smart
Pulse

PV AND BATTERY ENERGY MANAGEMENT OPTIMIZATION

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TABLE OF CONTENTS

Project Definition

“This project aims to optimize the energy flows of a PV and battery system using PV forecasts and electricity prices, and to analyze the economic performance.”

OBJECTIVES

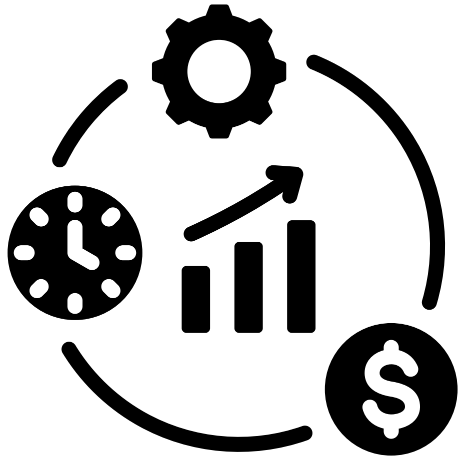
- Optimize electricity delivered from PV, Grid and Battery
- Maximize net profit
- Ensure energy management within constraint limits

SCENARIOS

- a) PV Only: No battery, PV production is sold directly to the market.
- b) Battery Only: No PV, energy is charged from the grid and discharged to the market.
- c) PV + Battery: Combined system operation.

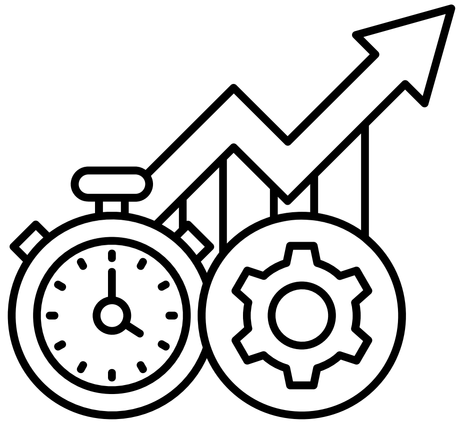
GOALS

- Electricity from PV to Grid (MW, hourly, scenario 1 and 3)
- Electricity from PV to Battery (MW, hourly, scenario 3)
- Electricity from Battery to Grid (MW, hourly, scenario 2 and 3)
- Electricity from Grid to Battery (MW, hourly, scenario 2 and 3)
- Battery Energy Content (SOC) (MWh, hourly, scenario 2 and 3)
- Total Financial Revenue (TL, scenario 1-2-3 comparison)
- Total Battery Usage (Total Discharge, MWh) and Battery Usage Cost (TL) (scenario 2 and 3)
- Comparison of financial revenues and battery usage costs across 3 scenarios



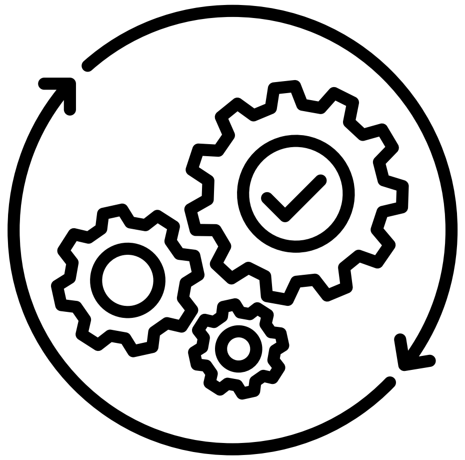
PROBLEM TYPE

- Linear Optimization Problem (LP)
- Objective: Maximize net profit subject to linear operational constraints



MODELİNG LANGUAGE

- Pyomo (Python-based optimization modeling language)
- Open-source, flexible, widely used for mathematical programming
- Enables integration with Python libraries (data, visualization, analysis)



SOLVERS USED

GLPK (GNU Linear Programming Kit):

- Open-source LP/MIP solver
- Used for testing and reproducibility

CBC (Coin-or Branch and Cut):

- Open-source solver specialized in LP and MIP
- Efficient alternative to GLPK

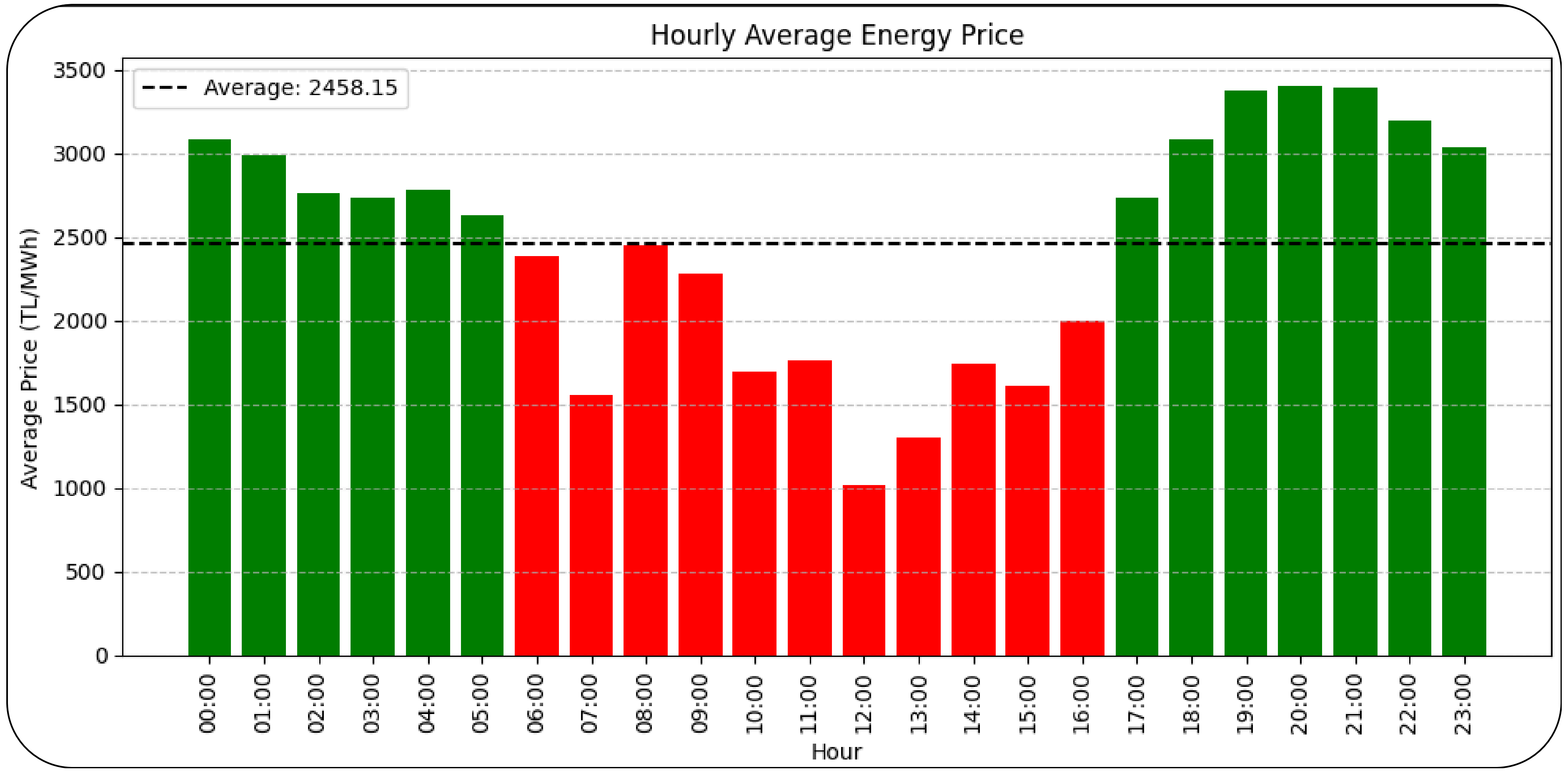
Technical Information of PV AND Battery

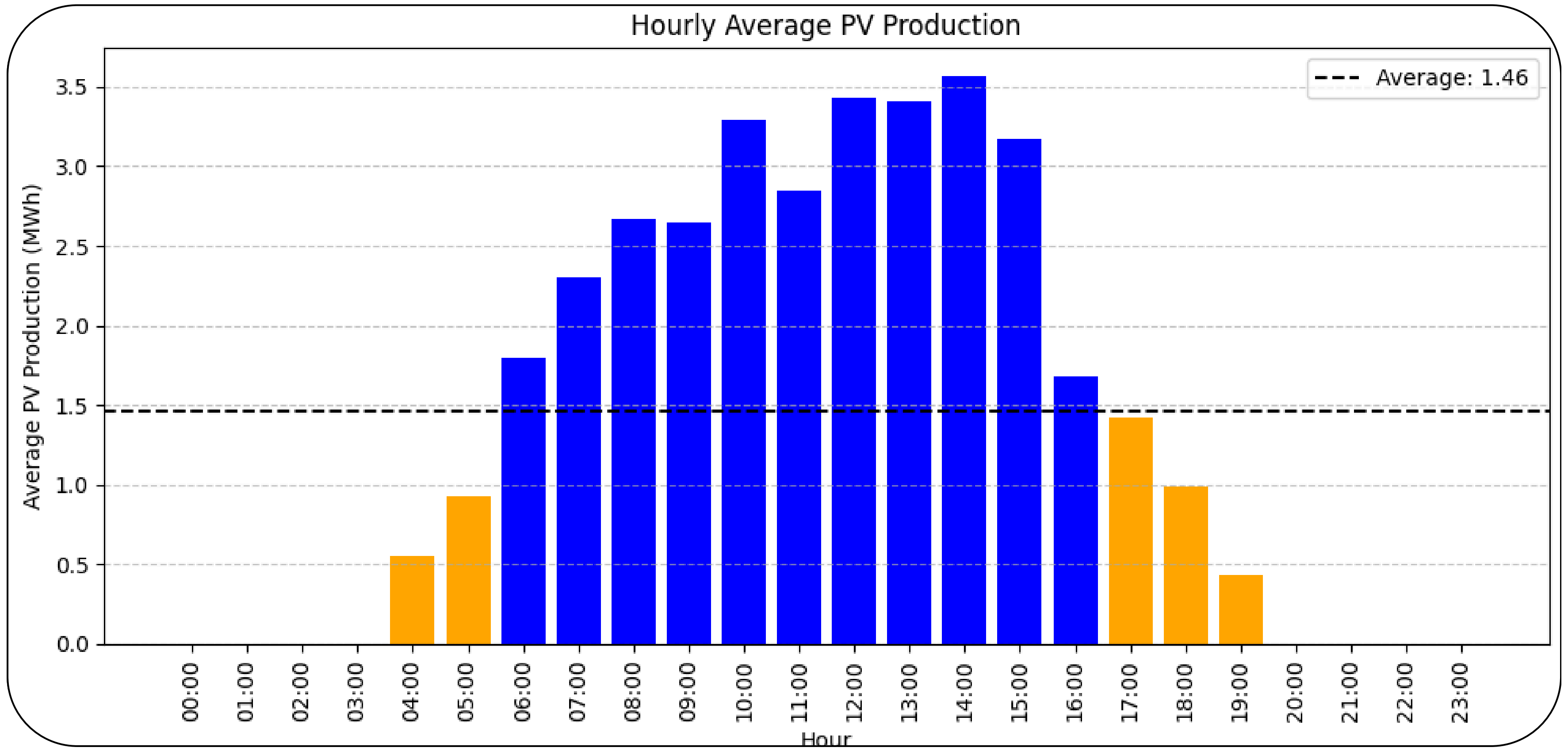
Parametre	Değer	Birim
PV Kapasitesi	5	MWh
Batarya Kapasitesi	10	MWh
Batarya Gücü	5	MW
Şarj Verimliliği	90	%
Deşarj Verimliliği	90	%
Minimum Batarya Doluluğu	10	%
Maximum Batarya Doluluğu	90	%
Batarya Kullanım Maliyeti	600	TL/MWh
Şebeke Kapasitesi	8	MW
Başlangıç Enerji Miktarı	5	MWh
Bitiş Enerji Miktarı	1	MWh

Dataset

- PV Production Forecast (MWh): Hourly PV generation forecast
- Price (TL/MWh): Hourly electricity prices

