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Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements

Carl Johan Rydh [a,b,*], Björn A. Sandén [b]

[a] *Department of Technology, University of Kalmar, SE-391 82 Kalmar, Sweden*
[b] *Environmental Systems Analysis, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

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Abstract

The technical performance and energy requirements for production and transportation of a stand alone photovoltaic (PV)-battery system at different operating conditions are presented. Eight battery technologies are evaluated: lithium-ion (Li-ion), sodium–sulphur (NaS), nickel–cadmium (NiCd), nickel–metal hydride (NiMH), lead–acid (PbA), vanadium-redox (VRB), zinc–bromine (ZnBr) and polysulfide-bromide (PSB). In the reference case, the energy requirements for production and transport of PV-battery systems that use the different battery technologies differ by up to a factor of three. Production and transport of batteries contribute 24–70% to the energy requirements, and the PV array contributes 26–68%. The contribution from other system components is less than 10%. The contribution of transport to energy requirements is 1–9% for transportation by truck, but may be up to 73% for air transportation. The energy requirement for battery production and transport is dominant for systems based on NiCd, NiMH and PbA batteries. The energy requirements for these systems are, therefore, sensitive to changes in battery service life and gravimetric energy density. For systems with batteries with relatively low energy requirement for production and transportation (Li-ion, NaS, VRB, ZnBr, PSB), the battery charge–discharge efficiency has a larger impact. In Part II, the data presented here are used to calculate energy payback times and overall battery efficiencies of the PV-battery systems.

* Corresponding author. Address: Department of Technology, University of Kalmar, SE 391 82 Kalmar, Sweden. Tel.: +46 491 680 65; fax: +46 491 681 90.
E-mail addresses: carl.johan.rydh@saftbatteries.com, carl.johan.rydh@hik.se (C.J. Rydh).

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1. Introduction

In many types of stand alone photovoltaic (PV) systems, batteries are required to even out irregularities in the solar irradiation and concentrate the solar energy to higher power. Today, lead–acid and nickel–cadmium batteries are commonly used in PV systems. Some emerging battery technologies may also be suitable for storage of renewable energy, such as different types of redox flow batteries and high temperature sodium–sulphur batteries. Identification of the important parameters in PV applications can be used to direct research and product improvements, and comparison of different battery technologies can be used to guide battery choice for specific user conditions.

For energy technologies, the energy requirement for producing equipment is an important performance parameter. Large energy requirements in comparison to energy output will limit the range of possible applications to small niches. Energy requirements for producing PV modules have been studied and debated since the early 1970s, while batteries have gained less attention. In a study of solar home systems, Alsema [1] concluded that lead–acid batteries contribute significantly to the energy requirements. Rydh [2] compared the energy requirements for lead–acid and vanadium redox flow batteries for stationary energy storage, but other battery technologies have not been assessed in this context.

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 the energy requirements for manufacturing the different systems, increased awareness may lead to improved energy management of energy storage systems. This paper presents the background data [3] to the calculation of energy payback times and overall battery efficiencies of PV-battery systems that are presented in Part II [4] of the study.

2. Goal and scope

The goal of this study is to assess the indirect energy requirements for production and transportation of different battery technologies when used in a stand alone PV-battery system at different operating conditions. The contribution of different PV-battery components to the gross energy requirement and important parameters are identified for each battery technology.

The following battery technologies are evaluated: lithium-ion nickel (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 polysulfide-bromide (PSB), vanadium-redox (VRB) and zinc–bromine (ZnBr). The battery parameters investigated are battery charge–discharge efficiency, service life, gravimetric energy density and energy requirements for production and transport of the batteries (see Section 4).

Nomenclature

AC	air conditioning
α_5	coefficient of performance (heat to electricity ratio) of air conditioning
β_i	fraction of primary fossil energy used to generate electricity used in production of component i
C	battery energy storage capacity (Wh)
d	battery energy density (Wh/kg)
DOD	depth of discharge (%)
E_B	annual electricity output from battery (MJ_{el}/yr)
E_{D5}	annual direct electricity use for air conditioning (MJ_{el}/yr)
$E_{I,i}$	average annual primary fossil energy required to produce PV-battery component i (MJ_{pf}/yr)
E_{use}	annual electricity output from PV-battery system (MJ_{el}/yr)
e	energy intensity of transportation (MJ_{pf}/kg km)
H	annual solar irradiation at site of operation (MJ/m^2 yr)
i	energy system component: 1 = PV array, 2 = charger, 3 = battery, 4 = inverter, 5 = air conditioning (AC)
k_1	over capacity factor for PV array; compensation for cloudy days
k_3	over capacity factor for battery; number of days of storage capacity
L	length of one way journey to site of operation (km)
m_i	mass of component i (kg)
N_{DOD}	maximum number of battery charge–discharge cycles at 25 °C and at specified depth of discharge (DOD) (cycles)
n	number of charge–discharge cycles per year to specified depth of discharge (yr^{-1})
η_i	energy conversion efficiency of component i
P_{use}	maximum output power of PV-battery system (W)
P_5	maximum output power of air conditioning system (W)
Q	primary fossil fuel required to build component of energy system (MJ_{pf})
$q_{P,i}$	gravimetric energy requirement for production of component i (MJ/kg)
q_{R3}	gravimetric energy requirement for battery material recycling (MJ/kg)
q_{M3}	gravimetric energy requirement for battery manufacturing (MJ/kg)
q_{RV3}	gravimetric energy requirement for battery material production from virgin material (MJ/kg)
q_{RR3}	gravimetric energy requirement for battery material production from recycled material (MJ/kg)
$q_{T,pf}$	gravimetric energy requirement for transportation (MJ/kg)
r	recycled fraction of battery materials
S_p	maximum solar irradiance (W/m^2)
$\sigma(T)$	temperature correction factor for battery service life at temperature T (°C)
t_{float}	battery service life at float charging (yr)
t_i	service life of component i (yr)

v_i	mass per installed unit of power of the component i (kg/W)
x	weight fraction distilled water in batteries
y	weight fraction of electrolyte and active materials, excluding distilled water, in redox flow batteries
w	mass per square meter PV array (kg/m^2)

The study includes the energy requirements from the cradle to the grave for production of PV arrays (PV modules, module frames and roof integrated array supports), batteries, inverter, charge regulator and air conditioning (AC) (Fig. 1). Transport 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 yr. 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 (197 GJ_{el}/yr)".

