When Does the Operation of a Battery Become Environmentally Positive?

Karl-Heinz Pettinger* and Winny Dong

*Technology Center for Energy, University of Applied Sciences Landshut, 84036 Landshut, Germany

© The Author(s) 2016. Published by ECS. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 License (CC BY, http://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse of the work in any medium, provided the original work is properly cited. [DOI: 10.1149/2.0401701jes] All rights reserved.

Electricity generated by photovoltaics in residential systems is stored in battery systems with a typical capacity between 5 and 20 kWh. In this application Pb-acid and Li-ion batteries are the most common storage technologies. The environmental benefits of electricity stored by a 10 kWp PV-generator in combination with a 7.5 kWh battery is compared to the environmental costs of producing the storage system (Fig. 1). In analyzing the environmental costs of producing a battery storage system, the energy usage in the following processes were compared for lithium-ion and lead-acid technology.

- cell production
- production of the battery system
- transport to the customer

This is then compared to the environmental benefits of the photovoltaic system, resulting in the minimum operation time needed for ecological amortization of the different battery technologies.

**Methodology**

The applied methodology was to investigate the real demand of primary energy for the production of 1 kWh storage capacity. For this reason, the energy demands of two battery production lines were analyzed. One line produces 1.4 million pieces Pb-acid SLI batteries per year with 12 V and 60 Ah energy content. The other line has the capability to produce 1.5 million Li-ion cells with 3.7 V nominal voltage and 20.5 Ah energy content per year.

The data were obtained from real operating lines. All the energy demands along production steps, starting from the raw materials to the final battery have been taken into account. The operating time of both lines was set to 280 days per year in 3 shift mode. Production scrap was taken into account with 5% for the Pb-acid line and 8% for the Li-ion line.

Based on the total energy demand for one year of operation the primary energy demand for the production of one cell or battery, as well as the demand for producing 1 kWh storage capacity has been calculated for each battery technology. On the cell level the degrees of utilization (depth of discharge in recommended use) and lifetime during usage were taken into account (Table I).

On system level the operation of both battery technologies in a photovoltaic home storage system is compared.

Both cell types are assembled to 7.5 kWh buffer systems and compared for an expected lifetime of 20 years of operation. The basic data used for the simulation are real measured PV-data and were obtained in Southern Germany (location Ruhstorf a. d. Rott) and standard load profiles for a typical 4-person household.2

Additionally a scenario for the transport has been added to analyze the influence of the transport onto the overall energy balance. This was set to a worst case scenario with full assembly of the system in Asia (Shenzhen) and transport to Germany by sea- (Hamburg harbor) and road freight to Southern Germany.

Based on these calculations the total demand on primary energy for production, assembly and transport of the assembled systems has been calculated.

In a final step both technologies are compared with respect to their ecological amortization in the home PV-application.

**Results**

**Lead-acid technology (per cell).**—The production data for 60 Ah SLI batteries in Pb-acid technology were obtained based on a running production line for 1.4 million pieces per year. The production steps from elementary Pb to formation of the assembled battery were taken into account.

Figure 2 shows the primary energy demand for the production of a 720 Wh Pb-acid battery based on individual production steps.

**Lithium-ion technology (per cell).**—In Figure 3 the demand of primary energy for the production of a 72 Wh Li-ion battery is analyzed. It has to be remarked that the Li-ion production is significantly lower than the Pb-acid production.

Figure 1. Storage utilization in photovoltaics, modeling with real localized data; location: Germany – Bavaria, degree of self-sufficiency = 72%, self-consumption = 36%.
Table I. Typical conditions for use in on cell level.

| Cell Technology | Depth of utilization | Number of cycle | Efficiency |
|-----------------|----------------------|-----------------|------------|
| Li-Ions         | 80%                  | 10,000          | 96%        |
| Pb-acid         | 50%                  | 3,000           | 80%        |

Comparison between solvent based and water based electrode production.—There are two basic routes for the production of electrodes in Li-ion technology. One is the traditional solvent based technology. Within this strategy PVDF-copolymers are used as binders which are dissolved in organic solvents such as N-methyl-pyrrolidon (NMP). The newer and more environmentally friendly method is to use carboxy-methyl-cellulose (CMC) and styrene-butadiene-rubber (SBR) as binder systems. They are dissolved and dispersed in water. The use of such water-based binders reduces emission problems and does not require explosion-proof machinery for electrode production.

Figure 4 and Figure 5 analyze the total energy demand for electrode production in a 40 Ah Li-ion cell.

