68 354
4_40%RES_5%EV_30%Batt(Household)	20 527	1 002	51 532	2 703	68 354
6_110%RES_40%EV_0%Batt	52 621	23 688	48 906	2 219	75 619
3_110%RES_40%EV_15%(Grid)	52 621	21 423	52 368	7 947	75 619
7_110%RES_40%EV_30%(Household)	52 621	22 295	48 317	3 024	75 619
9_110%RES_40%EV_80%(Household)	52 621	19 709	47 314	4 608	75 619
10_110%RES_40%EV_80%(Grid)	52 621	13 486	45 296	8 813	75 619

Table 4: Share of PV electricity injected into the HV grid in the generated electricity, share of losses and share of electricity generated with PV in consumed electricity for the investigated scenarios

Scenario	% PV into HV in generation [%]	% Losses in Consumption [%]	% PV in Consumption [%]
1_40%RES_5%EV_0%Batt	7%	2%	28%
2_40%RES_5%EV_15%Batt(Household)	5%	3%	28%
4_40%RES_5%EV_30%Batt(Household)	5%	4%	29%
6_110%RES_40%EV_0%Batt	45%	3%	38%
3_110%RES_40%EV_15%(Grid)	41%	11%	41%
7_110%RES_40%EV_30%(Household)	42%	4%	40%
9_110%RES_40%EV_80%(Household)	37%	6%	44%
10_110%RES_40%EV_80%(Grid)	26%	12%	52%

In the LCA, the effect from surplus PV on the electricity generation mix needs to be included. Depending on the scenarios, the MV/HV transformer shows negative flows, representing electricity traveling into the high voltage grid. This electricity is produced by PV plants, neither consumed nor stored in the MV and LV grid and effects the electricity generation in the transmission network: electricity generation by other power plants can be replaced.

The network simulation focused on the technical effects in the distribution grid. Which electricity generation units are influenced by surplus PV electricity was not investigated in the simulation. Therefore, in the LCA different options for the replaced and consumed grid electricity were assumed (Table 5):

- Option 1: For the consumed and replaced grid electricity, the Belgium electricity mix is assumed.
- Option 2: For the consumed grid electricity, the Belgium electricity mix is used. For surplus PV electricity, it is assumed that the electricity generation in a natural gas power plant can be replaced, since natural gas power plants are flexible electricity generation units.
- Option 3: For surplus PV electricity, it is assumed that this electricity is stored in a hydro pump storage. For the consumed grid electricity, the Belgium electricity mix is used

plus the share of electricity stored in the hydro pump storage – reduced by storage losses.

- Option 4: For the consumed and replaced grid, electricity generation with a natural gas power plant is assumed.

The amount of replaced electricity is reduced by grid transmission losses in all options.

Table 5: Investigated options for the generation of consumed and replaced grid electricity

	Option 1	**Option 2**	**Option 3**	**Option 4**
Consumption of grid electricity	Belgium electricity mix	Belgium electricity mix	Belgium electricity mix + Pump storage hydro power	Natural gas CC power plant
Surplus PV into HV	Replacement: Belgium electricity mix	Replacement: Natural gas CC power plant	Pump storage hydro power	Replacement: Natural gas CC power plant

2.2.2 Demo-scale scenarios

Compared to the large-scale integration scenarios, the demo scale scenarios focus on a smaller distribution grid section and are more closely related to a demonstration case. Here we show the results for scenarios, which are based on the demonstration of a medium scale battery in Suha, Slovenia. In this case, a medium scale storage unit (170 kW, 450 kWh) was built and connected to 400-kVA OLTC MV/LV transformer station of DSO Elektro Gorenjska supplying the Suha village residential grid.

The basic layout of the scenario is similar to the large-scale scenarios: The electricity demand from the households is covered by local PV plants and electricity from the grid. Surplus electricity is injected into the power grid and/or stored in a battery system. However, the scenario only includes the Suha village LV network and its transformer station, whereas the grid model of the large-scale integration covered several LV networks, LV/MV transformer stations, the MV network with a rural and urban feeder and different storage capacities and types.

In the simulation, the scenarios shown in Table 6 were investigated:

Scenario 0 shows the theoretical electricity production potential of the PV plant. Grid limitations are not considered.

In Scenario 1, the limitations from the distribution grid are considered. If demanded by the PV droop control, the PV production is curtailed due to increased voltage levels in the network.

In Scenario 2, the battery system placed at the MV/LV transformer station is considered. The battery performs peak shaving, it charges in intervals with high PV production and discharges in morning and evening demand peak. It will additionally charge during the night only up to 100 kW of power flows in the network and will not lower power flows in the network below 50 kW during the day. PV production is curtailed with droop control if needed.

All scenarios are simulated for two different amounts of PV units installed in the grid: 210 kWp and 630 kWp installed peak power.

In the LCA, we investigated the real-world scenarios 1 and 2. Their annual energy balance is shown in Table 7. Table 8 shows share of PV and share of losses in the electricity demand of the investigated grid section.

If 210 kWp of the PV or in other words 6 units are installed in the investigated grid section, all three scenarios show no differences in electricity generated with the PV plants. Curtailment is practically not needed due to the LV grid resiliency. If 630 kWp of PV generation is installed in 18 units in the LV grid, the situation changes. In scenario “S1: PV (curtailment)”, PV generation needs to be curtailed; only 75% of the theoretical PV production potential are generated. In scenario “S2: PV+battery” 96% of the theoretical PV production potential are produced.

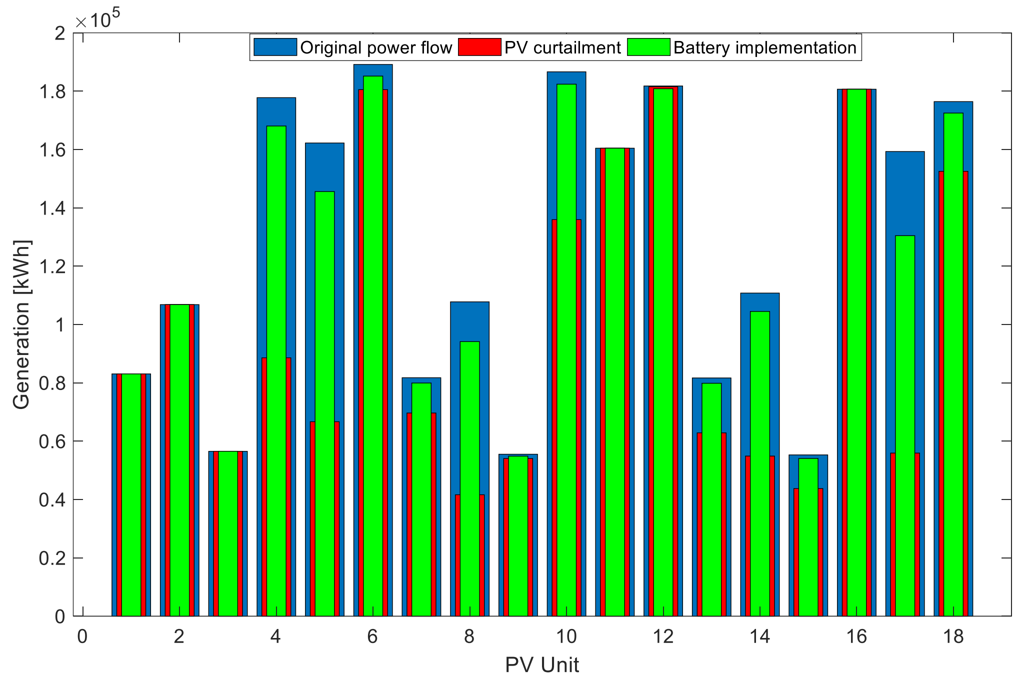

Figure 5 shows the power flows per PV unit for 18 PV units. It also shows that the implementation of the battery in “S2: PV+battery” enables a significantly higher PV electricity generation compared to “S1: PV (curtailment)”.