The choice of functional unit defines the depth of discharge (DOD) of the battery as 33% at daily cycling (150 kWh/day/450 kWh). The battery service life is assumed to be limited by either the cycle life or the float service life, depending on which life limiting condition will be achieved first.

To assess the uncertainties and improvement potential of different technologies, battery specifications are given for best demonstrated performance, presented as high, and average or normal

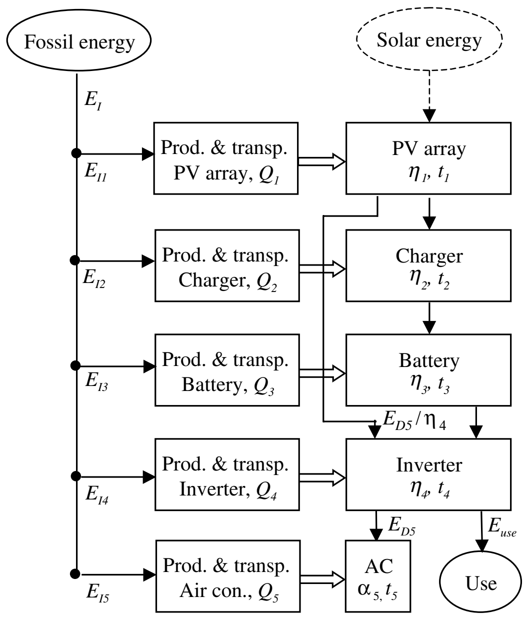

Fig. 1. The PV-battery system components, indirect energy requirements, E (annual) and Q (total), lifetimes t, efficiencies η and conversion factor α.

performance, presented as low. When cells are stacked together into battery modules, the performance values decrease due to the addition of structural materials, effects of unmatched cells, increased resistance in wires etc.

The effect of self-discharge is not included since the batteries are assumed to be cycled. Cooling requirements corresponding to energy losses in the charger, battery and inverter are included when air conditioning is turned on. The housing of batteries is assumed to be equal for different battery systems and is not included in the energy analysis. It is assumed that no energy for transport is required for maintenance of the PV-battery system.

3. Method

To enable aggregation of energy of different qualities, the different forms of energy have been converted to the same energy currency, primary energy equivalents. Primary energy is defined as the energy content of energy carriers that have not yet been subjected to any conversion. The conversion efficiency clearly differs between different forms of primary energy. Therefore, we have consequently assumed that data for primary energy refers to primary fossil energy equivalents (indicated by the index pf). To convert electricity used for component production to primary fossil energy equivalents, we have used the factor 1/0.35.

3.1. Energy requirements for production of the PV-battery system

There is an energy requirement Q_i (MJ_{pf}) for producing and transporting each component in the PV-battery system in Fig. 1. The system is divided into five components: PV array ($i = 1$), charger ($i = 2$), battery ($i = 3$), inverter, ($i = 4$) and air conditioning (AC) ($i = 5$). Since the service lives of the components differ, the energy requirement of the components is expressed per year E_I (MJ_{pf}/yr). The average annual energy required to produce and replace the PV-battery system, E_I (MJ_{pf}/yr) is calculated from

$$E_I = \sum_{i=1}^{5} E_{I,i} = \sum_{i=1}^{5} \frac{Q_i}{t_i} \tag{1}$$

3.2. Battery service life

The battery service life is limited either by cycle life

$$t_3 = \frac{N}{n} \cdot \sigma(T) \tag{2}$$

or float life

$$t_3 = t_{3,\mathrm{float}} \cdot \sigma(T) \tag{3}$$

where $t_{3,\mathrm{float}}$ is the float life at 25 °C, N is the maximum number of charge–discharge cycles at 25 °C and at a specified DOD (depth of discharge) (see Section 4.3.1) and n (yr^{-1}) is the number of charge–discharge cycles per year. The service life is dependent on the temperature T (°C) and $\sigma(T)$ is a temperature dependent correction factor (see Section 4.3.2).

3.3. Energy requirements for production and transport of the components

The energy requirement for producing and transporting component i is calculated from the mass m_i and the gravimetric energy requirement for production $q_{P,i}$ (MJ_{pf}/kg), and transport to the site of operation q_T (MJ_{pf}/kg):

$$Q_i = (q_{P,i} + q_T) \cdot m_i \quad i = 1,2,4,5 \tag{4}$$

For the batteries, we take into account reuse of liquids at the site of operation:

$$Q_i = ((1 - r \cdot y) \cdot q_{P,i} + (1 - x - r \cdot y) \cdot q_T) \cdot m_i \quad i = 3 \tag{5}$$

where x is the weight percentage of distilled water in the batteries. It is assumed that the water is filled at the site of operation. The factor r is the rate of recycling, and y is the weight fraction of the electrolyte and active materials, excluding distilled water, in the redox flow batteries. It is assumed that the electrolyte in recycled redox flow batteries is not sent back for recycling at the end of their life but is reused at the site. The factor y is equal to 0 for non-redox flow batteries.

The gravimetric energy for transportation of the components is

$$q_{T,pf} = 2L \cdot e \tag{6}$$

where L (km) is the length of the one way journey to the site of operation, e (MJ_{pf}/kg km) is the average energy intensity of transport. It is assumed that all components are returned after use (or sent an equal distance), no matter if they are recycled or not, hence the factor two in the formula.

The effect of recycling is not investigated for non-battery components. For batteries, the gravimetric energy requirement for production is divided into the energy requirements for material recycling q_{R3} and battery manufacturing q_{M3}. Materials may be of virgin q_{RV3} or recycled q_{RR3} origin:

$$q_{P3} = q_{R3} + q_{M3} = (1 - r) \cdot q_{RV3} + r \cdot q_{RR3} + q_{M3} \tag{7}$$

