Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 73 (2015) 18 – 28

Energy Procedia

9th International Renewable Energy Storage Conference, IRES 2015

A holistic comparative analysis of different storage systems using levelized cost of storage and life cycle indicators

Verena Jülch[a]*, Thomas Telsnig[b], Maximilian Schulz[a], Niklas Hartmann[a], Jessica Thomsen[a], Ludger Eltrop[b], Thomas Schlegl[a]

[a]*Fraunhofer Institute for Solar Energy Systems ISE*
Freiburg, Germany
[b]*University of Stuttgart, Institute of Energy Economics and the Rational Use of Energy IER*
Stuttgart, Germany

Abstract

In this study, a detailed economic analysis is combined with an ecological analysis of electricity storage systems. On the economic side, a "Levelized Cost of Storage (LCOS)" analysis is conducted, which assesses the cost of stored electricity. The LCOS is determined for a specific case of a private household in combination with a PV system. On the ecological side a "Life Cycle Assessment" (LCA) is used to calculate the environmental impact of electricity storage as well as the CO_2 abatement costs. In the parameterized LCA the energy generation process used to feed the storage system, the material and the energy demand during the life cycle of the storage options is considered. With the parameterized LCA approach, the ecologically most rational storage systems can be identified. Results show that PV storage systems at household level are an environmental friendly option to increase the self-consumption and will be economically attractive in about ten years.

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy
*Keywords:*storage; battery; LFP; Pb-Gel; LCOS; costs; LCA

* Corresponding author. Tel.: +49-761-4588-5076; fax: +49-761-4588-9076.
E-mail address: verena.juelch@ise.fraunhofer.de

1876-6102
Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy
doi:10.1016/j.egypro.2015.07.553

1. Introduction

Economic and ecological studies on electricity storage systems have been conducted before, but the combination of both has not been the focus in literature so far. Furthermore, in most studies the economics of storage systems are described and analysed on a general level, but not in great detail. Simplifications, such as analyzing storage systems in different supply tasks, are applied in most calculation methods. Ecological analyses of electric storage devices have been carried out so far based on conventional LCA approaches, quantifying the environmental impacts of the storage system on a given supply structure or its performance characteristics (e.g. emissions of battery system per battery weight).

Electricity storage technologies in distributed systems are technically mature and market ready, but the market is still small. In this paper, the "Levelized Cost of Storage" (LCOS) method is combined with the LCA analysis of an example PV battery storage system.

2. LCOS for Battery Technologies

The LCOS can be calculated by equations (1) and (2) [13]. The LCOS is the sum of all annual expenses A_t, and the capital expenditure *CAPEX*, divided by the sum of the energy output W_{out}over the lifetime n of the storage (1). Expenses and energy output are discounted by using the discount rate i. The annual cost A_t is composed of the operation cost *OPEX*, the necessary reinvestments in storage components $CAPEX_{re,t}$at the time t as well as the cost of electricity supply, which is determined by the electricity price c_{el}, multiplied with the sum of annual electricity input W_{in} (2). A recovery value of storage components is considered by R_n at the end of storage lifetime.

$$LCOS = \frac{CAPEX + \sum_{t=1}^{t=n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{W_{out}}{(1+i)^t}} \tag{1}$$

$$A_t = OPEX + CAPEX_{re,t} + c_{el} \cdot W_{in} - R_t \tag{2}$$

Regarding the battery, specific considerations for LCOS calculations need to be accounted for. The market prices for storage systems generally refer to the rated capacity C_r, which is higher than the effective 'net' capacity C_{net}(usable energy in kWh) because most batteries should not be fully discharged. The relation between the net capacity in the first year of operation and the rated capacity is described in (3). The extent to which the battery is discharged is described by the depth of discharge (*DoD*).

$$C_{net,1} = C_r * DoD \tag{3}$$

The lifetime n of the battery is calculated by dividing the technology specific cycle durability $LC_{max}$by the amount of yearly load cycles *LC* at which the battery is operated (4). In case this calculated lifetime exceeds the calendar life of the battery technology, n is set equal to the calendar life. *LC* is the quotient of the average energy output $W_{out,av}$ and the average net capacity $C_{net,av}$ (5).

