Including grid storage to increase the use of renewables – the case of an island in the North sea

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Abstract: Utilization of renewable energy supply is limited by fluctuations and lack of alignment with demand. Including storage technology in the grid can increase self-consumption of renewable energy in local applications as well as reduce peaks in supply and demand for local low voltage grids with a high share of renewable energy input. The project NETfficient, funded by the European Union under the Grant Agreement 646463, explores requirements and effects of storage solutions in a grid on different levels. On the island of Borkum in the North Sea, a variety of grid-connected use cases is installed and tested in pilot studies. This paper focusses on homes equipped with photovoltaic panels for harvesting energy and two different storage solutions. The research addresses the resource demand and emissions due to novel components and the potential to decrease resource demand during the use phase, applying a life cycle perspective for components and systems. Data from the project as well as from LCA databases are collected and used to calculate environmental impacts for three different systems or applications: Stand alone photovoltaic (PV) panels, PV panels and customized Li-Ion-batteries and PV panels with a disused Li-Ion battery from an electric vehicle. The results indicate that the customized or dedicated Li-Ion battery in combination with PV panels have a larger climate impact avoidance than the other systems.

1. Introduction

Utilization of renewable energy supply is limited by fluctuations and lack of alignment with demand. As an example, according to German renewable energy sources act [1] PV systems in low voltage grids have to be equipped with feed-in management or capped to 70% of the maximum capacity to avoid local peaks. This paper is about how to evaluate the environmental pros and cons of using storage systems in electrical grids with a high share of renewable energy input. As part of the EU-funded NETfficient project, several grid storage technologies have been investigated, e.g., batteries, hydrogen/fuel cell storage, heat storage in an aquarium and hybrid storage involving batteries and capacitors, on the island of Borkum. While the principal discussions and conclusions should be applicable for all grid storage technologies, this paper concerns storage of solar power in a 2nd life traction battery and in a dedicated lithium ion battery pack at the end of the grid. By end of grid is meant that the electrical storage system (ESS) and photovoltaic panels (PV) are used in a local low-voltage system. Thus the primary service or function of the ESS is to store the PV energy when it cannot be utilized by the end-user, thus increasing the use of the PV generated electricity and simultaneously decreasing use of marginal electricity. The stored PV energy may also be used for peak-shaving, load-leveling etc., thus possibly also resulting in a smaller or same dimension grid with a higher amount of renewable energy sources.

2. METHODOLOGY

Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave, i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Environmental impacts arise from emissions to air, water and soil as well as from consumption of resources to provide both energy and material, in the different stages of the life cycle. Oftentimes an LCA is performed as a comparative study to evaluate different options to serve a purpose. A core aim is therefore to get a fair and comparable evaluation of the environmental performance of a product (both services and goods can be assessed). The life cycle perspective is essential in order to avoid sub-optimization, which can occur when only parts of the life cycle are studied and the overall performance is not evaluated.

To facilitate the comparability of the results of a study, a clear definition of the functional unit used has to be delivered. The functional unit is derived from the purpose of (or service provided by) the evaluated system and describes the basis for the calculation.

Another important LCA concept that facilitates comparability is that of using similar system boundaries for the compared options. The system boundary describes what has been included in the assessment and what has not. It is important that the setting of the system boundaries follows the same principle when two products are compared with each other.

The life cycle assessment in this paper is performed in accordance with ISO 14040 and 14044 [2] and the ILCD Handbook [3]. LCA according to ISO 14040 and 14044 consists of four stages: Goal and scope definition, inventory, impact assessment and interpretation. The stages are often performed in an iterative way that gradually refines the assessment. None of the stages are unique to the LCA methodology. What makes LCA unique is that all (or as many as possible/relevant) life cycle phases of the analyzed object are considered.

Functional unit(s)

The fundamental functional unit of the study is a 4 kW Photovoltaic solar energy system operating for 30 years (with and without electrical storage) and delivering renewable electricity that replaces grid mix electricity. Other studies of ESS [5,6] use delivered energy by the storage system as functional unit, which is similar but not the same as in this study.

System boundary

The system boundaries of the three studied systems are shown below. The two PV systems including ESS are compared with each other and with a stand-alone PV system.

