Integrated Climate–Energy–Grid Modeling: Solar PV Variability and Optimal Dispatch

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Introduction

Power systems are increasingly exposed to weather-driven variability as solar PV penetration grows. Grid operators must balance a fluctuating net load (demand minus renewable generation) using dispatchable thermal units, while controlling costs and maintaining reliability.

This capstone project asks:

How does solar PV variability affect net load, and what is the minimum-cost dispatch strategy for conventional generators given that variability?

We build an integrated modeling chain:

1. Synthetic but realistic hourly electricity demand
2. Weather-driven solar PV generation
3. Net load calculation
4. Linear programming–based economic dispatch

This combines time-series modeling, renewable energy simulation, and numerical optimization into a single, coherent framework.

Methods

Load Model

We simulate one month of hourly electricity demand with:

- a strong daily cycle (morning/evening peaks),
- a weekday–weekend effect,
- random noise.

This reflects typical distribution-level or system-level load behavior.

Solar PV Model

Solar PV output is modeled as:

- a clear-sky irradiance curve based on hour of day,
- modified by a stochastic cloud cover process,

- converted to AC power using a simple efficiency and area model.

This captures both the predictable diurnal pattern and the unpredictable variability introduced by clouds.

Net Load

Net load is defined as:

$$\text{Net Load}(t) = \max\left(\text{Load}(t) - \text{PV}(t), 0\right)$$

This is the demand that must be met by dispatchable generators.

Dispatch Optimization

We consider three thermal generators with:

- maximum capacities,
- linear marginal costs,
- non-negativity constraints.

For each hour t, we choose generator outputs $g_i(t)$ to:

$$\min \sum_t \sum_i c_i g_i(t)$$

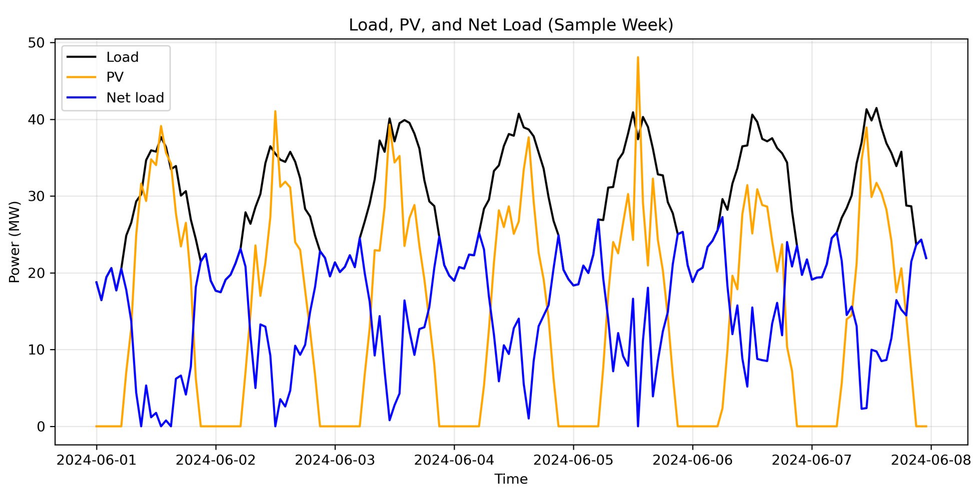
subject to:

$$\sum_i g_i(t) \geq \text{Net Load}(t), \quad 0 \leq g_i(t) \leq \text{Cap}_i$$

This is a linear program solved using PuLP with the CBC solver.

