Stochastic Programming for Energy Procurement with Targets: 24/7 Matching and Its Relaxations

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XVII[th] CONFERENCE ON STOCHASTIC PROGRAMMING
28 JULY – 01 AUGUST 2025, FRANCE

UNIVERSITY OF TWENTE.

Motivation

UN Sustainable Development Goals #7

“Ensure access to affordable, reliable, sustainable, and modern energy for all”

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CLIMATE GROUP
RE100

Climate Group RE100

Over 400 companies made a commitment to go 100% renewable

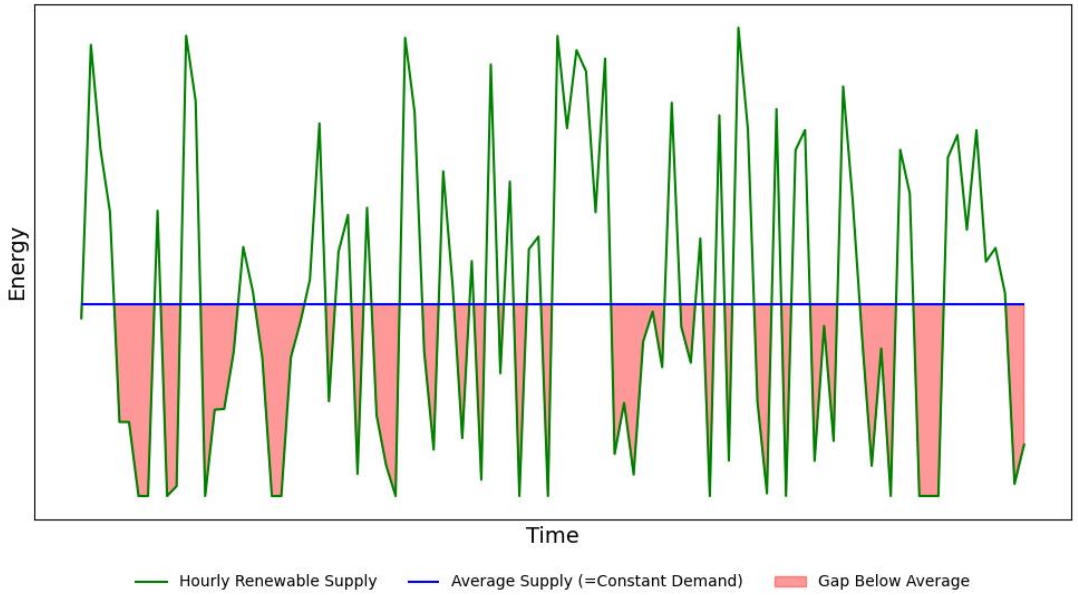
- Microsoft (since 2014)
- Google (since 2017)
- Apple (since 2018)

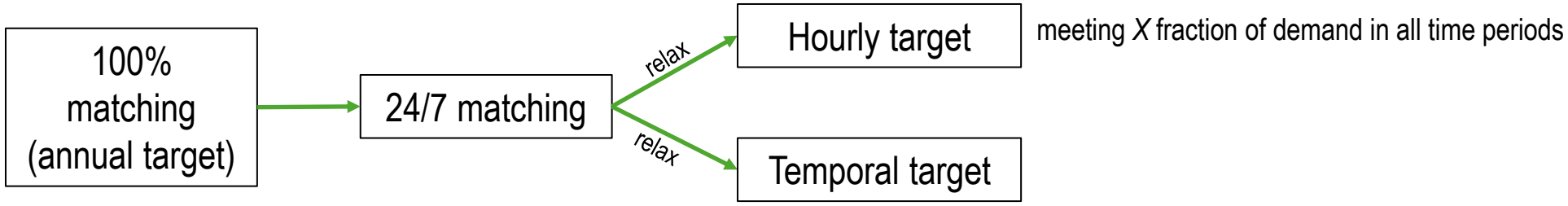
Google's 2030 goal: run all its operations using 24/7 carbon-free energy on every grid

24/7 Carbon-Free Energy Compact

Every kilowatt-hour of electricity demand with Carbon-Free Energy sources, every hour, every day, everywhere.

100% and 24/7 Matching





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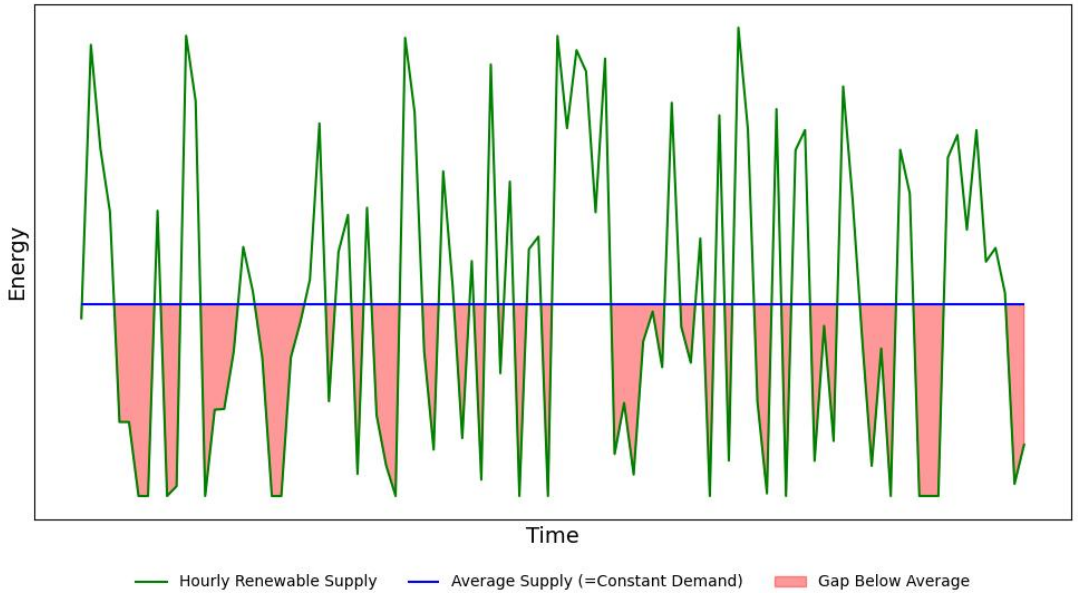

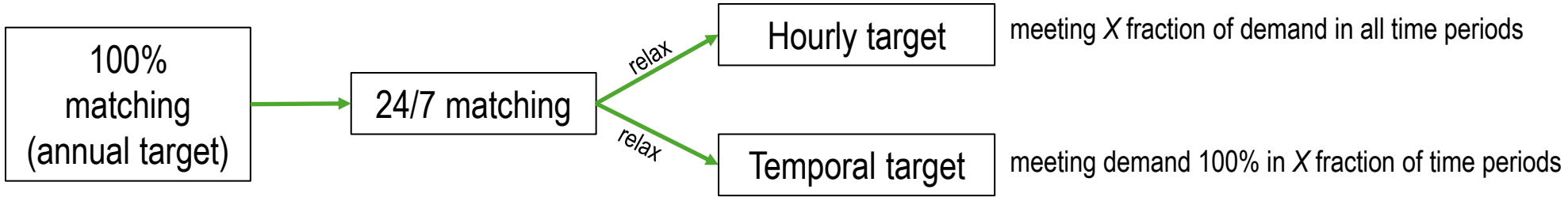

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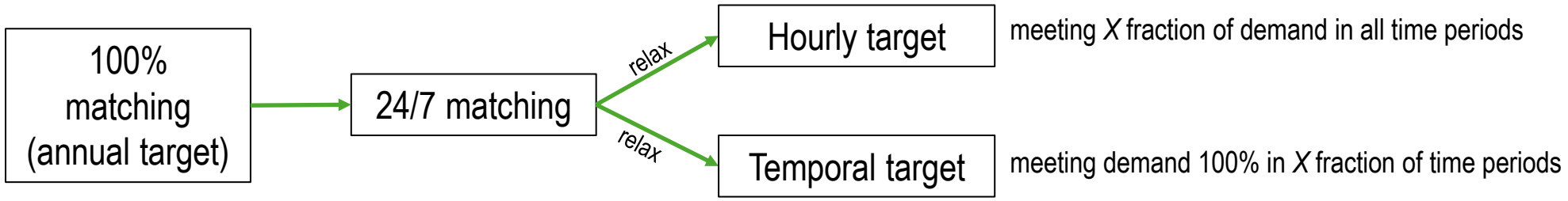
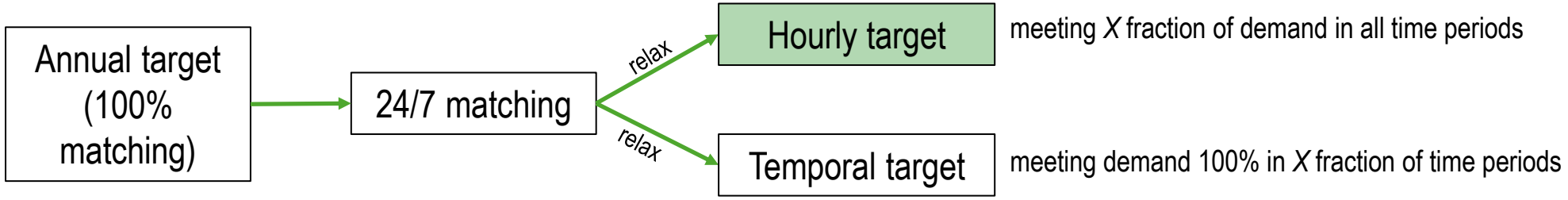