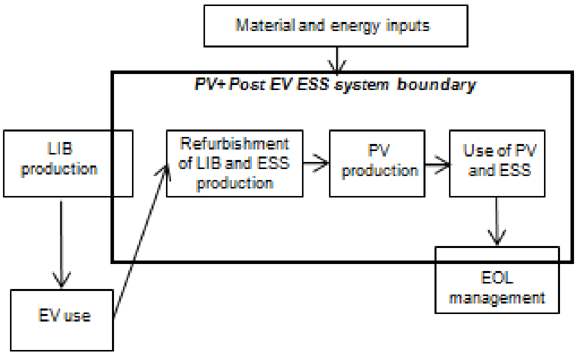

Figure 1System boundary for PV system including stationary storage in post EV battery

As can be seen from Figure 1, the post EV system involves decisions on how to share production and end-of-life, EOL, burdens between the electric vehicle and the stationary storage life cycles.

All systems have the same function, namely to store and deliver renewable energy, thus avoiding the burdens of the grid mix electricity.

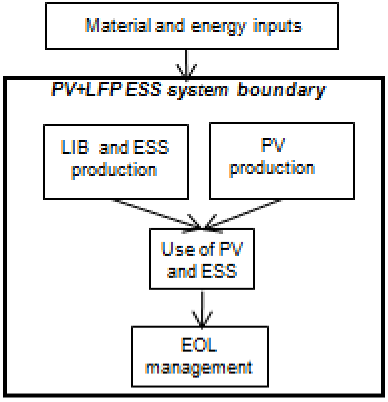

Figure 2 System boundary for PV system including stationary storage in LFP battery

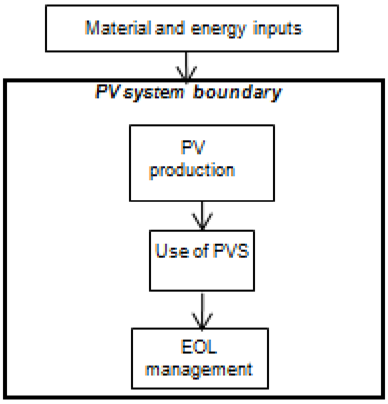

Figure 3System boundary for stand-alone PV system

Specific data from NETfficient's partners was used to some extent, but complemented with information based on generic data from existing databases for LCA. The data modules generally represent global or European averages. In particular, data has been taken from the commercial database Ecoinvent 3.4 [7]. For the system modelling and calculations, SimaPro 8.5.0.0 from Pré consultants was used.

Life cycle impact assessment

A wide variety of environmental aspects can be considered within an LCA, to analyse whether reduction of emissions causes shifting of burden between compartments, e.g. a reduced pollution of freshwater might be related to increased pollution of soil.

For the current study, resource demand and emissions of carbon dioxide were prioritized in the impact assessment, because the envisaged reduction of climate impacts can only be realised by adding components to the system. The indicator that will be used in this paper is global warming potential (GWP) expressed in kg CO_2 eq. according to [8]. Additional calculations for abiotic resource depletion and cumulative energy demand were calculated within the NETfficient project and showed similar results.

3. DATA AND CALCULATIONS

ESS based on batteries is eligible for subsidies according to German legislation [1] if it can limit the feed in power of a PV system to 50% of the maximum and thereby reduce peaks and variations that are typical for renewable energy sources. The scientific evaluation program for ESS in German electrical grids issues annual reports on monitoring results [9] and indicates that ESS allows a higher amount of renewable energy sources in local distribution grids without increasing grid capacity. The intake capacity of distribution grids is doubled by suitable ESS without further adaptation of infrastructure. The benefit of ESS for grids is acknowledged, however not quantified. For the evaluation in this paper, only the immediate system is considered: PV systems in low voltage grids are equipped with feed-in management to reduce local peaks that otherwise could lead to variation in voltage and subsequently damages to grids [9]. Therefore PV capacity cannot be fully used without storage; options are to install a feed-in management system or as a simpler solution for smaller units to cap the performance at 70% of the maximum capacity [1]. Thus, in the current paper the stand-alone PV system (i.e. stand-alone in the sense of not having a connected ESS) is assumed to use 70% of its harvested solar energy, minus 10% transformation losses, while the PV+ESS systems are assumed to use 100% of harvested solar energy minus 20%. charge/discharge losses, in the base case. The used solar energy is assumed to replace and thus avoid current German grid mix electricity. Additional effects of the systems for the grid (extended life length of transformers, avoided infrastructure components etc) potentially increase benefits but these are not quantified.

In the Borkum case, 24.8 m^2 PV panel per house was installed with a capacity of 6.12 m^2/kW, thus each house has 24.8/6.12=4 kW installed power. A suitable ESS has a storage capacity smaller or equal to the installed PV power [9], which in our case is 4 kW.

