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Scientific Machine Learning in Local Energy Systems

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A Case Study: Dutch Pilot Community

13 Nodes (LV 400V) | 5 PV | 425 kWh/200 kW BESS

Residential and Commercial Loads

Agenda

- I. Introduction and Research Gap
- II. Multi-Model Framework & Methodology
- III. Scientific Machine Learning
- IV. Simulation Setup
- V. Results and Discussion

Introduction: Energy Transition and Local Energy Communities

CONTEXT

The EU targets carbon neutrality by 2050 through the Clean Energy Package, driving large-scale integration of distributed renewable energy resources (DERs) into distribution grids.

This creates operational challenges: voltage fluctuations, line congestion reverse power flows.

The Challenge

- Traditional heuristic controllers are reactive and miss futuristic outlook.
- Battery Energy Storage Systems (BESS) need advanced predictive control integrating ML with physical constraints.

Core Innovation

Bridging the gap between pure data-driven ML and physics-based optimization through a lightweight co-simulation architecture

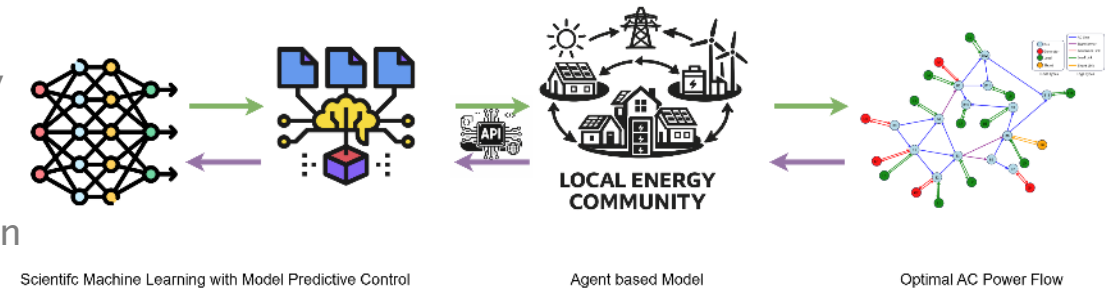
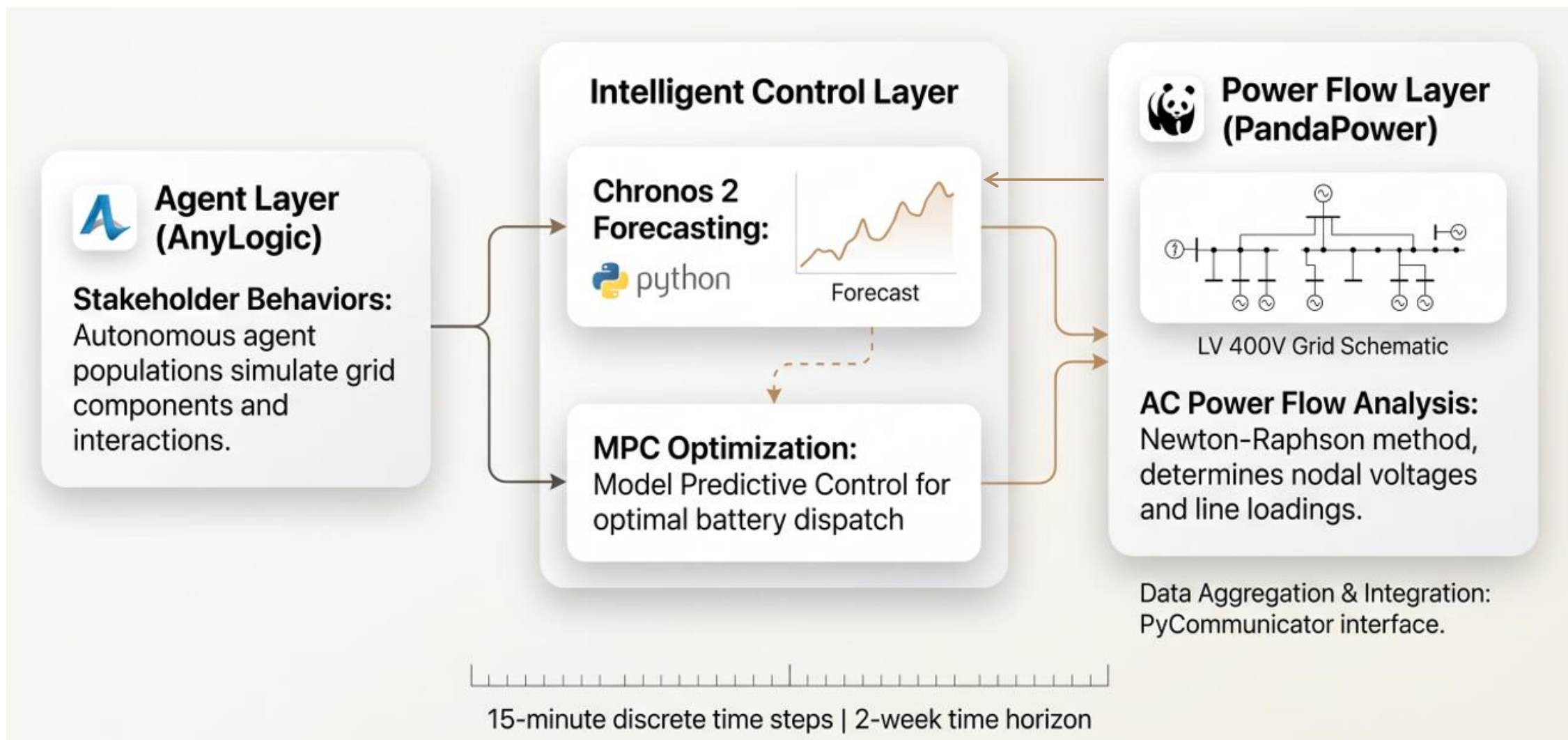