Table 6: Simulated demo-scale scenarios, scenario 1 and 2 are selected for LCA

Installed amount of PV: 6 units/ 210 kWp	
Scenario 0	No curtailment of PV – theoretical PV generation potential
Scenario 1	Curtailment of PV
Scenario 2	Battery performing peak shaving + curtailment of PV
Installed amount of PV: 18 units/ 630 kWp	
Scenario 0	No curtailment of PV – theoretical PV generation potential

Scenario 1	Curtailment of PV
Scenario 2	Battery performing peak shaving + curtailment of PV

Table 7: Annual energy balance for the investigated demo scale scenarios

	Demand [MWh/a]	**PV generation [MWh/a]**	**PV to MV grid [MWh/a]**	**PV consumed [MWh/a]**	**Electricity from MV grid [MWh/a]**	**Total losses [MWh/a]**
210 kWp PV installed / 6 units						
S0: PV - theoretical potential	458	194	138	56	412	10
S1: PV (curtailment)	458	194	136	58	412	13
S2: PV + Battery	458	194	81	113	367	22
630 kWp PV installed / 18 units						
S0: PV - theoretical potential	458	578	473	105	377	24
S1: PV (curtailment)	458	444	349	95	377	14
S2: PV + Battery	458	555	388	167	325	34

Table 8: Share of electricity generated with PV and share of losses in consumed electricity for the investigated scenarios

Scenarios	Share PV in Demand	Share losses in Demand
210 kWp PV installed / 6 units		
S0: PV - theoretical potential	12%	2%
S1: PV (curtailment)	13%	3%
S2: PV + Battery	25%	5%
630 kWp PV installed / 18 units		
S0: PV - theoretical potential	23%	5%
S1: PV (curtailment)	21%	3%
S2: PV + Battery	37%	7%

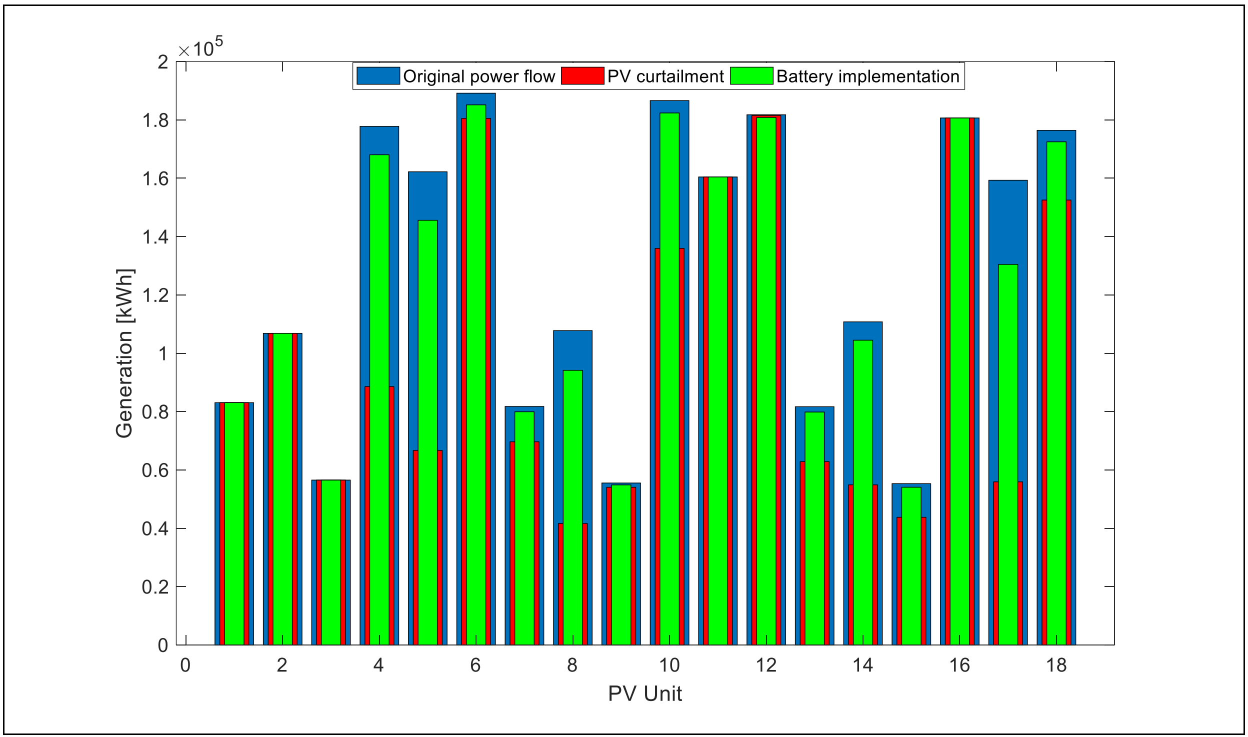

Figure 5: PV power flows for Scenario 0 (Original power flow), Scenario 1 (PV curtailment) and Scenario 2 (Battery implementation)

In the LCA, we included the effect from surplus PV on the electricity generation mix by investigating different options for consumed and replaced grid electricity. The investigated options (Table 9) are similar to the options defined in for the large-scale implementation scenarios. The only difference is that we used the Slovenian electricity mix instead of the Belgium electricity mix, as the demonstration is located in Slovenia.

The amount of replaced electricity is reduced by grid transmission losses in all options.

Table 9: Investigated options for the generation of consumed and replaced grid electricity for the demo-scale scenarios

	Option 1	**Option 2**	**Option 3**	**Option 4**
Consumption of grid electricity	Slovenian electricity mix	Slovenian electricity mix	Slovenian electricity mix + Pump storage hydro power	Natural gas CC power plant
Surplus PV into HV	Replacement: Slovenian electricity mix	Replacement: Natural gas CC power plant	Pump storage hydro power	Replacement: Natural gas CC power plant

2.2.3 Functional unit

The environmental impacts of the investigated scenarios are compared using their functional unit. Since the primary function of the investigated scenarios is to cover the electricity consumption of household and EV on an annual basis, MWh electricity consumption per year has been chosen as the functional unit. For each scenario, the GHG emissions are calculated for the yearly electricity consumption in the investigated grid section (large-scale, demo-scale). Results are presented in t CO_2-eq/year. Also specific GHG emission per MWh consumed electricity are presented indicating the climate impact of 1 MWh consumed electricity in the investigated set up.

2.3 Basic data

Two types of basic data were used in the LCA calculation: (1) Foreground data, and (2) Background data.

2.3.1 Foreground data

Foreground data is project specific data, which were collected for the investigated scenarios. If possible, monitoring data from the Suha demonstration were used (e.g. battery efficiency, auxiliary energy demand of the battery system, electricity demand of households, electricity generation from PV) and implemented in the grid simulation or directly used in the LCA calculation.

Table 10 and Table 11 show the basic parameters for the substation and household batteries.

Table 10: Data on MV/LV substation battery [6]

MV/LV substation battery		Large-scale	Demo-scale
Type		Li-Ion NCM	Li-Ion NCM
Capacity (used)	[kWh]	320	320
Rated Power	[kW]	170	170
Roundtrip efficiency			0.88
Life time	[a]	10	10
Auxiliary power1)	[kW]		4 kW constant load

1) For heating and cooling of the battery system

Table 11: Data on LV household battery [6]

LV household battery		Large-scale
Type		Li-Ion NCM
Capacity	[kWh]	16
Rated Power	[kW]	15
Roundtrip efficiency		
Life time	[a]	10

Consumption of grid electricity and replacement of grid electricity occurs at different times during the day in all scenarios. An example is shown Figure 6 for “large-scale scenario 6” on a summer day. During the night and in the evening hours the electricity demand is covered with grid electricity (positive values for HV/MV transformer). From 4:00 – 6:00 and 16:00 – 19:00, the electricity demand is covered by electricity from the PV and the grid. Between 6:00 and 16:00, PV generation is higher than electricity demand and the electricity is injected into the higher grid level (negative values for HV/MV transformer).

Depending on the electricity generation technologies, the generation mix changes during the times of the year and the time of the day. Therefore, the calculation of GHG emissions of consumed and replaced grid electricity was performed using hourly GHG emission factors.

