Liege Immersive Week

OPERATIONAL PLANNING AND SIZING

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PART 01: OPERATIONAL PLANNING

QUESTION NO: 01 Import the normalized load and power profile from profile.csv using your own yearly energy consumption.

The normalized load and power profile has been imported using the following syntax in utils.

```
data_df = pd.read_csv("profile.csv", index_col="DateTime",
                      parse_dates=True, date_format='%Y-%m-%d %H:%M:%S')
```

The yearly energy consumption of **7.5 MWh** has been considered for our case which is higher than the normalized base consumption of 4MWh (original data).

QUESTION NO: 02 Solve the operational planning problem (in OP opt.py) using a linear programming formulation. Here, the sizes of the devices are known, you just want to optimize the usage of each device to minimize OPEX.

To solve this, the objectives, constraints, and rules have been defined for three different cases: selling to the grid, giving it away and net-metering. In all cases, following points have been ensured for optimize usage of all the devices included:

- ✓ At every instant load demand is fully met and there is ***no load-shedding.***
- ✓ At every instant, high priority is of PV production while using grid and genset when necessary.
- ✓ All devices (PV panel, inverter, battery, generator) always ***operate within their defined operating limits***. Those devices whose power needs to pass through an additional device like PV and Battery must not exceed the inverter capacity as well.
- ✓ ***Reliable battery usage*** has been ensured while keeping SOC between 20% and 90%. The maximum charge/discharge rate of battery is also restricted by the pre-defined rate.
- ✓ Solver is bound to determine the ***optimal solution within defined limits***.

For all 3 cases, the criterion of optimization is the summation of different prices. Following matrix is showing the inclusion and exclusion of various pricing parameters in objective function for all 3 tariffs:

Pricing Parameter	Selling to Grid	Giving it away	Net Metering
Prosumer tariff	✗	✗	✓
Fuel price	✓	✓	✓
Grid Capacity price	✓	✓	✓
Grid Import price	✓	✓	✓
Grid export price	✓	✗	✗

QUESTION NO: 03 Compute the yearly system costs and compare you results for three different tariffs (net-metering, selling to the grid, or giving it away)

The optimized yearly costs and other parameters obtained by the solver for each case is given below:

Parameters	Selling to Grid (SG)	Giving it Away (GA)	Net Metering (NM)
Total negative energy (Consumption):			
Base consumption (kWh)	7499	7499	7499
Grid export (kWh)	6316	2885	5957
Battery charge (kWh)	2679	2679	1602
Total positive energy (Production):			
PV production (kWh)	12095	8665	7653
Genset production (kWh)	0	0	0
Grid import (kWh)	1980	1980	5957
Battery discharge (kWh)	2420	2419	1448
Optimal yearly cost (€)	**635**	**888**	**796**

As shown in the table above, grid export is reduced in the case of GA as compared to SG because of no cost benefits on exporting the units to grid, consequently the operation cost in GA is 40% higher than SG. However, for NM case, the solver has forced the export to be equal to import to maximize the cost benefit, resulting in lower operational cost compared to GA case but higher than SG due to no additional profit on export.

QUESTION NO: 04 What are the main decision variables in this problem?

The main decision variables are as follows:

- **model.gen_PV_sp**: It represents the output of PV panels, given that it should not exceed the PV and inverter capacities.
- **model.soc**: It monitors the energy stored in the battery at each time step. The initial SOC is set as 20% whereas upper and lower bounds are 90% and 20% respectively.
- **model.charge_storage_sp/model.discharge_storage_sp**: These variables determine the amount of power stored in or drawn from the battery at each time step.
- **model.imp_grid/model.exp_grid**: These variables represent the amount of electrical power fed to or taken from the grid.
- **model.steer_genset_sp**: It represents the power generated by diesel genset.

QUESTION NO: 05 What are the key parameters? How could they totally change the optimal results?

Approach: To evaluate the impact of key parameters on the optimal results, we have decreased and increased these parameters one by one. The consumption is changed by 20% whereas prices are changed by "2x" to see visible impacts w.r.t original case. The original case considered for this assessment is "Selling to the Grid" scenario and time period is "Yearly simulation".