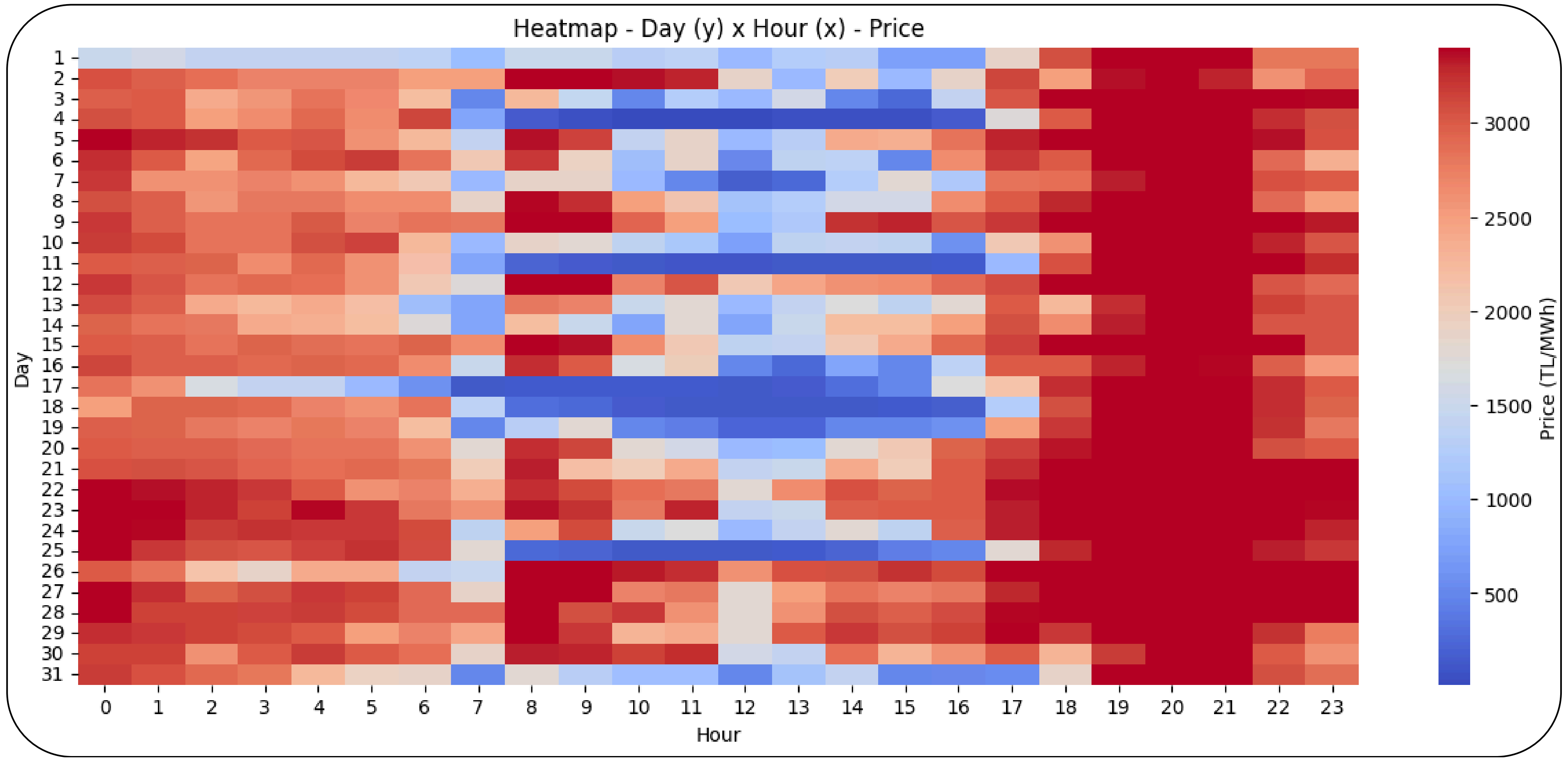
DATA ANALYSIS

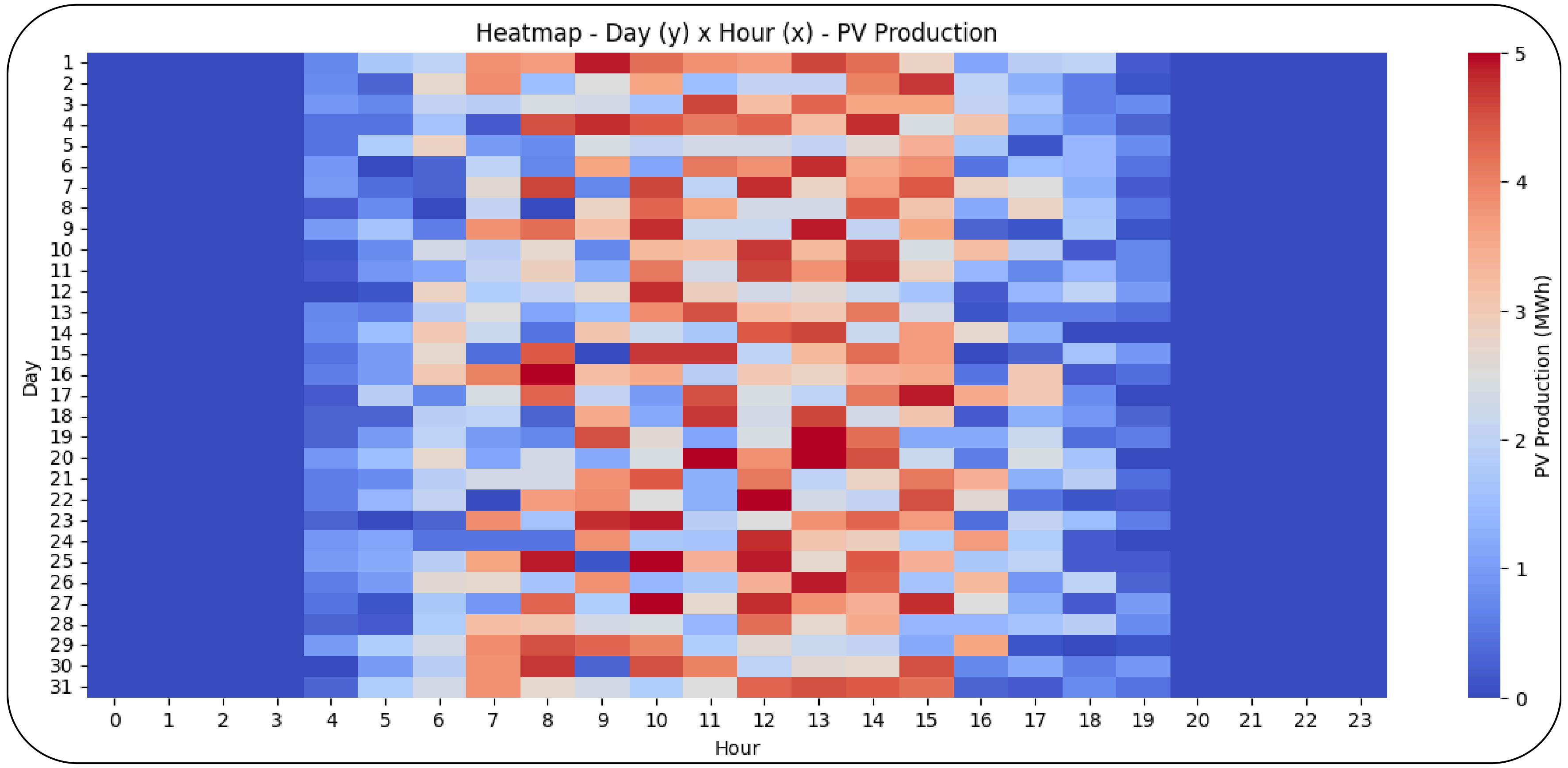




INSIGHT

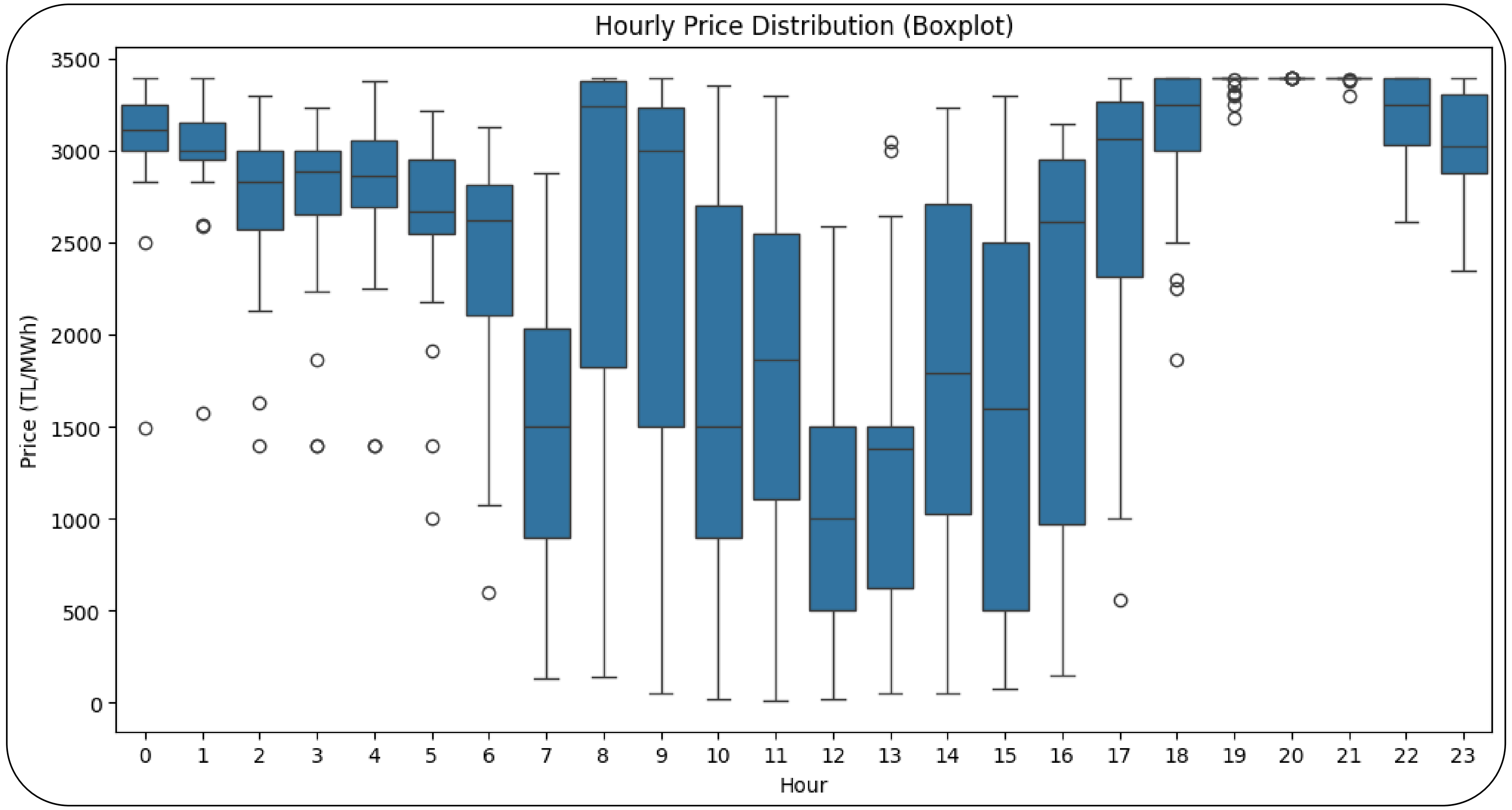
- Between 06:00 and 16:00, PV generation is consistently above the overall average, while energy prices remain below the average.
- During these hours, it is beneficial to charge the battery using PV production and, if needed, additional energy from the grid.
- In contrast, during the other hours of the day, when PV generation is low and energy prices rise above the average, the stored energy in the battery can be discharged and sold to the market to maximize profit.

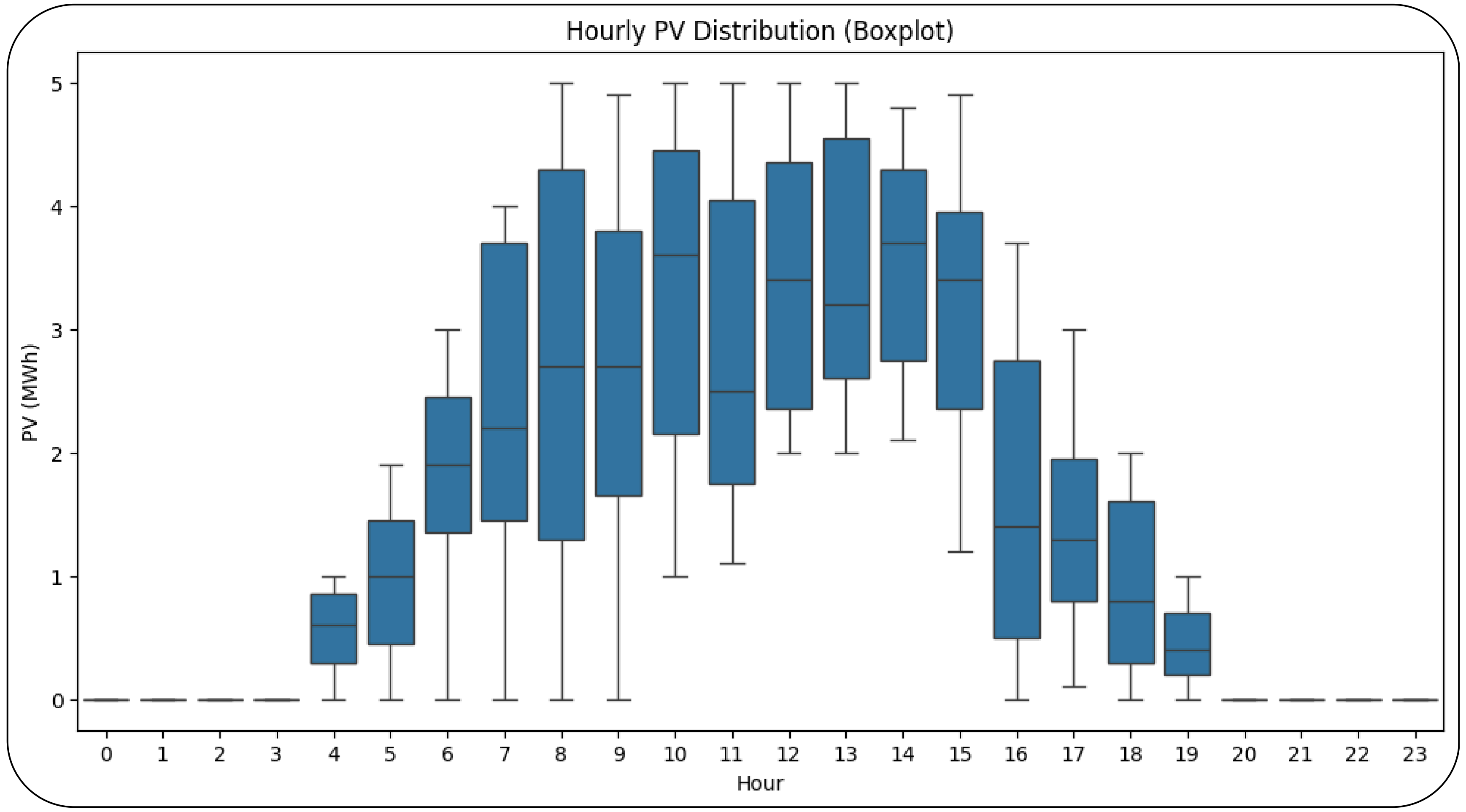




INSIGHT

- The heatmaps clearly illustrate the hourly patterns of both PV production and energy prices.
- Between 06:00 and 16:00, PV production is consistently high, while energy prices remain relatively low.
- This indicates that during these hours, it is optimal to charge the battery using PV generation and, if necessary, additional energy from the grid.
- Outside of these hours, when PV production drops and energy prices increase, the stored energy can be discharged and sold to the market to maximize profit.





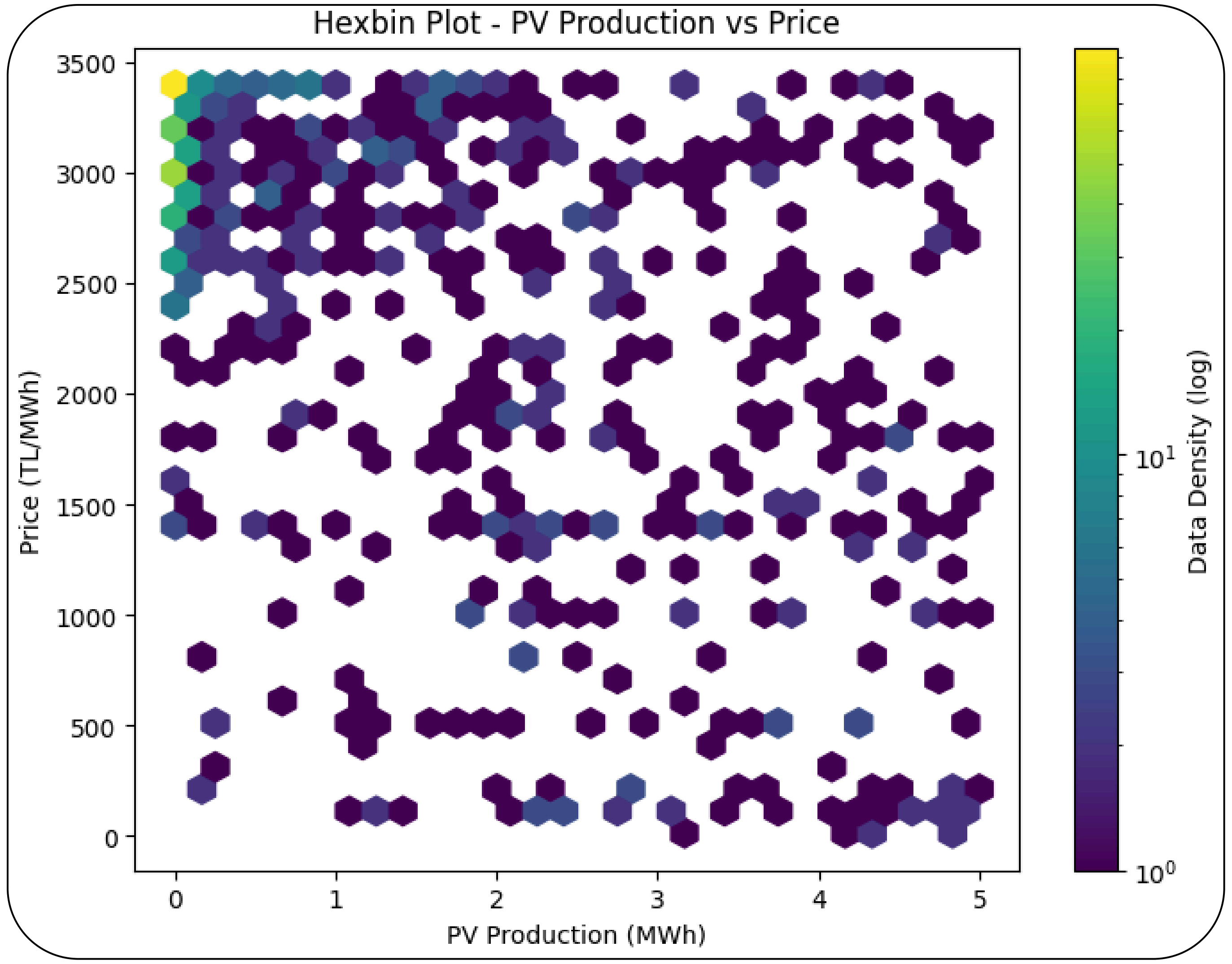
INSIGHT

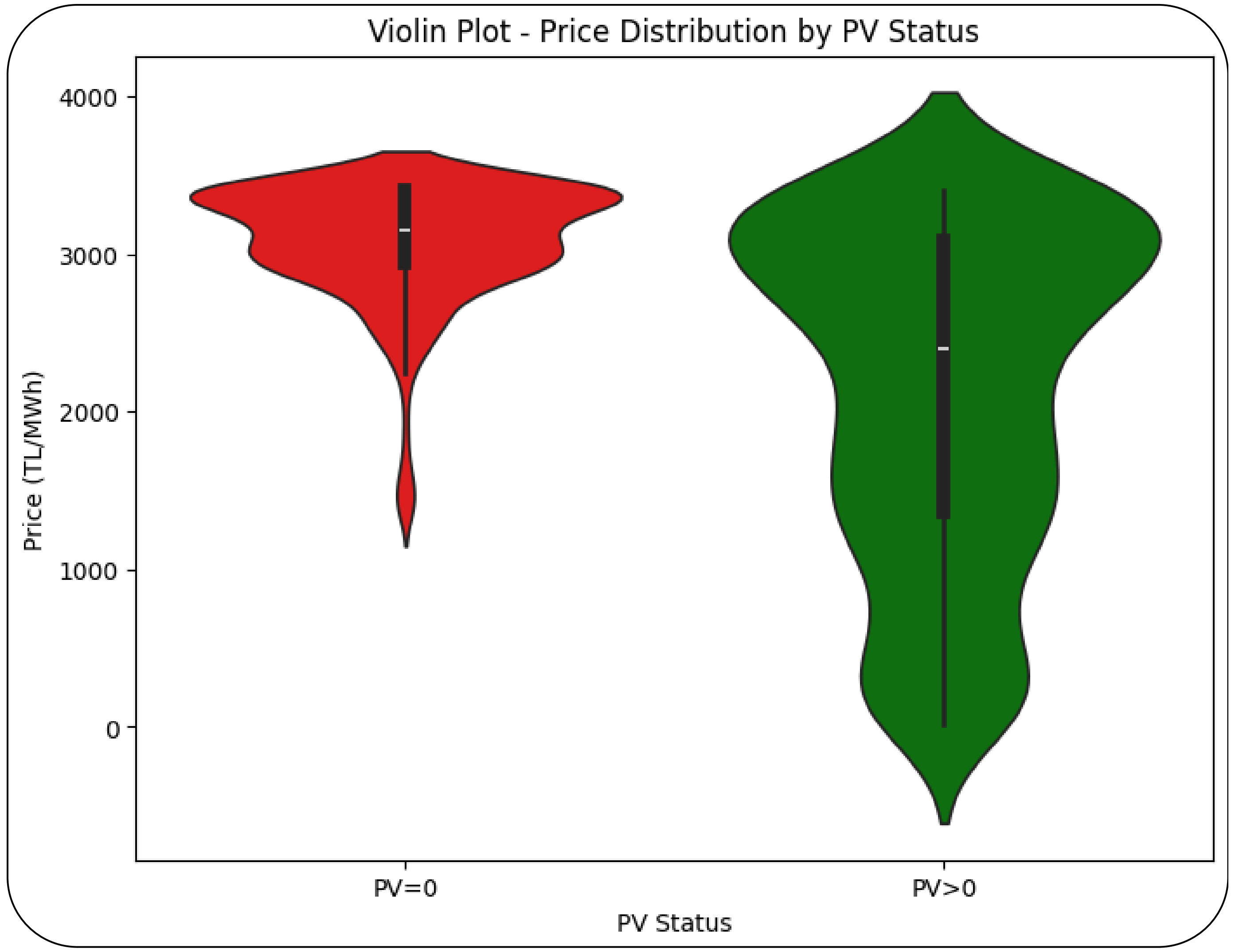
Price Distribution (Boxplot):

- Between 00:00–05:00 and 18:00–23:00, prices are relatively high.
- At 06:00 and 17:00, prices are around the average.
- From 07:00–16:00, prices are generally low, with particularly low prices at 07:00, 12:00, and 13:00. These low-price periods are ideal for charging the battery.

