Technology Collaboration Programme
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International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability

PVPS

Environmental Life Cycle Assessment of Residential PV and Battery Storage Systems 2020

Report IEA-PVPS T12-17: 2020

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association and the Cop- per Alliance are also members.

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What is IEA PVPS Task 12?

Task 12 aims at fostering international collaboration in safety and sustainability that are crucial for assuring that PV grows to levels enabling it to make a major contribution to the needs of the member countries and the world. The overall objectives of Task 12 are to 1. Quantify the environmental profile of PV in comparison to other energy technologies; 2. Investigate end of life management options for PV systems as deployment increases and older systems are decommissioned; 3. Define and address environmental health & safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy-, material-, and emission-flows in all the stages of the life of PV. The second objective is addressed through analysis of including recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest. Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and the University of New South Wales (UNSW Sydney). Support from DOE and UNSW are gratefully acknowledged.

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COVER PICTURE

Combined PV (28 MW) and storage (100 MWh) power plant in Hawaii. Credits: NREL.

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INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Environmental Life Cycle Assessment of Residential PV and Battery Storage Systems

IEA PVPS
Task 12: PV Sustainability

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LIST OF ABBREVIATIONS

a	year (annum)
AC	alternating current
BAU	business as usual
BMS	battery management system
CED	cumulative energy demand
CED nr	non-renewable cumulative energy demand
CH	Switzerland
CIS	copper indium selenium
DC	direct current
EF	environmental footprint
eq	equivalent
GHG	greenhouse gas
GWP	global warming potential
GLO	global
IEA	International Energy Agency
KBOB	Coordination Group for Construction and Property Services (Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes)
kWp	kilowatt peak
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
$LiFePO_4$	iron phosphate lithium-ion
MJ	megajoule
MPP	maximum power point
MPPT	maximum power point tracker
multi-Si	multicrystalline silicon
NCM	nickel cobalt manganese oxide
NO	Norway
PM	particulate matter
PV	photovoltaic
PVPS	photovoltaic power systems
RER	Europe

SF_6	Sulfur hexafluoride
tkm	tonne kilometre (unit for transportation services)
DETEC	Swiss Federal Department of the Environment, Transport, Energy and Communications

EXECUTIVE SUMMARY

Using a life cycle assessment (LCA), the environmental impacts from generating 1 kWh of electricity for self-consumption via a photovoltaic-battery system are determined. The system includes a 10 kWp multicrystalline-silicon photovoltaic (PV) system (solar irradiation about 1350 kWh/m^2/year and annual yield 1000 kWh/kWp), an iron phosphate lithium-ion ($LiFePO_4$) battery, and other components such as the control system, battery housing, and two inverters (one for the PV system and one for the battery system). Three options for the AC-coupled system with changing battery capacities (5, 10, or 20 kWh nominal capacity) are investigated.

The environmental impacts are assessed using the indicators greenhouse gas emissions and cumulative energy demand (separated into total and non-renewable cumulative energy demand). In addition, the four most important impact categories for PV electricity—respiratory inorganics (particulate matter), acidification, energy carrier resource use, and minerals and metals resource use—are assessed according to the environmental footprint (EF) method. Data are drawn from the DETEC data DQRv2:2018, recent literature, and product details provided by manufacturers.

The results show larger environmental impacts of PV-battery systems with increasing battery capacity; for capacities of 5, 10, and 20 kWh, the cumulative greenhouse gas emissions from 1 kWh of electricity generation for self-consumption via a PV-battery system are 80, 84, and 88 g CO_2-eq/kWh, respectively. The cumulative greenhouse gas emissions of PV electricity consumed directly or fed into the grid are 54 g CO_2-eq/kWh. The corresponding total cumulative energy demands are 5.27, 5.40, and 5.50 MJ oil-eq/kWh, with non-renewable energy carriers contributing 1.16, 1.22, and 1.29 MJ oil-eq/kWh. In the investigated EF impact categories, we similarly observe a larger environmental burden with increasing battery capacity, except in the use of minerals and metals.

Our sensitivity analyses show that using a nickel cobalt manganese oxide (NCM) lithium-ion battery, instead of an $LiFePO_4$ battery, leads to a comparable environmental impact in terms of greenhouse gas emissions and cumulative energy demand. However, the NCM battery increases the impact in the EF categories of acidification and respiratory inorganics by 7 and 10 %, respectively, whereas energy carrier resource use decreases by 4 % and minerals and metals resource use decrease by 1 %. Using a copper indium selenium (CIS) PV panel instead of a multicrystalline-silicon decreases greenhouse gas emissions by 24 %, non-renewable cumulative energy demand by 13 %, and particulate matter emissions by 60 % (the largest decrease).

Furthermore, the calculated environmental impacts are sensitive to the assumed battery lifetime. A decrease from 5000 to 3000 charge cycles increases non-renewable cumulative energy demand by 24 % and greenhouse gas emissions by 16 %. Increasing from 5000 to 7000 charge cycles decreases the environmental impacts by 6 % and 7 % in terms of non-renewable cumulative energy demand and greenhouse gas emissions, respectively. A utility-scale battery system case study shows that using batteries to store PV electricity overproduction reduces greenhouse gas emissions compared to using natural gas backup electricity generation.

1 INTRODUCTION AND OBJECTIVE

Several electric utilities are considering the implementation of photovoltaic (PV) products with battery storage. This can be seen as a further expansion in the field of PV, after the implementation of PV electricity products and PV prosumer schemes. PV prosumers generate PV electricity from private households or commercial enterprises. They consume some of this electricity themselves and feed excess energy into the grid. The objective of this report is to quantify the environmental impacts of residential PV-battery systems via life cycle assessment (LCA). The analysis described in this report addresses a 10 kWp PV system with battery storage of 5, 10, or 20 kWh nominal capacity located in Europe/Switzerland.

2 SCOPE

2.1 Functional Unit

The functional unit is defined as the generation of 1 kWh of electricity for self-consumption from the AC-coupled PV-battery system. It is composed of electricity partly drawn from the PV system directly and partly drawn from the battery.

2.2 System Design

The LCA includes all components of the AC-coupled PV-battery system installed in central Europe:

- Production of the 10 kWp multicrystalline silicon (multi-Si) PV system and installation on a pitched roof of a residential building;
- Production of the iron phosphate lithium-ion ($LiFePO_4$) battery including production of the battery management system (BMS), cooling system, battery cells, and battery case;
- Production of the control system, the inverter of the battery system, and the system housing;
- The battery system analysed in this study is coupled on the AC side (see left side in Fig. 2.1) and is equipped with a charge regulator and inverter.

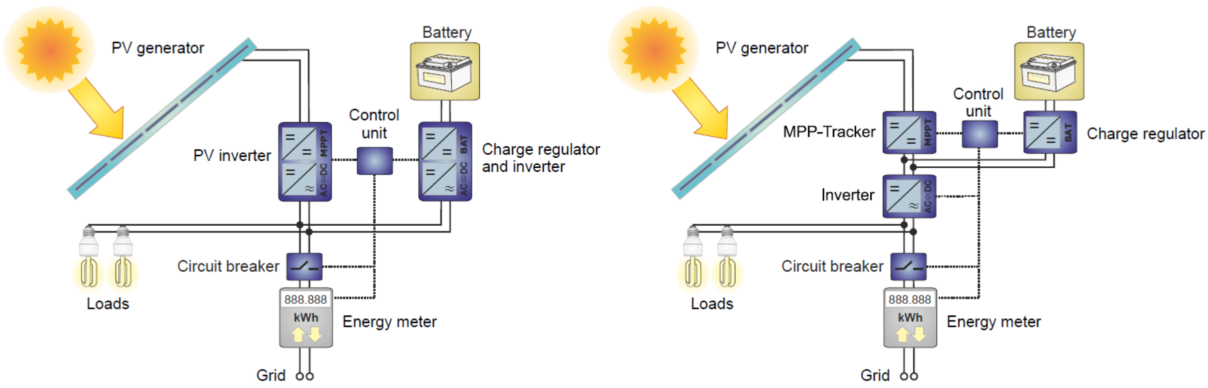

Fig. 2.1 System layout of AC-coupled (left) and DC-coupled (right) residential PV-battery systems (Weniger et al. 2014). The system in this study is AC coupled. MPP: Maximum Power Point; MPPT: Maximum Power Point Tracker

Electricity produced by the PV system is either:

- directly, i.e. at the same time when being produced, consumed in the building;
- used to load the battery;
- exported to the grid;

The performance of the PV and battery storage system (see Subchapter 3.5) depends on the location, the electricity production profile of the PV system and the electricity consumption profile of the building. The PV and battery storage systems analysed in this study are designed for Central Europe and residential buildings.

2.3 Allocation

The assessed PV-battery system does not include any multi-output processes (processes that generate various products). Therefore, no allocation is applied.

The environmental impacts of 1 kWh of PV electricity of the share consumed directly, of the share used to load the battery[1], and of the share fed into the grid[2] are identical (AC coupled layout, central junction, see Fig. 2.1). The present study covers PV electricity consumed directly and via the battery, and it excludes PV electricity fed into the grid.