Following are the important key parameters (other than asset sizes which are fixed for this case) impacting the optimal results:

- **Annual Consumption:** The optimal operation of all devices depends on the load consumption. Decreasing consumption results in overall cost reduction because of reduced grid import and battery operation. Also, this price reduction is also related to an increase in grid exports as the PV production is constant in both cases. Increasing consumption has the same reverse effects.
- **Grid Import Price:** By changing grid price, change is observed in the overall operational cost. Besides the cost variation, the decrease in grid price has no impact on energy production/consumption. But while increasing the import price, the energy production priority is shifted to genset from grid.
- **Grid Export Price:** Decreasing the export price increases the overall cost by 20% because of its impact on OPEX while no other impacts are observed. However, increasing by 2 times results in a decrease of overall OPEX by 4 times.
- **Genset Fuel Price:** Increasing this price has no impact on operational cost, however, by decreasing it by 2 times, the energy demand shifted to genset production that was previously being met through grid import. Also, it results in approximately a 50% decrease in the overall operational cost.
- **Grid Capacity Price:** Increasing and decreasing this leads to the increase and decrease in overall cost respectively because of its contribution in OPEX however no other impacts are observed.

QUESTION NO: 06 What are the strong assumptions made when solving this problem? Discuss.

There are several assumptions in our model which can be categorized as follows:

Deterministic Data:

- The model is provided with an assumed perfect Solar Irradiance data. However, intermittency is a major issue while dealing with renewable sources.
- Similarly, the model is provided with an assumed perfect load consumption for the whole year.

Perfect System Behavior:

- It has been assumed that throughout the operation, all the devices operate at their rated capacities with no consideration of degradation due to aging and operating conditions.
- The network is assumed to run at its perfect efficiency without incorporating any losses.

Market Behavior:

- One of the main assumptions lies with grid import and export prices. The prices are kept constant in the model throughout the duration of operation. Whereas these prices do fluctuate in the real world.

PART 02: SIZING

QUESTION NO: 01 Reformulate the optimization problem of the previous section as a sizing problem. Additional constraints are required, and the objective function must be adapted to include scaled CAPEX.

- In addition to previous decision variables, this optimization model for sizing problem also incorporates the device sizes as decision variable and the objective function is now the summation of CAPEX and OPEX.
- To get the cost "OPEX and CAPEX" for the same duration, we have taken the yearly share of "CAPEX" by dividing it with "INVESTMENT HORIZON".
- The CAPEX expression considers the installment cost of PV system, Inverter, Genset and storage system whereas OPEX expression has been the same as in part 01 for all three tariffs.

QUESTION NO: 02 and 03 Compute the optimal sizing considering only January. Apply the same procedure for June instead of January and finally for the whole year. Compare the results you obtain in each case.

The optimal sizing details along with their results for **"Selling to Grid"** are given in table below:

Parameters	January	June	Whole Year
Installed Capacities			
Storage Capacity (kWh)	6	20	18
Storage inverter capacity (kVA)	3	2	3
PV capacity (kWp)	10	9	10
PV inverter capacity (kVA)	2	5	6
Grid connection capacity (Amp)	8	8	15
Genset capacity (kVA)	1	0	0
Total negative energy (Consumption)			
Base consumption (kWh)	789	595	7499
Grid export (kWh)	13	726	6278
Battery charge (kWh)	140	345	2720
Total positive energy (Production)			
PV production (kWh)	152	1345	11705
Genset production (kWh)	30	0	0
Grid import (kWh)	632	9	2337
Battery discharge (kWh)	127	312	2455
Optimal cost (€)	**323**	**49**	**1329 (monthly average cost: 110.75)**
Performance Metrics			
Self Sufficiency (%)	19.92	98.44	68.83
Self-Consumption (%)	98.35	-22.17	16.28

Following key points are observed by comparing all the three cases:

- A high ***PV production*** is observed in the month of June (2.25 times higher than base consumption) whereas a low PV production is observed in January (20% of base consumption) which is directly related to the irradiance profile. Yearly PV production is also 1.56 times higher than its base consumption.
- Comparing the month of January to June, the ***storage size*** has been increased by 70% which is directly linked to high PV production in the month of June. Also, the optimized yearly storage capacity is close to the month of June. The reason behind this is a greater number of months with high PV production as compared to months with low PV production.
- The ***grid connection capacity*** is the same in the months of January and June, as this capacity is optimized based on the import (high for January) and export (high for June) values. For January, approximately 80% of load demand is met through grid import whereas for June this percentage is only 1.5%. The reverse is in the case of exports, for January the exports are 1.6% while for June this value is 1.22 times of base consumption. The difference in imports

and exports is directly related to high PV production. For the yearly case, the import and export % w.r.t base consumption is 31% and 87% respectively.