PV Distribution (Boxplot):

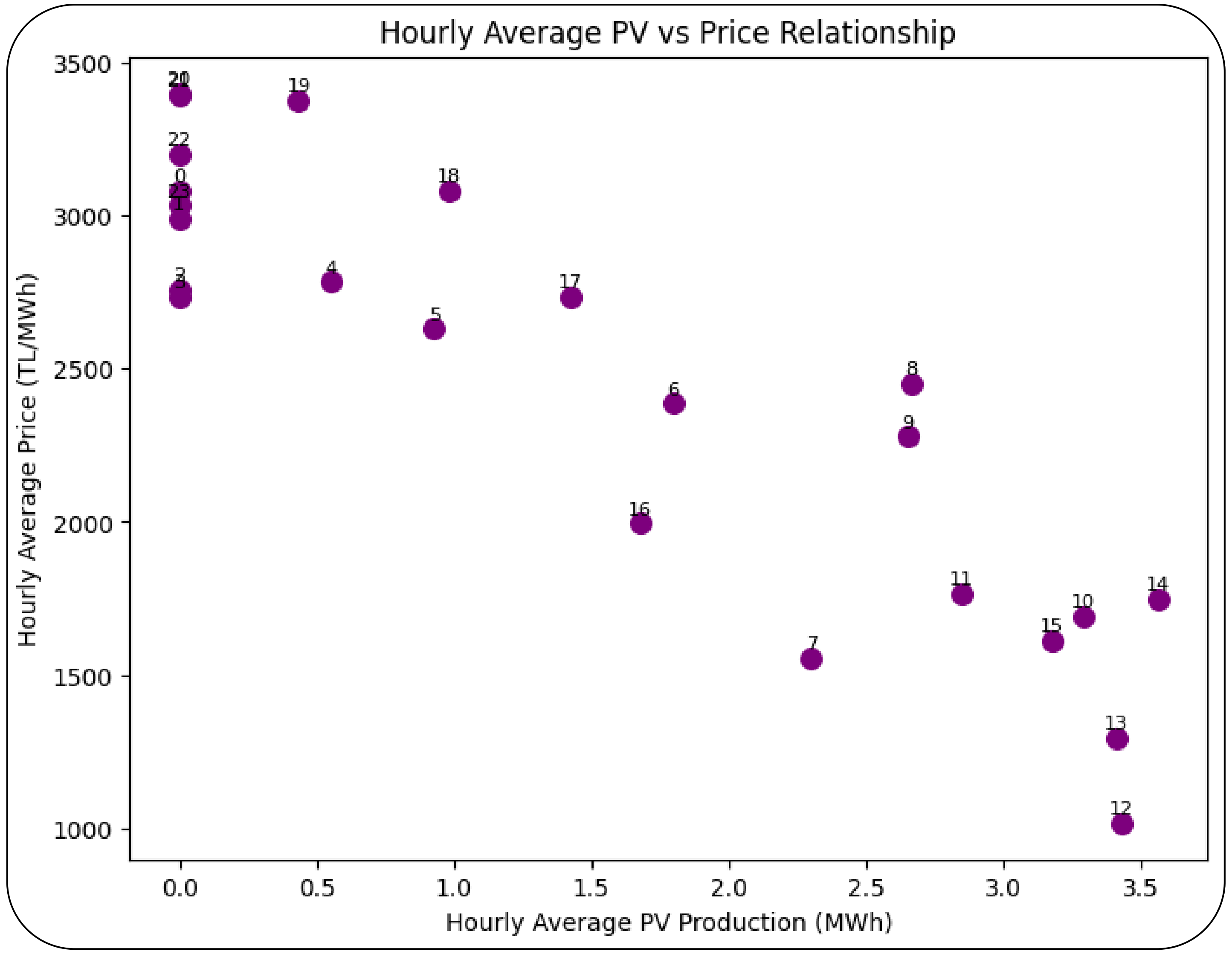
- PV production is low between 00:00–06:00 and 17:00–23:00, and zero between 00:00–03:00 and 20:00–23:00.
- At 06:00 and 17:00, production is around the average.
- From 08:00–15:00, PV production is high, providing an opportunity to charge the battery from PV.





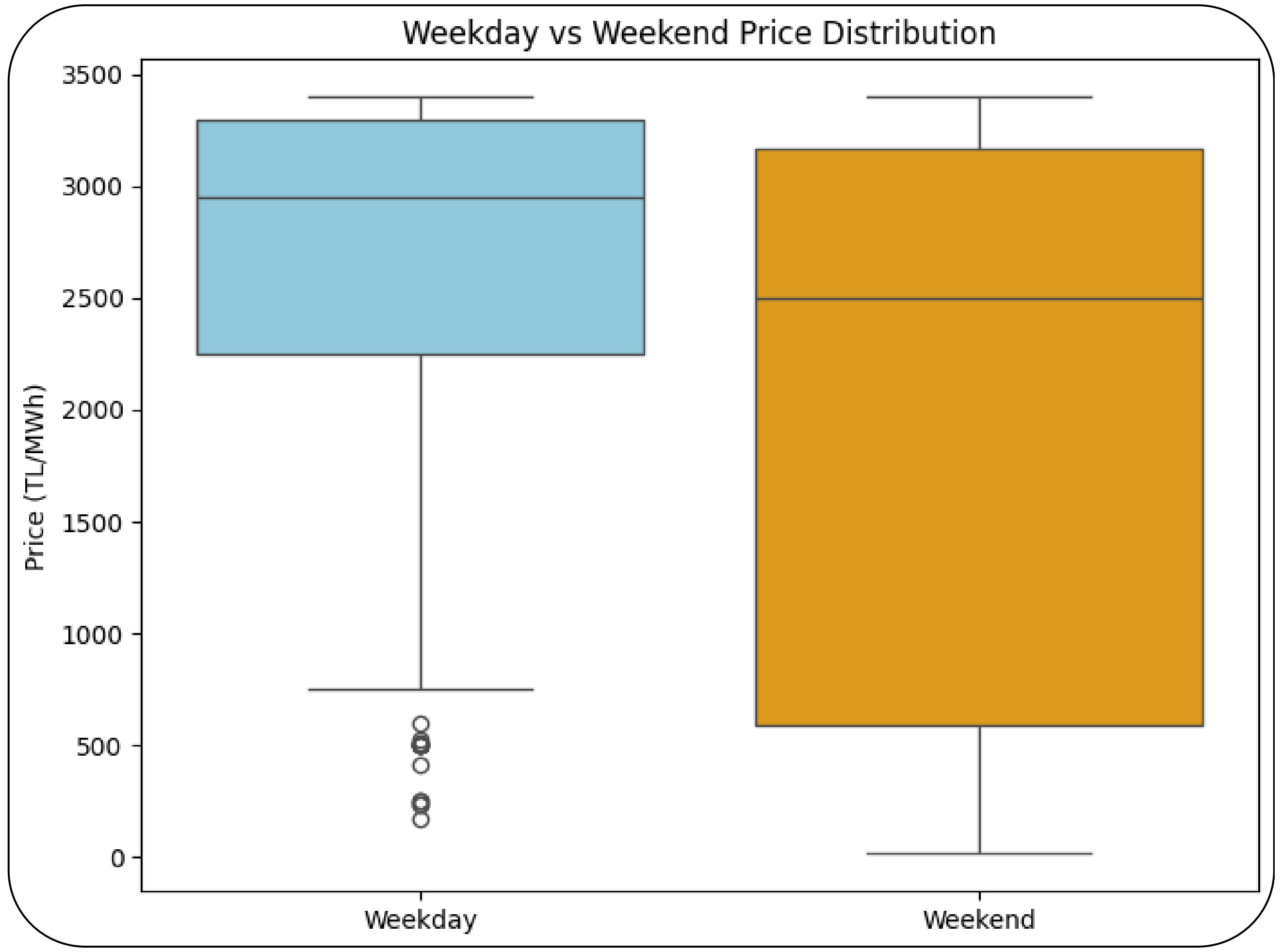
INSIGHT

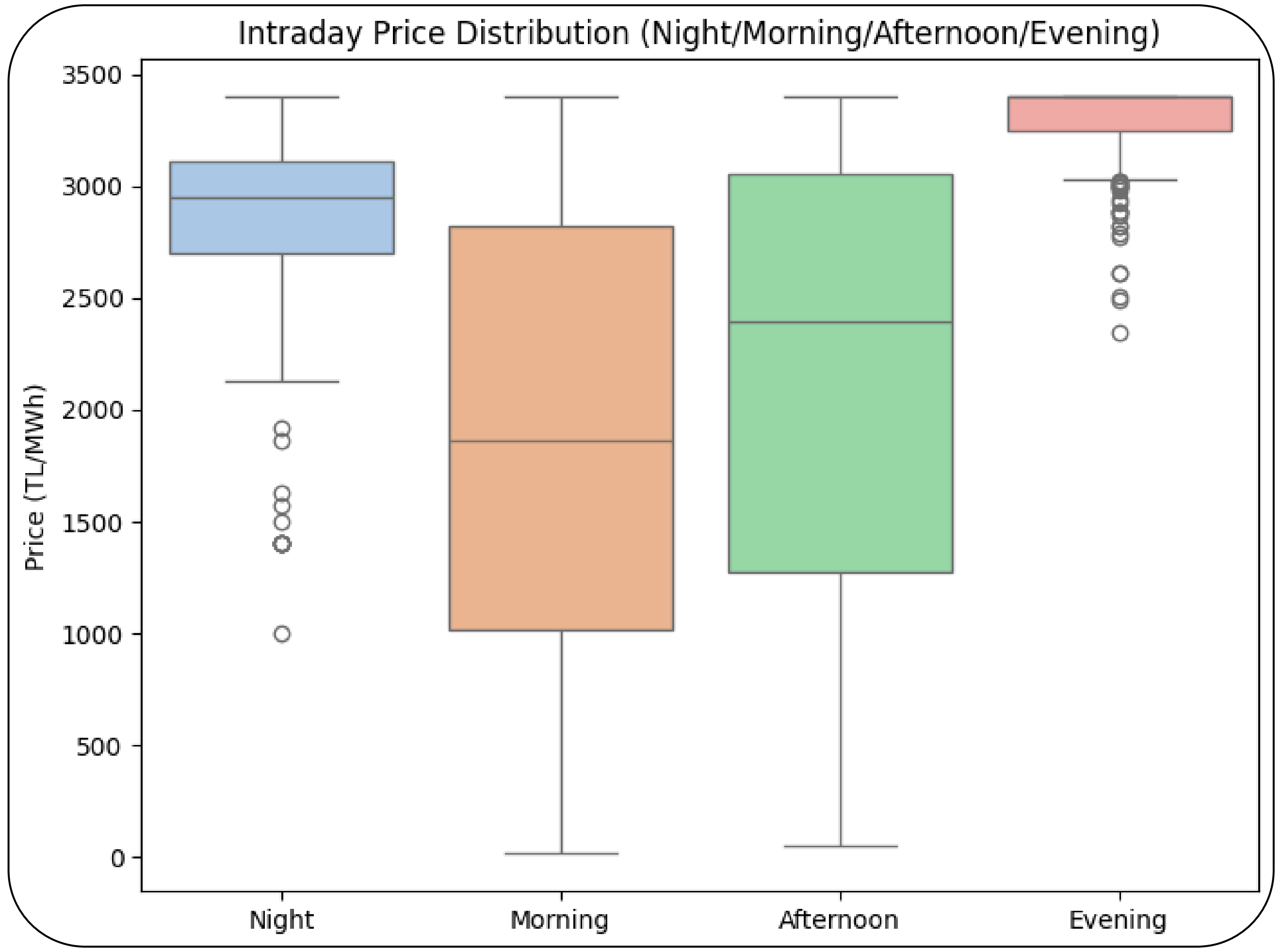
- **Hexbin Plot:** It is evident that prices are particularly high when PV production is low, indicating an inverse relationship between PV generation and energy prices.
- **Violin Plot:** When PV production is zero, energy prices tend to be consistently higher, highlighting the impact of PV availability on market prices.
- **Conclusion:** Both plots emphasize the importance of battery storage, allowing energy to be stored during high PV production / low-price periods and discharged during low PV / high-price periods to optimize profit.



INSIGHT

- In the upper-left region of the scatter plot (low PV production, high prices), it is optimal to discharge the battery to sell energy at higher prices.
- In the lower-right region (high PV production, low prices), it is advantageous to charge the battery using PV generation and, if needed, additional grid energy.





INSIGHT

Weekday vs Weekend Boxplot:

- During weekdays, it is generally more profitable to discharge the battery due to higher prices.
- During weekends, it is advantageous to charge the battery, as prices are typically lower.

Time-of-Day Boxplot:

- Daytime and noon hours are ideal for charging the battery, when prices are lower and PV production is higher.
- Evening and night hours are optimal for discharging the battery, taking advantage of higher energy prices.

SCENARIO A

Model A

SETS - PARAMETERS

Sets:

$$\mathcal{T} = \{0, 1, 2, \dots, T-1\} \quad \text{(time periods, hours)}$$

Parameters:

$$\begin{aligned} p_t &: \text{Electricity price (TL/MWh)}, && \forall t \in \mathcal{T} \\ PV_t &: \text{Forecasted PV production (MWh)}, && \forall t \in \mathcal{T} \\ \text{grid\_capacity} &= 8 \text{ MW} \end{aligned}$$

CONSTRAINTS

Constraints:

1. PV flow constraint:

$$PV_t^{grid} = PV_t \quad \forall t \in \mathcal{T}$$

2. Grid capacity constraint:

$$PV_t^{grid} \leq 8 \quad \forall t \in \mathcal{T}$$

DECISION VARIABLES

Decision Variables:

$$PV_t^{grid} \geq 0 \quad \forall t \in \mathcal{T} \quad \text{(PV energy fed into the grid)}$$

OBJECTIVE FUNCTION

Objective Function:

$$\max \sum_{t \in \mathcal{T}} p_t \cdot PV_t^{grid}$$

Model A

INSIGHT

- In Scenario A, there is no battery storage.
- As a result, all PV generation is directly fed into the grid.
- Total PV energy delivered to the grid: 1,089.40 MWh
- Total financial revenue from PV sales: 2,019,824.90 TL

SCENARIO B

Model B

SETS - PARAMETERS

Sets

$$T = \{0, 1, 2, \ldots, T-1\} \quad \text{(time periods)}$$

Parameters

- Electricity price at time t:

$$\text{price}_t \quad \forall t \in T$$

- Battery parameters:

$$C_{\text{bat}} = 10 \text{ MWh (battery capacity)}$$
$$P_{\text{bat}}^{\max} = 5 \text{ MW (max charge/discharge power)}$$
$$\eta_{\text{ch}} = 0.90 \text{ (charging efficiency)}$$
$$\eta_{\text{dis}} = 0.90 \text{ (discharging efficiency)}$$
$$E_{\min} = 0.10 \cdot C_{\text{bat}} = 1 \text{ MWh (minimum battery level)}$$
$$E_{\max} = 0.90 \cdot C_{\text{bat}} = 9 \text{ MWh (maximum battery level)}$$
$$E_{\text{init}} = 5 \text{ MWh (initial energy)}$$
$$E_{\text{final}} = 1 \text{ MWh (final energy)}$$
$$c_{\text{usage}} = 600 \text{ TL (battery usage cost)}$$
$$P_{\text{grid}}^{\max} = 8 \text{ MW (grid capacity)}$$

DECISION VARIABLES

Decision Variables

For each time period $t \in T$:

$$g_t \geq 0 \quad \text{Energy charged to the battery from the grid (MWh)}$$
$$d_t \geq 0 \quad \text{Energy discharged from the battery to the grid (MWh)}$$
$$E_t \geq 0 \quad \text{Battery charge level (State of Charge, MWh)}$$

Model B

CONSTRAINTS

1. Battery Charge Balance (State of Charge Dynamics)

For $t = 0$:

$$E_0 = E_{\text{init}} + \eta_{\text{ch}}\, g_0 - \frac{d_0}{\eta_{\text{dis}}}$$

For $t = 1, 2, \ldots, T-1$:

$$E_t = E_{t-1} + \eta_{\text{ch}}\, g_t - \frac{d_t}{\eta_{\text{dis}}}$$

Where:

- E_t = battery charge level at time t
- g_t = energy charged to the battery from the grid
- d_t = energy discharged from battery to the grid
- $\eta_{\text{ch}}, \eta_{\text{dis}}$ = charging/discharging efficiencies

2. Battery State of Charge Bounds

$$E_{\min} \le E_t \le E_{\max}, \quad \forall t \in T$$

3. Charge/Discharge Power Limits

$$0 \le g_t \le P_{\text{bat}}^{\max}, \quad \forall t \in T$$

$$0 \le d_t \le P_{\text{bat}}^{\max}, \quad \forall t \in T$$

4. Grid Capacity Constraint

$$g_t + d_t \le P_{\text{grid}}^{\max}, \quad \forall t \in T$$

5. Initial and Final Battery Charge

$$E_0 = E_{\text{init}}, \quad E_{T-1} = E_{\text{final}}$$

OBJECTIVE FUNCTION

$$\max\ Z = \underbrace{\sum_{t \in T} d_t \cdot \text{price}_t}_{\text{Revenue from battery discharge}} - \underbrace{\sum_{t \in T} g_t \cdot \text{price}_t}_{\text{Cost of charging from grid}} - \underbrace{\sum_{t \in T} d_t \cdot c_{\text{usage}}}_{\text{Battery usage/operational cost}}$$

Where:

- g_t = energy charged to battery from grid at time t
- d_t = energy discharged from battery to grid at time t
- price_t = electricity price at time t
- c_{usage} = cost parameter per MWh of battery discharge

Objective:

$$\max Z = \sum_{t \in T} \left(d_t \cdot \text{price}_t - g_t \cdot \text{price}_t - d_t \cdot c_{\text{usage}} \right)$$

Model B

INSIGHT

Battery-Only Scenario – Summary Metrics

- Total Battery Charge: 362.22 MWh (energy stored from the grid)
- Total Battery Discharge: 297.00 MWh (energy supplied back to the grid)
- Total Battery Usage Cost: 178,200.00 TL
- Total Charging Cost: 355,195.00 TL (cost of purchasing energy from the grid to charge the battery)
- Total Revenue from Battery Discharge: 939,418.10 TL
- Net Profit: 406,023.10 TL

Insights:

- The battery allows for energy arbitrage by charging during lower-price periods and discharging during higher-price periods.
- Even after accounting for charging and usage costs, the battery-only operation achieves a net profit of 406,023.10 TL. This demonstrates the economic value of battery storage in capturing price differences across hours.

SCENARIO C

Model C

SETS - PARAMETERS

Sets

$$T = \{0, 1, 2, \ldots, |T| - 1\} \quad \text{(hourly time periods)}$$

Parameters

- $C^{PV} = 5$ MWh (PV capacity)
- $C^{bat} = 10$ MWh (battery capacity)
- $P^{bat} = 5$ MW (maximum charging/discharging power)
- $\eta^{ch} = 0.90$ (charging efficiency)
- $\eta^{dis} = 0.90$ (discharging efficiency)
- $SOC^{min} = 0.10 \cdot C^{bat} = 1$ MWh (minimum state of charge)
- $SOC^{max} = 0.90 \cdot C^{bat} = 9$ MWh (maximum state of charge)
- $c^{use} = 600$ TL/MWh (usage cost)
- $C^{grid} = 8$ MW (grid capacity)
- $E^{init} = 5$ MWh (initial battery energy)
- $E^{final} = 1$ MWh (final battery energy requirement)

Time-series parameters

For each $t \in T$:

- $p_t = \text{price at time } t \; [TL/MWh]$
- $PV_t = \text{PV production forecast at time } t \; [MWh]$

DECISION VARIABLES

Decision Variables

For each $t \in T$:

- $x_t^{PV \to G} \geq 0$
  Energy sent from PV to the grid (MWh).
- $x_t^{PV \to B} \geq 0$
  Energy sent from PV to the battery (MWh).
- $x_t^{G \to B} \geq 0$
  Energy sent from the grid to the battery (MWh).
- $x_t^{B \to G} \geq 0$
  Energy discharged from the battery to the grid (MWh).
- $SOC_t \geq 0$
  Battery state of charge at time t (MWh).