The most energy intensive production step is the coating and drying process for both water and organic solvent based electrode production. This is related to the evaporation enthalpies of water and NMP and the necessary coating equipment. The evaporation enthalpy for NMP with 533 kJ/kg [Lit. 3] is much lower than that for water with 2,543 kJ/kg [Lit. 3]. But the boiling point of NMP with is 202°C [Lit. 4] and much higher than that of water with 100°C. The dryer in the NMP process has to be operated at much higher temperature can creates bigger losses than with water as solvent. Both effects compensate and the primary energy demands for both techniques do not differ significantly, even if the boiling points of the solvents are quite different. Most of the primary energy is not used for the compensation of the evaporation enthalpy but for heating the large drying units and energy losses by ventilation.

Comparison on system level.—The total energy required for production of 1 Wh of battery capacity is 41 kWh for Li-ion technology and 14 kWh for Pb-acid. In this sense, Pb-acid batteries are nearly 3-times more energy efficient with respect to the demand of primary energy for their production. However, Li-ion cells are more environmentally friendly when lifetime and system performance are taken into account (described in a later section.)

The most energy consuming step in lithium-ion battery production is the coating process using long drying units. For lead-acid battery production the formation process is the most energy consuming step. The primary energy demand for the production of storage systems with both types of cells has been analyzed. The calculation is based on cells, rack, assembly and inverter. The overall energy demand is
Figure 5. Energy demand by production steps for a 40 Ah Li-ion cell using water based electrode production processes.

| Table II. Primary energy demand for the production of a 7.5 kWh battery on system level. |
|-----------------------------------------------|-------------------|-------------------|
| Component                  | 7.5 kWh Pb-acid-storage (eff.) | 7.5 kWh Li-ion-storage (eff.) |
| Cells                      | 105.1 kWh            | 375.0 kWh         |
| Rack                       | 5.1 kWh              | 5.1 kWh           |
| Assembly                   | 17.3 kWh             | 17.3 kWh          |
| Inverters                  | 8.7 kWh              | 8.7 kWh           |
| Sum                        | 136.1 kWh            | 406.1 kWh         |

shown in Table II. It was assumed that systems with both cell technologies use similar racks, inverters and these do not differ significantly in their primary energy demand for production. The values in Table II refer to 7.5 kWh effective storage capacity in each technology.

Transport.—Transportation is an enormous factor in the total energy balance. Within this paper a “worst-case scenario” was applied to investigate the limits of a battery and its ecological amortization. The scenario is that the assembly of the battery system happens in Asia (e.g. Shenzhen, China) and require transportation to Hamburg harbor by sea freight (8,000 km) and then transported by road to Southern Germany (1,000 km). The energy demand5 is shown in Table III.

| Table III. Energy demand for transportation of a battery system in worst case scenario. |
|-----------------------------------------------|-------------------|-------------------|
| 7.5 kWh Pb-acid-storage (eff.) | 7.5 kWh Li-ion-storage (eff.) |
| Weight incl. cabinet and inverter           | 725 kg            | 300 kg            |
| Energy expenditure for 1.000 km truck-transports | 190 kWh       | 78 kWh           |
| Energy expenditure 20.000 km sea transport  | 803 kWh           | 328 kWh          |
| Total for transport from Asia to Southern Germany | 993 kWh       | 406 kWh          |

Table IV. Overall balance the consumption of 7.5 kWh net storage capacity, usage in PV-system, lifetime 20 years.

| Pb-acid technology | Li-ion technology |
|-------------------|-------------------|
| Primary energy demand for consumption of the overall system included cells | 136.1 kWh | 406.1 kWh |
| Transport from Asia (worst case scenario) | 993 kWh | 406 kWh |
| Expected cell life time | 8 years | 15 years |
| Primary energy demand for consumption of a 20 year storage system (sum) | 2,823 kWh | 1,083 kWh |

Lifetime energy balance.—Based on the operating conditions shown in Table I and the total demand on primary energy shown in Table IV, a total lifetime balance for both battery systems with Pb-acid and Li-ion technology was performed.

The limited life time of 8 years for Pb-acid cells means that within 20 years of operation the cells have to be changed 2.4 times. For Li-ion technology 1.25 cell-sets are required.

Table V shows this lifetime balance for a 20 year period of operation. This period is normally expected for the operation of battery systems in the PV-home storage application.