Fig: Multi-model framework for application of SciML in LEC



Multi-Model Framework Architecture



Scientific Machine Learning: Chronos 2 Forecasting

Model	Univariate Forecasting	Multivariate Forecasting	Past-Only Covariates	Known Covariates	Categorical Covariates	Cross Learning	Memory Scaling
Chronos-2	✓	✓	✓	✓	✓	✓	$\mathcal{O}(V)$
Toto-1.0	✓	✓	✓	✗	✗	✗	$\mathcal{O}(V)$
TabPFN-TS	✓	✗	✗	✓	✓	✗	$\mathcal{O}(V)$
COSMIC	✓	✗	✓	✓	✗	✗	$\mathcal{O}(V^2)$
Moirai-1.0	✓	✓	✓	✓	✗	✗	$\mathcal{O}(V^2)$
Chronos-Bolt	✓	✗	✗	✗	✗	✗	-
Moirai-2.0	✓	✗	✗	✗	✗	✗	-
Sundial	✓	✗	✗	✗	✗	✗	-
TimesFM-2.5	✓	✗	✗	✗	✗	✗	-
TiRex	✓	✗	✗	✗	✗	✗	-

Fig: Comparison of capabilities of pretrained forecasting models. [Source: Ansari, A.F. et.al., Chronos-2: From Univariate to Universal Forecasting]

SELECTED

Strategy A: Post-Processing

Clip forecasts to physical bounds, no model change

DEGRADED

Strategy B: Custom Loss

Physics penalty caused catastrophic forgetting

FUTURE WORK

Strategy C: Differentiable Injection

Hindered by non-differentiable tokenization

Dutch Pilot Site & Simulation Setup

Dutch Energy Community

- Real World Renewable Energy Community (REC) pilot
- 13 residential/commercial units (1 slack, 12PQ) at LV level

Component	Specification	Data
PV Generation	5 Installation	Real Data
Battery Storage	425kWh /200kW	Centralized
Demand	Mixed Residential/Commercial	Hourly
Transformer	1MVA, 10/0,4 kV	Slack Bus