$$n = \frac{LC_{max}}{LC} \tag{4}$$

$$LC = \frac{W_{out,av}}{C_{net,av}} \tag{5}$$

Due to the degradation d of the battery, the net capacity decreases over the storage system's lifetime (6). The average net capacity is the sum of the net capacity in each time step $C_{net,t}$, divided by the lifetime of the battery.

$$C_{net,t} = (1-d) * C_{net,t-1} \tag{6}$$

The degradation rate d of the battery is calculated by assuming that the rated capacity of the battery at the end of its lifetime will be 80% of its initial rated capacity C_r[5]. It is also assumed that the decrease is arithmetical, meaning the rated capacity decreases by a fixed rate in each operation year. The degradation d can be calculated by using (7). With an increasing use of the battery, the annual load cycles increase and the lifetime of the battery decreases, hence the degradation rate increases.

$$d = 1 - \left(\frac{0.8 * C_r}{C_r}\right)^{\frac{1}{n}} \quad (7)$$

The required annual amount of energy input $W_{in,t}$ can be calculated by the amount of energy output divided by the efficiencies of battery η_{bat} and inverter η_{inv}, plus the energy lost by self-discharge. These energy losses can be calculated by multiplying the monthly self-discharge rate r_{sd} with the rated capacity and the number of months per year (8).

$$W_{in,t} = \frac{W_{out,t}}{\eta_{bat} * \eta_{inv}{}^2} + 12\ \frac{months}{a} * C_r * r_{sd} \quad (8)$$

3. Technologies and Input Parameters

An exemplary case is chosen to show the type of results which can be achieved with the approach of using LCOS and LCA in combination. This case is assumed to be a household in a single residential building with 4,500 kWh yearly electricity consumption and a 5 kW_p photovoltaic (PV) system which can provide electricity for a self-consumption of 30% (1,350 kWh/a), which is a typical value for the rate of self-consumption in a household with PV system. A net storage capacity of 4 kWh is assumed to be necessary to increase the share of self-consumption to 60%. With regard to the DoD, different rated capacities for the storage technologies are needed. The geographic reference for the system is Germany. The main assumptions for the example case are listed in Table 1.

With changing DoD for the future, the rated capacity of the storage system is chosen accordingly. The technical and economic input data for the technologies are shown in Tables 2 and 3. The specific CAPEX for both technologies are analysed in a market research. [8]lists market prices in €/kWh net capacity, which is converted to €/kWh rated capacity by using the DoD values given in Table 2. The price range is calculated by using the mean deviation from the median of the values. Only for PbA the full price range is used due to the small number of data for that technology. All costs in this paper are given in Euros in real terms for the base year 2013.

Table 1.Basic assumptions on the investigated combined PV battery system.

Consumer	Residential building (4 persons)
Electricity demand	4,500 kWhel/year
Generation technology	PV rooftop system
Capacity PV system	5 kWp
Electricity output	1,000 kWhel/kWp
Storage option 1	Lead-acid (PbA) battery
Storage option 2	Lead-gel (Pb-Gel) battery
Storage option 3	Lithium-Ferrophosphate(LFP) battery
Lifetime	25 years

Table 2.Input data for the LCOS calculation for the battery storage system with 4 kWh net capacity located in Germany.

	Unit	PbA				Pb-Gel				LFP			
		2013		2020+		2013		2020+		2013		2020+	
Rated capacity	kWh	8		5		8		5		4.7		4	
Charging power	kW	4		4		4		4		4		4	
Battery efficiency	%	90	[8]	90	[17]	90	[8]	90	[17]	90	[8]	95	[17]
Inverter efficiency (one way)	%	95	a)	95	a)	95	a)	95	a)	95	a)	95	a)
Depth of discharge	%	50	[3]	80	[17]	50	[8]	80	[17]	85	[3]	100	[17]
Cycle durability	-	2,000	[7]	4,000	[17]	2,500	[3]	4,000	[17]	5,000	[3]	10,000	[17]
Self discharge rate	%/month	5.0	[4]	3.0	[17]	5.0	[4]	3.0	[17]	3.0	[18]	2.0	[17]b)
Specific CAPEX	€/kWh	440-530	[8]	130-270	[17]c)	540-710	[8]	130-270	[17]c)	1,560-1,670	[8]	250-550	[17]c)

a)–assumed as in [17]; b)–source states “<3%”, 2% assumed; c)–adapted using power related and energy related cost

Table 3. Additional input data for LCOS calculation.

