Operational planning and sizing

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Operational Planning

1)

The goal of the code is to minimize operational costs by optimally using 10 kW of PV, 40 kWh of battery, grid, generator, and EV under physical and economic constraints.

$$\text{OPEX minimization} = \Delta t \cdot (PI_{gen} \cdot P_{gen}(t) + PI_{imp} \cdot P_{imp}(t) - PI_{exp} \cdot P_{exp}(t))$$

Constraints:

Table 1. Constraints of the operational planning system

Constraint Type	Equation / Condition
Power Balance	$P_{pv} + P_{gen} + P_{dis,bss} + P_{dis,ev} + P_{imp} = P_{load} + P_{ch,bss} + P_{ch,ev} + P_{exp}$
PV Production Limits	$P_{pv} \leq P_{nom,pv}$
Battery SOC limits	$SOC_{min,bss} \leq SOC_{bss} \leq SOC_{max,bss}$
Battery SOC update	$SOC_{bss}[t] = SOC_{bss}[t-1] + \Delta t \cdot (\eta_{bss} \cdot P_{ch,bss}[t-1] - \frac{P_{dis,bss}[t-1]}{\eta_{bss}})$
EV SOC limits	$SOC_{min,ev} \leq SOC_{ev} \leq SOC_{max,ev}$
EV SOC update	If connected: $SOC_{ev}[t] = SOC_{ev}[t-1] + \Delta t \cdot (\eta_{ev} \cdot P_{ch,ev}[t-1] - \frac{P_{dis,ev}[t-1]}{\eta_{ev}})$ Else: $SOC_{ev}[t] = SOC_{ev}[t-1]$
Generator Capacity Limit	$P_{gen} \leq P_{max,gen}$
Export Limit	$P_{exp} \leq P_{pv} + P_{gen}$

2)

Table 2. Total cost of the system over a year

Component	Value (EUR)
Grid Import Cost	496.78
Generator Fuel Cost	0.00
Export Revenue	–231.06
Total Net Cost	265.72

The simulation confirms that PV was the primary energy source and the battery managed surplus and deficit periods effectively, while EV charging aligned with connection schedules and consistently met departure SOC targets. Minimal grid imports occurred, mainly during winter nights. The total net cost of €265.72 demonstrates the model's success in minimizing operational expenses while ensuring reliability and high self-sufficiency. In addition, since the generator's cost was higher than the cost of importing electricity, the system chose to rely on grid imports, which had no usage limit. As a result, the generator fuel cost is zero as shown in Table 2.

3)

Table 3. Key parameters impacting the system operation

Parameter	Explanation	Impact on Optimal Results
Annual Consumption	Decides which resources are required and how much they should be used.	Higher demand increases need for imports or genset usage. Combined with yearly EV km, this becomes a key driver of system sizing and scheduling.
Grid Import Price (`PI_imp`)	Cost of electricity bought from the grid.	High prices discourage imports and encourage battery/PV usage low prices may increase grid reliance or trigger genset usage when imports become too costly.
Export Tariff (`PI_exp`)	Income from selling surplus PV electricity.	Higher export price promotes more PV generation for sale. Low price favors storing or consuming PV locally.
EV Target SOC (`SOC_target_ev`)	Ensures EV is ready to drive.	Higher target increases charging load during connection, affecting dispatch strategy of other assets.
Power Ratings	Device limits on how fast energy can be delivered or absorbed.	Limits flexibility during high demand periods; may force reliance on imports or load shedding if insufficient.
Battery Inverter Rating	Defines how much power can be charged/discharged at once	limits flexibility during peak load or solar generation.
Generator Fuel Cost (`PI_gen`)	Cost of running genset.	If reduced, the generator may become favorable. In high-import scenarios, a low fuel price could make genset operation cost-effective despite emissions.

