Optimisation of Solar PV and Battery Storage Dispatch under Electricity Price Uncertainty

Supervisors: Dr. Shu Su; Fucheng Zheng

Ruotian Zhang 24246167

May 29, 2026

In collaboration with CNBM and Kiwi Solar

Agenda

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Section 01: Introduction

Introduction

Organization: China National Building Material Group (CNBM)

- One of the largest building materials group
- Currently supplying solar equipment and energy storage system to the New Zealand market

Industry partner: Kiwi Solar

- Specialise in developing, engineering, constructing, and maintaining solar farms
- Two developed solar farms, three farm projects under development

Introduction

Problems：

- Intermittent irradiation

↓

- Uncertainty of power generation

- Electricity price fluctuations

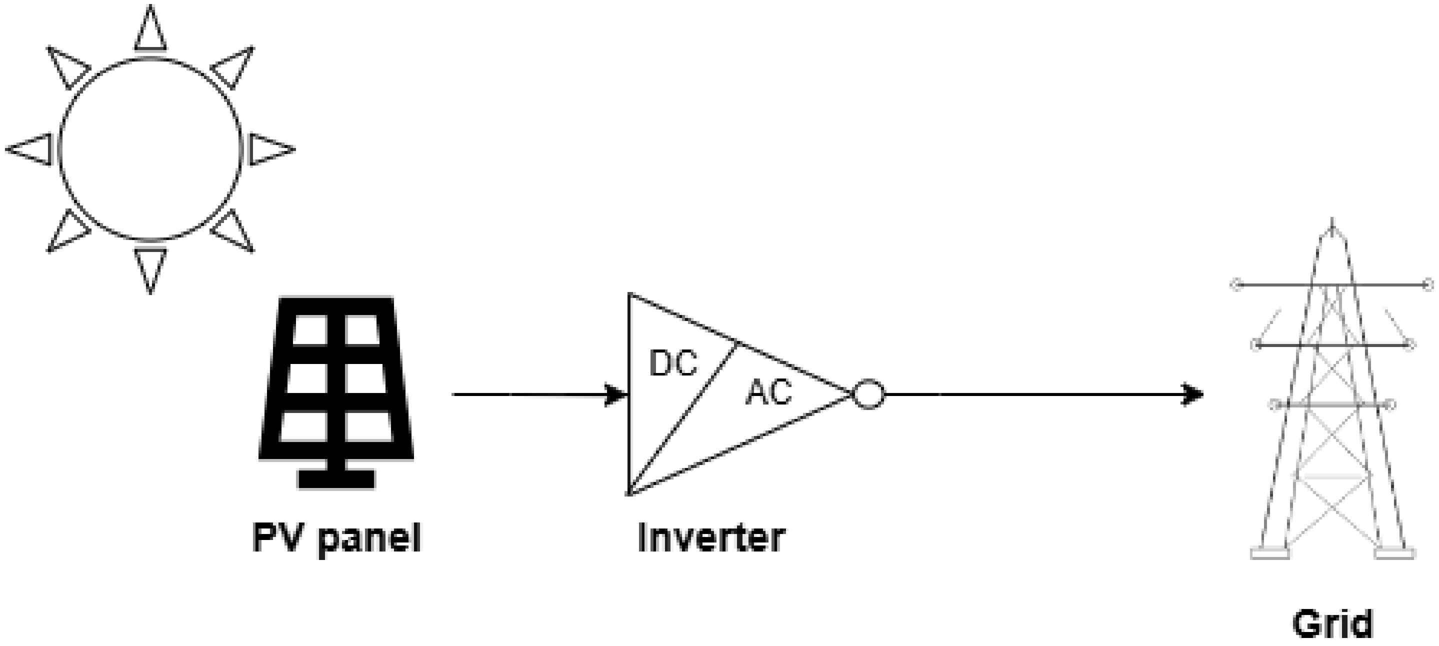
↓

- Unstable income

Motivation& Objective

- No storage → no time shifting → curtailment → value loss.

- Volatile prices (e.g. evening)→ arbitrage opportunity.



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Motivation& Objective

•Battery storage costs declined by 93% from 2010 to 2024, falling from USD 2 571/kWh to USD 192/kWh.
Renewable power generation costs in 2024 - Executive summary

Objective: Maximise solar farm profit by optimising battery charge/discharge under volatile prices.

Section 02:
Data & Analysis

Data source:

Kiwi Solar-data portal

- Input DC power
- AC power
- Array Characteristics
- System losses
- ……

Data source:

Earth Sciences New Zealand

- 10 mins radiation data for 20 years
- From PUKEKOHE EWS

Electricity Authority – EMI

- Half hour price data for five years
- Two different nodes:
  - Ōtāhuhu
  - Benmore (slightly different)

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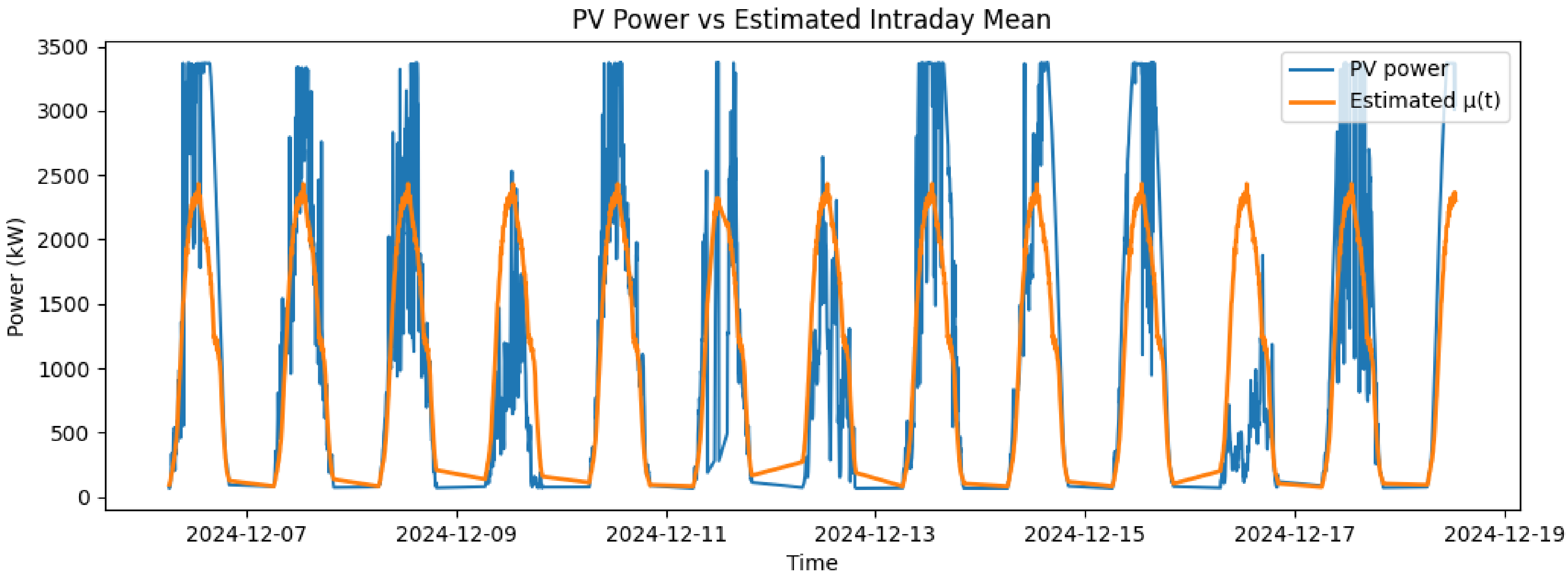
Analysis -Input Power