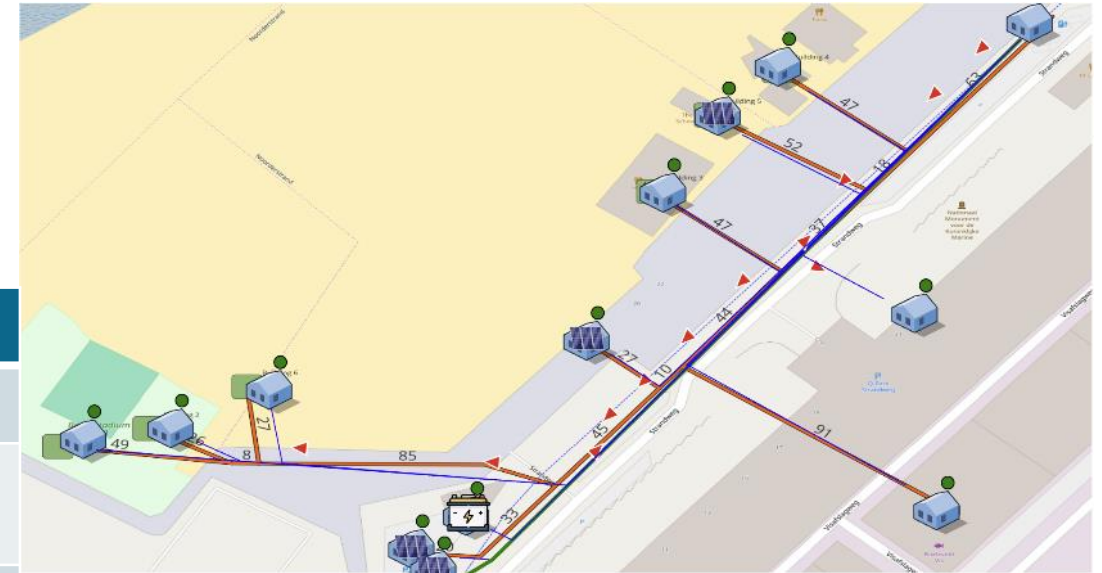
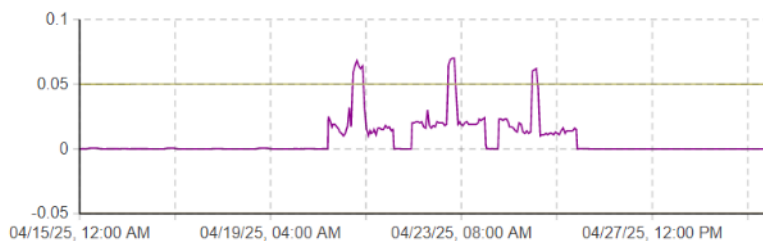


Fig: The Dutch Pilot site under the U2Demo Project

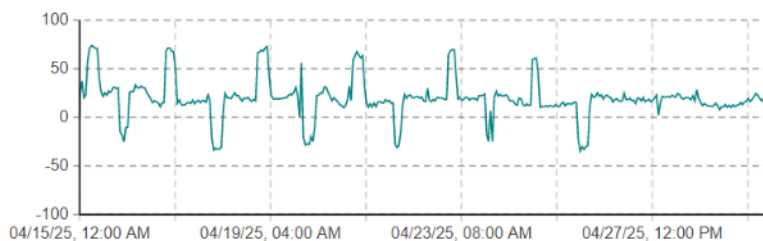
Simulation Parameters

- Horizon: 24 Hours | Timestep: 15min(96 steps/day)
- Power flow tolerance: 10^{-5} p.u.
- Voltage constraints: 0,95-1,05 p.u.
- Maximum line loading: 100%

