PV-BATTERY AND DIESEL HYBRID SYSTEM FOR IRRIGATION OF A FARM IN PATAGONIA

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ABSTRACT: An existing off-grid irrigation system of a 12’000 ha farm in Patagonia today powered by electrical pumps and diesel gensets, will be extended by a PV plant and a battery system to improve ecological ratings of the products and reduce energy costs. An optimal photovoltaic plant and a battery energy storage system had to be designed. The compiled hourly demand profile served as input to a simulation model of a photovoltaic diesel battery hybrid system. With the given assumptions the PV array should be oriented to north at an inclination of 30°. The analysis of electricity cost indicated the optimal system size of 1800 kWp PV nominal power and 500 kWh of battery capacity. With this system 55.2% of the energy used for irrigation will be provided by the photovoltaic plant in the first year. The electricity cost amount to $0.136 per kWh electrical energy compared to the $0.432 per kWh electrical energy currently produced by the diesel-only system. Further analysis showed high dependency of the electricity cost on the time until connection to the utility grid and its electricity price and future diesel price.
Keywords: Off-Grid, Battery Storage and Control, Hybrid, Islanding, PV Pumping

1 INTRODUCTION

POMCO (Patagonia Organic Meat Company) owns a farm of 12’000 ha in Patagonia, Argentina where it develops fertile land along the Rio Negro river to cultivate different crops and cattle. These crops need artificial irrigation measures for optimal yield. The irrigation pumps have to be fed by means of off-grid solutions. POMCO installed a quantity of electrical water pumps which are connected to diesel generators, since the company expects a connection to the utility grid by 2022. These diesel generators are manually started when water pumping is required. With their goal to reduce diesel consumption and the runtime of the diesel engines POMCO aims to install a PV plant with battery storage hybrid system. The diesel generators will be centralized and a local grid will be installed in 2017. The PV plant, diesel generators and battery storage will go into operation in 2018 and will feed the irrigation pumps through this local grid. A central controller has to turn on/off the diesel generators according to power demand, State of Charge of the battery and solar irradiation.

The highest profit in terms of relation of investment costs and diesel savings is achieved by optimally dimensioning of the PV array and the battery. The main parameters which need to be determined are:

- Nominal DC-Power of PV Array [kWp]
- Azimuth and inclination of PV Array [°]
- Battery Capacity [kWh]
- Battery Inverter Power [kVA]

1.2 Approach

The software Polysun [1] was found to be best suited to simulate the system with the parameters mentioned before since it allows multiple PV arrays with different angles and azimuth. Furthermore it was found more straightforward to simulate multi-year scenario compared to the widely used software HOMER [2] or PVSyst [3].

After generating the demand profiles for the pumps a model of the hybrid system was created. Several simulations in Polysun and further analysis in Matlab provided a selection of system dimensions as a basis to decide upon the system design. Apart from technological feasibility also the economic viability was an important factor to optimize the system dimension.

While the hybrid energy generation means less diesel fuel consumption it also means relatively high investment costs. The cost of electrical energy as an average of the combination of diesel and PV electricity generation costs and the expected future price for energy bought from the utility served as the main indicator of system performance and economic viability.

2 SIMULATION PARAMETERS

In order to facilitate the simulation and due to constraints of the simulation software, model assumptions had to be made. The assumptions comprise the transformation of the demand profile as well as the simplification of the electrical performance of the diesel generators, battery inverter and control system.

2.1 Demand Profile

POMCO aims to develop new crop land year by year. With increasing crop land the demand for irrigation and thus electrical energy rises as well. Table I summarizes the planned peak power and the yearly energy demand for the next five years.

Table I: Planned peak power and yearly energy demand of the irrigation pumps for the next five years.

Year	Peak Power [kW]	Yearly Energy Demand [MWh]
2017	425	1253
2018	649	1842
2019	768	2384
2020	887	2987
2021	1024	3476

Due to lower temperatures and solar irradiation and thus lower evaporation in winter the irrigation demand is reduced from April to October. The energy demand from April to October makes up around 10% of the yearly energy demand (see Figure 1). The solar irradiance follows this demand profile perfectly (compare Figure 1 & Figure 2).