	Unit	Value	Source
Insurance	% of CAPEX	1.1	d)
OPEX	€/year	20	[15]
Discount rate	%	3.5	[15]
Cost of inverter replacement	€	200	e)
Inverter lifetime	a	18	[15]

d)–assumed to be included in PV insurance; e)–assumed as in [8]

Today’s market prices for lead batteries are much lower than market prices for LFP batteries. For the future, large price drops are expected due to the fact that the market is expected to grow extensively. However, a higher DoD and a larger number of maximum load cycles per life period for LFP batteries put the higher costs in perspective. The charging power of all batteries is assumed to be 4 kW as this is a common value for batteries sold in the market today. A discount rate of 3.5% is assumed for all calculations.

Table 4. Additional input data for system cost calculation.

	Unit	Value	Source
Energy from storage	kWh/a	1,350	
Cost of PV electricity 2013	€/kWh	0.12-0.14	[14]
Cost of PV electricity 2025	€/kWh	0.09-0.10	[14]
Cost of German electricity mix 2013	€/kWh	0.08	[16]
Cost of German electricity mix 2025	€/kWh	0.10	[16]

Table 4shows the input data for the system cost calculation. The Levelized Cost of Electricity (LCOE) for PV is the price of electricity for the battery system as used in (2). An energy output of the storage of 1,350 kWh/a corresponds to an increase in self-consumption to 60%.

4. LCA Analysis

A Life Cycle Assessment (LCA) is used to analyse the environmental impacts of a product "from cradle to grave". Standardized principles, described in ISO 14040 and ISO 14044 are used for the analysis [11, 12]. All relevant stages of this approach are applied in this analysis, which include:

- Goal and scope definition
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation

4.1. Goal and Scope Definition

The objective of this assessment is to quantify the environmental impact of the combined photovoltaic-storage systems that were described previously. The functional unit of all investigated combined PV battery systems is 1 kWh_{el}. The system boundaries of this assessment include the materials needed to build the combined PV battery systems and the energy required to gain raw materials and the energy to convert the raw materials into the system components (e.g. cathode, anode). Recycling of different materials is not assessed in detail but is considered through the reported energy demand in [20], which quantifies the use of recycled materials in material production. Moreover, no additional infrastructure is considered regarding the surplus energy which is fed by the PV system directly into the electricity grid.

4.2. Life Cycle Inventory Analysis (LCI)

The life cycle processes of the battery systems and the photovoltaic system are modelled by considering the material and energy requirements during their life cycle. Material and energy data to perform the LCA of these combined PV battery systems were obtained from LCA studies and technical data sheets and are based on data from the ecoinvent LCA database [1, 6, 9, 10, 19, 20].

During the lifetime of the combined PV battery systems the battery is replaced based on the calculated battery lifetimes of 5 (10) years for the lead-batteries and 12.5 (25) years for the LFP battery for today (future).

Following the shares of the material composition by [1] and [20], the life cycle inventory of the PbA battery system is given in Table 5inAppendix A.The life cycle inventory of a Pb-Gel battery system was compiled based on data of [9] and [10]. In contrast to conventional PbA batteries, in Pb-Gel batteries silicon dioxide is added to the electrolyte to thicken the sulphuric acid (see Table 6 inAppendix A). LCA data on the material of PbA and Pb-Gel batteries is retrieved from [6].

For both battery systems the energy demand during material production and material manufacturing were obtained from [6] and [20]. Since in lead battery production recycling is common, it was assumed that 75% of the material used for the batteries is retrieved from a recycling process whereas 25% is made of new raw materials.

