Abstract

With rising electricity costs, increasing environmental awareness and aggravating legal requirements, production plants demand innovations in the field of energy efficiency and utilization of renewable energies. Here we perform a techno-economical assessment of photovoltaic-battery storage systems for industrial peak-shaving and self-consumption applications. In order to consider individual load profiles, different battery types, aging mechanisms, varying costs for electricity and storage capacity, a simulation tool was developed. Net present value method was applied to evaluate the costs over the systems’ service life. The case study shows positive net present values for system configurations with large photovoltaic systems compared to storage capacity.

1. Introduction

Nowadays, the transformation towards a green energy supply system is one of the greatest political, economic and societal challenges. Especially in countries with high electricity costs production plants are struggling with rising fees that are endangering their profitability. In Germany industrial customers with an electrical energy consumption of more than 100 MWh per year are paying up to 0.15 € per kWh. Additionally, major consumers have to pay a demand charge for the peak power they use. Their load profile is highly volatile due to starting of production lines, starting torque of auxiliary drives, machine failure or changing workload during shifts [1]. Demand charge typically ranges from 5 to 15 € per kW and month, depending on the peak power utilities have to keep in reserve [2]. Consequently, electricity costs for industrial customers can not only be reduced by saving energy but also by lowering peak power demand, e.g. with intelligent peak load management. To ensure technical feasibility, ecologic sustainability and most important economic efficiency practical design methods for renewable peak-shaving and self-consumption applications need to be developed and evaluated.

Neugebauer [1] proposes photovoltaic systems for industrial peak-shaving applications. Direct self-consumption of solar energy can reduce power demand to a certain degree in case of matching load and production profiles. Thus electricity costs for the industrial consumer can be reduced.

Oudalov et al. [2, 3], Leadbetter and Swan [4], Johnson et al. [5] and Even et al. [6] present grid-connected battery storage systems for peak-shaving. In times of low energy demand batteries can be charged. During peak load demand the power supply from the grid can be reduced by discharging the batteries. As a result the grid can be relieved and demand
charges for the industrial customer can be lowered. Johnson et al. [5] note that in this case the total energy demand for production plants increases due to conversion losses.

Schanz et al. [7] state that profitability of photovoltaic systems can be raised with increased self-consumption. For optimization of self-consumption Neugebauer [1] proposes hybrid photovoltaic-battery-storage systems. Peak-Shaving is also possible with these systems. Bortolini et al. [8], Giraud and Salameh [9], Berrada and Loudiyi [10], Kaabeche and Ibtiouen [11] show that the integration of one or more power generating systems with energy storage increases reliability and profitability of renewable technologies.

In this paper, two scenarios for industrial peak-shaving and self-consumption applications will be presented: (1) integration of photovoltaic (PV) and battery energy storage system (BES) for industrial peak-shaving and (2) self-consumption applications. To perform a techno-economical assessment of industrial peak-shaving and self-consumption applications a simulation tool was developed and individual load profiles, different battery types, aging mechanisms, varying costs for electricity and storage capacity were considered. To evaluate the costs over the systems’ service life net present value (NPV) method was applied. Finally, a case study was analyzed to compare exemplary system configurations.

### 2. Methods

At first, NPV is presented as economic criterion for optimal sizing followed by a description of the PV-BES model.

#### 2.1. NPV: economic criterion for optimal sizing

In practice, economic profitability represents the key factor when it comes to investment decisions. Besides technical and ecological conditions economic profitability is considered to answer the following questions: (1) Does it make economic sense to invest in a project? The money required could be used for alternative projects. (2) Which investment opportunity should be chosen? Economic benefits of different investment alternatives can be rated [12,13]. Based on a dynamic evaluation of economic efficiency revenues and expenditures over the service life of PV-BES systems can be considered. Accumulation and discount factors are used to compare future cash flows in relation to a reference time [14,15,16]. Therefore, NPV method is applied in this work to rate system configurations and to determine optimal sizing of the components PV and BES system. Maximum NPV\(_\text{max}\) is determined for definition of optimal sizing according to [13]:

\[
NPV_{\text{max}} = \max \left[ -A_0 + \sum_{t=1}^{T} \frac{Z_t}{q} \right] \tag{1}
\]

Where \(A_0\) represents initial investment costs, \(T\) is planning horizon (e.g. 20 years), \(Z\) is cash flow at time \(t\) and discount factor \(q\).