OBJECTIVE FUNCTION

$$\max \; Z = \underbrace{\sum_{t \in T} p_t \cdot \left(x_t^{PV \to G} + x_t^{B \to G}\right)}_{\text{Revenue from selling to grid}} - \underbrace{\sum_{t \in T} p_t \cdot x_t^{G \to B}}_{\text{Cost of buying from grid}} - \underbrace{\sum_{t \in T} c^{use} \cdot x_t^{B \to G}}_{\text{Battery usage cost}}$$

Model C

CONSTRAINTS

1. PV Allocation

All PV production must either go to the grid or to the battery:

$$x_t^{PV\to G} + x_t^{PV\to B} = PV_t \quad \forall t \in T$$

2. Battery State of Charge (SOC) Dynamics

For the first period:

$$SOC_0 = E^{init} + \eta^{ch}\left(x_0^{PV\to B} + x_0^{G\to B}\right) - \frac{x_0^{B\to G}}{\eta^{dis}}$$

For all subsequent periods:

$$SOC_t = SOC_{t-1} + \eta^{ch}\left(x_t^{PV\to B} + x_t^{G\to B}\right) - \frac{x_t^{B\to G}}{\eta^{dis}} \quad \forall t \in T \setminus \{0\}$$

3. SOC Bounds

$$SOC^{min} \le SOC_t \le SOC^{max} \quad \forall t \in T$$

4. Battery Charging Power Limit

$$x_t^{PV\to B} + x_t^{G\to B} \le P^{bat} \quad \forall t \in T$$

5. Battery Discharging Power Limit

$$x_t^{B\to G} \le P^{bat} \quad \forall t \in T$$

6. Grid Export Capacity

$$x_t^{PV\to G} + x_t^{B\to G} \le C^{grid} \quad \forall t \in T$$

7. Grid Import Capacity

$$x_t^{G\to B} \le C^{grid} \quad \forall t \in T$$

8. Initial SOC

$$SOC_0 = E^{init}$$

9. Final SOC

$$SOC_{|T|-1} = E^{final}$$

Result Table

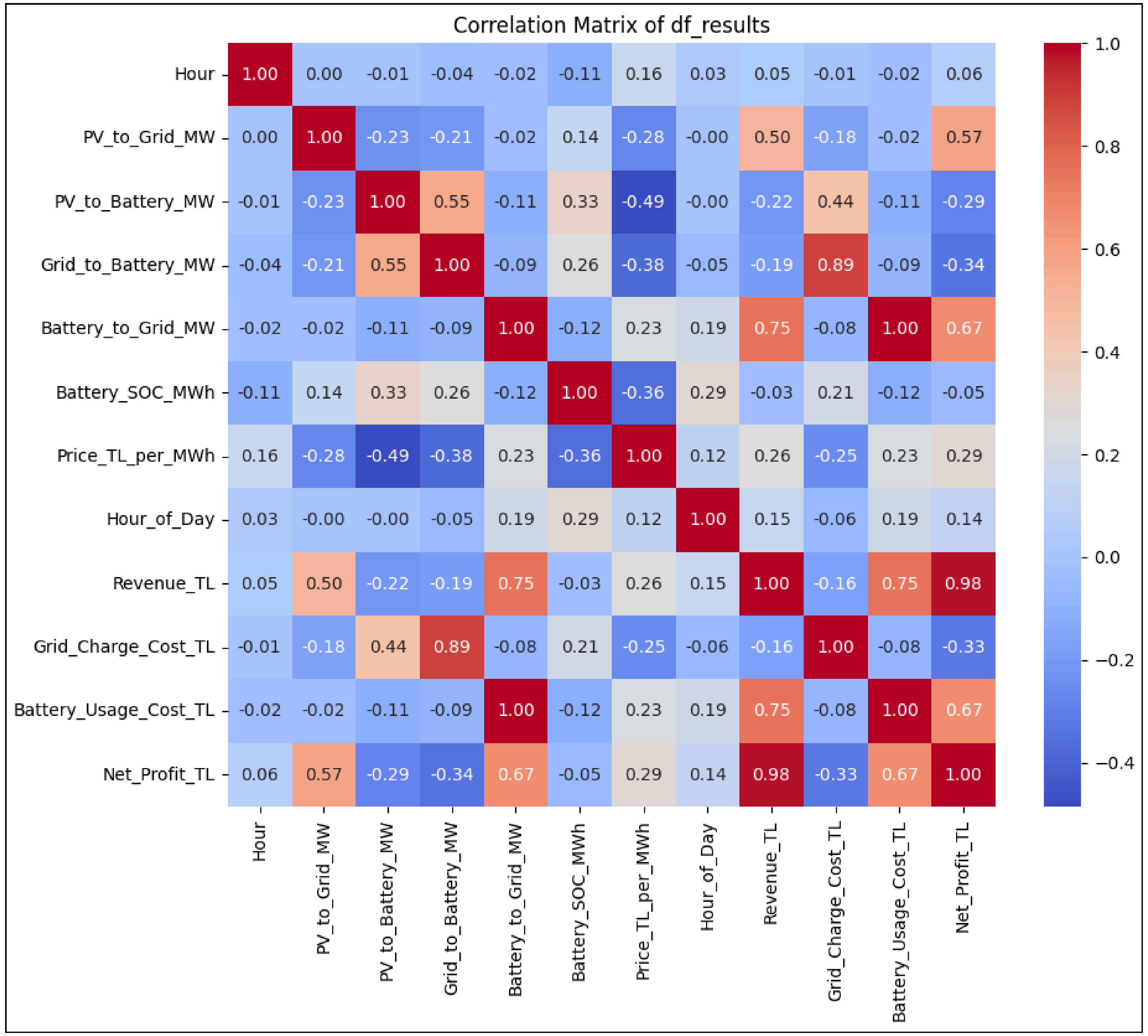
	Hour	PV_to_Grid_MW	PV_to_Battery_MW	Grid_to_Battery_MW	Battery_to_Grid_MW	Battery_SOC_MWh	Price_TL_per_MWh	Hour_of_Day	Revenue_TL	Grid_Charge_Cost_TL	Battery_Usage_Cost_TL	Net_Profit_TL	Price_Level	Prod_Level
0	0	0.0	0.0	0.0	0.0	5.000000	1499	0	0.0	0.0	0.0	0.0	Low	Low
1	1	0.0	0.0	0.0	3.6	1.000000	1575	1	5670.0	0.0	2160.0	3510.0	Low	Low
2	2	0.0	0.0	0.0	0.0	1.000000	1400	2	0.0	0.0	0.0	0.0	Low	Low
3	3	0.0	0.0	0.0	0.0	1.000000	1400	3	0.0	0.0	0.0	0.0	Low	Low
4	4	0.7	0.0	0.0	0.0	1.000000	1400	4	980.0	0.0	0.0	980.0	Low	Low
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
739	739	0.5	0.0	0.0	0.0	9.000000	3390	19	1695.0	0.0	0.0	1695.0	High	Low
740	740	0.0	0.0	0.0	5.0	3.444444	3400	20	17000.0	0.0	3000.0	14000.0	High	Low
741	741	0.0	0.0	0.0	2.2	1.000000	3400	21	7480.0	0.0	1320.0	6160.0	High	Low
742	742	0.0	0.0	0.0	0.0	1.000000	3080	22	0.0	0.0	0.0	0.0	Mid	Low
743	743	0.0	0.0	0.0	0.0	1.000000	2871	23	0.0	0.0	0.0	0.0	Mid	Low

744 rows × 14 columns

INSIGHT

- The results table provides hourly decision variables, showing how the model operates at each time step.
- It also includes the objective function value (Net Profit) along with its main components (revenues, costs, and usage).
- Additional columns such as Electricity Price and Hour of the Day were created to enable grouping and further analysis.
- The Price Level and Production Level columns were introduced to perform more advanced analyses and visualizations.

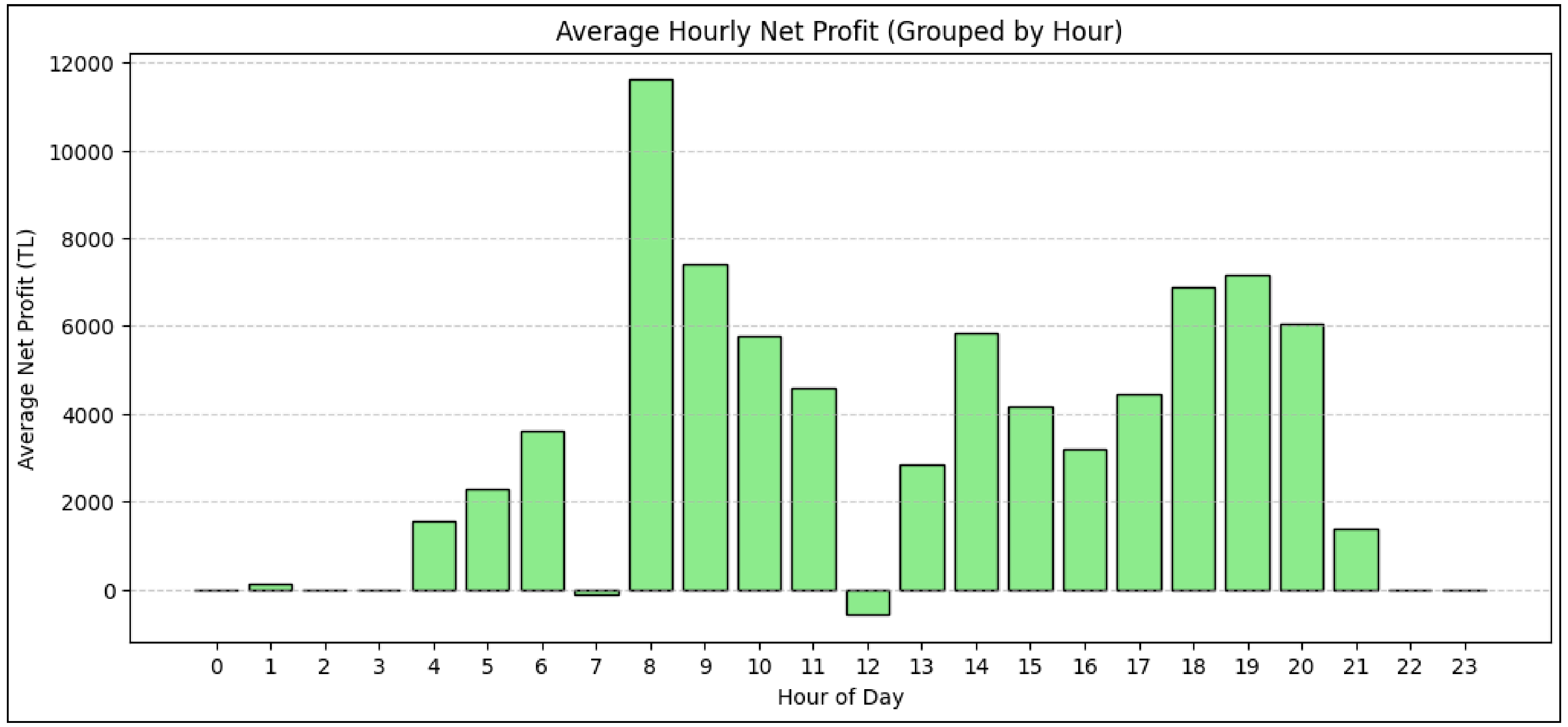
Correlation Matrix

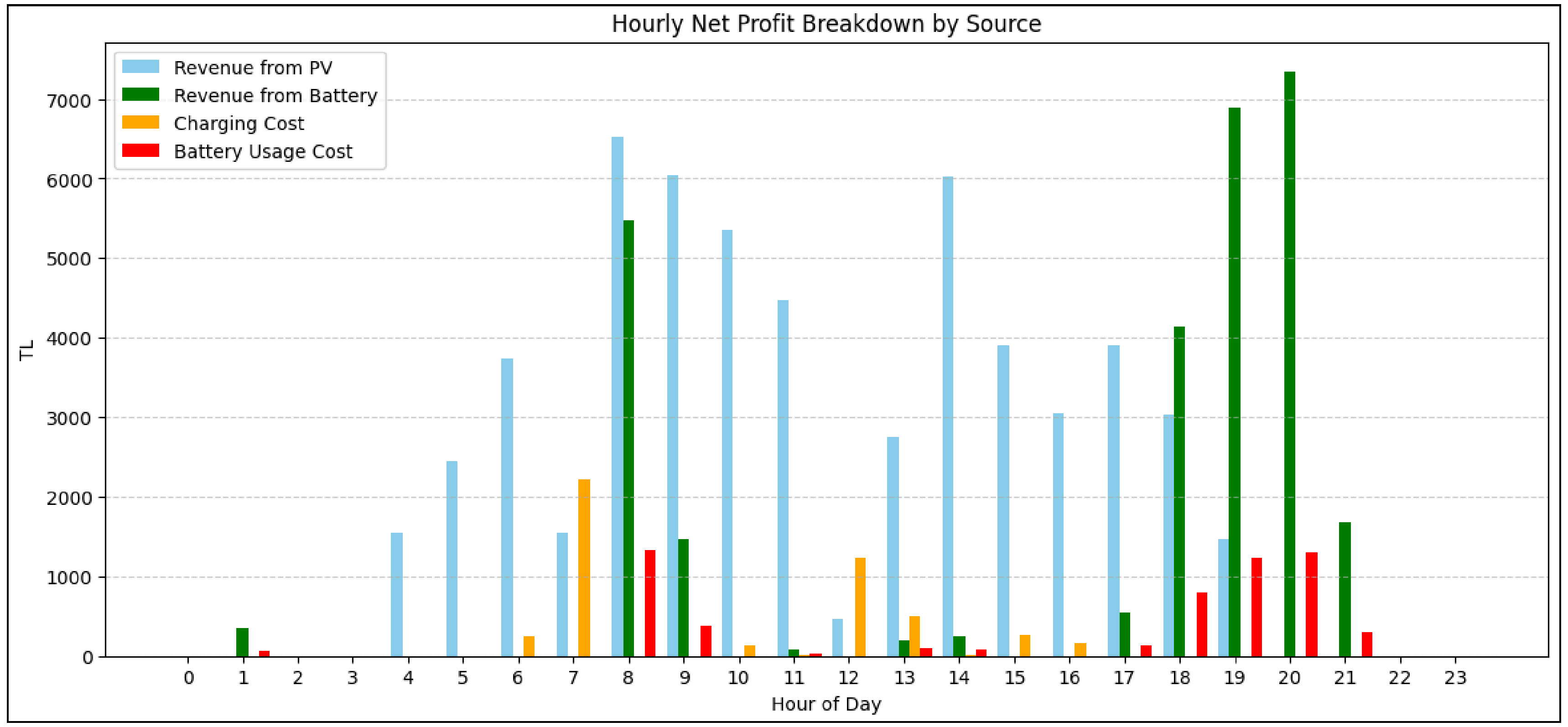


INSIGHT

- A positive correlation is observed between Grid-to-Battery and PV-to-Battery. This indicates that the battery is often charged from different sources at similar times.
- Electricity Price shows a negative correlation with Grid-to-Battery, PV-to-Battery, and Battery SOC. This confirms the desired behavior: the battery charges when prices are low and discharges when prices are high.
- Interestingly, Electricity Price also has a negative correlation with PV-to-Grid, whereas a positive relationship would normally be expected.
- Grid Charge Cost is, as expected, positively correlated with battery charging flows and the battery's state of charge, and negatively correlated with electricity prices, meaning that grid charging mainly occurs when prices are low.
- The Battery Usage Cost is positively correlated with electricity prices, reflecting that discharging happens when prices are high.
- Finally, Net Profit behaves as intended: it is negatively correlated with charging flows and positively correlated with discharging flows, confirming that the objective function is working correctly.