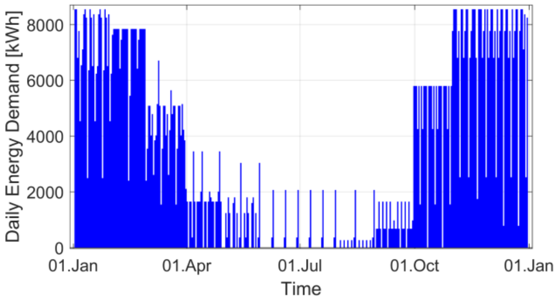

Figure 1: Daily sum of the energy demand of the irrigation pumps in kWh in 2017.

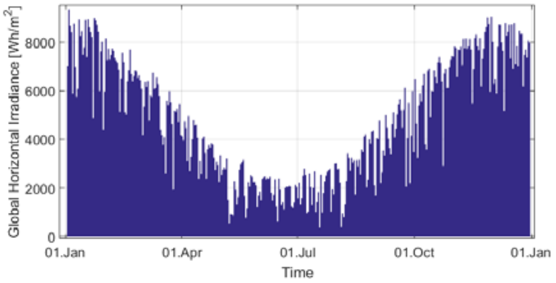

Figure 2: Daily sum of the global horizontal irradiance [Wh/m^2] as provided by the Meteonorm [4] profile of Neuquen (250 km North-West of the farm).

2.2 Simulation Model

The simulation software Polysun is a tool to primarily calculate energies of thermal and electrical components over a longer period (usually a whole year). Dynamic electrical phenomena and component transients in the duration range of a few miliseconds to a few minutes happening e.g. during the starting of a diesel generator or current harmonics are not the focus of the software. It also regards electrical components as purely resistive loads or sources. Consequently Polysun does not differentiate between apparent, reactive and real power. The power factor of the generators and pumps is not taken into account in the simulation. Polysun calculates only with active power. The demand profile is resolved in one-hour steps. This simplification leads to a neglection of peak power demands due to large inrush currents in the AC motors of the irrigation pumps.

The model behind the simulations in Polysun is illustrated in Figure 3.

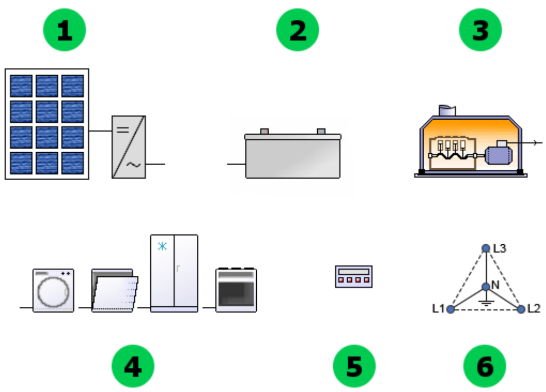

Figure 3: Schema of the model designed for the simulations in Polysun. Its components are: (1) PV Array and PV inverter, (2) Battery and Battery inverter, (3) Diesel Generator, (4) Load Profile, (5) programmable controller, (6) internal low-voltage grid.

The micro grid central controller (MGCC) is modelled by the programmable controller. A flow chart of the control logic is depicted in Figure 4. If the power demand of the irrigation pumps is lower than the power output of the PV array, the battery can be charged if not fully charged yet. On the other hand, if the power demand exceeds the current PV output, first the battery is discharged and after reaching a State of Charge (SOC) threshold of 33% the remaining power demand will be fed with the diesel gensets.

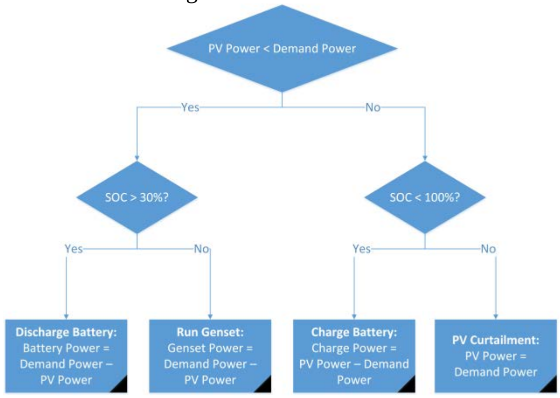

Figure 4: Flow chart of the control logic implemented in the Polysun model.