Table 7 in Appendix Adepicts the material and energy demand for an LFP battery system. Appropriate LCA process data was retrieved from the ecoinvent V2.2 database [6]. An exception was the cathode which is modelled by performing a stoichiometric calculation of the production of $LiFePO_4$ by calcination using lithium carbonate [24].

$$4\,Fe(PO_4) + 2\,Li_2CO_3 + C \rightarrow 4\,LiFePO_4 + 3\,CO_2 \uparrow \tag{9}$$

To obtain 1 g of $LiFePO_4$, 0.96 g of iron phosphate, 0.23 g of lithium carbonate and 0.02 g of carbon are needed. The described process emits 0.21 g of CO_2 per gram of produced $LiFePO_4$. The cathode is made up by a mixture of $LiFePO_4$, carbon black and a styrene acrylate latex binder which are attached onto an aluminium foil. The LCA process data for respective materials for $LiFePO_4$ production was obtained from [6].

The main materials of the anode are graphite, carbon black, copper and a styrene acrylate latex binder. Other parts of the LFP battery include the electrolyte, the separator between the cathode and the anode, electronic components and the packaging of the cell.

The information on energy demand for material production and material manufacturing was obtained from [6] and [20]. As detailed information on material recycling for lithium-ion (Li-Ion) batteries is not available, only the share of recycled materials based on the standard ecoinvent processes is considered in the energy demand for material production. [20]assume that the energy demand for battery manufacturing accounts for 0.68 MJ/Wh.

To assess the life cycle impacts of the residential PV system, LCA data of the ecoinvent process "electricity, PV, at 3kW$_p$ slanted-roof, multi-Si, panel, mounted" was used. This standard LCA process was scaled upto the investigated PV capacity of 5 kW$_p$ and adjusted to represent German irradiation conditions.

4.3. Life Cycle Impact Assessment (LCIA)

The main indicator to measure the environmental impact is the impact category "Global Warming Potential (100 years)" in grams of CO_2 equivalents (gCO_{2eq}). It results in the life cycle greenhouse gas (GHG) emissions of the investigated technology configuration. This impact category is referred to the electricity output (functional unit = 1 kWh$_{el}$) of the PV battery system. The energy losses from the battery system are considered.

The emissions caused by the energy requirements for the material production and manufacturing were calculated using the specific CO_2 emissions of the German electricity mix of 2010, which account for 542 gCO_{2eq}/kWh_{el}[22]. To assess the emissions caused by the energy requirement of future systems, the specific CO_2 emissions of the German electricity mix in the year 2025 were used, which are 271 gCO_{2eq}/kWh_{el}[2], thus a decrease in emissions of 50% compared to today's emissions.

4.4. CO_2 Abatement Cost

The CO_2 abatement cost calculation combines cost analysis and LCA to a holistic comparative analysis of PV storage systems. Fig. 1 shows the schematic of the energy flow in the reference system. The abatement cost calculation refers to all electricity provided by the PV storage system (see blue arrows in Fig. 1).

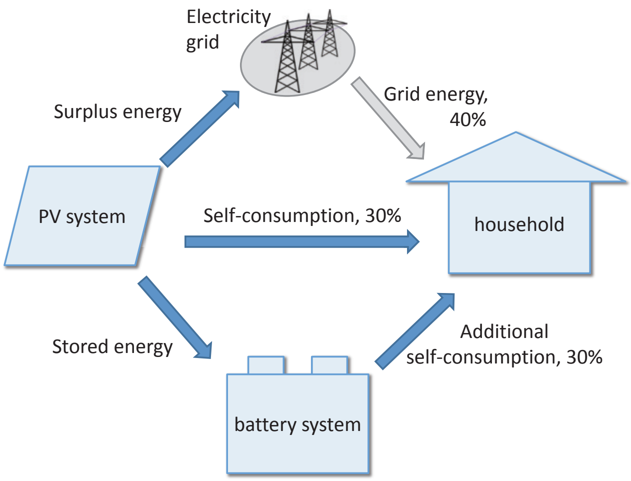

Fig. 1. Schematic of the energy flows in the reference system.