Compliance target (X) = 0.8

100% and 24/7 Matching



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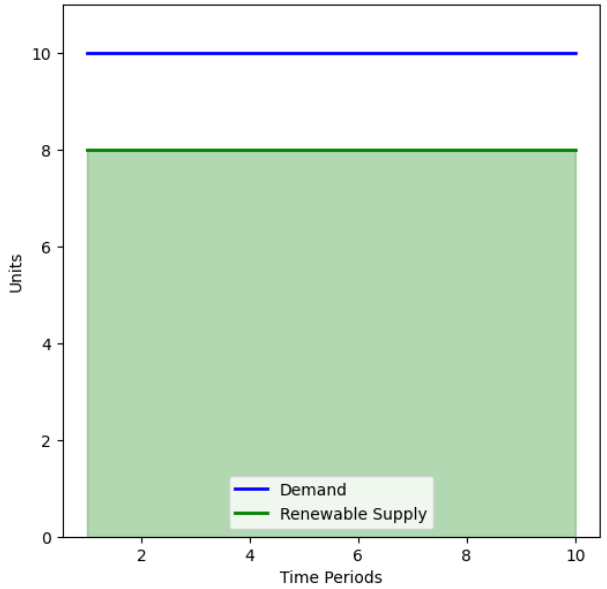
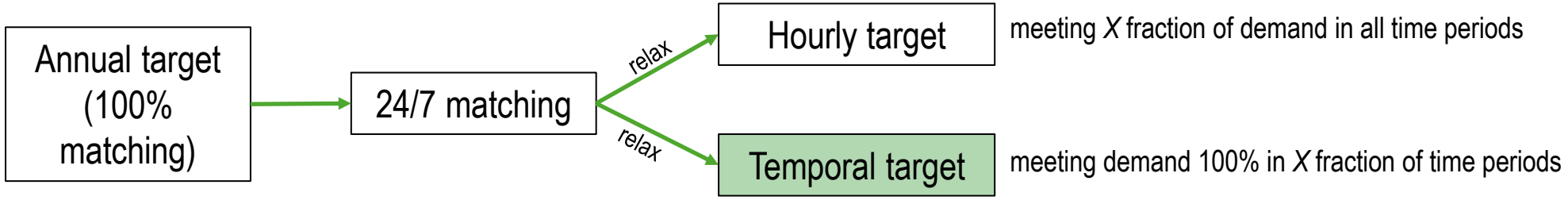


80% satisfied in all periods

100% and 24/7 Matching



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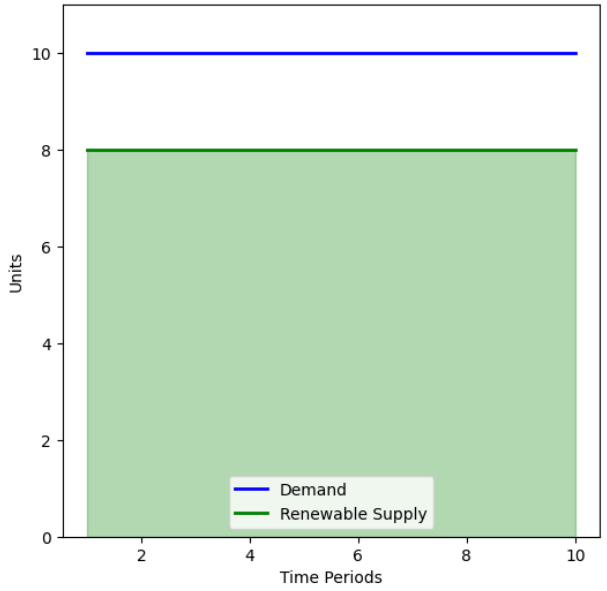

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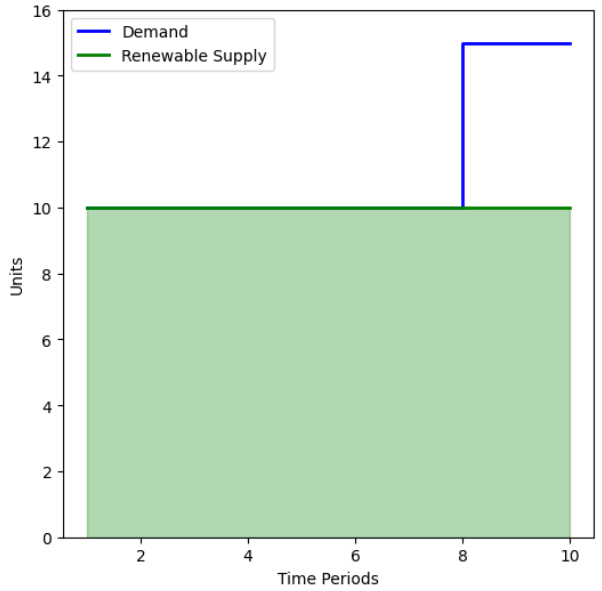

100% satisfied in 80% of time periods

Two-Stage Problem

Problem Setting

Power purchase agreements ✚ Energy attribute certificates ✚ Energy storage

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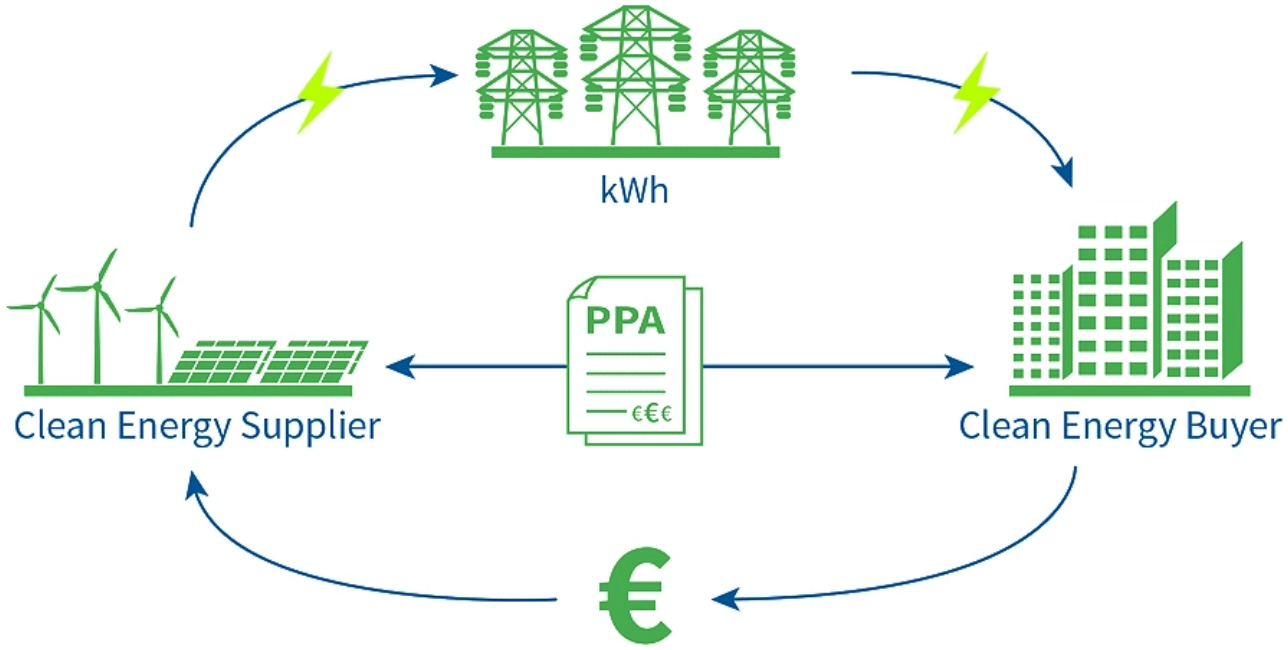
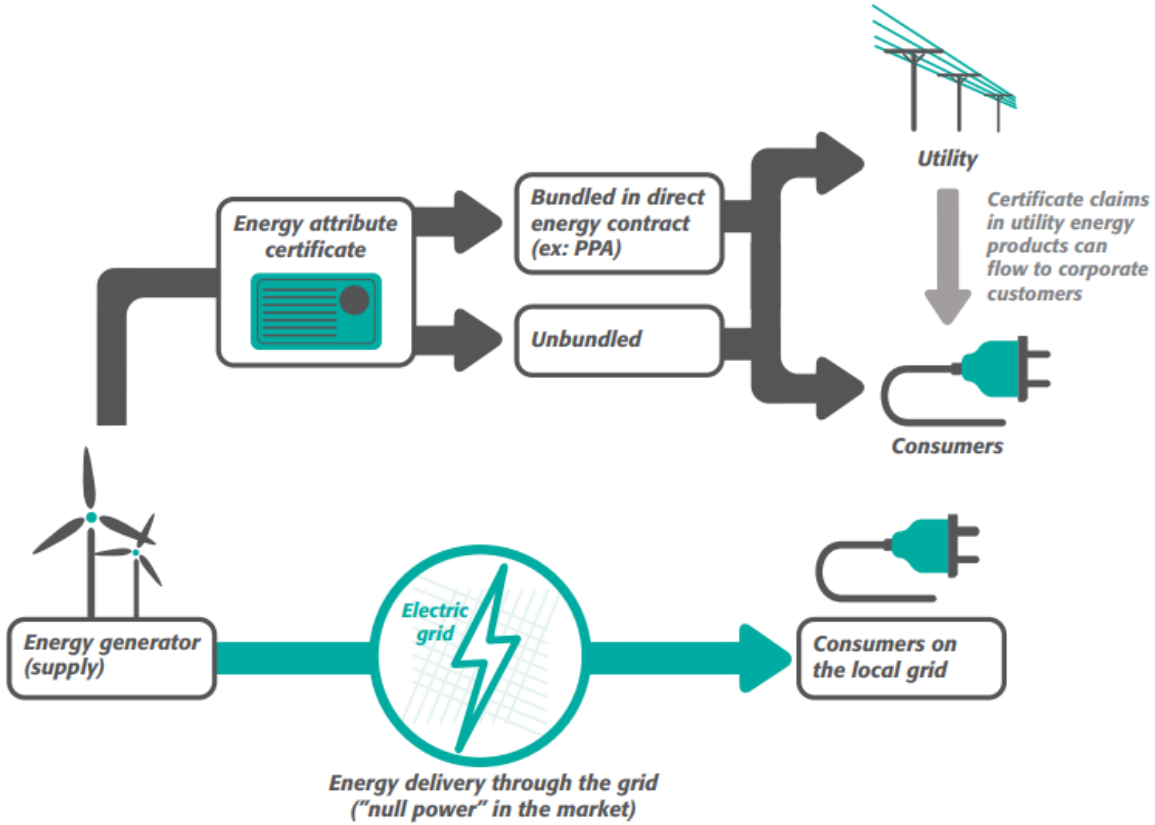
"**Long-term contracts** to buy electricity directly from renewable producers at agreed prices."



