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Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies

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Abstract

Energy return factors and overall energy efficiencies are calculated for a stand-alone photovoltaic (PV)-battery system. Eight battery technologies are evaluated: lithium-ion (nickel), sodium–sulphur, nickel–cadmium, nickel–metal hydride, lead-acid, vanadium-redox, zinc–bromine and polysulphide–bromide. With a battery energy storage capacity three times higher than the daily energy output, the energy return factor for the PV-battery system ranges from 2.2 to 10 in our reference case. For a PV-battery system with a service life of 30 yr, this corresponds to energy payback times between 2.5 and 13 yr. The energy payback time is 1.8–3.3 yr for the PV array and 0.72–10 yr for the battery, showing the energy related significance of batteries and the large variation between different technologies. In extreme cases, energy return factors below one occur, implying no net energy output. The overall battery efficiency, including not only direct energy losses during operation but also energy requirements for production and transport of the charger, the battery and the inverter, is 0.41–0.80. For some batteries, the overall battery efficiency is significantly lower than the direct efficiency of the charger, the battery and the inverter (0.50–0.85). The ranking order of batteries in terms of energy efficiency, the relative importance of different battery parameters and the optimal system design and operation (e.g. the use of air conditioning) are, in many cases, dependent on the characterisation of the energy background system and on which type of energy efficiency measure is used (energy return factor or overall battery efficiency).

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1. Introduction

To warrant support, new technologies need to prove that they have a potential to solve the problems they are designed to solve. For example, if a renewable energy technology shall be able to contribute substantially to energy supply, it needs to be able to convert significantly more energy from the renewable energy source than that used for production of the conversion system itself. Over time, the inability to do so will become evident, but in the meantime, a lot of effort and money could have been wasted on an inferior technology. The ability to generate positive net energy has recently been at the heart of a debate over the benefits of producing ethanol from corn [1,2]. The energy balance of solar photovoltaics (PV) has also been used as an argument against PV dating back to a study in 1972 that claimed that it took 40 yr for a PV module to generate the electricity that was required to produce it, i.e. the energy payback time was 40 yr [3]. It should be noted that for some small energy loads, it is of less importance to supply net energy. In some cases, it is enough that a device works as a battery and moves energy from one place to another. This could, for example, be the case for PV in satellites or in small solar home systems in poor rural areas. [1]

With current technology and production methods, the energy payback time for PV modules has been estimated at 1.1–5 yr depending on the technology and solar intensity [4–9]. Over a lifetime of 25 yr, PV modules thus generate 5–23 times the energy required to produce them. The balance of systems (BOS) components can add significantly to energy payback times. Heavy support structures could increase energy payback times by over 6 yr [10]. Depending on the application, PV systems have to be equipped with auxiliary components such as inverters, charge regulator and energy storage systems. Contributions to energy requirements from such components are normally small for grid-connected systems. Inverters usually add only a few months [10].

In many types of stand alone systems, batteries are required to even out irregularities in solar irradiation and concentrate solar energy to a higher power. In a study of solar home systems, Alsema [11] concluded that batteries contribute significantly to the gross energy requirements. Lead-acid batteries' addition to the energy payback time of the solar home systems was 10–11 yr and even more, 15–19 yr, without recycling of materials. Rydh [12] 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. In Part I of the study, we quantified the energy requirements for producing and transporting batteries and other components for a PV-battery system designed to deliver 150 kW h/day [13]. By quantifying energy efficiencies and energy

[1] Likewise, if corn based ethanol is produced to function mainly as a low percentage additive to gasoline to reduce regulated emissions and not as an alternative fuel, the net energy argument is less relevant.

Nomenclature

$\alpha_{pf,el}$ conversion factor from primary fossil fuel to electricity
$\alpha_{pf,th}$ conversion factor from primary fossil fuel to thermal energy
$\alpha_{pf,tr}$ conversion factor from primary fossil fuel to transport energy
$\alpha_{el,el}$ conversion factor from electricity to electricity
$\alpha_{el,th}$ conversion factor from electricity to thermal energy
$\alpha_{el,tr}$ conversion factor from electricity to transport energy
β_i fraction of primary fossil energy used to generate electricity used in production of component i
η_i direct energy conversion efficiency of component i
η_B^* overall battery system efficiency
η_0^* overall efficiency of alternative way to produce functional unit, e.g. Diesel generator
E_{D5} (MJ_{el}/yr) annual direct electricity use for air conditioning
E_G (MJ_{el}/yr) gross electricity input to PV-battery system
E_{G0} (MJ_{pf}/yr) average annual gross primary fossil energy use of Diesel system
$E_{I,i,pf}$ (MJ_{pf}/yr) average annual primary fossil energy required to produce PV-battery component i
$E_{I,i,el}$ (MJ_{el}/yr) average annual electric energy required to produce PV-battery component i
E_{use} (MJ_{el}/yr) annual electricity output from energy system
E_{W2} (MJ_{el}/yr) energy loss in charger
E_{W3} (MJ_{el}/yr) energy loss in battery
f energy return factor
i energy system component: 1 = PV-array, 2 = charger, 3 = battery, 4 = inverter, 5 = air conditioning (AC)
$Q_{i,pf}$ (MJ_{pf}) primary fossil energy required to build component of energy system
$Q_{i,el}$ (MJ_{el}) electrical energy required to build component of energy system
t_i (yr) service life of component i
t^* (yr) energy payback time

requirements 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, and a comparison of different battery technologies can be used to guide battery selection for specific user conditions.

However, energy efficiencies can be measured in different ways and sometimes point in different directions. The energy payback time is the most commonly used measure for the energy economy of power plants that harness renewable energy flows, such as PV and wind power. In this paper, we use the related concept: *energy return factor*. Net energy output is a similar measure, often used in the context of biofuels. None of these measures takes into account how efficiently the renewable energy source is used. When the share of renewables in the energy mix increases, the efficient use of renewable energy will grow in importance. Therefore, we will, in this paper, not only estimate energy return factors but also use a measure we term *overall efficiency*.

2. Goal and scope

The goal of this study is to analyse the energy efficiencies of different battery technologies when used in stand alone PV-battery systems and to compare two different measures of energy efficiency. The contribution of different PV-battery components to the gross energy requirement and important parameters is identified for each battery technology. The performance of the PV-battery system is evaluated by the energy return factor and the overall battery energy efficiency. It should be noted that this paper exclusively deals with energy and that energy efficiency is only one aspect of the performance of a PV-battery system. Monetary costs are not included, nor is non-energy related environmental aspects.