A PVGIS calculation tool provided by the EU Joint Research Centre [10] indicates that 4 kW PV gives around 4000 kWh on Borkum. With an ESS, instead of using 70% of 4000 minus 10% losses, i.e. 2520 kWh, 100% of 4000 minus 20%, i.e. 3200 kWh of grid mix electricity will be avoided annually thanks to the PV+ESS system.

Post EV battery

This case involves secondary usage of a Nissan LEAF 24 kWh battery with a remaining charge capacity of 18 kWh, i.e. well above the installed PV power 4 kW.

Refurbishment in this case involves putting the 294 kg battery in a 160 kg box (of aluminium and stainless steel) together with more than 40 kg electronic equipment and cables including an inverter.

The expected life time of the second use of the battery is unknown. An earlier study involving a Nissan LEAF battery indicates that there would be approximately 4416 kWh remaining storage capacity left in the battery [11] after 200000 km in a Nissan LEAF. Since we have an ESS, it is assumed that all the harvested solar power, i.e. 4000 kWh, minus 20% losses, will be used and thus replacing grid electricity. [9] indicates that PV systems without ESS has at least 40% self-utilization of harvested energy, thus only 60% of 4000 needs storage, i.e. 2400. Thus the post EV battery would last 4416/2400=1.8 years. Since the PV system is expected to last 30 years; 30/1.8= 16 batteries are needed to sustain the 30 years. Since the "refurbishing" box is a very solid construction it is in the base case assumed to be exchanged every second time the battery is changed, i.e. 8 boxes are needed for the whole 30 year life cycle. The LIB production data emanates from the same study [11]. With reference to Figure 1and Figure 4, as a base case, the LIB production is allocated to the EV use, while the EOL is allocated to the secondary stationary storage use.

LiFePO4 battery

The LiFePO4, or LFP, battery production was modelled from a bill of materials received from the manufacturer in combination with data from [11 and 12].

The investigated LFP battery has a nominal capacity of 5.1 kWh i.e. just above the installed PV power 4 kW. Assuming a depth of discharge of 65% that can store and deliver 2400 kWh annually, the maximum number of cycles can be calculated to $1331*65^{-1.825}$ = 2900 cycles according to [13]. This equals 2900*0.65*5.1= 9613 kWh stored and delivered, indicating a life expectancy of 9613/2400= four years, thus 30/4=8 batteries during total life cycle of the system.

Break-even

In addition to presenting the results per delivered kWh, break-even is calculated as the number of years the system needs to operate in order to save climate impact from the avoidance of grid mix electricity burdens equal to the climate impact from production of the systems.

5. RESULTS AND DISCUSSION

The results are summarized in Table 1.

Table 1 Result parameters for 4 kW PV solar energy system operating for 30 years delivering renewable electricity that replaces grid mix electricity

Parameter	Unit	PV+post EV ESS	PV+LFP ESS	PV
Delivered kWh electricity	kWh	96000	96000	75600
Climate avoidance	kg CO2 eq	-25273	-46306	-43315
Climate avoidance	kg CO2 eq/kWh	-0,26	-0,48	-0,57
Break-even	years	18	8	4

PV + post EV ESS

The figure below shows the life cycle climate impacts for the base case PV+post EV ESS.

Only blue bars are summed up in *Total PV+ESS* amounting to -25273 kg CO_2eq. LIB production and EV use of LIB are not included in the base case. The break-even for the PV+post EV ESS system is 18.0 years

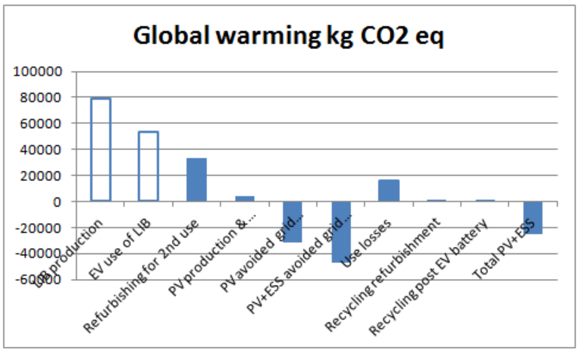

Figure 4Life cycle climate impacts for the PV + post EV ESS system

The PV+post EV system thus avoids 25273 kg CO_2eq during its 30 year of life. Reuse of the 200 kg of refurbishing, at least once, is very feasible. This means that the Refurbishing is shared between two ESS and thus halved per one ESS, see Figure 2, resulting in -0.26 kg CO_2eq/kWh delivered by the system.