4)

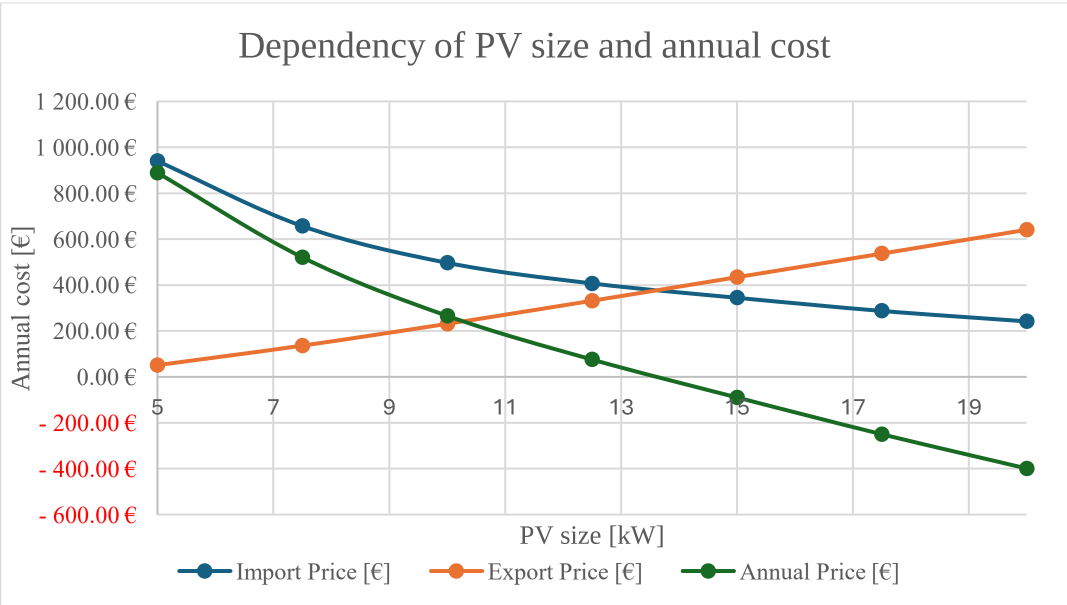

Figure 1: Dependency of PV size and annual cost

As it can be observed in Figure 1, the graph of the income from export is linear, but the import cost is non-linear, hence the total annual price (operational cost) is also not linear as it is the sum of these two. If the storage system size had also been changed, it would lead to linear change in the import price as well. The reason is that we have to import energy during nighttime, when there is no PV production and since the battery size is not big enough, we cannot use it to discharge to satisfy the whole consumption.

5)

Table 4: Monthly data for Net Cost, Self-consumption, Self-sufficiency, BSS and PV usage

	Net Cost	Self-cons	Self-suff	BSS usage [kWh]	PV usage [kWh]
Jan	146.88 €	14.64 %	9.26 %	12.41 kWh	381.07 kWh
Feb	48.47 €	11.00 %	13.96 %	16.88 kWh	845.74 kWh
Mar	-24.74 €	9.53 %	18.41 %	18.06 kWh	1418.35 kWh
Apr	-38.76 €	9.24 %	24.74 %	9.13 kWh	1851.03 kWh
May	-23.31 €	15.36 %	30.89 %	10.98 kWh	1649.56 kWh
Jun	-28.19 €	12.48 %	27.76 %	12.30 kWh	1696.16 kWh
July	-27.49 €	7.87 %	19.49 %	8.75 kWh	1612.62 kWh
Aug	-22.93 €	13.48 %	25.46 %	15.72 kWh	1501.67 kWh
Sep	-24.74 €	9.61 %	18.16 %	23.05 kWh	1561.53 kWh
Oct	10.72 €	10.68 %	13.46 %	29.17 kWh	1021.39 kWh
Nov	90.32 €	13.04 %	10.58 %	11.84 kWh	458.01 kWh
Dec	143.06 €	18.91 %	10.90 %	4.83 kWh	308.84 kWh