The required battery mass is given by the gravimetric energy density d (Wh/kg) and the required battery capacity C (Wh), which is determined from the annual electricity output E_{use} (MJ_{el}/yr), the efficiency of the inverter η_4 (–), the over capacity factor k_3 (–) (indicating the number of days of storage capacity) and the number of charge–discharge cycles per year n (yr^{-1}) (to the depth of discharge (DOD) $1/k_3$):

$$m_3 = \frac{C}{d} = \frac{k_3 \cdot E_{use}}{d \cdot n \cdot \eta_4} \tag{8}$$

For the PV array ($i = 1$), the required mass is calculated from

$$m_1 = \frac{w}{H \cdot \eta_1} \cdot \left(\frac{k_1 \cdot E_{use}}{\eta_2 \cdot \eta_3 \cdot \eta_4} + \frac{E_{D5}}{\eta_4} \right) \tag{9}$$

where w (kg/m^2) is the mass per square metre of array, H is the annual solar irradiation at the site of operation (MJ/m^2 yr) and k_1 (–) is a factor indicating the over capacity of the PV array. In this application, we have assumed that $k_1 = 1.1$. [1] When the AC is in use, it requires electric energy from the PV array (via the inverter) E_{D5} (kW h_{el}/yr) that can be calculated from the coefficient of performance of the AC α_5 (–) and the energy losses in the charger, inverter and battery:

$$E_{D5} = E_{use} \frac{(1 - \eta_2 \cdot \eta_3 \cdot \eta_4)/(\eta_2 \cdot \eta_3 \cdot \eta_4)}{\alpha_5 - (1 - \eta_4)/(\cdot \eta_4)} \quad (10)$$

The required mass of the charger ($i = 2$) and the inverter ($i = 4$) is dimensioned proportional to the peak output power of each component, while the mass of the AC ($i = 5$) is proportional to the input power. The required peak power of the charger is related to the maximum solar irradiance S_P (W/m^2), and that of the inverter is related to the maximum power required at the point of use, P_{use} (W). The power of the air conditioning P_5 is dependent on the use of electricity E_{D5} and the number of operating hours per year. The latter is dependent on the daily solar availability. Here, we use the relation between the annual solar irradiation H and the maximum solar irradiance S_P and get 1889 h/yr or 5.2 h/day of operation. [2]

$$m_2 = v_2 \cdot \frac{S_p}{H} \cdot \left(\frac{k_1 \cdot E_{use}}{\eta_3 \cdot \eta_4} \right), \quad (11)$$

$$m_4 = v_4 \cdot P_{use} \quad (12)$$

$$m_5 = v_5 \cdot P_5 = v_5 \cdot \frac{S_p}{H} \cdot E_{D5} \quad (13)$$

where v_i (kg/W) is the mass per installed unit of output power or input power in the case of AC. The extra power requirement of the inverter when the AC is turned on is neglected.

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

4.1. Description of the batteries

Of the battery technologies studied (Table 1), PbA and NiCd batteries are most widely demonstrated for use in PV applications. NiCd and PbA batteries for PV applications are normally based on flooded electrolytes to give the best performance at high temperatures. At temperatures above 30 °C, gelled electrolytes may dry out, while flooded cells may lose some heat by decomposition of water and thereby get longer service life. However, advanced gelled electrolyte PbA batteries have showed good performance at extensive cycling and high temperatures [5]. The high values for the assumed PbA battery service life are representative for this battery type.

[1] It is assumed that the battery is fully charged from the PV array every day, corresponding to E_{use}. In the case of cloudy days, the battery will not be completely charged, and the stored energy in the battery will gradually decrease at continued cycling. To enable the battery to be charged to full capacity again, the power rating of the PV array has to be increased.

[2] This number is to some extent arbitrary. Using the reference yield of 4.7 h/day would, for example, lead to 11% higher power requirements. However, this is of little importance here since the energy used for producing and transporting the AC is a negligible part of total energy requirements.

Table 1
Description of the batteries used in the PV-battery system

Technology	Abbreviation	Model	Description	Positive electrode or catholyte	Electrolyte	Negative electrode or anolyte
Li-ion	Li-ion	SAFT Li-ion VL 50 E Mixed oxide: LiNi0.8(Co+M) 0.2 O_2[a]	Cylindrical, sealed maintenance free cells	$Li_{1-x}MeO_2$/ $LiMeO_2$[a]	PC, $LiPF_6$	Li_xC/C
Sodium–sulphur	NaS	NGK-TEPCO E50 module, 50 kW, 430 kW h/module	384 T5 cells (8 serial × 6 parallel) × 8 serial, 128 V	xS/S_x^{2-} ($x = 5 - 3$)	β-Al_2O_3	Na/Na^+
Nickel–cadmium	NiCd	SAFT Sunica.plus 1110	Pocket plate, thick electrodes, felt-isolated, vented, flooded electrolyte	$NiOOH/Ni(OH)_2$	20% KOH (1.2 kg/dm^3)	$Cd/Cd(OH)_2$
Nickel–metal hydride	NiMH	SAFT NH12.3, 12 V module	EV battery plates, foam electrodes, sealed maintenance free	$NiOOH/Ni(OH)_2$	KOH	MmH/Mm[b]
Lead–acid	PbA	Tudor Exide 16OGi 1260	Vented, pasted flat plates, flooded electrolyte[c]	$PbO_2/PbSO_4$	1.3 kg/dm^3 H_2SO_4	$Pb/PbSO_4$
Polysulfide-bromide	PSB	Regenesys	Redox flow	$NaBr_3$(aq)/ 3 NaBr(aq)	H_2SO_4	2 Na_2S_2(aq)/ Na_2S_4(aq)
Vanadium	VRB	Sumitomo Electric Industries	Redox flow, 4 stacks × 80 cells (serial)	VO_2^+(aq)/VO^{2+}(aq)	1.8 M V in 4.2 M H_2SO_4	V^{2+}(aq)/ V^{3+}(aq)
Zinc–bromine	ZnBr	ZBB research	Redox flow	Br_2(aq)/2 Br^-(aq)	2.25 M $ZnBr_2$	Zn/Zn^{2+}(aq)

Sources: [6,11–17].
[a] Me = mixed oxide lithiated cathode LiNi0.8(Co+M)0.2 O_2. M = different combinations of Mn, Al and other metals are used.
[b] Mm = Misch metal. AB_5 alloy of rare earth metals.
[c] Advanced gelled electrolyte PbA is assumed for high performance values [5].

We have also included NiMH and Li-ion batteries since their use in small scale applications is growing rapidly. However, their relatively high production cost has precluded them from employment in applications for storage of several hundreds of kiloWatt hour. The NiMH battery is sealed, i.e., it has immobilised electrolyte and safety vent, and the electrolyte has to be added on the site of manufacture. Li-ion batteries are only available as sealed cells.

The NaS battery uses a sodium ion conducting solid electrolyte operating at 310–350 °C to maintain the electrodes in a molten state and to obtain adequate electrolyte conductivity [6]. The NaS battery is commercially produced and is used in applications for power quality and uninterrupted power supply.