Problem Setting

Power purchase agreements ✚ **Energy attribute certificates** ✚ Energy storage

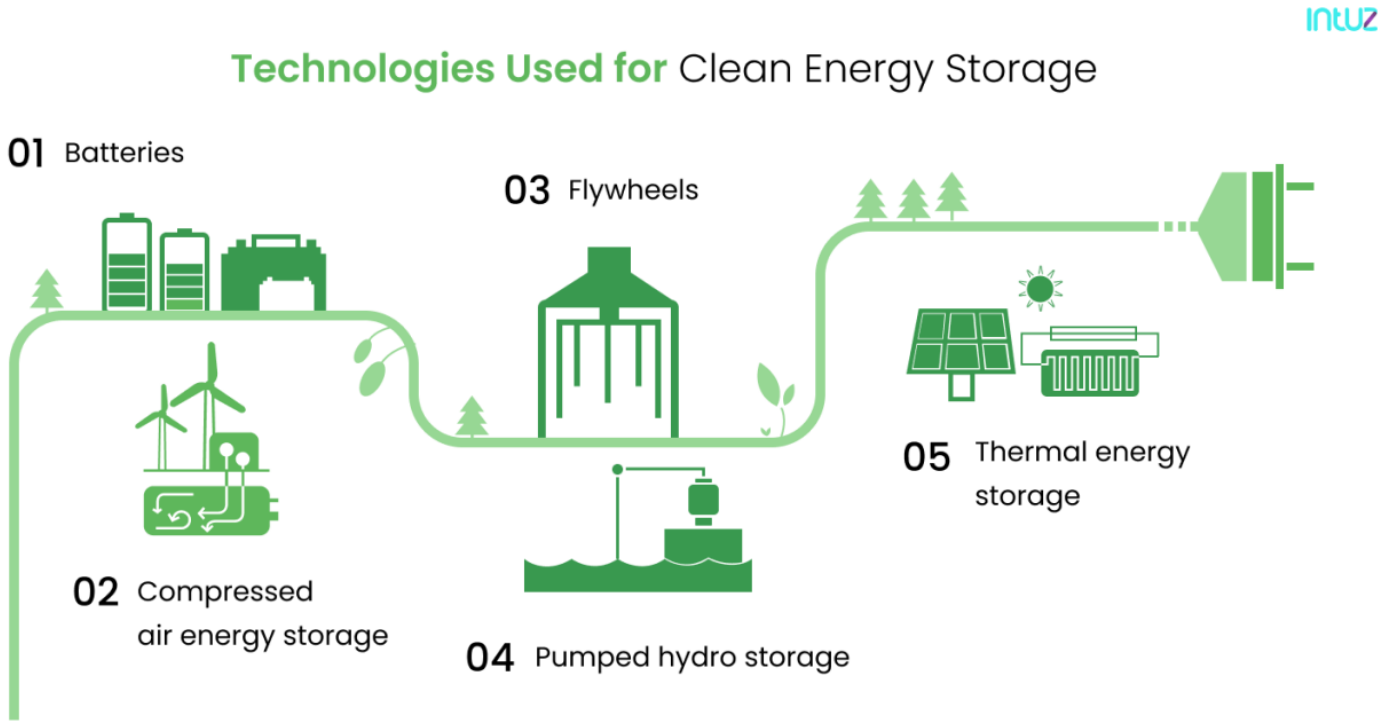
"Proof of **renewable origin** of electricity — used to claim green energy usage."



Problem Setting

Power purchase agreements ✚ Energy attribute certificates ✚ **Energy storage**

"Technology that **stores electricity** for use when renewable supply is low or demand is high."



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- Trade-offs between annual and 24/7 matching, with relaxations
- Optimal PPA sizes and storage capacities
- Effect of uncertainty on decision-making

- Two-stage problem by nature

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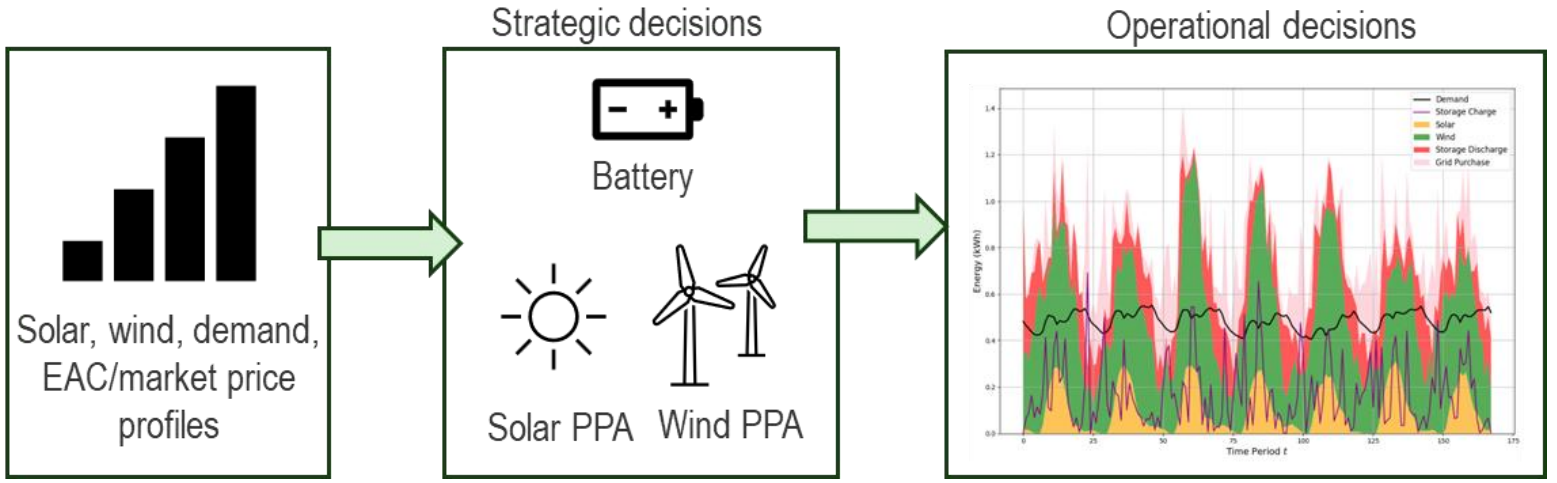
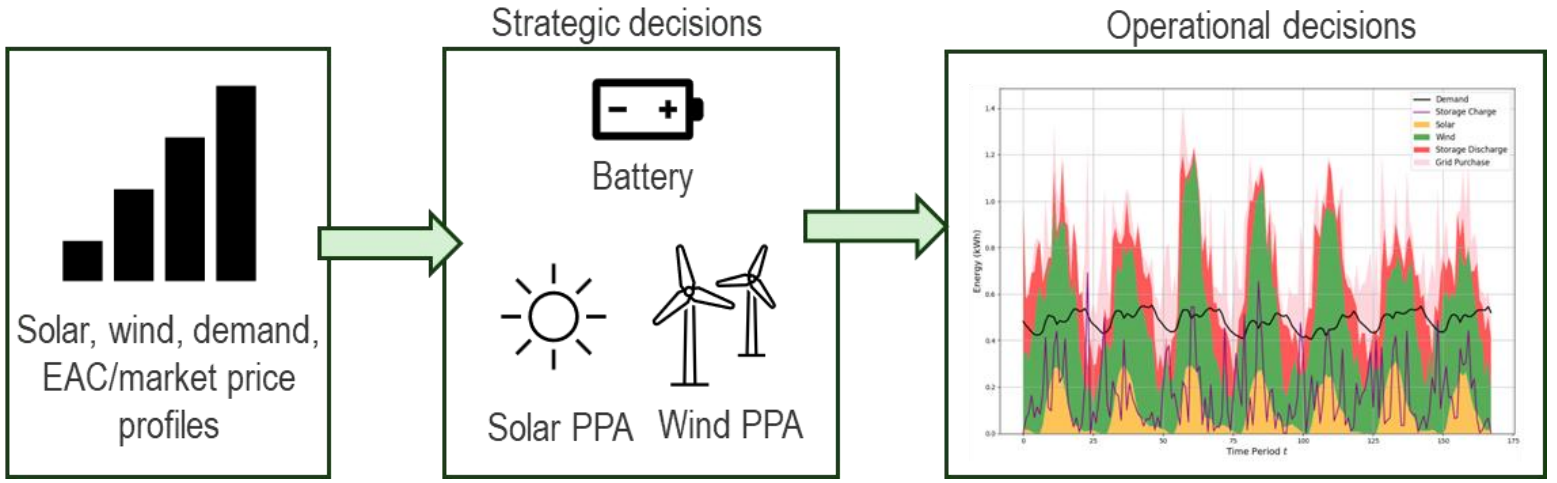


Problem Setting

Power purchase agreements + Energy attribute certificates + Energy storage

- Trade-offs between annual and 24/7 matching, with relaxations
- Optimal PPA sizes and storage capacities
- Effect of uncertainty on decision-making
- Two-stage problem by nature
  - **Analytical** comparison of targets
  - **Numerical** insights based on a MILP model



Comparing Hourly and Temporal Targets

Proposition 1. *For all* $X \in (0,1)$ *and* $\gamma > 0$, *there exist instances* I, I' *such that:*

$$(a) \quad C^*_{T,X}(I) > \gamma + C^*_{H,X}(I)$$

and

$$(b) \quad C^*_{H,X}(I') > \gamma + C^*_{T,X}(I').$$

"For all target levels, it is possible to find instances such that the hourly compliance and temporal compliance targets have arbitrarily different costs."