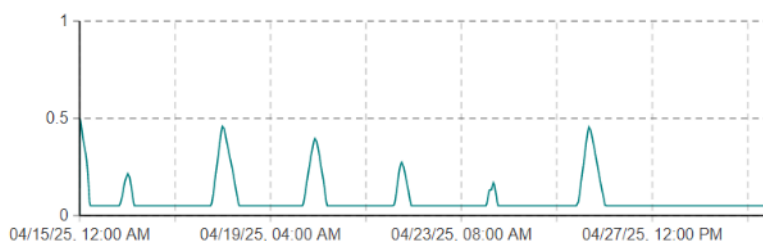
Results and Discussion



Substation Power (p.u MW) min max

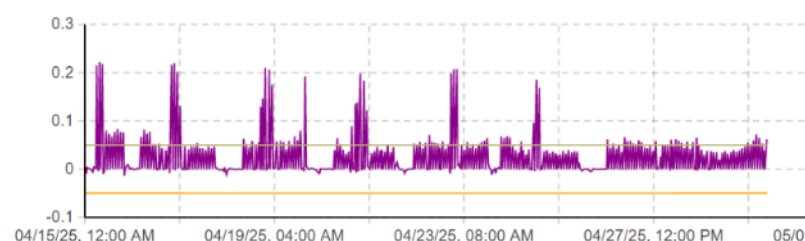


NetLoad(kWh)

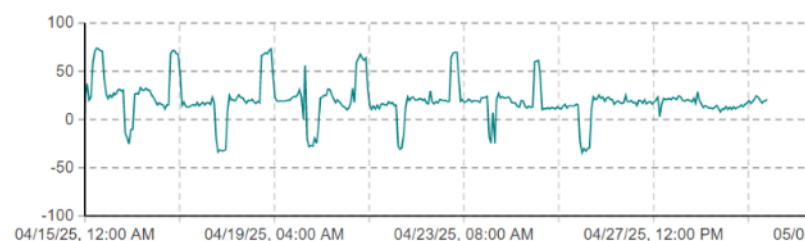


Battery SOC

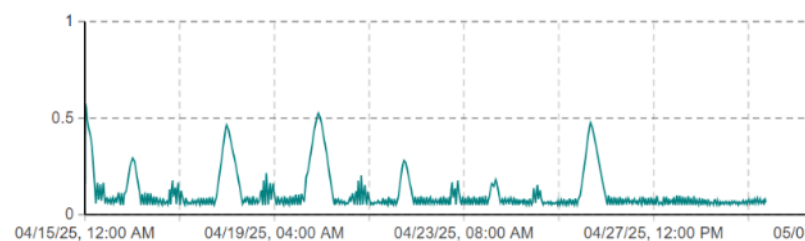
Base Case



Substation Power (p.u MW) min max

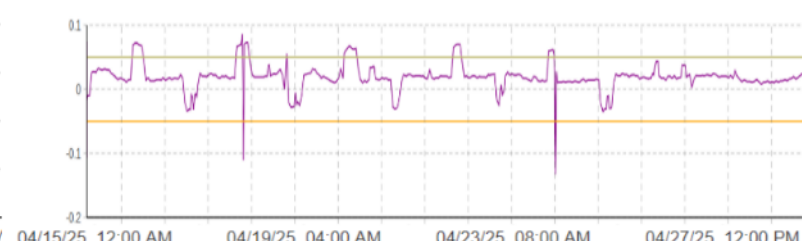


NetLoad(kWh)