Hourly Net Profit Analysis

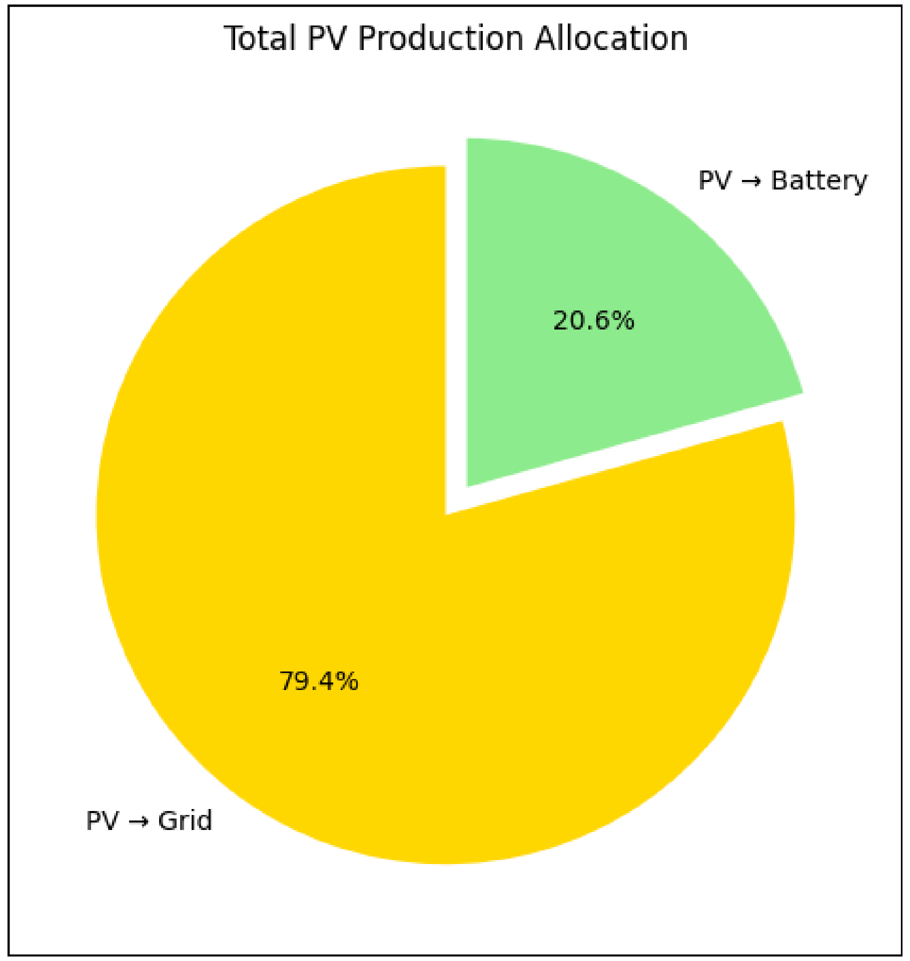


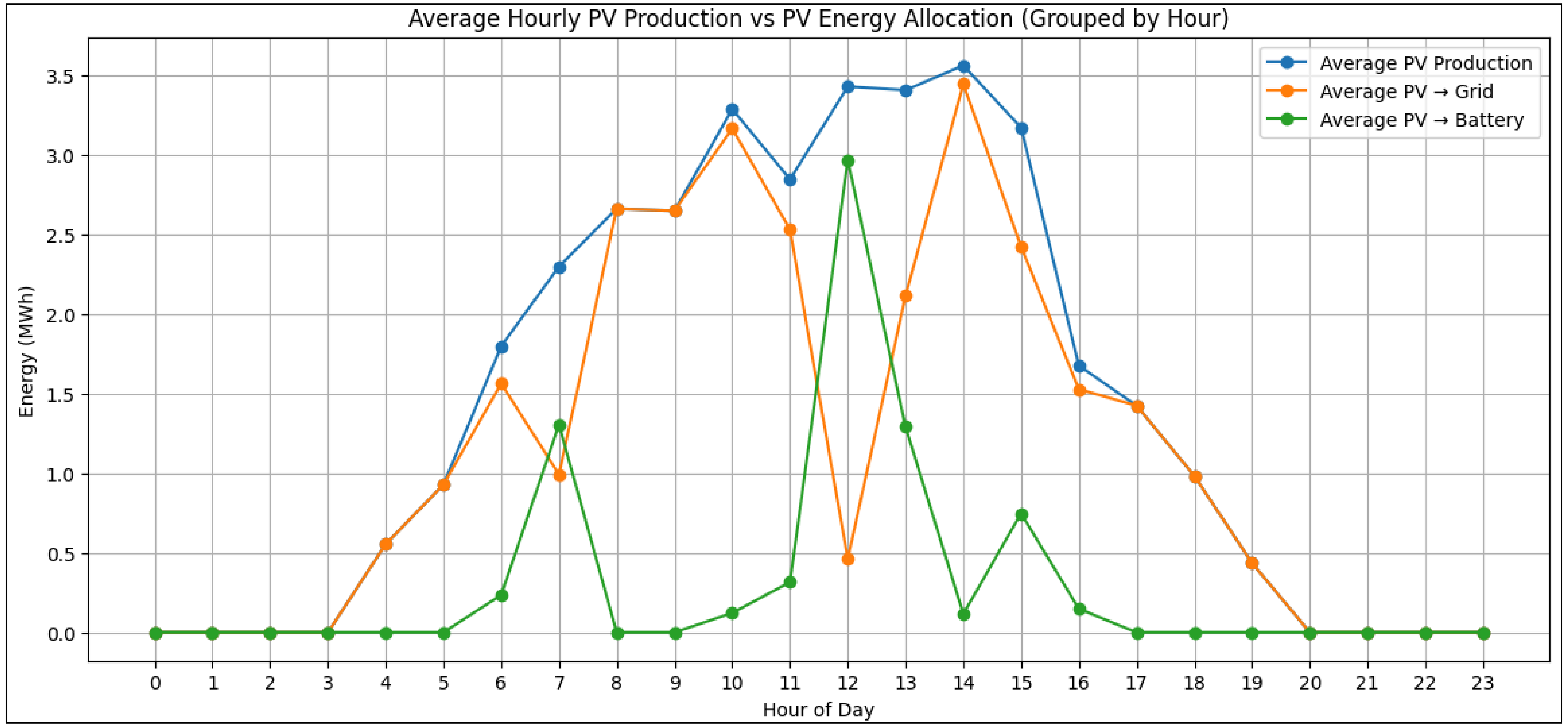


INSIGHT

- In the bar chart showing average net profit by hour, I initially expected to see higher profits during the night hours. To better understand this, we analyzed the sources of profit.
- The new chart reveals that during the daytime and noon hours, a significant portion of profit comes from direct PV sales to the grid. In the afternoon and evening, the battery contributes sufficiently to profits. However, during the night hours, almost no profit is generated.
- This suggests that PV energy is often sold directly to the grid rather than being stored in the battery, leaving insufficient energy available for discharge at night.

PV Analysis

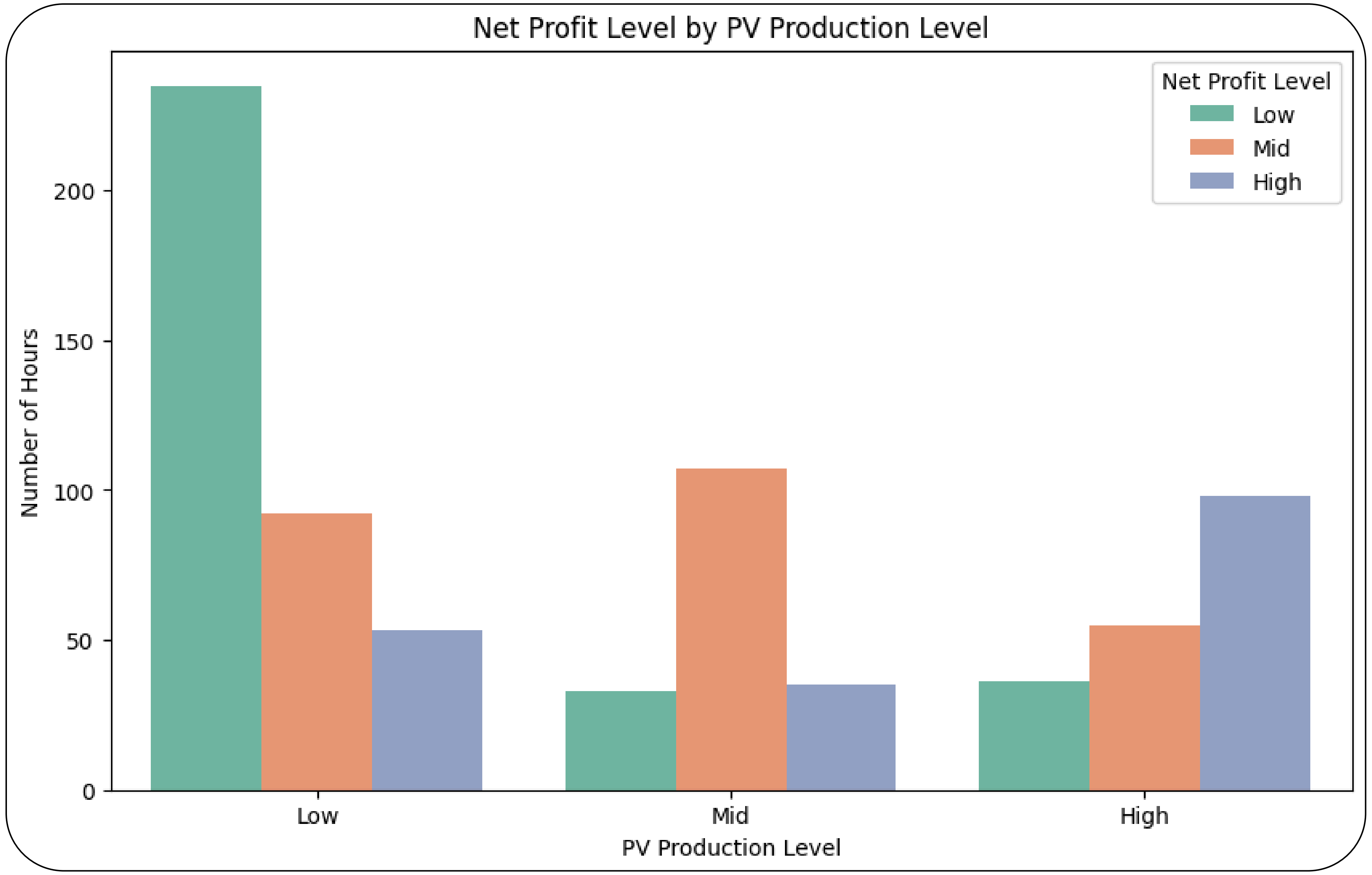




INSIGHT

- The pie chart shows the proportion of PV energy allocated either directly to the grid or stored in the battery. It confirms that the majority of PV production—around 80%—is sold directly to the grid.
- The line chart further illustrates how PV production is split between the grid and the battery across different hours of the day. As expected, we observe battery charging during certain low-price hours. However, there are also low-price hours where the majority of PV production is still sent directly to the grid, which is not the outcome we would ideally expect.

PV Analysis

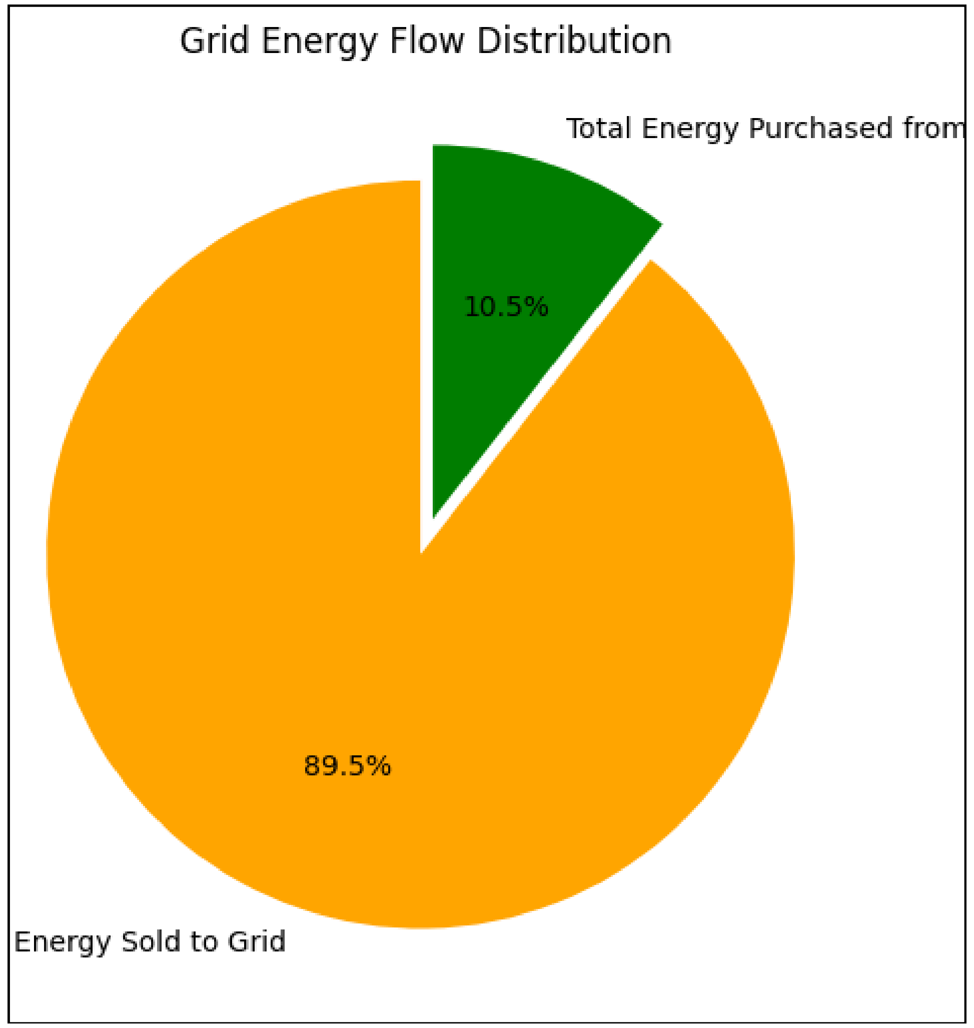


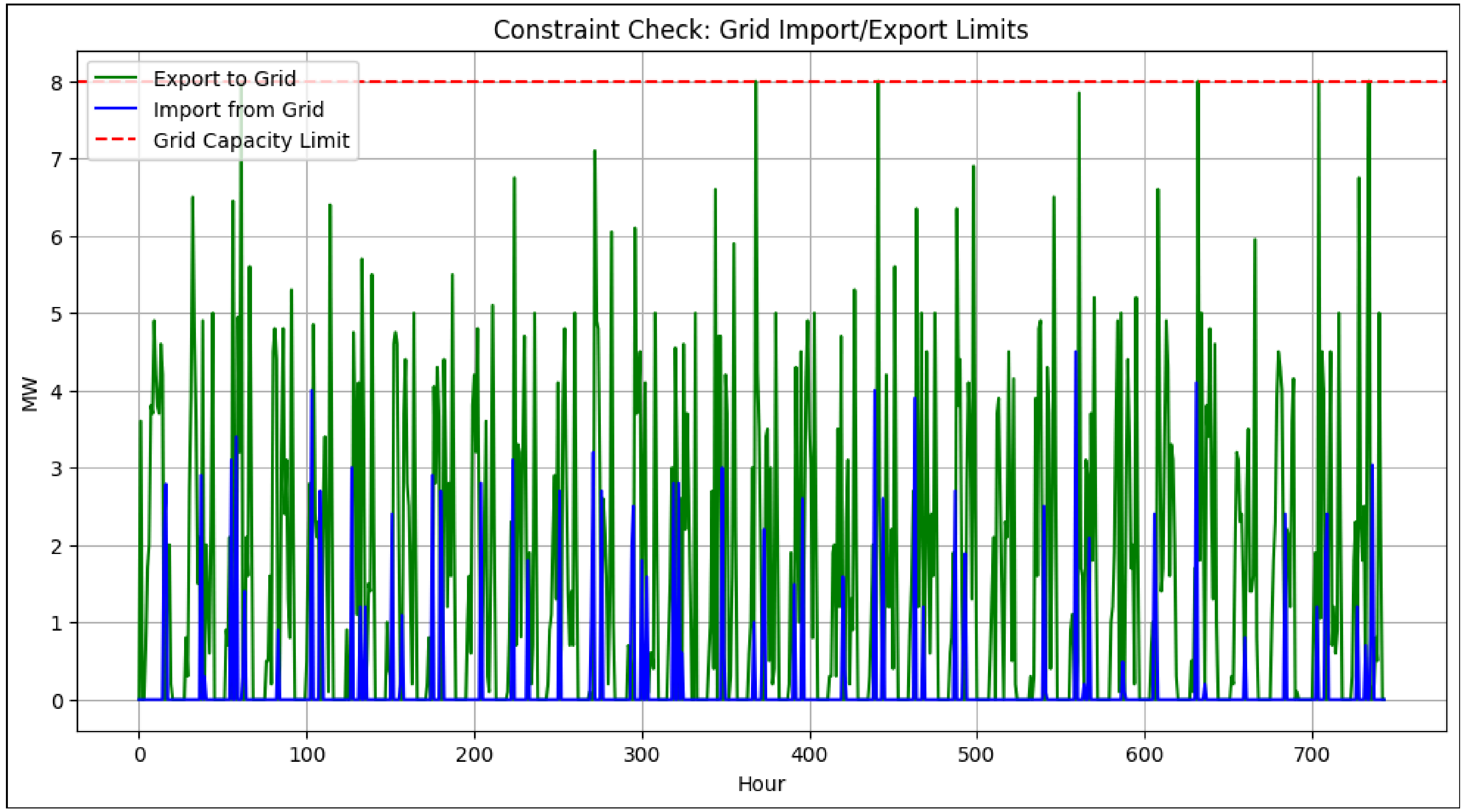
INSIGHT

When PV production is high, prices are actually expected to be low, so PV revenues would be expected to fall more in the low category. However, in this chart, the high revenue category is more prominent, which may indicate that a large amount of PV was sold during these hours.

During low production hours, a significant share of results corresponds to low profit levels. During hours with low production, especially at hours with zero PV output, no PV is sold to the grid. Once PV generation starts, the small amount of PV is sold at high and medium prices, so the medium and high profits in the low production category are achieved during these periods.

