Energy Analysis Of Batteries In Photovoltaic Systems

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1. Introduction

To be become widely spread, electricity from renewable energy systems, such as wind turbines and solar cells, have to give net surplus of energy yield and be CO_2 neutral throughout their lifetime. With current technology and production methods, energy payback time (EPBT) for photovoltaic (PV) modules has been assessed to be 1.1-5 years depending on the solar intensity [1-3]. Over a lifetime of 25 years, PV modules generate 5-23 times the energy required to produce them [3]. Renewable energy systems have to be equipped with auxiliary components such as inverters, charge regulator and energy storage systems. Balance of systems components can add significantly to EPBT when heavy support structures or batteries are involved (over 6 years in [4]).

Previous energy system studies have focused on PV modules [1, 2, 5, 6] charge regulators/ inverters [5] and solar home systems [7]. Alsema [7] concluded that the batteries in solar home systems contribute significantly to the total energy use. EPBT for lead-acid batteries is 10-11 years and 15-19 years without recycling of materials [7]. Rydh [8] compared the energy requirements for lead-acid and vanadium redox flow batteries for stationary energy storage but other battery technologies have not been studied. Ongoing European Union funded research programs [9, 10] are reviewing energy storage technologies but results from these studies have not been published yet.

The purpose of this study is to provide an energy analysis to enable comparison of different battery technologies in renewable energy applications. By quantifying energy efficiencies and energy requirements for manufacturing of different systems, increased awareness may lead to improved energy management of energy storage systems. Identification of important parameters can be used to direct research and product improvements. By developing a computer model, the effects of changes in performance can be easily updated and evaluated. A comparison of different battery technologies can be used as a guide to optimal battery selection for specific user conditions. The energy model and data used in this paper is presented by Rydh and Sandén [11].

2. Goal and scope

The goal of this study is to analyse energy flows and present energy return factors for different battery technologies when used in stand-alone PV systems at different operating conditions. The contribution of different PV-battery components to the gross energy requirement and important parameters will be identified for each battery technology.

The following battery technologies were evaluated: lithium-ion Co (Li-ion), sodium-sulphur (NaS), nickel-cadmium (NiCd), nickel-metal hydride AB_5 (NiMH) and lead-acid (PbA). Three types of redox flow batteries (regenerative fuel cells) are included namely vanadium-redox (VRB), zinc-bromine (ZnBr) and polysulfide-bromide (PSB). The battery parameters investigated were battery charge-discharge efficiency, service life, gravimetric energy density and energy requirements for production and transportation of batteries.

The study includes energy requirements from the cradle to the grave for production of PV arrays (PV modules, module frames and array supports), batteries, inverter, charge regulator and air conditioning (AC). Transportation of PV-battery system components from manufacturing to the site of use and return at the end of life is included. The stand-alone system has three days of autonomy and the average solar irradiation is 1.7 MWh/m^2 year. To make energy storage technologies with different characteristics comparable, they are normalised to fulfil a functional unit. The functional unit is defined as ”an electricity storage system with a power rating of 50 kW, a storage capacity of 450 kWh and an output of 150 kWh electricity per day”.

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The uncertainties of the values of the energy return factor are presented in Section 5.1 for a reference case when the battery service life was limited by cycle life and the temperature was 20°C, the batteries were produced from 100% recycled materials and the different components were transported 3 000 km by heavy truck. The contribution of different components to the gross energy requirement was analysed.

To evaluate the importance of the battery service life influenced by depth of discharge and battery temperature (20°C and 40°C), four different cases were analysed. The effects of using AC were evaluated to assess for which batteries it can be motivated to install AC. Battery service life was limited by cycle life except for Case 2, when it is limited by float service life.

Consequences of transportation by plane instead of truck from component manufacturer to the site of operation, respectively, using recycled materials and the effects of changes in battery performance were analysed.

3. Method

Energy analysis was performed from cradle to grave based on life cycle assessment methodology [12]. For the selected battery technologies, data was compiled for energy efficiencies, cycle life and energy requirements for production of the PV-battery system and the battery transportation.

The energy return factor and the energy payback time were used as indicators of how efficiently the PV-battery system use non-solar primary energy in comparison to an alternative way of producing the same service. To allow direct comparison of energy data, energy of different forms was converted to the same energy quality. Since the major share of the global energy system and electricity generation is based on combustion of fossil fuels, energy was converted to primary fossil fuel (MJ_{pf}). The value of the electricity output in terms of primary fossil fuel can only be determined after comparison with a reference energy system, which electricity generation is displaced by the PV-battery system. Electricity supply by a diesel generator was chosen as a reference because it is generally applicable in stand-alone systems and back-up systems.

