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Financial analysis of utility scale photovoltaic plants with battery energy storage

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HIGHLIGHTS

- Generation shifting with batteries allows PV projects to generate additional revenues.
- Battery lifetime, lifecycles and price are less relevant than electricity market prices.
- Installed battery capacity of up to 50% of the daily PV energy boosts project economy.
- A 25% higher premium for energy storage could improve NPV by approximately 65%.

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ABSTRACT

Battery energy storage is a flexible and responsive form of storing electrical energy from Renewable generation. The need for energy storage mainly stems from the intermittent nature of solar and wind energy sources. System integrators are investigating ways to design plants that can provide more stable output power without compromising the financial performance that is vital for investors. Network operators on the other side set stringent requirements for the commissioning of new generation, including preferential terms for energy providers with a well-defined generation profile. The aim of this work is to highlight the market and technology drivers that impact the feasibility of battery energy storage in a Utility-scale solar PV project. A simulation tool combines a battery cycling and lifetime model with a solar generation profile and electricity market prices. The business cases of the present market conditions and a projected future scenario are analyzed.

1. Introduction

Solar energy generation has increased rapidly within the last years. In 2011 solar Photovoltaic (PV) has become the number one finisher of new installations, overtaking all other forms of energy sources. PV cumulates worldwide a total capacity of 68 GW and has increased by around 70% (28 GW), in 2011 (EPIA, 2011). Approximately 21 GW of the annual growth took place on the European continent indicating the political and entrepreneurial commitment towards the 20% target share of renewable energy at the final energy consumption by the year 2020 (EREC, 2008).

The strong growth of PV has been supported by an increase of PV production and silicon supply capabilities (Jäger-Waldau et al., 2012). This trend has been strengthened by a rapid decrease in silicon price from around 500 $/kg in 2008 to around 50–55 $/kg in 2009 and only a minor increase at the beginning of 2011 (Jäger-Waldau et al., 2012). This development has led to a decrease in PV prices and an additional wave of new installations throughout the world. Despite the economic crisis, which has affected several markets, PV production facilities were expanded in 2011 and forecasts predict this development to go on, mainly driven by asian production facilities (Jäger-Waldau et al., 2012).

The decrease in PV prices has triggered the interest of private investors, leading gradually to a shift from small scale (< 200 kW) to Utility-scale (multi-megawatt) installations. More specifically, in 1995, the majority of new PV plants were small scale, designed for domestic rooftop applications. Only 3% were large scale, providing more than 500 kW peak power (Solarpraxis, 2010). The ratio of large scale installations had further increased from 21.1% in 2008 to 47.5% in 2010 (Solarpraxis, 2011).

The transition from residential to Utility-scale PV generation puts more stress on energy storage technologies that may help to overcome the intermittency of renewable sources. Energy Storage Systems may also be used to shift electricity to times when it is most needed in a way that decouples the generation profile from the consumption profile. The possible use of energy storage systems may, therefore, be grouped in the following three operational scenarios:

- The **Generation Shifting** aims to balance power generation with power demand over a period of time. In doing so in a market with variable energy tariffs it maximizes the revenues

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by charging the energy storage elements during periods of a low energy price and discharging it to the grid during periods of a high energy price to generate additional revenues.

- The **Intermittency Mitigation** on the other hand is driven by grid stability requirements. It stabilizes the adjacent grid by matching the supply demand situation of electricity. The energy storage system stores electricity when the adjacent grid's power lines are operating close to their power rating and is releasing the energy when they are not sufficiently utilized.
- The **Baseload Generation** uses stored electricity to provide constant supply 24 h a day. It could be used to electrify remote areas.

The *generation shifting* scenario is expected to be the first widespread application of energy storage systems as it is the one that may potentially generate additional revenues in a PV project. Hence, this work focuses on Generation Shifting and investigates its economical viability in the present and future electricity markets.

2. Battery energy storage systems

During the process of identifying suitable Energy Storage technologies for Generation Shifting a number of requirements have been identified (Beltram et al., 2011)

- The Energy Storage System should be constructible in the vicinity of the PV plant;
- It should respond fast to sufficiently exploit spot market changes;
- It needs to be able to execute shifting cycles within the range of few minutes to some hours;
- It should offer a long lifetime and maintenance ease;
- Power and capacity should be freely scalable and dimensioned in regard to the PV plant; and
- The used technology should be mature.