2.4 Data Sources

For assessing production and installation of the PV system, existing datasets from the DETEC LCA data DQRv2:2018 are used (KBOB et al. 2018). Production of the lithium-ion battery is modelled using detailed literature data (Ellingsen et al. 2014, Majeau-Bettez et al. 2011).

For the other components (system housing, cabling, and control system), product details for the PV battery storage “Fortelion™” from Sony are used (Sony 2015).

For other processes, such as background processes for which no specific data could be collected, the datasets in the DETEC LCA data DQRv2:2018 are used (KBOB et al. 2018).

2.5 Impact Assessment Indicators

The environmental impacts of the three PV-battery systems are quantified using the following three indicators:

- Greenhouse gas emissions (IPCC 2013);
- Cumulative energy demand, distinguished between renewable and non-renewable energy sources (Frischknecht et al. 2015);
- The environmental footprint (EF) method developed by the European Union (Fazio et al. 2018). Impact categories include respiratory inorganics, terrestrial and freshwater acidification, energy carrier resource use, and mineral and metal resource use. Long-term emissions are excluded.

[1] PV electricity taken from the battery has additional losses and thus slightly higher environmental impacts compared to PV electricity used to load the battery.

[2] The shares of self-consumption and of electricity fed into the grid are given in Subchapter 3.5.

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 Overview

The life cycle inventory analysis is divided into the following subprocesses, discussed separately in different subchapters: production of the lithium-ion battery (subchapter 3.2), production and installation of the 10 kWp PV system (subchapter 0), other components of the PV-battery system (subchapter 3.4), and electricity generation for self-consumption via the PV-battery system (subchapter 3.5).

3.2 Production of the lithium-ion battery

Each battery comprises 12 battery modules with 30 battery cells each. The battery cell itself consists of the following five components: anode, cathode, separator, electrolyte, and cell container. The separator is composed of a porous polyolefin film and separates the anode from the cathode within the battery cell. Lithium Fluorophosphate serves as liquid electrolyte. In accordance with specifications provided by ewz (Zurich Municipal Electric Utility),[3] the lifetime of a lithium-ion battery is assumed to be 5000 charge cycles with a depth of discharge of 80 %. During the lifetime of the PV system of 30 years, 2.25, 2 and 1.5 battery packs are needed for 5 kWh, 10 kWh, and 20 kWh storage capacity, respectively.

The data on the lithium-ion battery used in the present life cycle inventory analysis are from a study by Ellingsen et al. (2014), which quantified the environmental footprint of a nickel cobalt manganese oxide (NCM) lithium-ion battery manufactured by a Norwegian company. For that study, the data on the production of all four main components (battery cells, battery case, BMS, and cooling system) were provided by the Norwegian battery producer and made publicly available. The assessed battery consisted of a $Li(Ni_xCo_yMn_z)$ cathode and a graphite-based anode, with a weight of 253 kg, of which the battery cells constituted 60 %. The energy capacity of the battery was 26.6 kWh, and the efficiency was 95 – 96 % (Ellingsen et al. 2014, p.114). For the current study, we adopt the required data for all components of the lithium-ion battery except the $Li(Ni_xCo_yMn_z)$ cathode from the paper and supporting information of Ellingsen et al. (2014). Instead of the $Li(Ni_xCo_yMn_z)$ cathode, we assume use of a $LiFePO_4$ cathode, because some utilities are using a $LiFePO_4$ battery in existing PV-battery systems. The data for the materialisation of the $LiFePO_4$ cathode are from a study by Majeau-Bettez et al. (2011).

[3] Personal communication with Mr Florian Kienzle, ewz, 06.07.2015.

Tab. 3.1 shows the weights of the five main components of the lithium-ion battery as well as the power consumption during production of the cells and assembly of the battery. More detailed information on material, energy, and transportation service demand during battery production can be obtained from Ellingsen et al. (2014) and its supporting information. The life cycle inventories of battery production, which are slightly adapted from and linked to KBOB LCA data DQRv2:2016, are published in Appendix A of Stolz et al. (2016).

Tab. 3.1 Weights of the main components of a lithium-ion battery and power consumption during battery cell production and assembly. The copper content of the battery is 35.4 kg (14 % of battery weight).

Battery weight	**253.0**	**kg (100 %)**
Battery cell	152.3	kg (60.3 %)
Anode	59.0	kg (23.6 %)
Cathode	65.0	kg (26 %)
Separator	3.3	kg (1.3 %)
Electrolyte	24.0	kg (9.6 %)
Cell container	1.0	kg (0.4 %)
Battery case	81.0	kg (32 %)
BMS	9.4	kg (3.7 %)
Cooling system	10.0	kg (4.0 %)
Power consumption during production		
Cell production (in East Asia)	12300	MJ/battery
Assembly (in Norway)	0.36	MJ/battery

3.3 Production and installation of the 10 kWp PV system

The data for a 3 kWp multi-Si PV system, available in the DETEC LCA data DQRv2:2018 (KBOB et al. 2018), serve as a basis for assessing the production and installation of the 10 kWp PV system. The data are adjusted as follows:

- The size of the inverter (lifetime 15 years) is adjusted to a power output of 10 kWp.
- The amount of electrical components (lifetime 30 years) is scaled using a factor of 3.33.
- The panel efficiency is 16.5 %, from which the areas of the panel and the slanting roof installation are derived (Stolz & Frischknecht 2020).
- The transportation demand is aligned with the larger amounts of transported goods.
- The electricity demand for on-site installation is scaled with a factor of 3.33 to align with the increased system size.

Tab. 3.2 shows the inventory data for producing a 10 kWp multi-Si panel and installing it on a slanted roof.

Tab. 3.2 Inventory data for producing a 10-kWp multi-Si panel and installing it on a slanted roof. Transport distances: light commercial vehicle: 100 km; lorry: 500 km (panel only)

	Name	Location	Unit	10kWp slanted-roof installation, multi-Si, panel, mounted, on roof	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			unit			
product	10kWp slanted-roof installation, multi-Si, panel, mounted, on roof	CH	unit	1			
technosphere	electricity, low voltage, at grid	CH	kWh	1.33E-1	1	1.28	(3,4,3,1,1,5,BU:1.05); ;
	inverter, 2500W, at plant	RER	unit	8.00E+0	1	3.02	(2,4,1,1,1,,BU:3); ;
	electric installation, photovoltaic plant, at plant	CH	unit	3.00E+0	1	3.08	(3,4,3,1,1,5,BU:3); ;
	slanted-roof construction, mounted, on roof	RER	m2	6.06E+1	1	3.01	(3,1,1,1,1,,BU:3); ;
	photovoltaic panel, multi-Si, at regional storage	RER	m2	6.24E+1	1	3.08	(3,4,3,1,1,5,BU:3); ;
	transport, freight, light commercial vehicle	CH	tkm	1.19E+2	1	2.09	(3,4,3,1,1,5,BU:2); ;
	transport, freight, lorry, fleet average	RER	tkm	4.71E+2	1	2.09	(3,4,3,1,1,5,BU:2); ;
emission air, high population density	Heat, waste	-	MJ	4.80E-1	1	1.28	(3,4,3,1,1,5,BU:1.05); ;

3.4 Other components of the PV-battery system

The following weight and length specifications, provided by Sony for its PV-battery storage product “Fortelion™” are used for the other components of the PV-battery system (Sony 2015):

- Weight of control system: 8 kg
- Weight of system housing: 88 kg
- Length of cabling: 0.73 m

The PV-battery system is constructed modularly; therefore, the number of battery modules can be varied according to the required battery capacity without affecting the other components. In consequence, the weight and length specifications above are identical for all three battery storage options.

3.5 Electricity generation for self-consumption via the PV-battery system

The PV system generates 10000 kWh of electricity (solar irradiation: about 1350 kWh/m^2/year; annual yield: 1000 kWh/kWp). It shows a production profile of an optimally tilt PV system installed in Europe. The PV system is designed such that the annual production equals the annual electricity consumption of the building. The electricity produced is either used for self-consumption or fed into the grid.

Self-consumption of electricity produced by the PV system can be immediate (simultaneous with production) or via the battery. Hence, the process of electricity generation for self-consumption via the PV-battery system is divided into two subprocesses: electricity from the 10 kWp PV system and electricity from the battery (nominal capacity of 5, 10, or 20 kWh).

For the first subprocess, the data in the DETEC LCA data DQRv2:2018 (available for the process of electricity generation in a 3 kWp PV system) are adjusted to the scale of a 10 kWp PV system through the following adaptations:

- Water consumption for PV module cleaning and the amount of resulting sewage water are adjusted with a scaling factor of 3.33.
- The size of the PV system is adapted to the annual production of 10000 kWh of electricity during the 30-year lifetime.

Tab. 3.3 shows inventory data for generating 1 kWh of electricity using a 10 kWp PV system.