- ***Genset incorporation*** is only observed in the month of January as the PV production is low, and it is optimal to meet the load demand from genset production instead of completely importing from the grid.
- Comparing the ***cost*** of all three cases, January is the highest, June is the lowest while the monthly scaled average of year falls in between these two scenarios. The relation depends on the optimal usage of all devices with high priority of PV production.
- Comparing the ***performance metrics*** for all three cases, the highest self-sufficiency (low reliance on grid and genset) is observed in June whereas the highest self-consumption (direct consumption of PV production by load) is observed in January.
- A comparison of ***capacity utilization*** factors of various assets is shown below. The considered PF for inverter is 1.0 whereas for genset is 0.8.

Parameters (Utilization Factor)	January	June	Whole Year
Storage Capacity (%)	3	2	2
Storage inverter capacity (%)	6	24	11
PV capacity (%)	2	21	13
PV inverter capacity (%)	42	20	12
Genset capacity (%)	5	0	0

In general, among all the renewable sources, PV system has the lowest capacity utilization factors as per literature. This low factor is due to weather conditions, however optimal tilting angles of PV, shading analysis and other such techniques can help to maximize this utilization factor. For our case, in June, this factor is 21% whereas for January and yearly period, the values are low. The utilization factors for battery are related to the max charge discharge rate of battery which is already fixed as 1.8 in our case. Similarly, the capacity factor for storage inverter depends on battery charging/discharging whereas for PV inverter it depends on import/export from/to the grid.

QUESTION NO: 04 **Size the microgrid over the entire year considering the three export tariffs explained previously (giving it away, selling to the grid and net metering). How do these influence your results?**

Parameters	Selling to Grid (SG)	Giving it Away (GA)	Net Metering (NM)
Installed Capacities			
Storage Capacity (kWh)	18	18	0
Storage inverter capacity (kVA)	3	3	0
PV capacity (kWp)	10	10	6
PV inverter capacity (kVA)	6	3	4
Grid connection capacity (A)	15	10	17
Genset capacity (kVA)	0	0	1
Total negative energy (Consumption)			
Base consumption (kWh)	7499	7499	7499
Grid export (kWh)	6278	404	7406
Battery charge (kWh)	2720	3838	0
Total positive energy (Production)			
PV production (kWh)	11705	5952	7496
Genset production (kWh)	0	0	3
Grid import (kWh)	2337	2321	7406
Battery discharge (kWh)	2455	3468	0
Optimal yearly cost (€) *Monthly Average	**1329 (110.75*)**	**1548 (129*)**	**259 (21.5*)**
Performance Metrics			
Self Sufficiency (%)	68.83	69.03	1.25
Self-Consumption (%)	16.28	94.60	1.25

- In the case of **SG**, high grid capacity is observed due to the cost benefit on exporting the unit to grid, which also results in high PV production. Battery charging and discharging is also high in SG to reduce the need for import in absence of PV.
- In the case of **GA**, grid connection capacity is reduced. This is linked directly to the 0 price of exports which makes the grid export non profitable. A high PV curtailment and decline in export energy is also observed in GA due to the same reason. This ultimately results in high battery charging and discharging, leading to high self-consumption.
- While in the case of **NM**, no battery being sized to minimize the cost as the load demand is already being met with grid import and genset in absence of PV. Grid connection capacity is high due to high grid import and export but at the same time PV size and consequently its production is relatively lower to prevent excessive export and import to maximize the cost benefits from NM regulation.
- The **overall cost** is the lowest for NM followed by SG and is highest for GA. The low cost of NM is due to the total exclusion of battery system and reduced sizing of PV system to fulfill load demand and prevent excessive export.

