“Energy Financial Planning for a Sustainable Data Centre: A 25-Year Techno-Economic Analysis”

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Contents

Abstract

This report presents a comprehensive Long-Term Energy Supply Planning for a new data centre, which requires a continuous 100 MW power supply at each hour. The primary objective is to develop a cost-effective and reliable energy mix that sources a minimum of 75% of its annual energy from renewable sources and the remaining from non-renewable sources. The analysis integrates a solar photovoltaics (PV), a battery energy storage system (BESS), and a natural gas power plant.

The analysis concludes that an optimal system configuration consists of a **563.9 MW solar PV plant**, a **31.8 MW natural gas power plant**, and an **5896 MWh battery energy storage system**. This configuration is meticulously designed to ensure 100% operational reliability while adhering to the sustainability target. The solar plant is oversized relative to the load to generate sufficient energy to meet the 75% renewable fraction and to charge the BESS during daylight hours and to meet the demand whenever low solar energy is available. The gas plant is sized to cover the maximum 25 MW load, serving as a backup during periods of low solar generation, thereby guaranteeing uninterrupted power. The BESS is sized to shift daytime excess solar to cover the nighttime load, enabling a high renewable penetration.

The financial viability of this configuration is robust, yielding a projected 25-year Levelized Cost of Energy (LCOE) of **$0.084 per kWh**. The total Net Present Cost (NPC) of the project over its lifecycle is estimated at **$1.859 billion**. The operational strategy prioritizes the dispatch of solar energy first, followed by battery discharge, with the gas plant utilized to cover any remaining shortfalls, ensuring it contributes the mandated 25% of annual energy. The primary operational bottleneck is managing multi-day solar intermittency, which necessitates the full-capacity gas plant. The key long-term financial risk is the recurring cost of BESS replacement.

1. Introduction

1.1 The Imperative for Sustainable Data Centres

The global economy is at the confluence of two defining megatrends: the exponential growth of digital infrastructure and the urgent, worldwide transition toward a low-carbon energy system. Data centres, the backbone of the digital age, are immense consumers of electricity, and their energy demand is projected to rise significantly. This places the industry at the forefront of the challenge to reconcile technological advancement with environmental responsibility. The project detailed in this report addresses this challenge directly. It concerns the establishment of a new data centre requiring a continuous and highly reliable power supply of 100 MW per hour. In a strategic move that reflects growing investor, regulatory, and consumer pressure, the organization has mandated that this facility operate with a high degree of sustainability. The core objective is to source 75% of the data centre's total annual energy demand from renewable sources, with the remaining 25% supplied by non-renewable sources to ensure absolute reliability.[1] This mandate transforms the project from a simple infrastructure build-out into a sophisticated exercise in energy system design, optimization, and long-term financial planning.

This report provides a comprehensive 25-year investment and operational plan to meet the specific requirements of the data centre project. The plan is designed to achieve three co-equal objectives as outlined in the case study [1]:

1. **Cost-Effectiveness:** To determine the optimal mix of solar, gas, and battery capacity that minimizes the total cost of energy over the 25-year project lifetime.
2. **Sustainability:** To ensure that at least 75% of the total energy delivered to the data centre annually is derived from renewable sources (solar and battery storage).
3. **Reliability:** To guarantee that the data centre's constant 100 MW power demand is met at every hour of every day, with no shortages.

The analysis will establish the optimal capacity for each power source, define a long-term deployment and operational strategy, and provide a detailed financial assessment, including the project's LCOE and total lifecycle cost.

2.0 Framework

To develop the 25-year energy financial plan, a rigorous optimization framework is employed. This framework is designed to identify the least-cost combination of generation and storage assets that satisfies all technical, operational, and sustainability constraints defined in the project mandate.

Battery Replacement Logic: We explored two logics for our battery replacement[1].

Max discharge from the battery

= Capacity of the battery x Max depth of discharge x Max number of cycles to fail

Logic 1:

If the cumulative discharge from the battery at the end of the year = the maximum discharge from the battery, then Battery Replacement must occur at the end of that year.

Then, the objective function must include the replacement cost of the battery. The cumulative discharge must reset after battery replacement.