The PSB, VRB and ZnBr batteries are redox flow batteries based on liquid electrolytes, which are pumped into the battery stack. The size of the stack determines the power rating, and the volume of the electrolyte determines the storage capacity. The PSB battery technology has not yet been demonstrated in commercial operation, and the construction of two plants with a power rating of 12–15 MW and an energy capacity of 120 MWh was stopped in 2003 [7,8]. The VRB battery technology has been demonstrated by different manufacturers for load levelling and PV applications with power ratings up to 1.5 MW and an energy capacity up to 5 MWh [9]. Demonstration units of the ZnBr battery have been built for PV applications with the ratings of 50 kW/100 kWh and 250 kW/500 kWh [10]. It is assumed that the different technologies of redox flow batteries can be constructed to meet the battery requirements of the PV-battery system in this study.

4.2. Energy efficiencies of the components and direct energy use of air conditioning

The PV modules are assumed to be based on multi-crystalline silicon (mc-Si), i.e. the PV technology that currently dominates the market. Table 2 shows that the energy efficiencies were estimated to be 0.12–0.13 for the PV modules, 0.90–0.95 for the charge regulator and 0.92–0.94 for the inverter. Corrections for power or temperature deviation, incomplete utilisation of irradiation etc. are not explicitly considered for these components but are assumed to be included in these efficiency ranges.

The charge–discharge efficiency is highest for the Li-ion battery and lowest for the PSB battery (Table 2). For batteries requiring pumps and auxiliary components, these losses are included.

The annual solar irradiation (H) was assumed to be 1.7 MWh/m^2 yr, representing medium irradiation levels, which can be found in Southern Europe and large parts of the USA [25]. The maximum solar irradiance (S_p) is assumed to be 1000 W/m^2.

The temperature of the battery room can be held constant with passive or active systems. Passive systems do not actively change the temperature and are based on insulation, heat driven fans or water circulation systems. An active system was considered to enable evaluation of its energy related significance. The air conditioning systems provide active temperature regulation and require electricity for the compressor, fan and electronic regulation. It is assumed that the daily cooling requirement is generated during daytime directly from the PV array (via the inverter), and energy is stored as ice or cold water, which enables cooling at a constant level during day and night.

The electricity use for air conditioning to get rid of excess heat from energy losses in the components was calculated to be 12–69 MJ$_{el}$/yr from Eq. 10, the energy efficiencies of the components

Table 2
Energy efficiencies of the PV-battery system components

Components	η_i	α_5
1 PV (mc-Si)	0.12–0.13	
2 Charge regulator	0.90–0.95	
3 Batteries[a]		
Li-ion	0.85–0.95	
NaS[b]	0.75–0.83	
PbA	0.70–0.84	
NiCd	0.65–0.85	
NiMH	0.65–0.85	
VRB[c]	0.60–0.80	
ZnBr[d]	0.60–0.73	
PSB[d]	0.60–0.65	
4 Inverter	0.92–0.94	
5 Air conditioning		3

Sources: [6,9,12–24].
[a] DC/DC efficiency. T = 20–25 °C. Low value = 100% SOC charge and 100% DOD cycles, charge–discharge rates of C/1–5 h. High value = shallow cycling at C/10 h currents.
[b] 3–4% lower absolute efficiency included due to loss in operation of heaters required at low cycling operation. The battery is cycled between 10–90% SOC.
[c] The lower value includes losses in pumps etc. The higher value is based on suppressed pump losses [9].
[d] Including losses in pumps etc. η for ZnBr is projected to be 0.80–0.85 [22].

in Table 2 and a coefficient of performance (kW h heat per kW h electricity) of 3 for air conditioning (Table 2).

4.3. Service life of the components

4.3.1. Float life and cycle life of batteries and service life of PV array, charger and inverter

The end of battery service life is when the battery capacity has reached 80% of its initial capacity or when it fails to function. The effects of ambient temperature on the performance and service life of redox flow batteries and the NaS battery are limited since their operating temperatures are regulated by pumping of the electrolytes or by thermal management systems.

When Li-ion, NiCd, NiMH and PbA batteries are used in applications with shallow cycling, their service life normally will be limited by float life [26]. [3] In systems where the cycling is deep, but occurs only a few times a year, temperature dependent corrosion processes is the normal life limiting factor, even for batteries with low cycle life [27]. In systems with deep daily cycling, the cycle life determines the service life of the battery [26]. Because of the uncertainties in specifying

[3] Float life testing is used to estimate the service life of batteries due to corrosion processes. Float charge is defined as a method of maintaining a battery in a charged condition by continuous, long term constant voltage charging at a level sufficient to balance self-discharge [12]. Determination of float life includes capacity testing by full discharges at certain intervals (e.g. every 20 days). Float service life of redox flow batteries may be difficult to estimate since these technologies have been mainly demonstrated in cycling operation. For longer periods of storage of the battery, the stacks can be drained from electrolyte to limit corrosion processes.

Table 3
Service life of PV-battery system components

Component	t_i (yrs)	N_{100} [a] (1000 × cycles)	N_{80} [b] (1000 × cycles)	N_{33} [c] (1000 × cycles)	$t_{3,\text{cycle}}$ [d] (yrs)	$t_{3,\text{float}}$ [e] (yrs)	$t_{3,\text{limit}}$ [f] (yrs)
1 PV array (mc-Si)	30						
2 Charge regulator	10						
3 Batteries							
VRB[g]		2.8–3.0	3.0–4.0	7.0–8.0	19–22	15–20	15–20[h]
Li-ion		3.0–5.0	5.0–7.0	7.0–10	19–27[i]	14–16	14–16[h]
NaS		2.3–2.5	4.5–5.0	6.8–7.5	19–21	14–16	14–16[h]
NiCd		0.3–0.5	1.0–1.5	4.8–6.0	13–16	20–25	13–16
PSB[j]		9.0–10	9.0–10	9.0–10	25–27	14–15	14–15[h]
ZnBr		1.5–2.5	2.5–3.0	4.0–5.0	11–14	8.0–10	8.0–10[h]
NiMH		0.60–1.0	0.80–1.2	2.8–3.0	7.7–8.2	8.0–10	7.7–8.2
PbA[k]		0.32–0.80	0.40–1.0	0.90–2.0	2.5–5.5	8.0–12	2.5–5.5
4 Inverter	10						
5 Air conditioning	8						