QUESTION NO: 05 What are the main decision variables in this problem?

In addition to operational variables (as in part 01), some key sizing variables are being introduced in the problem to consider capex while performing optimization. Following are the variables:

- **storage_energy_capacity**: It determines the battery storage capacity.
- **storage_inverter_capacity**: It is the inverter capacity connected to battery.
- **PV_capacity**: It is the optimized installed capacity of PV.
- **PV_inverter_capacity**: It gives the value of inverter capacity connected to PV.
- **grid_capacity:** It is the value of maximum power transfer to/from the grid.
- **genset_capacity**: It gives the installed capacity of genset.

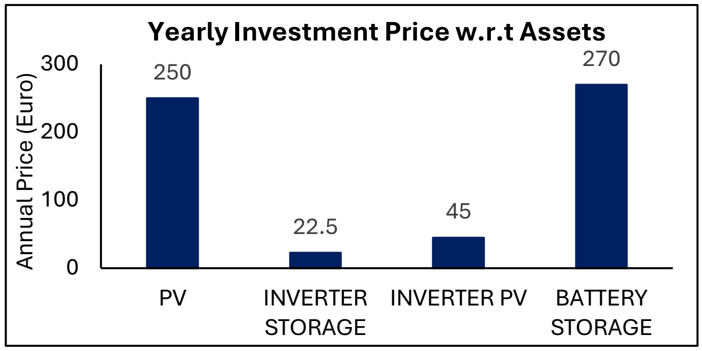
QUESTION NO: 06 What are the key parameters? Describe their impact on the results. How would a change in these parameters affect the results?

In this case, along with the key parameters discussed in part 01, question 05 (annual consumption, grid import/export price, genset fuel price and grid capacity price) following are the additional parameters which will impact the optimal results:

- **PV Capacity:** Decreasing the PV max capacity decreases the PV production and consequently increases the overall cost as the self-sufficiency of the system is compromised. The impact will be seen as an increase in grid connection capacity and imports. The reverse impacts are observed in case of increasing the PV capacity.
- **Inverter Price:** Increasing the inverter price by 2 times has an increase of 5% in the overall cost. The impact is co-related to a slight decrease in the export unit and inverter capacity as well as a slight increase in the storage capacity.
- **Storage Price:** A significant increase of 14% in overall cost is observed by increasing storage price by 2 times. Consequently, storage capacity has been decreased by 50% whereas import and export have been increased to minimize the cost.
- **PV Capacity Price:** Increasing the PV capacity price by 2 times increases the overall cost because of its contribution in CAPEX however, no visible impacts are observed in sizing and operation parameters. The reason being that PV is already sized at its maximum capacity bounded by the code i.e., 10kWp. However, decreasing the PV price by 2x and increasing the max capacity by 2x at same time reduces the cost by 44%. The PV has now been sized at 20kWp (at maximum), grid import has been reduced, exports have considerably increased and 12% improvement in self-sufficiency is witnessed.
- **Genset Price:** Genset Price has no considerable impact as genset production is not considered even by decreasing the price by 2 times, as it is not the optimal solution for our scenario.
- **Investment Horizon:** Investment horizon has a direct impact on cost as it determines time-period of recovering the initial investment. Decreasing it by 4 years increases the cost by 10% whereas increasing it by 4 years has a detrimental impact on the overall cost.

QUESTION NO: 07 Discuss the results and show how the asset sizes are linked. Also show the usage and price of each investment. Discuss the savings they create.

Our optimization algorithm well sized the system by keeping in view the objectives of no loadshedding, high PV priority, reliable battery usage and low or no genset usage. The PV system size (10kWp) is sufficient to meet the load demand and export the energy to the grid keeping in view the grid tariffs and cost benefit. (18 kWh) storage capacity is well designed to fully meet the load demand through energy storage in absence of PV. Similarly grid connection capacity in different tariff modes is well utilizing the grid in absence of PV and storage energy while minimizing the cost of the system.



The annual cost of the system is a summation of the CAPEX and OPEX of the designed system i.e., 1329 €. A breakup of this annual investment w.r.t each asset (selling to grid case) is shown in the graph.