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 polysulphide–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 batteries (see Section 4).

The study includes 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. 3). 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 MW h/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 kW h and an output of 150 kW h electricity per day (197 MJ$_{el}$/yr)".

The choice of functional unit defines the depth of discharge (DOD) of the battery as 33% at daily cycling (150 kW h/day/450 kW h). 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 reached first (see Part I).

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 performance, presented as low. When cells are stacked together into battery modules, the performance values decrease due to 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 the 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. Measures of energy efficiency

Energy efficiency can be defined in many ways, but in all cases, it is a measure of the amount of energy resources (inputs) that is needed to provide an energy service (output). In this paper, we will use two complementary measures of energy efficiency, the *energy return factor* and the *overall efficiency*.

3.1. Direct and indirect energy requirements

The gross energy requirement E_G of an energy conversion device with the energy output E_O can be decomposed into two parts (Fig. 1): the direct input of energy during operation E_D and the indirect energy requirement E_I, i.e. the energy used to produce the device and transport it to the site of operation.

$$E_G = E_D + E_I \tag{1}$$

From these energy flows, three measures of energy efficiency can be calculated: the direct conversion energy efficiency of the device

$$\eta = \frac{E_O}{E_D}, \quad 0 < \eta < 1 \tag{2}$$

the overall energy efficiency

$$\eta^* = \frac{E_O}{E_G}, \quad 0 < \eta^* < 1 \tag{3}$$

and the energy return factor

$$f = \frac{E_O}{E_I}, \quad f > 0 \tag{4}$$

3.2. Energy return factor

The *energy return factor* is used as an indicator of how efficiently a device (such as a PV-battery system) or a conversion system (such as ethanol production) uses non-renewable energy in comparison to an alternative method of producing the same service. In our case, the alternative means of producing electricity locally would normally be a Diesel generator. Therefore, it is convenient to use primary fossil energy (indicated by the index pf) as a common energy currency when we calculate the energy return factor (see Section 3.4 for further discussion on energy currencies).

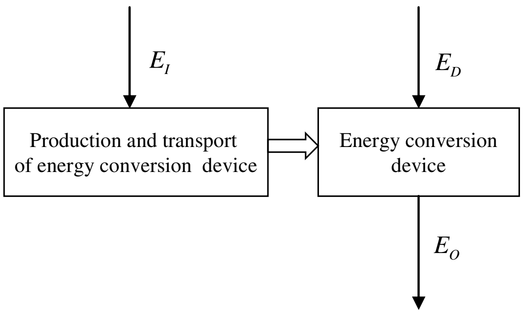

Fig. 1. The general energy balance of an energy conversion device.

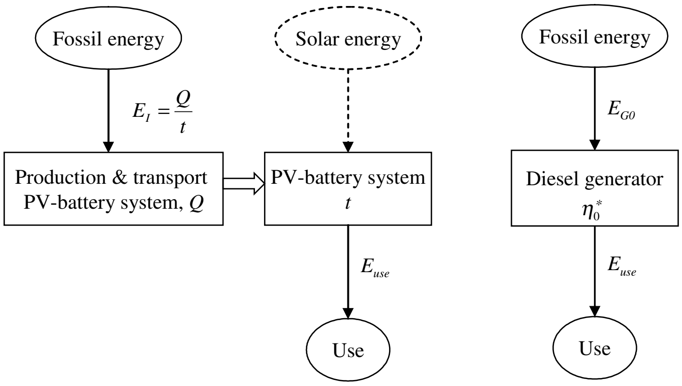

Fig. 2. The energy flows of the PV-battery system and the reference system (the Diesel generator).

Both systems have the same output E_{use} (MJ_{el}/yr), defined by the functional unit. The average annual gross primary fossil energy use of the Diesel system E_{G0} (MJ_{pf}/yr) is calculated from

$$E_{\text{G0}} = \frac{E_{\text{use}}}{\eta_0^*} \tag{5}$$

where η_0^*, is the overall efficiency of the Diesel generator. The energy return factor, f, is then the ratio between the replaced fossil energy (diesel) and the fossil energy required to produce the PV-battery system

$$f = \frac{E_{\text{G0}} \cdot t}{Q} = \frac{E_{\text{G0}}}{E_{\text{I,pf}}} \tag{6}$$

where t (yr) is the service life of the PV-battery system, Q (MJ_{pf}) is the primary fossil energy required to build and transport it and $E_{\text{I,pf}}$ (MJ_{pf}/yr) is the average annual energy required for production and transport. Eq. (6) is a version of Eq. (4) where the energy flows are translated into a common energy currency by the help of a reference system (the Diesel generator), Fig. 2.

A similar measure that is commonly used to describe the energy balance of a PV system (or any other energy flow conversion technology) is the energy payback time, t^* [4]. [2] After a certain time in operation, the energy payback time, the energy that was used to produce the PV-battery system is paid back by not using the Diesel generator.

$$t^* = \frac{Q}{E_{\text{G0}}} = \frac{t}{f} \tag{7}$$

Since the service lives of the components in the PV-battery system differ, the meaning of an energy payback time becomes ambiguous. The energy return factor is then a better measure, and for the more detailed representation of the system in Fig. 3, the energy return factor can be calculated from Eq. (6) and from

[2] The net energy (output) is defined in some studies as $E_{\text{O}} - E_{\text{I}}$, in relation to the indirect energy requirement $(E_{\text{O}} - E_{\text{I}})/E_{\text{I}} = f - 1$ or to the energy output $(E_{\text{O}} - E_{\text{I}})/E_{\text{O}} = 1 - 1/f$. The indirect energy requirements can also be expressed as a fraction of the energy output, $E_{\text{I}}/E_{\text{O}} = 1/f$.