PV+LFP ESS system

The figure below shows the life cycle climate impacts for the base case LFP battery used as stationary storage.

All bars are summed up in *Total PV+ESS base case* amounting to -46306 kg CO_2eq. The break-even for the PV+LFP ESS system is 8 years.

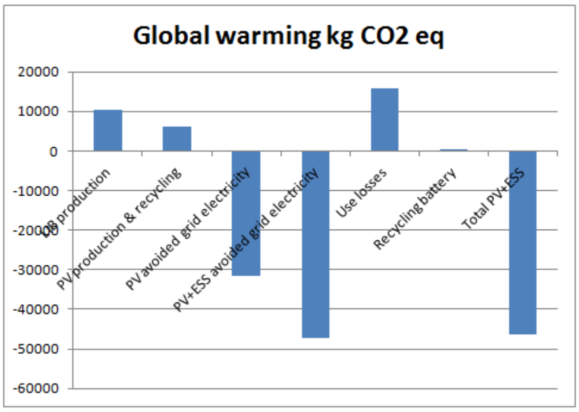

Figure 5Life cycle climate impacts for PV+5.1 kWh LFP battery used as stationary storage

PV alone

The figure below shows the life cycle climate impacts for the PV system without any ESS. The life cycle climate savings amount to -43315 kg CO_2eq. The break-even for the stand alone PV system is 4 years.

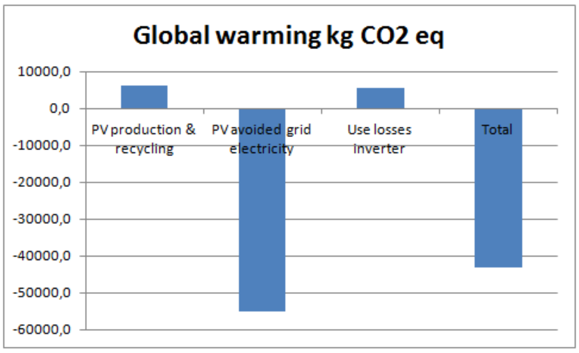

Figure 6 Life cycle climate impacts for the PV system

Comparison between systems

Figure 7 and Table 1 compares the life cycle climate savings of the three systems. It can be seen that the PV+LFP ESS system avoids slightly more climate impact than the PV stand alone system, while the PV+post EV system avoids considerably less. Climate break-even is considerably less for the stand-alone PV system and the post EV ESS system needs more than twice the time to break-even compared to the LFP ESS system.

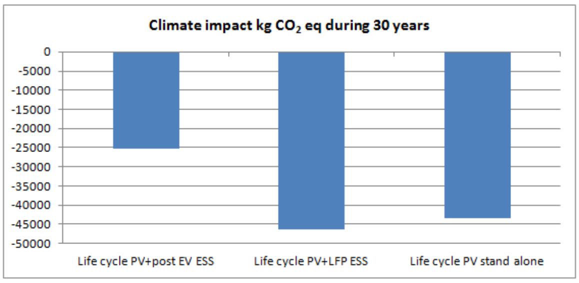

Figure 7Life cycle climate impacts of three different PV systems

Sensitivity and robustness of results

Sensitivity calculations with other grid mixes are not carried out as such. The German grid mix electricity used has a climate impact of 656 g CO_2eq /kWh. It is easy to grasp that doubling fossil fuels in the grid mix, like in China, would more or less double the climate impact avoidance of the systems. In countries with average share of fossil fuels in the grid mix, the marginal electricity is often around 600 g CO_2eq /kWh, e.g. electricity from natural gas. Thus it could be argued that the investigated systems would have a similar climate impact avoidance potential in those countries.

6. CONCLUSIONS

The results indicate that:

- ESS for stationary storage of solar power can potentially avoid more climate impact than stand-alone solar power systems.
- Post EV ESS may not be as attractive as dedicated ESS from a climate perspective. However, current results are based on pilot equipment that was designed to show feasibility of the concept and not optimised. As an initial reflection of the results so far, environmental impacts can be reduced when the design is simplified or alternatively when the very robust casing system is used for several batteries sequentially.

8. REFERENCES

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ABBREVIATIONS USED

CO_2eq	Carbon dioxide equivalents
EOL	End-of-life
ESS	Electric storage system
EV	Electric vehicle
kW	Kilowatt
kWh	Kilowatthour
LCA	Life Cycle Assessment
LFP	Lithium iron Phosphate
LIB	Lithium Ion battery
PV	Photovoltaic panel