Tab. 3.3 Inventory data for generating 1 kWh of electricity using a 10 kWp PV system.

	Name	Location	Unit	electricity, PV, at 10kWp slanted-roof, multi-Si, panel, mounted	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, PV, at 10kWp slanted-roof, multi-Si, panel, mounted	CH	kWh	1			
technosphere	tap water, at user	CH	kg	1.77E-2	1	1.09	(2,2,1,1,1,3,BU:1.05); ;
emission resource, in air	Energy, solar, converted	-	MJ	3.85E+0	1	1.09	(2,2,1,1,1,3,BU:1.05); ;
emission air, high population	Heat, waste	-	MJ	2.50E-1	1	1.09	(2,2,1,1,1,3,BU:1.05); ;
technosphere	treatment, sewage, from residence, to wastewater treatment, class 2	CH	m3	1.77E-5	1	1.09	(2,2,1,1,1,3,BU:1.05); ;
	10kWp slanted-roof installation, multi-Si, panel, mounted, on roof	CH	unit	3.33E-6	1	3.02	(3,2,1,1,1,3,BU:3); ;

For consumption of electricity from the battery, the following data provided by ewz[3] and extracted from the studies of Ellingsen et al. (2014) and Majeau-Bettez et al. (2011) are used:

- Energetic efficiency of $LiFePO_4$ and NCM lithium-ion batteries: 95 %[4,5]
- Overall efficiency (including charge/discharge and inverter efficiency) of $LiFePO_4$ and NCM lithium-ion battery storage system: 90 %
- Energy density of $LiFePO_4$ battery: 0.110 kWh/kg cell; 0.088 kWh/kg battery
- Energy density of NCM lithium-ion battery: 0.175 kWh/kg cell; 0.105 kWh/kg battery
- Nominal capacity of the battery: 5, 10, or 20 kWh
- Useable capacity of the battery: 4, 8, or 16 kWh (80 % depth of discharge, per ewz[3])
- Self-consumption via battery per year (ewz[3]): 1500 kWh (nominal capacity 5 kWh), 2700 kWh (nominal capacity 10 kWh), or 3900 kWh (nominal capacity 20 kWh)
- 5000 charge cycles with a depth of discharge of 80 % (ewz[3])

[4] Personal communication with Mr Christian Ochsenbein, Bern University of Applied Sciences, 12.12.2019.

[5] Personal communication with Mr Marcel Held, Empa, 12.12.2019.

Tab. 3.4 shows inventory data for generating 1 kWh of electricity using a lithium-ion battery with a nominal storage capacity of 10 kWh.

Tab. 3.4 Inventory data for generating 1 kWh of electricity using a lithium-ion battery with a nominal storage capacity of 10 kWh.

	Name	Location	Unit	electricity, PV, at battery LiFePO4, 10KWh	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, PV, at battery LiFePO4, 10KWh	CH	kWh	1			
technosphere	battery, LiIo, rechargeable, prismatic,LiFePO4	CH	kg	2.81E-3	1	1.28	(3,4,3,1,1,5,BU:1.05); ; ewz
	electricity, PV, at 10kWp slanted-roof, multi-Si, panel, mounted	CH	kWh	1.11E+0	1	1.28	(3,4,3,1,1,5,BU:1.05); ; Majeau-Bettez et al. (2011)
	electronics for control units	RER	kg	9.88E-5	1	1.22	(2,1,1,1,1,5,BU:1.05); ; ewz
	cable, three-conductor cable, at plant	GLO	m	9.01E-6	1	1.30	(4,1,1,1,3,1,BU:1.05); ; ewz
	steel, low-alloyed, at plant	RER	kg	1.09E-3	1	1.30	(4,1,1,1,3,1,BU:1.05); ; ewz
	sheet rolling, steel	RER	kg	1.09E-3	1	1.30	(4,1,1,1,3,1,BU:1.05); ; ewz
	inverter, 2500W, at plant	RER	unit	9.88E-5	1	3.09	(4,1,1,1,3,1,BU:3); ; ewz
	transport, freight, rail	RER	tkm	3.44E-3	1	2.09	(4,1,1,1,3,1,BU:2); ; ewz
	transport, freight, lorry, fleet average	RER	tkm	8.59E-4	1	2.09	(4,1,1,1,3,1,BU:2); ; ewz

The full process “electricity, self-consumption via PV-battery system” is composed of the two subprocesses described above and is thus modelled with the following data, provided by ewz[3]:

- Annual consumption: 10000 kWh (typical consumption profile of residential dwellings)
- Annual self-consumption directly from the PV system (without battery): 3000 kWh
- Total annual self-consumption (directly from PV system and from battery): 4500 kWh (5-kWh battery), 5700 kWh (10-kWh battery), or 6900 kWh (20-kWh battery).

Tab. 3.5 shows inventory data for generating 1 kWh of electricity for self-consumption via a PV-battery system (10 kWp PV system, lithium-ion battery with 10 kWh storage capacity).

Tab. 3.5 Inventory data for generating 1 kWh of electricity for self-consumption via a PV-battery system (10-kWp PV system, lithium-ion battery with 10-kWh storage capacity).

	Name	Location	Unit	electricity, own consumption, PV, with 10kWh batteryLiFePO4	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, own consumption, PV, with 10kWh batteryLiFePO4	CH	kWh	1			
technosphere	electricity, PV, at battery LiFePO4, 10KWh	CH	kWh	4.74E-1	1	1.28	(3,4,3,1,1,5,BU:1.05); ; ewz
	electricity, PV, at 10kWp slanted-roof, multi-Si, panel, mounted	CH	kWh	5.26E-1	1	1.28	(3,4,3,1,1,5,BU:1.05); ; ewz

4 LIFE CYCLE IMPACT ASSESSMENT

4.1 Overview

Tab. 4.1 lists the environmental impacts of 1 kWh of electricity generation for self-consumption via the three investigated PV-battery systems. Environmental impacts increase in line with increased battery capacity. With a storage capacity of 5 kWh, 33 % of the self-consumption is covered by electricity from the battery (ewz[3]). Larger storage capacities (10 kWh, 20 kWh) lead to higher percentages of electricity for self-consumption (47 % and 56 %, respectively) taken from the battery.

The results are discussed in more detail and separated by components and substances in subchapters 4.2 and 4.3.

Tab. 4.1 Environmental impacts of generating 1 kWh of electricity for self-consumption via a PV-battery system with three battery capacity options (5, 10, and 20 kWh).

	GHG (kg CO_2-eq/kWh)	CED nr (MJ oil-eq/kWh)	CED total (MJ oil-eq/kWh)
PV electricity	0.054	0.70	4.77
Electricity self-consumption, option 1 (5kWh)	0.080	1.16	5.27
Electricity self-consumption, option 2 (10kWh)	0.084	1.22	5.40
Electricity self-consumption, option 3 (20kWh)	0.088	1.29	5.50

CED = cumulative energy demand, CED nr = non-renewable cumulative energy demand, GHG = greenhouse gases

4.2 Greenhouse gas emissions

The emissions of all greenhouse gases (which are regulated within the Kyoto Protocol) are weighted according to their global warming potential (GWP), as specified in the latest Intergovernmental Panel on Climate Change report (IPCC 2013) over a time horizon of 100 years, and summed. The greenhouse gas emissions of PV electricity amount to 53.6 g CO_2-eq/kWh. For the three storage capacities (5, 10, and 20 kWh), the total greenhouse gas emissions from 1 kWh of electricity generation for self-consumption via a PV-battery system are 80, 84, and 88 g CO_2-eq/kWh, respectively (Tab. 4.1 and Fig. 4.1). Production of the PV panel accounts for around half (49 – 53 %) of the total calculated greenhouse gas emissions for all three battery options. The absolute contribution of greenhouse gas emissions caused by producing the PV panel, mounting structure, and cabling increases only slightly with increasing battery capacity, because the maximum power output of the PV system is identical. However, the relative contribution of these components to total greenhouse gas emissions decreases with increasing battery storage capacity owing to higher emissions caused by the battery. The battery is responsible for 17, 23, and 28 % of the total greenhouse gas emissions for the three storage capacity options of 5, 10, and 20 kWh, respectively. The greenhouse gas emissions attributed to the battery are mainly caused during production of the battery cells through electricity consumption. The two inverters in the system contribute 18, 15, and 13 %, to the cumulative greenhouse gas emissions with storage options of 5, 10, and 20 kWh, respectively. The roof installation is the fourth-largest contributor to greenhouse gas emissions, at 6 % for the 5 kWh battery option and 5 % for the 10 and 20 kWh battery options. The contributions of the other components (control system, housing, electrical installations, etc.) are below 2 %.