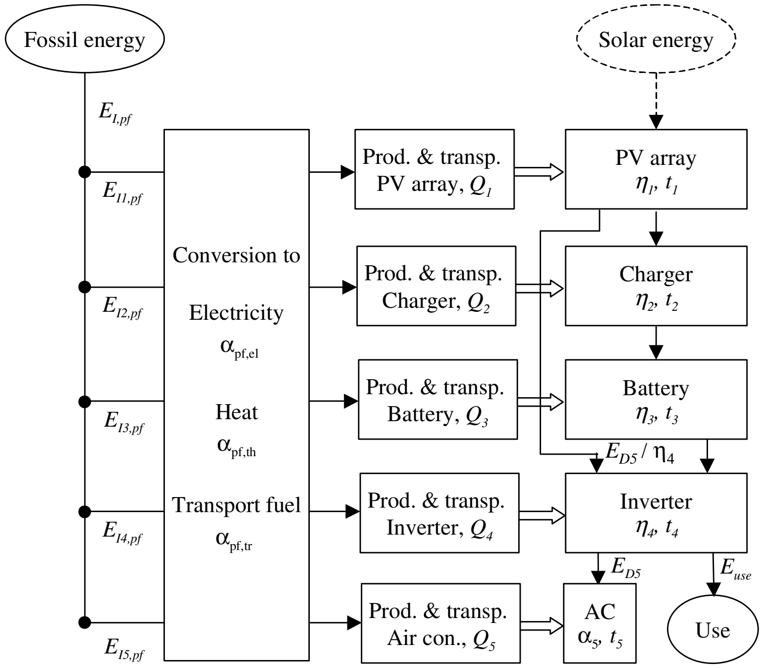

Fig. 3. The PV-battery system components, indirect energy requirements, E (annual) and Q (total), lifetimes t, efficiencies η and conversion factors α.

$$E_{\mathrm{I,pf}} = \sum_{i=1}^{5} E_{\mathrm{I},i,\mathrm{pf}} = \sum_{i=1}^{5} \frac{Q_{i,\mathrm{pf}}}{t_i}. \tag{8}$$

3.3. Overall efficiency of the battery system

The overall efficiency of the battery system (charger, battery and inverter), η_{B}^{*}, is the ratio between the output from the battery system, E_{use} ($\mathrm{MJ_{el}}$/yr), and the total inputs, here translated into an electricity equivalent, E_{G} ($\mathrm{MJ_{el}}$/yr) (Fig. 4). Since the direct energy input and the output are electricity, electricity (indicated by the index el) will be used as the energy currency for calculation of the overall efficiency.

$$\eta_{\mathrm{B}}^{*} = \frac{E_{\mathrm{use}}}{E_{\mathrm{G}}} \tag{9}$$

When the energy return factor is used as a measure of energy efficiency, the solar electricity is implicitly regarded as an abundant free resource. When the overall efficiency is used, the electricity input is seen as the scarce resource worth saving. [3] This could be a relevant measure of efficiency

[3] The overall efficiency of the PV-battery system (instead of only the battery system) could be calculated by taking into account the direct efficiency and indirect energy requirements for the PV array. This would then become a measure of how efficiently the solar irradiation is used. However, here the focus is on battery performance.

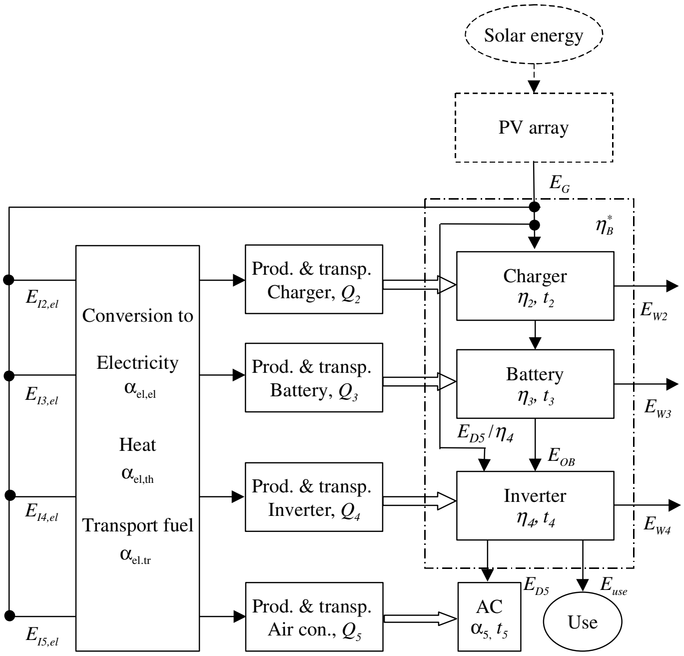

Fig. 4. The gross energy requirement of the battery system E_G is the sum of the energy output, direct losses in the battery system and the indirect energy requirement for production and transport of components.

in a closed solar energy system. For a designer of a PV-battery system, the direct efficiency of the battery system is of interest. A large direct efficiency would save resources (materials, energy, capital and labour) used to produce the PV-system and space used by the PV arrays. In a world that, to a larger extent, relied on solar energy, the production of the battery system must also be produced from solar energy (we can not borrow fossil fuels to build the system anymore). Thus, more PV systems (or other solar energy technologies) would have to be produced. Total electricity inputs can, thus, be interpreted as the output from PV arrays at the site and from PV arrays producing electricity that is used to produce and transport the batteries. The closed solar energy system is one example. The overall efficiency measure is valid for electricity produced from any energy source.

The gross electricity input E_G can be written as the sum of the electricity output E_{use} and the energy losses in the charger E_{W2}, in the battery E_{W3} and in the inverter E_{W4} and the energy used for the production and transport of the charger $E_{I2,el}$, the battery $E_{I3,el}$ and the inverter $E_{I4,el}$ and the direct and indirect energy requirement of the air conditioner E_{D5} and $E_{I5,el}$ when it is in use.

$$E_G = E_{use} + E_{D5} + \sum_{i=2}^{4} E_{W,i} + \sum_{i=2}^{5} E_{I,i,el} \tag{10}$$

where

$$E_{W2} = E_{use}\left(\frac{1-\eta_2}{\eta_2 \cdot \eta_3 \cdot \eta_4}\right) \tag{11}$$

$$E_{W3} = E_{use}\left(\frac{1-\eta_3}{\eta_3 \cdot \eta_4}\right) \tag{12}$$

$$E_{W4} = (E_{use} + E_{D5}) \cdot \left(\frac{1-\eta_4}{\eta_4}\right) \tag{13}$$

$$E_{I,i,el} = \frac{Q_{i,el}}{t_i}, \quad i = 2,3,4,5 \tag{14}$$

$$E_{D5} = \frac{1}{\alpha_5}\sum_{i=2}^{4} E_{W,i} \tag{15}$$

where α_5 is the coefficient of performance of air conditioning (heat to electricity ratio). It is assumed that the air conditioner uses electricity from the PV array that has passed the inverter but not the charger and the battery. The cooling requirement of the battery room depends on the heat losses from the charger, the battery and the inverter. Heat transmission from the ambient air is not considered since it is estimated to have rather low influence in a battery room located below ground level. In cases when air conditioning is not used, E_{D5} and $E_{I5,el}$ are put to zero.