Results

Load, PV, and Net Load

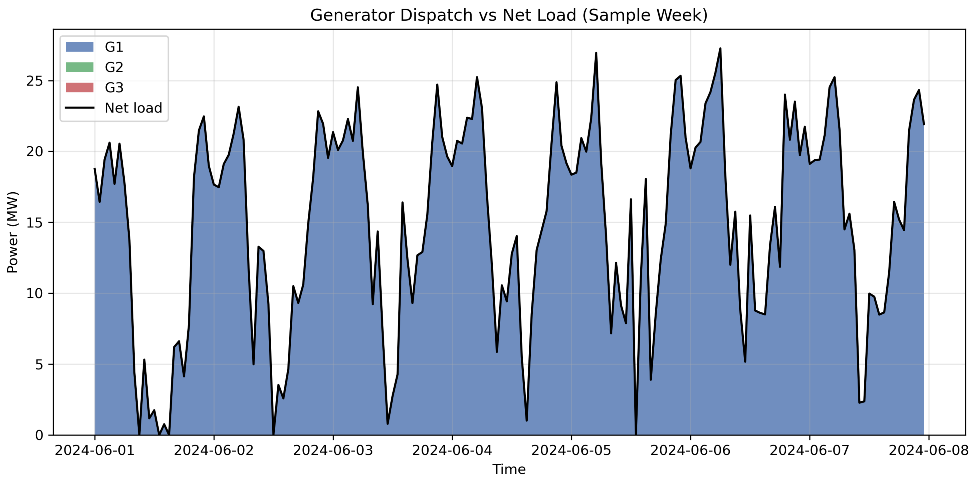


The sample week illustrates:

- a smooth daily load pattern,
- a strongly diurnal PV profile modulated by clouds,
- a net load curve that is reduced and reshaped by PV.

Midday net load is often significantly lower due to PV, while evening net load remains high when PV output drops.

Dispatch vs Net Load

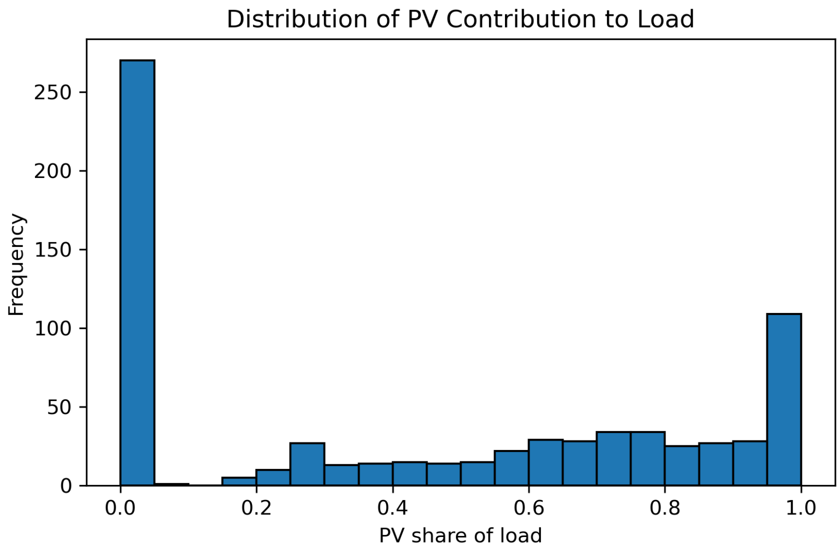


The stacked area plot shows:

- how the three generators share the burden of meeting net load,
- preferential use of lower-cost units,
- higher-cost units ramping up only when net load is high.

This is a classic economic dispatch pattern: cheap units run as much as possible, expensive units fill the residual.

PV Contribution



The distribution of PV share of load shows:

- many hours with modest PV contribution,
- some hours where PV covers a large fraction of demand,
- hours (especially evenings and nights) with negligible PV.

This highlights the challenge of integrating solar: it is valuable but intermittent.

Total Cost

The total generation cost over the month is stored in:

- `results/total_cost.txt`

This scalar summarizes the economic outcome of the dispatch under the given PV and load conditions.

Discussion

This integrated model demonstrates several key points:

- **Weather-driven PV reshapes net load**, reducing midday demand on thermal units but leaving evening peaks largely intact.
- **Economic dispatch naturally prioritizes low-cost generators**, but capacity limits and net load variability require higher-cost units at times.
- **PV reduces total generation cost**, but also introduces variability that must be managed by flexible conventional units.

From a methodological perspective, this capstone shows your ability to:

- construct realistic time-series models for load and PV,
- link them into a net load representation,

- formulate and solve a linear programming dispatch problem,
- interpret results in both physical and economic terms.

Conclusion

By combining load modeling, solar PV simulation, and optimal dispatch, this capstone provides a compact but powerful illustration of climate–energy–grid interactions. It demonstrates how weather-driven renewables affect system operations and how optimization can be used to design cost-effective dispatch strategies.

As a portfolio piece, this project integrates your strengths in time-series analysis, energy modeling, and numerical optimization into a single, coherent narrative that is directly relevant to modern power systems and energy analytics roles.