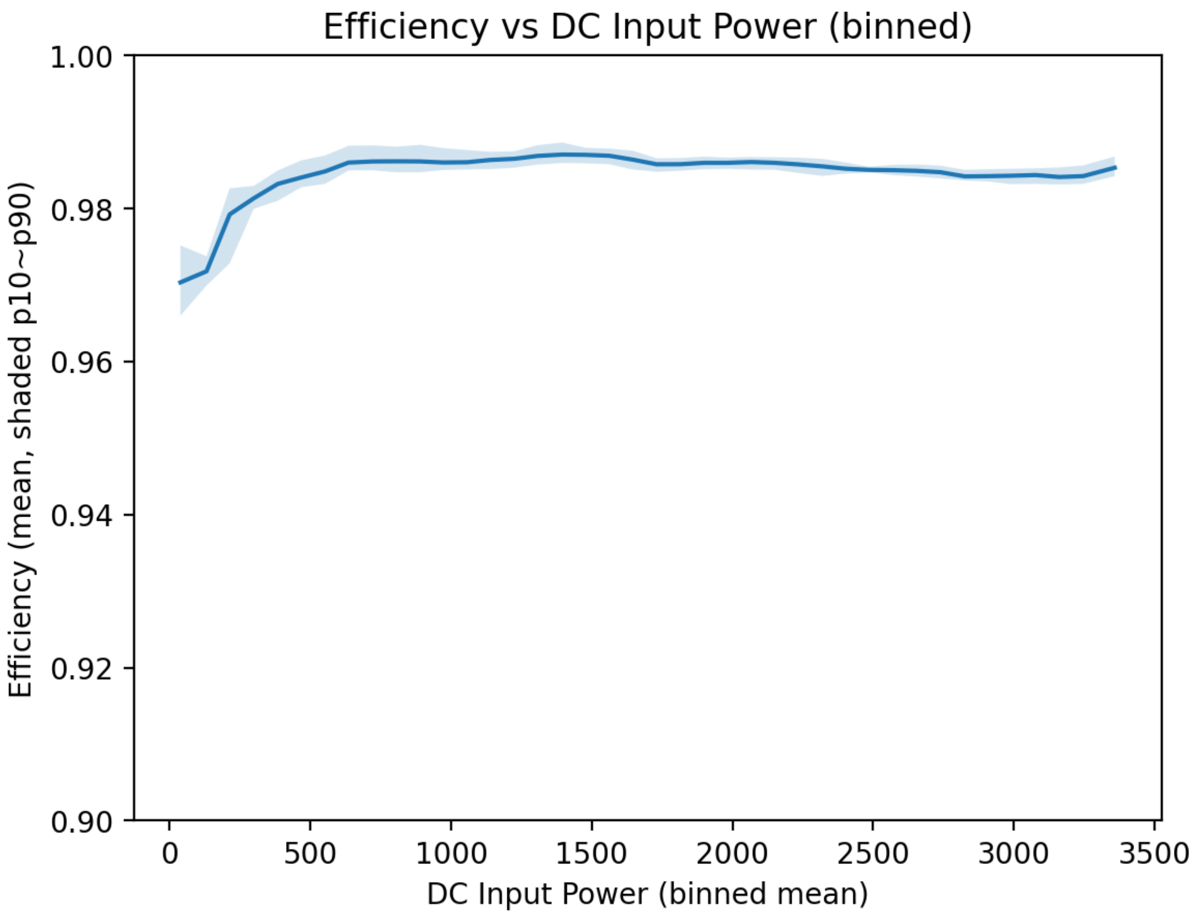
A clear intraday pattern is visible, have difference in each day (weather impact)

Analysis -Curtailment

- Export point limit: 3300 kW
- Total curtailed energy: 3.69 MWh
- Curtailment percentage: 0.06%
- Inverter curtailment: 0 MWh
- Export point curtailment: 3.69 MWh

Curtailment is very small in the observed one-year input power data. The inverter limit is not binding, and almost all curtailment comes from the export point limit.

