OPTIMAL SIZING OF MICROGRIDS
CASE: THE SKAGERAK STADIUM IN NORWAY

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1. Introduction

The growing concern of global warming has increased the demand to incorporate renewable energy source to power infrastructure, starting from the residential, office area, factory, and public infrastructure. Based on the characteristic of its connectivity to the grid, the application of renewable energy can be divided into the connected on, which is the on-grid mode, or it can be installed independently from the grid which is called the off-grid or islanded mode.

In the case of on-grid applications, the inadequacy of power from the installed renewable energy source can be compensated by exporting from the grid. In retrospect, when excess power is produced, it can be sold to the grid. Meanwhile, when there is no connection to the grid, the renewable energy power plant needs to become self-reliant. Furthermore, it is possible to install additional storage system such as battery storage systems. This Battery Energy Storage System (BESS) is typically used for peak shaving, self-consumption maximization of renewable energy sources, energy arbitrage, voltage regulation, frequency control, and backup power [1]. At present, application of BESSs yielding the highest profit is in the provision of frequency containment reserve (FCR) which is demonstrated in Germany [2] and Norway [3].

The present project will focus on the application of powering a football stadium with combined Photovoltaic and BESS system connected to the grid. The system is realistically installed at the Skagerak Energy Lab, which is located in the Skagerak Arena football stadium, Norway (Figure 1). Therefore, the load profile and the solar irradiance data used in the project will be based on this location.

Figure 1 : *Soccer Club Skagerak Arena in Norway*

In this system, the electricity is solely produced by the installed photovoltaic with additional role of battery is to store the electricity such that it enables the stadium to be fully supplied by the electricity produced by the photovoltaic. Moreover, the distinct load profile of the football stadium and the energy generation coming from PV in Norway results in high enough excess power coming from the electricity generation. This situation leads to the choice to connect the system to the grid with the main objective to sell the excess electricity produced.

One of the keys determining factor of installing a system is its economic evaluation in which one of the main components is its initial investment, especially since energy sector is one of the capital-intensive systems. Hence, such decision needs to be weighed in a serious consideration. Since the system consists of two sub-system which are photovoltaic and the BESSs, it is crucial to decide how much of each sub-system needs to be applied to sufficiently supply the needed electricity in the least investment cost needed.

Therefore, the project is carried out to optimize the size of each sub-system, which are PV panels and battery cella, needs to be installed. In addition to that, analysis of the yearly revenue and the payback period will also be made while taking into account the amount of electricity sold to the grid. The optimization is carried out using the genetic algorithm (GA) method. The algorithm was developed by John Holland and this collaborators in the 1960s and 1970s and is an algorithm modeled from the biological evolution based on Charles Darwin's theory of natural selection [4].

The following section of the report describes the methodology applied to the study, including the algorithm description, definition of variables, constraints, and objective function, as well as the mathematical modelling. The last part of the report will consist of the result, discussion, and conclusion.

2. Methodology

As discussed in the introduction, the aim of the project is to optimize an energy scenario with the objective of minimizing the investment cost of energy production required to supply the load demands of the stadium facility.

The model developed to solve the problem takes in input parameters such as weather data of location and average load profile of the stadium in the worst possible case (Winter season). The simulation results of the model output the number of PV panels, battery cells and minimum state of charge of the battery required to satisfy the load demand within the specified constraints, as well as the overall investment cost. The steps involved in the methodology includes collection and cleaning of the weather data, mathematical definition for the objective function, constraints and variables.

2.1 Variable Definitions

The following sub-sections describes the mathematical modelling of the variables.

PV generator output:

$$P_{PV}(t) = N_{PV} \cdot \eta_{PV} \cdot P_{STC} \cdot \frac{GSR(t)}{G_{STC}} \cdot \left(1 - C_T \cdot (T(t) - T_{STC})\right)$$

Equation 1

Where N_{PV} is number of panels; η_{PV} is the panel efficiency; P_{STC} is the nominal power under standard test conditions; G_{STC} is Global solar radiation (1kW); C_T is the temperature coefficient; T_{STC} is 25°C

The upper bound on the number of panels is calculated as

$$N_{PV\ max} = \frac{(Total\ Available\ Surface\ area\ for\ PVs)}{Surface\ area\ for\ one\ PV\ panel}$$

Equation 2

Total Available area to mount PVs was estimated to be 5330m^2 and surface area for one PV is 1.6 m^2. [1]

Battery cells:

Lithium-ion battery cells were considered for this micro-project, and the State of Charge is mathematically modelled as:

$$SOC(t + \Delta t) = SOC(t) - \eta_{Bat} \cdot \frac{P_{Bat}}{N_{Cell} \cdot C_{Cell}} \cdot \Delta t$$

Equation 3

Where SOC is the state of charge; η_{Bat} is the battery efficiency; P_{Bat} is the battery power; N_{Cell} is the number of cells; C_{Cell} is the battery cell capacity [5].