2.3 Electricity Cost

The common indicator for economic viability of renewable energy generation is the levelized cost of electricity (LCOE) [5][6]. Since the farm is expected to be connected to the utility grid, the LCOE does not represent the actual cost of electrical energy and the comparability to other renewable energy generation plants remains inaccurate. To get a more accurate approximation of the future electrical energy cost and also a more representative decision variable for investing, the weighted mean between LCOE and price of the energy supplied by the future utility grid was calculated:

$$ElectricityCost = \frac{I_{pv}+I_{batt}+I_{genset}+\sum_{t=1}^{20}\frac{M_t+F_t+E_{in,t}\times Pr_t}{(1+r)^t}}{\sum_{t=1}^{20}\frac{E_t}{(1+r)^t}}$$

Where:

I_{pv} : *CapEx of PV in the year t*

I_{batt} : *CapEx of Battery in the year t*

I_{genset}: *CapEx of Gensets in the year t*

M_t : *OpEx of PV, Battery and maintenance cost of Gensets in the year t*

F_t : Diesel fuel costs in the year t

$E_{in,t}$: Electrical energy fed into utility grid (negative) or supplied by the utility grid (positive)in the year t

Pr_t : Electrical energy price from utility in the year t

E_t : Total Electrical energy consumed in the year t

r : *Discount rate*

The following assumptions were made and were included in the calculation:

- Overall system life time of 20 years
- Replacement of battery after 10 years
- Replacement of Diesel Generators after 10 years
- Connection to utility grid in 2022
- Constant electrical energy price from utility (Pr_t) of \$0.05 per kWh
- Constant diesel fuel costs (F_t) of \$0.41 per kWh_{el}

- CapEx of $750.- per kWp for PV & BOS [7]
- CapEx of $1000.- per kWh for Battery, Battery inverter, MGCC, etc.
- CapEx of $370.- per kVA for Diesel Generators [8]
- OpEx of 2% of investment costs p.a. for PV and Battery
- Maintenance cost of 5% of investment costs p.a. for Diesel Gensets
- Constant discount rate (r) of 5% [9]

3 OPTIMAL SYSTEM DIMENSIONS

Applying the Formula in sub-section 2.3 reveals that the electrical energy cost for the diesel-only system without connection to the utility grid, amount to $0.432 per kWh. As mentioned in section 1 it seems economically viable to partly substitute the diesel-energy generation with PV energy, especially since the diesel price in the future is expected to rise. Consequently the most economically viable solution will hereinafter be identified.

3.1 Rough estimate of PV Power

It can be estimated that the optimal PV array size is for a yearly total PV production in the order of the yearly electricity demand. The theoretical nominal operating hours for a PV array inclined at 30° and oriented to north amount to 1680 h. Hence, for the purpose of a rough estimate the PV array size can be calculated:

$$W_{PV,yearly} = W_{demand,yearly} = 3476\ MWh$$

$$P_{n,PV} = \frac{W_{pumps,yearly}}{t_{nominal}} = \frac{3476\ MWh}{1680\ h} \approx 2000\ kWp$$

3.1. PV Nominal Power and Battery Capacity

As discussed in Section 1 the battery storage needs to be able to maintain the grid frequency in its specified boundaries by compensating for high ramp rates of the PV generator. These high ramp rates manifest mainly due to moving clouds and can only be limited in the upward direction by the PV inverter. The downward ramp rate thus has to be compensated by increasing the battery inverter output (see Figure 5: Time = 1s) to keep the grid frequency stable. For persistent coverage of the sky the diesel gensets have to be started (see Figure 5: Time = 11s) to make up for the PV power loss.

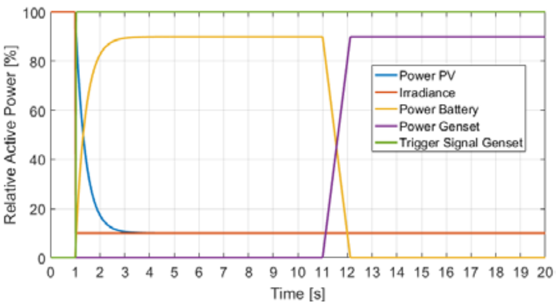

Figure 5: Schematic visualisation of the ramp-down of the PV generator (blue) from 100% active power to 10% active power (irradiance (red) decreases to 10% e.g. due to cloud covered sky) within two seconds. The battery (yellow) immediately has to compensate for the generation loss until the generator has started (purple).

The minimum required battery capacity depends on the maximum discharge power of the battery cells (see next paragraph) and on the spinning reserve to be maintained to cover for PV power fluctuations. This on the other hand depends on the delay time for starting up the diesel generators and the maximum power demand. It has to be assumed that the maximum spinning reserve equals the maximum power demand over 10 seconds, when a start time of the genset of 10 seconds is assumed [10].