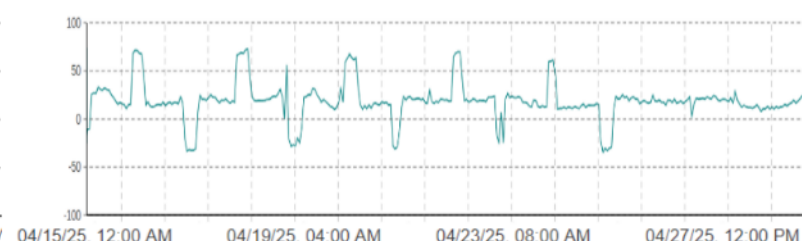


Battery SOC

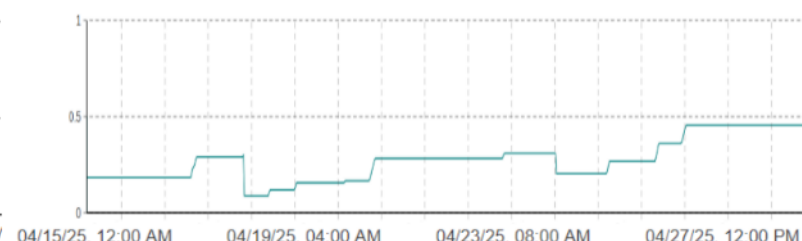
ML Heuristic Case



Substation Power (p.u MW) min max



NetLoad(kWh)



Battery SOC

ML + MPC Case

Results and Discussion

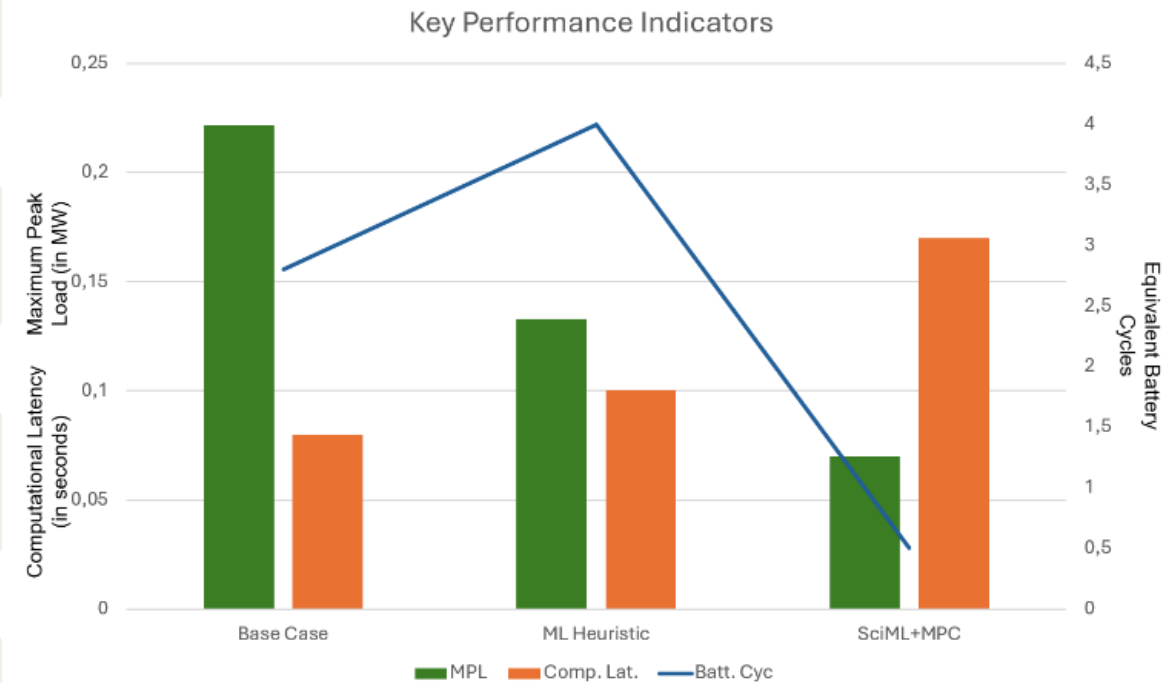
KEY FINDINGS

✓ SciML+MPC kept peak load closest to constraints with proper demand response

⚠ ML alone can be **detrimental** with limited data, causing oscillations

📈 Both ML cases **improved peak load** significantly over RBC baseline

🔋 ML Heuristic **increased battery cycling**; SciML+MPC showed balance



Core Result: SciML+MPC outperforms pure data-driven ML. Physics-constrained optimization is essential for real-world deployment



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Thank You



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