The energy return factor, f, is the ratio between the replaced fossil energy (diesel) E_{G0}, (MJ_{pf}/yr), and the fossil energy required to produce the PV-battery system, $E_{I,pf}$ (MJ_{pf}/yr) (Eq. 1). The average annual indirect energy required to produce and replace the PV-battery system is calculated from the primary fossil energy that is required to build the PV-battery system, Q_{pf} (MJ_{pf}) and the service life of the PV-battery system, t (yr). After a certain time, the energy payback time, t^*, the energy that was used to produce the PV-battery system is paid back by not using the diesel generator (Eq. 2).

$$f = \frac{E_{G0} \cdot t}{Q_{pf}} = \frac{E_{G0}}{E_{I,pf}} \qquad \text{Eq. 1}$$

$$t^* = \frac{t}{f} \qquad \text{Eq. 2}$$

4. Performance and energy requirements of the PV-battery system components

4.1. Energy efficiencies of the PV-battery system components

The energy efficiencies were estimated to be 0.90-0.95 for the charge regulator and 0.92-0.94 and for the inverter. Energy efficiencies for batteries were specified at 20-25°C and discharge rates of 0.1 C and 1-5 C. Battery charge-discharge efficiencies were estimated at: Li-ion 0.85-0.95, NiMH 0.65-0.85, NaS 0.75-0.83, VRB 0.60-0.80, PbA 0.70-0.84, NiCd 0.65-0.85, ZnBr 0.60-0.73 and PSB 0.60-0.65 [11]. The resulting system efficiencies range from 0.50 to 0.87. The battery energy storage capacity was compensated for the energy loss in the inverter which gives the capacity 479 - 489 kWh. The efficiency of the diesel generator was estimated to η_0= 0.20.

4.2. Service life of the PV-battery system components at different temperatures

The life limiting factors for batteries are due to corrosion processes (determined by float life testing) or that the maximum number of cycles is achieved 0. In systems with deep daily cycling, it is the cycle life that determines the service life of the battery 0. Battery service life limited by cycle life was used in the reference case since the batteries are assumed to be daily cycled at DODs below 33%.

Due to the uncertainties in specifying service life and to assess the variability of different modes of cycling and temperatures, float life and cycle life limited batteries were compared. Table 1 shows that NiCd and VRB batteries have the highest float service life while Li-ion, VRB, NaS and ZnBr have the highest cycle life at 33% DOD.

Table 1. Service life of the PV-battery system components.

Component	t_i (years)	$t_{3,\ float}$ [a] (years)	$N_{33,\ cycle\ life}$ [b] (1 000 x cycles)	$t_{3,\ cycle}$ [c] (years)	$\sigma_{40°C}$ [d]
1. PV (mc-Si)	30				
2. Charge regulator	10				
3. Batteries					
NiCd		15 – 25	4.8 - 6.0	13 – 16	0.73
VRB		15 – 20	7.0 - 8.0	[e] 15 – 20	0
Li-ion		14 – 16	7.0 - 10	19 – 27	0.30
NaS		14 – 16	6.8 - 7.5	14 – 16	0.92
PSB		14 – 15	9.0 - 10	[e] 14 – 15	0
PbA		8 – 12	0.90 - 2.0	2.5 – 5.5	0.37
NiMH		8 – 10	2.8 - 3.0	7.7 – 8.2	0.65
ZnBr		8 – 10	4.0 - 5.0	[e] 8.0 – 10	0.92
4. Inverter	10				
5. Air conditioning	8				

Sources: References are given by Rydh and Sandén [11]. [a] Battery service life at 20-25°C at no-cycling (float charge). [b] Cycle life at 33% DOD and 20-25°C. [c] $t_{3,\ cycle}$= $N_{n,\ cycle\ life}$ / n, n= 365 cycles/year at 33% DOD. [d] Battery service life temperature correction factor. New knowledge from 29 November 2003 will lead to updates of this data, see [11]. [e] Limited by float service life when cycled one cycle per day. Cycle life= float life (2 900 - 7 300 cycles).