Sources: [2,5,6,9,12,14,15,17,22–24,28–30].
[a] Cycle life at 100% DOD and 20–25 °C.
[b] Cycle life at 80% DOD and 20–25 °C.
[c] Cycle life at 33% DOD and 20–25 °C.
[d] $t_3 = N_{33}/n$ (Eq. 2), where n = 365 cycles/yr at 33% DOD.
[e] Battery service life at 20–25 °C at no-cycling (float charge).
[f] Limited by either the cycle life or the float service life, depending on which life limiting condition will be achieved first.
[g] Ionic membranes have to be replaced every 10 years.
[h] Limited by float service life when cycled one cycle per day.
[i] Expected service life for emerging technology. Five years shown in practice for Li-ion (Co) [30].
[j] Electrolyte management assumed for this cycle life performance [7]. Float life may be up to 20 years.
[k] The higher values represent the performance of advanced gelled electrolyte PbA [5].

service life, the battery service life in the reference case is defined as $t_{3,\text{limit}}$, which is the service life limited by either the cycle life or the float service life, [4] depending on which life limiting condition will be reached first.

Table 3 shows that NiCd and VRB batteries have the highest float service life while PSB, Li-ion, VRB and NaS have the highest cycle life at 33% DOD. Considering life limiting conditions, the VRB, Li-ion and NaS have the highest service lives.

4.3.2. Temperature corrected service life of batteries

The values in Table 4 present extreme temperatures under which the batteries preferably should work for only short periods. Elevated temperatures result in accelerated ageing but also higher available capacity. NiCd has a robust mechanical design, and its service life is relatively little affected by ambient temperatures above 40 °C. The NaS battery is operated at 310–350 °C, and insulation and heaters are used to maintain its temperature.

[4] Battery specifications stated for calendar life is assumed to be equivalent to float service life. Data for shelf life, which is the duration of storage at the end when a battery still retains the ability to give specified performance, was not considered.

Table 4
Ambient temperatures for battery operation and factors for temperature corrected battery service life

Technology	Temperature (°C)	$\sigma_{30\,°C}$	$\sigma_{35\,°C}$	$\sigma_{40\,°C}$	$\sigma_{45\,°C}$	$\sigma_{50\,°C}$
Li-ion	−20 to 50	0.72	0.55	0.40	0.30	0.23
NaS[a]	−40 to 50	1.0	1.0	1.0	1.0	1.0
NiCd	−50 to 50	0.90	0.80	0.73	0.65	0.57
NiMH	0 to 40	0.85	0.75	0.65	0.52	0.35
PbA	−30 to 40	0.69	0.51	0.37	0.25	0.14
PSB	−40 to 50[b]	1.0	1.0	1.0	1.0	1.0
VRB	15 to 40[c]	1.0	1.0	1.0	N/A	N/A
ZnBr	10 to 40[c]	1.0	1.0	1.0	N/A	N/A

Sources: [12,23,30–32]; Note: σ = temperature correction factor. Change in service life relative 25 °C for battery cycle life and float service life. N/A = not applicable.

[a] The battery operating temperature is 310–350 °C for the NaS battery.

[b] Heat generated in the battery prevent the electrolytes from freezing.

[c] Optimal operating temperature is 25–30 °C. Heat exchanger has to be operated at $T > 30$ °C.

The charge regulator and the inverter require cooling of the electronics. Cooling is achieved by fans, which energy use is assumed to be included in the efficiency of the inverter and the charger.

As the temperature increases, the electrochemical activity of the battery increases as well as the speed of the natural ageing of the active material. Accelerated life tests at elevated temperature, correlated with corrosion studies, provide a basis for estimating service life. Service temperature is the key factor in determining corrosion. As a rule, for PbA batteries every 10 °C increase in temperature reduces service life by 50% [33]. Valve regulated lead-acid batteries have been shown to have >15 years float service life at 20 °C and >10 years at 25 °C [33]. The rate of ageing for NiCd batteries is about 20% reduction in life for 10 °C increase in temperature [34]. NiCd is less affected than PbA since increased electrochemical activity has little effect on the steel structural components of the NiCd electrode assembly.

To include the effects of operating temperature on the battery service life, temperature correction factors, σ, were estimated relative to 25 °C (Table 4). The temperature correction factors are assumed to be equal for both cycle life and float service life. Operational data is available for PbA and NiCd, while data is uncertain for NiMH and Li-ion.

The PSB and VRB batteries are little affected by varying ambient temperatures, since pumps are used to circulate the electrolyte to heat exchangers, which maintain their operating temperatures. No degradation of the NaS battery has been documented, but the temperature of the electronic control systems has to be controlled. Elevated temperature may degrade the plastic materials of the ZnBr battery, but no degradation has been quantified.

4.4. Energy requirements for production and transport of the PV-battery system components

4.4.1. Mass requirements of the components

Material intensities are used to calculate the mass of components that is required to give a certain service. [5] The gravimetric density for the PV array, including module frame, was estimated at

[5] The sizing has not been corrected for capacity changes with operating temperature.

Table 5
Densities and mass of complete PV-battery system components

Component	w (kg/m^2)	v_i (kg/kW$_{el}$)	d (Wh/kg)	mass, m_i[a] (tons)
1 PV array (mc-Si)	9.0[b]			2.6–4.9
2 Charge regulator		10		0.56–0.91
3 Batteries				
NaS			103–116	4.1–4.8
Li-ion			80–120	4.0–6.1
ZnBr			70–85	5.6–7.0
NiMH			35–55	8.7–14
NiCd			22–30	16–22
PbA			20–32	15–24
VRB			15–20	24–33
PSB			10–15	32–49
4 Inverter		10		0.50
5 Air conditioning		42[c]		0.086–0.50

Sources: [2,6,11,12,14–17,35].
[a] C = 479–489 kW h, P_{use} = 50 kW, P_5 = 2.0–12 kW.
[b] Including module, frame and roof mounted array supports.
[c] Electrical power of air conditioning unit. (45 kg/3.2 kW$_{heat}$) × 3 kW$_{heat}$/kW$_{el}$ = 42 kg/W$_{el}$ [36].

9 kg/m^2 for roof integrated systems and 12 kg/m^2 for ground mounted systems. Table 5 shows that the mass of the PV array is 2.6–4.9 tons depending on the energy efficiency of the battery technology used. The PSB and VRB are the heaviest ones (24–49 tons) followed by PbA (15–24 tons). The mass of these systems is 5–8 times higher than that of the Li-ion battery, which has the lowest weight. The weight fraction of the electrolyte active material, y, is 0.32–0.40 for the redox flow batteries (PSB, VRB and ZnBr) and 0 for the other batteries (Eq. 5).