To further investigate the linkage between asset sizes and costing, we have designed an approach where the asset sizes are changed one by one and CAPEX over 20 years horizon is calculated and consequently savings are determined. For this, firstly an upper bound was assigned to all the sizing variables. To see the visible impact by changing asset sizes, this bound was given the value equal to the sizing that was frequently being achieved by the solver for that asset in various cases pre simulated as shown in snippet. This bound was then decreased by a factor "0.8" for each asset and solver was forced to choose new optimum lower than normal optimum values. The simulated cases and their results are shown in table below:

```
# Sizing variables
model.storage_energy_capacity = Var(within=NonNegativeReals, bounds=[0,18e3])
model.storage_inverter_capacity = Var(within=NonNegativeReals, bounds=[0,3e3])
model.PV_capacity = Var(within=NonNegativeReals, bounds=[0,PV_MAX_CAPACITY])
model.PV_inverter_capacity = Var(within=NonNegativeReals,  bounds=[0,6e3])
model.grid_capacity = Var(within=NonNegativeReals, bounds=[8,15])
model.genset_capacity = Var(within=NonNegativeReals, bounds=[0,6e3])
```

Assets	Storage capacity (kWh)	Storage inverter capacity (kVA)	PV capacity (kWp)	PV inverter capacity (kVA)	Genset capacity (kVA)	CAPEX (€)	CAPEX Savings (€)
Base Case (Optimal asset sizes and CAPEX over 20 years investment horizon)							
	17	3	10	6	0	11450	
Modified Scenarios (Assets sizes are reduced one by one by factor of 0.8 of their base case)							
Storage energy capacity	14	2	10	6	0	10400	1050
Storage inverter capacity	16	2	10	6	0	11000	450
PV capacity	15	3	8	5	0	9700	1750
PV inverter capacity	17	3	10	4	0	11150	300
Genset capacity	17	3	10	6	0	11450	0

The gray highlighted size is the reduced optimal asset size in each scenario.

Following comparison is drawn with the base case (CAPEX: €11450):

- When storage energy capacity reduces, decrease in storage inverter capacity, and increase in grid capacity is observed. This results in around €1050 savings on CAPEX relative to base case.
- Reduction in storage inverter capacity also leads to similar changes in optimization as storage energy capacity, and results in around €450 savings on CAPEX.
- Forcing the reduced PV capacity creates the highest savings of €1750 on CAPEX due to reduction in sizes of linked assets, that are, PV inverter capacity, storage energy capacity, and grid capacity.
- Reducing the size of PV inverter capacity leads to reduction in grid capacity and creates the savings of around €300 on CAPEX.
- Genset capacity has no impact whatsoever because the optimized solution does not size the genset due to high fuel price that leads to higher overall cost.

The adopted approach provided a linkage between asset sizes and CAPEX savings when the solver is forced to reduce the sizes one by one. However, the base case (for all three tariffs) still proves to be an optimal solution for our case, keeping in view that total cost (CAPEX+OPEX) is lowest in the base case.

QUESTION NO: 08 **Solve the same problem after removing the grid connection to isolate your house from the grid.**
The system optimal sizes, energy units and performance in isolation from grid are given in table below:

Parameters	Values
Installed Capacities	
Storage Capacity (kWh)	20
Storage inverter capacity (kVA)	3
PV capacity (kW)	10
PV inverter capacity (kVA)	3
Grid connection capacity (A)	0
Genset capacity (kVA)	2
Total negative energy (Consumption)	
Base consumption (kWh)	7499
Grid export (kWh)	0
Battery charge (kWh)	5061
Total positive energy (Production)	
PV production (kWh)	5726
Genset production (kWh)	2266
Grid import (kWh)	0
Battery discharge (kWh)	4569
Optimal yearly cost (€) *Monthly Average	1708 (*142)
Performance Metrics	
Self Sufficiency (%)	100
Self-Consumption (%)	100

As the system is isolated from the grid now, grid import, and export quantities have no role in the results. The optimal sizing of the system is such that the PV production and Genset production can fully meet the load consumption with no load-shedding for the entire year.
Compared with grid connected scenarios, the storage capacities are being increased as well as genset production is considered. This change is directly related to achieving 100% self-sufficiency as there is no grid available. The yearly cost is also increased as to size and operate the system to be able to 100% self-sufficient and self-consumed in terms of load demand.