Logic 2 :

Battery Replacement cost ($ / MWh) = Replacement Cost/(Max Discharge from battery x Discharging Efficiency)

Replacement Cost (in objective function) = Battery Replacement cost ($ / MWh) x Total discharge from battery

For our model, we used logic 1 to check for the replacement.

We had formed a process flowsheet to understand how the flow of power occurs in the whole system.

Process Flowsheet:

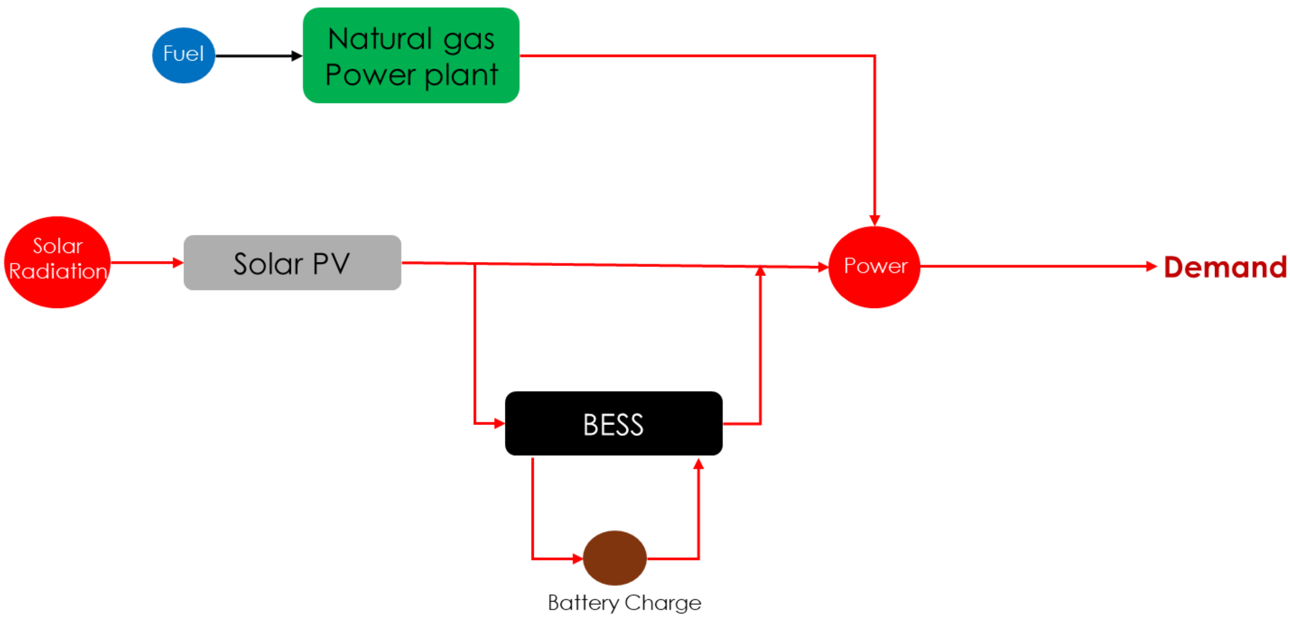

Figure 1. Complete flowsheet of the process.

3.0 Methodology

The model is structured to make investment and operational decisions simultaneously to achieve the most cost-effective outcome over the project's entire 25-year lifespan.

Objective function:

We have solved an MILNP, the objective being to minimize the total net present cost of the system, including both capital and operational costs.

$$min \;\; C_{total}$$

The total cost is given by equation 1:

$$C_{total} = C_{cap} + C_{op}^{disc} + C_{fuel}^{disc} + C_{replace} - C_{salvage} \qquad 1$$

Where, C_{cap} is the total capital cost, C_{op}^{disc} is the total discounted operation and maintenance cost, C_{fuel}^{disc} is the total fuel cost, $C_{replace}$ is the total replacement cost, and $C_{salvage}$ is the salvage value at the end of the operating years.

