

Accelerating Transparency in Home & Community Energy Management Through Benchmarking Platforms

Rui Li ¹, Anurag Mohapatra ², Tao Sun ³

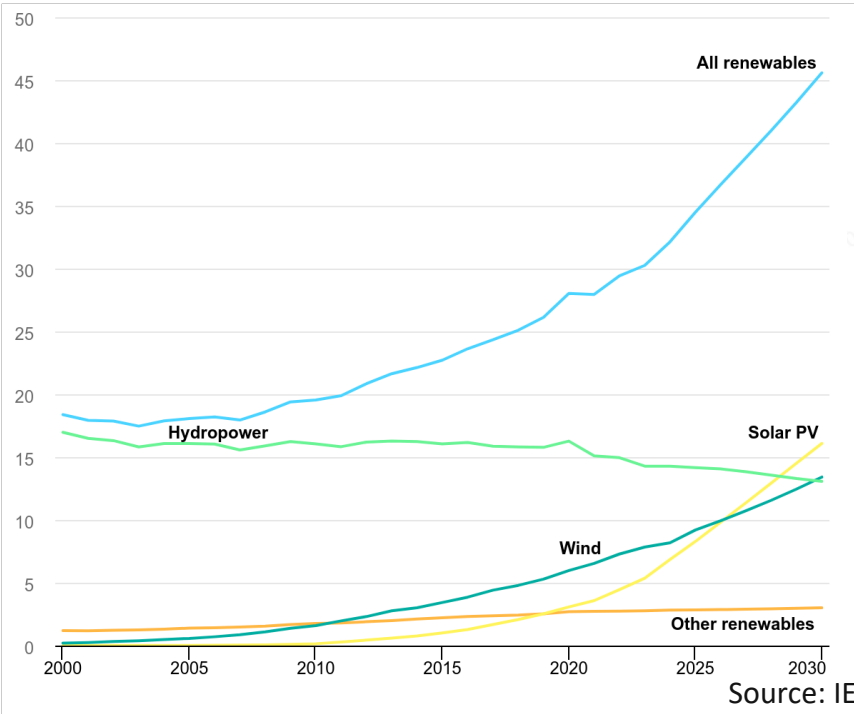
Sep 11, 2025

¹ EcoFlow Technology Inc., ² Technical University of Munich, ³ Stanford University

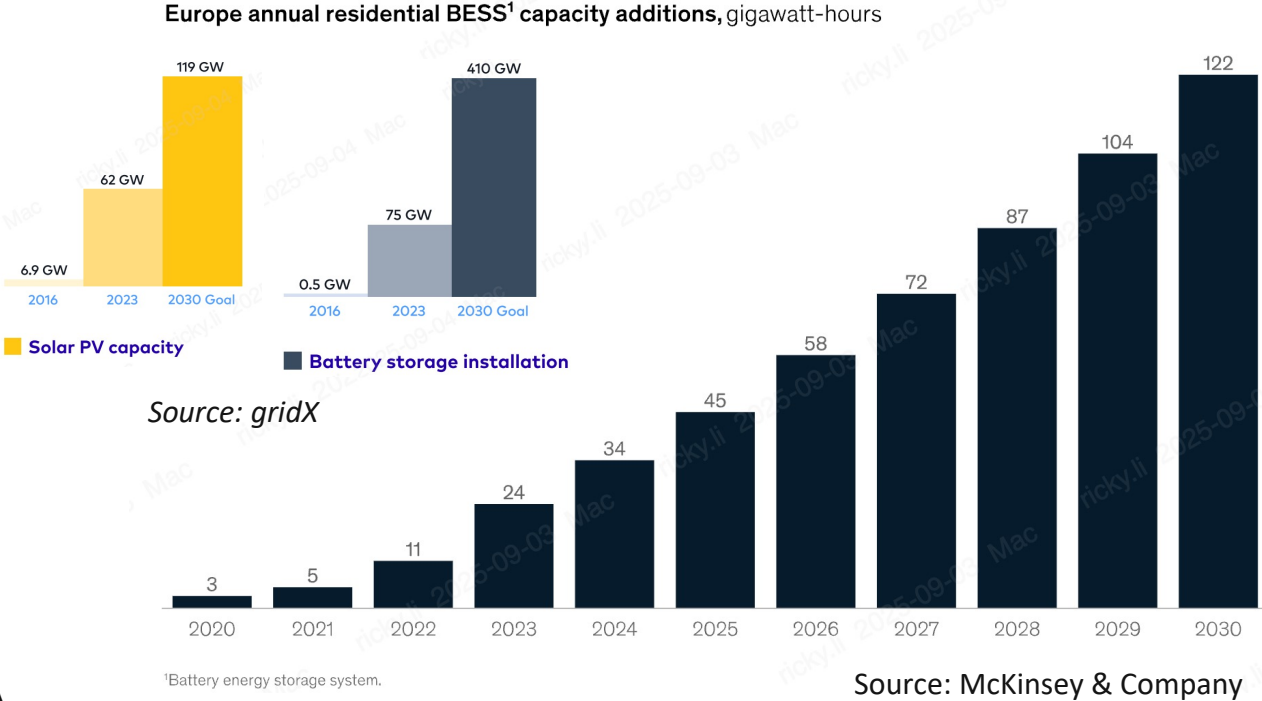
Ricky Li E03/08
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- Background
- Framework & Method
- Dataset & Preliminary Result
- Platform Integration
- PhyLFLex HEMS Benchmarking Suite
- Roadmap & Open-source
- Takeaways

Household installation of PV and ESS is increasingly adopted to lower electricity costs and enhance backup power availability.



By 2030, solar PV is projected to be the largest renewable energy source, contributing ~80% of global capacity growth from 2024–2030, driven by utility-scale projects and rising rooftop adoption.

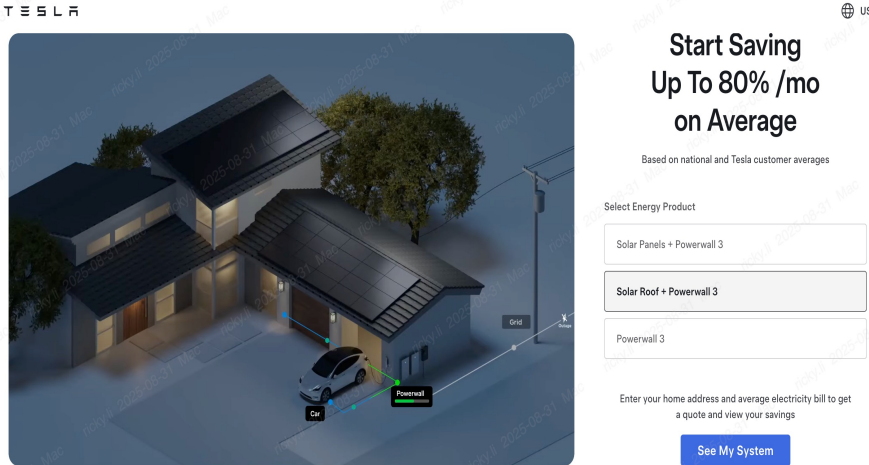


Residential BESS is projected to expand rapidly, supported by falling costs, higher electricity prices, and stronger government incentives, enabling wider integration with PV systems through 2030.

DERs (PV & ESS) location and sizing, HEMS, and grid support are key to maximizing PV/ESS revenues, but fragmented benchmarking and low transparency can yield divergent and unreliable results for end users.

1

Location & Sizing



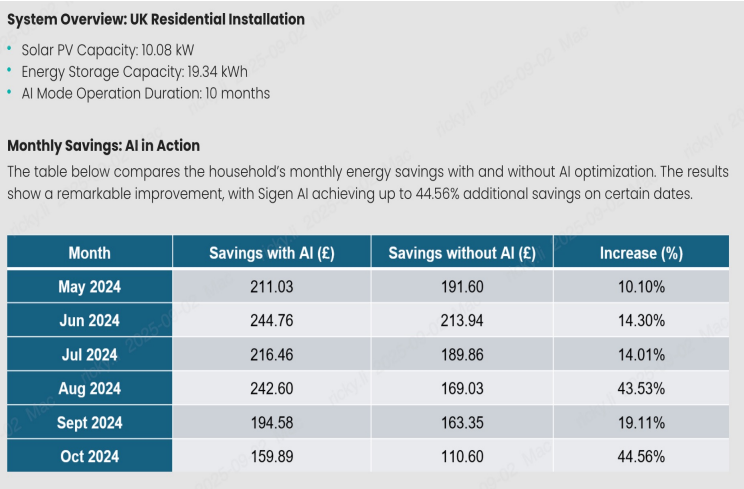
Source: Tesla

Tesla, Huawei, and other leading companies have developed advanced tools to optimize PV and ESS sizing under specified conditions.

Results vary across platforms due to differing technical methods and business considerations.

2

HEMS



Source: Sigenergy

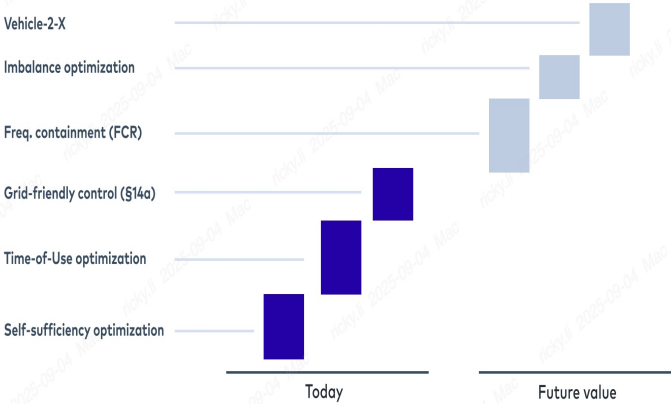
The absence of standardized scenarios hampers the evaluation of system sizing and energy management algorithms.

Proprietary datasets impede fair and transparent comparisons of vendor performance.

3

Grid Support

Value stacking is the key to unlock customer potential



Source: gridX

Participation in grid support markets—such as FCR and imbalance optimization—through VPPs can generate new revenue streams.

However, systematic evaluation of residential DERs in VPPs remains limited.

Teams from China, Europe, and the US addressed complementary phases of residential DERs, combining expertise to advance benchmarking via open-source collaboration.



1

PV & ESS R&D (2012), Energy Hub (2019)

Dr. Rui Li installed his first PV and ESS on campus in 2012, and published a study on Energy Hub market participation in *IEEE TSG*, recognized as an ESI Highly Cited Paper.