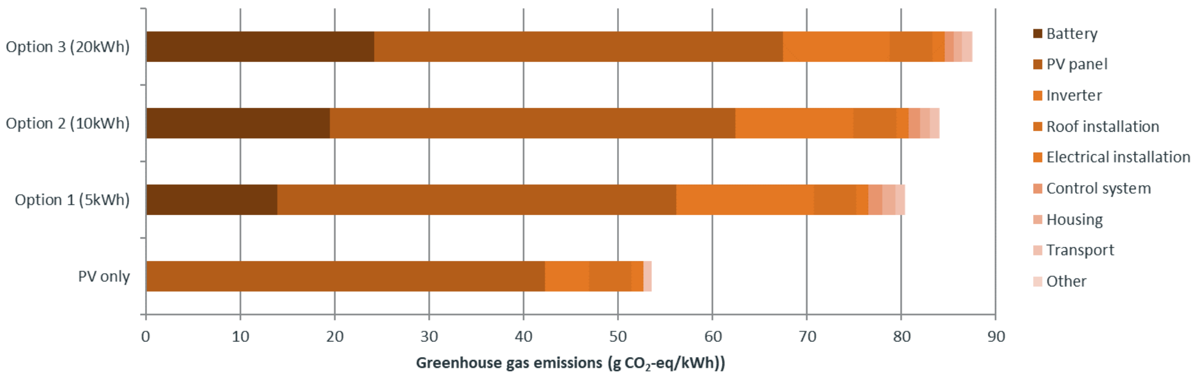

Fig. 4.1 Greenhouse gas emissions from generating 1 kWh of PV electricity (PV only) and for self-consumption via a PV-battery system with three battery capacity options (5, 10, and 20 kWh).

Most of the total greenhouse gas emissions (87 %, Fig. 4.2) are contributed via CO_2, which is mainly emitted during PV panel production and battery cell production (due to high electricity consumption). Methane (CH_4) contributes 9.4 % from the supply chain of coal electricity generation (coal mining) for producing the battery cells and PV panels. Only 1.6 % of cumulative greenhouse gas emissions are emitted as SF_6. These emissions arise during transmission of the electricity used for producing the PV panels.

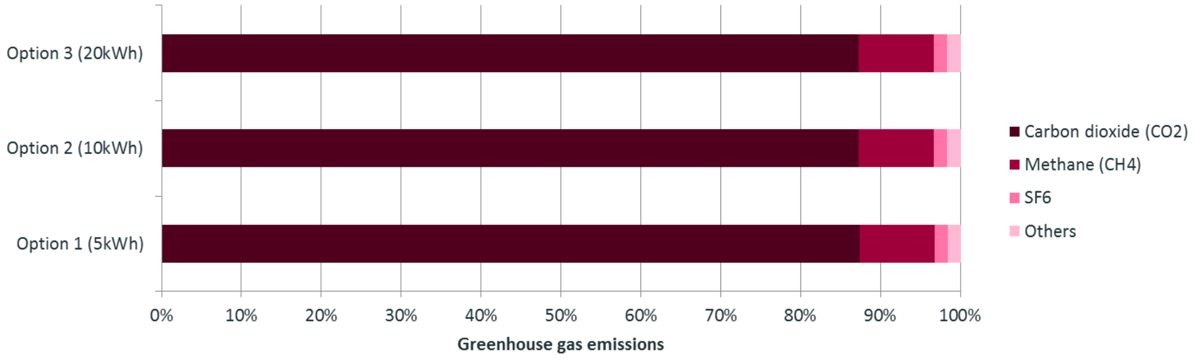

Fig. 4.2 Contribution of different greenhouse gases to total greenhouse gas emissions from generation of 1 kWh of PV electricity and of PV electricity for self-consumption via a PV-battery system with three battery capacity options (5, 10, and 20 kWh).

4.3 Cumulative primary energy demand

The cumulative energy demand is determined according to a method developed by Frischknecht et al. (2015). The contributions of the individual components of the PV-battery system to total and non-renewable cumulative energy demand are shown in Fig. 4.3 and Fig. 4.4.

The total cumulative energy consumption is 5.27, 5.40, and 5.50 MJ oil-eq/kWh for the three battery capacities of 5, 10, and 20 kWh, respectively and 4.77 MJ oil-eq/kWh for pure PV electricity. Solar energy converted into electricity contributes the largest share at around 75 % (listed in Fig. 4.3 as “other”). The non-renewable cumulative energy demand is 1.16, 1.20, and 1.29 MJ oil-eq/kWh for the three battery capacities of 5, 10, and 20 kWh, respectively and 0.70 MJ oil-eq/kWh for pure PV electricity, PV panel production (44, 43, and 40 %, respectively), the battery (22, 29, and 34 %, respectively), and the inverter (21, 17, and 15 %, respectively) are the largest contributors (Fig. 4.4). The non-renewable cumulative energy demand is caused by electricity demand and transportation, which are mainly supplied by fossil energy resources.

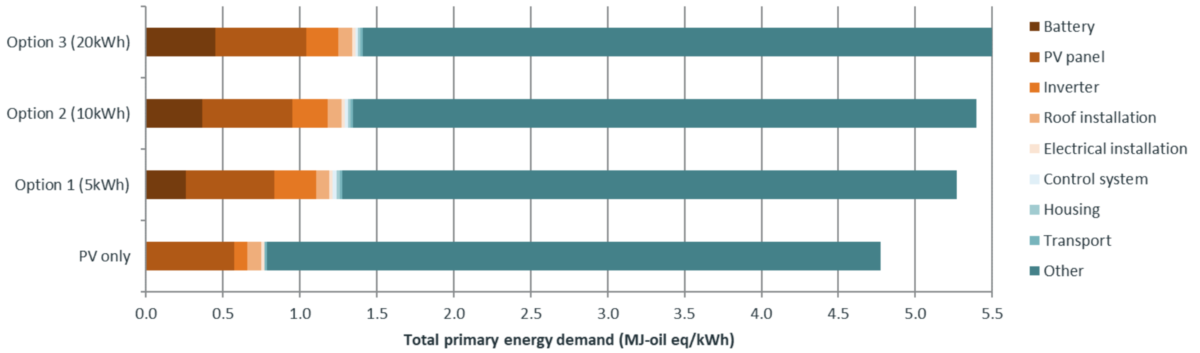

Fig. 4.3 Total cumulative energy demand from generating 1 kWh of PV electricity and of PV electricity for self-consumption via a PV-battery system with three battery capacity options (5, 10, and 20 kWh). The category "Other" represents the solar energy converted by the PV panel.

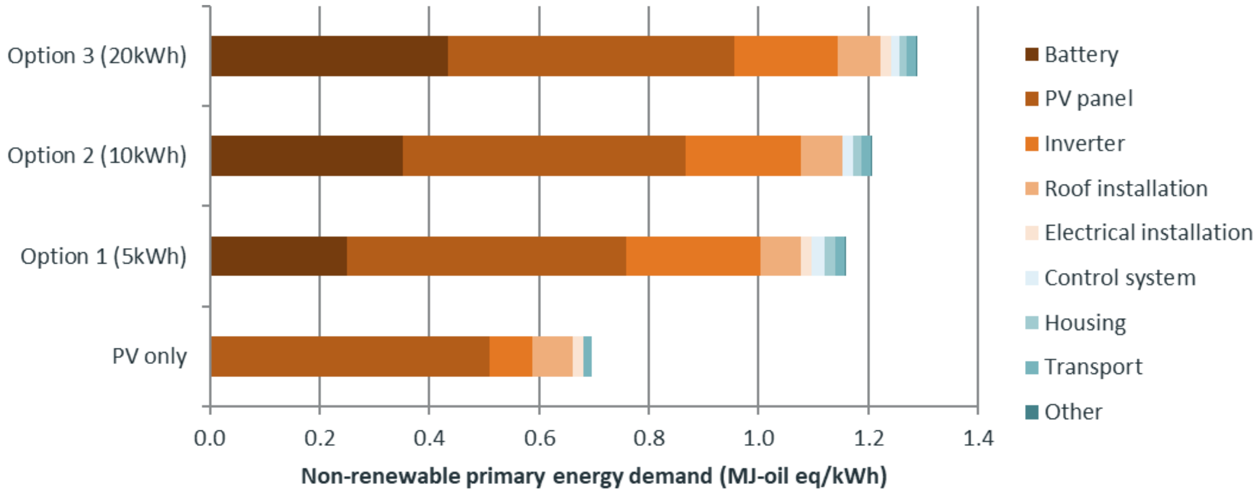

Fig. 4.4 Non-renewable cumulative energy demand from generating 1 kWh of PV electricity and of PV electricity for self-consumption via a PV-battery system with three battery capacity options (5, 10, and 20 kWh).

4.4 Environmental Footprint Method

The Product Environmental Footprint (PEF) developed by the European Union (European Commission 2014) presents a standardised LCA approach to assess the overall environmental impacts of a product. The EF life cycle impact assessment method used in PEF includes 16 indicators that quantify the environmental impacts on climate, resource depletion, and air, water, and soil quality. The indicators are aggregated into a single score indicator through normalization and weighting (European Commission 2017; Fazio et al. 2018).

This study investigates the environmental impact of PV-battery systems in the following four impact categories at midpoint level:

- Respiratory inorganics;
- Terrestrial and freshwater acidification;
- Resource use, energy carriers;
- Resource use, minerals and metals.