4.3. Material and energy requirements for production of the PV-battery system components

Material intensities are used to calculate the mass of components that is required to give a certain service. The gravimetric energy densities (Wh/ kg) were estimated at: Li-ion 80-120, NaS 103-116, ZnBr 70-85, NiMH 35-66, NiCd 22-30, PbA 20-32, VRB 15-20 and PSB 10-15 [11]. PSB and VRB are the heaviest batteries (24-49 tons/ 479-489 kWh) followed by PbA (15-24 tons).

Energy requirements for battery manufacturing are assumed to be constant while energy requirements for materials vary depending on virgin or recycled materials recovery (Table 2). The electricity requirement for battery production was estimated from LCA reports on batteries. The required AC system power rating was calculated to be 10 kW and estimated to be operated 10 h per day. Energy requirements for transportation depend on the mode of transportation, the transported mass and the distance. The transportation distances were set to 3 000 km with heavy truck (0.72 MJ_{th}/ton km) or by plane (20 MJ_{th}/ ton km) [11]. The transported mass depends on the battery energy density, battery capacity requirement, number of replacements batteries throughout the service life and materials available on the site of use.

Table 2. Energy requirements for production of the PV-battery system components.

Component	Materials and manufacturing (MJ_{pf}/m^2)	Materials and manufacturing (MJ_{pf}/W_{el})	Recycled materials recovery (MJ_{pf}/ Wh)	Virgin materials recovery (MJ_{pf}/ Wh)	Manufacturing (MJ_{pf}/ Wh)
1. PV array (mc-Si)	[a] 5400				
2. Charge regulator		[b] 1.0			
3. Batteries					
Li-ion			0.31	0.67	1.2
NaS			0.29	0.80	0.60
NiCd			1.0	2.0	2.1
NiMH			0.60	1.6	2.1
PbA			0.45	0.77	0.42
PSB [c]			1.1	1.7	0.59
VRB [c]			1.4	2.1	0.74
ZnBr [c]			0.30	1.2	0.60
4. Inverter [b]		[b] 1.0			
5. Air conditioning		[d] 3.0			

Sources: References are given by Rydh and Sandén [11],[a] Incl. module, frame and roof mounted array supports. mc-Si multi crystalline silicon η= 12-13%, [b] Based on 3 kW inverter module, [c] C= 479-489 kWh, P_{use}= 50 kW, [d] Estimated based on inverter data

5. Results

5.1. Uncertainties and contributing components

To present the uncertainties and the contribution of different components to the gross energy requirement, the following section presents the results for the reference case (Case 1). Fig. 1 shows that the energy return factor for the PV-battery system ranges from 1.5 for the NiMH battery to 11 for the Li-ion battery. The NaS-battery has the highest average f (8.3), which means that the PV-NaS battery system will generate 8.3 times more energy throughout its life time than the energy required for its production. The uncertainty around the average value is +/- 26-61%, which shows the importance of using specific data when comparing different battery technologies. For a PV–battery system with a service life of 30 years, the energy pay back time is 2.7-20 years depending on the battery technology. The PV-system without batteries has an energy return factor of 10-18. With a service life of 30 years, the energy payback time is 1.7-3.0 years for the PV-array. The energy payback time is 1.0-17 years for the battery and charge regulator, showing the significance of batteries in PV-battery systems.

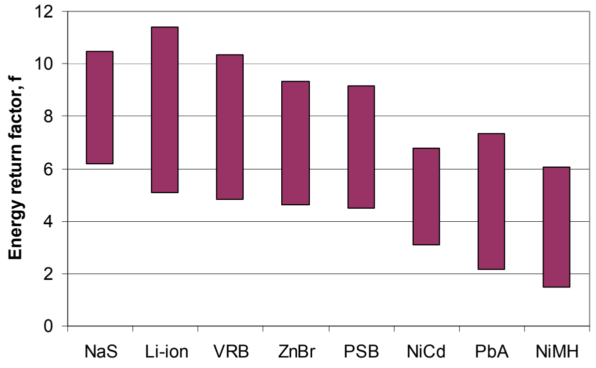

Fig. 1. Energy return factor for the PV-battery systems in Case 1 (t_3= cycle life, T=20°C, recycled materials 100%, e_j= heavy truck). The variation around the average value is +/-26 to 61%.