Head of AI Department, EcoFlow
Ph.D., Tsinghua University



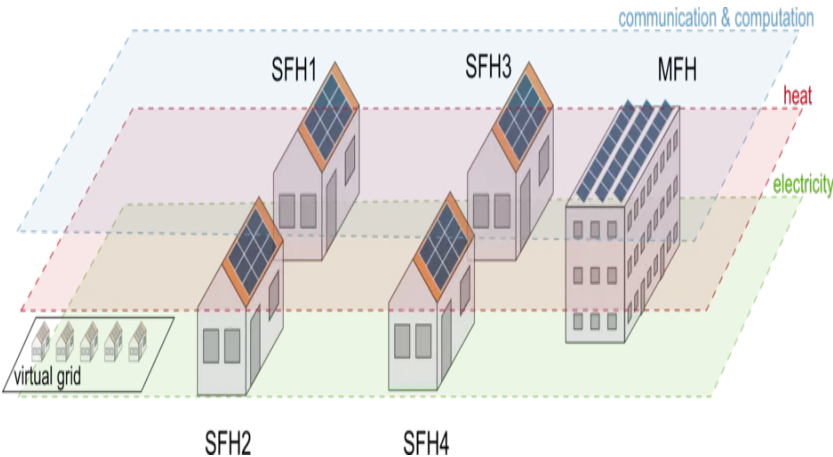
Group Leader, CoSES, TUM
Ph.D., Technical University of Munich

Dr.-Ing. Anurag Mohapatra established a PHIL platform for multi-energy systems in a microgrid context, which supports multi-family, multi-carrier (heat and electricity) simulations



2

Multi-energy system PHIL (2024)



3

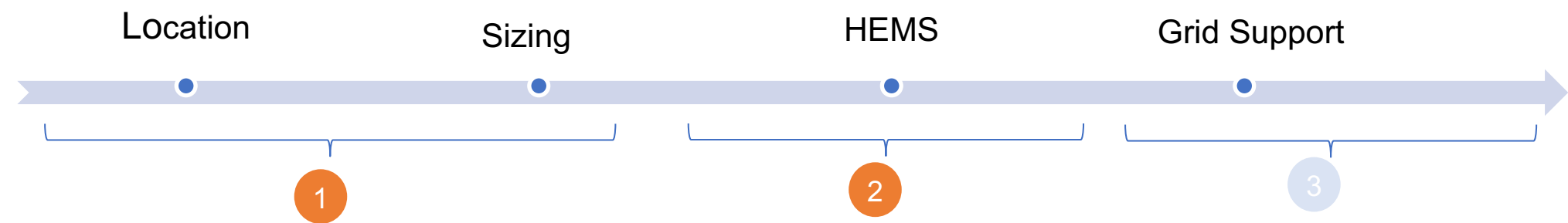
DER Evaluation (2025)

Dr. Tao Sun published a systematic feasibility assessment of PV and ESS for the United States in *Nature Energy*.

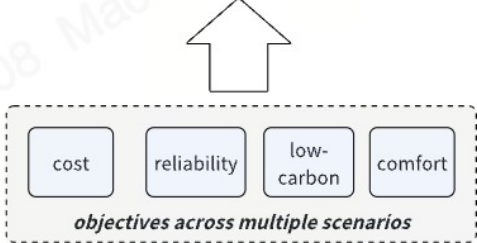
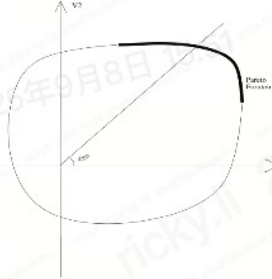
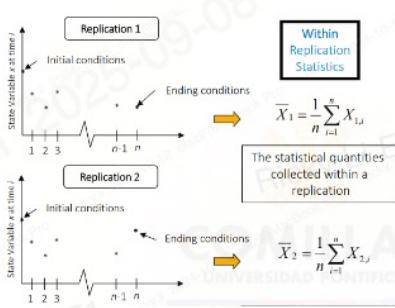
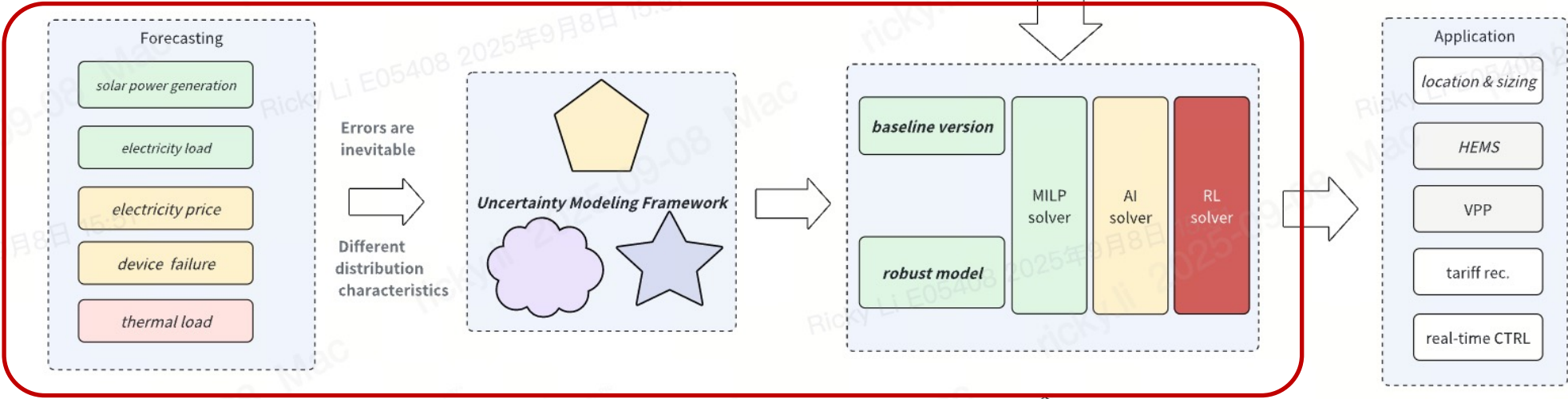
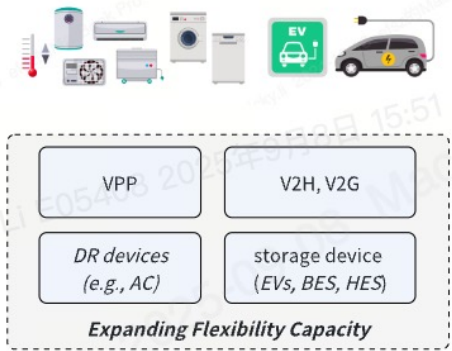
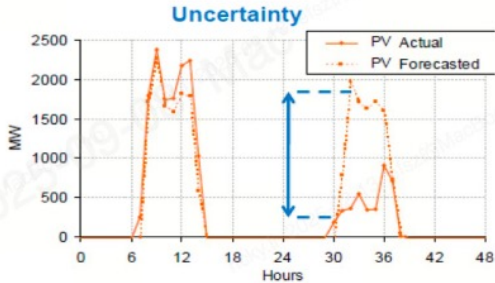
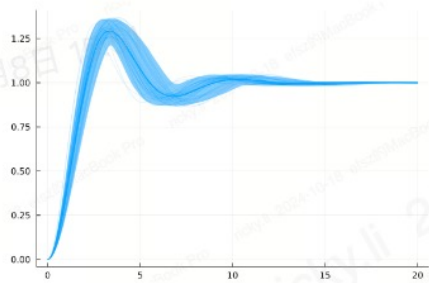


Postdoctoral Scholar, Stanford University
Ph.D., Stanford University

Decision-making over the lifecycle of DERs (PV, ESS) can be modeled as an optimization problem with varying decision variables, objectives, and risks, across time horizons from 1 day to 15 years.



Phase	Location & Sizing	HEMS (single-household)	Grid Support
<i>Decision</i>	installation location; capacity	charging/discharging behavior	capacity reserved for VPP
<i>Concern</i>	electricity cost reduction; backup power supply	self-consumption; self-sufficiency; comfort level	additional revenues from grid market
<i>Time horizon</i>	DER lifecycle (~15 years)	typically 1 day	typically 1 year
<i>Risk</i>	accounting for long-term incentive uncertainty	PV generation uncertainty; price mechanism	DER degradation; market scope



- Example for Location & Sizing & HEMS

Sample:  ResStock

- 500,000 ResStock load profiles (statistically representative of U.S. households).

Data Layers:

- Hourly solar generation (PVWatts)
- Technology costs (NREL)
- Retail electricity rates (URDB)
- Local outage events (PRESTO)

Constraints:

- Battery charge/discharge limits
- Physical space limitations
- Cost nonincreasing (affordability)**

Simulation runs:

- Economic viability** → max cost reduction
- Backup viability** → max backup power

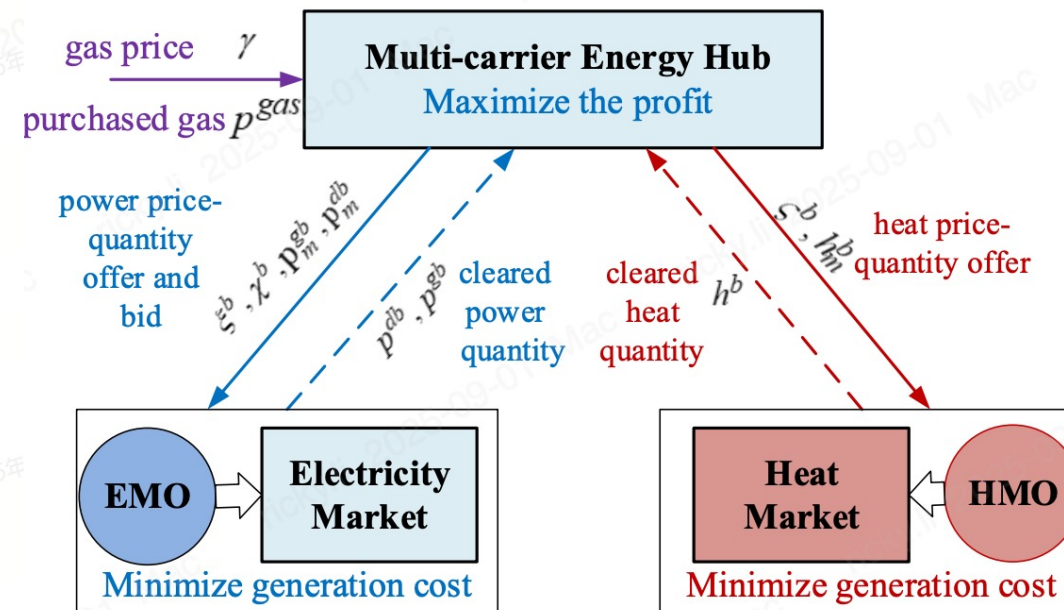
Decision variables:

- Whether to install
- System Sizing

Output:

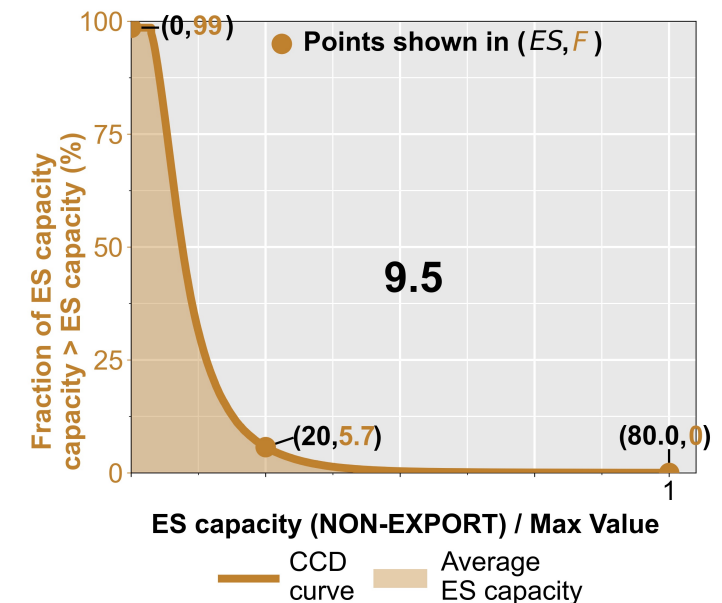
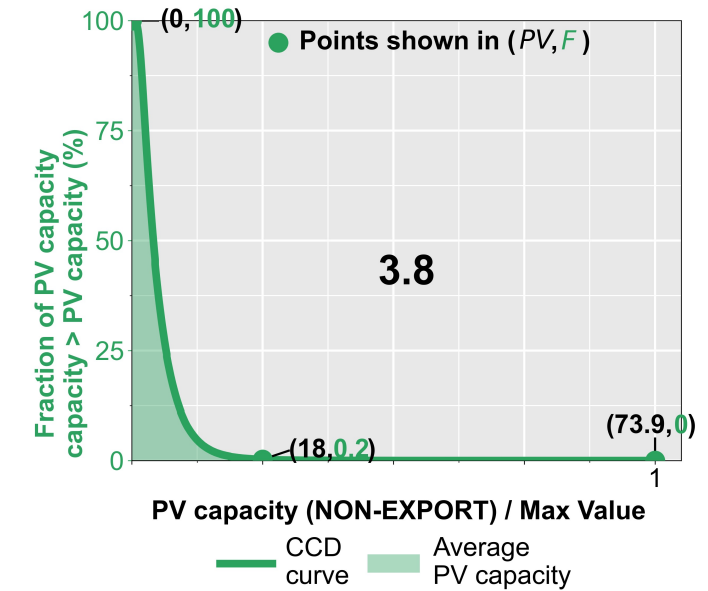
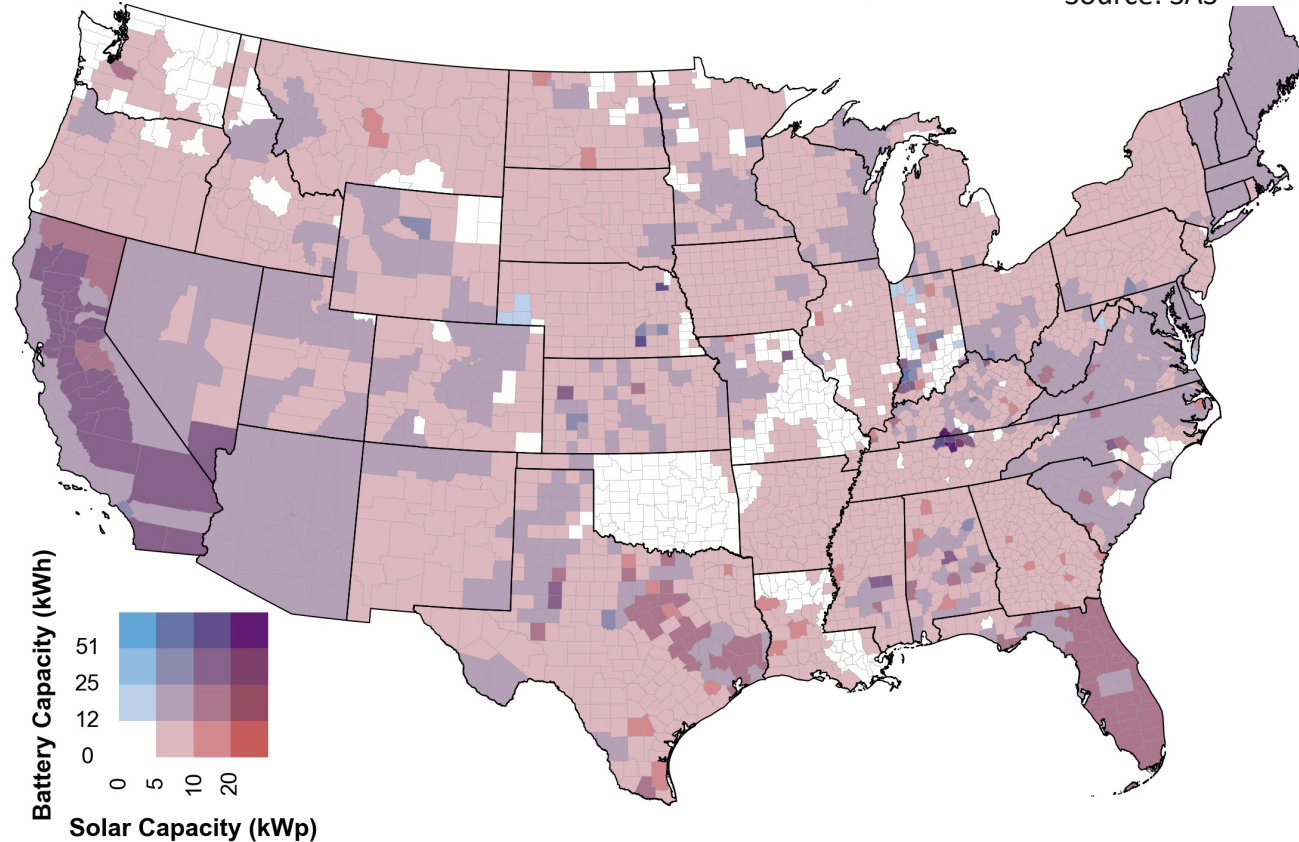
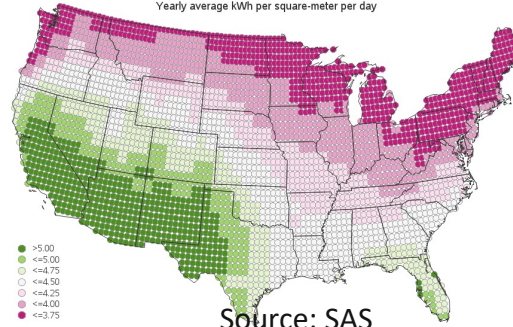
- Optimal solar-battery sizing
- Electricity cost reduction (%)**
- Critical consumption backup (%)**