QUESTION NO: 09 **For the previous cases, compute the yearly CO2 emissions. Discuss your findings**.
In this case, two types of emissions, i.e., fixed and variable have been computed for each tariff. Fixed emissions are mainly dependent on the installed capacities of the equipment (PV, storage system, Inverter and genset) whereas variable emissions are dependent on grid import/export units and genset production.

CO2 Yearly Emissions	Selling to Grid	Giving it Away	Net Metering	Isolated
Variable Emissions (grams)	1499.28	475.53	2578.49	679.8
Fixed Emissions (grams)	1067052.41	1062132.12	583872.98	1075246.65
Total Emissions	**1068551.69**	**1062607.65**	**586451.48**	**1075926.46**

- For **variable emissions**, there is a considerable decrease in "GA" case as compared to the "SG" case which is directly related to low export in the former scenario. In the case of NM, the variable emissions are the highest due to high import/export and slight genset production. The variable emission in isolated case depends on the genset production only as there is no import or export from grid is involved.
- Comparing the **fixed emissions**, the value marginally differs in the case of SG and GA as the sizing parameters do not vary much in these cases. The slight decrease in GA case is due to a decreased size of PV inverter capacity and

grid capacity as compared to SG case. For NM case, the exclusion of battery system and decreased PV size accounts for low fixed emissions. For the isolated case, the fixed emissions are the highest due to an increased capacities of storage system and genset consideration.

QUESTION NO: 10 How would you implement such an algorithm considering uncertain forecasts instead of perfect predictions? How would it affect the results? Discuss.

- To consider the uncertainties, the algorithm will be modified and may consider the stochastic methods for determining the optimal system sizing. Instead of relying solely on precise predictions, the revised model would integrate probability distribution forecasts for factors such as PV generation and household consumption. These forecasts could be drawn from various sources such as historical data, weather forecasts, and machine learning techniques like the Monte Carlo method, or a combination thereof.
- Additionally, the use of AI (neural networks) may be employed to forecast the weather and load models.
- Shading analysis may be explored to maximize the PV production w.r.t to changing weather conditions.
- Additionally, introducing a secondary objective to minimize peak shaving would improve overall system efficiency and grid stability. This approach ensures more accurate and practical solutions for microgrid operation and management.

BONUS PART: CONNECTION OF ELECTRIC VEHICLE:

To incorporate the EV, **"selling to the Grid"** case is chosen as a representative case and the results and comparison is discussed in accordance with the selected case. The results for EV connection are given below:

Parameters	Operational Planning Part	Sizing Part
Installed Capacities		
Storage Capacity (kWh)		18
Storage inverter capacity (kVA)		9
PV capacity (kWp)		10
PV inverter capacity (kVA)		6
Grid connection capacity (A)		15
Genset capacity (kVA)		0
Total negative energy (Consumption)		
Base consumption (kWh)	7499	7499
Grid export (kWh)	6197	6169
Battery charge (kWh)	2920	3128
EV Charge (kWh)	9782	10117
Total positive energy (Production)		
PV production (kWh)	12095	11758
Genset production (kWh)	0	0
Grid import (kWh)	2093	2452 2300
Battery discharge (kWh)	2638	2824 2455
EV discharge (kWh)	9573	9879
Optimal yearly cost (€)	685	1434

In the case of **operational planning**, after including EV, the operational cost has increased by 8%. This increase can be linked with an increase in grid import and decrease in grid export as compared to the "SG case without EV". The increase in grid import can be related to the excess energy needed to charge the EV.

In the case of **sizing part**, there is a considerable increase observed in the storage inverter capacity as it has increased by 3 times compared to case without EV. This increase can be explained as the storage inverter is now being utilized to discharge the EV. The other assets have not seen any considerable change in their designed capacities. In the case of operation, grid export has reduced while grid import has increased which indicates that excess PV power and increased import are now being utilized to charge the EV. Consequently, the cost has been increased by 8%.