For the large-scale integration scenarios, historic data on the hourly Belgium electricity generation mix was taken from [7] for the period from 11/2017 – 12/2018. To correspond the grid simulation the hourly electricity generation was needed for a typical day per season. An autoregressive integrated moving average (ARIMA) model and for wind generation a Markov chain was used to simulate the hourly electricity generation mix for a typical day per season.

For the demo-scale scenarios, hourly generation data for Slovenia was taken from [8] for the year 2018.

Table 12 gives an overview on peak power and area of the PV units considered in the different scenarios.

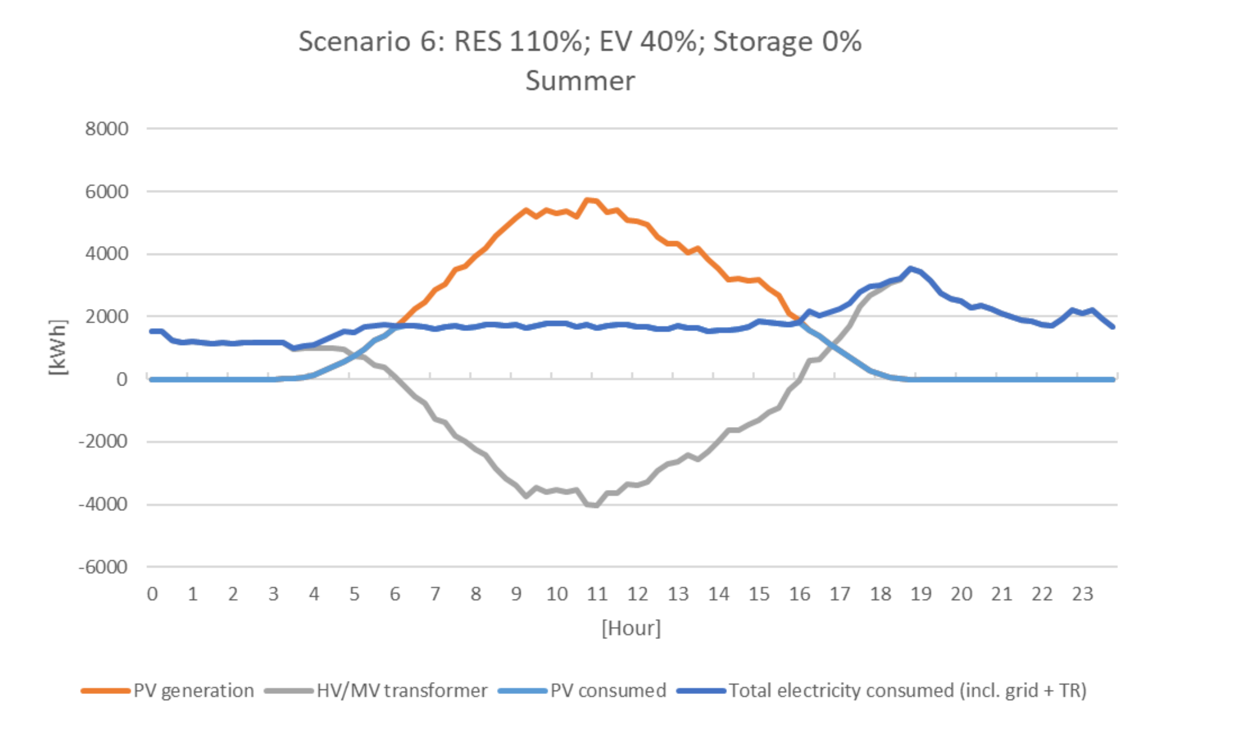

Figure 6: Electricity flow during a summer day in Scenario 6_110% RES_40%EV_0%Batt

Table 12: Data on PV units

Scenarios	**PV peak power [kWp]**	**PV area [m²]¹⁾**	**Life time [a]**
Large-scale integration			
40% RES	12 000	90 909	10
110% RES	33 000	250 000	10
Demo-scale			
6 PV units	210	1 591	10
18 PV units	630	3 773	10

1) Calculated using a nominal conversion efficiency of 13.2% for a multi-crystalline silicone module [9]

2.3.2 Background data

Additional background data are needed to calculate the climate impacts of the investigated scenarios. These are mainly specific emission factors for energy processes, transport processes and materials. The main sources for background data were LCA databases GEMIS [10] and ecoinvent [11].

The following tables summarise selected data on the GHG emission for the production of the PV units and batteries and electricity generation technologies. LCA calculation was performed using one selected value (expert estimation) and a range (min-value, max-value).

Table 13: GHG emission factors for electricity generation technologies [10]

Electricity generation from	**GHG emissions** Expert estimate [kg CO_2-eq/kWh]	Min [kg CO_2-eq/kWh]	Max [kg CO_2-eq/kWh]
Solid biomass[1)]	36	36	36
Biogas[1)]	252	252	252
Brown coal/lignite	1 064	982	1 092
Coal	960	895	1 087
Fossil gas	412	400	447
Fossil oil	799	797	869
Hydro Pump Storage[2)]	43	12	83
Hydro Run-of-river	4	1	10
Nuclear	33	8	67
Solar/PV[3)]	52	42	57
Waste	996	448	1 710
Wind onshore	13	9	28

[1)] no Min/Max value considered, as share in investigated electricity mix is below 1%

[2)] storage of electricity from nuclear power plants assumed

[3)] for Slovenian solar radition data

Table 14: GHG emission for production of multi-crystalline silicone PV plant [11]

	GHG emissions Expert estimate [kg CO_2-eq/m²]	Min [kg CO_2-eq/m²]	Max [kg CO_2-eq/m²]
Production of PV plant	270	220	300

Table 15: GHG emission for production of Li-Ion NCM battery [12], [13]

	GHG emissions Expert estimate [kg CO_2-eq/kWh]	Min [kg CO_2-eq/kWh]	Max [kg CO_2-eq/kWh]
Production of Li-Ion NCM	124	68	186

2.4 Results

The result section is divided into LCA results on the GHG emissions of the large-scale storage implementation and the demo-scale scenarios.

2.4.1 Large-scale storage implementation

Figure 7 to Figure 10 show selected results on the GHG emissions of the network development scenarios on large-scale storage implementation.

In Figure 7, the annual GHG emissions for scenarios with high amount of PV installation and high amount of EVs are shown for option 1, where the Belgium electricity mix is used for consumed and replaced grid electricity. The figure shows the total annual GHG emissions and contributions from PV plant production, battery production, electricity from HV grid, electricity into HV grid. Electricity injection into HV grid replaces electricity generation, therefore the GHG emissions are negative.

GHG emission of PV production are in all scenarios 2 250 t CO_2-eq/year, as all shown scenarios have the same amount of installed PV power.

GHG emissions of battery production range from 120 to 770 t CO_2-eq/year, depending on the size of the batteries installed in the scenarios. Scenario "9_110%RES_40%EV_80%(Household)" has lower GHG emissions for battery production compared to scenario "10_110%RES_40%EV_80%(Grid)" (320 versus 770 t CO_2-eq/year) although the installed battery charging/discharging power is 24 MW in both scenarios. However, household batteries and grid batteries have different ratios between storage power and storage capacity. Scenario 10 has a total storage capacity of 45.2 MWh, whereas scenario 9 has a total storage capacity of 25.6 MWh. In all scenarios with batteries, the contribution of battery production to the total GHG emissions is rather low, ranging from 2% to 11%.

Of stronger influence on the total GHG emissions is the contribution of the consumed and replaced grid electricity. In scenario "6_110%RES_40%EV_0%Batt", without batteries, the total amount of surplus electricity from PV is injected into the HV grid and the amount of saved GHG emissions is highest. The scenarios with batteries use more of the PV electricity in the investigated MV and LV grid sections and therefore saved GHG emissions are lower. In three of the four scenarios with batteries, the GHG emissions of consumed grid electricity are lower compared to GHG emissions of consumed grid electricity in scenario "6_110%RES_40%EV_0%Batt", as less grid electricity is needed due to the battery systems. However, scenario "3_110%RES_40%EV_15%(Grid) has higher GHG emissions for consumed grid electricity compared to scenario "6_110%RES_40%EV_0%Batt". This is explained due to losses of the MV/LV substation battery system. The system needs auxiliary energy for cooling and heating of the container, where the battery system is located; leading to relatively high overall system losses of 11% in consumed electricity (see Table 4).