The CO_2 abatement cost$c_{ab\,CO_2}$ can be calculated by dividing the additional electricity cost of this system (LCOE of PV and the cost of stored electricity c_{PV+st} minus the cost of the reference system c_{ref}) by the abated emissions per kWh (specific emissions of reference system e_{ref} minus specific emissions of the PV storage system e_{PV+st}) (10) [21]. The cost of the electricity from the PV storage system can be calculated by weighing the cost factors by the correspondent energy flows (11). Data for the CO_2 emissions of the fossil energy sources are retrieved from [23]. Cost data for brown coal and hard coal are from [14].

$$c_{ab\,CO_2} = \frac{c_{PV+st} - c_{ref}}{e_{ref} - e_{PV+st}} \tag{10}$$

$$c_{PV+st} = \frac{c_{PV} \cdot (W_{PV} - W_{out} - W_{loss}) + c_{PV\ st} \cdot W_{out}}{W_{PV} - W_{loss}} \tag{11}$$

5. Results of LCOS and LCA Analyses

Fig. 2 shows the cost of stored PV electricity for PbA, Pb-Gel and LFP batteries for 2013 and 2020+ at a storage energy output of 1,350 kWh per year. It is the cost of the electricity which is generated by the PV system, stored in the battery and then consumed. It does not include the cost of the PV electricity which is directly consumed or supplied to the grid without being stored in the battery (i.e. only the costs of stored electricity are calculated, not the weighted system electricity cost). The LCOE of the PV system is used as the cost of electricity input for the battery. The combined cost of electricity is therefore the cost of electricity out of a battery which is filled by PV electricity. If the whole system was regarded, the cost of electricity would be lower on average due to lower cost of the share of electricity which is not stored. In this case only the cost of stored electricity is regarded to allow a more detailed cost analysis.

Since the cost of electricity input has a strong impact on the cost of electricity from the battery, the cost of electricity per kWh stored electricity (in €/kWh$_{st}$)is shown for lower and higher LCOE of PV electricity and regarded for today's prices as well as for future prices (see Table 4).

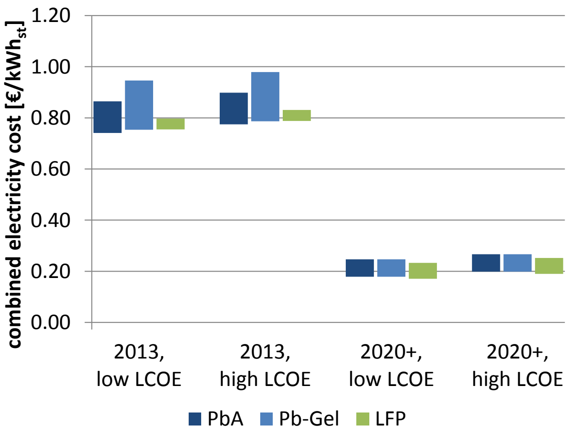

Fig. 2. Combined cost of stored PV electricity for the selected battery technologies.

The results show that the LCOS from lead batteries today are between 0.74 and 0.98 €/kWh$_{st}$, while the LCOS of LFP batteries varies between 0.75 and 0.83 €/kWh$_{st}$, depending on PV LCOE and specific CAPEX of the battery. For the future, the combined cost of electricity will decrease to about 0.18 to 0.27 €/kWh$_{st}$ for lead batteries and 0.17 to 0.25 €/kWh$_{st}$ for LFP batteries. The smaller range for the future costs results from the cost estimations of [17], which can be interpreted as target costs, while today's prices represent the current market which is very diverse.

Fig. 3 shows the present and future life cycle GHG emissions for the combined PV battery systems. All investigated combined PV storage systems show significant CO_2 reduction potential compared to the German electricity mix, which accounts for 542 and 271 gCO_{2eq}/kWh_{el} in 2013 and 2020+, respectively [2, 23]. Today specific CO_2 emissions for PV combined with PbA, Pb-Gel and LFP account for 73 to 93 gCO_{2eq}/kWh_{el}. The composition of the emissions shows that with a share between 63 and 82%, the majority of the GHG emissions stem from the life cycle emissions of the PV system. The energy demand for material production of the battery systems causes 6 to 20%, whereas the life cycle emissions caused from material demand necessary to build the battery systems range from 12 to 17%. Results show that life cycle GHG emissions of the combined PV battery systems increase between 21 and 59% compared to PV systems without storage device. Compared to the conventional

German electricity mix in 2010, an emission reduction of 83 to 87% can be achieved. Due to the increased performance characteristics of future battery systems and the reduced specific CO_2 emissions of the German electricity mix, the global warming potential of the different investigated systems account for 60 to 66 gCO_{2eq}/kWh_{el}.