These categories were previously identified as the most relevant in the field of PV (TS PEF Pilot PV 2018), together with climate change (see subchapter 4.2). Long-term emissions (those occurring beyond 100 years from today) are excluded.

Tab. 4.2 shows results for the three PV-battery system options with 5, 10, and 20 kWh of capacity, according to the four impact categories of the EF method.

Tab. 4.2 Environmental impacts from generating 1 kWh of PV electricity and of PV electricity for self-consumption via a PV-battery system 5, 10, or 20 kWh capacity based on four of the five most relevant impact categories of the EF method. Climate change impacts are addressed in subchapter 4.2.

	Respiratory inorganics	Acidification, terrestrial and freshwater	Resource use, energy carriers	Resource use, mineral and metals
	(µg PM2.5/kWh)	(mmol H^+-eq/kWh)	(MJ/kWh)	(mg Sb-eq/kWh)
PV electricity	5.18	0.49	0.66	4.16
Electricity self-consumption, option 1 (5kWh)	6.18	0.77	1.09	7.87
Electricity self-consumption, option 2 (10kWh)	6.33	0.81	1.16	7.44
Electricity self-consumption, option 3 (20kWh)	6.47	0.85	1.22	7.20

In all four categories, the most important contributors are the production of the battery, PV panel, and inverter. A larger storage capacity generally leads to higher environmental impacts. In the case of minerals and metals, the impact decreases with larger storage capacity. The larger the storage capacity, the more kWh are processed by the inverter and the control system, leading to a smaller specific (per kWh) use of minerals and metals needed for the production of the inverter and control system with increasing battery capacity (Fig. 4.5). This is particularly visible when comparing the impacts of self-consumed PV electricity to PV electricity only. In the latter case only one inverter is needed and this inverter processes 10000 kWh yearly, whereas only about one sixth of the electricity (1500 kWh compared to 10000 kWh) is processed by the second inverter in the case of the 5 kWh capacity PV battery system. In this system, battery stored PV electricity contributes roughly two third to the self-consumed electricity.

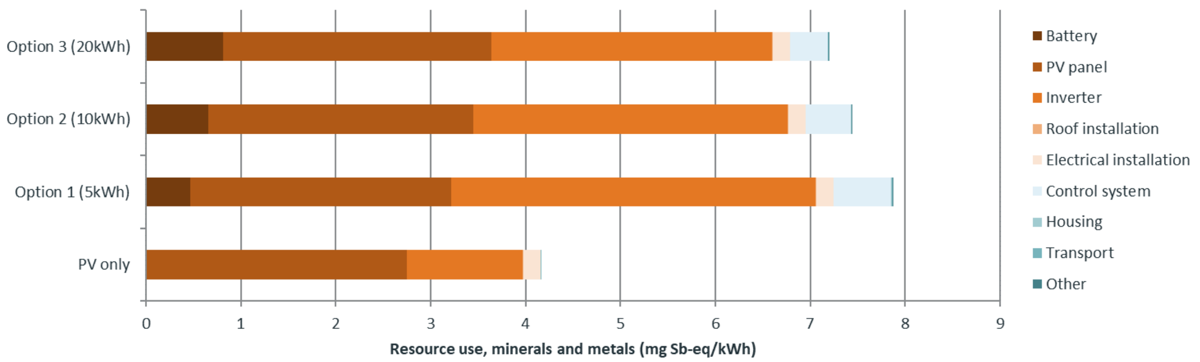

Fig. 4.5 Minerals and metals used for generating 1 kWh of PV electricity and of PV electricity for self-consumption via a PV-battery system with three battery capacity options (5, 10, and 20 kWh).

5 SENSITIVITY ANALYSES

5.1 Overview

Based on the results of the impact analysis, the following three parameters were selected for sensitivity analyses of the PV system combined with a 10-kWh battery (option 2):

- Battery type: lithium-ion battery with NCM cathode compared to $LiFePO_4$ battery (subchapter 5.2)
- Battery lifetime: 3000 and 7000 charge cycles with a depth of discharge of 80 % compared to 5000 charge cycles (subchapter 5.3)
- PV panel type: copper indium selenium (CIS) panel with an efficiency of 14 % (Stolz & Frischknecht 2020) compared to multi-Si panel (subchapter 5.4)

Subchapter 5.6 discusses data quality and uncertainty.

5.2 Sensitivity to battery type

For comparing a PV-battery system using a 10-kWh NCM lithium-ion battery versus a system using a 10-kWh $LiFePO_4$ battery, we assume a battery lifetime of 5000 charge cycles with a depth of discharge of 80 %. The results show that the environmental impacts from using an NCM battery are comparable to those from using an $LiFePO_4$ battery (Fig. 5.1). NCM batteries have a higher energy density compared with $LiFePO_4$ batteries and therefore require a lighter and smaller battery for a particular storage capacity. However, the higher environmental impacts caused by the materialisation of the NCM battery compared with the $LiFePO_4$ battery mostly offset this effect.

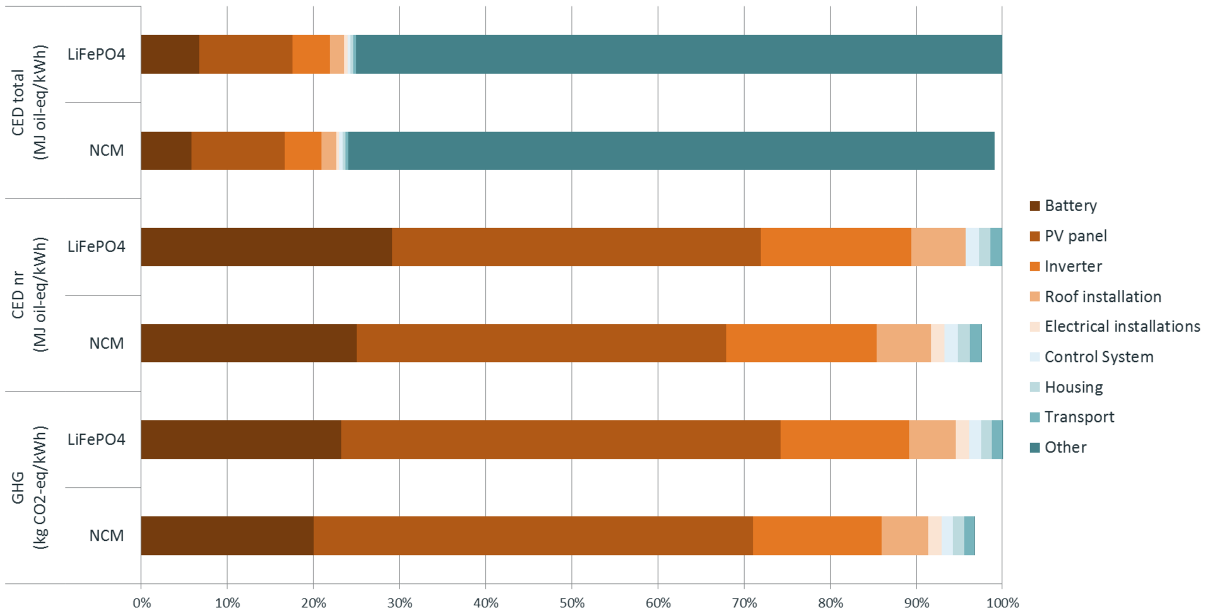

Fig. 5.1 Comparison of environmental impacts of generating 1 kWh of electricity for self-consumption via a PV-battery system using a 10-kWh NCM lithium-ion battery and a 10-kWh $LiFePO_4$ battery. Results shown are relative to the scores of the basic scenario $LiFePO_4$ battery (= 100 %).

In terms of the four assessed EF impact categories, the respiratory inorganics impact, which accounts for the adverse effects on human health due to particulate matter (PM) emissions, is around 10.3 % larger when using an NCM battery instead of an $LiFePO_4$ battery (Fig. 5.2). Similarly, the environmental impact related to acidification increases by 7.1 %. Conversely, using an NCM battery decreases energy carrier resource use by 4.1 % and minerals and metals resource use by 1.3 %.