Analysis -Inverter Efficiency



Inverter efficiency increases at low power, then levels off at a high plateau

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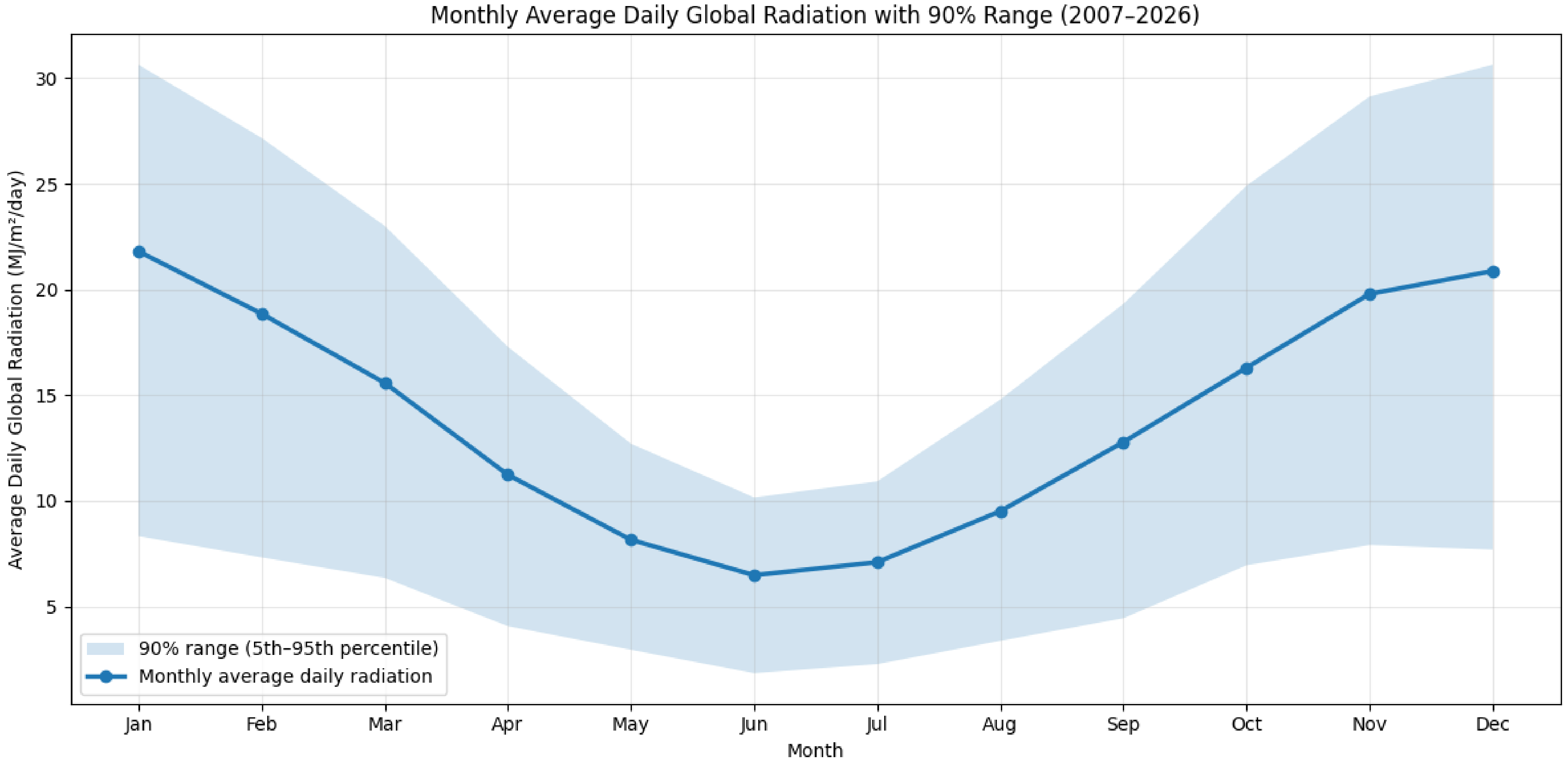
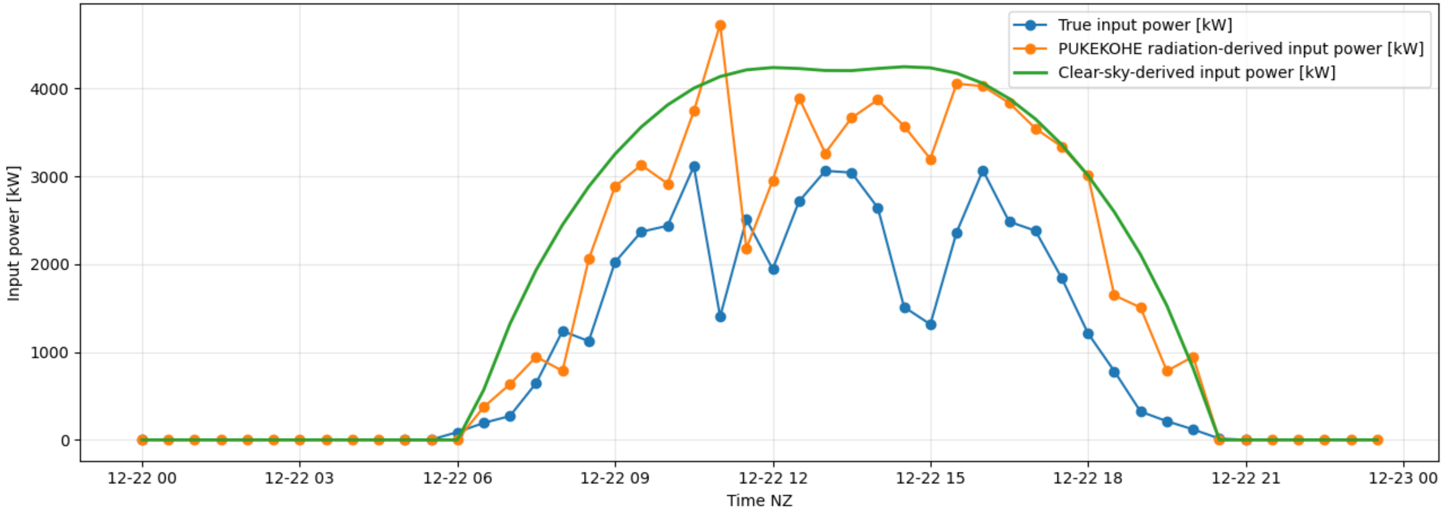
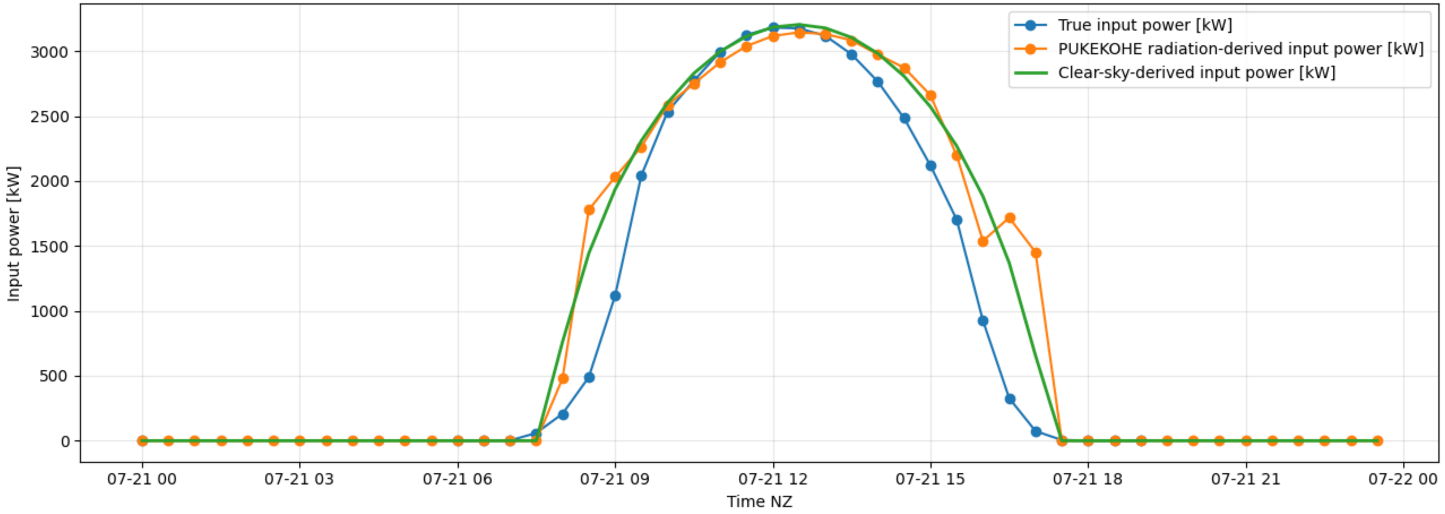
Analysis -Radiation



Solar radiation shows seasonality, with the highest average daily radiation in summer and the lowest in winter. Meanwhile, the shaded areas indicate that there are still significant historical fluctuations in each month.