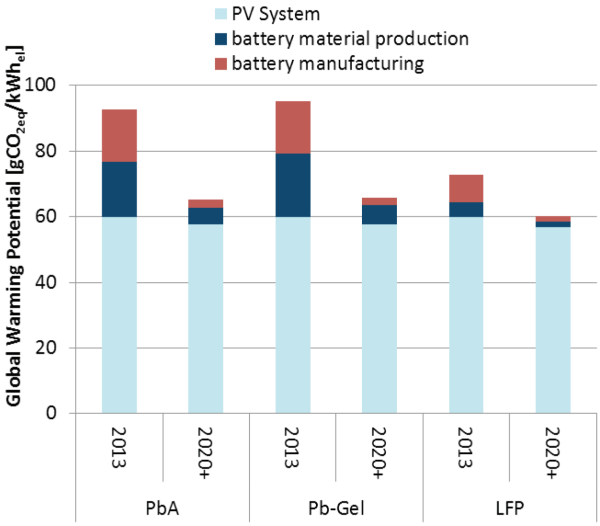

Fig. 3. Global warming potential of the investigated combined PV battery systems.

Fig. 4 shows the CO_2 abatement cost of the combined PV storage system for today and 2020+. The costs are between 220 and 650 €/t CO_{2eq} today and are expected to decrease drastically down to between 40 and 230 €/t CO_{2eq} beyond 2020, depending on the battery type, the cost of PV electricity and the fossil energy that the system is compared to.

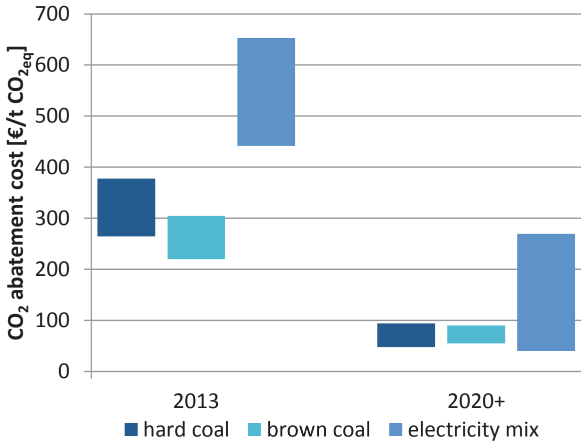

Fig. 4. CO_2 abatement cost of PV storage systems today and beyond 2020 compared to fossil sources and the German electricity mix.

6. Conclusion and Outlook

This paper presents a holistic comparative analysis of cost and life cycle impact for PbA, Pb-Gel and LFP batteries.

The cost of electricity from a battery storage system supplied by PV electricity is 0.74 and 0.98 €/$kWh_{st}$for today's systems, but with the expected price decreases for the years beyond 2020, the cost may decrease to about 0.17 to 0.27 €/kWh_{st}. In a PV battery system not all energy needs to pass through the storage, thus the resulting average cost of directly-consumed and stored electricity will be even lower. A comparisonof these values with the European household electricity prices, which are most probably going to increase in the future, shows that combined PV battery systems will be economically attractive in less than ten years.

The global warming potential of all three investigated PV storage combinations ranges between 73 and 95 gCO_{2eq}/kWh_{el} today and between 60 and 66 gCO_{2eq}/kWh_{el} in the future; which is very low compared to the German electricity mix (542 gCO_{2eq}/kWh_{el} today and 271 gCO_{2eq}/kWh_{el} beyond 2020). In comparison with the global warming potential of a PV system, the value for the PV storage system is only slightly higher. Therefore, a storage system can be seen as an environmental friendly option to complement PV systems.