Overall, Figure 7 shows that the scenarios with batteries only have a small advantage as compared to the scenarios without batteries. This is a result of less GHG emissions for electricity consumption from the HV grid. This small advantage cannot compensate the lower amount of saved GHG emissions from replaced grid electricity and additional GHG emissions for battery production. Therefore, scenario "6_110%RES_40%EV_0%Batt" without the battery, has the lowest GHG emissions. Figure 8 shows the same result for specific GHG emissions per MWh electricity demand. Scenarios without the battery have lower specific GHG emissions as scenarios with batteries, though the differences for scenarios with low PV and low EV (40%RES, 5% EV) are very low.

When interpreting the results, two aspects need to be considered. Firstly, we must point out, that for the considered amount of PV power in the investigated LV grid section the grid model showed no limitation in technical parameters. So up to the assumed amount of PV power curtailment is not needed in any of the scenarios. Transporting the electricity to another place in the network ("grid as a storage") has less losses than storing the electricity in the battery system. Secondly, data for LV/MV substation battery is mostly based on real-world data from the Suha demonstration case, whereas data on the household batteries is from literature only. In the demonstration case, the battery storage capacity was oversized; leading to higher GHG emissions for battery production. Data for auxiliary energy demand for cooling and heating of the battery system installed in a container at a transformer station is from a first of a kind solution, which will be improved in the future. Literature data on the household batteries does not include performance losses due to changing temperatures, which might take place in reality although the batteries are installed indoor.

Figure 9 and Figure 10 show the GHG emissions for "option 3 - Belgium electricity mix + hydro pump storage". In this option, we assumed that surplus electricity is stored in a hydro pump storage. Therefore, Figure 9 shows no saved GHG emissions. The bar "electricity into HV grid (pump storage)" represents the GHG emissions for storing the electricity in a hydro pump storage. It includes emissions from the construction of the hydro pump storage only (3 g CO_2-eq / MWh electricity). The hydro pump storage operation is included in the GHG emissions of "Electricity from HV grid".

For all investigated options on consumed and replaced grid electricity the LCA shows, that scenarios with battery systems have the lowest total GHG emissions under the investigated circumstances.

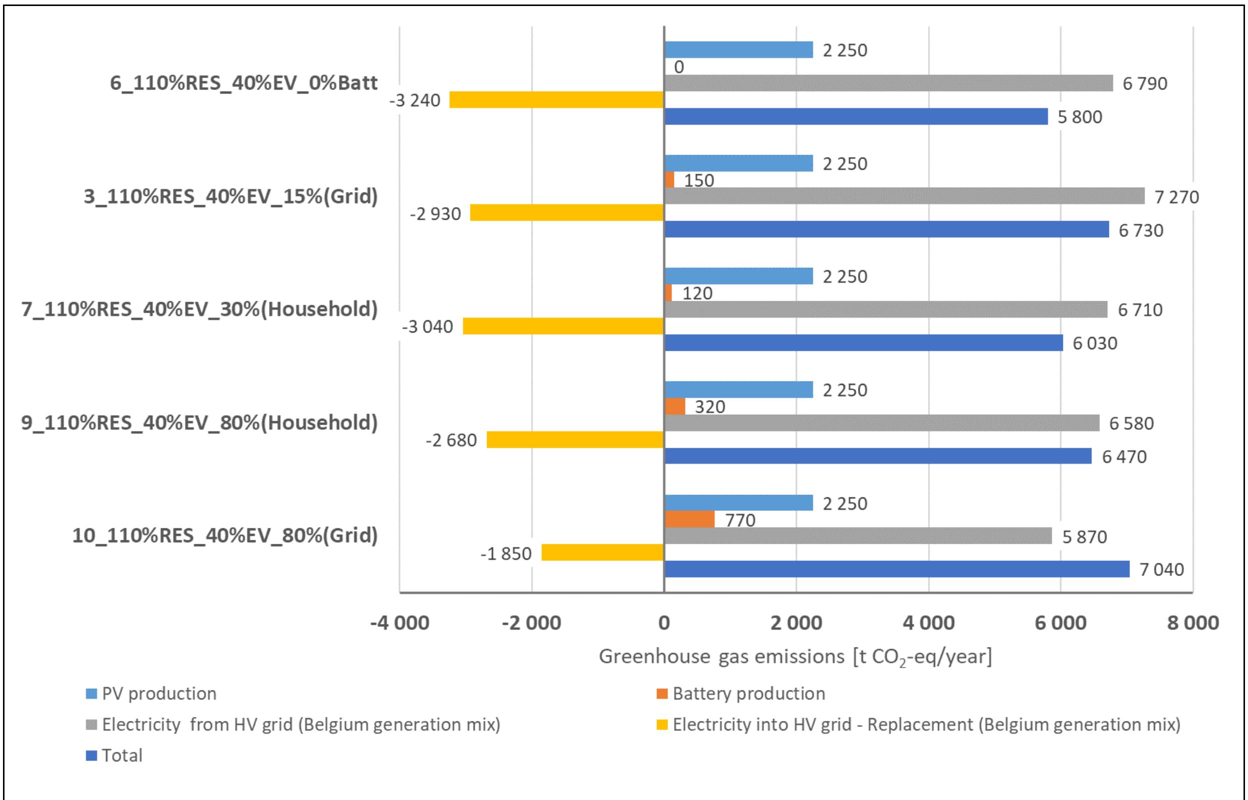

Figure 7: Annual GHG emissions for large-scale storage implementation scenarios with high PV and high EV for option 1- Belgium electricity mix

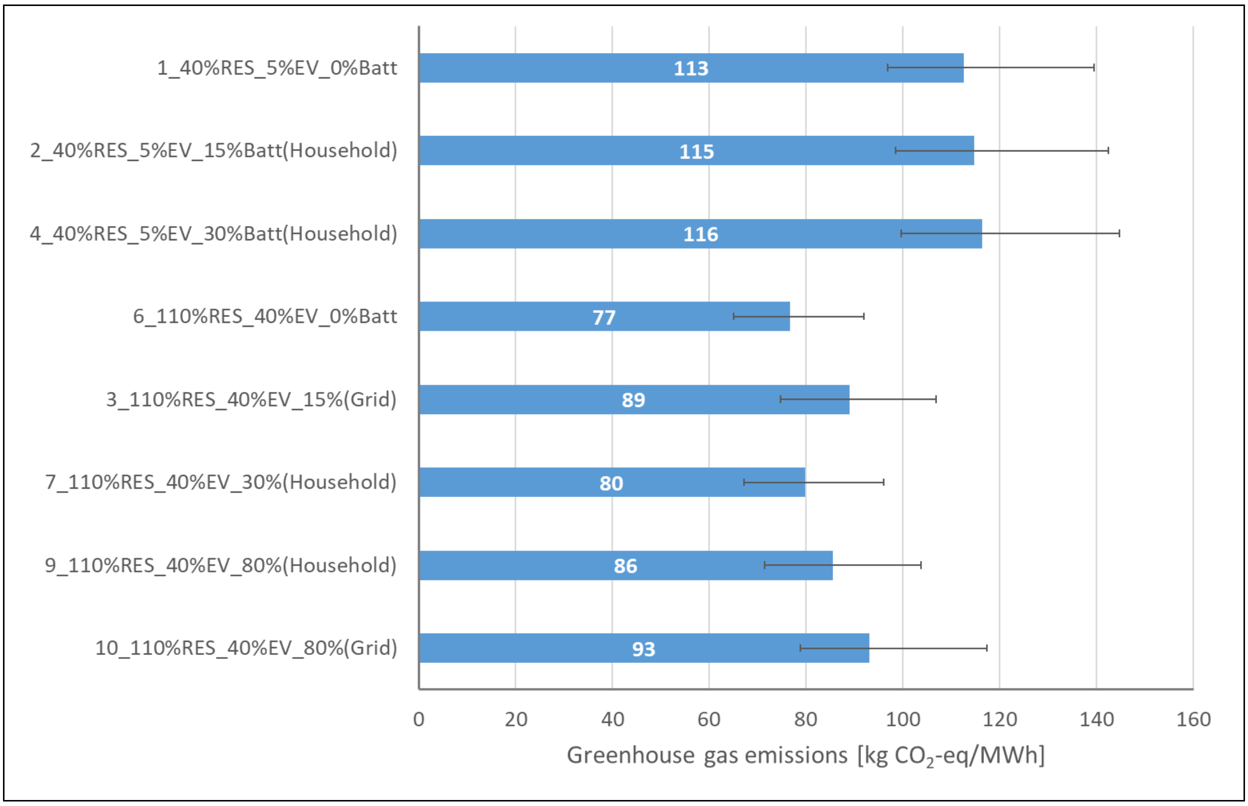

Figure 8: GHG emissions per MWh electricity demand for option 1 – Belgium electricity mix