The data in Table V does not take self-consumption of the system into account. It is shown that the ecological amortization in a typical residential storage application can occur after less than one year of operation, even for the Pb-acid system.

| Table V. Overall balance for the use of 7.5 kWh net storage capacity, usage in PV-system, lifetime of 20 years. |
|-----------------------------------------------|-------------------|-------------------|
| Pb-acid technology | Li-ion technology |
| Primary energy demand for consumption of a 20 year storage system (sum) | 2,823 kWh | 1,083 kWh |
| Energy utilization from storage | 1.517 kWh, p.a. | 1.908 kWh, p.a. |
| Ecological amortization time | 1.86 years | 0.65 years |
The decision to exclude recycling from the calculation is due to the lack of a Li-ion recycling system, thus making a true comparison impossible. This report compares the energy required by the manufacturers to produce the batteries and are based on actual factory data, not estimates. Of course, a true comparison of the two types of batteries requires a full cradle-to-grave analysis (Ref. 4). Below is a summary of various life cycle analysis (LCA), each based on different parameters and assumptions. McManus\(^6\) presents a study of the materials required and production of the batteries based on accepted LCA methodology (ISO 14040 and 14044). This study does not include length of use or performance. Recycling is also not included in this study. McManus reports an estimate of 6 kg of CO\(_2\) equivalent generated for each kWh of Li-ion battery capacity produced and under 2 kg of CO\(_2\) equivalent generated for each kWh of Pb-acid battery capacity produced. This is significantly lower than estimates from other studies.

Zaricksson et al.\(^7\) present a LCA of Li-ion for automotive use. This is a case-study and not an analysis of an actual commercially available Li-ion battery. LCA was performed according to ISO 14044 standard. The study estimates 250 kg CO\(_2\) equivalent per kWh of Li-ion battery capacity generated during battery production. This study includes material sourcing but not recycling. Rydh et al.\(^8\) Table VI conducted a study of the energy requirements for production and transportation of a PV-battery system. Batteries included in the study are Li-ion, NaS, NiCd, NiMH, Pb-acid, V-redox, ZnBr, and PSB. This study reports an estimate of 9 kg of CO\(_2\) 51 equivalent generated for each kWh of Li-ion battery capacity produced and 242 kg of CO\(_2\) equivalent generated for each kWh of Pb-acid battery capacity produced. This is for production only and do not include transportation or recycling of the batteries. In contrast, according to our study, if we assume that each kWh of electricity used produces roughly 1 kg of CO\(_2\) equivalent, then the Li-titanate battery would create 79 kg of CO\(_2\) equivalent per kWh of capacity produced. Similarly, a Pb-acid battery would create 14 kg of CO\(_2\) equivalent per kWh of capacity produced.

### Discussion and Outlook

The production of a 35 Ah Lithium-titanate battery is compared with the production of a 60 Ah Lead-acid, SLI battery. The energy needed to produce one cell is calculated based on fabrication data provided by the manufacturers (Table VI). Both types of batteries are based on a production size of roughly 1 million cells per year.

From the data above, it is clear that Pb-acid batteries require less energy to produce (per kWh of battery capacity.) However, a more accurate comparison takes into account the oversizing required (due to depth of discharge recommended) and the cycle life of the batteries. When these parameters are included, Li-ion batteries require 40% less energy to manufacture compared to Pb-acid batteries (Table VII). It is important to note that the values in Table VII do not take into account the energy required to source the materials or to recycle the batteries. The decision to exclude energy required to source the materials is based on the highly variable nature of these values. They depend on the geographical origin of the materials and often change as materials are depleted or new sources are discovered. The decision to exclude recycling from the calculation is due to the lack of a Li-ion

### Acknowledgments

This work was supported by the Bavarian Research Foundation (Bayerische Forschungsstiftung). The authors gratefully thank for their support.

### References

1. SOVEMA S.p.A, Via Spagna 13, 37069 Villafranca (VR) – Italy (2014).
2. VDI 4655, Beuth Verlag, Berlin 2008.
3. Reinigung mit Kohlenwasserstoffen, Kontakt und Studium, 469, Expert Verlag Renningen-Malmsheim 1995.
4. oncise International Chemical Assessment Document 35, World Health Organization, Geneva (2001).
5. A. Kranke, M. Schmied, and A. Schön, CO2-Berechnungen in der Logistik, Verlag Heinrich Vogel (2011).
6. M. C. McManus, *Applied Energy*, 93, 288 (2012).
7. M. Zackrisson, L. Avellan, and J. Orlenius, *Journal of Cleaner Production*, 18, 1519 (2010).
8. C. J. Rydh and B. A. Sanden, *Energy Conversion and Management*, 46, 1957 (2005).