Analysis -Radiation





$$P_t^{input} = \frac{R_t \times 10^6}{\Delta t} \times A_{PV} \times \eta_{PV}$$

Where:

$R_t =$ *global radiation* (MJ/m^2);

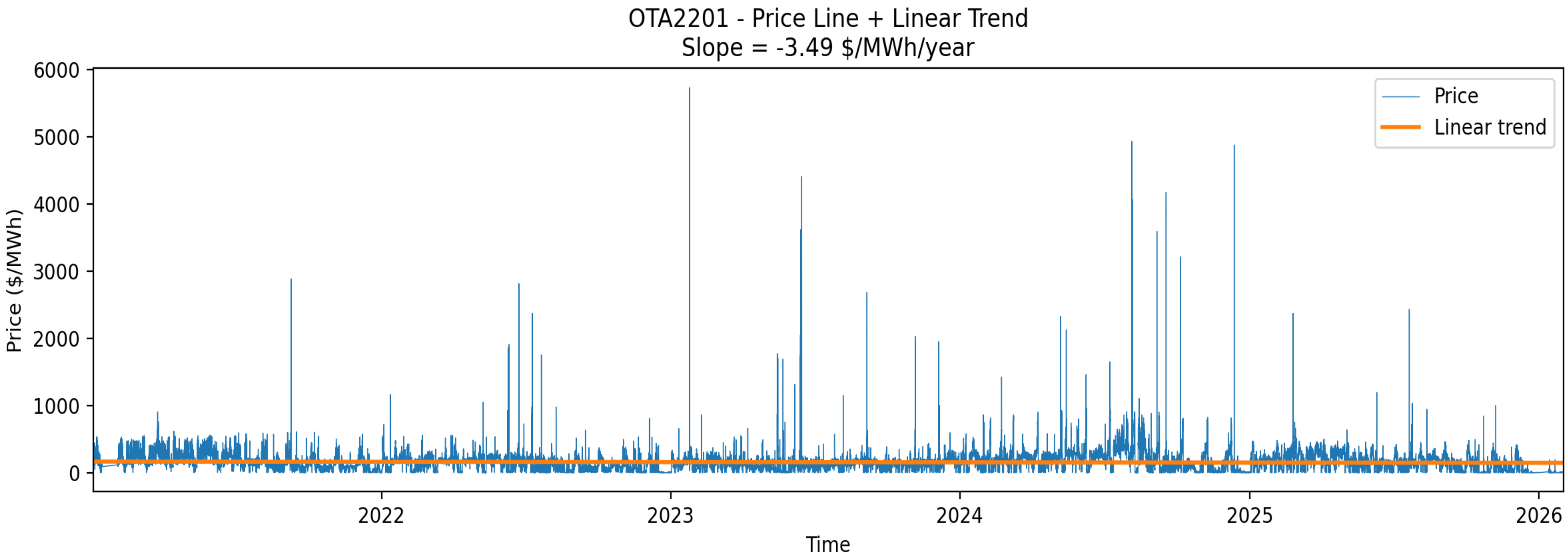
$\Delta t = 600s$;

$A_{PV} =$ *total PV panel area* (m^2);

$\eta_{PV} =$ *PV conversion efficiency*

The input-power-derived curve and the radiation-derived curve generally change in the same direction, supporting the use of radiation data as a proxy for solar resources in estimating PV input power.

Analysis -Electricity Price



Prices show strong volatility with occasional extreme spikes with small slope.

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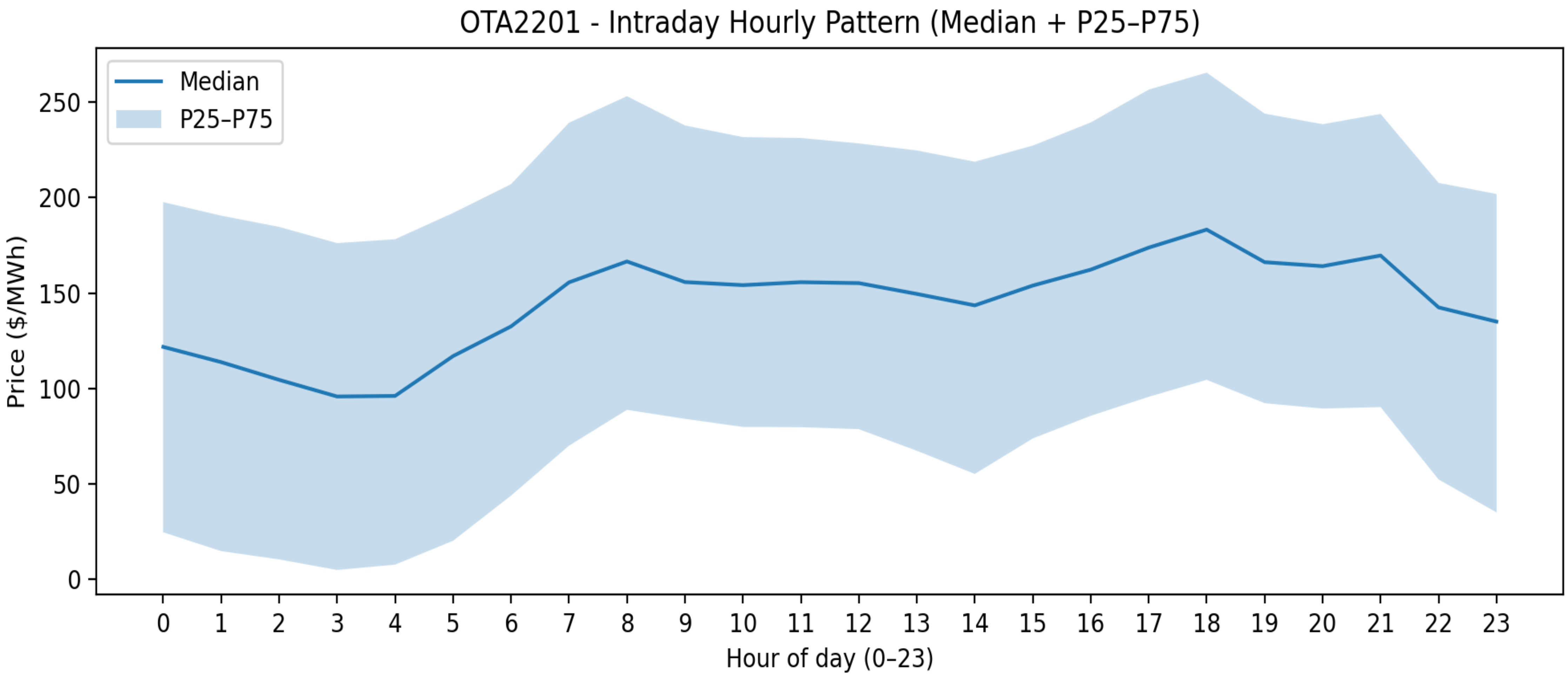
Analysis -Electricity Price



Shows a clear daily cycle, while the band remains wide.