Grid Analysis

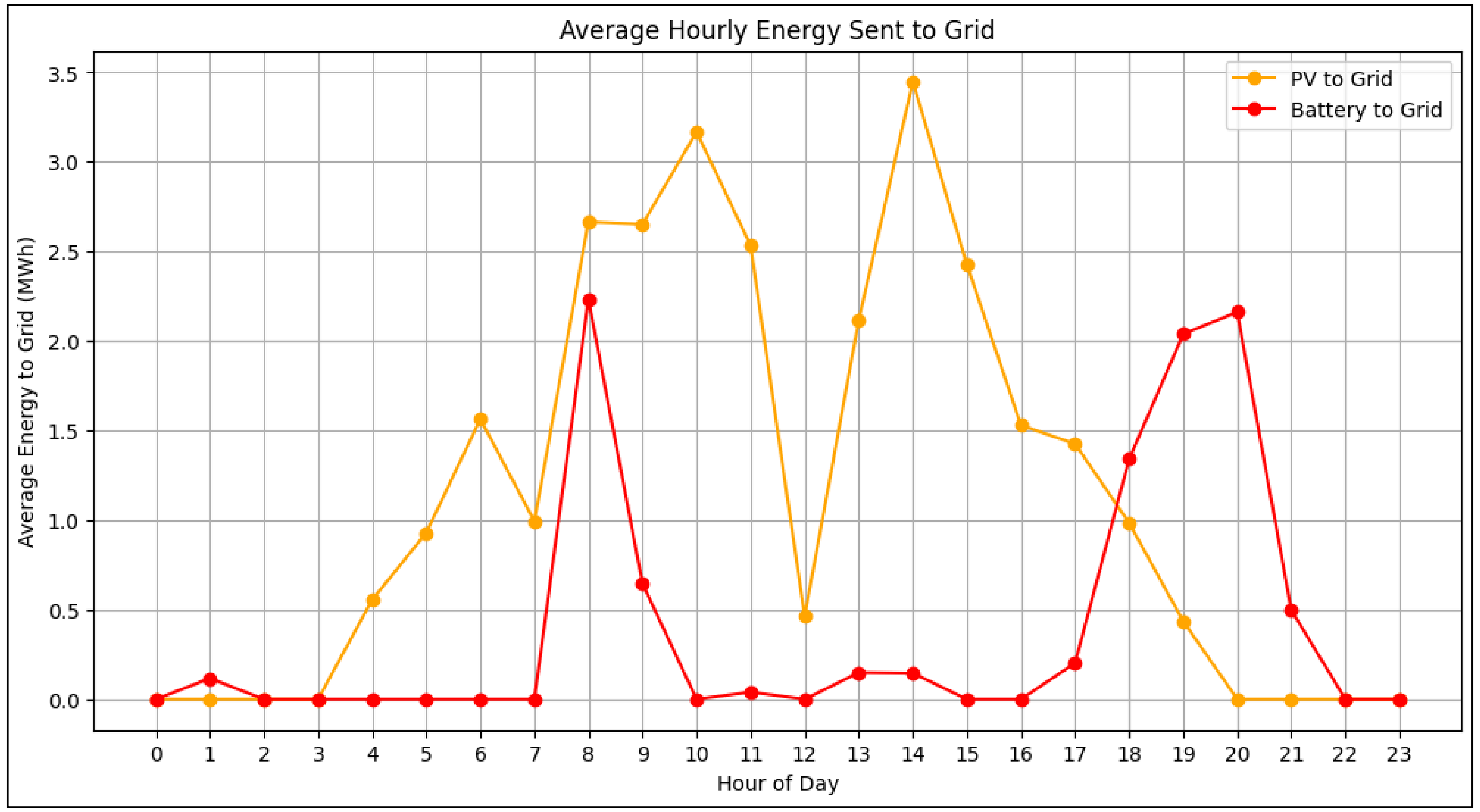


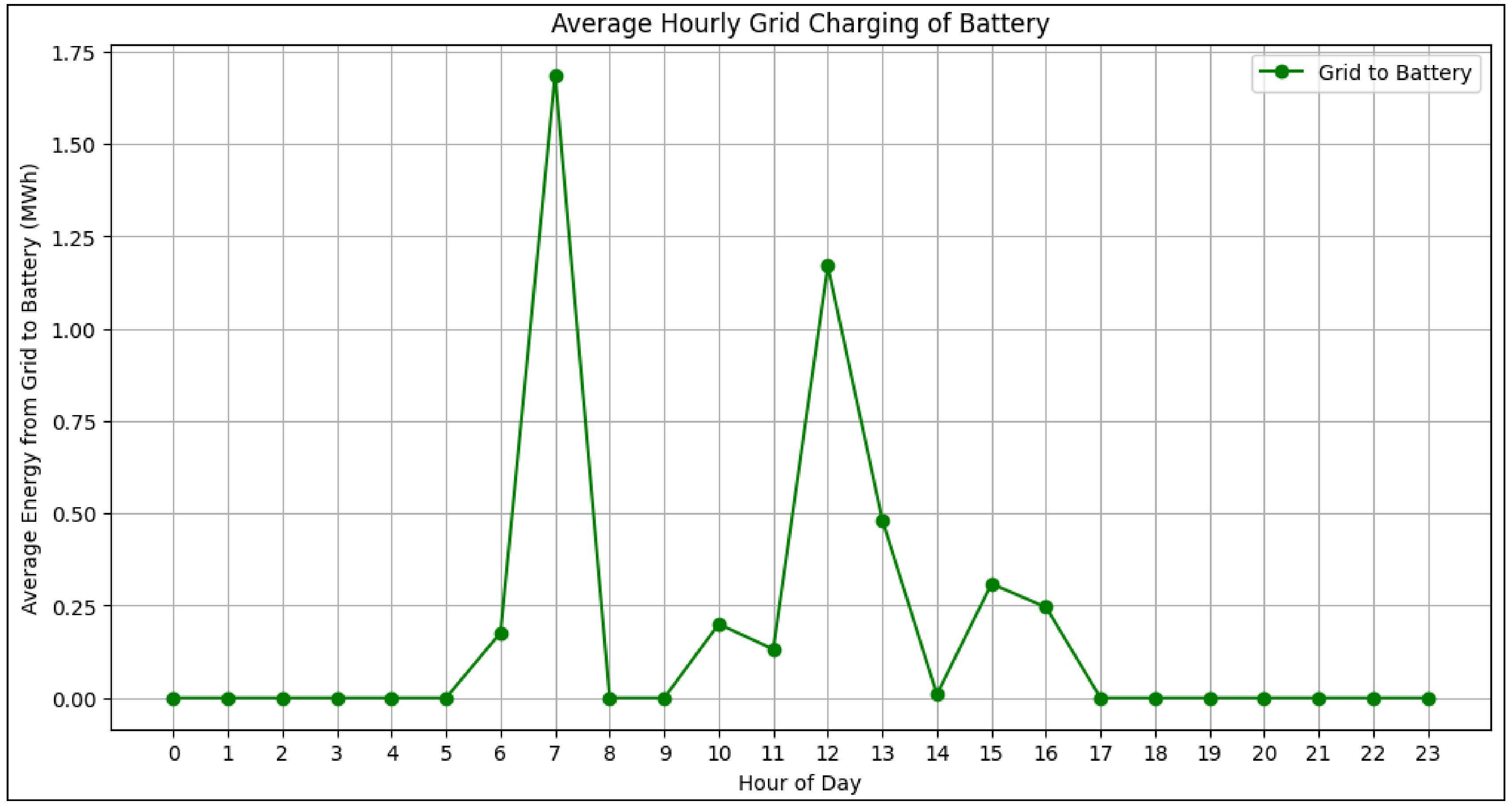


INSIGHT

- The line chart confirms that the grid capacity limits have been correctly enforced, as all import and export values remain within the defined boundaries.
- The pie chart shows the overall proportion of energy sold to the grid versus energy purchased from the grid. As expected, the share of energy sales to the grid is significantly higher than that of grid purchases, highlighting the system's focus on maximizing revenue from PV generation and battery discharge.

Grid Analysis

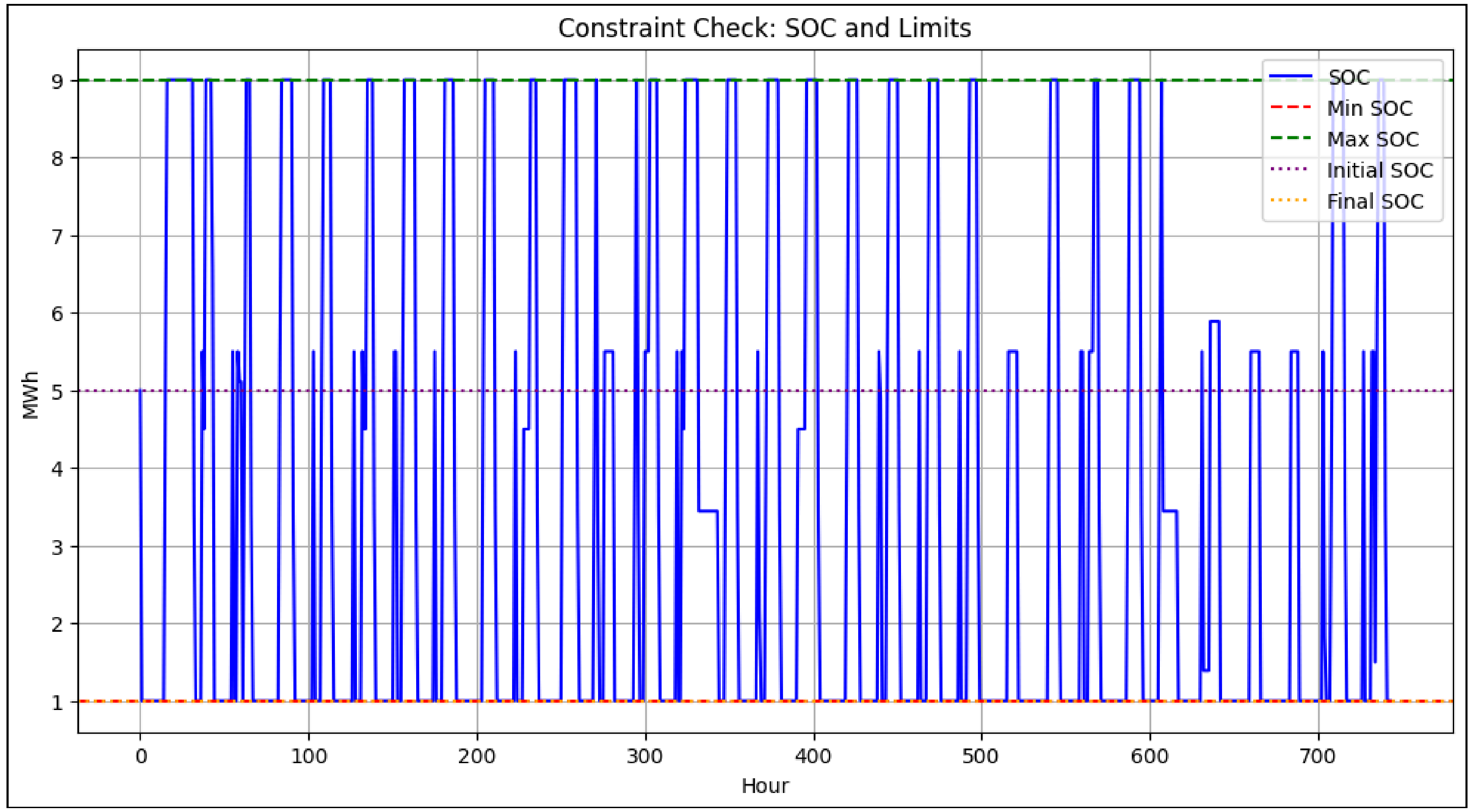


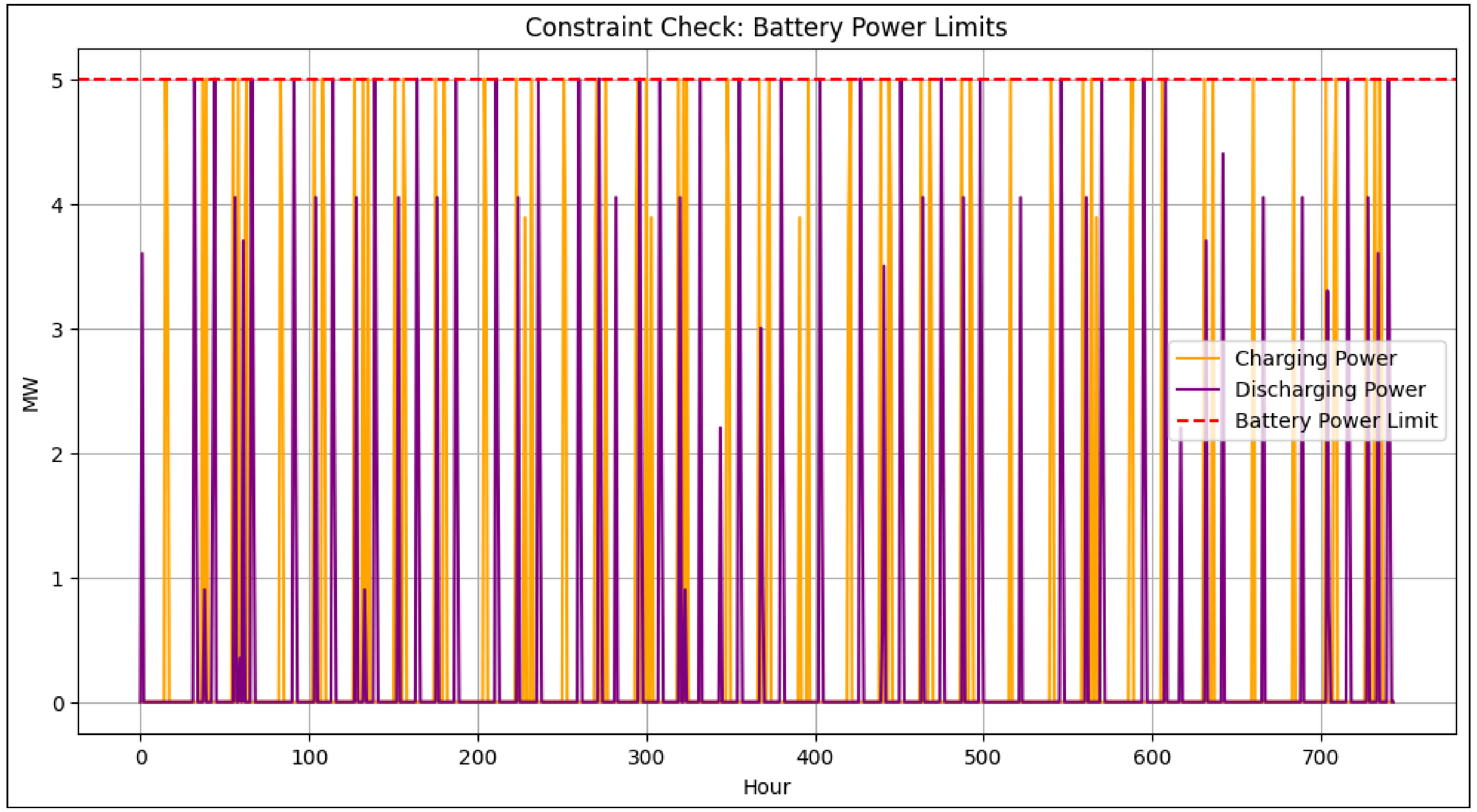


INSIGHT

- The line plot of average hourly energy sent to the grid shows that PV contributions during daytime and midday hours were expected to be lower, yet in some periods, this was not the case. Battery discharge to the grid performs reasonably well in the evening and early morning hours, but it is almost absent at night — a period where higher contributions would have been desirable.
- The line plot of average hourly grid-to-battery charging indicates that charging primarily occurs during periods of low electricity prices. This confirms that the charging flow is aligned with the intended operational strategy.

Battery Analysis

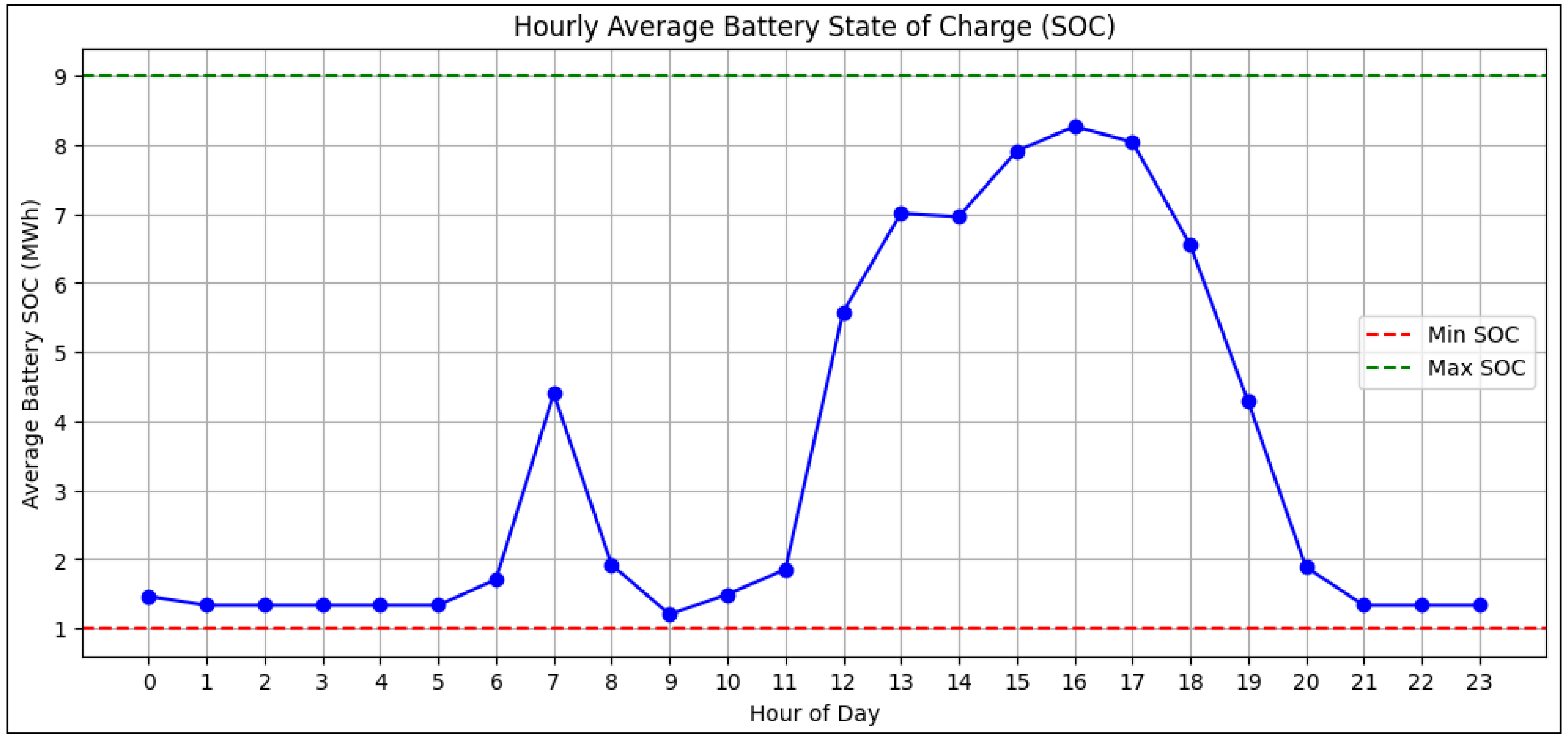


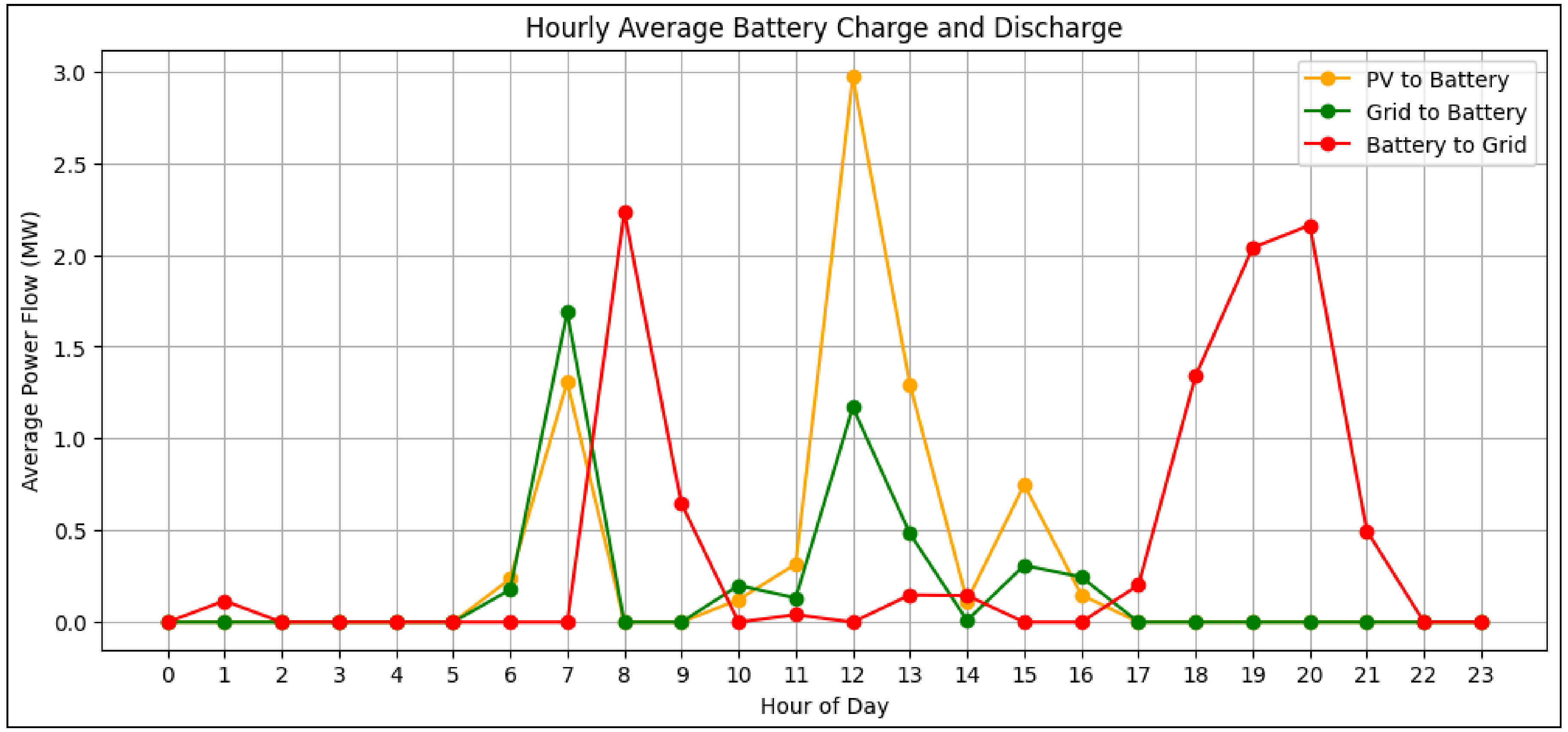


INSIGHT

- The line chart of battery SOC confirms that the minimum, maximum, initial, and final state-of-charge limits are correctly enforced throughout the operation.
- Similarly, the line chart of battery charging and discharging powers verifies that the battery's power limits are fully respected.