4.4.2. Energy requirements for production of the components

The energy requirements for mc-Si modules are estimated at 4200 MJ$_{pf}$/m^2 or 32 MJ$_{pf}$/W$_p$ [37]. The energy requirements for production of single crystalline silicon (sc-Si) and amorphous silicon (a-Si) modules are 16–20% higher and 0–17% lower, respectively, than that for mc-Si.

Module frames are assumed to use 2.5 kg Al/m^2 module corresponding to 500 MJ$_{pf}$/m^2 [37]. Energy requirements for array supports in roof integrated and ground mounted systems have been estimated to be 700 MJ$_{pf}$/m^2 and 1800 MJ$_{pf}$/m^2, respectively [37]. The total energy requirements for production of PV arrays (module, frame and array support) were calculated to be 5400 MJ$_{pf}$/m^2 (roof integrated) and 6500 MJ$_{pf}$/m^2 (ground mounted), corresponding to 45–54 MJ$_{pf}$/W$_p$ (Table 6).

Energy requirements for producing the inverter, charger and AC were estimated to be 1 MJ$_{pf}$/W$_{el}$, resulting in 70–100 MJ$_{pf}$/kg (Table 7). The power required of the PV array to operate the AC (P_5 = 2.0–11 kW$_{el}$) via an inverter is 2.1–12 kW, which means that the PV array rating has to be increased by 2–17% if AC is to be used.

Energy requirements for production of batteries were assessed from cradle to gate, including materials production and battery manufacturing. To enable a thorough evaluation of different LCA studies, they need to report the following parameters: (1) battery mass, (2) battery capacity,

Table 6
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 production (MJ_{pf}/Wh)	Virgin materials production (MJ_{pf}/Wh)	Manufacturing (MJ_{pf}/Wh)	Refs.
1 PV array (mc-Si)	5400[a]					[25,37]
2 Charge regulator		1.0[b]				[25,37]
3 Batteries						
Li-ion			0.31	0.67	1.2	[3,41]
NaS			0.29	0.80	0.60	[38]
NiCd			1.0	2.0	2.1	[40–42]
NiMH			0.60	1.6	2.1	[39–41]
PbA			0.45	0.77	0.42	[2]
PSB[c]			1.1	1.7	0.59	[3]
VRB[c]			1.4	2.1	0.74	[2]
ZnBr[c]			0.30	1.2	0.60	[3]
4 Inverter[b]		1.0[b]				[25,36]
5 Air conditioning		1.0[d]				[25,36]

[a] Incl. module, frame and roof mounted array supports. mc-Si multi crystalline silicon, $\eta = 12–13\%$ [25].
[b] Based on 3 kW module [25] and on 500 kW converter [43].
[c] $C = 479–489\,kWh$, $P_{use} = 50\,kW$.
[d] Estimated based on inverter data.

Table 7
Energy requirements for production of the PV-battery system components expressed per kilogram component

Component	Materials and production, $q_{P,i}$ (MJ_{pf}/kg)	Recycled materials production, q_{RR3} (MJ_{pf}/kg)	Virgin materials production, q_{RV3} (MJ_{pf}/kg)	Manufacturing, q_{M3} (MJ_{pf}/kg)	β_i[a]
1 PV array (mc-Si)[b]	600				
2 Charge regulator	100				0.50
3 Batteries					
Li-ion		25–37	53–80	96–144	0.75
NaS		30–34	82–93	62–70	0.70
NiCd		22–30	44–60	46–63	0.68
NiMH		21–40	54–102	74–139	0.68
PbA		9.0–14	15–25	8.4–13	0.65
PSB		11–17	17–26	5.9–8.9	0.50
VRB		21–29	32–42	11–15	0.41
ZnBr		21–26	84–102	42–51	0.50
4 Inverter	100				0.50
5 Air conditioning	70				0.50

Sources: Tables 5 and 6.

[a] Share of primary energy used to generate electricity.

[b] Incl. module, frame and roof mounted array supports. mc-Si = multi crystalline silicon.

(3) choice of system boundaries (geographical, temporal, technological), (4) electricity's share of gross primary energy requirements, assumed efficiency of electricity production and method for adding up different energy qualities, (5) recycling rate of used batteries, (6) energy requirements for battery manufacturing processes and production of virgin and recycled materials, respectively, (8) battery design, (9) battery material composition and (10) the allocation principles for multi-output processes. Based on published life cycle assessments and estimates [3], the energy requirements for production of different batteries were estimated. The energy requirements for battery production were scattered between studies, and there are uncertainties on the material requirements and manufacturing processes, particularly for the Li-ion, NaS and all the redox flow batteries. The best estimates are presented in Table 6.

The energy requirements of batteries with active materials in solid phase are assumed to be independent of the required PV-battery system output power by changing the cell configuration and voltage of the battery strings. Energy requirements for redox flow batteries were divided into stack production (MJ_{pf}/W) and energy storage capacity electrolyte (MJ_{pf}/Wh) and aggregated corresponding to a stack of 53–54 kW (C/P_{use} = 9.8), which makes it necessary to revise the data for assessments of applications with other power-capacity ratios.

The energy requirements for production of batteries range from 0.87 MJ_{pf}/Wh (PbA based on recycled materials) to 4.1 MJ_{pf}/Wh (NiCd based on virgin materials) (Table 6). Differences are partly explained by the energy intensity of materials production. For the NiCd battery, steel and nickel contribute 60–70% to the energy requirements of materials production. Production of nickel requires 2–8 times more energy than that for the lead used in PbA batteries. The energy requirements for manufacturing processes contribute 33–78% of the energy requirements for battery production, resulting in relatively small changes between virgin and recycled materials.

The energy requirements for battery manufacturing are assumed to be constant while the energy requirements for materials vary depending on the recycling of materials. The production of recycled materials requires 32–75% less energy than virgin materials since the energy for extraction from mines and reduction of metals are allocated to the first material life cycle (Table 6). For redox flow batteries, it is assumed that the energy requirements for production of stack and other battery components are the same as for electrolyte production.

At the end of the service life of redox flow batteries, they can be renovated by renewing the stacks while the electrolyte with active material is assumed to be used indefinitely (y = 0.32–0.40). Batteries based on active materials in solid phase (Li-ion, NaS, NiCd, NiMH, PbA) need to be manufactured and replaced completely.