Capital cost is given by the following equation 2

$$\boldsymbol{C_{cap} = C_{solar}^{capex} + C_{land}^{capex} + C_{gas}^{capex} + C_{battery}^{capex}} \quad (2)$$

Where,

$$C_{solar}^{capex} = CAP_{solar} * CAPEX_{solar} \quad (2.1)$$

$$C_{gas}^{capex} = CAP_{gas} * CAPEX_{gas} \quad (2.2)$$

$$C_{battery}^{capex} = CAP_{battery} * CAPEX_{battery} \quad (2.3)$$

$$C_{land}^{capex} = Land_{solar} * \mathrm{land\_cost}_{solar} \quad (2.4)$$

To find out the operational cost, we used the following equations

$$\boldsymbol{C_{op} = C_{solar}^{opex} + C_{gas}^{opex} + C_{battery}^{opex}} \quad (3)$$

$$C_{solar}^{opex} = CAP_{solar} * CAPEX_{solar} * Opex\_per_{solar} \quad (3.1)$$

$$C_{gas}^{opex} = CAP_{gas} * CAPEX_{gas} * Opex\_per_{gas} \quad (3.2)$$

$$C_{battery}^{opex} = CAP_{battery} * CAPEX_{battery} * Opex\_per_{battery} \quad (3.3)$$

Equations 3.1 to 3.3 give the operational cost, but we need to calculate the discounted price. Let's first find out the fuel cost.

$$C_{fuel,y} = \sum_{t} prod_{gas,t,y} * fuelcost_{gas} \quad (4)$$

We use the following equation to make the cost discounted for fuel, operational, and maintenance costs.

$$D_{op} = \sum_{y \epsilon Y} \frac{(1+\sigma)^y}{(1+\pi)^y} \quad 5$$

This is the discounted operational and maintenance cost. Where, σ is O & M growth rate, π is the discount factor, and y is the number of years. Equation 6 is used for fuel discount.

$$D_{fuel,y} = \frac{1}{(1+\pi)^y} \quad 6$$

Final discount calculated for total cost.

$$C_{op}^{disc} = C_{op} * D_{op} \quad 7.1$$

$$C_{op}^{disc} = \sum_y C_{fuel,y} * D_{fuel,y} \quad 7.2$$

For calculations of replacement and salvage cost, we used following equations.

$$C_{replace} = \sum_y replace_y * \frac{CAP_{battery} * CAPEX_{battery} * \left(1 - CAPEX_{battery}^{decline}\right)^y}{(1+\pi)^y} \quad 8$$

$$C_{salvage} = \frac{CAP_{solar} * CAPEX_{solar} * \beta_{solar} + CAP_{gas} * CAPEX_{gas} * \beta_{gas}}{(1+\pi)^y} \quad 8.1$$

Constraints:

Production from solar is always equal to its capacity, multiplied by a factor. The annual degradation will reduce its usable capacity.

$$prod_{solar,t,y} = CAP_{solar} * solar_t * (1 - \delta_{solar})^y \quad \forall\, t \in T, y \in Y \quad 9$$

Production from the gas plant is always less than its capacity. The annual degradation will reduce its usable capacity.

$$prod_{gas,t,y} \leq CAP_{gas} * \left(1 - \delta_{gas}\right)^y \quad \forall\, t \in T, y \in Y \quad 9.1$$

Land required by the solar is also an important decision. It should be less than the maximum land available.

$$Land_{solar} = reqLand_{solar} * CAP_{solar} \tag{10}$$

$$Land_{solar} \leq land^{max} \tag{10.1}$$

Total production at any hour is sum of production from solar and gas is given by:

$$totalprod_{t,y} = prod_{solar,t,y} + prod_{gas,t,y} \qquad \forall\, t \in T, y \in Y \tag{11}$$

Total production from solar at any hour is distributed between the demand, battery charging, and curtailment.

$$prod_{solar,t,y} = curtail_{t,y} + prod_{solartobattery,t,y} + prod_{solartodemand,t,y} \; \forall\, t \in T, y \in Y \tag{12}$$

Demand at data centre should be satisfied at every hour.

$$\begin{aligned} prod_{solartodemand,t,y} + prod_{gas,t,y} + discharging_{battery,t,y} \\ = Demand_t \qquad \forall\, t \in T, y \in Y \end{aligned} \tag{12.1}$$

Minimum 75% demand should be satisfied by solar or Battery at every hour.

$$prod_{solartodemand,t,y} + discharging_{battery,t,y} \geq \lambda * Demand_t \quad \forall\, t \in T, y \in Y \tag{12.2}$$

Balance on storage of power for different time period is given by following constraints. For starting hour in first year.

$$\begin{aligned} stor_{battery,0,0} = InitialStorage + \gamma_{battery} * charging_{battery,0,0} \\ - discharging_{battery,0,0} \end{aligned} \tag{13}$$

For the first hour of every year except the first year, maintain the inventory cyclicity for carrying inventory from the previous year.