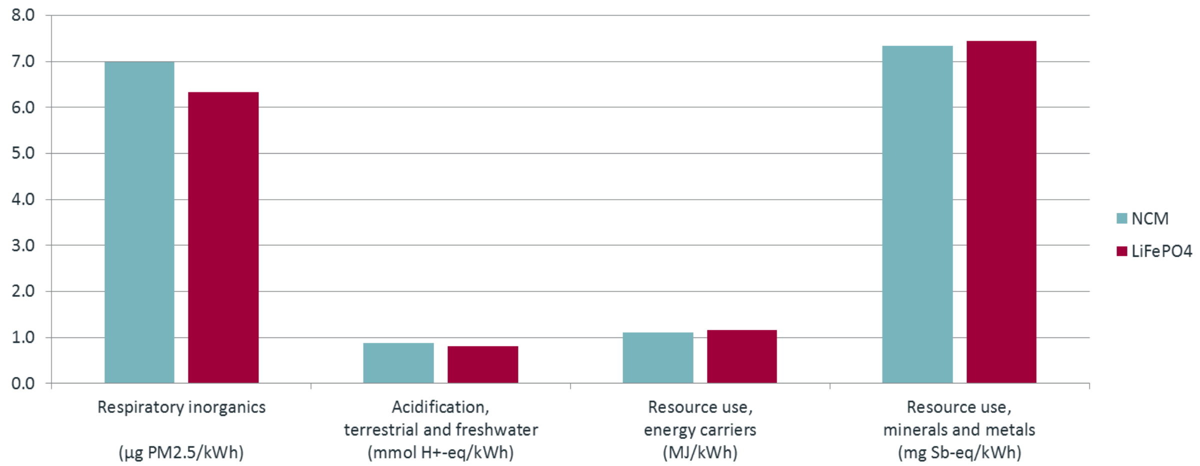

Fig. 5.2 Environmental impacts based on four of the five most relevant impact categories of the EF method, from generating 1 kWh of electricity for self-consumption via a PV-battery system using a 10-kWh NCM lithium-ion battery or a 10-kWh $LiFePO_4$ battery.

5.3 Sensitivity to battery lifetime

Specifications differ substantially among manufacturers for a battery's lifetime number of charge cycles with a depth of discharge of 80 % (C.A.R.M.E.N. & Energie-Netzwerk 2015). For $LiFePO_4$ batteries, the range is 2500 to 7000 charge cycles (C.A.R.M.E.N. & Energie-Netzwerk 2015). Because we expect relatively high lifetimes in the future, we evaluate the 10-kWh $LiFePO_4$ battery case assuming a 7000-cycle lifetime. This longer battery lifetime reduces greenhouse gas emissions by 7 %, non-renewable cumulative energy demand by 6 %, and cumulative energy demand by 2 %, compared with the baseline case of a 5000-cycle lifetime (Fig. 5.3). Reducing the battery lifetime to 3000 charge cycles increases these environmental impacts by 5 – 24 % relative to the baseline, with the largest increase (24 %) for non-renewable cumulative energy demand.

With regard to the four EF impact categories, impacts increase non-linearly when reducing the battery lifetime from 7000 to 5000 and 3000 charge cycles (Fig. 5.4). The number of cycles has the largest impact on energy carrier resource use: compared with a lifetime of 5000 cycles, assuming 7000 cycles decreases this value by 7 %, whereas assuming 3000 cycles increases it by 22 %. The acidification category exhibits similar changes due to varying battery lifetime (7 % reduction to 20 % increase).

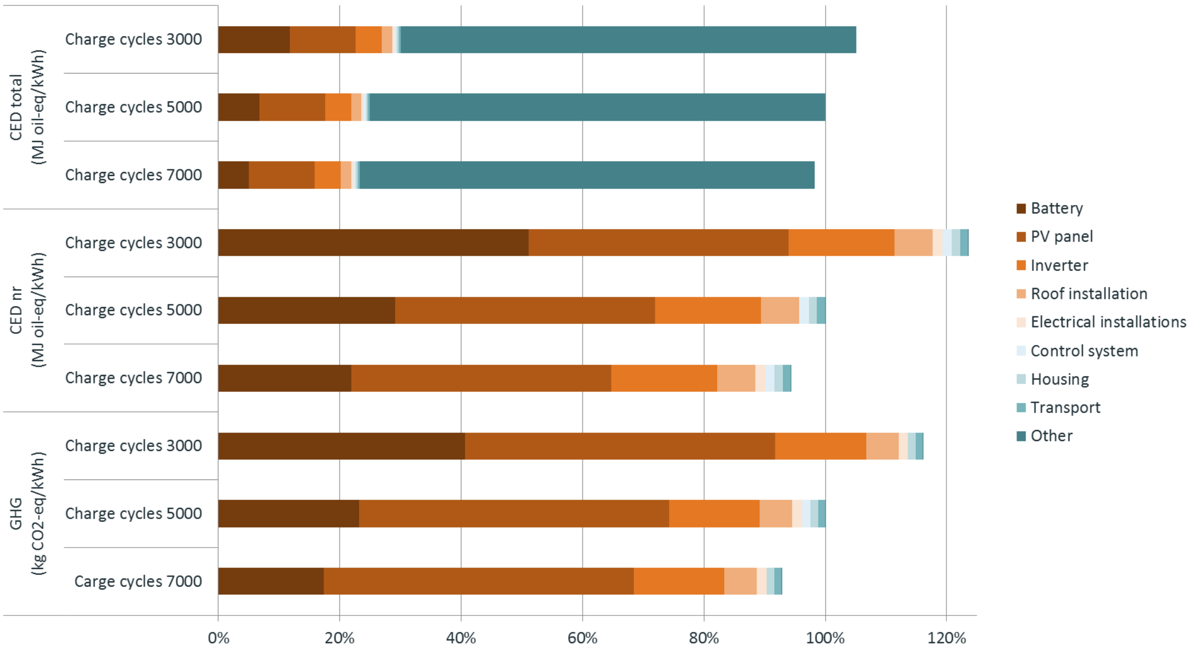

Fig. 5.3 Comparison of environmental impacts of generating 1 kWh of electricity for self-consumption via a PV-battery system using a 10-kWh $LiFePO_4$ battery with different lifetime assumptions (3000, 5000, and 7000 charge cycles). Results are shown relative to the scores of the basic scenario 5000 charge cycles (= 100 %).

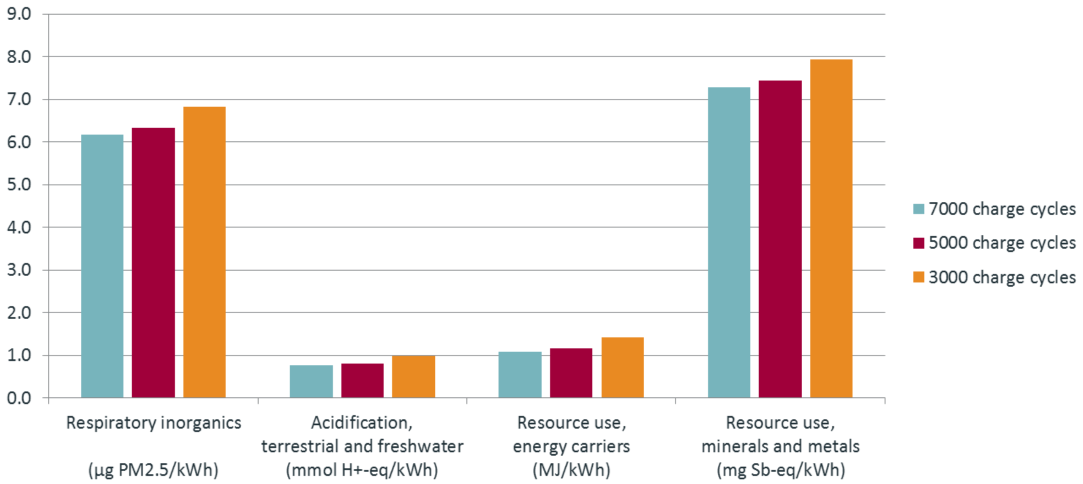

Fig. 5.4 Environmental impacts based on four of the five most relevant EF impact categories, from generating 1 kWh of electricity for self-consumption via a PV-battery system using a 10-kWh $LiFePO_4$ battery with different lifetime assumptions (3000, 5000, and 7000 charge cycles).

5.4 Sensitivity to PV panel type

Our core results show that producing multi-Si PV panels accounts for much of the PV-battery system's total environmental impacts, including about 50 % of the greenhouse gas emissions and 40 – 44 % of the non-renewable cumulative energy demand, depending on the battery storage capacity. Using a CIS panel (panel efficiency 14.0 %) instead of a multi-Si panel reduces greenhouse gas emissions by 24 % (Fig. 5.5) owing to lower CO_2 and CH_4 emissions (Fig. 5.6). Using a CIS panel also decreases cumulative energy demand by 3 % and non-renewable cumulative energy demand by 13 % (Fig. 5.5). Similarly, the CIS panel reduces environmental impacts compared to the multi-Si panel in all assessed EF impact categories (Fig. 5.7). PM emissions decrease by 60 %, minerals and metals use by 36 %, acidification by 34 %, and energy carrier use by 14 %.