3.4. Energy quality and conversion factors

The fact that energy may take different forms poses a problem. The gross energy requirement and the indirect energy requirement are normally made up of many different kinds of energy inputs. To be able to define single measures for the overall efficiency or the energy return factor, the different energy forms need to be converted to a common energy currency. In the calculation of the energy return factor, we use primary fossil energy as the energy currency. This is the normal procedure but obviously a somewhat coarse approach since there are great differences between coal, oil and gas (for example with regard to CO_2 emissions or resource availability). However, in principle, the Diesel oil saved could be used for the heat, electricity and motor fuel production required for the production and transport of the PV-battery system.

In all estimates, we use data on indirect energy requirements from Part I [13] given as primary fossil equivalents. In the calculation of energy return factors, we assume an overall conversion efficiency from primary fossil energy via diesel to electricity in 'the Diesel generator' of 0.2 [11] (Table 1).

Table 1
Energy conversion factors

	Conversion from primary fossil energy		Conversion from electricity		
			Energy exchange		All PV
Electricity	$\alpha_{pf,el}$	0.35	$\alpha_{el,el}$	1.0	1.0
Thermal energy	$\alpha_{pf,th}$	0.95	$\alpha_{el,th}$	2.71	1.0
Transport fuel	$\alpha_{pf,tr}$	0.88	$\alpha_{el,tr}$	2.51	0.85
Diesel generator electricity	η_0^*	0.20			

To calculate the overall efficiency of the battery system, we need to convert values given as primary fossil equivalents into electricity equivalents. To do this, the energy requirements $Q_{i,\mathrm{el}}$ are subdivided into electricity and thermal energy use in production $Q_{\mathrm{P},i}$, and transport fuel $Q_{\mathrm{T},i}$.

$$Q_{i,\mathrm{el}} = Q_{\mathrm{P},i,\mathrm{el}} + Q_{\mathrm{T},i,\mathrm{el}} \tag{16}$$

$$Q_{\mathrm{P},i,\mathrm{el}} = Q_{\mathrm{P},i,\mathrm{pf}} \cdot \left(\beta_i \frac{\alpha_{\mathrm{pf,el}}}{\alpha_{\mathrm{el,el}}} + (1-\beta_i) \frac{\alpha_{\mathrm{pf,th}}}{\alpha_{\mathrm{el,th}}} \right) \tag{17}$$

$$Q_{\mathrm{T},i,\mathrm{el}} = Q_{\mathrm{T},i,\mathrm{pf}} \cdot \frac{\alpha_{\mathrm{pf,tr}}}{\alpha_{\mathrm{el,tr}}} \tag{18}$$

where the conversion factors α are given in Table 1. The factor β_i is the estimated proportion of primary fossil energy used to generate the electricity used in the production of component i.

The average conversion efficiency for electricity generation from primary fossil fuels is assumed to be 0.35 [14]. Losses in distribution and conversion of primary fossil fuel to thermal energy result in a conversion efficiency of 0.95. The efficiency for refining and distribution of primary fossil fuel to Diesel for transportation is 0.88 [15]. Two extreme assumptions for the conversion of solar electricity into thermal energy and transport fuel are investigated, the *energy exchange* and the *All PV* assumption.

The *energy exchange* assumption corresponds to a PV-battery system that is open to other energy sources. The fuel and heat required for production and transport is not converted directly from solar electricity. Instead, the solar electricity is exchanged for electricity produced from primary fossil energy, which, in turn instead, can be used to produce the required heat and transport fuel. When electricity replaces the need for the combustion of fossil fuels for electricity generation, the conversion factor for electricity to heat is 2.71 ($\alpha_{\mathrm{el,th}} = 0.95/0.35$). For transportation, the primary fossil fuel includes 12% losses for refining and distribution of Diesel fuel [15], resulting in an energy conversion factor of 2.51.

The All PV assumption corresponds to a closed renewable energy system where solar electricity cannot be traded and heat and a transport fuel have to be made from solar electricity. Electricity is then used directly for the generation of high temperature thermal energy (heat pumps not considered) with the conversion factor 1. Transportation in a renewable energy system may be based on vehicles powered by fuel cells and electrical motors where hydrogen is used as a motor fuel. The conversion efficiency of electricity to hydrogen by electrolysis of water is estimated at 80%, and the energy efficiency of hydrogen distribution is assumed to be 80% [15]. A fuel cell vehicle is assumed to be 33% more energy efficient per ton kilometer transported goods than a conventional diesel truck [15], resulting in a conversion factor of 0.85. [4]

[4] This should only be seen as an example that is used to illustrate the effect of how the energy requirement for different types of end uses could shift when the major energy sources are changed. There are, for example, other ways of splitting water to produce hydrogen gas directly with solar energy.

4. Performance parameters and energy requirements of system components

A detailed model and input data for the calculation of energy requirements of the PV-battery system components for five different operating conditions (Case 1–5, Table 2) are given in Part I [13]. Direct energy conversion efficiency, service life and energy requirements for production and transportation of different components for Case 1 are provided in Table 3. The electricity share of primary energy input in component production (β) is also given to enable calculation of overall

Table 2
Parameter settings for evaluation of the PV-battery system

Case	Service life ($t_{3,\mathrm{limit}}$[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	$t_{3,\mathrm{limit}}$	25	Off	100	Truck
2	$t_{3,\mathrm{limit}}$	25	On	100	Truck
3	$t_{3,\mathrm{limit}}$	40	Off	100	Truck
4	$t_{3,\mathrm{limit}}$	25	Off	0	Truck
5	$t_{3,\mathrm{limit}}$	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 3
Parameters for the system components

	η_i, α_5	$t_{i,\mathrm{limit}}$[a](yr)	$Q_{\mathrm{P.}}$[b] ($\mathrm{GJ_{pf}}$)	Q_{T}[c] ($\mathrm{GJ_{pf}}$)	β[d]
PV (mc-Si)	0.12–0.13	30	1800–3800	13–27	
Charge regulator	0.90–0.95	10	40–64	1.7–2.8	0.50
Inverter	0.92–0.94	10	50	2.2	
Air conditioning	3	8.0	5.7–33	0.36–2.0	0.75
Batteries					0.70
Li-ion	0.85–0.95	14–16[e]	480–1100	17–26	0.68
NaS	0.75–0.83	14–16[e]	380–490	18–21	0.68
NiCd	0.65–0.85	13–16[f]	1100–2100	50–71	0.65
NiMH	0.65–0.85	7.7–8.2[f]	820–2500	38–60	0.50
PbA	0.70–0.84	2.5–5.5[f]	260–680	56–93	0.41
PSB	0.60–0.65	14–15[e]	370–810	28–42	0.50
VRB	0.60–0.80	15–20[e]	530–920	21–28	0.50
ZnBr	0.60–0.73	8.0–10[e]	230–320	4.9–6.0	0.50

Source: [13].