13.1

$$stor_{battery,0,y} = stor_{battery,8759,y-1} + \gamma_{battery} * charging_{battery,0,y} - discharging_{battery,0,y} \qquad \forall\, y \in Y$$

For any hour in any year storage in battery is given by:

13.2

$$stor_{battery,t,y} = stor_{battery,t-1,y} + \gamma_{battery} * charging_{battery,t,y} - discharging_{battery,t,y} \forall t \in T, y \in Y$$

Battery storage should always be less than or equal to capacity of battery.

13.3

$$stor_{battery,t,y} \leq CAP_{battery} \qquad \forall t \in T, y \in Y$$

We cannot charge a battery more than the capacity

13.4

$$charging_{battery,0,y} \leq \frac{CAP_{battery}}{Min_{battery}} \qquad \forall t \in T, y \in Y$$

For the first hour of every year except the first year, maintain the inventory cyclicity for carrying inventory from the previous year.

13.5

$$discharging_{battery,t,y} \leq \frac{CAP_{battery} * \alpha_{battery}}{Min_{battery}} \qquad \forall t \in T, y \in Y$$

Total discharge from battery in first year is calculated to balance the total lifetime discharge for replacement of battery. The replacement of the battery will occur in two cases if its capacity falls below 70% or the total cycles are above 5500.

14

$$discharge_0 = \sum_t discharging_{battery,t,0}$$

Total discharge from battery in any year is similarly counted.

$$discharge_y = \left(1 - replace_{y-1}\right) * discharge_{t-1} + \sum_t discharging_{battery,t,y} \ \forall\, y \in Y \tag{14.1}$$

Total discharge should be less than the maximum, otherwise we must replace the battery:

$$discharge_y \le cycles^{max} * CAP_{battery}\left(1 - replace_y\right) + M * (replace_y) \tag{14.2}$$

We have nonlinear constraints and an objective function. To linearize, we introduced auxiliary variables.

$$z_y \le M * (replace_y) \tag{15}$$

$$z_y \le CAP_{battery} \tag{15.1}$$

$$z_y \ge CAP_{battery} - M * (1 - replace_y) \tag{15.2}$$

$$z_y \ge 0 \tag{15.3}$$

Above z_y an auxiliary variable is used to replace $CAP_{battery} * replace_y$ where M is some large number near the capacity of the battery to balance

$$a_y \le M1 * (replace_{y-1}) \tag{16}$$

$$a_y \le discharge_{y-1} \tag{16.1}$$

$$a_y \ge discharge_{y-1} - M1 * (1 - replace_{y-1}) \tag{16.2}$$

$$a_y \ge 0 \tag{16.3}$$

Above a_y an auxiliary variable is used to replace $discharge_{y-1} * replace_y$ where M is some large number near the capacity of the battery to balance

4.0 Results and Conclusion

This techno-economic analysis has developed a 25-year plan for the proposed 100 MW constant demand for a data center. The resulting strategy provides a clear path to achieving the organization's goals for sustainability and cost effectiveness.

4.1 Results

We need **563.9 MW** of solar PV, **31.8 MW** of natural gas generation, and **5896 MWh** of battery energy storage capacity to achieve an optimal energy system. These capacities will meet the project's requirements:

- **Sustainability:** The system is designed to source over 75% of its annual energy from solar PV, either through direct consumption or discharge via the BESS, fulfilling the project's renewable energy target.
- **Cost-Effectiveness:** Total Levelized Cost of Energy is **$0.084/kWh**. This tells that renewable energy with technologies like BESS and gas is economically viable.

Additionally, we need initial storage of batteries as **2717.3 MWh** to fulfill the renewable requirement for the initial hours of year 1, when solar availability is 0.