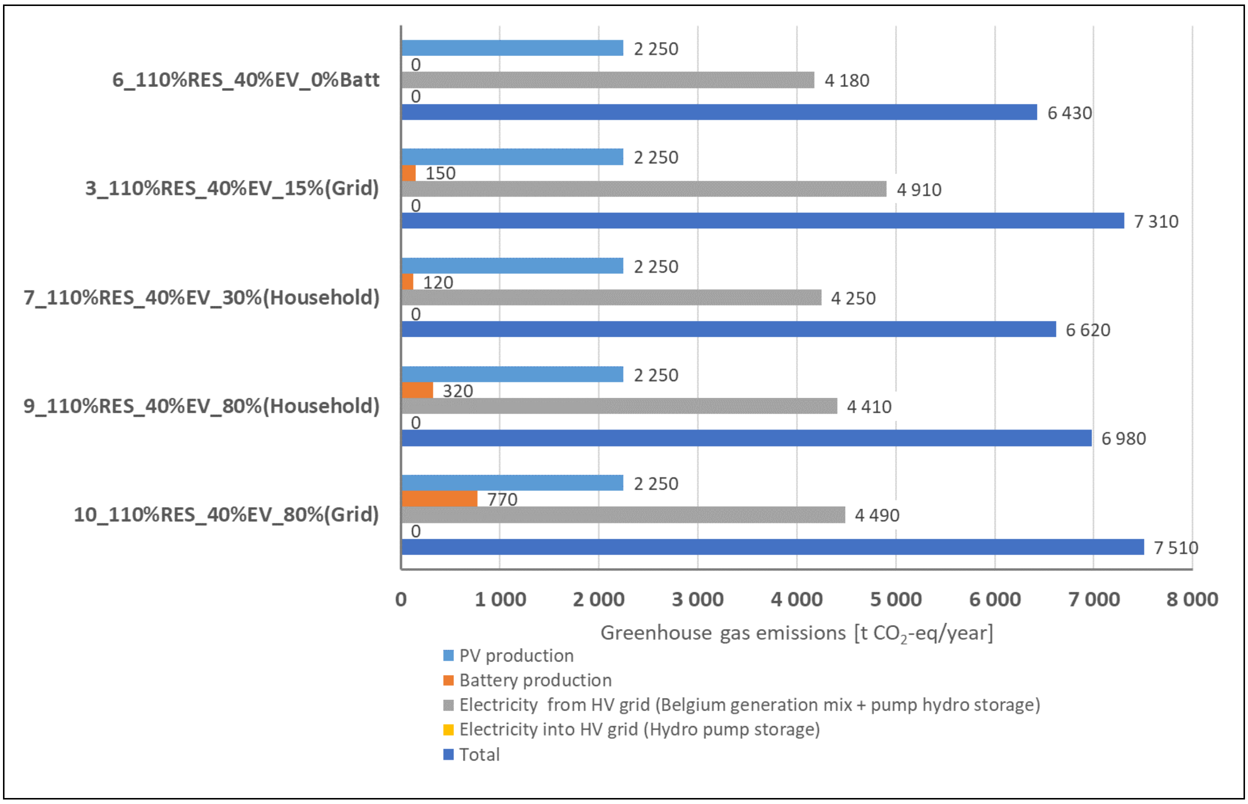

Figure 9: Annual GHG emissions for large-scale storage implementation scenarios with high PV and high EV for option 3- Belgium electricity mix + pump hydro storage

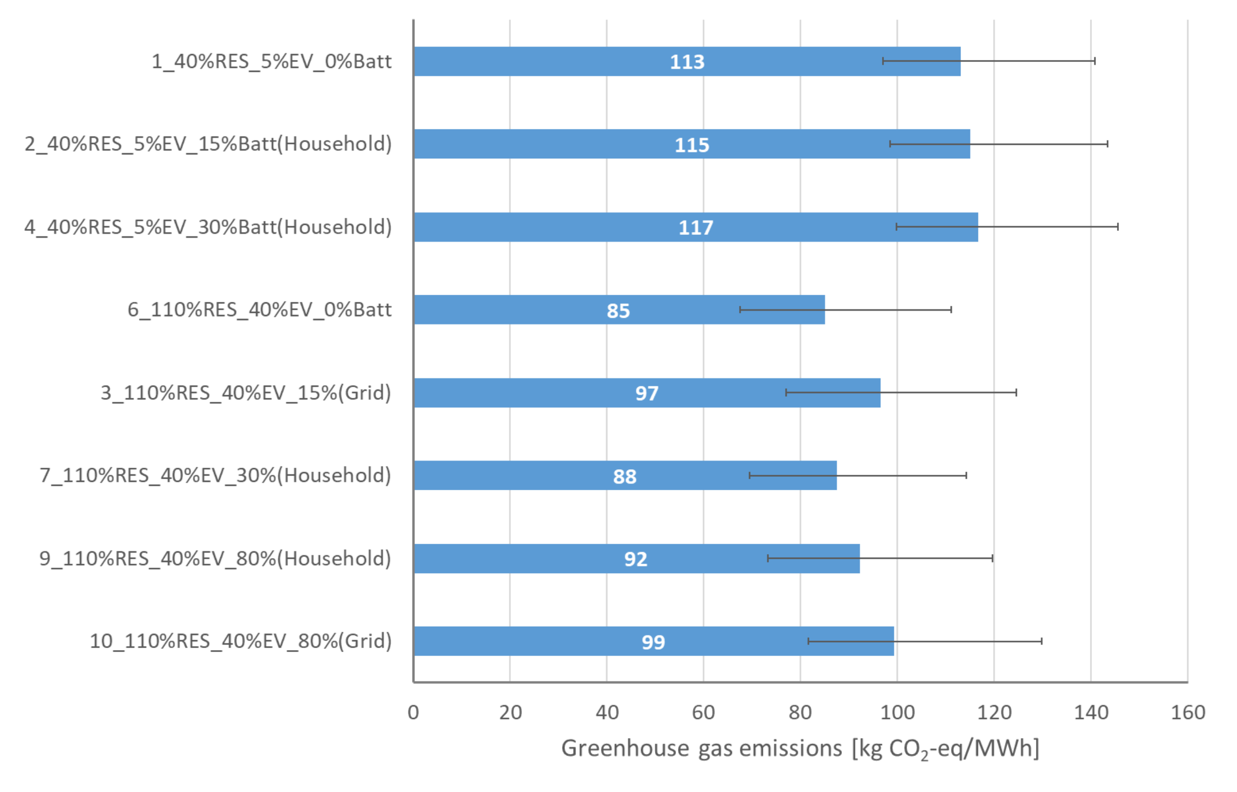

Figure 10: GHG emissions per MWh electricity demand for option 3 – Belgium electricity mix + pump hydro storage

2.4.2 Demo-scale scenarios

Figure 11 to Figure 14 show selected results on the GHG emissions of the demo scale scenarios.