#### 2.1.1. Costs

Planning horizon for NPV method is 20 years according to the average useful life of PV plants [17]. BES systems with average useful life less than 20 years will be replaced at end of life and the replacement investment will be considered as negative cash flow in the economic analysis. Investment costs for PV-BES systems \((A_{0,\text{PV}})\) consist of installed peak power \((P_{\text{pk}})\) and specific costs per kW \((c_{\text{kw}})\) [18,19]:

\[
A_{0,\text{PV}} = P_{\text{pk}} \cdot c_{\text{kw}} \tag{2}
\]

BES system investment costs \((A_{0,B})\) can be calculated from the sum of capacity \((C_B)\) and discharging power \((P_{\text{dis}})\) related costs multiplied by specific costs per kWh \((c_{\text{kw}})\) and kW \((c_{\text{kw}})\) respectively [20]:

### Nomenclature

- \(A_0\) initial investment costs (€)
- \(A_{0,B}\) investment costs for battery energy system (€)
- \(A_{0,\text{PV}}\) investment costs for photovoltaic system (€)
- \(AC\) alternating current
- \(BES\) battery energy storage
- \(BMS\) battery management system
- \(C_B\) battery storage capacity (kWh)
- \(c_{\text{dm}}\) revenues from direct marketing (€/kWh)
- \(c_{\text{el}}\) costs of electrical energy from public grid (€/kWh)
- \(c_{\text{ew}}\) specific costs per kW discharging power (€/kW)
- \(c_{\text{eh}}\) specific costs per kWh of storage capacity (€/kWh)
- \(c_{\text{ew,p}}\) specific costs per kWp installed peak power (€/kWp)
- \(c_p\) demand charge for electrical power (€/kW)
- \(d\) self discharge rate (%/(15 min))
- \(DC\) direct current
- \(E_0\) irradiance at standard test conditions (W/mp²)
- \(G\) global radiation on tilted surface (kWh/mp²)
- \(NPV\) net present value (€)
- \(P_{\text{dis}}\) discharging power of battery energy system (kW)
- \(P_{\text{pk}}\) installed peak power (kWp)
- \(P_p\) peak-shaving (kW)
- \(PR_0\) performance ratio of photovoltaic cells (-)
- \(PV\) photovoltaic
- \(q\) discount factor (-)
- \(R\) revenues (€)
- \(S\) storage level (kWh)
- \(T\) planning horizon (a)
- \(t\) time (h)
- \(W_{\text{dis},\text{Grid}}\) energy supplied by the grid (kWh)
- \(W_{\text{load}}\) energy consumption (kWh)
- \(W_{\text{saved}}\) reduced electrical energy supplied by the grid (kWh)
- \(W_{\text{from Grid}}\) electrical energy fed to the public grid (kWh)
- \(Z\) cash flow (€)
- \(\eta_{\text{DC/DC}}\) battery dis-/charging efficiency (-)
- \(\eta_{\text{DC/DC}}\) DC/DC-inverter efficiency (-)
- \(\eta_{\text{inv}}\) inverter efficiency (-)
2.1.2. Revenues