- Example for VPP

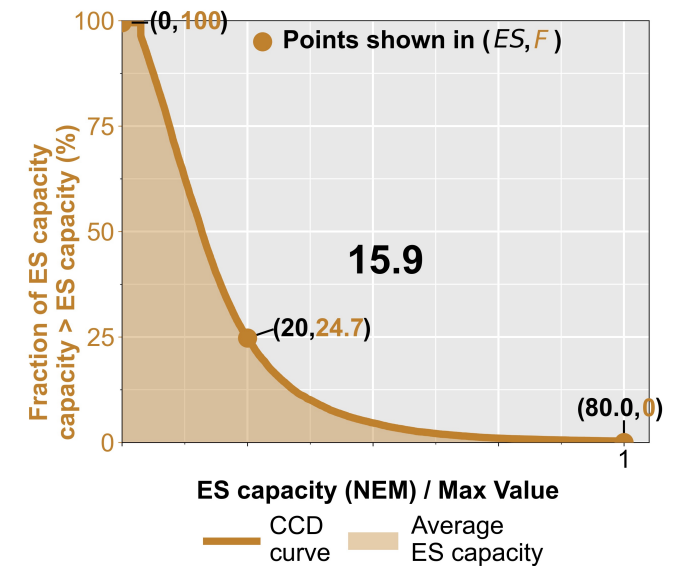
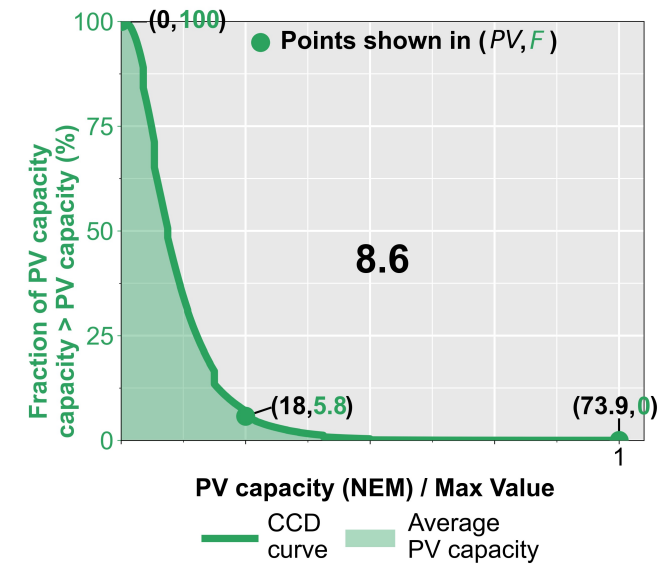
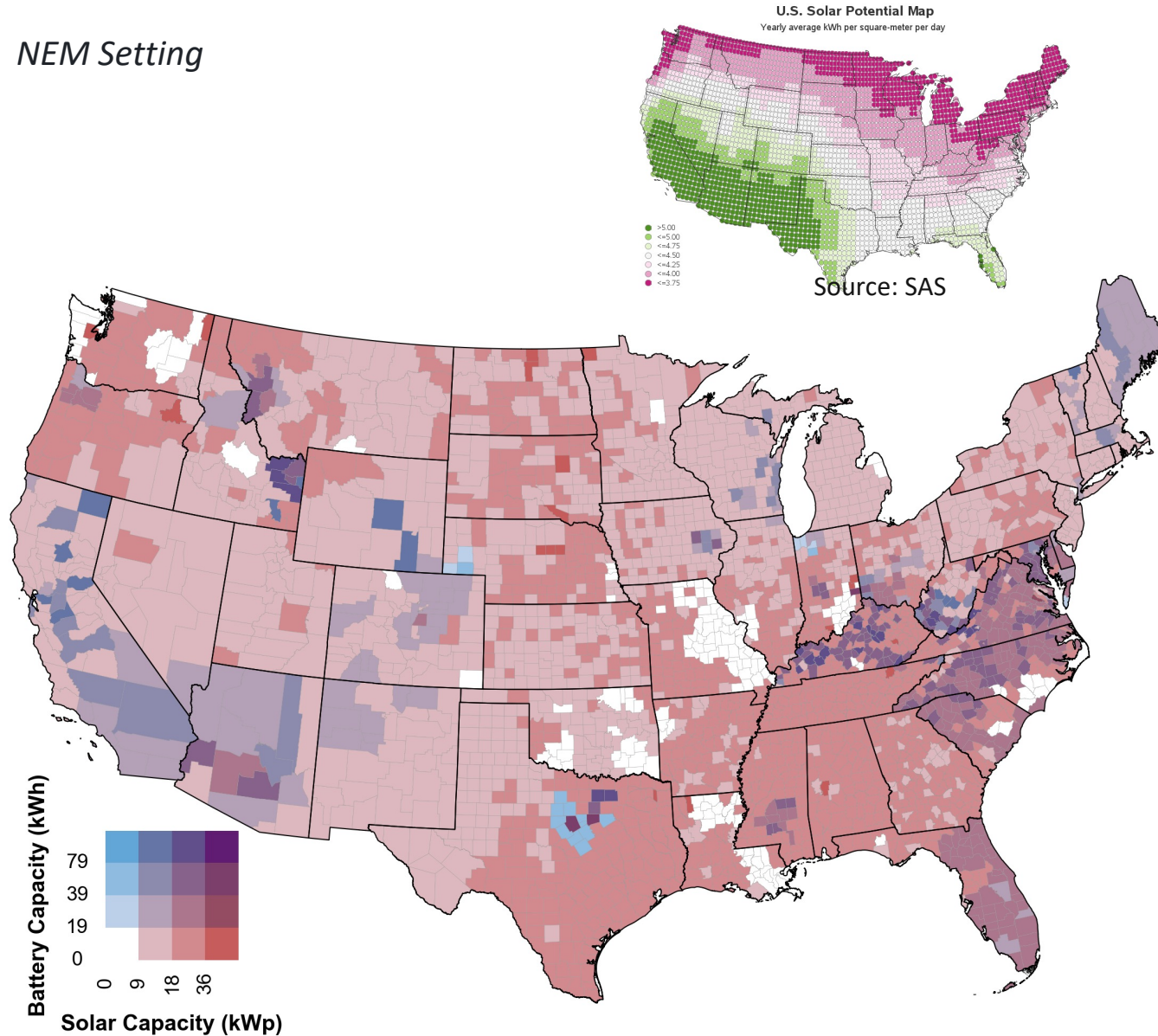


Sun, Tao, et al. "Solar and battery can reduce energy costs and provide affordable outage backup for US households." *Nature Energy* (2025): 1-16.

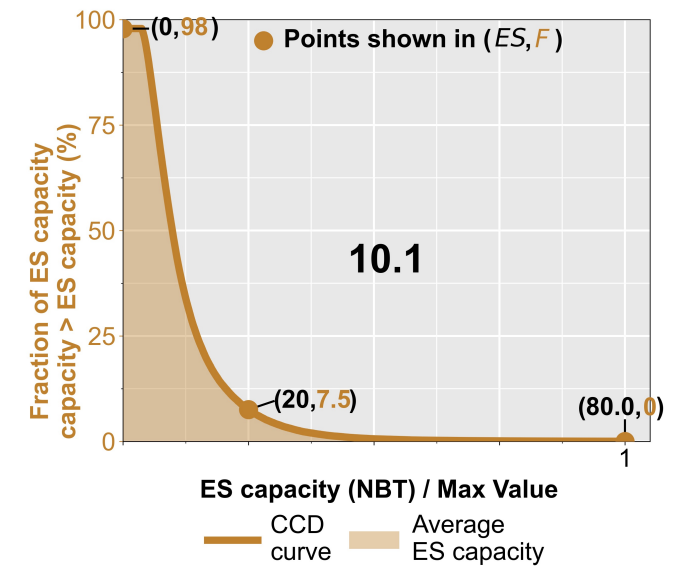
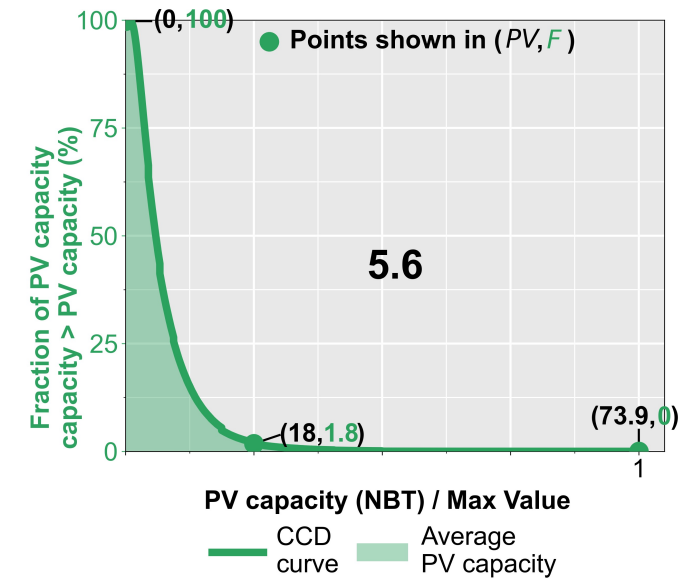
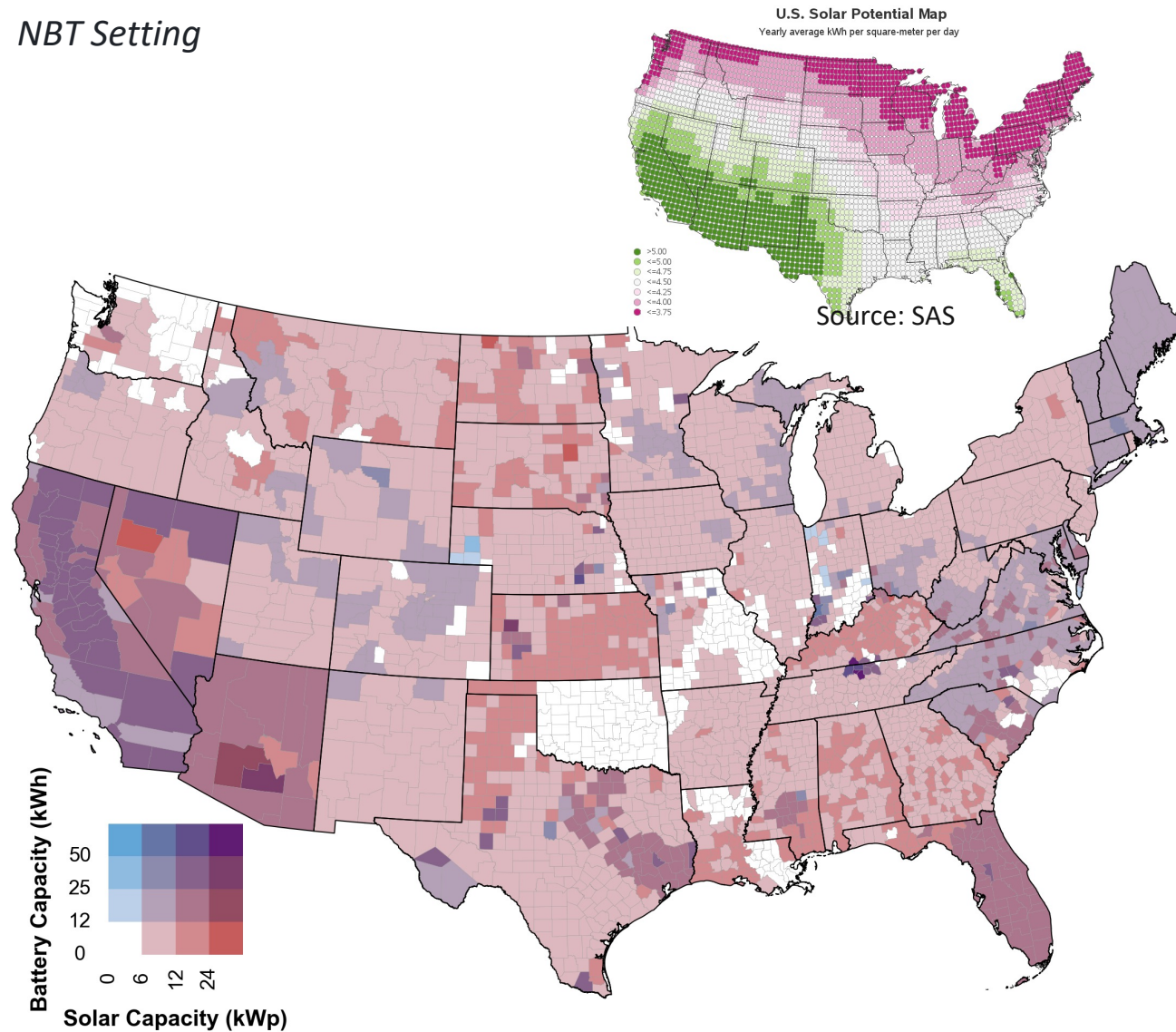
Li, Rui, et al. "Participation of an energy hub in electricity and heat distribution markets: An MPEC approach." *IEEE Transactions on Smart Grid* 10.4 (2018): 3641-3653.