In Figure 11 the annual GHG emissions for scenarios with 210 kWp PV and 630 kWp PV are shown for option 1, where the Slovenian electricity mix is used for consumed and replaced grid electricity. The figure shows the total annual GHG emissions and contributions from PV plant production, battery production, electricity from HV grid, electricity into HV grid. Electricity injection into HV grid replaces electricity generation therefore the GHG emissions are negative.

In the scenarios with 210 kWp PV power the scenario “S2: PV+Battery” has slightly higher GHG emissions (123 t CO_2-eq/year) than the scenario “S1: 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 production. With 210 kWp, PV power curtailment of the PV plants is practically not needed. In both scenarios, PV plants can use the grid almost unlimited. The situation changes in the second set of scenarios, where 630 kWp PV are installed. Here, the grid model showed grid limitations and, in both scenarios, curtailment is needed. However, in scenario “S2: PV+Battery” less curtailment is needed using the battery for peak shaving. Therefore, GHG emissions for consumed grid electricity are lower in scenario “S2: PV+Battery”, but also saved GHG emissions are higher as the amount of PV electricity injected into the next grid level is higher.

Figure 12 shows the specific GHG emissions per MWh electricity demand for option 1, where the Slovenian electricity mix is used for consumed and replaced grid electricity.

With 210 kWp PV power the specific GHG emissions of the investigated scenarios “S1: PV (curtailment)” and “S2: PV+Battery” are in same range with approximately 250 kg CO2-eq/MWh. With 630 kWp PV power the specific GHG emissions of scenario “S2: PV+Battery” (~ 90 kg CO_2-eq/MWh) are clearly lower than the specific GHG emissions of “S1: PV(curtailment)” (~ 140 kg CO_2-eq/MWh).

Figure 13 and Figure 14 show the GHG emissions for option 3 - Slovenian electricity mix + hydro pump storage. In this option, we assumed that surplus electricity is stored in a hydro pump storage. Therefore, Figure 13 shows no saved GHG emissions. The bar “electricity into HV grid (pump storage)” represents the GHG emissions for storing the electricity in a hydro pump storage. It includes emissions from the construction of the hydro pump storage only (3 g CO_2-eq / MWh electricity). The hydro pump storage operation is included in the GHG emissions of “Electricity from HV grid”. Also in this option the scenario with the battery has similar GHG emissions compared to the scenario without the battery, if 210 kWp PV power are installed. If 630 kWp PV power are considered, annual and specific GHG emissions are significantly lower in the scenario where the battery is used for peak shaving and prevents PV curtailment compared to the scenario without the battery. For all other investigated options, for consumed and replaced grid electricity the main findings are the same as for the described options.

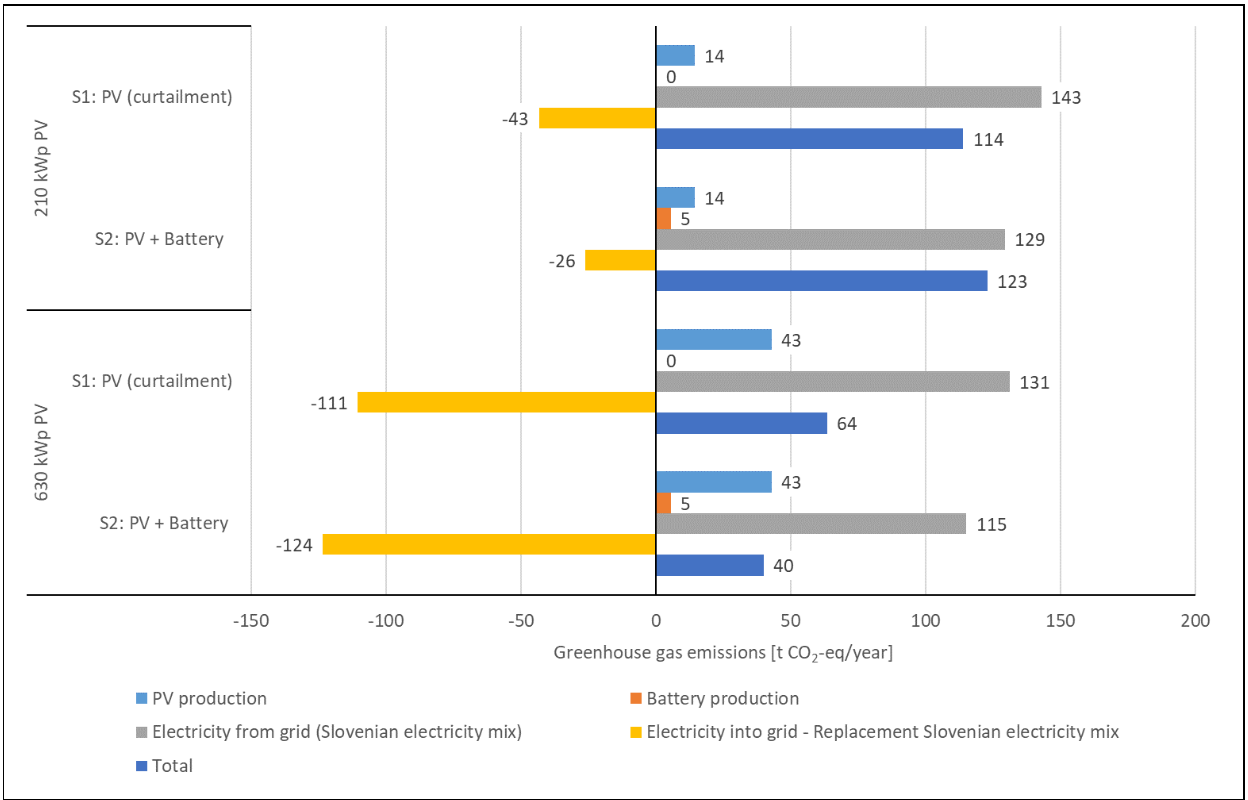

Figure 11: Annual GHG emissions of demo scale scenarios, option 1 – Slovenian electricity mix