No liquidation proceeds are assumed after an average useful life of 20 years. Moreover, no state subsidies are granted. Thus, revenues are generated by direct marketing of excess renewable electricity \( W_{\text{toGrid}} \) (\( c_{\text{dm}} = 0.038 \) €/kWh, no inflation) and savings due to a reduction of electricity purchased from the public grid \( W_{\text{saved}} \) (\( c_{\text{el}} = 0.1375 \) €/kWh, annual inflation rate 3.99 %). The latter results from self-consumption. Additionally, peak-shaving lowers demand charge fees for industrial consumers \( P_{\text{max}} - P_{\text{ps}} \) (\( c_{\text{p}} = 6.43 \) €/kW per month) reducing peak power consumption from the public grid. These reductions in electricity use are booked as fictitious revenues in the NPV method [22]. Annual fictitious revenues (\( R \)) can be calculated according to Eq. 4:

\[
R = W_{\text{toGrid}} \cdot c_{\text{dm}} + W_{\text{saved}} \cdot c_{\text{el}} + (P_{\text{max}} - P_{\text{ps}}) \cdot c_{\text{p}}
\]  

(4)

2.2. Photovoltaic battery energy storage system modeling: grid-connected system for peak-shaving and self-consumption applications

At first, a description of the structure of the simulation program is given. Following, fundamental assumptions and the system configuration including control strategies are presented.

2.2.1. Structure of simulation model

The Microsoft Excel© integrated development environment Visual Basic for Applications© was used for techno-economical simulation of PV-BES systems for industrial peak-shaving and self-consumption applications. The procedure is organized as follows:

1. Definition of time resolution: Typically 15-minute time steps are chosen (corresponds to the load profile provided by utility companies).

2. Input: Electrical load profile in kW and profile of global radiation on a tilted surface in W/m² for one year have to be entered. Additional inputs are technical and economical parameters of the corresponding PV-BES technologies, e.g. available roof area for PV plant, orientation of building, allowed depth-of-discharge of BES, cyclical/calendrical aging of BES, costs for system components etc.

3. Simulation of an average useful life of 20 years including technical and economic aspects. For system sizing an iterative approach is chosen to avoid oversizing and to guarantee operating ability with minimum component sizing over the useful life, e.g. in case of peak-shaving the storage capacity is increased until the PV-BES system can satisfy the requested peak-shaving task over the systems lifetime.

4. Variation of: height of peak-shaving, i.e. maximum allowed peak power demand from public grid, installed peak power of PV system, installed BES capacity for maximization of NPV. As a result, the combination of system components with the highest NPV can be identified.

5. Sensitivity analysis: E.g. variation of annual price increase for electricity and costs of PV and BES systems.

6. Output: PV-BES system configuration with maximum NPV.

2.2.2. Fundamental assumptions

Assumption 1: Perfect forecast of load and production profiles based on the past is assumed. Load is increased linearly per annum due to positive economic development (+2.5 %) whereas PV production regresses due to degradation of the PV modules (-1 %). Concluding, in case of peak-shaving a reference value can be defined. Therefore, maximum peak power demand from the production plant is identified from previous load profiles provided by the utility. The height of peak-shaving is defined. E.g. if peak power demand from the grid is 700 kW and a peak-shaving of 30 kW is analyzed the reference value is 670 kW.

Assumption 2: Perfect system control is assumed, i.e. no losses occur in the control system and the PV-BES system is controlled ideally depending on forecasts of supply and demand. Therefore, this marginal observation results in a maximum economic benefit of a default system configuration represented by the maximum NPV.

Assumption 3: The BES cannot be charged and discharged at the same time. Electricity consumption from the grid and feed-in of excess energy from the PV system cannot occur at the same time.
The PV-BES system consists of interconnected PV modules (referred to as PV system), DC/DC-inverter, battery management system (BMS), BES, DC/AC-inverter, electric load (W_{load}= e.g. load profile from utility) connected to the low-voltage grid with three phases. Standard-type monocrystalline silicon cells are considered.