Combining the LCOS analysis and the environmental impact analysis, the CO_2 abatement cost of PV storage systems was calculated. Depending on the fossil based reference technology, the costs are between 220 and 650 €/t CO_{2eq} for today and 40 and 230 €/t CO_{2eq} for the future.

The presented results show that the LCOS method is suitable to compare the cost of different electricity storage systems. Also it becomes clear that the method can be combined with an LCA approach to allow a holistic comparative analysis for energy storage systems.

Since the cost of stored energy is highly dependent on the storage operation mode, the cost of storage for defined supply scenarios needs to be analysed. Regarding the LCA, further research will include the recycling of batteries in the assessment. In the current assessment, assembly of the battery is assumed to be in Germany. A further research topic would be the LCA for batteries from other countries.

Acknowledgements

This work has been financially supported by the state of Baden-Wuerttemberg as part of the Baden-Wuerttemberg Research Program Securing a Sustainable Living Environment (BWPLUS).

Appendix A.

Table 5.Life cycle inventory data of a PbA battery system (based on [20, 1,10]).

	8 kWh PbA Battery	
Material	Unit	
Antimony	[kg]	4.0
Copper	[kg]	1.2
Glass	[kg]	8.1
Lead	[kg]	100.8
Lead Oxides	[kg]	141.1
Plastics	[kg]	40.3
Sulfuric Acid	[kg]	40.3
Water	[kg]	63.9
Energy demand battery manufacturing	[MJ]	2400

Table 6 Life cycle inventory data of a Pb-Gel battery system (based on [20, 9,10]).

	8 kWh Pb-Gel Battery	
Material	Unit	
Arsenic	[kg]	0.3
Calcium	[kg]	0.3
Tin	[kg]	3.3
Lead	[kg]	166.4
Lead Oxides	[kg]	75.8
Lead Sulfate	[kg]	1.8
Plastics	[kg]	19.8
Sulfuric Acid	[kg]	23.1
Silicon Dioxide	[kg]	38.7
Antimony	[kg]	4.8
Copper	[kg]	1.6
Water	[kg]	64.0
Energy demand battery manufacturing	[MJ]	2400

Table 7Life cycle inventory data of a lithium-ion (LFP) battery system (based on [20,24]).

	4.7 kWh LFP battery	
Material	Unit	
LiFePO4	[kg]	19.8
Iron (III) phosphate	[kg]	19.0
Lithium carbonate	[kg]	4.6
Carbon	[kg]	0.4
Carbon dioxide into air	[kg]	4.1
Aluminum foil	[kg]	0.9
Carbon black	[kg]	1.3
Styrene acrylate latex	[kg]	1.6
Ethylene glycol dimethyl ether	[kg]	7.4
Lithium salt (Lithium chloride)	[kg]	1.3
Polypropylene	[kg]	0.4
Polyethylene	[kg]	0.4
Transistor	[kg]	0.5
Resistor	[kg]	0.5
Graphite	[kg]	7.9
Carbon black	[kg]	0.2
Copper	[kg]	2.2
Styrene butadiene latex	[kg]	0.3
Polypropylene	[kg]	0.2
Aluminum foil	[kg]	0.3
Energy demand battery manufacturing	[MJ]	3176