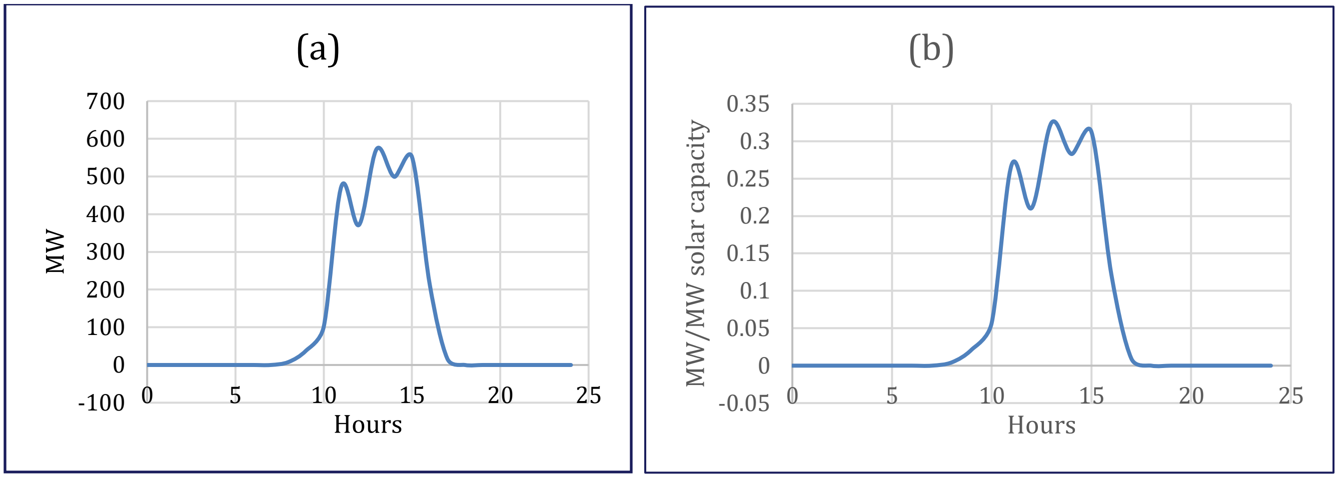

Figure 2. (a) Total daily solar power produced, (b) Daily Solar availability

Solar power production is a linear function of solar availability. We can see from the figure that solar production is varying with time.