The PV-BES system can be described with an energy balance to calculate energy supply from the public grid (W_{fromGrid}) when PV production is less than the energy load (W_{load}) or energy feed-in (W_{toGrid}) when PV production exceeds energy demand (see Eq. 5):

\[ W_{fromGrid} - W_{toGrid} = W_{load} - W_{el} + W_{ch} - W_{dis} \]  

Energy output from PV system (W_{el}) can be calculated from Eq. 6 [25]:

\[ W_{el} = \frac{P_{pk} \cdot G \cdot \eta_{DC} \cdot \eta_{inv}}{E_0} \]  

Where \( P_{pk} \) represents the installed peak power depending on the available roof area. \( G \) is the global radiation on a tilted surface (generated with meteonorm© software, \( \eta_{DC} \) is the performance ratio of the PV cell and \( \eta_{inv} \) is the DC/DC-inverter efficiency. DC/DC-inverter are used for maximum power point tracking of PV modules [26]. \( \eta_{inv} \) is the efficiency of the inverter unit and \( E_0 \) is the irradiance at standard test conditions. A recommended regressive annual degradation of PV electricity production of 1% is implemented in the model [24,28]. Meteonorm© software was used for generation of global radiation profiles on tilted surfaces.

Eq. 7 determines the BES level depending on the energy charged/discharged [27]:

\[ S = S_{t-1} \cdot (1-d) + W_{ch} \cdot \eta_{ch} - \frac{W_{dis}}{\eta_{dis}} \]  

In which \( S \) is the storage level at time \( t \), \( S_{t-1} \) is the storage level at time \( t-1 \) and \( d \) is the self-discharge rate. \( W_{ch} \) represents the energy that is added to the BES and \( W_{dis} \) is the energy that is discharged taking into account charging (\( \eta_{ch} \)) and discharging (\( \eta_{dis} \)) efficiencies respectively. In contrast to PV degradation, more complex ageing mechanisms for lead-acid, lithium-ion, sodium-sulphur and redox-flow BES systems were applied. Therefore, a combination of calendrical and cyclical aging of BES systems is implemented in the simulation based on literature values for definition of end of life and cycle stability [20,28,29]. Stress factors influencing battery life negatively, e.g. depth of discharge and number of charging/discharging cycles, thus can be analyzed [20]. Table 1 compares key values of the different battery types.

\[ \omega_{eb} \] is the battery depth of discharge (%), \( \varepsilon_{ch} \) is the charging efficiency of the battery and \( \varepsilon_{dis} \) is the discharging efficiency of the battery.

\[ \eta_{ch}, \eta_{dis} \] are the charging and discharging efficiencies of the battery.

Iteration is used to determine minimum BES capacity and discharge power required. Optimization criterion is maximum NPV.

System components for industrial peak-shaving and/or self-consumption applications are assumed to be identical, whereas control strategies differ significantly (see section below).

2.2.4. Control strategy for peak-shaving

As described in section 2.2.2 a reference value for mains supply is chosen. When load minus PV production exceeds the reference value BES system is discharged to ensure that power supply from the grid does not exceed the reference value. Further control strategies were implemented in the model: (1) BES system is kept at maximum storage level. The BES system is charged from the grid or PV production. (2) Power supply from the grid never exceeds the reference value.

2.2.5. Control strategy for self-consumption

To increase self-consumption a PV-BES system is implemented in the model. BES system is used to shift electricity produced by the PV system from periods of low load to peak load periods [1]. In contrast to peak-shaving applications in production plants the control strategy for self-consumption is prioritized as follows: (1) PV production is used to cover the load of the industrial consumer. (2) PV production is used to charge the BES system. (3) If PV production is greater than the sum of load and charging energy surplus electricity is fed into the grid for direct marketing. (4) In general, BES system is charged with excess power from the PV system (Exception: buffering from the grid is accepted when the storage level falls below a critical value to prevent battery damage).