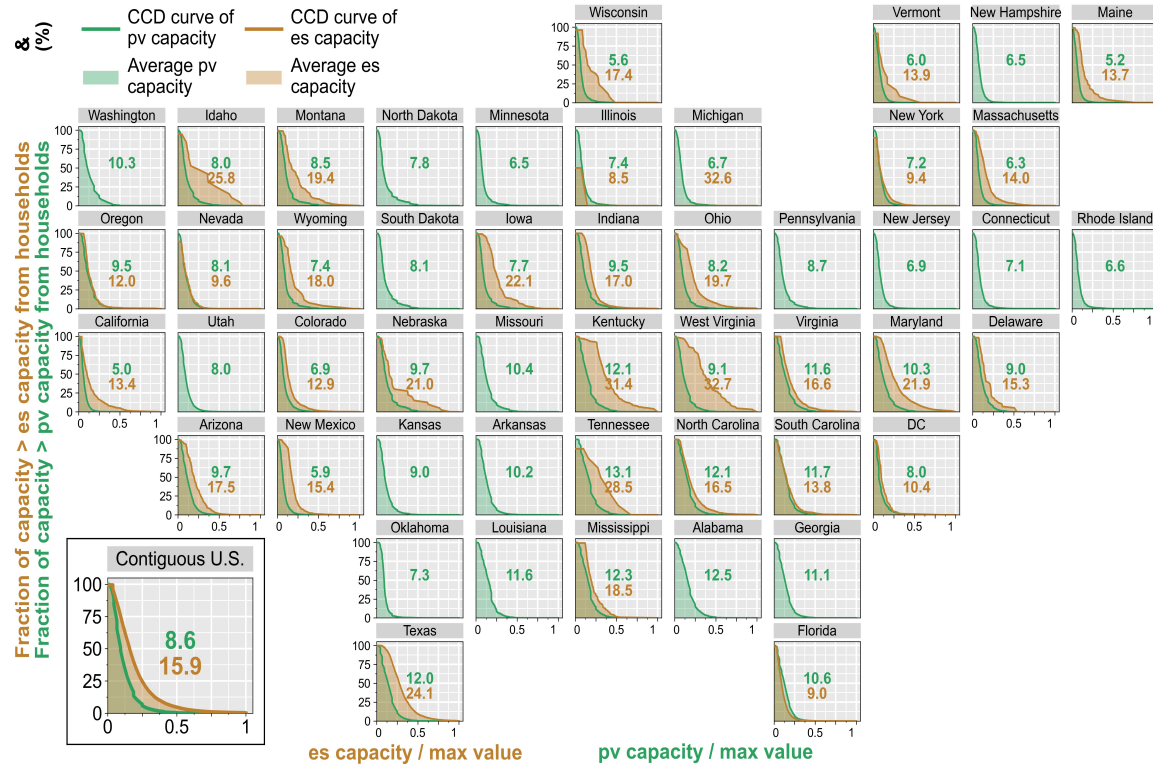
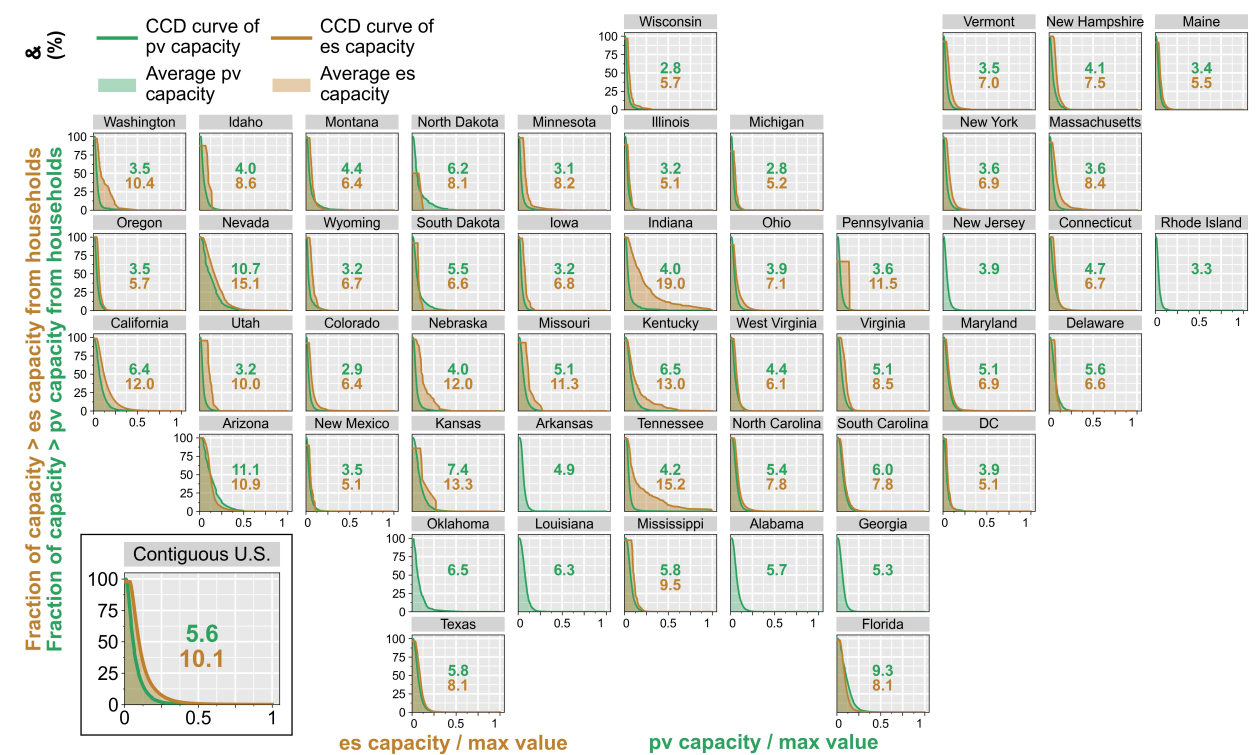
- Non-export SettingOver **500K** householdU.S. Solar Potential Map
Yearly average kWh per square-meter per day

- NEM Setting



• NBT Setting

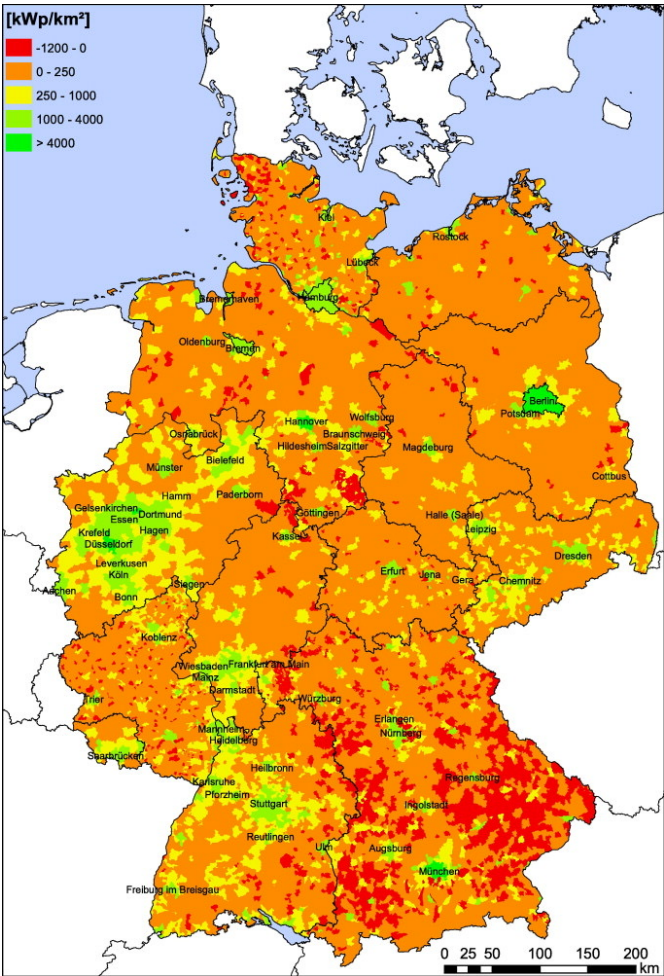


-NEM**-NBT**

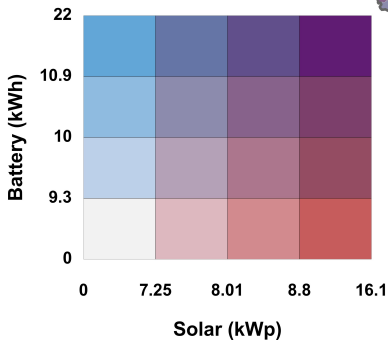
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Germany