Production and transportation of batteries contributes 22-76% to the total production energy of the PV-battery system showing the significance of batteries in PV systems (Fig. 2). The relative contribution of production of batteries is lowest for the VRB battery (19%) and highest for the NiMH battery (74%). The contribution of production and transportation of the PV array is 20-66% (NiMH-NaS). The highest absolute energy requirement for PV array production is 85-90 GJ/year for the redox flow batteries due to their relatively low efficiency resulting in a larger PV array and charge regulator. Production and transportation of the charge regulator contribute 2-7% (NiMH-VRB) of the gross energy requirement. The corresponding figures for the inverter are 2-5% (NiMH-NaS). The contribution of transportation of all components to the gross energy requirement is low (0.8-8.5%) for 3 000 km transportation with heavy truck. The lowest energy requirement for transportation is for the Li-ion battery due to high energy density and long cycle life. Transportation of PSB and PbA batteries contributes 4-9% of the gross energy requirement since these batteries have relatively low energy density and low cycle life and therefore a larger mass of batteries has to be transported.

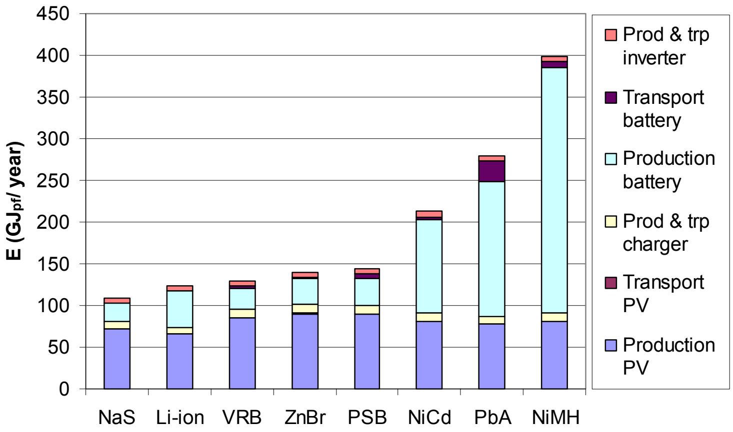

Fig. 2. Energy requirements for production and transportation of the PV-battery systems for Case 1 (t_3= cycle life, T=20°C, recycled materials 100%, 3000 km transportation with heavy truck). The uncertainty is +/- 26 to 61%.

5.2. *Influence of service life*

To evaluate the importance of the battery service life influenced by depth of discharge and battery temperature, four different cases were analysed. Battery service life was limited by cycle life in all cases except for Case 2, when it is limited by float service life. The battery temperature was set to (1) 20°C, (2) 20°C, float (3) 20°C by using active cooling with AC and, (4) 40°C. Fig. 3 shows that the energy return factor for the PV-battery system ranges from 2.6 (PbA at 40°C) to 8.3 (NaS at 20°). The uncertainty is +/- 8 to 64%. Float service life is higher than cycle life for NiCd, NiMH and PbA batteries, resulting in 15-44% higher energy return factor for these batteries. For Li-ion, NaS, PSB, VRB and ZnBr the energy return factor decreases 2-16% for float service life compared with cycle life.

Operation of AC increases the gross energy requirement by 16-25% compared with Case 1. For batteries which service life is temperature sensitive, operation of AC improve the service life resulting in an increase of the energy return factor for NiMH from 2.9 to 3.2 (+10%), for Li-ion from 5.2 to 6.1 (+17%), and for PbA from 2.6 to 3.9 (+50%). For NiCd, NaS and ZnBr batteries, the use of AC results in 2-24% lower energy return factor compared with 40°C. This means that AC is not justified for these technologies. VRB and PSB batteries are excluded in Case 4 since they are assumed not to function at temperatures at 40°C. At a temperature of 40°C instead of 20°C, the energy return factor decreases 2-45% for the different battery technologies to f = 2.6-8.2.