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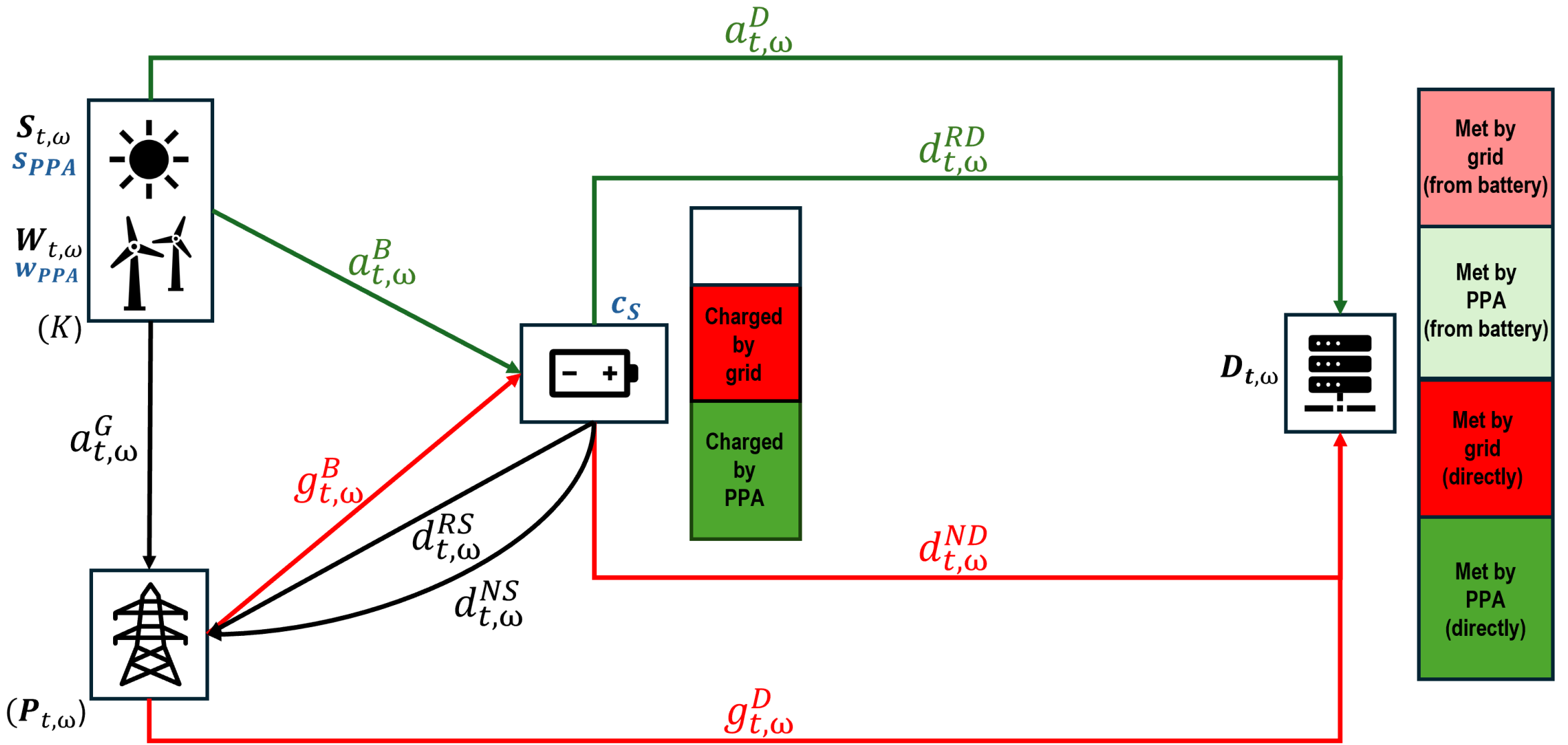
Hourly and temporal targets are incomparable: Either one can lead to significantly higher cost.

Flow-Based Setting



Full Mathematical Formulation

$$\min \quad P_S c_S + H(C_{PPA} + C_{market} + C_{EAC} - R_{market})$$

s.t.

$$D_{t,\omega} = a^D_{t,\omega} + d^{RD}_{t,\omega} + g^D_{t,\omega} + d^{ND}_{t,\omega} \qquad \forall t \in T, \omega \in \Omega \qquad (1)$$ **Demand satisfaction**

$$a^D_{t,\omega} + a^B_{t,\omega} + a^G_{t,\omega} = s_{PPA} SG_{t,\omega} + w_{PPA} WG_{t,\omega} \qquad \forall t \in T, \omega \in \Omega \qquad (2)$$ **PPA supply equal to PPA usage**

$$b^R_{t+1,\omega} = b^R_{t,\omega} + \eta a^B_{t,\omega} - \frac{d^{RS}_{t,\omega} + d^{RD}_{t,\omega}}{\eta} \qquad \forall t \in T, \omega \in \Omega \qquad (3)$$ Storage balance renewable part

$$b^N_{t+1,\omega} = b^N_{t,\omega} + \eta g^B_{t,\omega} - \frac{d^{NS}_{t,\omega} + d^{ND}_{t,\omega}}{\eta} \qquad \forall t \in T, \omega \in \Omega \qquad (4)$$ Storage balance non-renewable part

$$b^R_{t+1,\omega} + b^N_{t+1,\omega} \leq c_S \qquad \forall t \in T, \omega \in \Omega \qquad (5)$$ Storage capacity constraint

$$b^R_{0,\omega} + b^N_{0,\omega} = b^R_{T,\omega} + b^N_{T,\omega} \qquad \forall \omega \in \Omega \qquad (6)$$ Initial storage equal to end storage

$$a^B_{t,\omega} + g^B_{t,\omega} \leq C_C \qquad \forall t \in T, \omega \in \Omega \qquad (7)$$

$$a^B_{t,\omega} + g^B_{t,\omega} \leq c_S - b^R_{t,\omega} - b^N_{t,\omega} \qquad \forall t \in T, \omega \in \Omega \qquad (8)$$

Charging capacities

$$d^{RD}_{t,\omega} + d^{RS}_{t,\omega} \leq b^R_{t,w} \qquad \forall t \in T, \omega \in \Omega \qquad (9)$$

$$d^{ND}_{t,\omega} + d^{NS}_{t,\omega} \leq b^N_{t,w} \qquad \forall t \in T, \omega \in \Omega \qquad (10)$$

$$d^{RS}_{t,\omega} + d^{NS}_{t,\omega} + d^{RD}_{t,\omega} + d^{ND}_{t,\omega} \leq C_D \qquad \forall t \in T, \omega \in \Omega \qquad (11)$$

Discharging capacities

$$a^B_{t,\omega} + g^B_{t,\omega} \leq C_C \cdot z_{t,\omega} \qquad \forall t \in T, \omega \in \Omega \qquad (12)$$

$$d^{RS}_{t,\omega} + d^{NS}_{t,\omega} + d^{RD}_{t,\omega} + d^{ND}_{t,\omega} \leq C_D \cdot (1 - z_{t,\omega}) \qquad \forall t \in T, \omega \in \Omega \qquad (13)$$

No simultaneous charge/discharge

Targets

100% Renewable Energy
Organizations purchase enough renewable energy to match their **annual electricity use.**

*total available PPA + total EACs ≥ X * total demand*

$$\sum_{t\in\mathcal{T}}(a^D_{t,\omega} + a^B_{t,\omega} + a^G_{t,\omega} + e_{t,\omega}) \geq X \cdot \sum_{t\in\mathcal{T}} D_{t,\omega} \quad \forall\omega \in \Omega \qquad (\mathrm{AC})$$

(average target)

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24/7 Carbon-Free Energy
Matching electricity **demand** with Carbon-Free Energy **generation** in **each hour** and on **each grid** where demand occurs (ensuring they don't emit in the first place).

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*renewable used in satisfying demand ≥ X * demand*

$$a^D_{t,\omega} + d^{RD}_{t,\omega} + e_{t,\omega} \geq X \cdot D_{t,\omega} \qquad \forall t \in T, \omega \in \Omega \qquad (\mathrm{HC})$$

(hourly target)

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(hourly target)

fraction of fully renewable hours ≥ X

$$g^D_{t,\omega}+d^{ND}_{t,\omega}-e_{t,\omega}\leq D_{t,\omega}(1-q_{t,\omega}) \qquad \forall t\in T,\ \forall\omega\in\Omega \qquad (\mathrm{TC})$$

(temporal target)

$$\frac{\sum_{t=1}^{T} q_{t,\omega}}{|T|}\geq X \qquad \forall\omega\in\Omega \qquad (\mathrm{TC})$$

$$q_{t,\omega}=\begin{cases}1, & \text{if } g^D_{t,\omega}+d^{ND}_{t,\omega}-e_{t,\omega}\leq 0\\ 0, & \text{otherwise}\end{cases}$$

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$$\frac{\sum_{t=1}^{T} q_{t,\omega}}{|T|} \geq X \qquad \forall\omega \in \Omega \qquad (\mathrm{TC})$$

- If $X = 1$, (TC) is equivalent to (HC)
- If $X \leq 1$, (AC) is a relaxation of (HC)

$$q_{t,\omega} = \begin{cases} 1, & \text{if } g^D_{t,\omega} + d^{ND}_{t,\omega} - e_{t,\omega} \leq 0 \\ 0, & \text{otherwise} \end{cases}$$

GBM-Based Scenario Generation Algorithm for Demand

Multi-year projections

- Long-term corporate PPAs and renewable targets
- Uncertain demand growth
- Geometric Brownian Motion

Managing complexity

- Full resolution year modelling-intractable
- Sampling approaches, ensuring alignment

Scenario construction

- Scale sampled weeks with GBM multipliers
- Generate N synthetic years
- Sample N' years out of the N years

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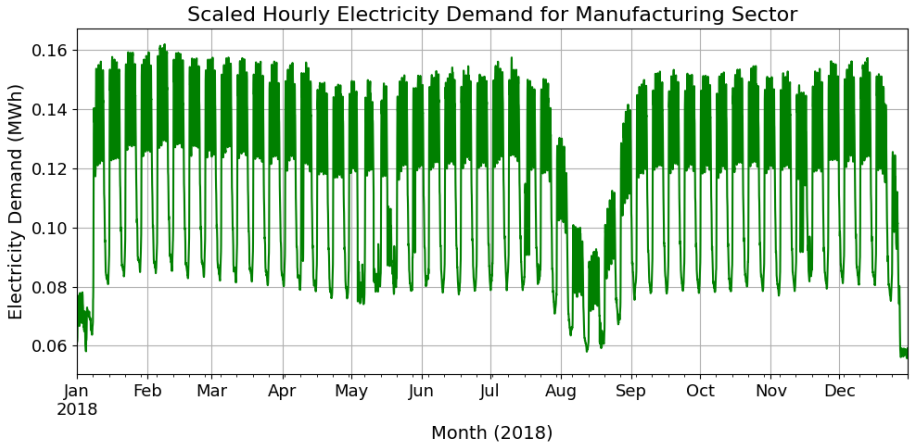
Parameter selection