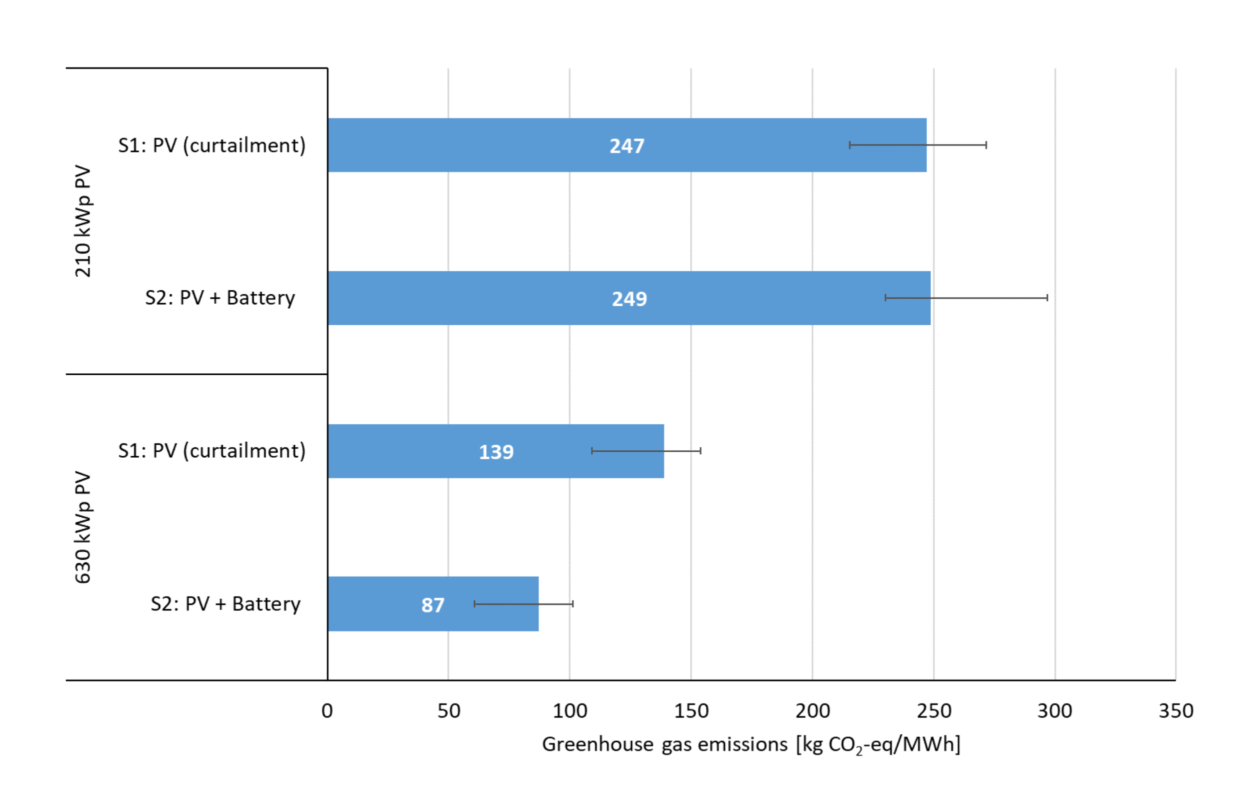

Figure 12: Specific GHG emissions of demo scale scenarios per MWh electricity demand, option 1 – Slovenian electricity mix

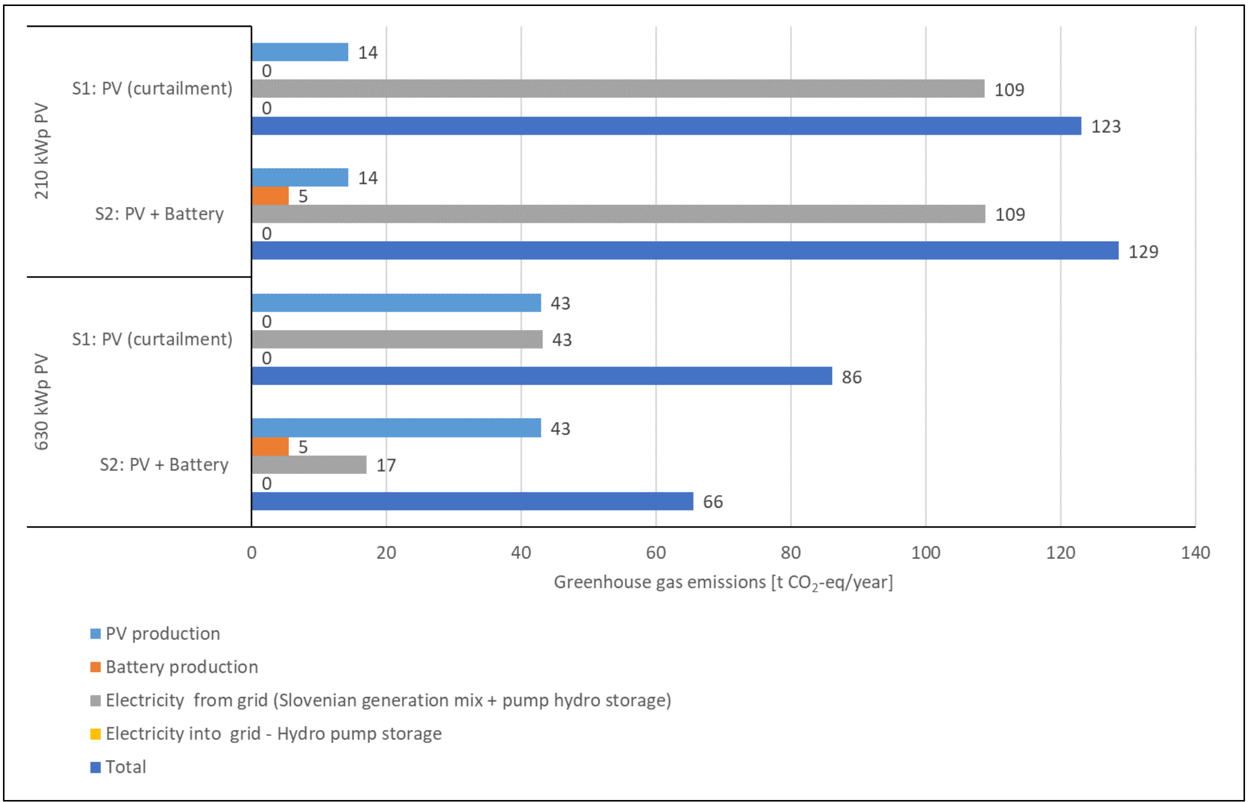

Figure 13: Annual GHG emissions of demo scale scenarios, option 3 – Slovenian electricity mix + Hydro pump storage

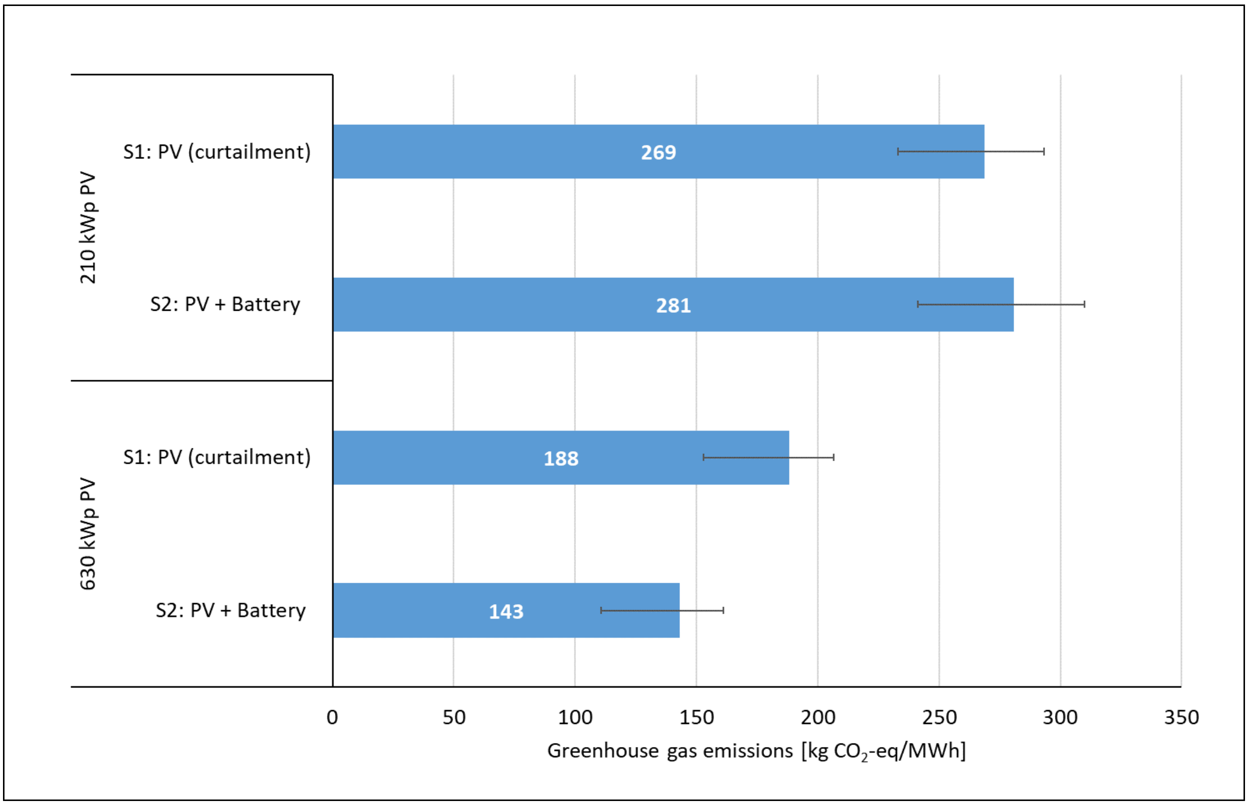

Figure 14: Specific GHG emissions of demo scale scenarios, option 3 – Slovenian electricity mix + Hydro pump storage

3 Social impact

While the use of LCA is quite widespread, comparable approaches for the economic and social dimensions of sustainability are still limited in their application. Similar to LCA, Social Life Cycle Assessment (sLCA) incorporates the traditional LCA methodological steps while having social impacts as a focus. SLCA, in principle, follows the ISO 14040 framework and is used to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle, from the extraction of raw materials, till the final disposal. sLCA is complimentary to traditional environmental LCA.