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

[b] Energy requirements for production of system components for the energy exchange assumption, Case 1, air conditioning data = Case 2.

[c] Energy requirements for transportation of system components for the energy exchange assumption, Case 1, air conditioning data = Case 2.

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

[e] Limited by float service life when cycled one cycle per day.

[f] Limited by cycle life at 33% DOD and 20–25 °C.

battery efficiencies with different assumptions for conversion factors from electricity to other energy carriers (Eqs. (17) and (18)). According to the functional unit stated in Section 2, E_{use} = 197 GJ_{el}/yr.

5. Results

5.1. Energy return factor

Fig. 5 shows that the energy return factor (Case 1) for the PV-battery system ranges from 2.2 for NiMH batteries (low estimate) to 10 for Li-ion batteries (high estimate). The NaS battery has the highest average energy return factor (8.5), which means that the PV–NaS battery system will replace 8.5 times more energy throughout its lifetime than the energy required for its production.

The uncertainty intervals of many batteries are overlapping (Fig. 5). This shows the importance of using case-specific data when comparing different battery technologies. The greatest uncertainty is found for systems with a PbA battery due to the high variability in lifetime and energy requirements. If we add results from other design and operating conditions represented by the different cases in Table 2, this point is further strengthened. The low estimate of the energy return factor for PbA in Case 5 (air transport) is as low as 0.68. If the operating temperature at the same time is increased to 40 °C (Case 3) and no material is recycled (Case 4), then the energy return factor is 0.25. In this extreme case, four times more primary fossil energy is needed to produce and transport the system than what is replaced.

Production and transportation of batteries contributes 24–70% to the total indirect energy use of the PV-battery system compared to 26–68% for the PV array (Fig. 6). Given a system lifetime of 30 years, the PV array contributes 1.8–3.3 yr and batteries 0.72–10 yr to the energy payback time depending on the technology, showing the energy related significance of batteries in PV-battery systems.

The relative contribution from batteries is lowest for the ZnBr battery and highest for the NiMH battery. The absolute energy requirement for PV array production is highest for the redox

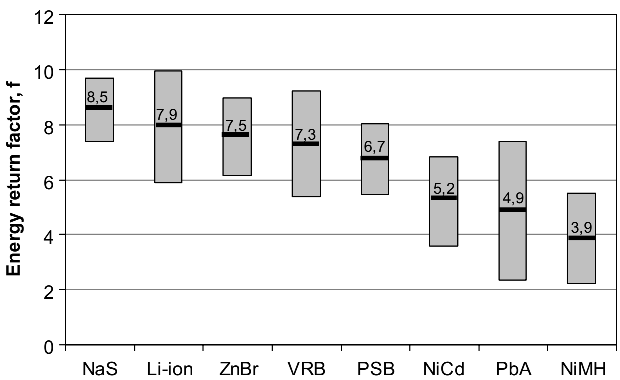

Fig. 5. Energy return factors for the PV-battery systems for Case 1 (see Table 2). The variation in the average value is ±14% to 52%.

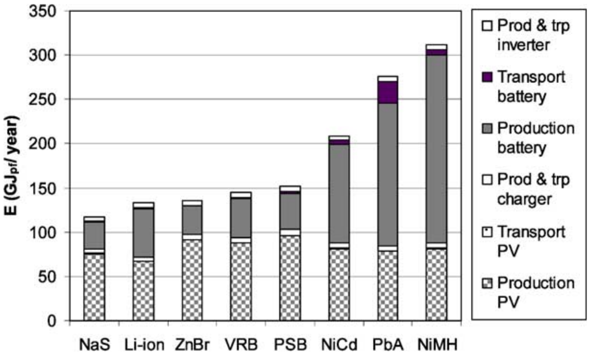

Fig. 6. Energy requirements for production and transport of various PV-battery systems for Case 1. The uncertainty is ±14% to 52%.

flow batteries due to their relatively low efficiency, resulting in the need for a larger PV array. The contribution from the charge regulator and the inverter is 2–4%, respectively.

The contribution of transport of all the components 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 indirect energy requirements since these batteries have a relatively low energy density and cycle life, and therefore, a larger mass of batteries has to be transported. For more energy intensive transportation, this contribution can become significant. The effects of plane transport and no recycling (Cases 4 and 5) are analysed in Part I [13].

The importance of energy requirements for battery production increases in relation to PV at locations with high irradiation and vice versa. At locations with low irradiation levels, the power rating of the PV arrays has to be increased to produce the same amount of electricity. [5] This results in higher indirect energy requirements for production of PV arrays. The importance of the level of solar irradiation for the total energy return factor depends on the relative contribution of the PV array to the indirect energy requirements of the PV-battery system. For Case 1, an increase of the solar irradiation by 30% to 2.2 MWh/m^{2}yr, increases the energy return factor of the PV-battery system by 9–20%. For the conditions in Case 1, the energy return factor equals one (zero net output) at irradiation levels below 100–250 kWh/m^{2}yr. This low irradiation is not relevant for practical applications and may only be found indoors. [6]

The energy return factor is very sensitive to assumptions about the conversion efficiency of the electricity generation technology the PV system replaces (η_0^*). A conversion efficiency of 0.20 was selected as a default value to represent a Diesel generator since it is likely that a PV-battery system can replace its use in an off grid application. If the efficiency of the Diesel generator is 0.25, the

[5] High irradiation (2.2 MWh/m^{2}yr) can be found in southwestern USA and the Sahara, medium (1.7 MWh/m^{2}yr) levels can be found in large parts of the USA and Southern Europe and low levels (1.1 MWh/m^{2}yr) can found in the middle of Germany [6]. A PV module installed in the middle of Germany, therefore, has a 55% lower energy return factor than a module installed in Southern Europe.