References

[1] Ashby, M. F. and Polyblank, J. 2012. Materials for Energy Storage Systems—A White Paper -, University of Cambridge.
[2]Bundesumweltminsterium (BMU), w. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global.
[3]C.A.R.M.E.N. e.V. Marktübersicht Batteriespeicher. Ein Informationsangebot. http://www.carmen-ev.de/sonne-wind-co/stromspeicher/batterien/813-marktuebersicht-fuer-batteriespeichersysteme. Accessed 13 January 2015.
[4]Crastan, V. 2012. Elektrische Energieversorgung II. Energie- und Elektrizitätswirtschaft, Kraftwerkstechnik und alternative Stromversorgung. Springer-Verlag.
[5]DIN 43539/Teil 4. 1984. Akkumulatoren; Prüfungen, Ortsfeste Zellen und Batterien, 43539/Teil 4.
[6] EcoInvent. 2010. Swiss Center for Life Cycle Inventories, Duebendorf, Switzerland.
[7]Fuchs, G., Lunz, B., Leuthold, M., and Sauer, D. U. 2012. Technologischer Überblick zur Speicherung von Elektrizität. Überblick zum Potenzial und zu Perspektiven des Einsatzes elektrischer Speichertechnologien. Im Auftrag der Smart Energyfor Europe Platform GmbH (SEFEP). RWTH Aachen, Berlin.
[8]Fuhs, M. 2014. Zwei Jahre Speichermarkt. Produktübersicht. pvmagazine, 2, 39–56.
[9] Hoppecke. 2014. HOPPECKE OPzV Material Safety Data Sheet Valve Regulated Lead Acid Battery. Version: MSDS OPzV 28.02.06.
[10] IBC Solar. 2014. – Technische Datenblätter IBC SolStore XL1 und IBC SolStore L1. www.ibc-solar.de. Accessed 17 December 2014.
[11]ISO 2006a. 2006. Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006), Europäische Norm ISO 14040 DIN Deutsches Institut für Normung e.V., Berlin DIN Deutsches Institut für Normung e.V., 14040. Accessed 16 January 2015.
[12]ISO 2006b. 2006. Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044:2006), Europäische Norm ISO 14044. DIN Deutsches Institut für Normung e.V., Berlin, 14044. Accessed 16 January 2015.
[13]Jülch, V., Jürgensen, J., Hartmann, N., Thomsen, J., andSchlegl, T. 2015. Levelized Cost of Storage Method Applied to Compressed Air Energy Storage. proceedingsSmartER Europe 2015.
[14] Kost, C., Mayer, J. N., Thomsen, J., Hartmann, N., Senkpiel, C., Philipps, S., Nold, S., Lude, S., Saad, N., andSchlegl, T. 2013. Levelized cost of electricity renewable energy technologies. Version November 2013. Fraunhofer Institut für Solare Energiesysteme, Freiburg.
[15] Lorenz, C. and Schröder, G. 2014. Wirtschaftlichkeit Batteriespeicher. Berechnung der Speicherkosten und Darstellung der Wirtschaftlichkeit ausgewählter Batterie-Speichersysteme. IE.
[16]Nitsch, J., Pregger, T., Naegler, T., Heide, D., de Tena, D. L., Trieb, F., Scholz, Y., Nienhaus, K., Gerhardt, N., Sterner, M., Trost, T., Oehsen, A. v., Schwinn, R., Pape, C., Hahn, H., and Wickert, M. 2012. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Schlussbericht. Deutsches Zentrum für Luft- und Raumfahrt (DLR); Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES); Ingenieurbüro für neue Energien (IfnE), Berlin.
[17] Sauer, D. U., Lunz, B., andMagnor, D. 2013. Marktanreizprogramm für dezentrale Speicher insbesondere für PV-Strom. Kurzgutachten. Institut für Stromrichtertechnik und Elektrische Antribe (ISEA), RWTH Aachen.
[18]Sterner, M. and Stadler, I. 2014. Energiespeicher. Bedarf, Technologien, Integration. Springer Vieweg, Berlin Heidelberg.
[19] Sullivan, J. L. and Gaines, L. 2010. A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs. Energy Systems Division, IL,USA. http://www.transportation.anl.gov/pdfs/B/644.PDF. Accessed 16 January 2015.
[20] Sullivan, J. L. and Gaines, L. 2012. Status of life cycle inventories for batteries. Energy Conversion and Management 58, 134–148.
[21] Telsnig, T., Tomaschek, J., Özdemir, E. D., Bruchof, D., Fahl, U., andEltrop, L. 2013. Assessment of selected CCS technologies in electricity and synthetic fuel production for CO_2 mitigation in South Africa. EnergyPolicy 63, 168–180.
[22]UBA. 2014. Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2012. Climate Change 23/2014, Dessau-Roßlau.
[23]Umweltbundesamt. 2013. Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2012.
[24] Zackrisson, M., Avellán, L., andOrlenius, J. 2010. Life cycle assessment of lithium-ion batteries for plug-in hybrid electricvehicles – Cr iticalissues. Journal of Cleaner Production, 18, 1519–1529.