Commercially available battery storage solutions feature maximum discharge rates of 0.5-3C [11]. The simulations were performed with batteries of maximum discharge rates of 1C and battery inverters of the same maximum power, hence the battery capacity required for the first year of operation must not be lower than

$$Capacity_{min} \geq \frac{P_{max}}{1C} = \frac{425kW}{1\frac{1}{h}} = 425kWh$$

The next bigger capacity value simulated is 500 kWh. It has to be noted that typical battery storage systems in this range are contained in 20 foot containers and feature fixed costs for the control system, switchgear, transformer, air conditioning and fire prevention. The battery system price thus is not proportional to the battery capacity as assumed in sub-section 2.3 due to fix costs of transport, engineering and installation. The electricity cost (see sub-section 2.3) for the simulated systems is depicted in Figure 6. The simulations performed comprise PV nominal values ranging from 100 kWp to 4000 kWp in 100 kWp steps and battery capacities ranging from 0 kWh to 4000 kWh in 100 kWh steps.

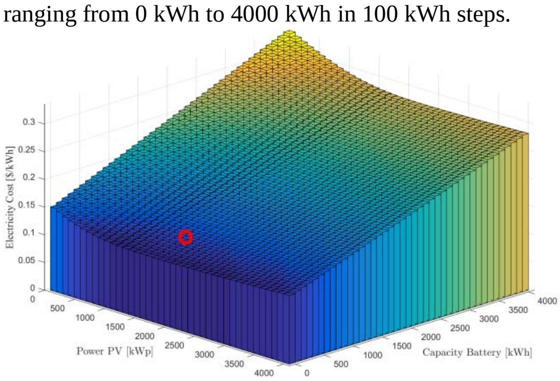

Figure 6: Electricity cost in $ per kWh at twenty years of amortisation. Each bar represents a simulated value of electricity price (Z-Axis) at specific PV nominal power (X-Axis) and battery capacity (Y-Axis). The chosen system size according to Table II is circled in red.

Figure 6 shows that the lowest electricity price of $0.117 is with a nominal PV power of 1700 kWp and without a battery. This system does not meet the goal of using the battery as a grid forming unit as required in Section 1 though. The lowest electricity price for systems with battery capacities ≥ 500 kWh of $0.136 is the system with 1800 kWp PV power and 500 kWh battery capacity. The PV array size is in the same order as the rough estimate of 2000 kWp in sub-section 3.1. Henceforth, these values will be chosen as optimal system sizes. Increasing the PV nominal power has a much lower impact on the electricity price than increasing the battery size.

An indicator of how much diesel is saved is the share of PV energy on the total energy demand as shown in Figure 7. The share of PV energy with the system as described above (1800 kWp, 500 kWh) in 2017 is expected to be 55.2%. Hence, roughly half of the energy needed for irrigation is produced from renewable PV energy. Due to increasing energy demand the PV share is expected to gradually decrease in the next few years if the PV array is not expanded (see Table II).

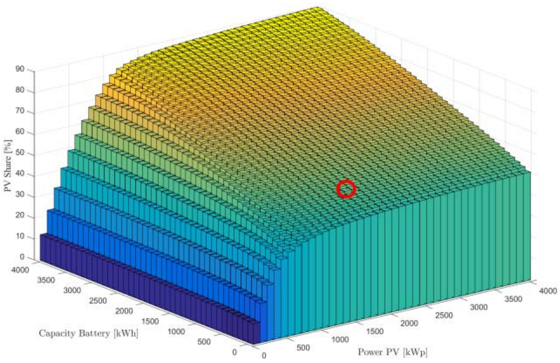

Figure 7: Share of PV energy on the total yearly electrical energy demand of 2017 in percent. Note that the X-/Y-axes are switched compared to Figure 6 for better readability. The chosen system size according to Table II is circled in red.

Summarized in Table II are the optimal system sizes and their corresponding performance indicators as discussed in this chapter.

Table II: Optimum system parameters, its electricity cost and PV Shares as explained in sub-section 3.1

Quantity	**Value**	**Unit**
PV Nominal Power	1800	kWp
Battery Capacity	500	kWh
Electricity Cost	0.136	$\frac{\$}{kWh}$
PV Share 2017	55.2	%
PV Share 2018	52.0	%
PV Share 2019	51.0	%
PV Share 2020	48.6	%
PV Share 2021	46.8	%

3.2 Sensitivity Analysis of Electricity Cost

Due to the assumptions made in sub-section 2.3 a sensitivity analysis on the electricity cost is performed. Figure 8 shows that the time until connection to the utility grid, the diesel fuel price and the energy price from the utility, have the highest impact on the electricity cost, whereas the CapEx and OpEx of PV plant, battery storage and gensets have a low impact. Since the electricity cost as charged by the utility ($0.05/kWh) is way below the LCOE, the averaged electricity cost rises for increasing time until connection to the utility grid. It has to be expected that the optimal system size changes with changing input values.