- # generated years = 20 (~storage lifetime/PPA duration)
- # selected years = 5
- # representative weeks/season = 2
- # scenarios = 10

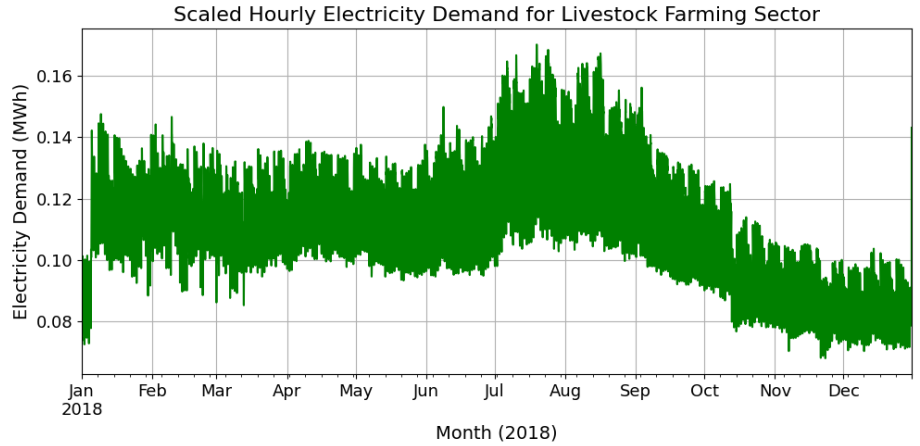
Different parameter combinations tried, aiming for computational efficiency

Real Demand Profiles

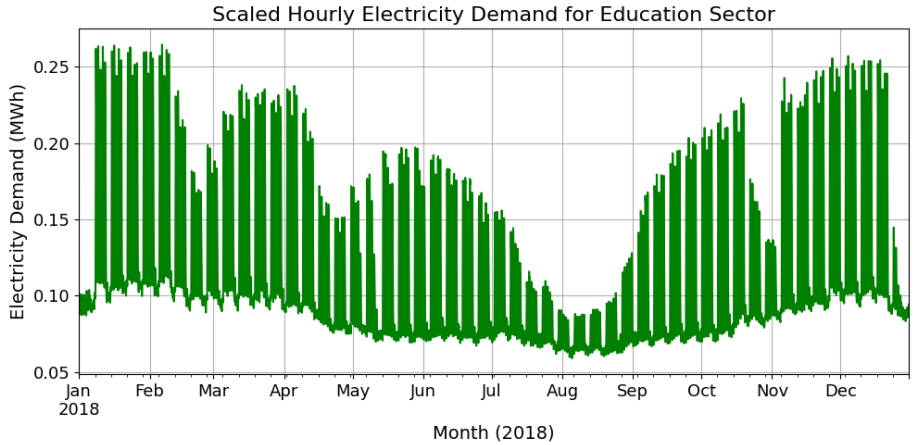
Manufacturing



Livestock Farming

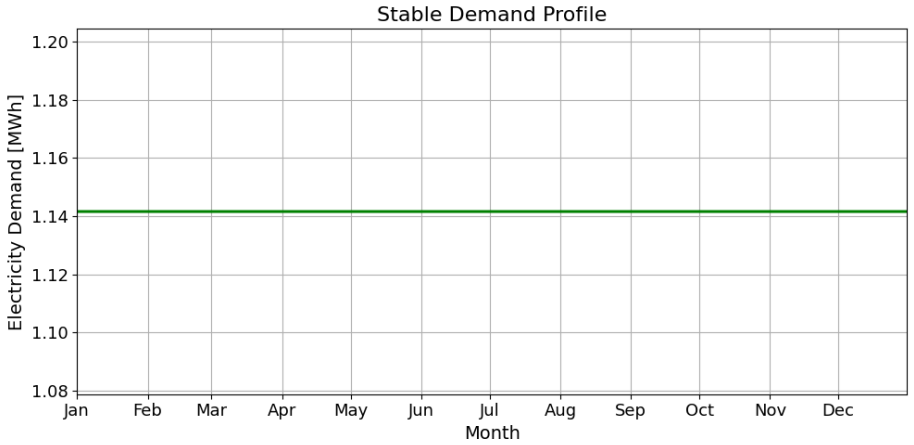


Education

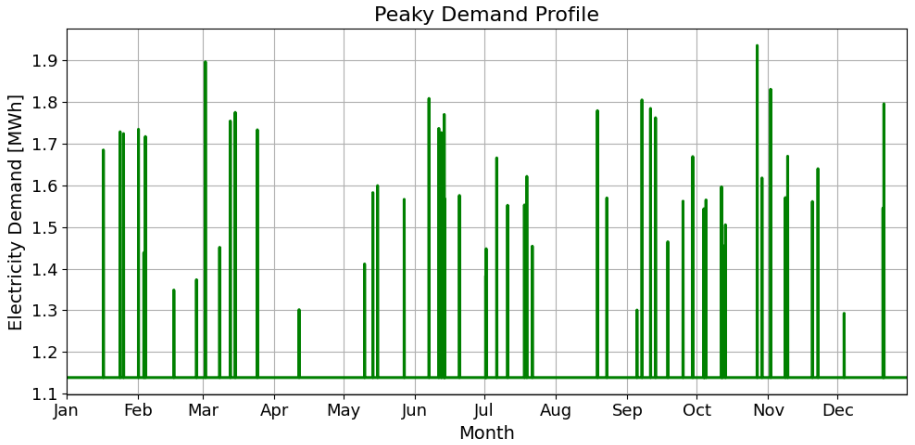


Artificial Demand Profiles

Stable Profile



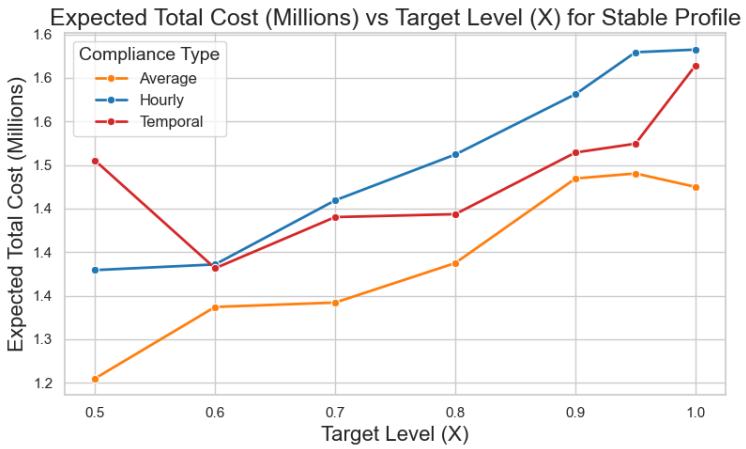
Peaky Profile

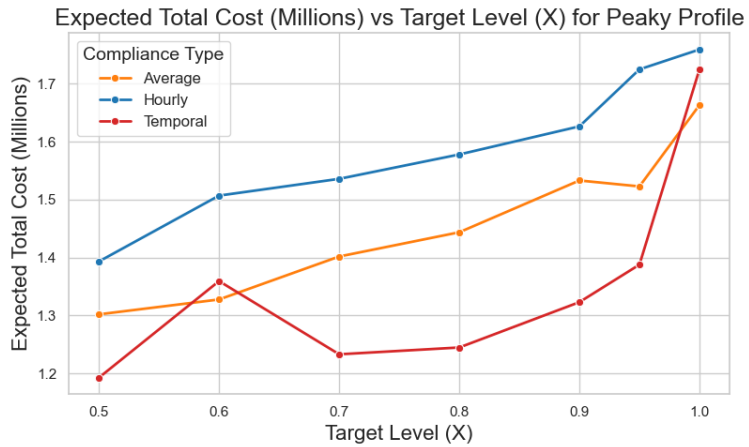


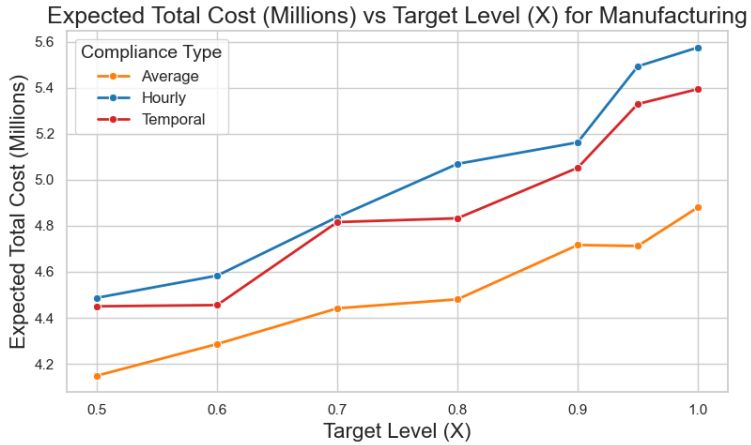
Uncertainty in **stable** profile: **GBM**
Uncertainty in **peaky** profile: **peak generation**