An sLCA has two main objectives:

- to enable a comparison of products/services and processes for decision making; and
- to identify potential improvement within the system in order to reduce social impacts.

The attempt of a sLCA is to get a complete picture of the situation, meaning

- which stakeholders are relevant,
- which topics are of interest (definition of subcategories),
- define indicators to describe these topics, and
- assessing these indicators.

The challenge to include a social assessment in a LCA approach is that the social dimension is determined by factors like personal behaviour, general moral values, interaction with other social groups, etc. and besides that, has a very strong regional character and differs from case to case.

Social impacts may be observed in five main stakeholder categories:

- workers/employees,
- local community,
- society (national and global),
- consumers and
- value chain actors (which are not consumers).

Each of these stakeholder categories consists of a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. The stakeholder categories provide a comprehensive basis for the articulation of the subcategories. The proposed stakeholder categories are deemed to be the main group categories potentially impacted by the life cycle of a product [14]. Figure 15 shows the assessment system from the stakeholder categories to the unit of measurement.

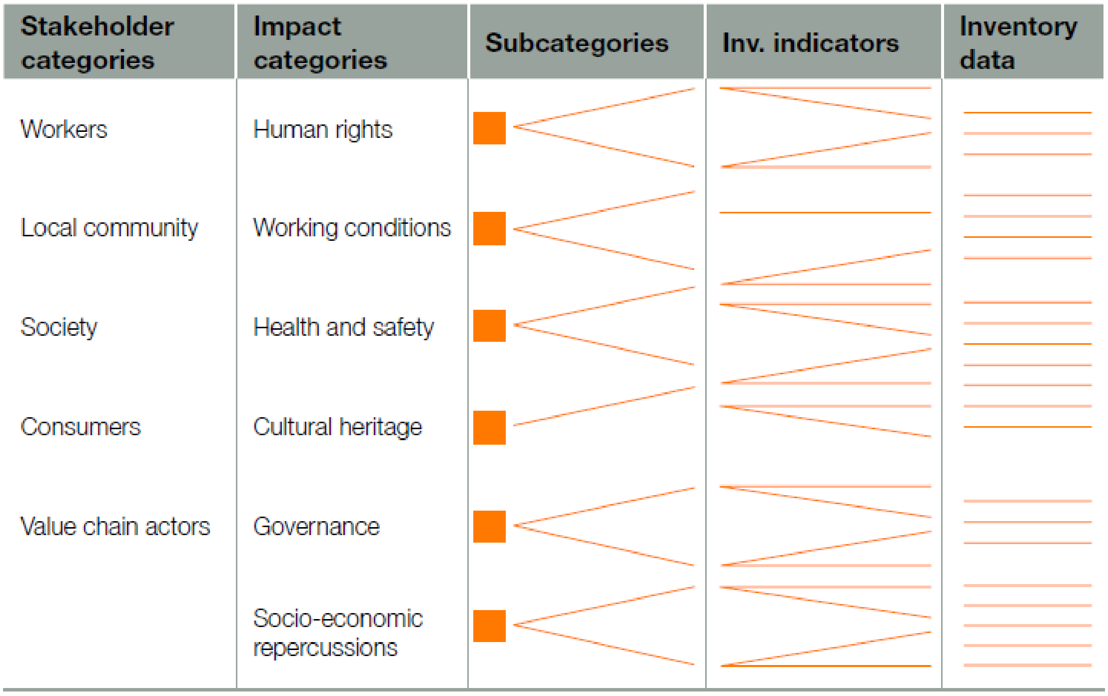

Figure 15: Assessment system from categories to unit of measurement (adapted from Benoît et al., 2007, UNEP, 2009).

The challenges with social categories and indicators are that

- they are very complex as they are the result of relationships and a function of politics, economy, ethics, legal issues, culture, etc.,
- they are complex cause-effect chains,
- social indicators are subjectively perceived and hard to evaluate,
- it is hard to find appropriate indicators, there are hardly any generic databases,
- reliable data are difficult to find for some aspects as child labour, discrimination, etc.,
- data are needed at different levels: country level, regional level, sector level, company level and site level,

- they are a mixture of quantitative, semi-quantitative and qualitative data and
- it is hard to compare between companies, processes and products.

In the project STORY, the focus in the life cycle lies on the manufacturing and the operation of the battery energy storage. Therefore, the main issue, which is assessed within STORY is the value chain of the batteries, dealing with the following questions:

- where do the raw materials come from?
- are they "critical minerals and/or minerals of concern"? (from conflict-affected and high-risk regions)?

In sLCA, one often combines a generic assessment with data from different official sources like the International Labour Organisation (ILO), the Worldbank, etc. with a specific assessment, where data is gained "on-site" from data published by the producers themselves and from interviews with stakeholders.

So, in a first step, desktop research has been done to gain an overview of the batteries and the raw materials used in the different demos within STORY. Cobalt, Lithium, Graphite and Nickel are the four essential raw materials for battery production. Among the materials used in Li-ion cells, three are listed as critical raw materials (CRMs)[1] by the European Commission [15] namely, cobalt, natural graphite and silicon (metal). Lithium is not a CRM but has an increasing relevancy for the Li-ion battery industry. 4 out of 6 batteries used in the STORY demo sites are Lithium based batteries.

This report from the European Commission [15] also shows, that the EU is sourcing primary battery raw materials mostly from countries such as Democratic Republic of Congo, Russia, Chile and Brazil. However, the demand increase for EV Li-ion batteries is increasing the prices of Lithium and Cobalt salts and there is no price transparency in those markets. In a first assessment on social hot spots, two main subcategories, according to the assessment system from UNEP were identified to have the highest relevance in these countries: unsafe working conditions and child labor.

A survey among the partners in the project also showed that only little information on social issues can be gained from the information that are supplied with the Safety Data Sheets and other information provided to the user. With only little information, only a rough assessment on potential risk could be done.

4 Conclusions

Within the STORY Value Analysis Framework an environmental and social impact assessment of battery systems in the distribution grid was performed.

The LCA, which was conducted for large-scale and demo-scale scenarios, shows that the different factors influence the results on the GHG emission of battery systems. The most

[1] According to critical raw materials.org (http://criticalrawmaterials.org/critical-raw-materials/), Critical Raw Materials (CRMs) are those raw materials which are economically and strategically important for the European economy, but have a high-risk associated with their supply. Used in environmental technologies, consumer electronics, health, steel-making, defense, space exploration, and aviation, these materials are not only 'critical' for key industry sectors and future applications, but also for the sustainable functioning of the European economy.

important factor is the amount of PV power installed in the distribution grid and the ability of the grid to transport the PV electricity. If the battery system can prevent PV curtailment, and due to the battery, a higher amount of PV electricity is used, the battery system can have less GHG emissions than the electricity supply without the battery. We were able to show this for a demo-scale scenario with an increased amount of PV power installed in the distribution grid (3 times more than the current situation). As long as no PV curtailment is needed and the PV electricity is “stored in the grid” and replaces other electricity generation types, the battery system leads to higher GHG emissions compared to the system without battery. It is explained by higher system losses in the scenarios with batteries. Also, additional GHG emissions from the production of the battery arise, although the contribution of battery production on the total GHG emissions of the scenarios was rather low (2-11% in large-scale scenarios). In the investigated large-scale storage implementation scenarios, the considered PV power was not high enough to show a benefit on GHG emissions of the battery systems, although a set of scenarios was investigated with a high amount of installed PV power (33 MW, in a grid model with 30 MVA HV/MV transformer).

The sLCA shows that the most interesting questions are the ones concerning the raw materials of the batteries used, their origin and the circumstances under which the raw materials are extracted. Due to a lack of information, only a rough assessment could be made during the STORY project, with a need for further research in the future.

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