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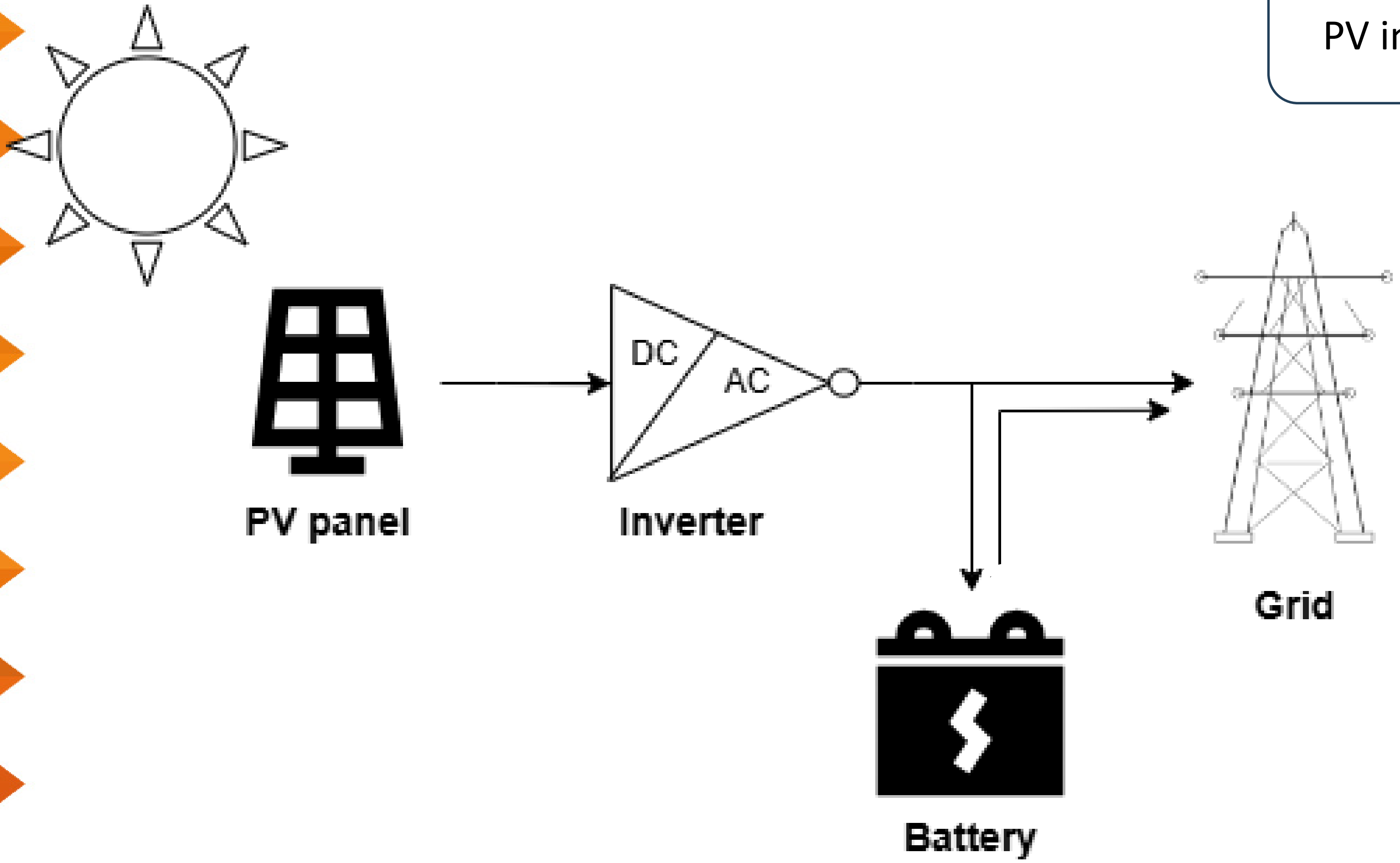
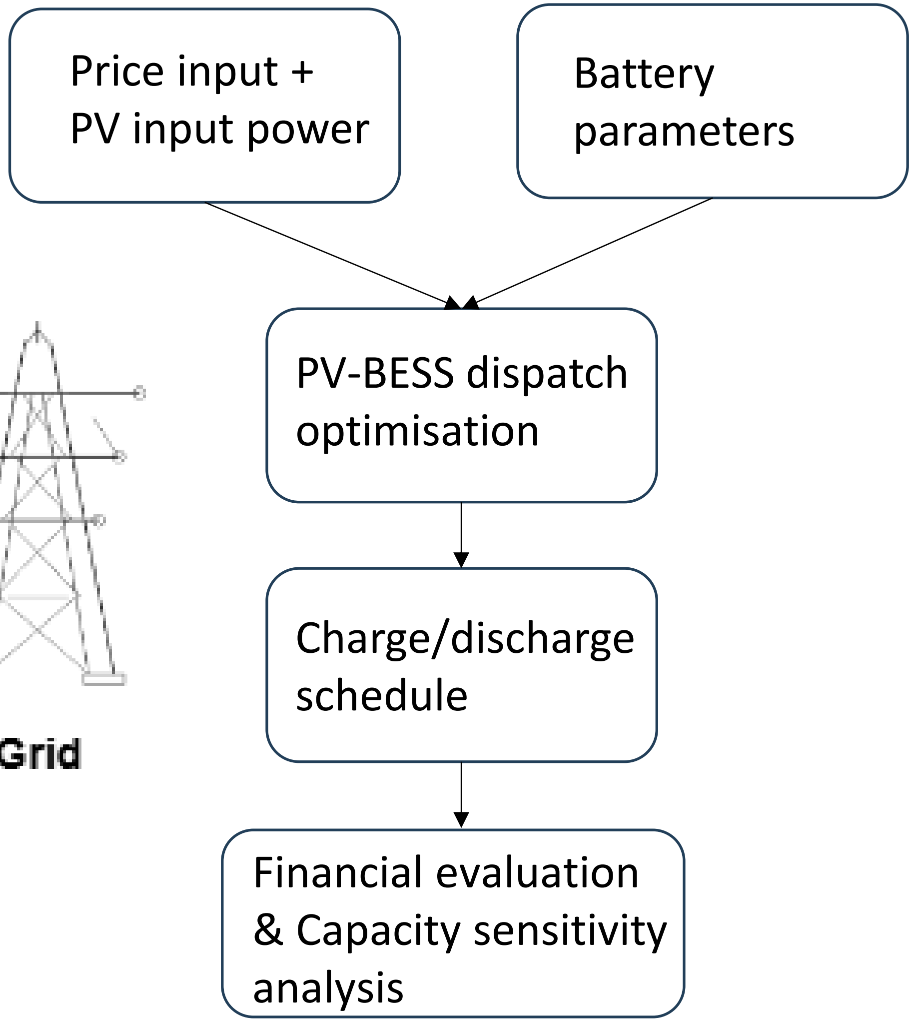
Section 03:
Model& Methodology