*All profiles are scaled to the same total annual demand

Costs vs. Compliance Levels







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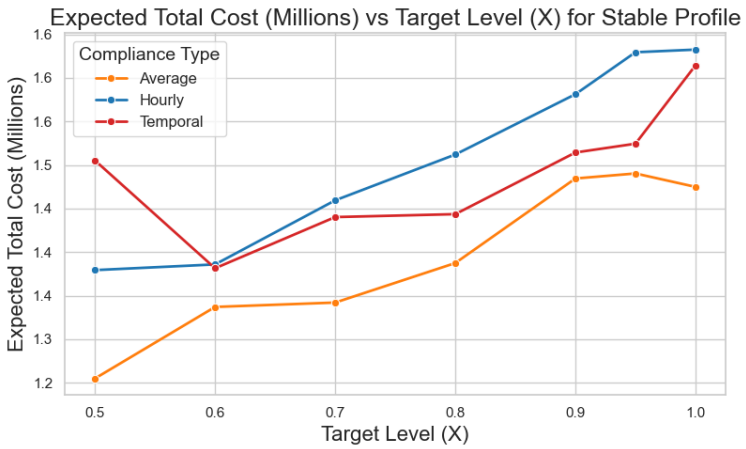
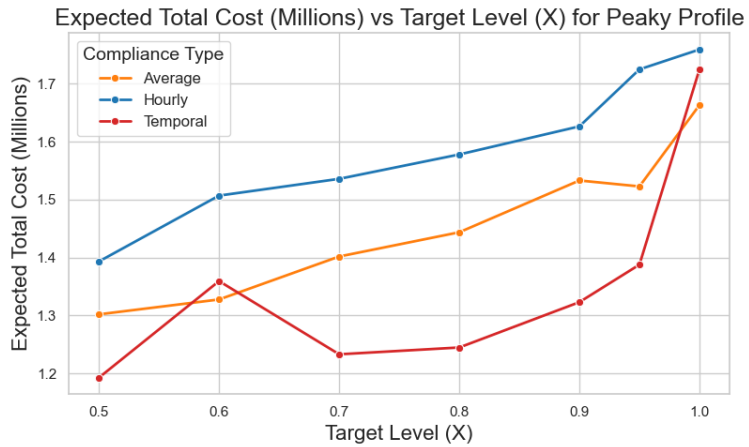
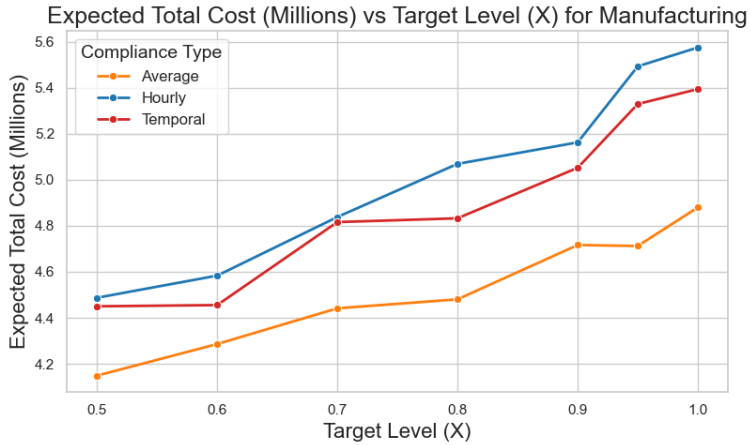


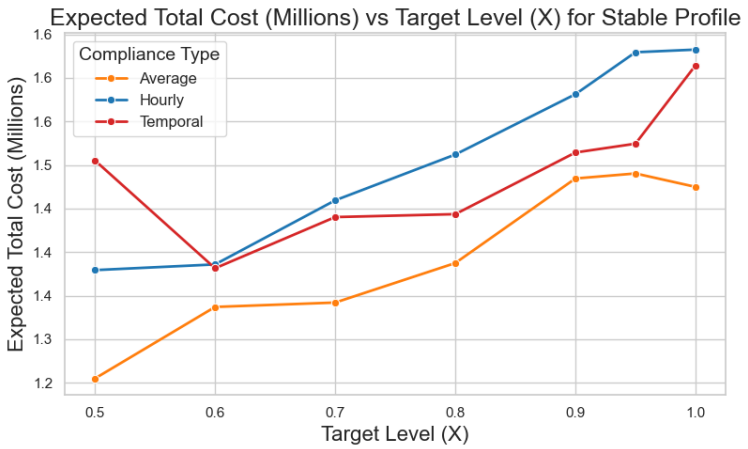


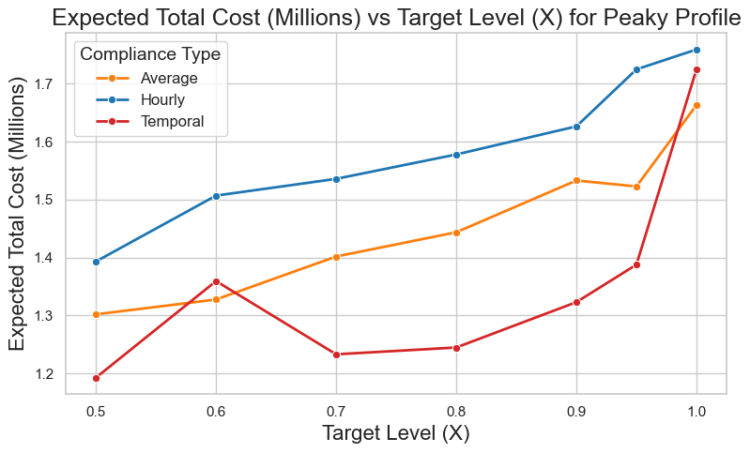


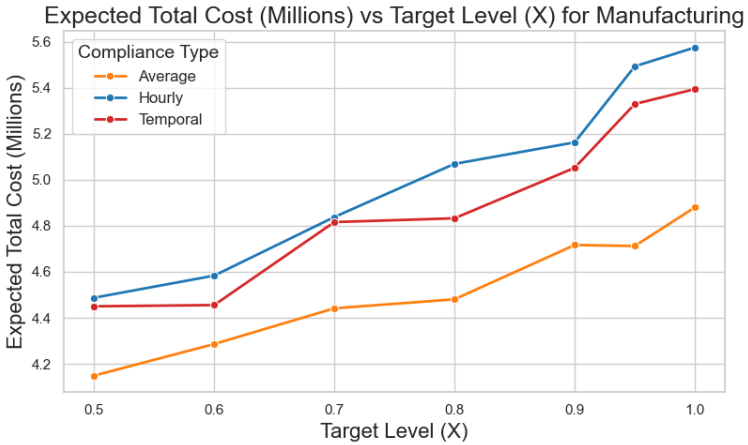
- Manufacturing representative of real profiles
- Solved with 2-hour time limit

- Costs increase with higher compliance targets
- Hourly compliance is consistently most expensive
  → (AC) is a relaxation of (HC)

Costs vs. Compliance Levels







Cost trend depends on demand shape

- Stable: temporal > average
- Peaky: average > temporal (temporal skips peak hours)

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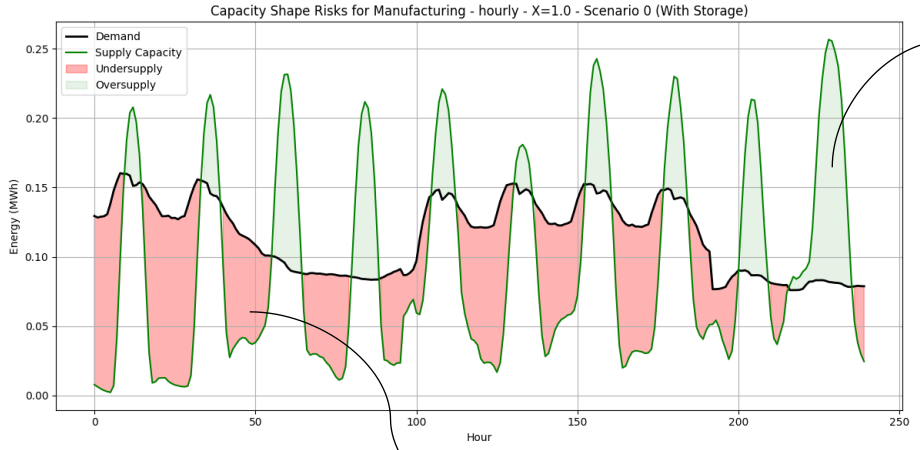
Shape Risk

Capacity-based shape risk (X=1)

renewable supply $= WG_{t,w}w_{PPA} + SG_{t,w}s_{PPA}$

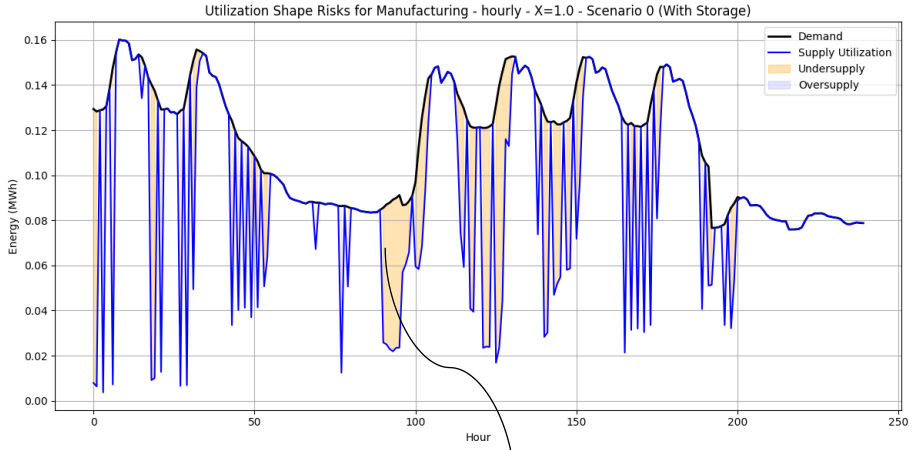


oversupply

undersupply

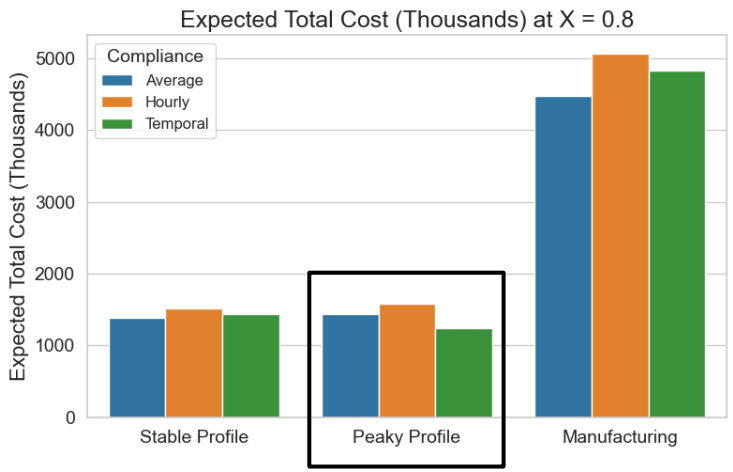
Utilization-based shape risk (X=1)