2.2.6. Boundary conditions and simulation parameters

Simulation parameters and boundary conditions of the conducted case study are summarized in Table 2.
Table 2. Boundary conditions and simulation parameters of PV-BES system [19,25].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of time steps</td>
<td>35,040</td>
</tr>
<tr>
<td>Time interval</td>
<td>15 min</td>
</tr>
<tr>
<td>$P_{pk}$</td>
<td>202 – 545 kWp</td>
</tr>
<tr>
<td>$E_0$</td>
<td>1,000 W/m²</td>
</tr>
<tr>
<td>$PR_0$</td>
<td>0.84</td>
</tr>
<tr>
<td>$\eta_{inv}$</td>
<td>0.98</td>
</tr>
<tr>
<td>$\eta_{DC}$</td>
<td>1.00</td>
</tr>
<tr>
<td>$P_{ps}$ (only for peak-shaving)</td>
<td>10 – 100 kW</td>
</tr>
<tr>
<td>$C_B$ (only for self-consumption)</td>
<td>10 - 200 kWh</td>
</tr>
<tr>
<td>$c_{ckWp}$</td>
<td>1,199 €/kWp</td>
</tr>
</tbody>
</table>

3. Results and discussion

In the present case study PV-BES systems with monocrystalline solar cells and lead-acid, lithium-ion, sodium-sulphur and redox-flow BES system, respectively, for peak-shaving and self-consumption applications were simulated, as described in the previous section. An exemplary annual load profile was taken from a company of the metalworking industry: maximum peak power demand in 2014 is 700 kW, energy consumption is 3 GWh. Fig. 2 shows an example for a weekly load profile. Results can be summarized as follows:

3.1. NPV of PV-BES system for peak-shaving applications

Simulation of peak-shaving between 10 to 100 kW and installed PV peak power of 315 kW yields a maximum NPV of 65k € at 30 kW peak-shaving with lead-acid batteries. For lithium-ion, sodium-sulphur and redox-flow batteries the maximum NPV is 64k €, 58k € and 48k €, respectively, with a peak-shaving of 10 kW. A sharp increase of storage capacity required (30 to 250 kWh) for peak-shaving greater than 30, 52, 66 and 72 kW leads to negative NPV for redox-flow, sodium-sulphur, lithium-ion and lead-acid batteries, respectively (s. Fig. 3).

3.2. NPV of PV-BES system for self-consumption applications

Simulation of self-consumption with installed PV peak power of 202, 315, 430 and 545 kWp and lead-acid BES with storage capacities of 10 to 190 kWh yields a maximum NPV of 40k € at 545 kW and storage capacity of 10 kWh. NPV ranges between 27k € and 40k € for 202 to 545 kWp at 10 kWh storage capacity. (s. Fig. 4).

Rated self-consumption for 202 kW of installed peak power is 86 % (direct consumption of electricity from PV plant). Shifted discharging of the PV-BES with storage capacity of 190 kWh enables a rated self-consumption of 90 %. In comparison, rated self-consumption for 545 kW of installed peak power is 77 % (direct). Shifted discharging of the PV-BES system results in a rated self-consumption of 79 %. Therefore, it is obvious that high levels of direct consumption can only be increased moderately by implementation of expensive BES systems (s. Fig. 5).
Fig. 5. Rated self-consumption for PV-BES system with lead-acid batteries (direct/shifted with BES) depending on storage capacity and installed peak power.

4. Conclusion

Concluding it can be stated that optimal sized PV-BES systems for industrial peak shaving applications can result in positive NPV. Therefore, representing an economic viable investment without governmental subsidies. Moreover, benefits for grid stability should not be neglected.

In self-consumption applications with installed PV peak power up to approximately 2/3 of electrical peak load and high-rated solar coverage preferably PV systems without BES for direct self-consumption should be implemented.

Besides economic developments of PV-BES system and electricity costs, technological aspects are influencing investment decisions. In particular, battery ageing mechanisms. Over the service life of 20 years the simulated BES needs to be replaced one to three times.

Nevertheless, further studies should focus on a detailed sensitivity analysis of economic influences, detailed costs for system components, financial aspects (e.g. contracting, life-cycle assessment etc.) including multi-objective optimization. Additionally, implementing thermal applications, in the simulation model would enable an integrated analysis of energetic systems in industrial environment.

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References