Framework


DC
AC
PV panel
Inverter
Battery
Grid


Price input + PV input power
Battery parameters
PV-BESS dispatch optimisation
Charge/discharge schedule
Financial evaluation & Capacity sensitivity analysis

Model

Objective Function

$$\max_{\{P_t{}^{\exp}\}_{t=1}^{T}} J \; = \mathbb{E}\left[\sum_{t=1}^{T-1} \Pi_t \, P_t^{\exp} \;\; \Delta t + E_T \Pi_T\right]$$

where

Π_t: electricity price at time t (\$/MWh)

$P_t^{exp} \; = P_t^{AC} + P_t^{bat} \; - \; P_t^{\mathrm{curt}}$

Δt: time step length — half hour

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Model

Constraints:

Power balance: $P_t^{PV} + P_t^{dis} = P_t^{exp} + P_t^{ch} + P_t^{curt}$

Battery energy: $E_{t+1} = E_t + \eta_{ch} P_t^{ch} \Delta t - \frac{1}{\eta_{dis}} P_t^{dis} \Delta t$

Battery energy limits: $E^{min} \leq E_t \leq E^{max}$

Inverter limits: $P_t^{AC} \leq P_{max}^{Inv}$

Charge/discharge limits:$0 \leq P_t^{ch}, P_t^{dis} \leq P_{max}^{B}$

POC limits: $P_t^{exp} \leq P_{max}^{POC}$

All energy non-negativity limits

Methodology

Linear Programming Dispatch Optimization

Input:

- electricity price: Π_t
- PV input power: P_t^{PV}

Decision variables:

- Battery energy: E^{bat}

Solver:

- CLARABEL

Methodology

Why CLARABEL:

Advantage:

- Suitable for convex optimisation
- Handles large full-horizon problems
- Suitable for continuous dispatch decisions
- Optimises all time steps together

Section 04:
Cost& Benefit Analysis

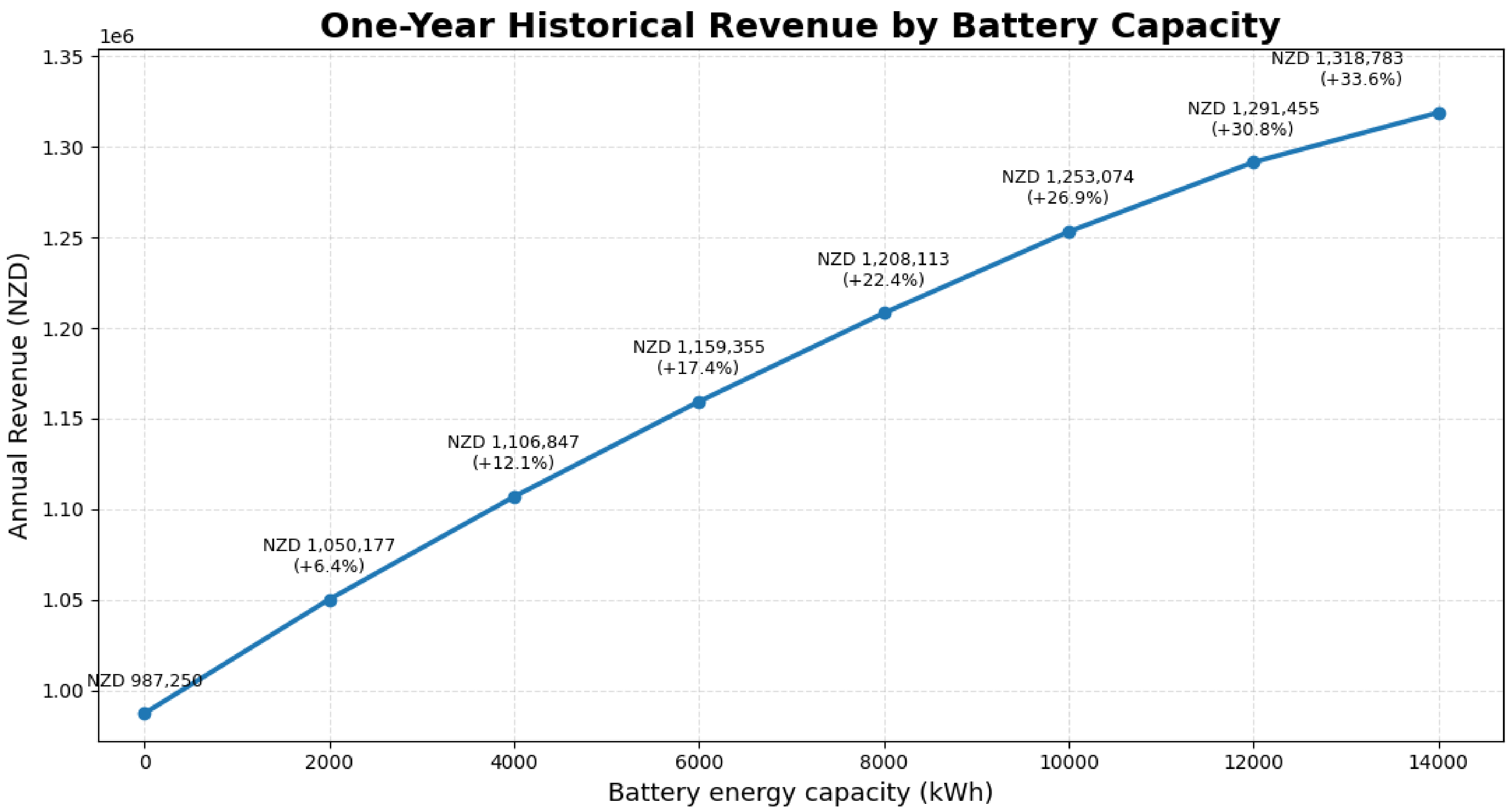
One-year result

Statistic of one-year schedule

Statistic	Value
Average charge power	342.60 kW
Average discharge power	441.06 kW
Maximum charge power	500.00 kW
Maximum discharge power	500.00 kW
Charging periods	4,257
Discharging periods	2,976
Avg. charging price	120.12 NZD/MWh
Avg. discharging price	211.39 NZD/MWh
Battery curtailed energy	≈ 0 kWh

The battery mainly charges during lower-price periods and discharges during higher-price periods, showing clear price arbitrage behaviour. It also removes all curtailment by storing energy.