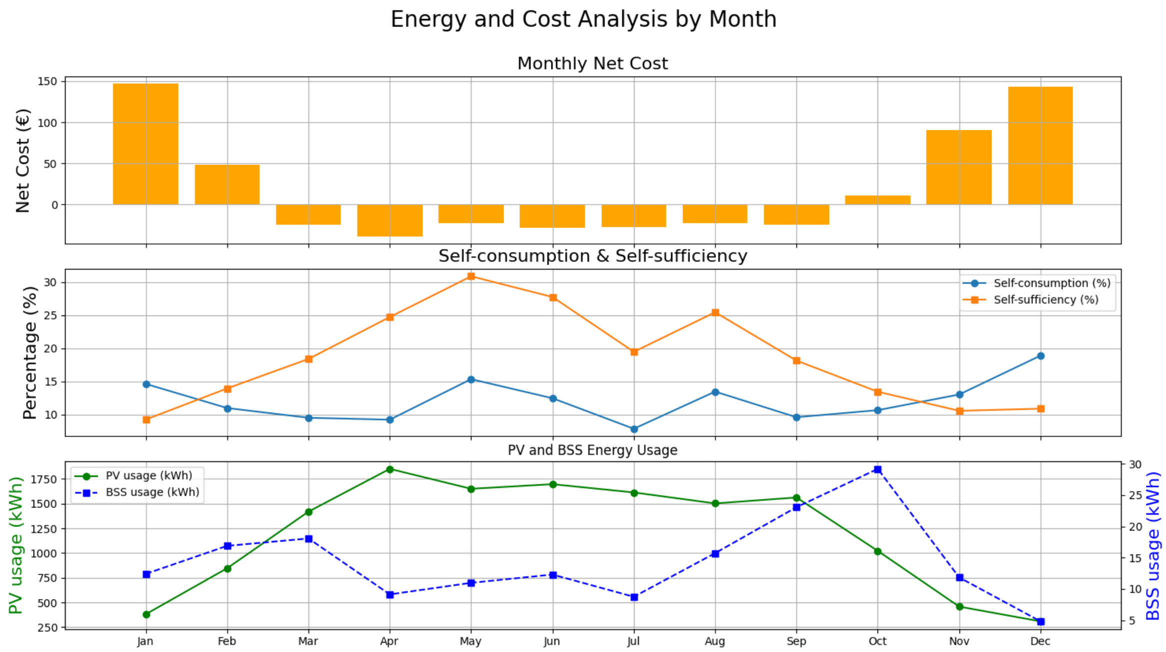

Figure 2: Energy and Cost Analysis by Month for a Year

10 kWp PV, 40 kWh battery capacity, 10 kW max generator power.

$$\text{Self} - \text{Consumption} = \frac{\text{used on\_site generation}}{\text{Total energy generation}}$$

$$\text{Self} - \text{Sufficiency} = \frac{\text{used on\_site generation}}{\text{Total energy demand}}$$

It can be seen in *Table 4* and *Figure 2* that from March to September, the monthly net cost of the system is negative meaning they sell for more than the import and generator fuel cost. It means that much more energy is exported as the export price is significantly lower than the import price and the generator price (0.03 €/kWh compared to 0.4 €/kWh and 0.6 €/kWh)

The PV produces more power than the system consumes, however since the PV is intermittent power source, it produces during the day and the battery storage system is not big enough to store all the excess energy which leads to a low self-consumption and self-sufficiency ratio and it also leads to exporting it on a very low price (0.03 €/kWh). In these months the net cost is negative which means that we export for more money than we import.

It can also be observed that the generator is not used since we have grid access and it is cheaper to import than to use the generator (0.4 €/kWh compared to 0.6 €/kWh).

6)

A few assumptions were made during the simulation:

- Fix cost for import price, export price and generator fuel price: In real life these prices could change even during the day
- Generator fuel cost is lower than the import price, so there will be no generator use
- Annual EV usage distribution: In real life there would be days when we use the car more and days when we use it less or even not use at all
- No limit for the import/export: we can import as much as we want instead of using the generator as it is cheaper and not limited
- No minimum power for the generator: Unlike in real life, this could cause flickering which is bad for the machine

Sizing

1)

For the sizing part, the same constraints were used as for the operational planning one. Major difference in the code is that this time the size of the PV, battery storage system and inverters were not given, so these were set as variables instead of giving them a fixed value like in the first part of the assignment.

The objective function had to be modified. While for operational planning, the operational cost had to be minimized, in this case the investment cost also has to be used. It is important that the CAPEX must be scaled per year for an investment horizon of 20 years. This is necessary otherwise the investment cost will be extremely high compared to the operational cost, leading to using only the grid to import the energy instead of local production by PV or generator. If it is scaled to 1 year, it will be worth it to invest in PV because in a scale of 20 years it will be profitable.

$$\text{Total cost minimization} = \Delta t \cdot \left(\mathrm{PI_{gen}} \cdot \mathrm{P_{gen}}(t) + \mathrm{PI_{imp}} \cdot \mathrm{P_{imp}}(t) - \mathrm{PI_{exp}} \cdot \mathrm{P_{exp}}(t)\right) + (\mathrm{PI}_{C,PV} \cdot C_{PV} + \mathrm{PI}_{C,BSS} \cdot C_{BSS} + \mathrm{PI}_{inv} \cdot C_{inv} + \mathrm{PI}_{C,gen} \cdot C_{gen}) \cdot \left({}^{n_{days}}/_{(investment\ horizon \cdot 365)}\right)$$