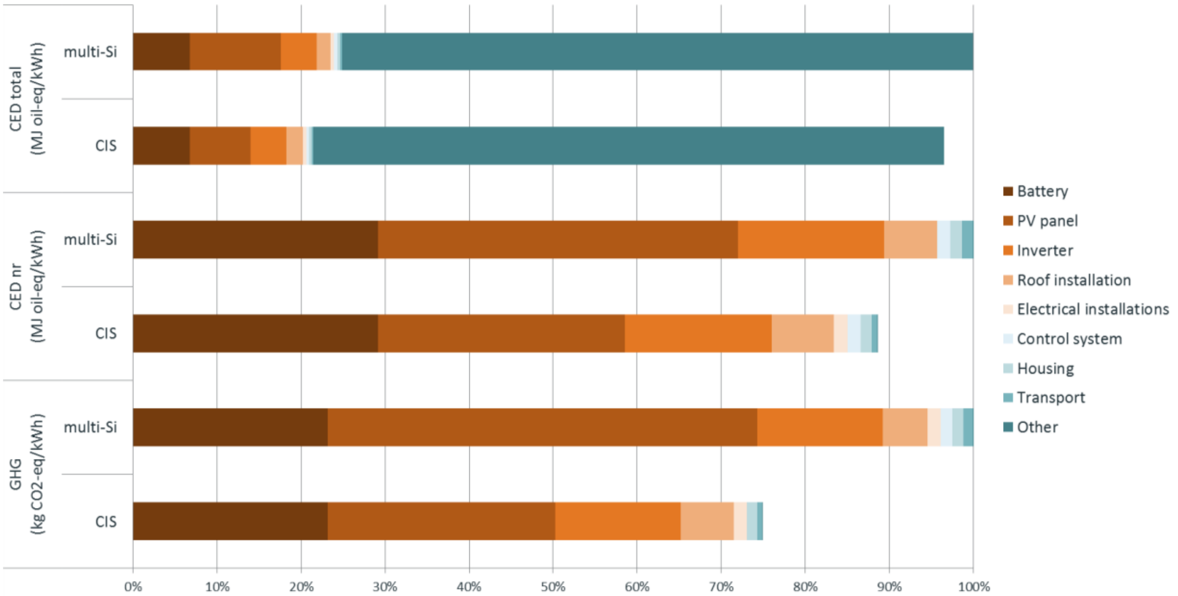

Fig. 5.5 Comparison of the environmental impacts of generating 1 kWh of electricity for self-consumption via a PV-battery system (10 kWh battery capacity) using a CIS and a multi-Si PV panel. Results are relative to the scores of the basic scenario multi-crystalline Si panel (= 100 %).

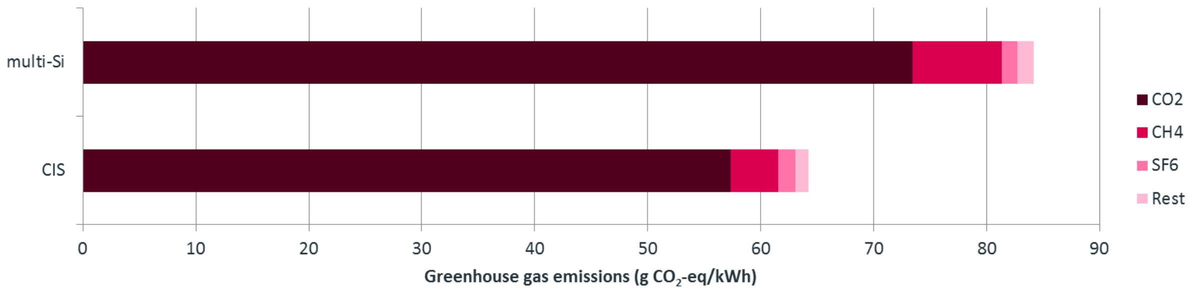

Fig. 5.6 Contribution of different greenhouse gases to the total greenhouse gas emissions from generating 1 kWh of electricity for self-consumption via a PV-battery system (10 kWh battery capacity) using a CIS and a multi-Si PV panel.

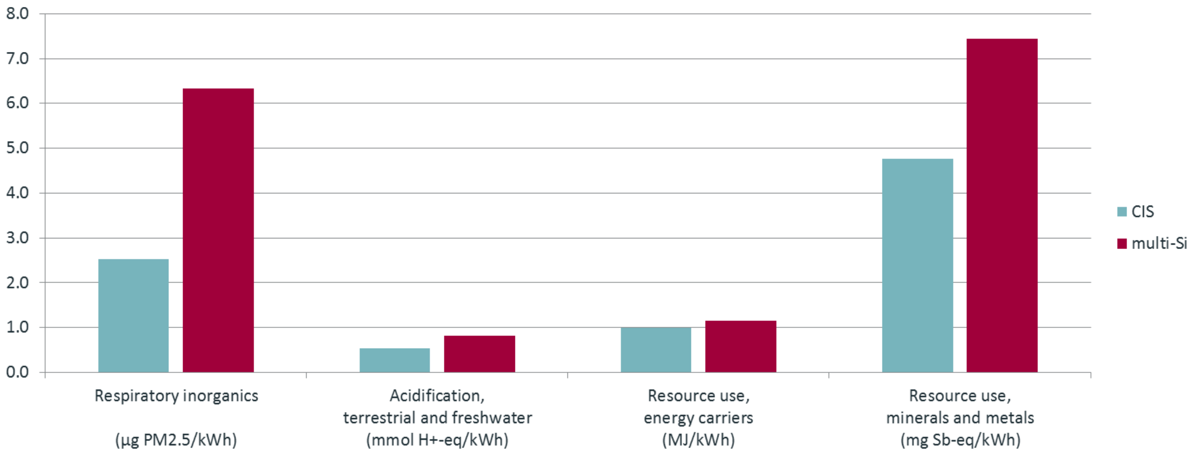

Fig. 5.7 Environmental impacts based on four of the five most relevant impact categories of the EF method, from generating 1 kWh of electricity for self-consumption via a PV-battery system (10-kWh battery capacity) using a CIS panel compared to using a multi-Si panel.

5.5 Sensitivity to annual irradiation and electricity production

The environmental performance of PV battery systems at locations with different irradiation and electricity production would differ. However, the LCA of PV battery systems with different annual production volumes would require a careful modelling of electricity production and consumption to determine the amounts of electricity self-consumed directly and via the battery system. The results shown in this chapter should thus be considered indicative. A simple linear extrapolation of the system described and analysed in this report to other locations is discouraged.

5.6 Data quality and uncertainty

This life cycle inventory analysis is based mostly on reliable data drawn from literature or industry. Therefore, the results for producing the PV panel and battery are reasonably certain. The largest uncertainties relate to system components such as the cabling, housing, and control system, because only estimates of length/weight were available, without exact information about material composition and the production process.

An additional large uncertainty is connected to battery lifetime. Our core analysis uses information from ewz.[3] Because manufacturers give varying information about battery lifetime, our sensitivity analysis investigates the effect of battery lifetime on environmental impacts.

The overall efficiency of PV-battery systems is another uncertain parameter that influences the environmental impacts of electricity for self-consumption by a few percentage points. We assume an identical system efficiency for the three battery capacities assessed, which we consider appropriate for the scope of this study. In reality, battery efficiency depends on charging current and, hence, the system setup. The higher the storage capacity of the battery in relation to the maximum power output of the PV system, the higher the battery efficiency tends to be.

6 EXAMPLE EXTENSION TO UTILITY-SCALE SYSTEMS

The life cycle inventory data used in this report for producing lithium-ion batteries (Ellingsen et al. 2014, Majeau-Bettez et al. 2011) can be extended to evaluate utility-scale battery storage systems in combination with utility-scale battery storage balance-of-system life cycle inventory data (Stenzel et al. 2018) and utility-scale battery storage specifications (Balakrishnan et al. 2019). Analysis of utility-scale battery storage can help evaluate the potential for grid flexibility under high solar energy penetration scenarios. For example, Balakrishnan et al. (2019) used the battery life cycle inventory data mentioned before to evaluate the potential role of utility-scale battery storage in meeting California's 2030 renewable portfolio standard (60 % renewable electricity by 2030). Specifically, they quantified the potential environmental impacts of utility-scale lithium-ion battery storage systems compared to natural gas power for delivering grid electricity over a 14-year period (2016 – 2030). They used this information to determine the cumulative environmental impacts of using natural gas power to back up (meet undergeneration by) solar, with and without utility-scale battery storage as a complementary technology (Fig. 6.1).