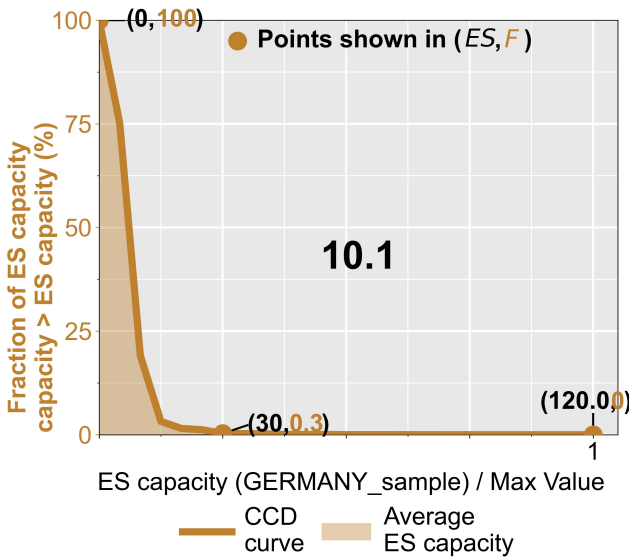
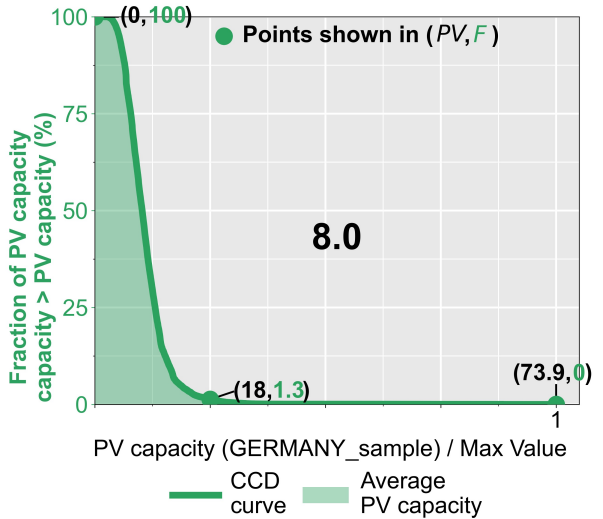
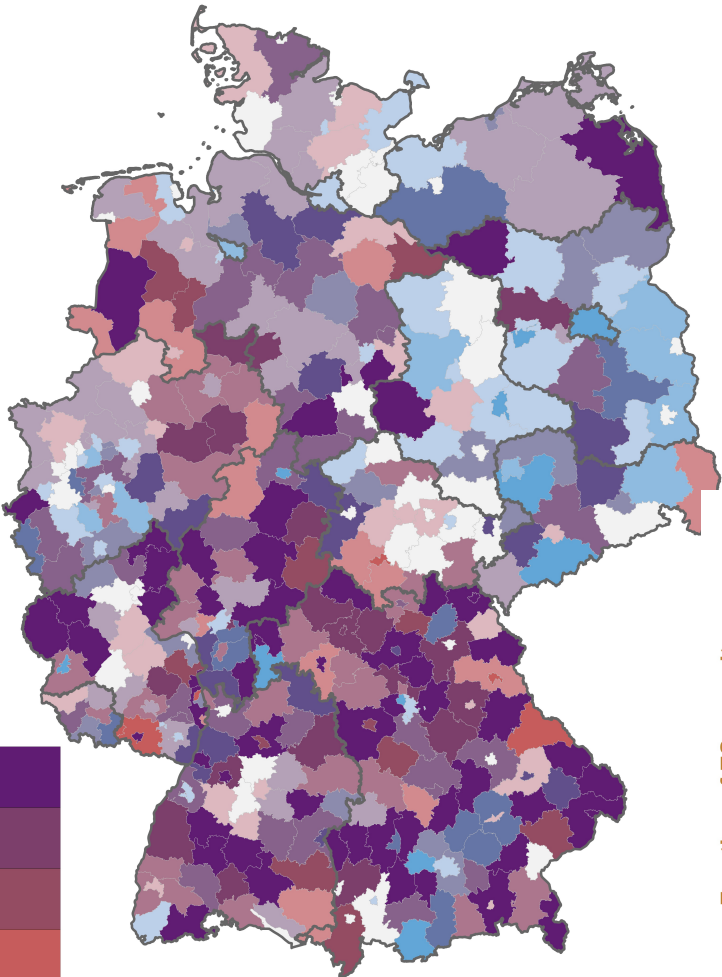
solar resource potential



Source: Solar Energy

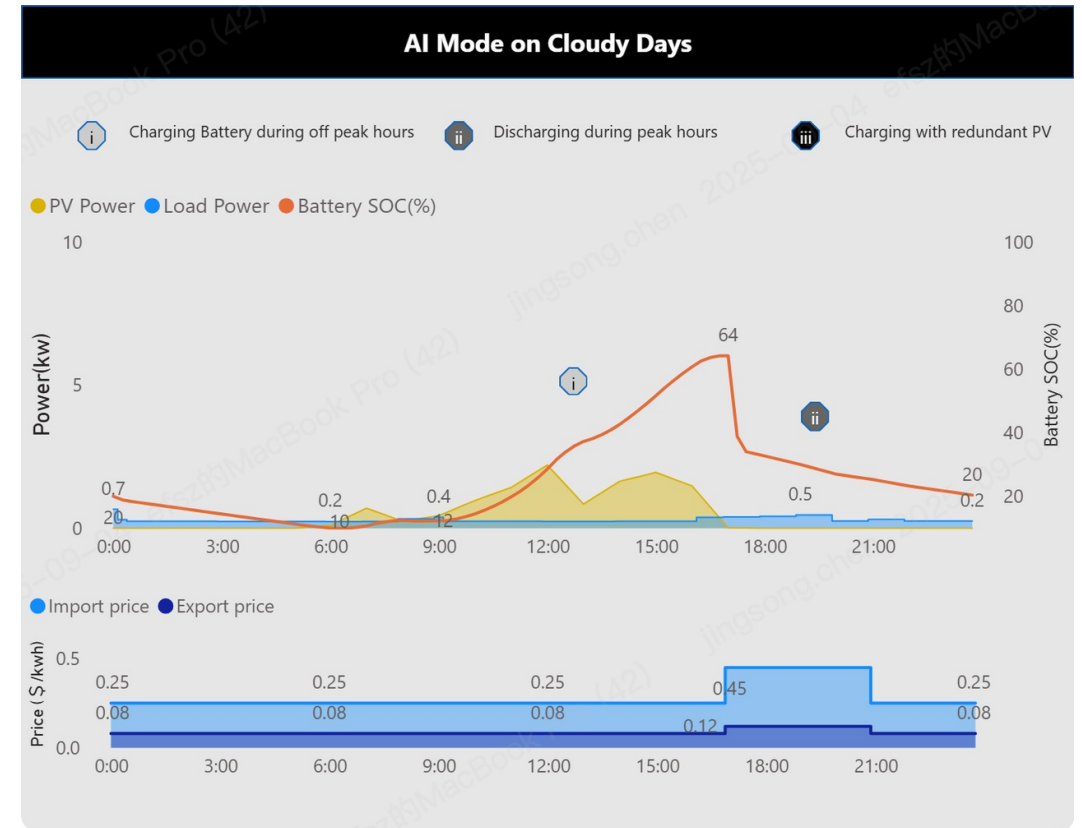
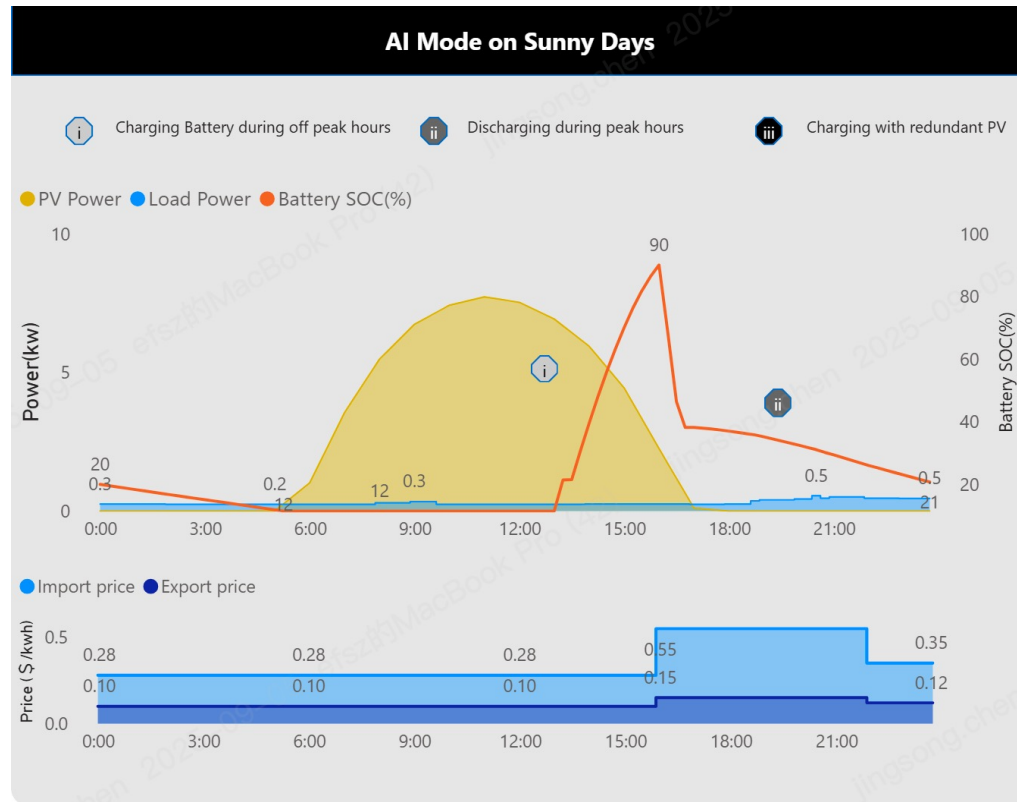