2-3)

Table 5: Sizing results for simulating only for January, June and a year

	January	June	Year
PV size [kW]	9.02	9.79	8.81
PV inverter size [kW]	9.02	9.79	8.81
Battery capacity [kWh]	29.08	24.23	22.91
Battery inverter [kW]	4.58	3.30	3.51
Generator size [kW]	0.00	0.00	0.00
EV charger [kW]	10.00	10.00	10.00
EV battery capacity [kWh]	60.00	60.00	60.00
Load [kWh]	465.99	369.54	4500.00
Import [kWh]	413.27	35.39	1818.00

Export [kWh]	19.21	1062.91	6626.30

As it can be seen in Table 5, there is a difference between the sizing if it is done only for January, only for June or for the whole year. Previously it was expected that the PV size will be higher in January than in June thanks to the lower irradiance and the higher load, but the simulation results show it is actually lower. The reason behind this is that in January the system relies on the grid more, importing more than 88.6% of the total load. It happens because due to the low irradiance, the system would have to be oversized in order to have a higher self-consumption. Another reason is that on the other hand, in June the system is sized to have a higher PV size and the reliance on the grid is lower, only 35.39 kWh is imported, while a larger amount is exported. Because of the higher irradiance, it is worth it to oversize our system a bit in order to satisfy the load and the extra energy can be either stored or sold to the grid. For the whole year simulation, in the sizing all the months have to be taken into account, that is why the size of the PV and battery are lower than either January or June as in December these are 6.03 kW PV and 5.71 kWh battery.

The generator is not used in any of the cases as the import price is still cheaper than the generator fuel price and in case of the generator, the investment cost also has to be added to the costs.

4)

When simulating for the whole year, with the investment horizon of 20 years, the costs are the following:

Table 6: Price of the system for the annual simulation

	Annual cost [EUR/year]	Total cost [EUR/20 years]
PV	793.34	15866.8
Battery	320.69	6413.8
Inverters	92.47	1849.4
Generator	0.00	0.00
Total CAPEX/year	**1206.50**	**24130**
Import	727.20	14544
Export	-198.79	-3975.8
Generator	0.00	0.00
Total OPEX	**528.41**	**10568.2**
Total Cost	**1734.91**	**34698.2**

As Table 6 shows, the majority of the CAPEX cost comes from the PV being responsible for more than 65% of total investment cost. This shows that the PV has a significant role in the solution. After the PV, the storage system is the second most costly in terms of investment cost. Even though the price is lower than the PV, but the price is also much cheaper (280 EUR/kWh compared to 1800 EUR/kW) leading to a higher battery capacity. The investment cost for the inverters (both for PV and battery) is negligible compared to the other CAPEX costs. The generator is not used due to its high price.

In terms of operational cost, we can see that the annual cost for energy import is nearly as high as the PV investment cost. Import is needed because the PV is intermittent and in order to satisfy the load when PV is not available, either huge oversizing is needed for both PV and battery system, or we rely on the grid import. Despite avoiding the oversizing, there is still a nice income coming from the export income.

5)

The combination of export tariffs and import costs in annual micogrid sizing is performed below:

- Export tariff: 0.000, 0.062,0.092 Euro/kwh (reflecting German EEG 2023 feed-in-tariff variation [Source]

- Import costs: 0.40, 0.30, 0.25EUR/kWh (based on retail and wholesale electricity price trends [Source]

From that, we defone two sets of simulation:

i) Scenario group 1: Varying Export Tariff, Fixed Import Cost

- Import Cost: Fixed at 0.40 EUR/kWh.
- Export Tariff Variations:
  - Scenario 1: 0.000 EUR/kWh (no feed-in tariff)
  - Scenario 2: 0.062 EUR/kWh
  - Scenario 3: 0.092 Euro/kWh