One-year result



Without considering battery cost, larger battery capacity leads to higher revenue.

Battery Cost& Revenue Calculation

No-battery baseline revenue

$$R^{base} = \sum_{t=1}^{T} \Pi_t P_t^{export,base} \Delta t$$

Revenue improvement

$$\Delta R = R^{BESS} - R^{Base}$$

Battery CAPEX

$$\mathrm{CAPEX} = \mathrm{E}^{\max} \times \Pi^{bat}$$

Annual O&M

$$\mathrm{O\&M_y} = 2\% \times \mathrm{CAPEX}$$

Net cash flow

$$\mathrm{CF_y} = \Delta \mathrm{R_y} - \mathrm{O\&M_y}$$

NPV

$$\mathrm{NPV} = -\mathrm{CAPEX} + \sum_{y=1}^{N} \frac{CF_y}{(1+r)^y}$$

Where: $N = 15$ years, $r = 7\%$ discount rate

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Battery Information

Battery type	Estimated total CAPEX	Round-trip efficiency	Degradation	Lifetime
NMC	£484/kWh	85%	3.50% p.a.	15 years
LFP	US$125/kWh	90%	2.00% p.a.	20 years
Lead-acid	£451/kWh	80%	10.00% p.a.	5 years
2nd-life LMO	£436/kWh	85%	3.50% p.a.	5 years

Source: Adapted from Laksahapsoro et al. (2025), Table 4 & Ember

- LFP was identified as a cost-effective option with good performance and low degradation.
- Therefore, this project uses LFP.

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Simulation of Input Data

Electricity Price:

$$d\Pi_t = \left[\kappa_\Pi(\theta_\Pi(t) - \Pi_t) + \frac{d\theta_\Pi(t)}{dt}\right]dt + \sigma_\Pi \Pi_t dW_t^\Pi + dJ_t$$

where

$$J_t = \sum_{i=1}^{N_t} Y_i\,, \quad N_t \sim \mathit{Poisson}(\lambda t), \quad Y_i \sim \mathcal{N}\left(\mu_J, \sigma_J^2\right)$$

AC Power:

$$P_t^{\mathrm{AC}} = \eta_{inv} f(Z_t)$$

and Z_t:

$$dZ_t = \kappa_Z(\theta_Z(t) - Z_t)dt + \sigma_Z Z_t(1 - Z_t)dW_t^Z$$

where

$$0 \leq Z_t \leq 1$$

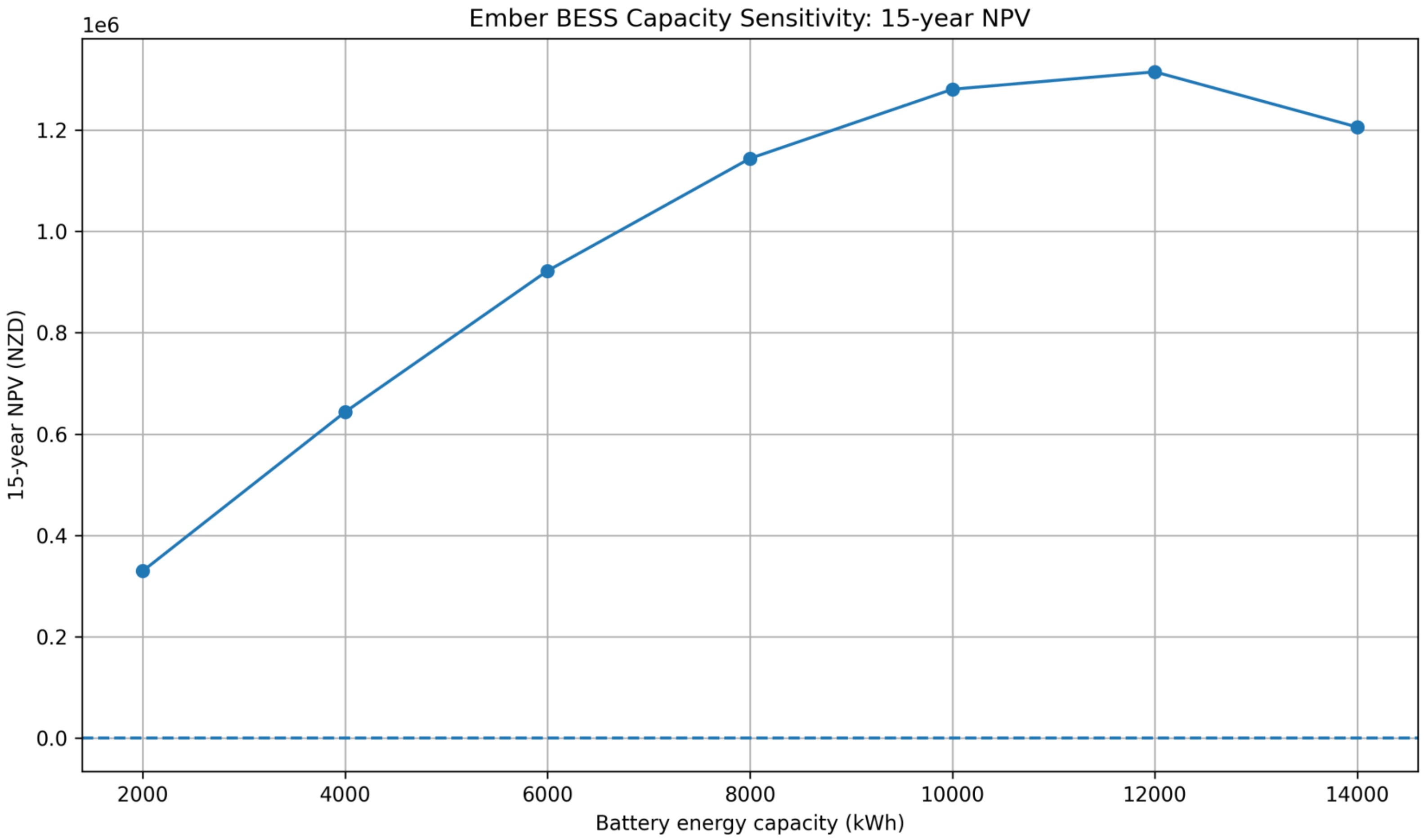
Source: Adapted from Bermúdez and Padín (2025).