2.2 Objective Function and Constrains

With the aim to minimize the investment costs required to power the stadium facility and within certain constraints, the constraints are:

1) **Bounds on the variables**: The maximum available area for PV panels is bound by (Equation 2), Also, the battery cells size is bound at 100 min and 25,900 cells max.

2) **No unsupplied Load**: The model is simulated with the restriction to always supply the load demand of the stadium either by supply from PV generation or battery capacity.

3) **$SOC_{min} \leq SOC \leq SOC_{max}$**: The minimum and maximum state of charge is bound to 5% and 95% respectively.

4) **$SOC_{(end\ of\ day)} \geq SOC_{(beginning\ of\ day)}$:** The battery should have a higher state of charge at the end of day compared to the SOC at the start of the day.

Therefore, objective function is mathematically modelled as:

$$
\begin{aligned}
&\min_{\mathbf{x}} \; Cost^{inv}(\mathbf{x}) \\
&\text{subjected to:} \quad \mathbf{x}^{\mathbf{l}} \leq \mathbf{x} \leq \mathbf{x}^{\mathbf{u}} \\
&\qquad SOC_{min} \leq SOC(\mathbf{x}, t) \leq SOC_{max}, \; \forall \, t \in \text{Day} \\
&\qquad P_{unsup}(\mathbf{x}, t) = 0, \; \forall \, t \in \text{Day} \\
&\qquad SOC(\mathbf{x}, t_{final}) \geq SOC(\mathbf{x}, t_{start})
\end{aligned}
$$

Equation 4

Where,

$Cost^{inv}$ is Investment Cost, P_{unsup} is Unsupplied power, and SOC is State of Charge of the battery.

2.3 Simulation – Operation Strategy

As the objective function is a Mixed Integer Non-Linear Programming problem, the Genetic Algorithm is adopted to simulate and optimize the model. The simulation follows a strategy defined by our objective function and constraints. Basically, it follows a pattern that aims to supply all the stadium's load demands with the PV generation, with a logic flow to trigger the use of the battery's energy if the PV generation is insufficient to handle the load demand at any point.

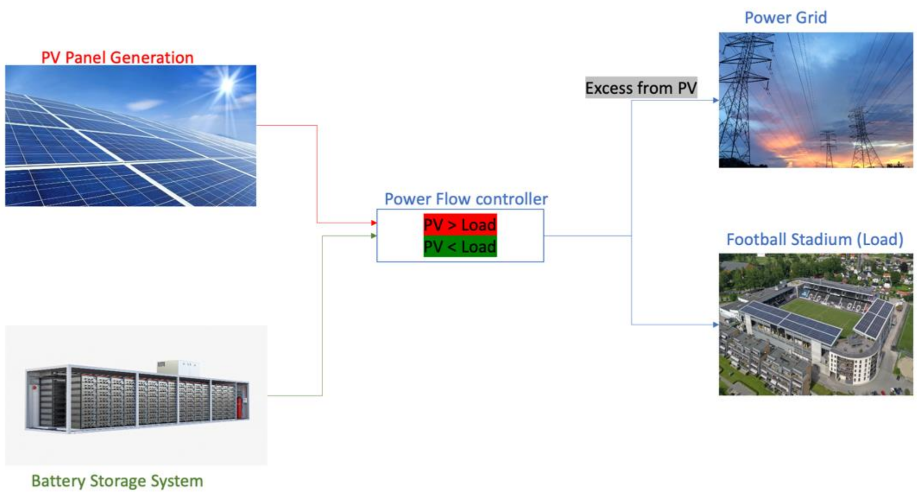

Figure 2 : *Simulation-Operation Strategy*

2.4 Parameter, Data, and Algorithm

The simulation aims to size the power generation and storage system (PV + battery) necessary to supply the stadium without importing power from the grid.

The set of parameters and input data used to perform the simulation are presented and described as follows:

Simulating the power system requires precise data including information related to standard condition of operation of PV panels, specifications of the chosen battery system and interactions with the grid. Table 1 lists the parameters used in this project based on [5] [1].