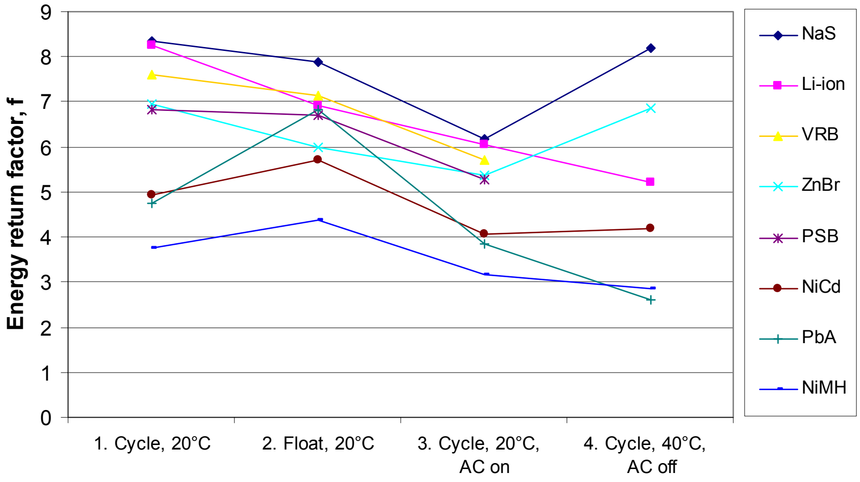

Fig. 3. Energy return factor for the PV-battery systems at different battery service life. The uncertainty is +/-8 to 64%.

5.3. *Influence of materials recycling and transportation*

Consequences of using virgin and recycled materials recovery and transportation by plane instead of truck from component manufacturer to the site of operation shows that the energy return factor for the PV-battery system ranges from 1.4 (PbA, 0% recycling, plane) to 8.3 (NaS, 100% recycling, truck) (Fig. 4). The uncertainty is +/- 23 to 60%. The greatest uncertainty (+/- 60%) of f is for the NiMH battery due to the great variability in cycle life performance. Considering the uncertainty interval, the lower values of the energy return factor is below one for the PbA and the NiMH battery when transported by plane.

When using primary materials recovery, the energy return factor decreases 1-16% (*f*= 3.1-8.2) compared with secondary material recovery. The greatest change of the energy return factor is for the NiMH battery, which decreases from 3.8 to 3.1.

Batteries with low energy density are most influenced by plane transportation. Plane transportation decreases the energy return factor by 15-68% (*f*= 1.4-5.9). The plane transportation of the PbA battery contributes 67-71% of the gross energy requirement for the production of the PV-battery system. This is explained by the relatively short cycle life and the low energy density of the PbA battery.

6. Conclusions

Energy return factors and energy pay back times were estimated for eight different battery technologies used in a stand-alone PV-battery system. The average energy return factor for the PV-battery system ranges from 1.4 +/- 57% to 8.9 +/- 26% for the different cases. If the value of the energy return factor is less than one, the indirect energy used to produce and replace the device is larger than the direct energy output. In that case the device works as a primary battery moving energy from one place to another.

Production and transportation of batteries contribute 22-76% to the gross energy. The contribution of production and transportation of the PV array is 20-66% depending on the battery technology used.

For a PV–battery system with a service life of 30 years, the energy pay back time is 2.7-20 years depending on the battery technology. The energy payback time is 1.7-3.0 years for the PV-array 1.0-17 years for the battery and charge regulator, showing the significance of batteries in PV-battery systems.

The contribution of all transportation to the gross energy requirements is low (0.8-9%) with 3 000 km transportation with heavy truck. When transportation is done by plane, transportation may contribute up to 71% of the gross energy requirements for batteries with low energy density (<30 Wh/kg) and short cycle life (<3 000 cycles at 33% DOD).

The influence of different operating conditions on the energy return factor were assessed to be as follows: (1) active cooling with air conditioning to 20°C compared with 40°C (-24 to +50%), (2) float life instead of cycle life (-16 to +44%), (3) plane instead of truck transportation (-15 to -68%), (4) 40°C instead of 20°C (-2 to -45%) and (5) virgin instead of recycled materials (-1 to -16%). When comparing battery technologies specific data has to be used corresponding to the particular application since the charge-discharge efficiency and service life of batteries depend on operating conditions.

To improve the energy efficiency of batteries, it is important to identify those parameters, which have the greatest influence. The battery charge-discharge efficiency has high influence on the energy return factor for all battery technologies. Service life, gravimetric energy density and battery production are important for NiCd, NiMH and PbA batteries, since the energy requirements for battery production is 48-80% of the gross energy requirement compared to 17-31% for the other battery technologies.

PV-battery systems can be made more energy efficient by matching operating conditions and battery characteristics in a life cycle perspective. The energy efficiency of the PV-battery system can be increased by: (1) optimised charging algorithms, (2) passive temperature regulation to ~ 20°C, (3) increased utilisation of the active battery material, (4) lower material requirements for battery production and, (5) efficient production and transportation of PV-battery system components.

For a comprehensive report of recent input data and updated results is referred to Rydh and Sandén [11].

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