Battery Analysis

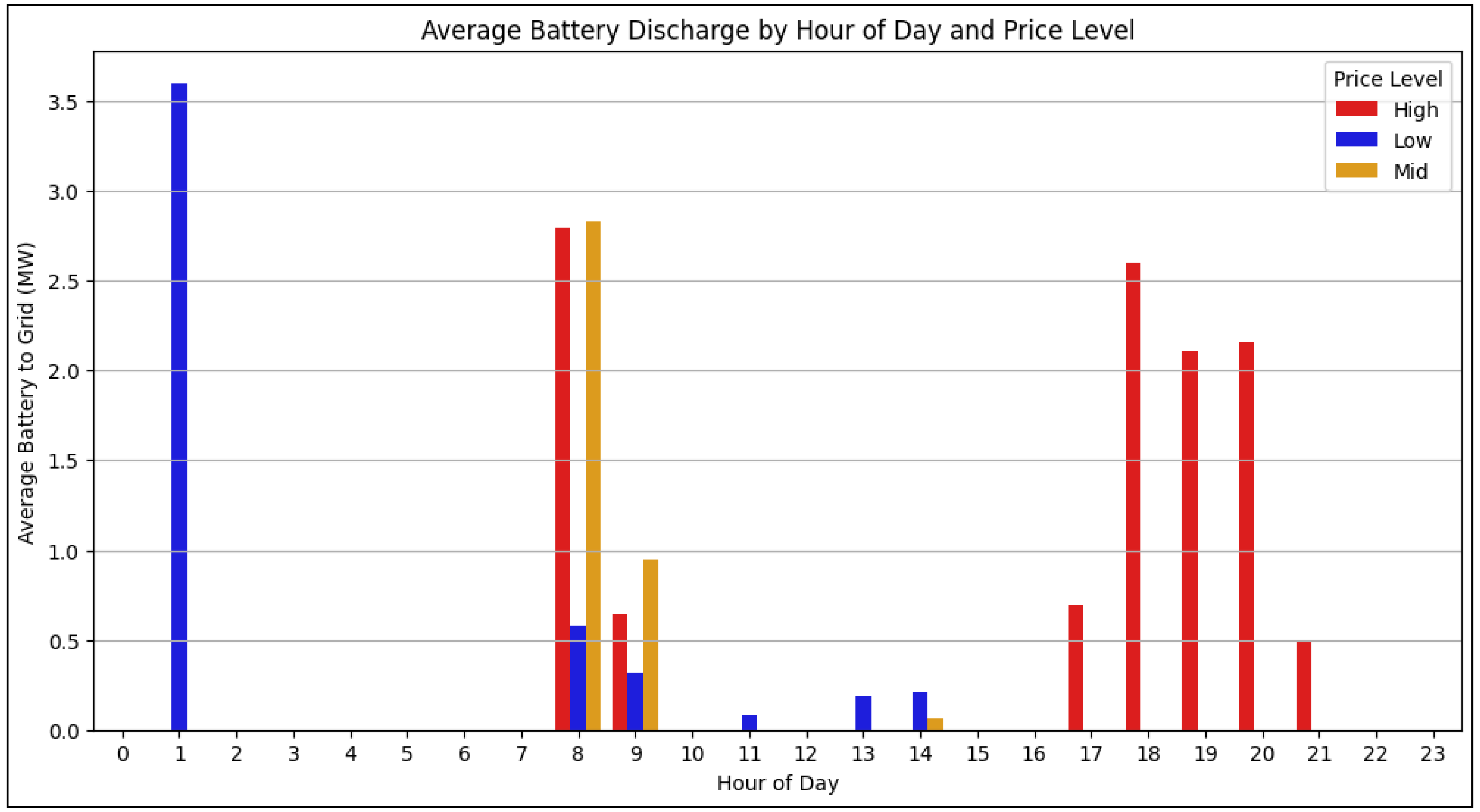


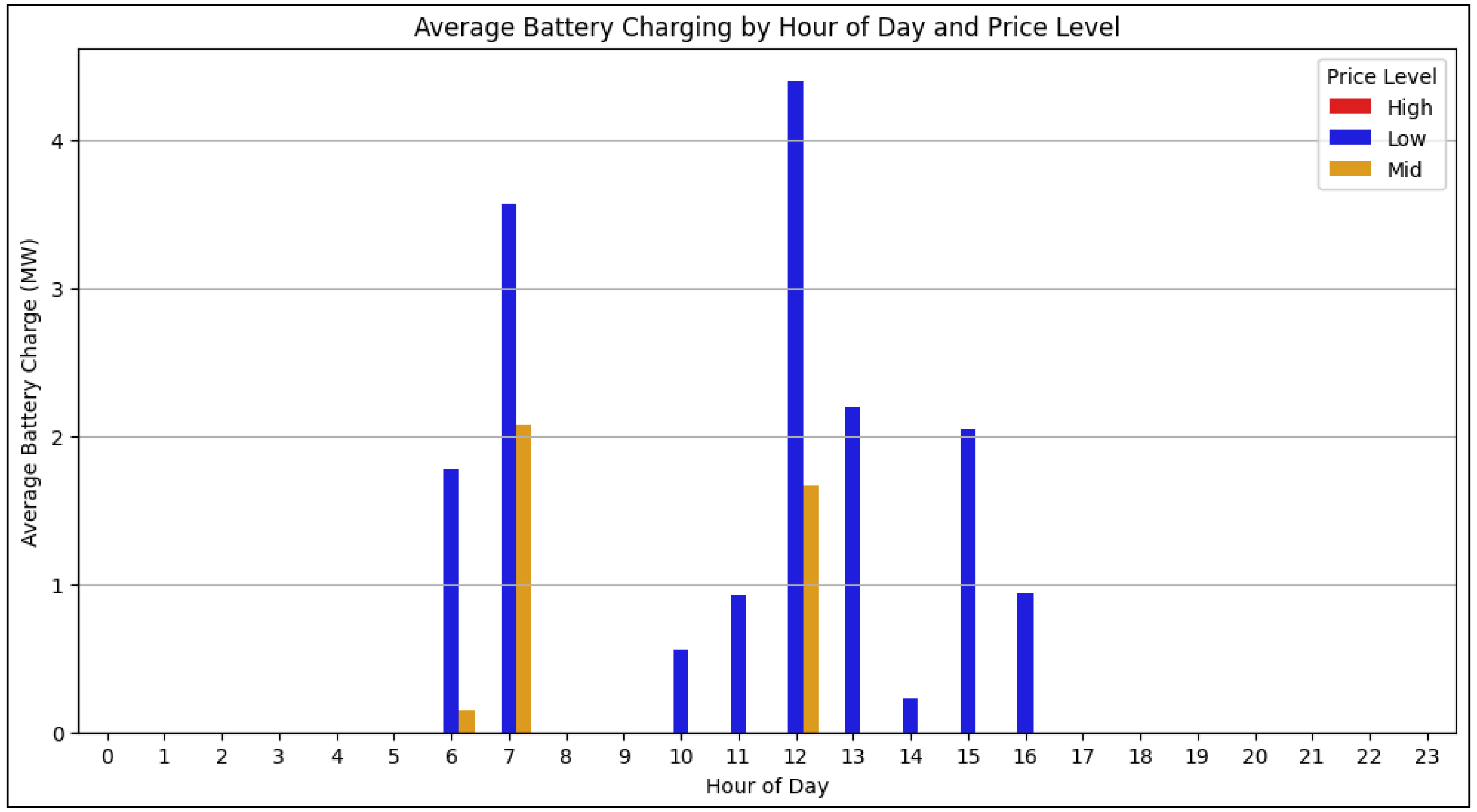


INSIGHT

- The hourly average SOC plot shows that the battery is slightly charged in the early morning hours and then discharged. Later, it is charged again during periods of high electricity prices and discharged in the evening. However, since all the stored energy is discharged in the evening, no energy remains available for trading during the night.
- The average hourly charge and discharge flow plot further confirms this behavior. While the battery is generally charged at the correct times, the complete discharge in the evening leaves no stored energy for profitable use overnight.

Battery Analysis

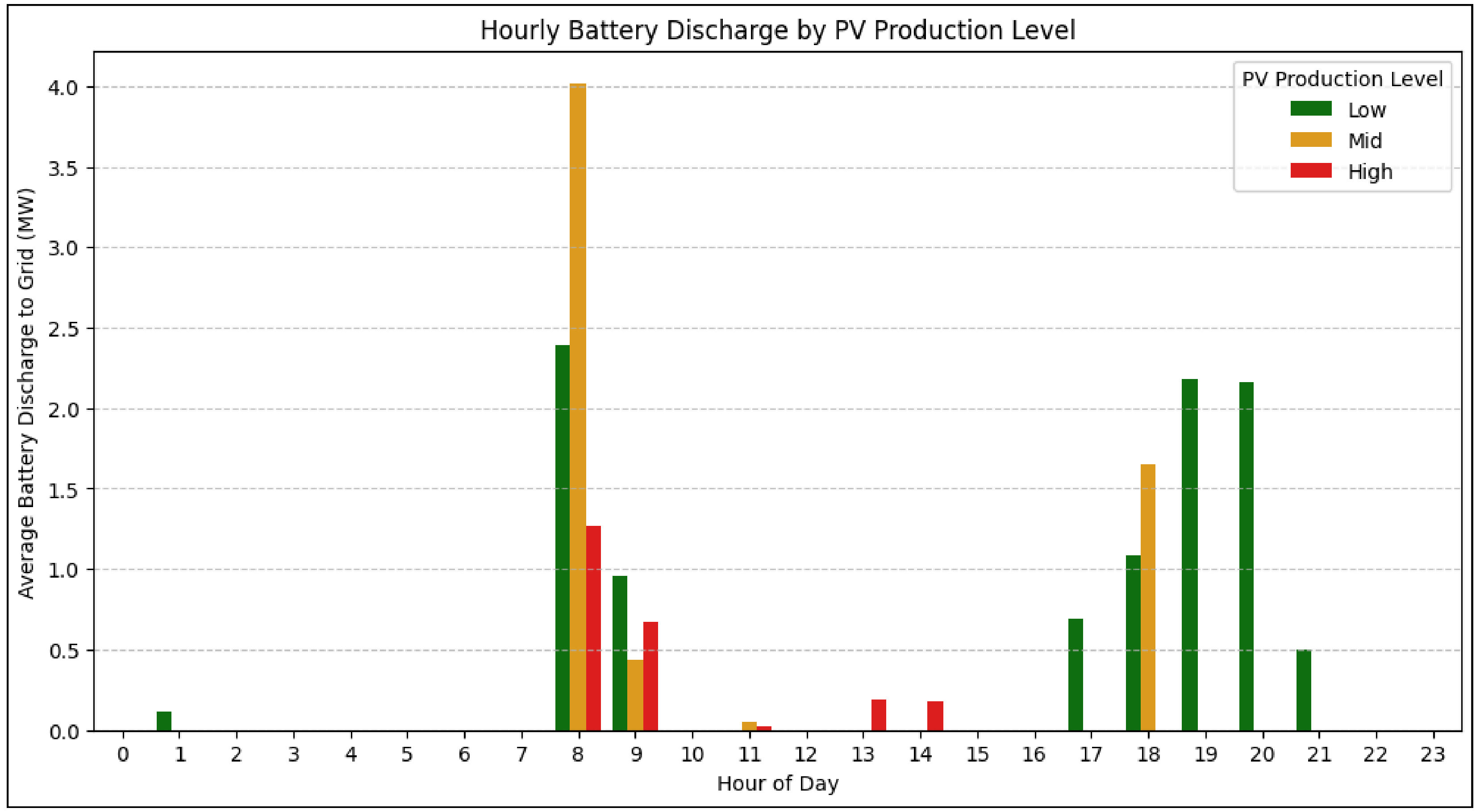


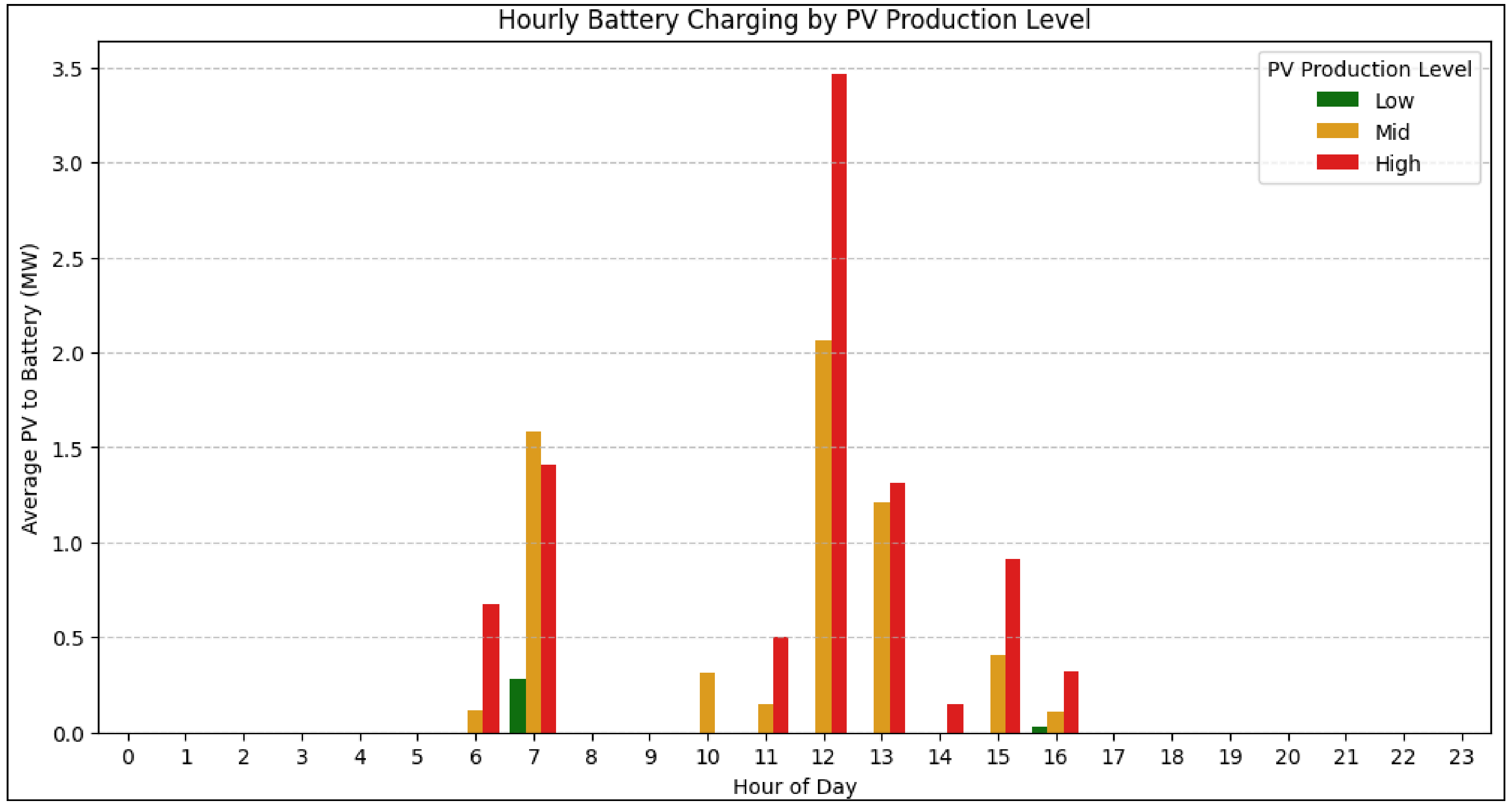


INSIGHT

- The discharge distribution chart shows that the battery is discharged in the evening when electricity prices are high, which is expected. However, the same pattern should also be visible during nighttime hours, but it is not observed.
- The charging distribution chart confirms that the battery is charged during low-price hours, which aligns with the intended strategy.