Germany — County-level: Average PV and Storage Capacity per Household



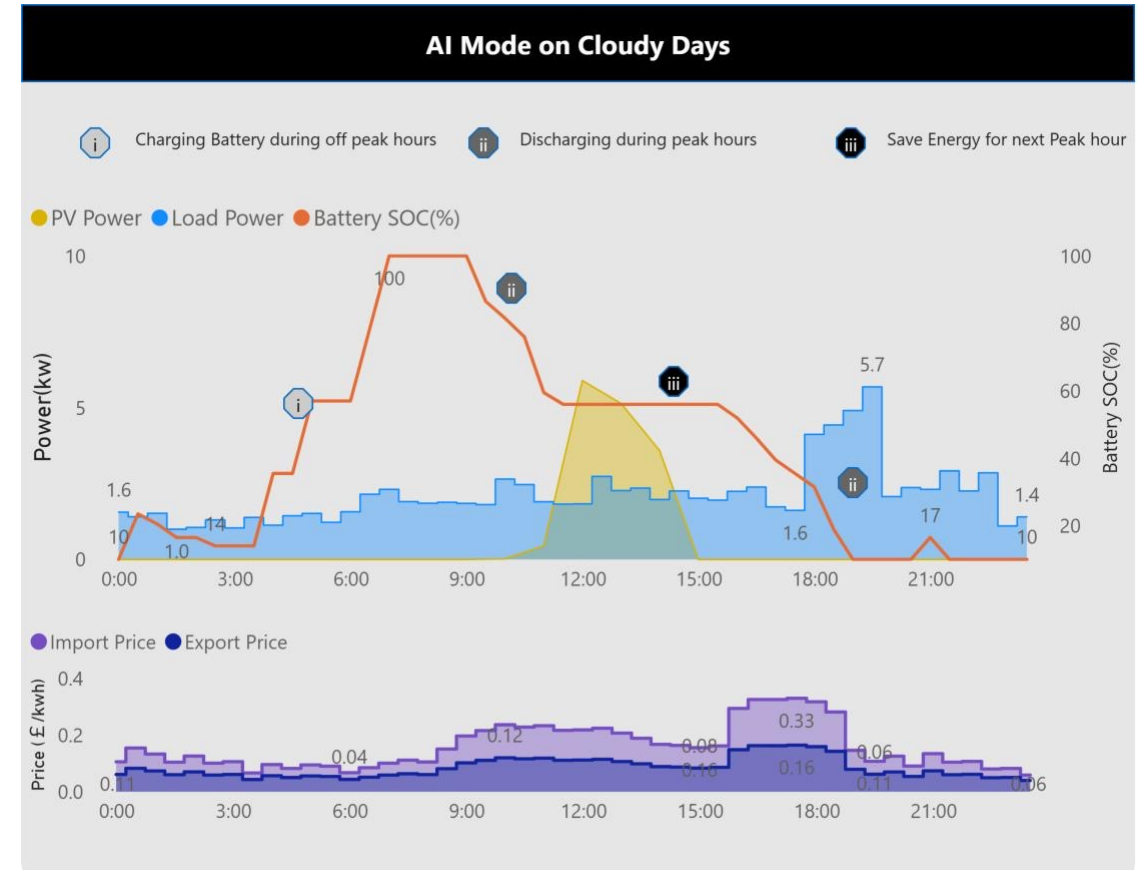
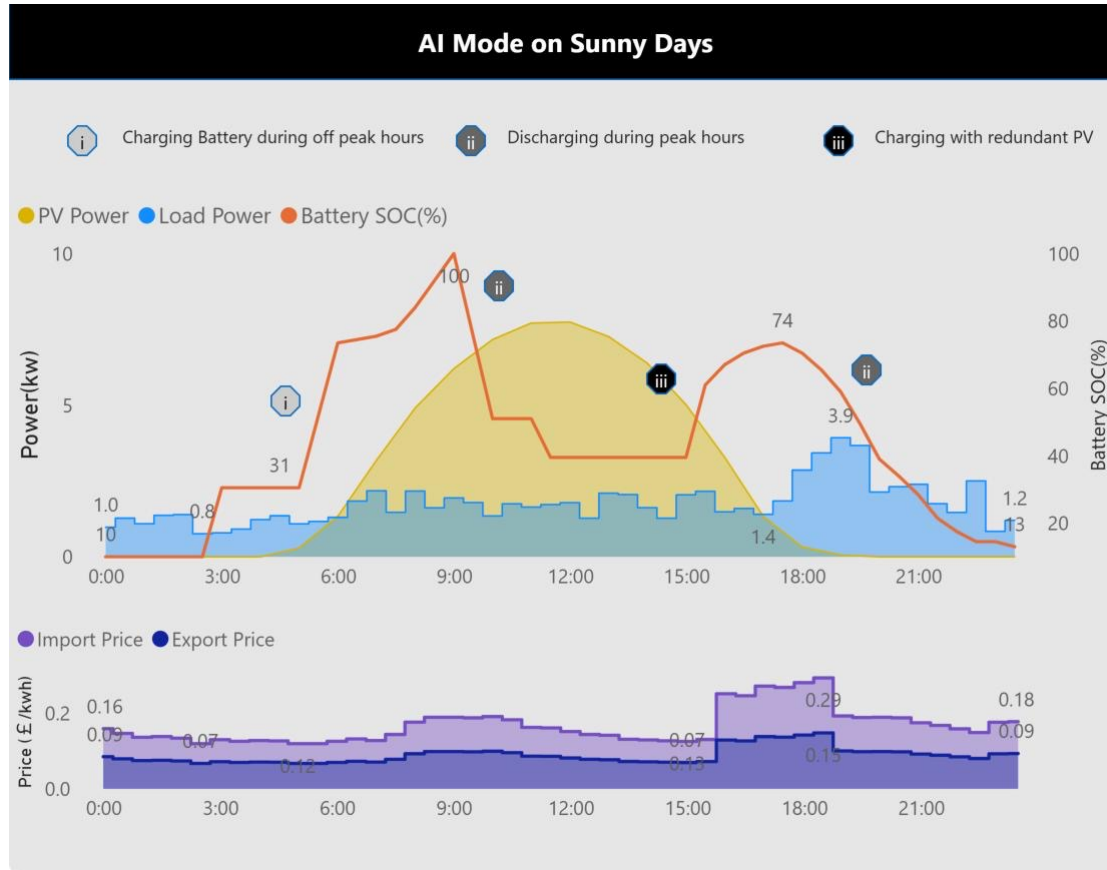
• *Selected US Case*

10kWp PV + 10kWh ESS + TOU



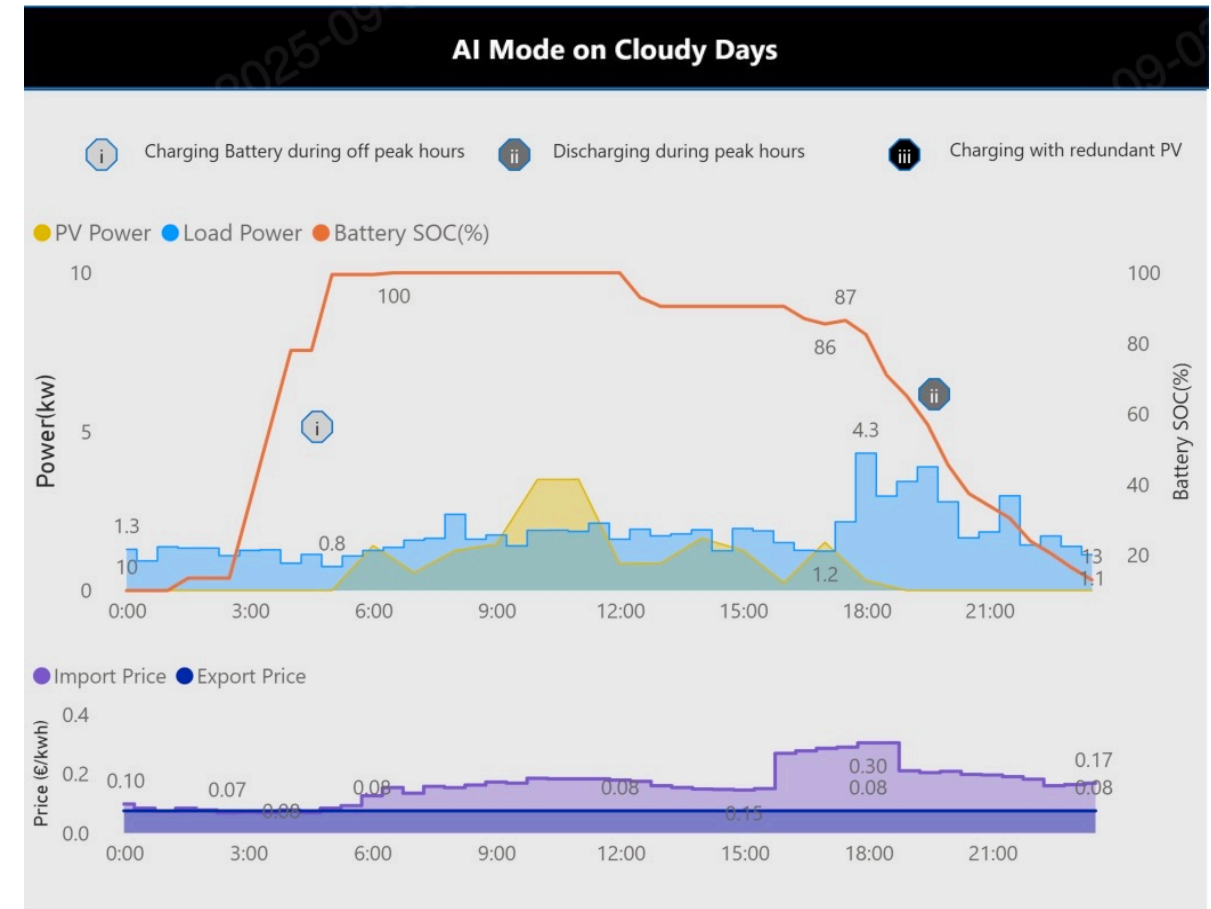
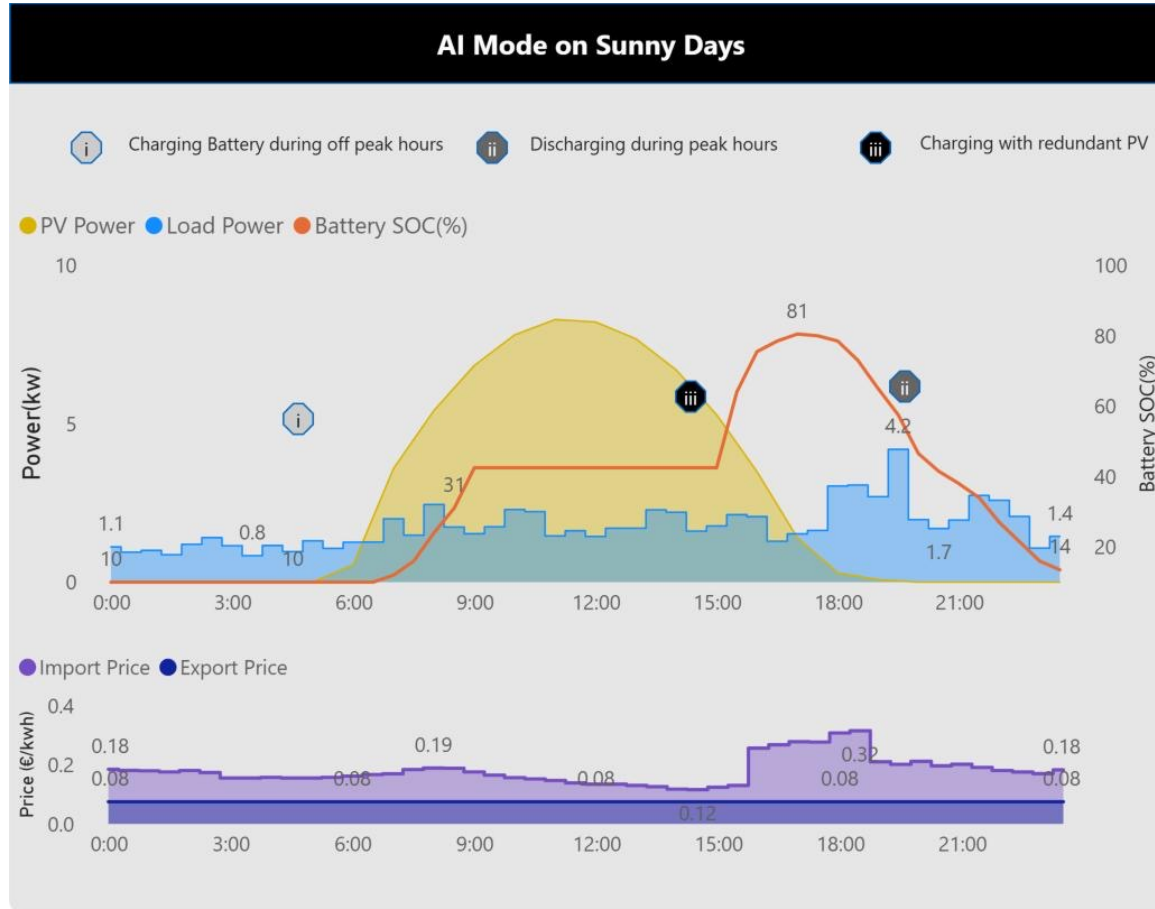
• *Selected UK Case*