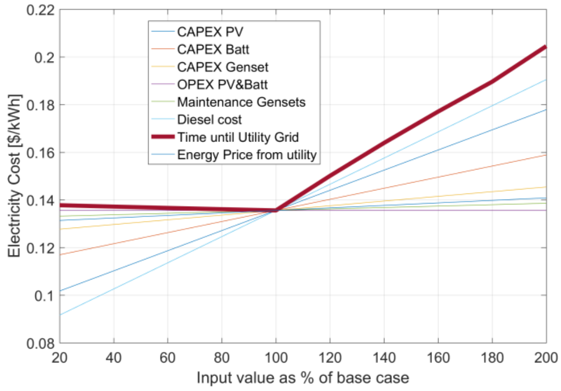

Figure 8: Sensitivity analysis of the electricity cost of the hybrid system (see Table 4.1) for its input values according to Equation 3.1 in percent deviation of its base value. The time until connection to the utility grid (ruby red) and the diesel energy price (turquoise) has the highest impact.

The dependency of the electricity cost on the time until connection to the utility grid is indicated in Figure 9. The electricity cost of the system discussed would increase to $0.299/kWh if the farm were connected to the utility grid only in 20 years (see Figure 9). The gradient of the electricity cost in direction of battery capacity in Figure 6 is much steeper than in Figure 9 since the battery does not contribute to the PV share of the total energy after connection to the utility grid.

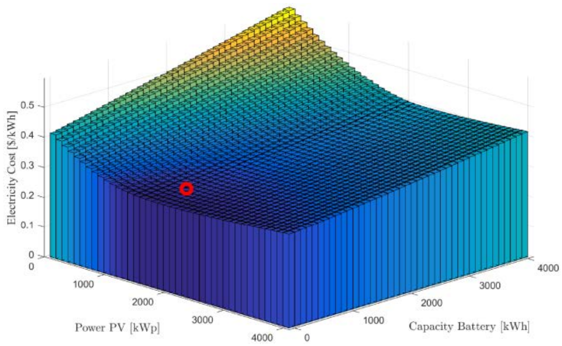

Figure 9: Levelized Cost of Electricity in $ per kWh at 20 years of amortisation without the connection to the utility grid. The chosen system size according to Table II is circled in red.

3.3 Battery Inverter Power

As discussed in the previous sub-section 3.1, as a worst case scenario it has to be assumed that all loads are simultaneously switched on when the PV-inverter output is zero. Only with this scenario considered a stable operation of the grid is possible. The discharge power of the battery inverter has to be higher than this peak power demand. The highest expected peak power according to Table I is 1024 kW. It has to be checked with the battery cell manufacturer if the resulting peak power discharge rate is compliant.

3.4 PV Array Inclination and Azimuth

The goal of optimizing the inclination and azimuth usually is to maximize the PV output over the year (Approach A). Since this PV plant currently is not utility grid-connected and hence cannot feed in excess electrical energy and in particular does not receive feed-in incentives, this is not the only solution.

Another approach is to maximise the fuel saving of the diesel generators (Approach B). Since the farm is expected to be connected to the public grid in a few years, it has to be assessed which approach is preferable. The simulation series which aimed to narrow down the optimum comprised 360° azimuth values from -180° (North) to +180° in steps of 30° and inclination values from 0° (horizontal) to 45° in 5° step values. The option for two PV arrays of identical nominal power but with different orientations was as well simulated. The nominal power of the PV array was chosen to be 1 MW since it is incidental to the optimization of the inclination and azimuth.

Figure 10 shows the relative theoretical PV yield over the first year as deviation from the maximum value of all inclinations and orientations in percent if the PV array were grid-connected i.e. all PV energy could directly be used or fed into the grid (Approach A). The theoretical yearly yield is maximised at -180° (North) for both arrays and elevated to 30°. The PV yield is not increased by using two differently oriented PV arrays (e.g. East-West orientation) and thus is not displayed in Figure 10.