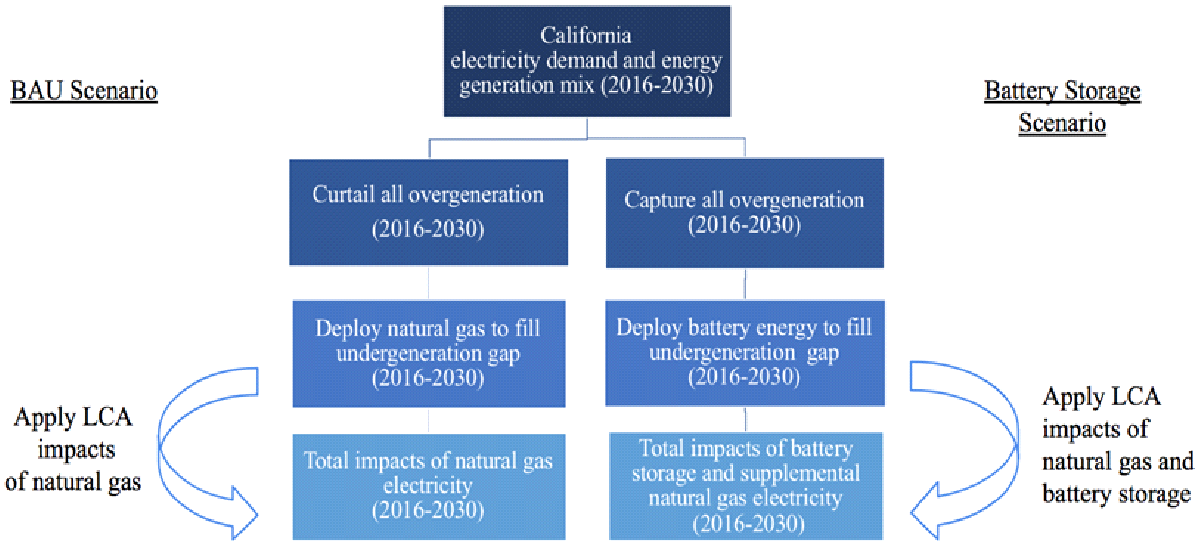

Fig. 6.1 Business-as-usual (BAU: solar and natural gas back up) and battery storage (solar and utility-scale battery storage and natural gas back up) scenarios over 2016 – 2030 to meet California's 2030 renewable portfolio standard (Balakrishnan et al. 2019).

As with the residential systems evaluated in this study, utility-scale battery storage systems evaluated in the California study had relatively low life cycle environmental impacts per kWh stored for climate change (greenhouse gas emissions) and air quality (photochemical ozone formation, fine PM, terrestrial acidification) impact categories, an order of magnitude below the impacts from natural gas generation. Under the battery storage scenario, in which only enough battery storage was deployed to capture solar overgeneration, cumulative greenhouse gas emissions were lower by about 15.5 million metric tons of CO_2-eq (about 8 %) over the 14-year timeframe compared to the BAU scenario (Fig. 6.2).

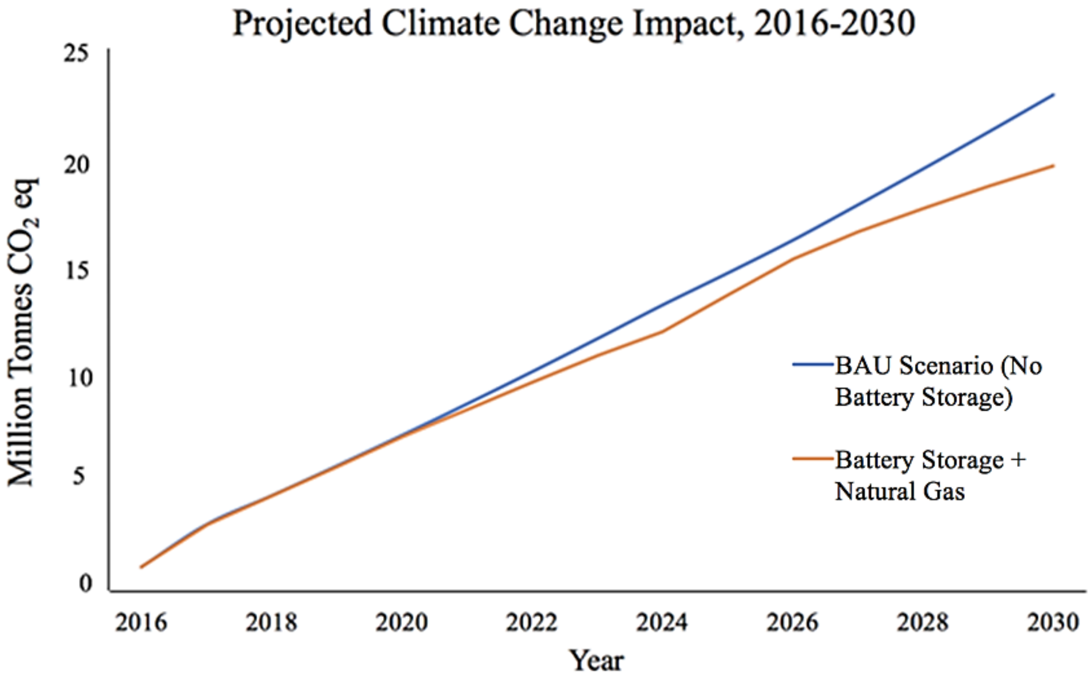

Fig. 6.2 Projected annual life cycle greenhouse gas emissions (2016 – 2030) from natural gas power used to back up solar, without and with battery storage (BAU and battery storage scenarios, respectively) based on the California scenarios in Fig. 6.1 (Balakrishnan et al. 2019); greenhouse gas emissions caused by manufacturing the PV plant are not included.

7 CONCLUSIONS

Most greenhouse gas emissions and non-renewable cumulative energy demand from generating 1 kWh of electricity for self-consumption via a PV-battery system installed and operated on residential buildings in central Europe (annual yield: 1000 kWh/kWp) can be attributed to producing the PV panel, battery, and inverter. We observe increased environmental impact per kWh self-consumed electricity with increased storage capacity — mainly owing to the environmental impacts caused by producing the additional battery cells used in the higher-capacity PV-battery-systems. Whether or not battery storage of PV electricity is environmentally beneficial requires a comparison of the environmental impacts of self-consumed electricity with those of the electricity mix of the country or the local utility. This has been shown in the case of utility scale battery systems installed in California, where battery storage reduces fossil fueled power generation and helps reducing greenhouse gas emissions. Our sensitivity analyses show that battery lifetime has a major influence on greenhouse gas emissions, non-renewable cumulative energy and further impact category indicators, while the type of Lithium ion battery has a minor influence on the mentioned impacts. The choice of the PV panel technology (i.e. thin film versus crystalline silicon) also may have a major influence on the environmental impacts of self-consumed electricity.

REFERENCES

Balakrishnan A., Brutsch E., Jamis A., Reyes W., Strutner M., Sinha P. and Geyer R. (2019) Environmental Impacts of Utility-Scale Battery Storage in California. In: IEEE Photovoltaic Specialists Conference (PVSC), Chicago, Illinois, USA.

C.A.R.M.E.N. e. V. and Energie-Netzwerk C. A.-R. M.-u. (2015) Marktübersicht Batteriespeicher.

Ellingsen L. A.-W., Majeau-Bettez G., Singh B., Kumar Srivastava A., Valøen L. O. and Hammer Strømman A. (2014) Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. In: Journal of Industrial Ecology, 18(1), pp. 113-124, DOI: 10.1111/jiec.12072.

European Commission (2014) Product Environmental Footprint Pilot Guidance - Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase. Version 4.0, European Commission.

European Commission (2017) PEFCR Guidance Document - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3, December 2017. European Commission.

Fazio S., Biganzioli F., De Laurentiis V., Zampori L., Sala S. and Diaconu E. (2018) Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, version 2, from ILCD to EF 3.0. PUBSY No. JRC114822. European Commission, Ispra.

Frischknecht R., Wyss F., Büsser Knöpfel S., Lützkendorf T. and Balouktsi M. (2015) Cumulative energy demand in LCA: the energy harvested approach. In: The International Journal of Life Cycle Assessment, 20(7), pp. 957-969, 10.1007/s11367-015-0897-4, retrieved from: http://dx.doi.org/10.1007/s11367-015-0897-4.

IPCC (2013) The IPCC fifth Assessment Report - Climate Change 2013: the Physical Science Basis. Working Group I, IPCC Secretariat, Geneva, Switzerland.

KBOB, eco-bau and IPB (2018) UVEK Ökobilanzdatenbestand DQRv2:2018. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: www.ecoinvent.org.

Majeau-Bettez G., Hawkins T. R. and Strømman A. H. (2011) Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. In: Environmental Science & Technology, 45, pp. 4548–4554.

Sony (2015) Product information FortelionTM Energy Storage Module and System.

Stenzel P., Schreiber A., Marx J., Wulf C., Schreieder M. and Stephan L. (2018) Renewable energies for Graciosa Island, Azores – Life-Cycle Assessment of electricity generation. In: Energy Procedia, 135, pp. 62-74, DOI: 10.1016/j.egypro.2017.09.487.

Stolz P., Messmer A. and Frischknecht R. (2016) Life Cycle Inventories of Road and Non-Road Transport Services. treeze Ltd., Uster CH.

Stolz P. and Frischknecht R. (2020) Life Cycle Assessment of National PV Electricity Mixes. treeze Ltd., Uster, CH.

TS PEF Pilot PV (2018) Product Environmental Footprint Category Rules (PEFCR): Photovoltaic Modules used in Photovoltaic Power Systems for Electricity Generation. treeze Ltd., commissioned by the Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.

Weniger J., Tjaden T. and Quaschning V. (2014) Sizing of Residential PV Battery Systems. In: Energy Procedia, 46, pp. 78-87, https://doi.org/10.1016/j.egypro.2014.01.160, retrieved from: http://www.sciencedirect.com/science/article/pii/S1876610214001763.

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