__Table 1.__ Parameters related to PV Panels, Battery System and Grid

Simulation Parameters	
Parameter	**Value**
Solar panels	
PV array rated power in standard test conditions (STC)	380 W
Solar radiation under STC	$1000\ \frac{W}{m^2}$
Temperature coefficient	-0.34·10^{-2}/ °C
Temperature STC	25 °C
Electrical Efficiency of PV Panels	0.95
Price of PV	7400 €/kW
Battery System Specifications	
Cell Capacity	30 Ah/3.6 V
Charging Efficiency	0.95
Minimum SOC	0.05
Maximum SOC	0.95
Minimum amount of cell	100
Maximum amount of cell	25900
DC/DC Efficiency	0.98
AC/DC Efficiency	0.95
Price of cell	470 €/kWh
Grid	
Export Price	0.04·10^{-3} €/kWh

Based on Skagerak stadium's load data provided by [1], the highest daily load demand of the stadium in 2018 was registered on March 11. Therefore, to account for the worst-case scenario in sizing the power generation system, the daily load profile considered is shown in Figure 2 and refers to March 11's load data.

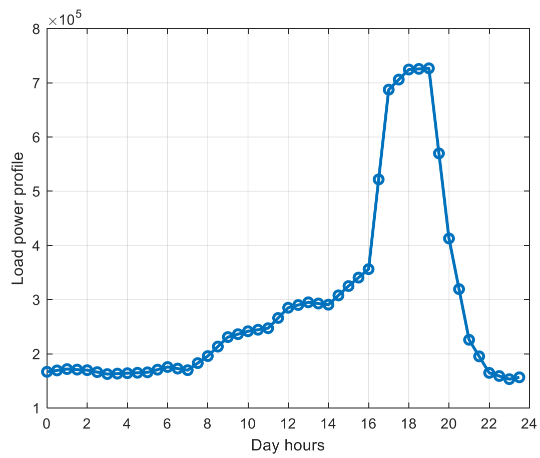

***Figure 3:** Load Profile of Skagerak stadium on March 11, 2018*

One should notice the atypical shape of this load profile. Most of the demand is concentrated between 16:00 and 20:00 which corresponds to the timeframe when the stadium is in use and the floodlights consuming large amount of energy.

The solar irradiation [6] on the same date of March 11, 2018 and the resulting power generated by one single solar panel are shown below:

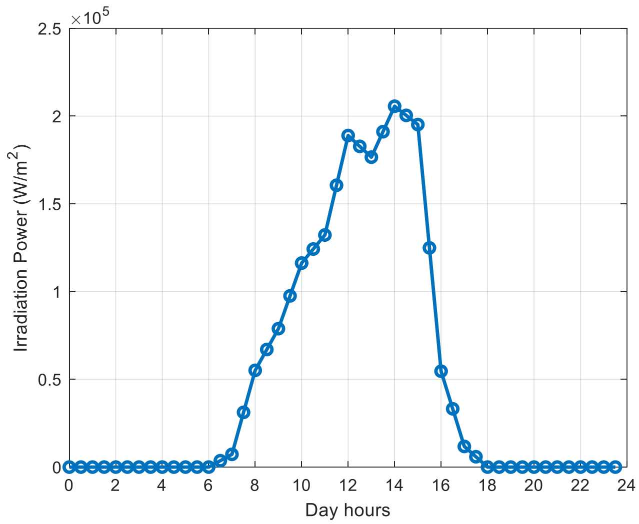

Figure 4: *Solar Irradiance on March 11, 2018*

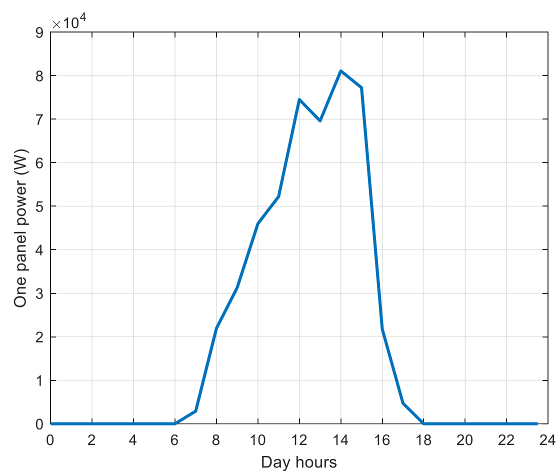

Figure 5: *PV Power Generated by 1 Solar Panel on March 11, 2018*

By inspection, one can readily notice that most of the solar power is generated during the interval 6:00 – 18:00 while the demand increases significantly between 16:00 and 20:00.

Considering the mathematical formulation of this optimization problem, the fact that some of the constraints are non-linear and/or restricted to integer values, the genetic algorithm implemented in MATAB, which repeatedly modifies a population of individual solutions over successive generations until the population evolves toward an optimal solution, stands as a suitable solution method.