NPV Comparation

Battery	CAPEX	Replacement	NPV
NMC	13.30M	none	-11.27M
Lead-acid	12.40M	Year 5, 10	-17.00M
2nd-life LMO	11.98M	Year 5, 10	-13.53M
LFP	2.63M	none	1.31M

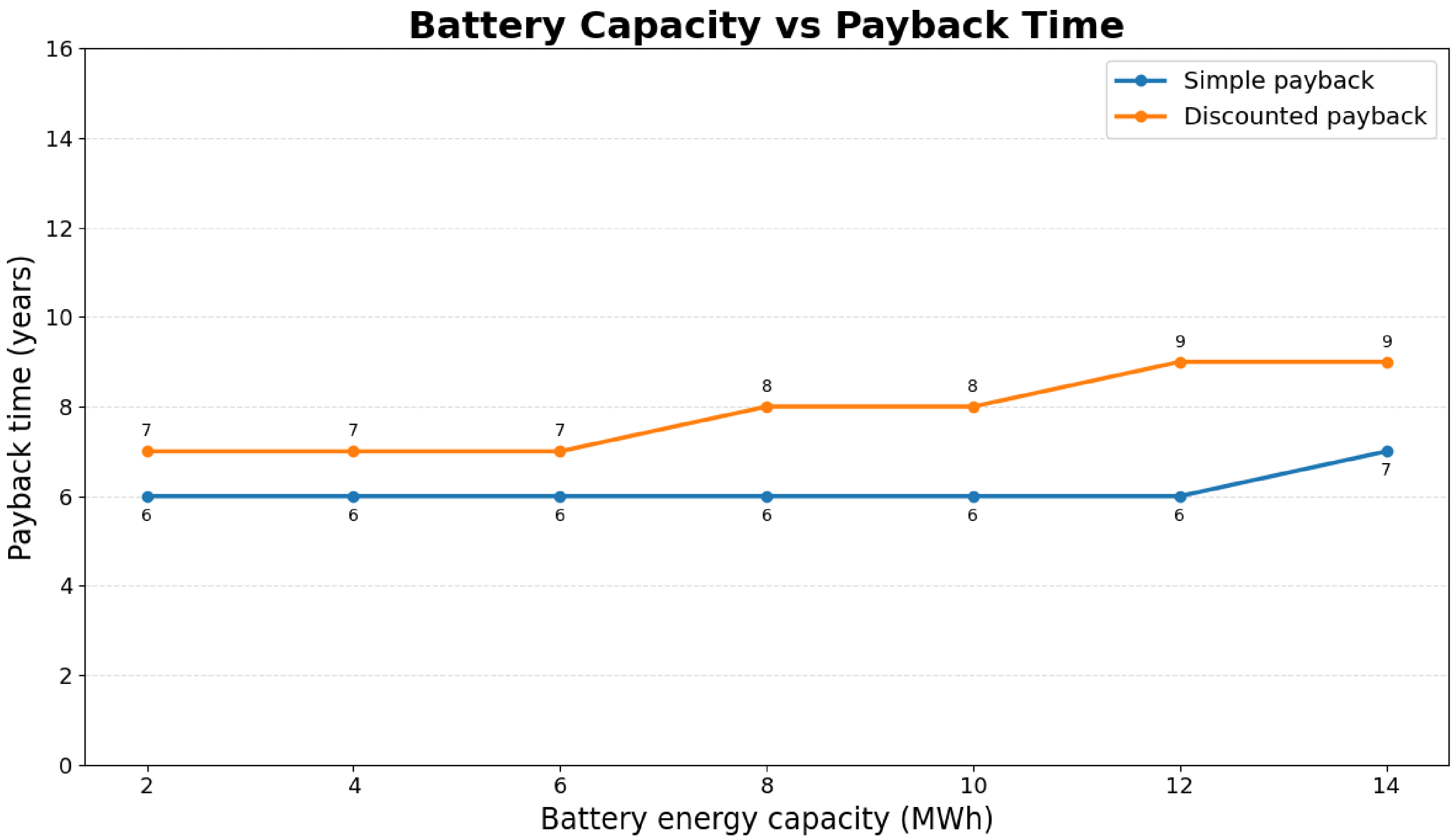
NMC, lead-acid, and 2nd-life LMO all fail to break even. It's not that they have no scheduling benefits, but rather that the costs are too high.

Capacity Sensitivity Analysis



12,000 kWh is the best-performing capacity in terms of 15-year NPV

Payback Analysis



The investment payback period, considering the time value of money, is approximately 7 to 9 years.

Section 05:
Conclusion

Limitations

- Electricity price input was simulated based on 5-year historical price rather than stochastic simulations.
- Long-term PV input power was estimated from 20-year radiation averages at each time point, rather than being represented by a continuous mean-reverting function.
- The assumption regarding the installation cost of batteries is based on the global market average, which may vary across different countries and regions.
- Battery degradation was represented using a simplified annual degradation.
- Grid connection and operational market requirements were not fully modelled.
- The optimisation was limited to a deterministic LP framework.

Future works

- Develop stochastic electricity price and PV generation.

- Obtain New Zealand-specific supplier for battery installation, grid connection, and O&M costs.

- Incorporate battery degradation directly into the optimisation model, including capacity fade and cycle-related degradation.

- Include more detailed grid connection and market participation requirements, such as ramp limits, reserve services, and operational compliance constraints.

- Develop stochastic optimisation methods to capture uncertainty in electricity prices, solar generation, and real-time battery operation.

Recommendation

- Adopt LFP as the preferred battery type.
- The recommended tested configuration is 12,000 kWh / 3,000 kW.
- NMC, lead-acid and 2nd-life LMO are not recommended under the high cost assumptions due to negative NPV.
- Final investment should be subject to NZ supplier quotations and grid connection assessment.

Section 06: Reference

References

- KiwiSolar: plant operational data

https://www.kiwisolar.co.nz/

- Electricity Authority (NZ) – EMI: nodal spot price data

https://www.emi.ea.govt.nz/

- Bermúdez, A., & Padín, I. (2025). State constrained stochastic optimal control of a PV system with battery storage via Fokker–Planck and Hamilton–Jacobi–Bellman equations. https://arxiv.org/abs/2506.11765(Used as a reference for stochastic state modelling and constraint-aware control formulation.)

- Earth Sciences New Zealand: radiation data
https://data.niwa.co.nz/

- International Renewable Energy Agency (IRENA)

https://www.irena.org/

- Ember

https://ember-energy.org/

- Laksahapsoro, B., Bird, M., Acha, S., & Shah, N. (2025). *Optimisation of photovoltaic and battery systems for cost-effective energy solutions in commercial buildings*. **Applied Energy, 392**, 125907.

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Thank you!

Q & A