[6] The solar irradiation has low influence on the overall battery efficiency since it only affects the power rating of the charger.

energy return factor is reduced by 20% (1 − 0.20/0.25). Assuming that the PV-battery system replaces a grid connected system where the electricity conversion efficiency is 0.35, the energy return factor decreases by 43%.

5.2. The overall battery efficiency

The direct efficiency of the battery system (charger, battery and inverter) is 0.50–0.85, which can be calculated from Table 3. Adding the indirect energy requirement results in overall efficiencies from 0.41 for the NiMH battery (low estimate) to 0.80 for the Li-ion battery (high estimate) (Fig. 7, Case 1, energy exchange assumption). The average efficiency of the NiMH battery system decreases by 18%, from 0.65 to 0.53, which shows the effect of high energy requirements for production on the overall efficiency. However, the estimate for NiMH also has the largest uncertainty interval due to its great variability in energy density.

Fig. 8 shows how the gross electricity requirement is used (Case 1, energy exchange assumption). The energy requirements for production and transport of the charger, the battery and the inverter have been converted to electricity. Energy losses in the batteries are significant and vary from 9% for the Li-ion battery to 27–33% for the redox flow batteries. Losses in the charger and inverter are 6–8% and 4–5% of the gross energy requirement, respectively. Production and transport of the charger and inverter contribute less than 1% of the gross energy requirement, while production and transport of batteries contribute 11–19% for NiCd, PbA and NiMH. With the All PV assumption, the gross energy requirement is increased for all batteries (the overall efficiency is decreased). The effect is larger for batteries, such as PbA and NiCd, with high energy requirements for battery production and transport (Fig. 9).

5.3. Different efficiency measures and battery ranking

As can be seen in Fig. 10, the ranking order of the batteries depends on the efficiency measure that is used. NaS and Li-ion, the two most energy efficient systems, change places at the top when

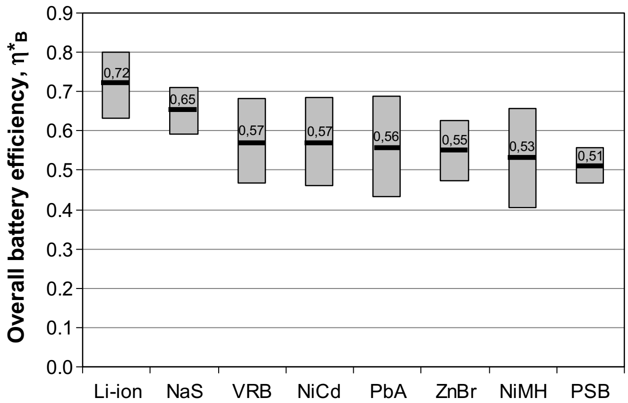

Fig. 7. Overall battery efficiencies including production and transport of charger, battery and inverter. Results for Case 1 and electricity conversion factors for the energy exchange assumption. The variation around the average value is ±9% to ±24%.

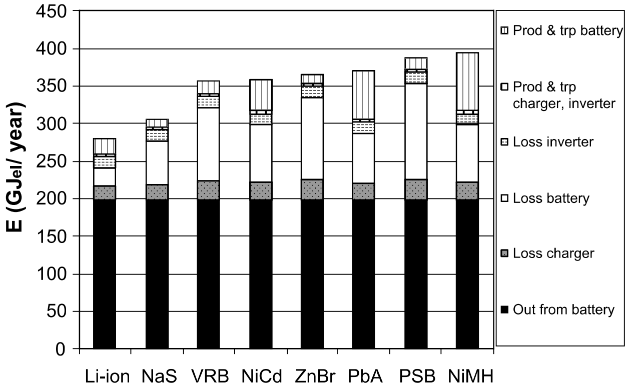

Fig. 8. Gross electricity requirements for charger, battery and inverter including their production and transport for Case 1 and the energy exchange assumption. The uncertainty is ±9% to 24%.

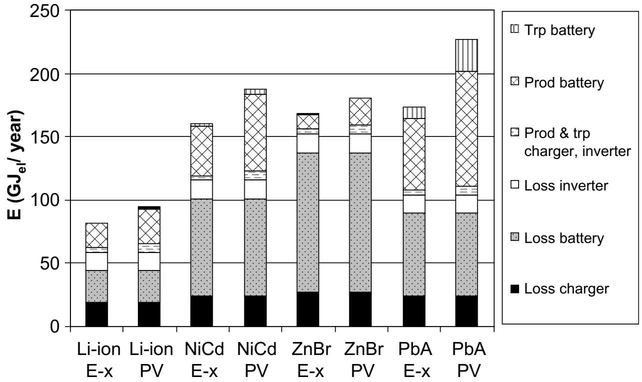

Fig. 9. Gross electricity requirements for charger, battery and inverter including their production and transport in Case 1. E_{use} = 197 GJ_{el}/yr, E-x = energy exchange and PV = All PV case.

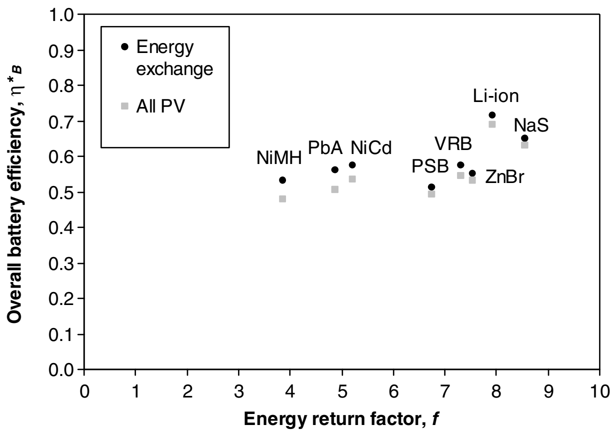

Fig. 10. Relation between overall battery efficiency and energy return factors for the energy exchange and All PV assumption in Case 1.

going from energy return factor to overall efficiency. The other batteries, which have diverging energy return factors, have very similar overall efficiencies. This results from the fact that NiMH, PbA and NiCd, which have low energy return factors, have higher direct energy efficiencies than the redox flow batteries and consequently lower losses during operation. For Case 1, this conclusion is also valid for the All PV assumption even though the ranking order of PbA, NiCd, PSB and ZnBr is changed (Figs. 9 and 10). For a case with larger energy use for production and transport (e.g. Case 5, see Part I [13]), the lower factors for conversion of electricity that is used for the All PV assumption result in larger differences in overall efficiency.