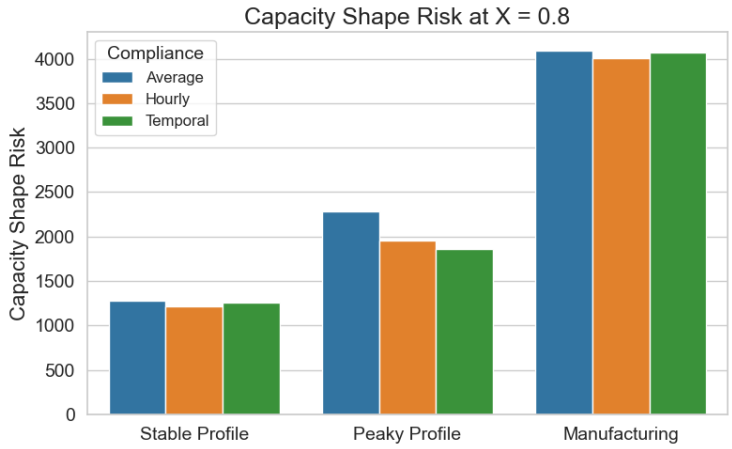
renewable supply $= a^{D}_{t,w} + d^{RD}_{t,w}$

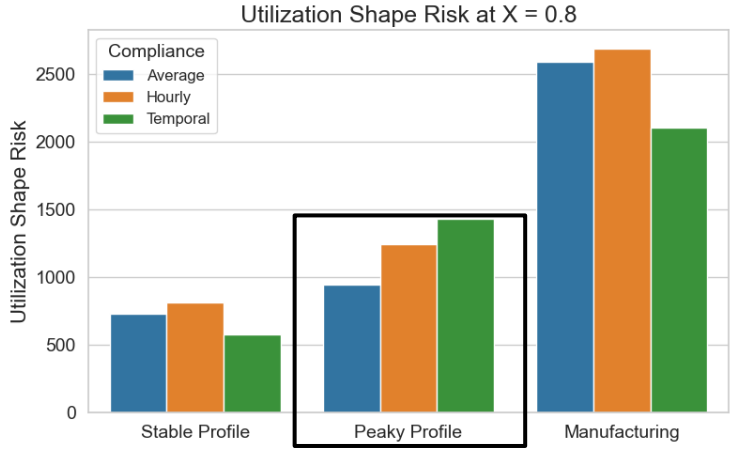


undersupply

Metrics Comparison







Hourly is more expensive than **temporal**

Temporal has more utilization shape risk than **hourly**

Cost vs. risk trade-off

Conclusions

Average, hourly and temporal target compared across different profiles

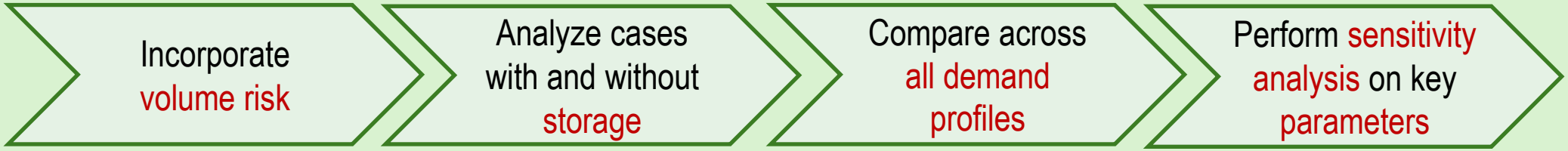
Demand shape matters when choosing a renewable target

GBM-based scenario generation algorithm to represent stochasticity in demand

There is a trade-off between cost efficiency and risk

Conclusions

Next Steps



Q & A

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Scenario Generation Algorithm

Input: 5 demand profiles, GBM params, *M* scenarios, *N* years per scenario, *N'* selected years, *K* weeks/season, 2 year solar/wind capacity factors and day-ahead prices

Phase 1: Week Sampling
For each scenario $m \in M$ and year $n \in N$:
- For each season, randomly select *K* weeks from a base profile
- Store week ID ($\boldsymbol{W_{m,n}}$)

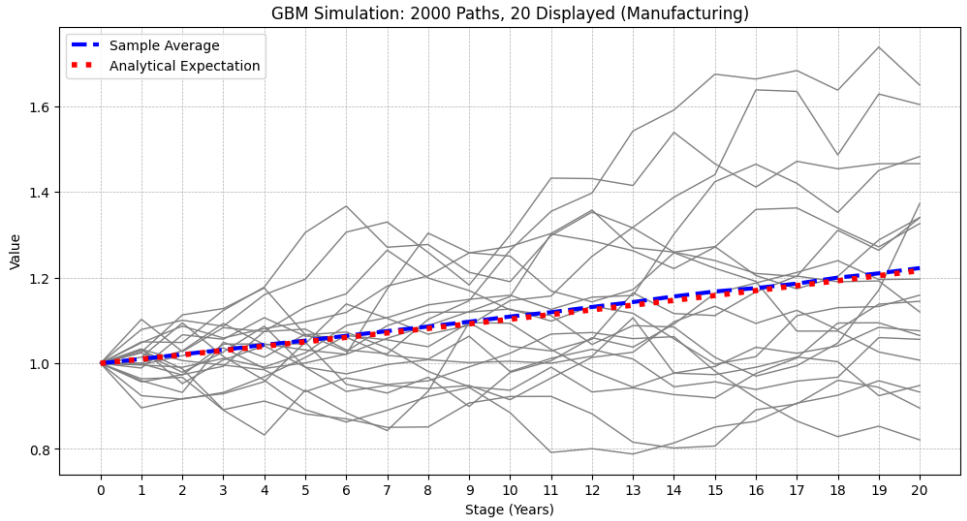
Phase 2: Year Selection
For each scenario $m \in M$:
- Divide *N* GBM years into *N'* blocks
- Sample 1 year from each block, add to $\boldsymbol{Y_m}$

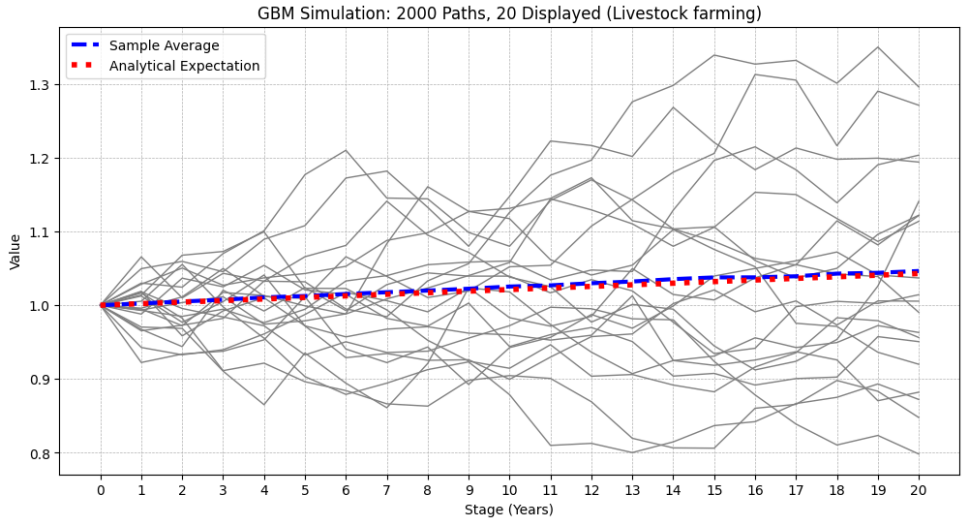
Phase 3: Demand Generation
For each profile $s \in S$:
- Simulate GBM paths using GBM params
- For selected years n $\in \boldsymbol{Y_m}$, retrieve data using selected weeks $\boldsymbol{W_{m,n}}$ and scale with GBM multipliers
- Stack weeks across years

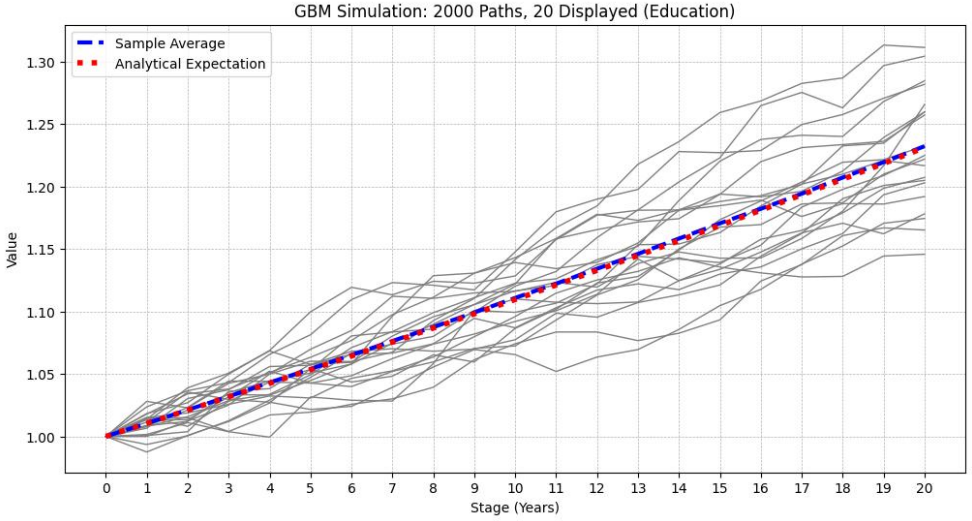
Phase 4: Supply-Side
For each scenario $m \in M$ and selected years n $\in \boldsymbol{Y_m}$:
- Use $\boldsymbol{W_{m,n}}$ to extract solar, wind and price data (from a randomly chosen year among two available)
- Stack weeks across years