The optimisation below is illustrated in Table 7

Table 7: Sizing Results with varying Export Tariff

Sc	PV Size (kW)	BESS Size (KWh)	Generator size (kW)	Import (kWh)	Export (kWh)	CAPEX/year (EUR)	OPEX/ year (EUR)	Total Cost/ year (EUR)
1	6.16	23.39	0.00	2306.99	1587.54	950.40	922.79	1873.20
Base	8.81	29.08	0.00	1818.00	6626.30	1206.50	528.41	1734.91
2	24.54	21.88	0.00	902.36	28196.53	2724.16	-1387.24	1336.91
3	50	21.87	0.00	535.97	64244.60	5208.15	-5696.12	-487.96

ii) Scenario group 2: Fixed Export Tariff, Varying Import Cost

- Export Tariff: Fixed at 0.062 EUR/kWh (standard feed-in tariff for 40–750 kW rooftop PV).
- Import Cost Variations:
  - Scenario 6: 0.3 EUR/kWh (current residential tariff)
  - Scenario 7: 0.2 EUR/kWh
  - Scenario 8: 0.1 EUR/kWh
- The optimisation below is illustrated in Table 8

Table 8: Sizing Results with varying Import Cost

Sc	PV Size (kW)	BESS Size (KWh)	Generator size (kW)	Import (kWh)	Export (kWh)	CAPEX/year (EUR)	OPEX/ year (EUR)	Total Cost/ year (EUR)
Base	8.81	29.08	0.00	1818.00	6626.30	1206.50	528.41	1734.91
1	6.72	19.11	0.00	2371.85	4208.09	942.84	585.31	1528.15
2	4.75	12.15	0.00	3356.35	2445.38	647.75	597.91	1245.66
3	0.61	0.00	0.00	6855.61	187.63	59.00	679.93	738.93

Conclusion:

- Higher export tariffs incentivize large PV systems with greater grid feed-in, shifting the system toward a producer model.

- Lower import costs discourage local generation and storage investment, making grid reliance more economical.
- The microgrid system shifts its design priorities based on the balance between export incentives and import cost savings.

6)

i) Increase in annual consumption (30 % in each scenario starting from 4500 kWh):

Table 9: Sizing Results with varying increase in Load Consumption

Sc	PV Size (kW)	BESS Size (kWh)	Generator size (kW)	Import (kWh)	Export (kWh)	CAPEX/year (EUR)	OPEX/ year (EUR)	Total Cost/ year (EUR)
0	8.81	22.91	0.00	1818.00	6626.30	1206.50	528.41	1734.91
1	10.23	26.25	0.00	2182.96	7629.50	1395.93	644.30	2040.23
2	11.69	32.10	0.00	2460.23	8591.84	1623.59	726.34	2349.93
3	13.13	35.71	0.00	2832.22	9637.97	1817.71	843.75	2661.46

ii) increase in kilometres per year (30 % in each scenario starting from 15000 km):

Table 10: Sizing Results with varying increase in Kilometre of EV

Sc	PV Size (kW)	BESS Size (kWh)	Generator size (kW)	Import (kWh)	Export (kWh)	CAPEX/year (EUR)	OPEX/ year (EUR)	Total Cost/ year (EUR)
0	8.81	22.91	0.00	1818.00	6626.30	1206.50	528.41	1734.91
1	10.01	25.86	0.00	2030.81	7606.08	1368.97	584.14	1953.11
2	11.11	29.97	0.00	2220.26	8408.93	1537.01	635.84	2172.84
3	12.16	33.48	0.00	2446.43	9178.87	1691.93	703.20	2395.13

As both annual load and kilometers driven per year increase by 30% increments:

- PV size, battery size (BESS), import energy, export energy, CAPEX/year, OPEX/year, and Total cost/ year all increase progressively.
- The growth is nearly linear across all parameters.

7, Discussion of Results and Asset Size Linkages from

From Table 5, across January, June, and the full year, the capacity and the inverter size can be observed below:

- Model: PV inverter size = PV capacity (AC/DC ratio = 1.0).
- Real life: PV inverter is often undersized (~0.8 ratio) to reduce cost and improve efficiency [Source].
- Model: BESS capacity/ Inverter ratio is ~0.14–0.16, meaning a 6–7-hour discharge time (1/0.15 ≈ 6.6 hours).
- In practice, residential systems tend to have: Battery inverter power ≈ 0.3–0.5 C-rate, meaning the inverter can discharge the battery fully in about 2–3 hours if needed [Source].

”The End”