Battery Analysis

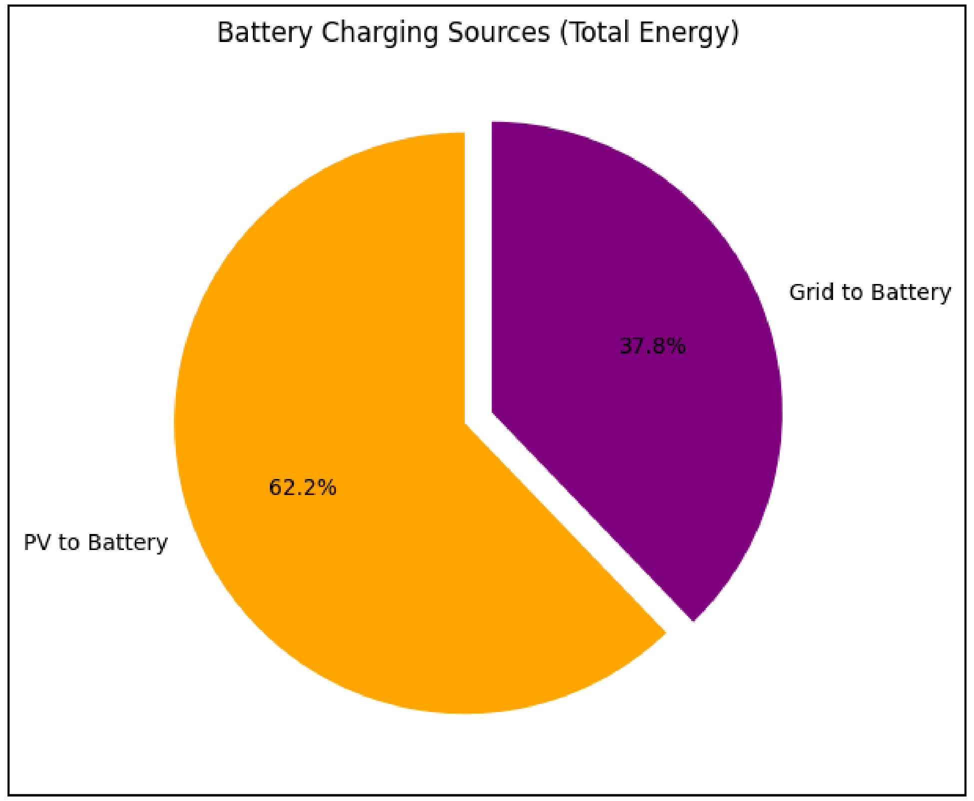


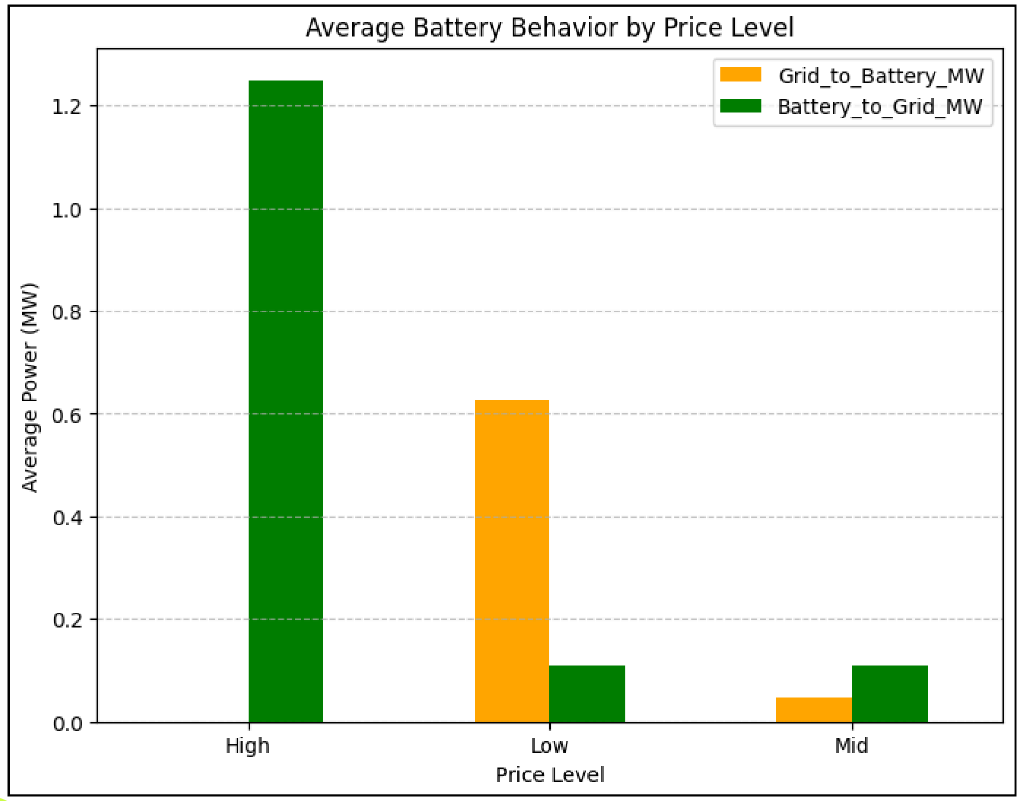


INSIGHT

- The discharge-to-grid chart and charging-from-PV chart reveal patterns similar to those observed in the electricity price analyses. That is, the battery tends to discharge during high-value periods and charges preferentially when PV production is available, confirming the consistency of the operational strategy across both price-driven and PV-driven conditions.

Battery Analysis

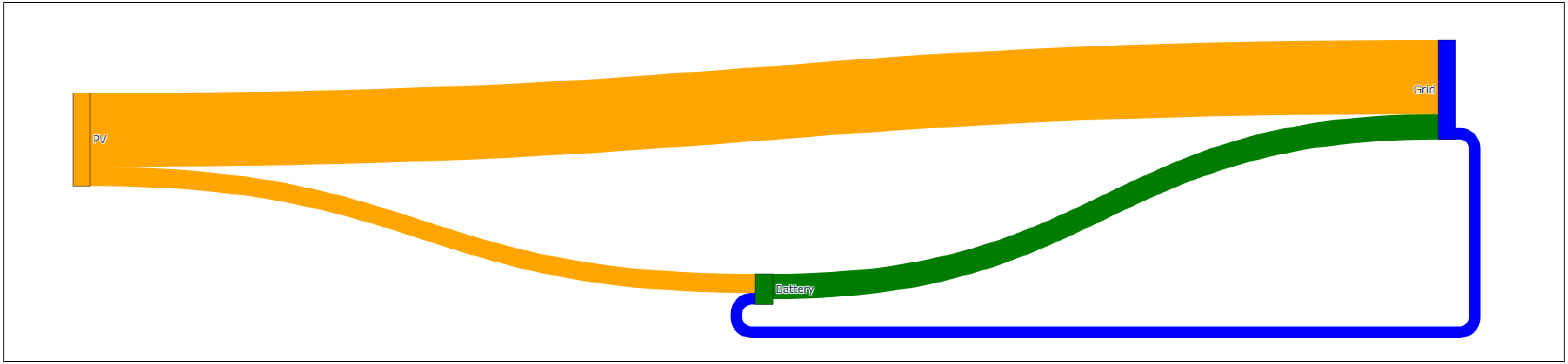




INSIGHT

- The pie chart shows that the battery is charged more from PV than from the grid, which is advantageous as it reduces costs associated with purchasing electricity from the grid.
- The bar chart illustrates how battery charging from the grid and discharging to the grid varies across high, mid, and low price periods. As expected, discharging occurs during high-price periods, while charging from the grid happens during low-price periods, indicating that the interaction between the grid and the battery is functioning correctly.
- Financial Performance:
  - Charging Cost (Grid → Battery): 147,594.84 TL
  - Discharging Revenue (Battery → Grid): 938,121.20 TL
  - Battery Usage Cost (Discharge): 177,930.00 TL
  - Net Profit: 612,596.36 TL
  - This demonstrates that the battery system not only operates according to the intended strategy but also generates a substantial net profit.

Behavior of Power Flows



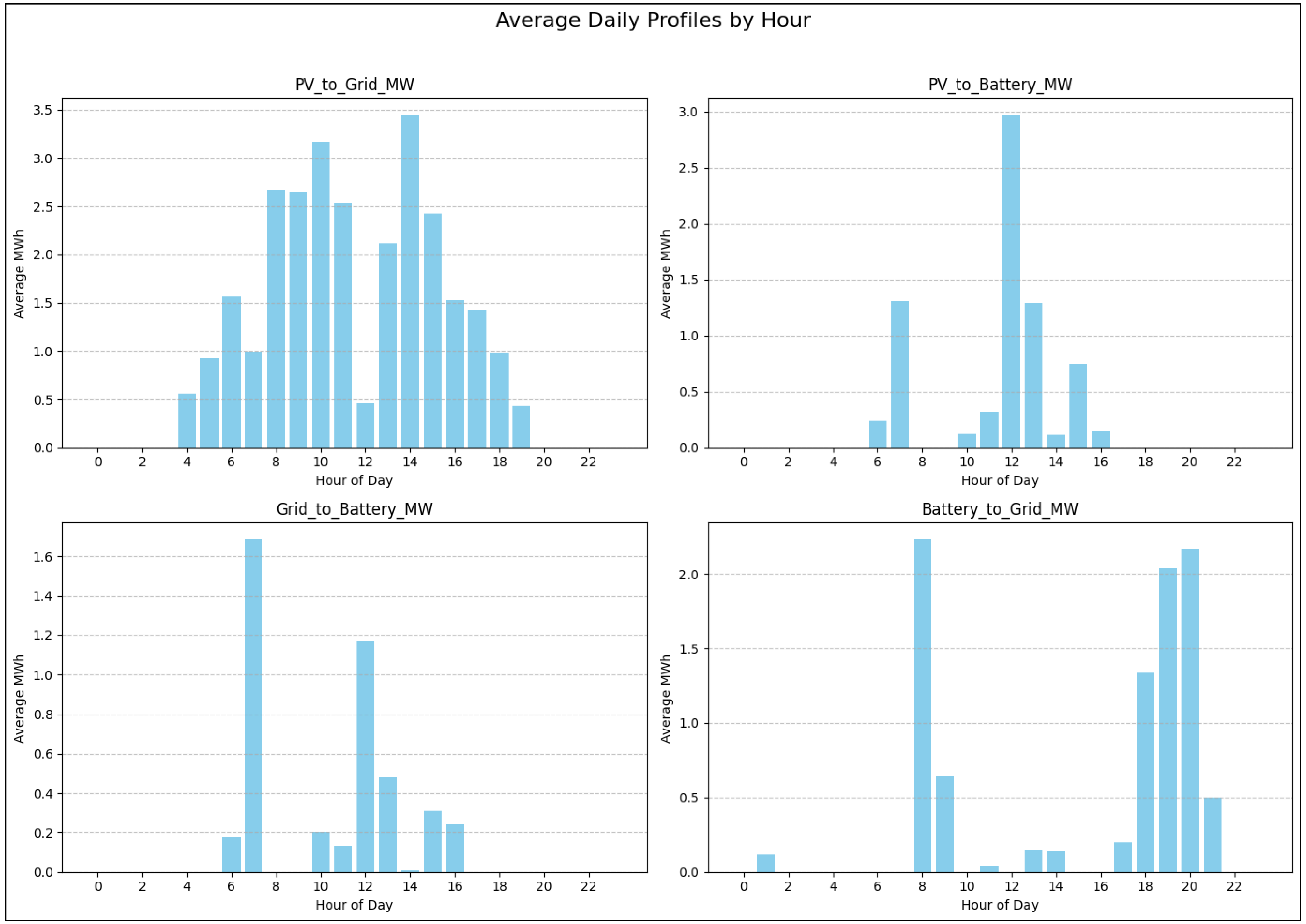
INSIGHT

The Sankey diagram illustrates how PV production is allocated and how energy flows between the battery and the grid, highlighting the relative magnitudes of each flow:

- Total PV → Grid: 864.47 MWh
- Total PV → Battery: 224.93 MWh
- Total Grid → Battery: 136.73 MWh
- Total Battery → Grid: 296.55 MWh

This visualization clearly depicts the energy flow behaviors discussed in the analysis.

Behavior of Power Flows

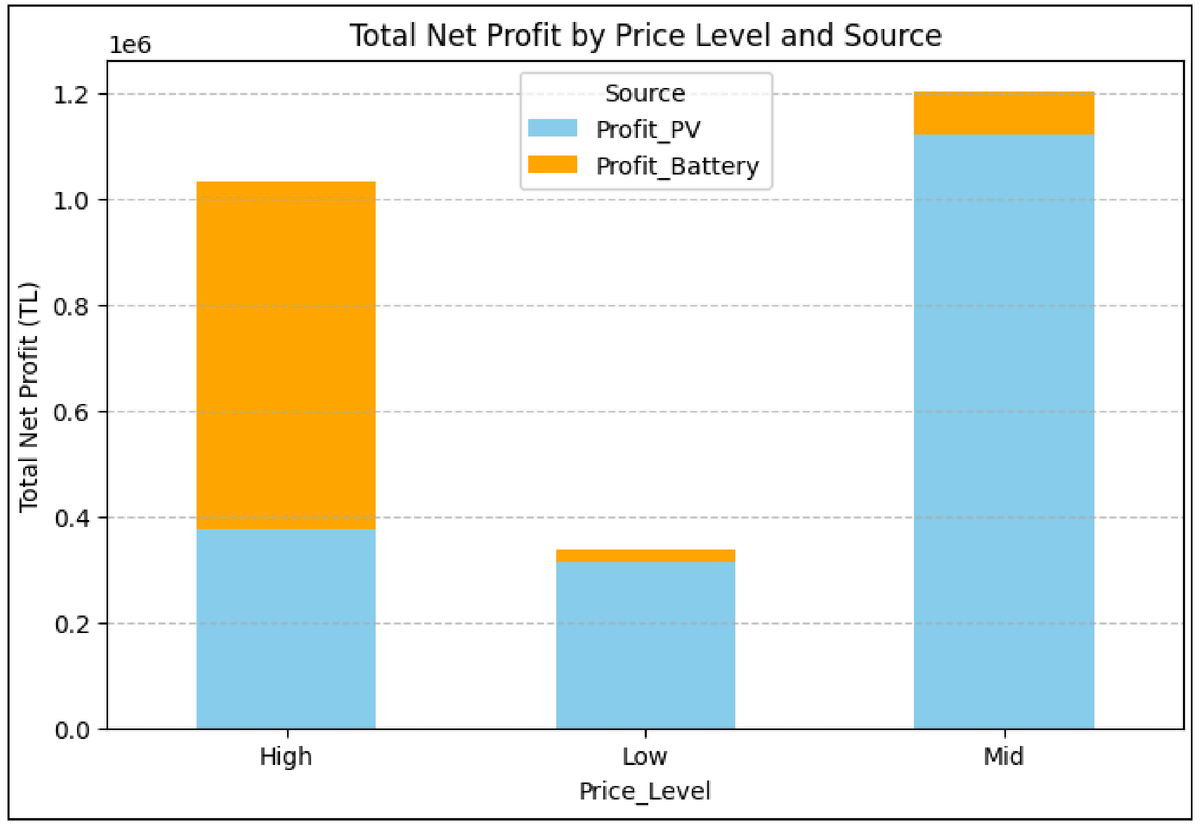


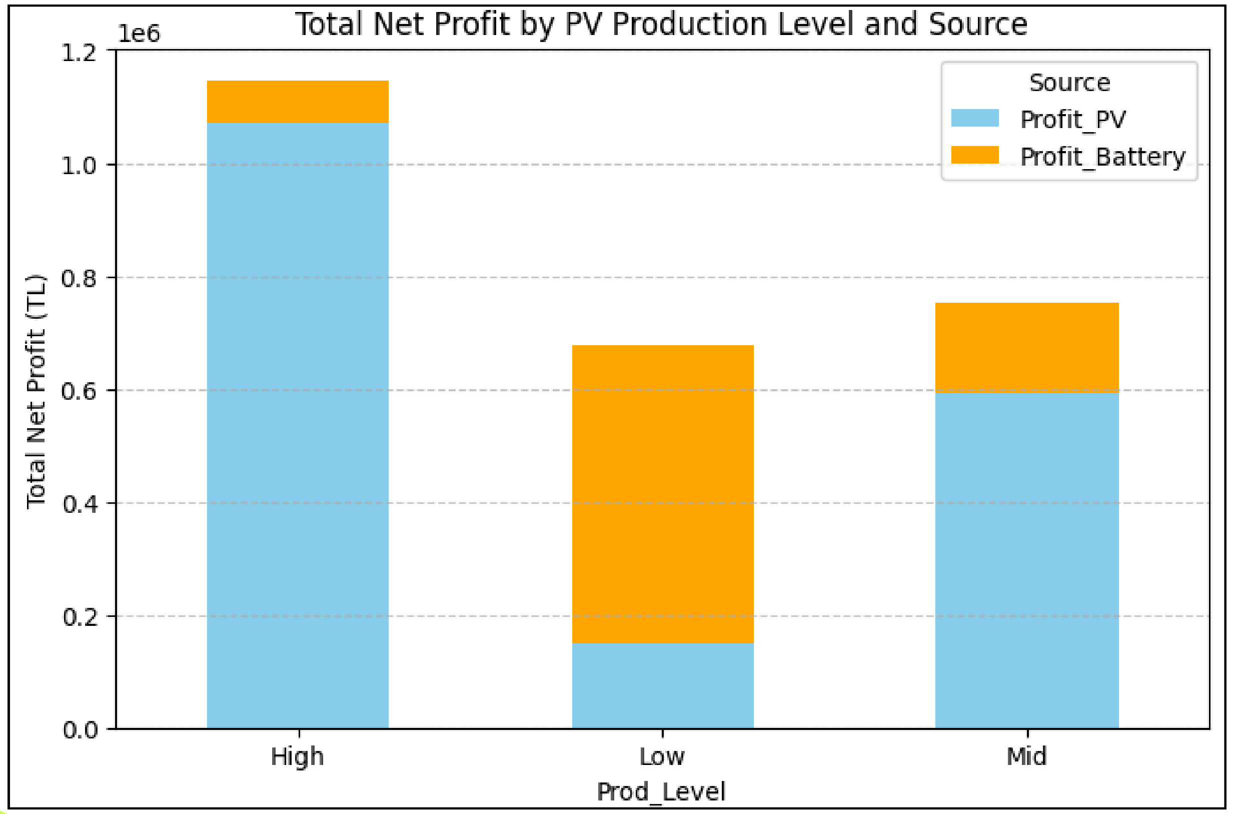
INSIGHT

The four bar charts showing average hourly behavior for different power flows reveal the following:

- PV-to-grid flows during low-price hours are excessive at most hours except hour 12, indicating that more energy is sold directly to the grid than might be optimal.
- PV-to-battery flows exist during low-price hours, but we would expect higher values to better store PV energy.
- Grid-to-battery flows occur correctly during low-price hours, as intended.
- Battery-to-grid flows are sufficient in the evening and late afternoon, but very limited during the night and early morning, leaving potential profit untapped.

Total Financial Results





INSIGHT

The model's economic outputs are summarized as follows:

- Total Revenue: 2,750,639.83 TL
- Total Grid Charge Cost: 147,594.84 TL
- Total Battery Usage Cost: 177,930.00 TL
- Net Profit: 2,425,114.99 TL
- Total Battery Discharge: 296.55 MWh

The stacked bar chart showing net profit by source (PV and Battery) and Price Level demonstrates that:

- During high-price periods, most profit comes from battery discharge, indicating correct model behavior.
- During low-price periods, almost no profit comes from the battery, with nearly all revenue derived from PV sales, as expected.
- During mid-price periods, revenue is primarily from PV sources.

The stacked bar chart by PV production level reinforces these observations, showing consistent behavior across different PV generation scenarios.

Scenario Comparison – Economic Performance

SCENARİO A – PV ONLY

- Total Revenue: 2,019,824.90 TL

SCENARİO B – BATTERY ONLY

- Total Revenue: 939,418.10 TL
- Battery Usage Cost: 178,200.00 TL
- Total Charging Cost: 355,195.00 TL
- Net Profit: 406,023.10 TL

SCENARİO C – PV + BATTERY

- Total Revenue: 2,750,639.83 TL
- Grid Charge Cost: 147,594.84 TL
- Battery Usage Cost: 177,930.00 TL
- Net Profit: 2,425,114.99 TL

SUMMARY

Profitability:
- PV-only generates strong revenue (~2.0M TL).
- Battery-only adds limited profit (~0.4M TL) through arbitrage.
- Combined PV + Battery achieves the highest profit (~2.43M TL), confirming integration benefits.

Revenue Sources:
- PV dominates at low/mid price levels.
- Battery adds value mainly in high-price hours.

System Behavior:
- Charging occurs in low-price periods (PV & Grid).
- Discharging aligns with evening peaks but leaves no energy for late night/early morning trading.

Synergy & Optimization:
- Combined scenario is profitable but slightly below the sum of A+B.
- Indicates underutilized synergy; improved PV-to-Battery allocation could raise performance.

Key Insight:
- PV provides a strong revenue base.
- Battery enhances flexibility but needs better operation strategy to fully unlock its economic value.

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Thank you for your attention