5.4. Different efficiency measures and optimal system design and operation

The choice of measure for energy efficiency (energy return factor or overall efficiency) and the choice of energy conversion factors (energy exchange or All PV) do not only have consequences for the ranking order of batteries but also for how systems should be designed and operated to maximise energy efficiency. We illustrate this by showing the effects of increased temperature and air conditioning. A raised temperature will shorten the battery lifetime and thereby increase the energy requirements for producing and transporting batteries [13]. On the other hand, using air conditioning will require energy to produce and transport the AC system and the larger PV area required to power the AC. These effects affect the overall efficiency as well as the energy return factor. However, the overall efficiency is also decreased due to the increased requirement for direct energy that is used to power the AC. [7]

Fig. 11 shows the relative decrease of energy efficiency for four batteries in comparison with Case 1 for increased temperature (Case 3, on the x-axis) and for using AC (Case 2, on the y-axis). The question is "Should air conditioning be used?" The three different measures of energy efficiency give varying recommendations for three of the four batteries. To the left of the dotted line, the relative decrease in energy efficiency is minimised if the AC is shut off; to the right, the AC should be turned on. Only the PbA battery is recommended to have AC turned on no matter what measure that is used.

For systems with a PbA battery, the relative decrease in efficiency is largest for raised temperature no matter which measure of energy efficiency is used. For an operating temperature of 40 °C, the energy return factor is decreased by almost 50%. Hence, the AC should be turned on in PbA-battery systems. For the other batteries, the choice of efficiency measure and conversion factors matter, and different measures give different recommendations. The energy return factor is most sensitive to a temperature increase for all batteries. This is not the case for the overall efficiency. The overall efficiency of the NiCd battery is reduced more if the AC is turned on. The overall efficiencies of the NiMH and Li-ion batteries are reduced more if the AC is turned on with the energy exchange conversion factors but are more sensitive to an increased temperature with the All PV conversion factors.

[7] The direct energy requirement for operating the AC accounts for 98% of the gross energy requirements of the AC unit.

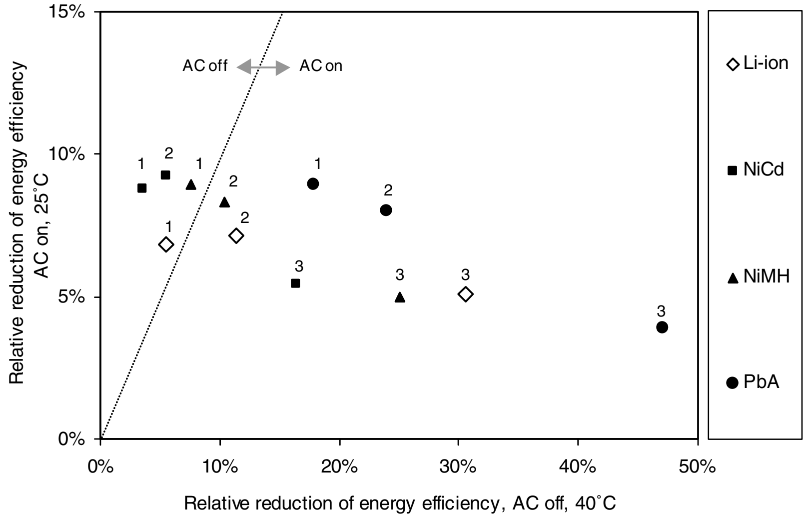

Fig. 11. Air conditioning of batteries or not? Change of energy efficiency relative to Case 1 for one case with raised temperature (x-axis, Case 3) and one with air conditioning (y-axis, Case 2). Measures of energy efficiency: (1) the overall battery efficiency for the energy exchange assumption, (2) the overall battery efficiency for the All PV assumption and (3) the energy return factor.

5.5. Different efficiency measures and battery design

To increase energy efficiency, the technical performance of batteries may be improved. The relative importance of different battery parameters for energy efficiency was, therefore, analysed including service life (t_3), charge–discharge efficiency (η_3) and energy requirements for production (Q_{P3}). For all batteries, the overall battery efficiency is most sensitive to changes of the charge–discharge efficiency (Table 4). For Case 1, this holds for both the energy exchange and All PV assumptions for electricity conversion. Changes in the efficiency of the Li-ion battery have a relatively small influence compared with the other battery technologies. This is because the losses in the Li-ion battery correspond to only 9% of the gross energy requirement, compared with 18–33% for the other technologies (Fig. 8).

Improvement in the charge–discharge efficiency is also most important for the energy return factor of Li-ion, NaS, PSB, VRB and ZnBr batteries (Table 4). Since losses in the battery must be compensated by higher energy input, low battery efficiency results in a larger PV array and charger, which means higher indirect energy requirements.

For NiMH, NiCd and PbA batteries, the energy return factor is more sensitive to changes in battery service life (and to energy density) and production energy. This is explained by the energy requirement for battery production being 53–68% of the gross energy requirement for NiMH, NiCd and PbA as compared with 23–41% for the other batteries (Fig. 6). The service life (and energy density) affects both energy requirements for production and transport. Short battery service life means that batteries have to be replaced more often, resulting in higher energy requirements for battery production and transport. The low energy density and short service life of PbA results in a larger share of transportation energy (Fig. 6). Therefore, the sensitivity to service

Table 4
Percent change of the energy return factor and the overall battery efficiency when changing different battery parameters

Technology	Energy return factor, f (% f/% Δ)			η_B^* Energy exchange (% η_B^*/% Δ)			η_B^* All PV (% η_B^*/% Δ)		
	η_3	t_{limit}	Q_{P3}	η_3	t_{limit}	Q_{P3}	η_3	t_{limit}	Q_{P3}
Li-ion	**0.38**	0.36	0.35	**0.67**	0.06	0.06	**0.64**	0.08	0.08
NaS	**0.68**	0.24	0.23	**0.96**	0.03	0.03	**0.93**	0.05	0.04
NiCd	0.43	**0.50**	0.48	**0.88**	0.10	0.09	**0.82**	0.14	0.13
NiMH	0.32	**0.61**	0.59	**0.81**	0.15	0.15	**0.74**	0.22	0.21
PbA	0.44	**0.49**	0.41	**0.85**	0.13	0.11	**0.77**	0.19	0.15
PSB	**0.68**	0.25	0.23	**0.95**	0.03	0.03	**0.92**	0.06	0.06
VRB	**0.65**	0.27	0.26	**0.95**	0.04	0.04	**0.90**	0.07	0.07
ZnBr	**0.71**	0.21	0.21	**0.96**	0.03	0.03	**0.93**	0.05	0.05

Note: Data for Case 1: service life limited by cycle or float service life, $T = 25$ °C, 100% recycled battery materials production and transportation by heavy truck. η_3 = charge–discharge efficiency, t_{limit} = cycle or float service life, Q_{P3} = energy requirements for battery production.
Bold face numbers indicate the highest values.

life is significantly larger than to the production energy for the PbA battery but not for other batteries.