Table 7 shows the energy requirements expressed per kiologram component. The fraction β_i of primary fossil energy requirement that is used for producing the electricity required for production of the batteries, charge regulator and AC was estimated from LCA reports.

4.4.3. Energy requirements for transport of the components

The transportation distance, L, was set to 3000 km and transportation was done by heavy truck (e = 0.72 MJ_{pf}/ton km) or by plane (e = 20 $MJ_{pf,}$/ton km) [44].

Distilled water was assumed to be available on the site of use and did, therefore, not have to be transported or returned at the end of battery life. For redox flow and flooded batteries the mass made up by water was subtracted from the total battery mass requiring transportation. The mass of the transported battery was reduced by a factor (x) for the following batteries: NiCd (26–27%), PbA (12–13%), PSB (45–48%), VRB (45–48%) and ZnBr (40–45%).

5. Results and discussion

5.1. Contributing components

To present the contribution of different components to the energy requirement, the following section presents the results for the reference case (Case 1) when the battery service life is limited by cycle or float life ($t_{3,\text{limit}}$) and the temperature is 25 °C. It is assumed that the batteries are produced from 100% recycled materials and that the different components are transported 3000 km by heavy truck.

Production and transportation of batteries contributes 24–70% of the energy requirements of the PV-battery system, also underlining the energy related significance of batteries in PV systems (Fig. 2). The relative contribution from the production of batteries is lowest for the ZnBr battery and highest for the NiMH battery.

Depending on the efficiency of the battery, the power rating of the PV array is 42–71 kW, corresponding to an area of 320–600 m^2. The contribution of production and transport of the PV array is 26–68% (NiMH–ZnBr). The highest absolute energy requirement for PV array production is 88–96 GJ/yr for the redox flow batteries due to their relatively low efficiency, resulting in the need for a larger PV array and charge regulator. Production and transport of the charge regulator and inverter contribute 2–4%, respectively.

The contribution of transport of all the components to the gross energy requirement is low (0.9–8.9%) for 3000 km transport by heavy truck. The lowest energy requirement for transport is for the ZnBr battery due to its high energy density and the possibility of recycling the electrolyte. The transport of PbA batteries contributes 8.9% to the gross energy requirement since these batteries have a relatively low energy density and cycle life, and therefore a larger mass of batteries has to be transported.

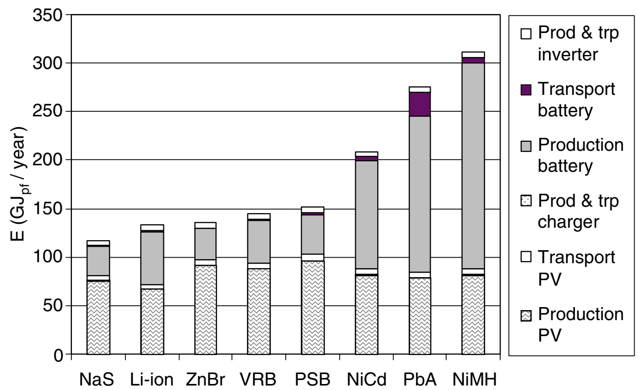

Fig. 2. Energy requirements for production and transport of various PV-battery systems for Case 1. The uncertainty is ±14–52%.

5.2. Influence of different user conditions

The influence of different user conditions was evaluated by calculating the energy requirements for different cases as shown in Table 8. Table 9 provides a summary of the energy requirements for the different cases. The results are further presented and evaluated below.

The effects of temperature on the energy requirements of the PV-battery system are assessed by comparing Cases 1, 2 and 3 in Fig. 3. To cool the battery with an air conditioning unit when the ambient temperature is high (Case 2), the energy requirements increase 2–17% for producing the AC system and a 1–12 kW (16–100 m^2) larger PV array compared with Case 1. In case 3 (40 °C), the increased temperature results in a shorter service life of the batteries. Compared with Case 1, the PbA battery has to be replaced more often, resulting in a doubled energy requirement.

The consequences of recycling of battery materials is analysed by comparing Case 1 with Case 4 (Fig. 4). When not using materials from recycled production, the energy requirement increases 17–75 GJ/yr, which is 10–53% higher than if materials of recycled origin are used. The difference between virgin and recycled materials production is greatest for the ZnBr battery.

Transport by plane instead of truck from the battery manufacturer to the site of operation is analysed in Cases 1 and 5 (Fig. 4). The energy intensity for plane transportation is 28 times higher than that for truck transportation. Compared with truck transportation, plane transport results in

Table 8
Parameter settings for evaluation of the PV-battery system

Case	Service life ($t_{3,\text{limit}}$[a])	Battery temperature (25 or 40 °C)	Air conditioning in operation (on or off)	Recycling battery materials (100% or 0)	Transportation 3000 km (truck or plane)
1	$t_{3,\text{limit}}$	25	Off	100	Truck
2	$t_{3,\text{limit}}$	25	On	100	Truck
3	$t_{3,\text{limit}}$	40	Off	100	Truck
4	$t_{3,\text{limit}}$	25	Off	0	Truck
5	$t_{3,\text{limit}}$	25	Off	100	Plane

[a] Limited by either the cycle life or the float service life, depending on which life limiting condition will be achieved first.

Table 9
Energy requirements (GJ_{pf}/yr) for production and transportation of PV-battery systems for the different cases

Technology	1. 25 °C	2. 25 °C, AC on	3. 40 °C, AC off	4. 0% Recycling	5. Plane transport
Li-ion	133	140	218	146	174
NaS	117	128	117	134	153
NiCd	209	222	252	245	324
NiMH	311	324	429	386	481
PbA	275	287	592	335	928
PSB	152	171	152	199	218
VRB	145	160	145	190	184
ZnBr	135	152	135	208	152

E_{use} = 197 GJ_{el}/yr. The uncertainty is ±14–61%.

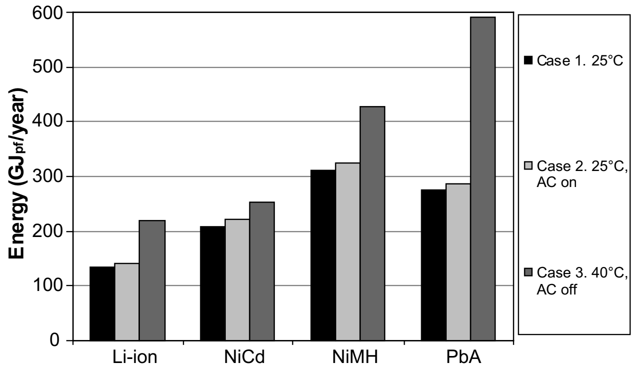

Fig. 3. Energy requirements for production and transport of PV-battery systems at different operating temperatures. Parameter settings for the cases are presented in Table 8. The uncertainty is ±14–61%.