2.1. Battery technologies

Batteries are identified as a suitable means of energy storage for power systems in regard to the mentioned requirements. They store energy by converting electrical energy into chemical through a chemical reaction (Li and Ke , 2011). Energy can be stored for a period of time and can be released when required by means of a conversion of chemical energy to a voltage potential across the positive and the negative electrodes that lie in the battery electrolyte. The classification of the battery technologies is based mainly on the electrolyte material that translates to specific battery properties. The most prominent technologies used in power system projects are

- Lead Acid batteries,
- Natrium sulfide (NaS) batteries,
- Lithium ion (Li-Ion) batteries.

Table 1 summarizes the battery properties that are most important for the operation with a PV plant. It can be seen that Li-Ion has the highest cost per stored kWh but also has the highest energy density of all technologies. The power yield capability of Lead-Acid and Li-Ion battery cells may be comparable whereas that of the NaS battery is approximately 20 times lower per unit of weight.

In Generation Shifting the operators transfer bulk amounts of energy in short time intervals. This calls for high power modules to be used. The evaluated 3 MW plant design in this paper has been investigated using NaS and Li-Ion batteries. The evaluation was performed using the model described in the following sections and the results indicated that NaS batteries generated approximately 3 times less revenue than the Li-ion system of identical storage capacity. In the evaluation described in the following sections of this paper, NaS batteries added 42% lower NPV value to the project when compared to Li-Ion. It is expected that NaS batteries would perform better in the Baseload Generation scenario where energy density is of key importance rather than power density. Li-Ion is further analysed in the following sections of this paper.

Table 1
Comparison of key battery properties (Mahnke and Mühlenho , 2012; Mauch et al., 2009; Bito, 2005; Foote et al., 2005).

Properties	Battery type		
	Lead-Acid	NaS	Li-Ion
Cost/kWh	€25–250	€220	€1500
Energy density (Wh/kg)	25–40	103	240
Power density (W/kg)	75–300	14	350
Lifetime (year)	12	15	20
	1000 #[a]	2500 #[a]	> 1000 #[a]
Operating temperature (°C)	< 100	300	< 100

[a] Number of charge-discharge cycles at a depth of discharge of 100%.

2.2. Battery lifetime prediction

One of the main requirements for a PV plant and consequently for a PV plant with Battery Energy Storage is to maximize its time of operation as this is directly linked to the energy yield and the gained revenues. Unnecessary outages of either the PV plant or the Battery Energy Storage System (BESS) infrastructure should be avoided. Thus, a key requirement for a sound business case is a reliable forecast of the *end of lifetime* (EoL) of the battery modules. In general, the EoL of a module has been reached when its capacity falls below 80% of its initial value (Nickoletatos and Tselepis, 2003).

The actual decrease of the battery capacity can be caused by two processes: the cycling (charging–discharging) and the battery material ageing. Each battery may therefore serve a maximum number of cycles that heavily depends on the mode of cycling or the used profile. This is called the *cycle lifetime* and is measured in number of cycles. The ageing process is independent from the actual operation of the battery and is therefore well defined by laboratory tests for each battery type. It is often called the *calendar lifetime* and is measured in calendar years.

As a consequence, the challenging part of the lifetime forecast is to calculate the time, when the battery has reached its cycle lifetime and should be replaced to ensure a proper operation of the PV plant with BESS. Due to the fact that the life-cycles are depended on several factors, such as the ambient temperature, the cycle depth, the duration of shifting cycles and the power level, it is difficult to accurately forecast the EoL (Sauer and Wenzl, 2008).

Several approaches exist for forecasting the EoL of a battery system, e.g. the physico-chemical ageing model, the weighted Ah ageing model or the event-oriented ageing model (Sauer and Wenzl, 2008).

The event oriented ageing model has been chosen as it relates the cycle lifetime directly with battery usage patterns that are a key input to this research. The foundation of this approach is that each event that effects the battery contributes to a small loss of lifetime. By summing all these events in a defined time framework the cumulated loss of lifetime can be calculated and the EoL can be