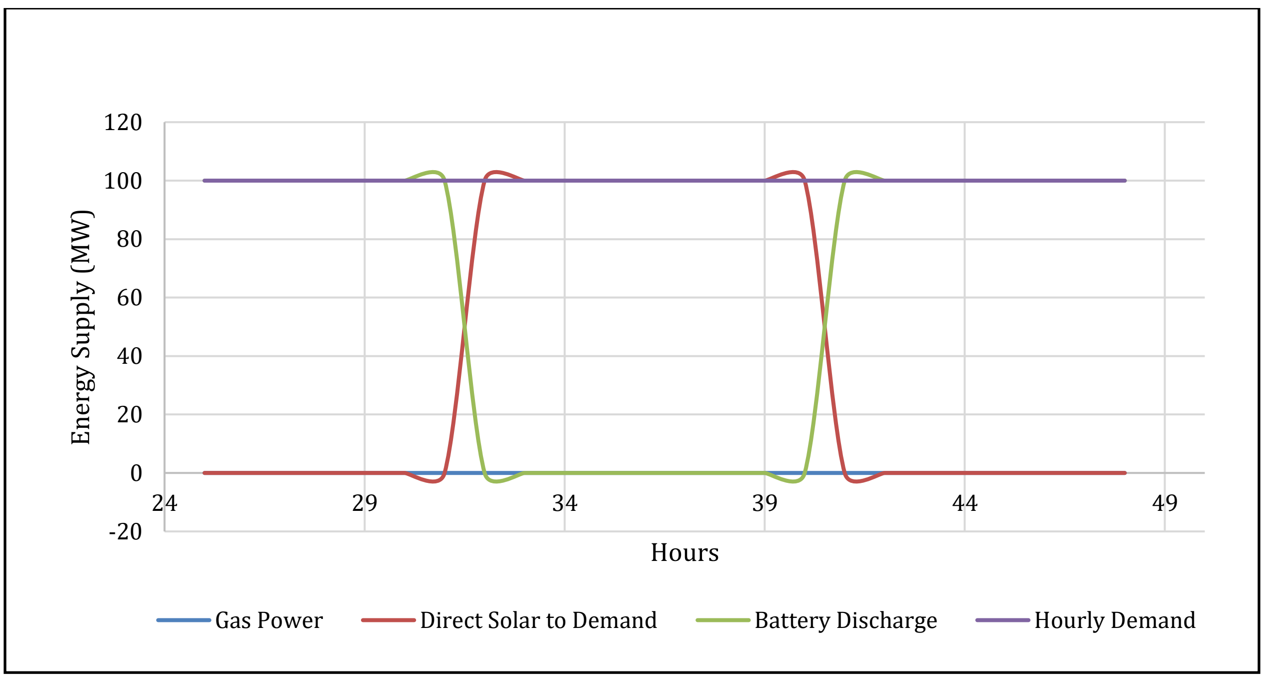

Figure 3. Demand Fulfillment (regular day)

In a regular day, demand is fulfilled by solar power fully in the daytime, battery charges in the daytime, and discharges at nighttime. In this case, we are not getting any gas power because the total solar and battery capacities are very large. So, on a regular day when availability is enough, using gas does not benefit the total cost. Additionally, the fuel cost will occur, so using only the renewable resources is a good choice.

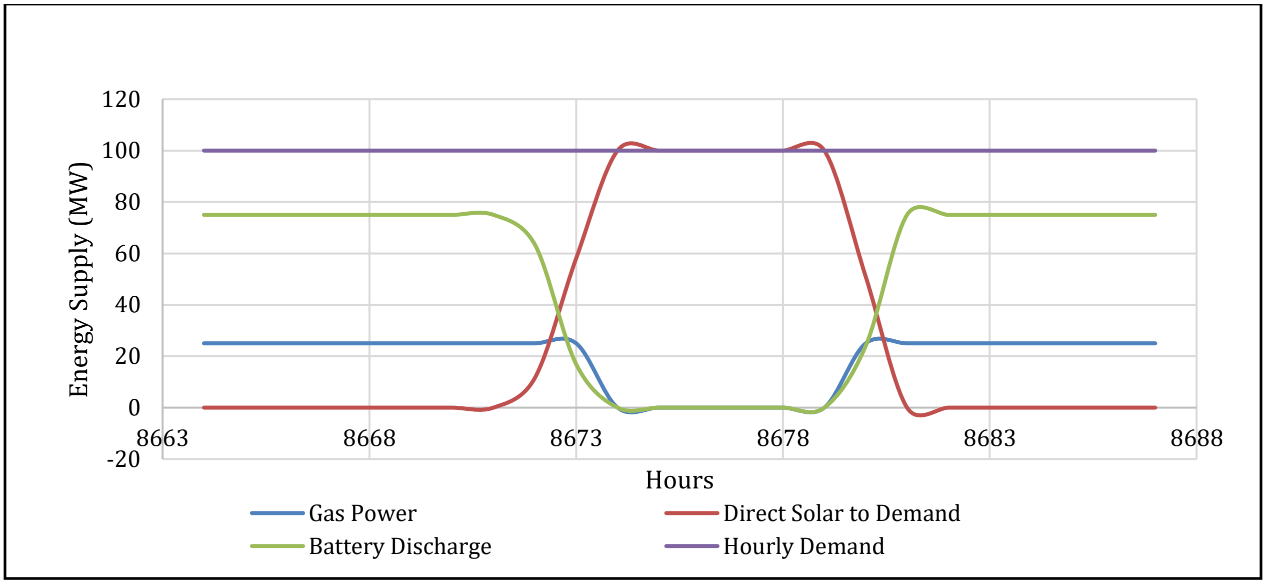

Figure 4. Demand Fulfilment (day with less solar availability)

In a day with less solar availability, we must use the gas power so that the total cost decreases. But increasing the capacity of the solar and gas further increases the cost, so it uses the gas as a power source.