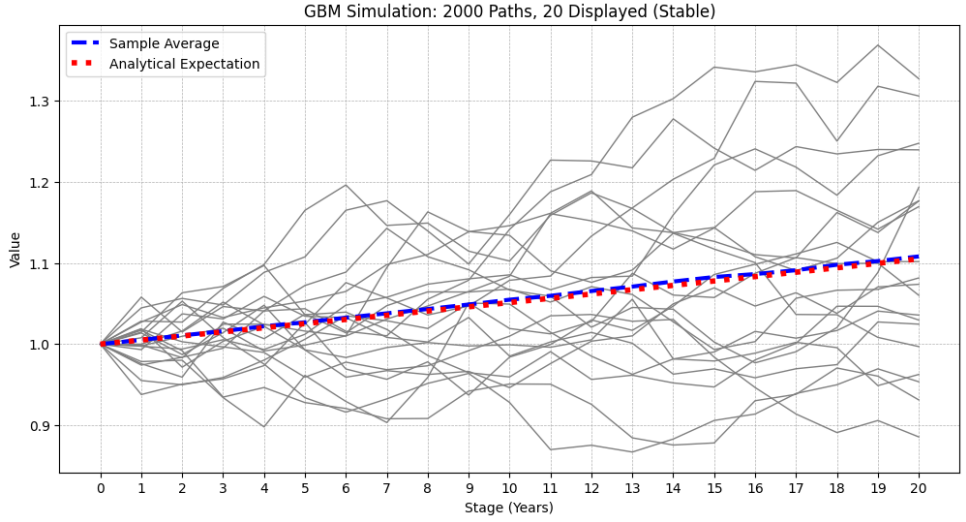
Output: Synthetic multi-year demand profiles, solar/wind capacity factors and electricity market prices

Generated GBM Paths

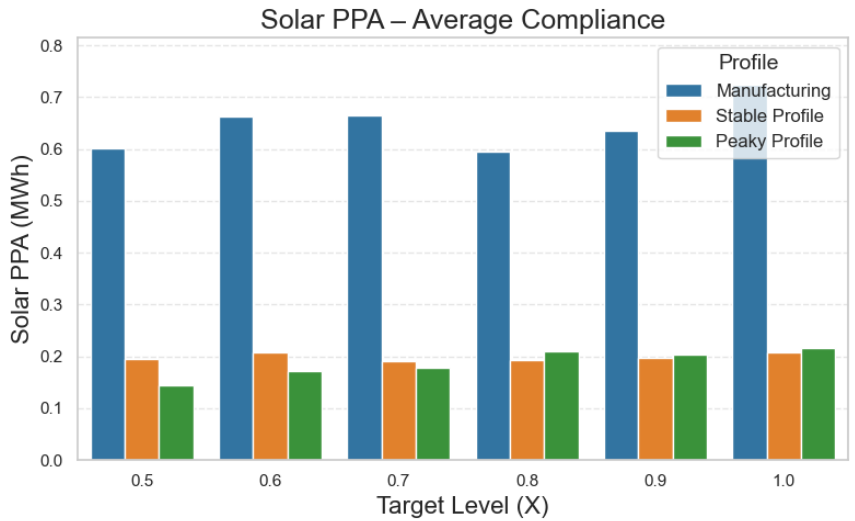


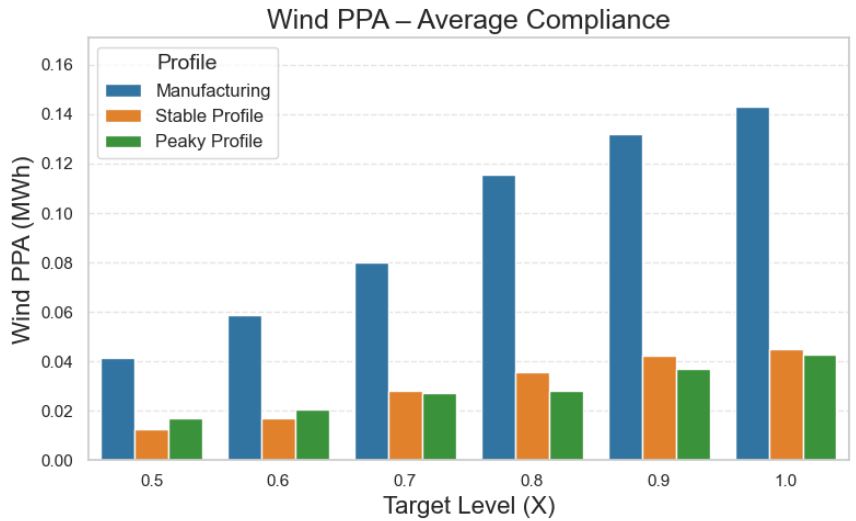


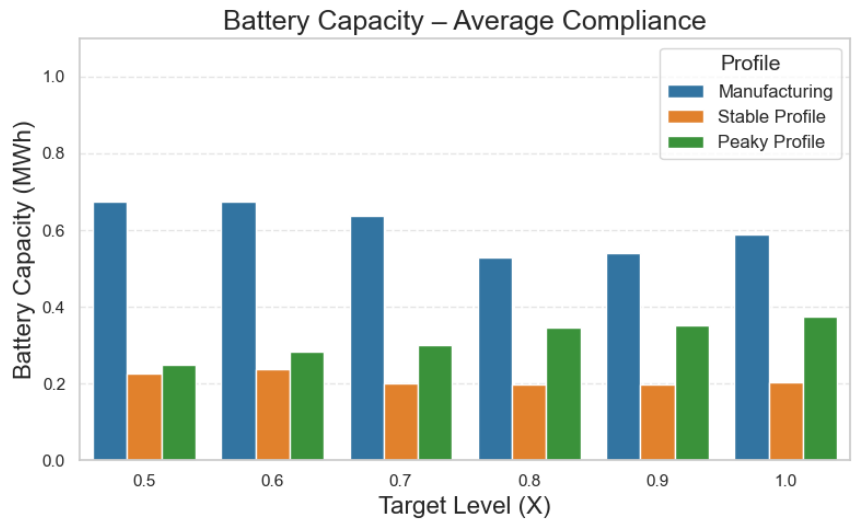




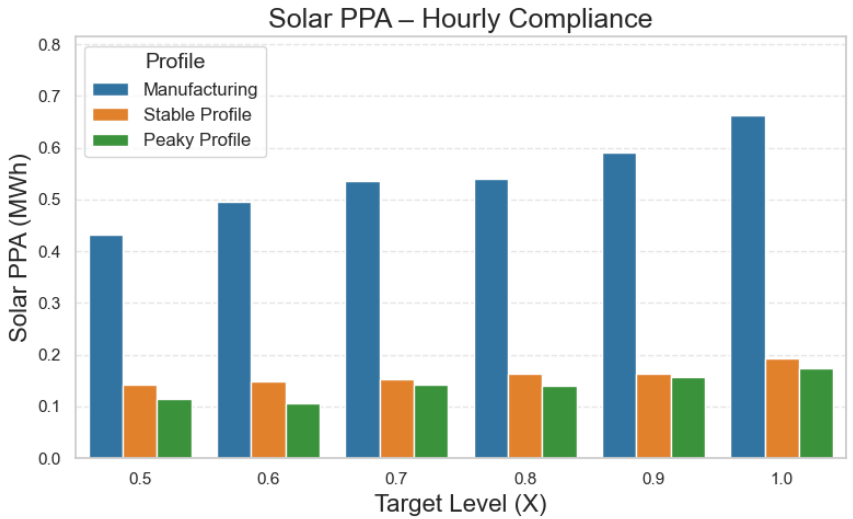
First Stage Decisions vs. Compliance Levels (Average Compliance)

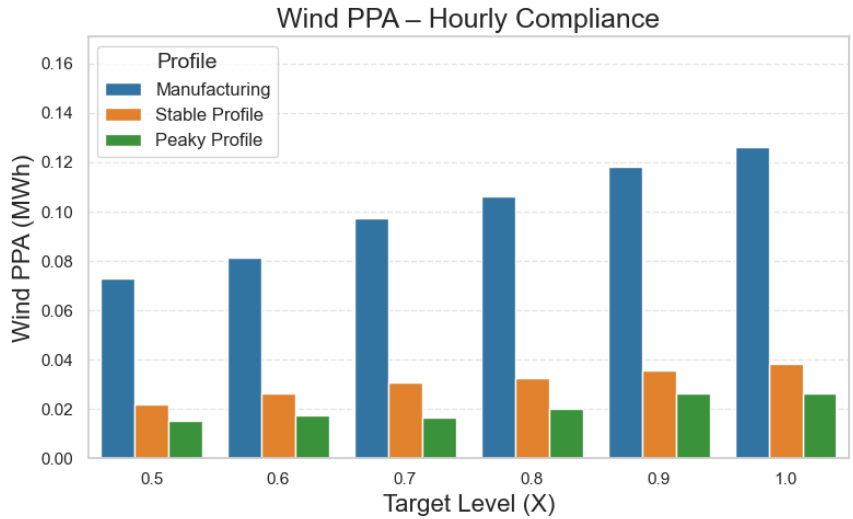


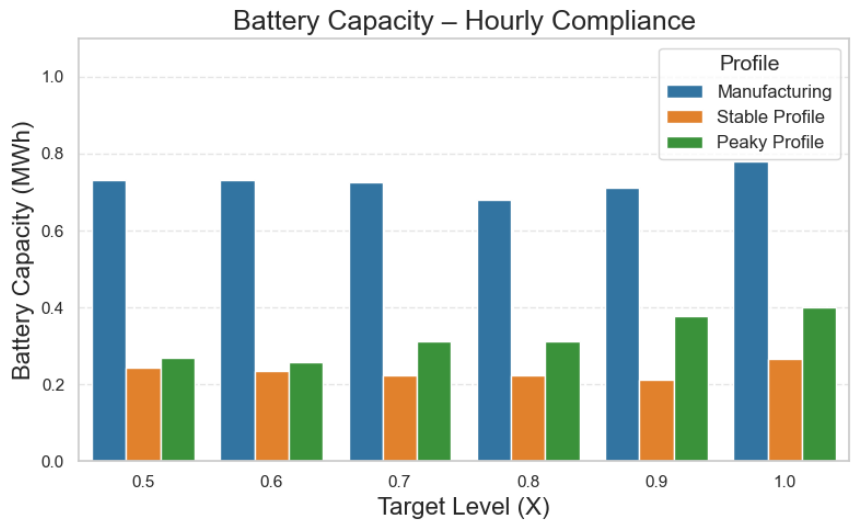




First Stage Decisions vs. Compliance Levels (Hourly Compliance)







First Stage Decisions vs. Compliance Levels (Temporal Compliance)