6. Discussion

6.1. Uncertainties

The low and high values indicate the uncertainties in the results as well as the improvement potential of different technologies. Input data with high influence 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, the stated uncertainties for the other batteries could be underestimated.

The performance ratio, which is the ratio between the final yield and the reference yield of a PV system, is a common indicator for expressing the efficiency from PV array to useful energy. Typical values of performance ratios are 0.20–0.60 for off grid and 0.60–0.85 for grid connected PV systems [16,17]. The corresponding measure in this study, the direct efficiency, is 0.50–0.85. Our values are, thus, rather high for a stand alone system. This can partly be explained by the fact that below maximum performance of the PV array due to heat and irregular irradiation is assumed to be included in the conversion efficiency of the PV array and not in the direct efficiency of the battery system. Of greater importance is the inclusion of the highly energy efficient Li-ion battery. Finally, the fact that optimised charging is assumed also contributes. In practice, batteries may be float charged occasionally, resulting in lower performance ratios.

The energy return factor in this study is given for a battery storage capacity three times higher than the daily energy output. Since the energy payback time for the battery and battery transport increases linearly with the battery storage capacity of the PV system, it can be recalculated for other storage capacities. Alsema [11] calculated the energy payback time for PbA batteries in a solar home system (SHS) to be 10–19 yr. The number of days of autonomy that was used for this calculation was 6.8–20 days (battery voltage 12 V, battery capacity 70–100 A h and array output 60–124 W h/day). Recalculated to 3 days of autonomy, the energy payback time for the battery is 1.5–8.4 yr, which can be compared with 1.8–9.6 yr in this study. The service life for the starting-lighting-ignition (SLI) battery is assumed to be 3 yr by Alsema [11] and 2.5–5.5 yr in this study when limited by cycle life (one cycle per day). In SHS, without charge regulator and poor battery maintenance, the service life may be less than 3 yr when standard SLI- PbA batteries are used. Improvement of the charge/discharge strategy can extend the service life of PbA batteries in PV applications [18].

6.2. The use of different measures for energy efficiency

Depending on the origin and availability of energy resources, different energy efficiency measures can be used to evaluate PV-battery systems. In applications where both solar and non-renewable energy are used as input energy to the PV-battery system, the energy return factor and the overall battery efficiency can be combined in order to make trade offs between competing interests.

In cases where the focus is on using fossil fuels efficiently, a high energy return factor is important. This measure may be important in the expansion phase of PV-battery systems. PV-battery systems with similar energy return factors (e.g. ZnBr and Li-ion, see Fig. 10) may have different overall battery efficiencies. In the case of battery systems being charged with electricity generated from fossil fuel, the direct and overall battery efficiencies are important measures. If the electricity is produced from solar energy and the solar electricity is considered as a free unlimited energy source, overall energy efficiency is a less important measure. However, it is an important measure of the efficiency of a closed renewable system, where renewable energy has to be used as efficiently as possible, for example due to a limited area for energy production [19].

For any analysis, it is important to consider the context with regard to (1) operating conditions (illustrated by our five cases), (2) what resource use that should be minimised (illustrated by the comparison between the energy return factor and the overall efficiency) and (3) the larger energy system the studied system is a part of (illustrated by the comparisons between the energy exchange and All PV assumptions and between different alternative systems for providing the functional unit, i.e. between a Diesel generator or a grid extension with centralised power production).

Assuming that the world's PV systems have to produce their own energy for manufacture, Lysen and Daey Ouwens [20] estimated that the first world wide net kW h on an annual basis was produced in 2002 and on a cumulative energy basis this will occur in 2007. To realise that PV and PV-battery systems will contribute to a renewable energy system, it is important to focus on improving the energy efficiency of all components of the energy system. Calculation of energy return factors and overall battery efficiencies can be used to monitor the development of energy technologies and identify areas for improvement.

7. Conclusions

Energy return factors and the overall battery efficiencies were estimated for eight different battery technologies used in a stand alone PV-battery system. With a battery energy storage capacity three times higher than the daily energy output, the energy return factor for the PV-battery system ranges from 2.2 to 10 in our reference case. In extreme cases, energy return factors below one occur, implying no net energy output.

In the reference case, production and transport of batteries contribute 24–70% to the indirect gross energy requirement. The contribution of production and transport of the PV array is 26–68% depending on the battery technology used. For a PV-battery system with a service life of 30 yr, this corresponds to an energy payback times between 2.5 and 13 yr. The energy payback time is 1.8–3.3 yr for the PV array and 0.72–10 yr for the battery, showing the energy related significance of batteries and the large variation between different technologies.

The direct energy efficiency of the battery system (charger, battery and inverter) is 0.50–0.85. When considering the overall battery efficiency for the energy exchange assumption, including the production and transport of charger, battery and inverter, the values are 0.41 and 0.80 for the different battery technologies.

The overall battery efficiency is most sensitive to changes of the charge–discharge efficiency. For batteries with relatively low energy requirements for production and transportation (Li-ion, NaS, VRB, ZnBr, PSB), this parameter is also most important for the energy return factor. Service life, gravimetric energy density and energy for battery production are of greater importance for NiCd, NiMH and PbA batteries.

Not only the ranking order of battery parameters but also the ranking order of batteries in terms of energy efficiency and the optimal system design and operation (e.g. the use of AC) are in many cases dependent on the type of energy efficiency measure that is used and the characterisation of the larger energy system the studied PV-battery system is a part of. For any analysis, it is important to characterise and be clear about the context with regard to operating conditions, what resource use should be minimised, alternative technologies and the character of the general energy system.

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