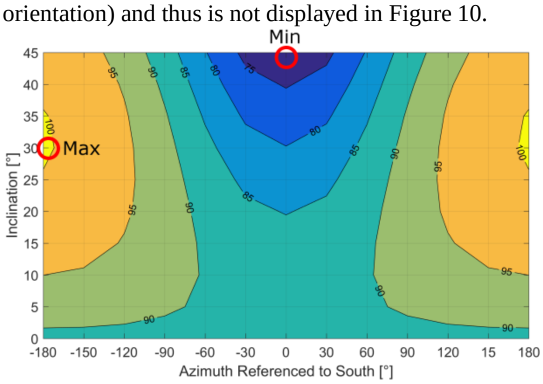

Figure 10: Approach A: Relative theoretical yearly PV yield (in % deviation from minimum value) plotted for each inclination from 5° to 45° (Y-Axis) and with azimuth values from -180° to +180° (X-Axis). The minimum value is at inclination 45° and azimuth 0° (South), the maximum value at inclination 30° and azimuth ±180° (North).

The value to maximise in Approach B is the fuel saving compared to the purely diesel generated electricity. Since this not only depends on the solar irradiation but also on the demand profile, the optimal inclination and orientation is different to Approach A. As a simplification only the demand values of 2017 were used. The error due to this simplification is marginal since the distribution of demand mostly remains the same in the future years while only the amplitude increases. Here, the maximum value was found with two differently oriented PV arrays, namely at an orientation of -90° and 90° respectively and at an elevation of 45°. Its magnitude is 7.2% higher than with the orientation of Approach A.

Since, in the scenario outlined by POMCO, the utility grid is expected to be connected to the farm in by 2022 and thus the PV plant is able to feed in excess energy for the major part of its life time, the Approach A has a lower electricity cost of $0.136/kWh compared to $0.141/kWh of Approach B. Approach B on the other hand has the advantage of more evenly distributed PV power and thus lower peak generation, which relieves the electrical grid. It can be expected that in the future the feed-in tariffs during peak PV production (e.g. lunchtime) are lower than during e.g. morning and evening hours.

4 CONCLUSION

The cleanest and most economical way to reduce fuel costs for the irrigation of the farm in Patagonia is to install a large-scale photovoltaic plant and a battery storage system. In order to maximise the fuel savings thorough analysis and simulations of the current and future demand of the irrigation were conducted.
For the following key data assumptions had to be made in order to simplify the model and the optimisation:

- Future demand in magnitude and time
- Future diesel price
- Time until connection to utility grid and its electricity price
- CapEx of PV system
- CapEx of battery

Due to the averaging of the electricity cost of off-grid generation in the first years with the cost of electricity of the utility the comparability with the LCOE of other hybrid systems is deceptive. Thus an average of LCOE and energy price from the utility grid was chosen as the main indicator for economic viability.

The optimal size of PV array and battery according to the estimations of sub-section 2.3 is 1800 kWp and 500 kWh. The gradient of the electricity cost in direction of higher PV nominal power is relatively low, thus the optimal size of the PV plant is much more flexible than the battery capacity. This system is expected to yield costs of $0.136 per kWh of electrical energy. In the first year 55.2% of the electrical energy will be provided by the PV plant whereas the rest needs to be covered by the diesel gensets. This PV-share on the total electrical energy demand will decrease marginally to 46.8% in the following five years due to increased energy demand.

It could be shown that the impact of delay in connection to the utility grid, volatility of the diesel price and the electricity cost of the utility have a high impact on the electricity cost, whereas the impact of changes in CapEx and OpEx is relatively low. Comparison of Figure 6 with Figure 9 highlights the dependency of the time until connection to the utility grid on the optimal battery size. Later examination of proposals for this hybrid system revealed that specific costs of especially the battery system decrease with increasing system size. This is due to the fixed costs of the containerized solution (Inverters, transformer, air-conditioning, fire prevention system, etc.) and the control as well as commissioning, engineering and economy of scale. Before commissioning of a system as discussed it is imperative to enquire concrete costs of a PV system and a battery in order to accurately describe the energy price.

Apart from technical feasibility and economical optimisation requirements to aesthetics, ease of installation and to the environment have to be respected during layout and dimensioning of the hybrid system. Two seperate PV arrays with different azimuth orientation, as proposed in Approach B of sub-section 3.4, possibly necessitate higher amount of labour input and land requirement. Since the farm is expected to be connected to the utility grid in five years, the optimal orientation is north with an inclination of 30°. The orientation of East-West with an inclination of 45° results in a <4% higher electricity cost and thus is equally interesting.

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