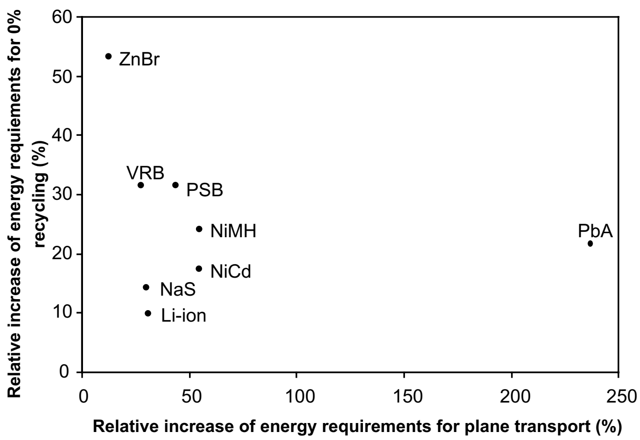

Fig. 4. Changes of energy requirements relative to Case 1 for different recycling rates (Case 4) and modes of transportation (Case 5).

3.4 times higher energy requirement for the PbA battery. ZnBr is least affected by plane transport due to its long service life and high energy density.

The results show that for certain battery technologies and conditions, batteries contribute significantly to the total energy requirement for production of PV-battery systems. The consequences of the technical performance and energy requirement on the energy return factor of the PV-battery system and the overall battery efficiency are presented in Part II [4] of this study.

5.3. System design-relationship between depth of discharge and cycle life

Depending on the characteristics of the battery, deep discharges may reduce the cycle life of the battery. This is particularly an issue for PbA batteries since deep discharges lead to morphological changes of the active material and creation of lead–sulphate crystals with low conductivity, which

Table 10
Energy requirements for a PV-battery system with lead–acid batteries producing 197 GJ_{el}/yr at different depth of discharge

Capacity battery (kWh)	DOD at 150 kWh/day (%)	Cycle life, N[a] (cycles)	Energy (GJ_{pf}/yr)
450	33	900–2000	134–417
188	80	400–1000	124–398
150	100	320–800	124–398

[a] Source Table 3.

may make it difficult to recharge the battery to full capacity. A PbA battery is therefore dimensioned not to exceed 80% DOD, resulting in a larger battery and thus higher energy requirements for its production. Case 1 is based on 33% DOD, resulting in a battery three times larger than for a design when the battery is discharged to 100% DOD. By analysing the consequences of different depths of discharge, it may be possible to optimise the over capacity of a PbA battery to reduce the energy requirements.

Table 10 shows that 80% and 100% DOD has 5–8% lower energy requirements than at 33% DOD. The relative change depends on the DOD versus cycle life characteristics of the battery. In this case, when no specific energy requirements for exchanging batteries have been included, it is more energy efficient to install a smaller PbA battery, which is discharged to 80% DOD even though the service life becomes shorter.

5.4. Uncertainties

The low and high values indicate the uncertainties in the data as well as the improvement potential of different technologies. Input data with large impact and large uncertainty interval is the battery charge–discharge efficiency and the battery service life. The uncertainty in output results for different battery technologies vary between 8% and 61%. The difference between low and high values of input data is 1.1–2.2 times, where the highest variability is for NiMH and PbA. Since all battery technologies, except for PbA and NiCd, are immature for PV applications, there are uncertainties about their performance.

Only a small number of demonstration units have been built of VRB, PSB, ZnBr and NaS batteries, and mass production is likely to improve the production efficiency of these batteries. Energy requirements for production of batteries may vary considerably depending on material requirements and where and how they are manufactured. Uncertainties are due to restricted availability of information since companies manufacturing batteries protect their technology from competitors. Material requirements for immature technologies can change fast in the course of development. However, this analysis indicates the technical potential of different technologies. Since the performance of a technology depends on the system design, data have to be compiled corresponding to the specific conditions of a particular application.

5.5. Future research

Data on energy requirements for production of batteries originate from different sources, which make comparisons unreliable because the system boundaries may be inconsistent. Further work is, therefore, needed to improve the data quality on material and energy requirements of batteries. For the redox flow batteries, energy requirements need to be expressed for power and storage capacity, respectively, in order to enable evaluation of the potential benefits of independent sizing of power and capacity of redox flow batteries. The influence of temperature on battery service life has to be further analysed. The effects of different battery charge–discharge efficiencies on the battery temperature and cooling requirements have to be further investigated. The energy model of this study can be further developed with functions for assessing the influence of the rate of battery self-discharge as well as different DOD due to different sizing of the battery capacity. The model can be extended to include assessment of resource use, emissions and potential environmental impact of different technologies. Flywheels, fuel cells with hydrogen storage in PV systems may be evaluated and compared with batteries.

6. Conclusions

The technical performance and energy requirements for production were estimated for eight different battery technologies used in a stand alone PV-battery system. In our reference case, the energy requirements for production of the PV-battery system differ up to a factor of three for the different battery technologies. Production and transport of batteries contribute 24–70% to the energy requirements. The contribution of production and transport of the PV array is 26–68%, depending on the battery technology used. The contribution of transport to the indirect gross energy requirements is 1–9% with 3000 km transportation by heavy truck. When transportation is done by plane instead of truck, the energy requirement may rise up to 3.4 times, and transport may contribute up to 73% of the total energy requirements for batteries with low energy density (<30 Wh/kg) and short cycle life (<3000 cycles at 33% DOD).

To reduce the energy requirements of producing and transporting battery systems, the development of battery technologies should aim at higher charge–discharge efficiencies and more efficient production and transport of batteries. The battery charge–discharge efficiency has a high influence on the system energy requirements for batteries with relatively low energy requirements for production and transportation (Li-ion, NaS, VRB, ZnBr, PSB). Service life, gravimetric energy density and battery production processes are of greater importance for NiCd, NiMH and PbA batteries. The data on energy requirements for production and transport can be used to calculate the energy return factors and overall battery efficiencies of PV-battery systems, as presented in Part II [4] of this study.

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