Table 2. Algorithm controlling power flow in the system

Algorithm – Cost Minimization

SOC_{bat}, Battery SOC in %
P_L , Load demand in kW
P_{PV} , PV generation in kW
P_{bat_c} , Power stored in the battery system in kW
P_{bat_d} , Power discharged from the battery system in kW
P_{lost} , Power generated but not used (subsequently sold to the grid) in kW
$P_{unsupplied}$, Unsupplied power in kW
$P_{unsupplied} = P_L - P_{PV}$
 	
for t=1:number of solar generation data points **do**
    if $P_{unsupplied} < 0$ and $SOC_{bat} < 95$ **then**
        $P_{bat\_c} = -P_{unsupplied}$
    else if $P_{unsupplied} < 0$ and $SOC_{bat} = 95$ **then**
        $P_{lost} = -P_{unsupplied}$
    else if $P_{unsupplied} > 0$ and $SOC_{bat} > 0$ **then**
        $P_{bat\_d} = P_{unsupplied}$

3. Results and Discussion

Following the simulation as previously defined, the optimal sizing of the power generation system reveals that 181 solar panels, 2589 battery cells are required and with an initial SOC of 62%. Furthermore, the total cost of the system amounts to 1.82 million € whereas the yearly revenue based on unused power sold to the grid reaches 1.15 million €. It follows that the approximate payback period lies around 19 months.

Table 3. Summary of the simulation results

Optimal Design Results					
Number of PV Panels	**Number of Battery Cells**	**Initial SOC of the Battery**	**Total Cost**	**Yearly Revenue**	**Payback Period**
181	2589	62	1.82 millions €	1.15 millions €	19 months

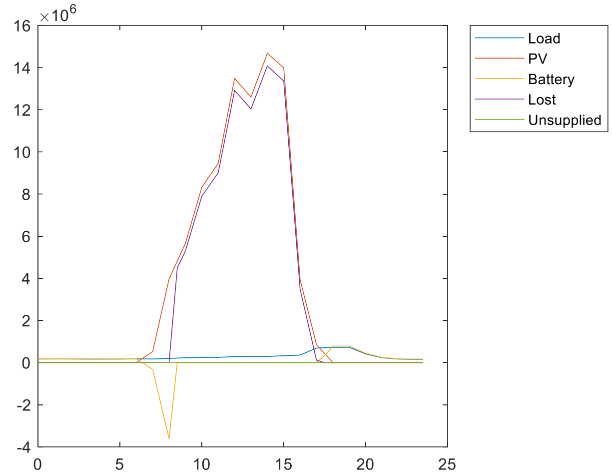

Figure 6: *Profile of load demand, PV generation, power stored in the battery system, unused power and unsupplied power on March 11, 2018 when supplied solely by the newly sized power generation system*

3.1 Interpretations of the results

The result of this optimization complies to the constraint of the maximum and minimum number of photovoltaic and battery used, and there is no unsupplied load. This constraint satisfaction is crucial on ensuring that the utilized optimization algorithm is valid and that the result can satisfy the real constrain if the plan is going to be realistically established.

With regards to the result shown in Figure 5, it is explicit that there is asynchronization between the peak of the power generated by the photovoltaic and the power needed by the load. With 181 number of PV panels, the power that can be produced in the peak hour of around 13h is up to 15 GW. Meanwhile, the load is peaking in around 17h – 20h when the PV production is already declining. This discrepancy results in the high amount of power lost which, in certain hour, its amount is as high as the power generated.

Figure 5 shows that in the early hours of PV generation at 7h – 9h, the generated power is concentrated to charge the battery as shown by the yellow line going to the direction of negative power. In this period, the generated power is stored in the battery and there is no power lost. However, when the battery starts to be fully charged to its upper bound constraint of 95%, the amount of power produced is not getting stored anymore and turned to be the lost power presented by the purple line in the graph. The amount of power generated by the PV and the lost power are then increasing to its peak before it starts decreasing, based on the solar irradiance of the hour during the day.

Based on the modeling carried out in this optimization problem, the lost power will then be sold to the grid with the export price of $0.04 \cdot 10^{-3}$ €/kWh. This exporting scheme makes the optimization result interesting since it can generate yearly revenue up to 1.15 million €. In comparison to the amount of total initial investment needed with is 1.82 million €, the difference is only 0.63 million €. When translated to the payback period, the investment in this photovoltaic-

BESSs system will start being fully profitable in its 19th month. This can be a value proposition to the potential investment since investing in this system means providing independent green energy for the football stadium and at the same time can be profitable in a relatively short amount of time.

References

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