4.2 Conclusion

Replacement of batteries is not occurring because our replacement logic tells us that replacement will occur when the total discharge from the battery exceeds the total lifetime discharge. Total lifetime discharge from the battery is **3242800 MWh,** and total discharge in 25-year operation is **21165143 MWh,** which is very much less than the given total lifetime discharge of the battery. So, the replacement cost is not adding up for the batteries.

Nomenclature:

Sets:

d $\in D\,\{1,\ 2,\ \ldots\ldots,\ 365\}$: Number of days in year

$y \in Y\,\{1,\ 2,\ \ldots\ldots,\ 25\}$: Total number of years

$t \in T\,\{0,\ 1,\ 2,\ \ldots\ldots,\ 8759\}$: Number of hours in Year

Parameters:

μ: Lifetime of Project

π: Discount rate to consider time value of money

σ: Operation & Management growth rate (annual)

$Demand_t$: Hourly Demand in MW

λ: Min renewable energy share to satisfy the demand %

$CAPEX_{solar}$: Capital cost of solar plant ($/MW)

$Opex\_per_{solar}$: Operational cost Percentage (of Capex)

δ_{solar}: Annual plant Degradation percentage

β_{solar}: Salvage value percentage of the Plant (of Capex)(at the end of 25 years)

$reqLand_{solar}$: Land Requirement (Acres/MW)

$land\_cost_{solar}$: Purchase cost of the land ($/Acre)

$land^{max}$: Max Land Available (Acres)

$CAPEX_{gas}$: Capital cost of Gas plant ($/MW)

$Opex\_per_{gas}$: Operational cost percentage(of Capex)

δ_{gas} : Annual plant degradation percentage

$fuelcost_{gas}$: Cost of fuel ($/MWh)

β_{gas} : Salvage value percentage of the Plant (of Capex)(at the end of 25 years)

$CAPEX_{battery}$: Capital cost of battery($/MWh)

$Opex\_per_{battery}$: Operational cost percentage($/MW) (of Capex)

$\gamma_{battery}$: Round Trip Efficiency of a battery %

$\alpha_{battery}$: Max depth of discharge %

$Min_{battery}$: min charging time for a battery = 1/0.5 = 2 hour

$CAPEX_{battery}^{decline}$: Annual decline in capital cost of battery (%)

$CAP1_{battery}$: Capacity of single battery (MWhr)

$cycles^{max}$: Maximum cycles

M: Big M factor for replacement balance

$solar_t$: Available Solar Power data at hour t (MW/MW Capacity of solar)

Variables:

Continuous Variables:

CAP_{solar}: Capacity of solar plant (MW)

CAP_{gas}: Capacity of Natural gas plant (MW)

$CAP_{battery}$: Energy Capacity of battery storage (MWhr)

$Land_{solar}$: Land Requirement for Solar plant (Acres)

$prod_{solar,t,y}$:Total Electricity production from solar at any time t in year y, (MW)

$prod_{solartobattery,t,y}$: Amount of Power sent from solar to battery storage at any time t in year y (MW)

$prod_{solartodemand,t,y}$: Amount of Power sent from solar to satisfy demand at any time t in year y, (MW)

$prod_{gas,t,y}$: Amount of power production from the gas plant at any time t in year y,

(MW)

$discharging_{battery,t,y}$:Amount of energy discharged by battery at any time t in year y (MWhr)

$charging_{battery,t,y}$: Amount of energy charged into battery at any time t in year y (MWhr)

$\mathrm{stor}_{\mathrm{battery},t,y}$: Battery storage at any time t in year y (MWhr)

$prod_{t,y}$: Total power production from all the sources, (MW)

$\mathrm{WASTE}_{t,y}$: Curtailment of excess power at any time t in year y (MW)

InitialStorage :initial battery storage (MWhr)

$discharge_{y}$: Total discharge from battery upto y years (MWhr)

Binary variables:

$replace_{y}$: replacement in year y

References:

[1] Bordin, C., Anuta, H. O., Crossland, A., Lascurain Gutierrez, I., Dent, C. J., & Vigo, D. A linear programming approach for battery degradation analysis and optimization in offgrid power systems with solar energy integration.
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