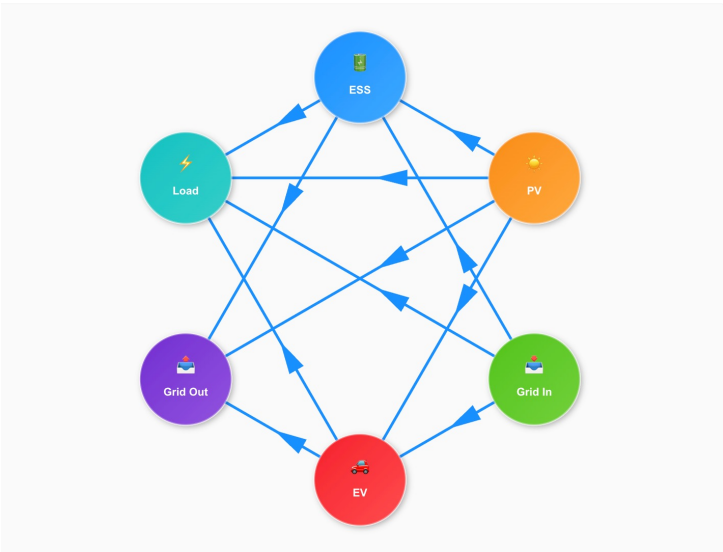
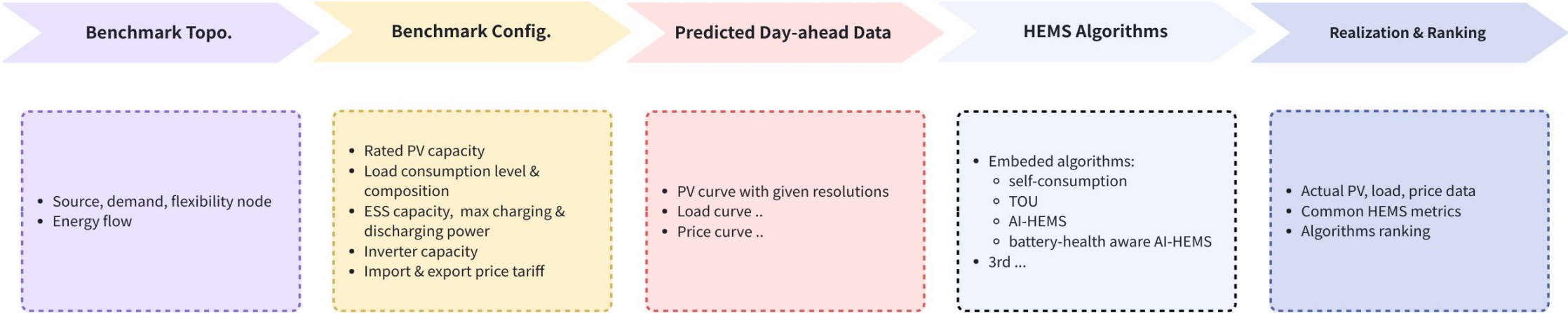
10kWp PV + 20kWh ESS + Octopus dynamic tariff

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• *Selected Germany Case*

10kWp PV + 10kWh ESS + Dynamic tariff

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Country: United States

State: California

City: Los Angeles

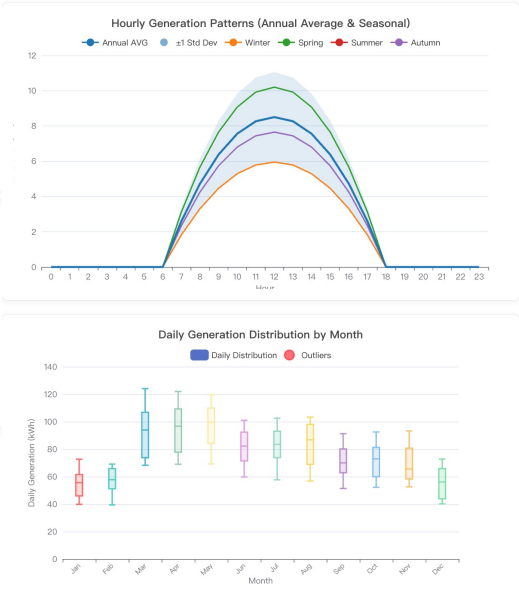
PV Baseline Capacity: 4.92 kWp

ESS Capacity: 6.93 kWh

Daily Power Consumption: 15 kWh

Grid Feed Power: 5.0 kW

Consumption Tariff: Tariff Name te



Universal description language connecting system topology to constraints within HEMS framework.

Benchmark capacity for PV and ESS derived from system location and sizing analyses.

Strategy Selection and Parameter Configuration

Choose the dispatch strategies to be evaluated

Grid-Only

BASIC

Power purchase from grid only, suitable for areas with stable and low grid electricity prices

- Stable Power Supply
- Zero Initial Investment
- Simple Operation

Energy Saving 0%

Cost Optimization 20%

Grid + PV

RECOMMENDED HIGH EFFICIENCY

Grid and PV combination, prioritize PV power during day, use grid power at night

- PV Priority During Day
- Grid Supplement at Night
- Reduce Electricity Bills

Energy Saving 35%

Cost Optimization 45%

Self-Consumption

RECOMMENDED PARAMETER CONFIG HIGH EFFICIENCY

PV power for self-consumption priority, ESS for load regulation, excess power feed-in for revenue

- PV Priority Consumption
- ESS Regulation
- Feed-in Revenue

Energy Saving 60%

Cost Optimization 70%

AI-TOU

RECOMMENDED PREMIUM HIGH EFFICIENCY

AI smart time-of-use price optimization, predict price fluctuations, automatically choose optimal charge/discharge timing

- AI Price Prediction
- Optimal Timing Selection
- Automatic Arbitrage Trading

Energy Saving 50%

Cost Optimization 85%

Robust-X

PREMIUM HIGH EFFICIENCY

Robust optimization strategy, cope with extreme weather and equipment failures, ensure stable system operation

- Extreme Weather Response
- Equipment Fault Tolerance
- Stable Operation Guarantee

Energy Saving 45%

Cost Optimization 80%

Supports sensitivity analysis over:

- PV capacity
- ESS capacity
- Load consumption level
- Grid export limit

Integrated with multiple HEMS algorithms and supports adding new 3rd ones.

- **Baseline:**
 - Grid-only
 - Grid + PV
 - Self-consumption
- **Advanced:**
 - AI-TOU
 - Battery health-aware
 - MPC

Parameter Sensitivity Analysis Configuration

Based on baseline values from step 2, set variation ranges for sensitivity analysis

Grid Power sensitivity analysis enabled

Configuration Instructions

- Default variation range: 80%-120% of baseline
- Minimum lower bound: 50% of baseline
- Maximum upper bound: 150% of baseline
- Minimum step size: 1 for integer parameters

Baseline Review

PV Capacity
4.92 kWp

Daily Consumption
15 kWh

ESS Capacity
6.93 kWh

Grid Power
5 kW

Parameter Configuration

PV Capacity Sensitivity

Enabled

3 ~ 6 kWp

Step 2 kWp

Daily Consumption Sensitivity

Enabled

12 ~ 18 kWh

Step 3 kWh

ESS Capacity Sensitivity

Enabled

5 ~ 9 kWh

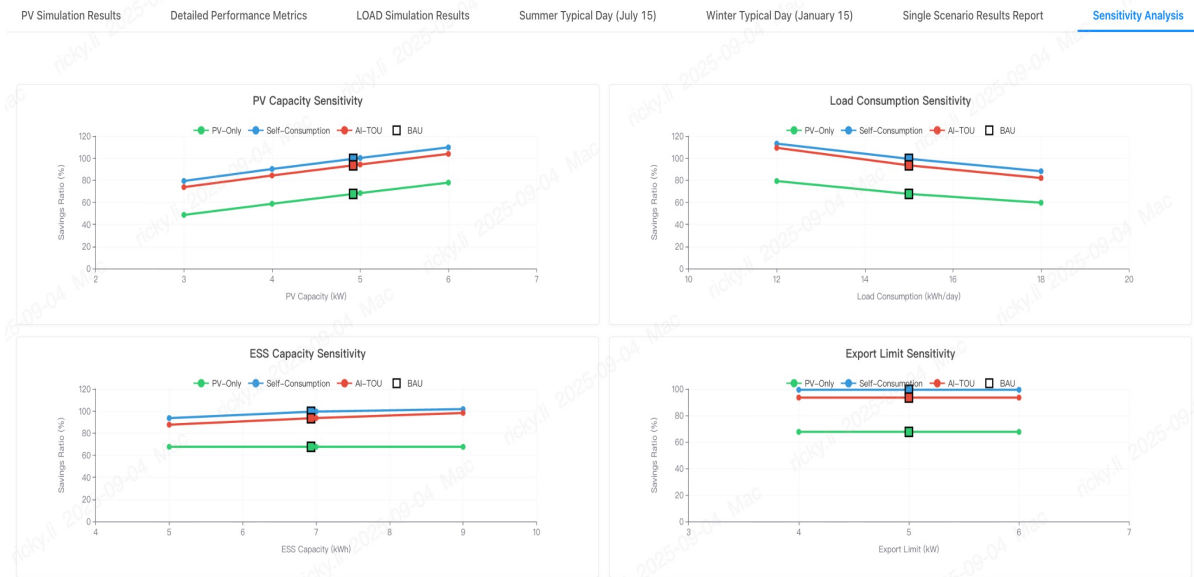
Step 2 kWh

Grid Power Sensitivity

Enabled

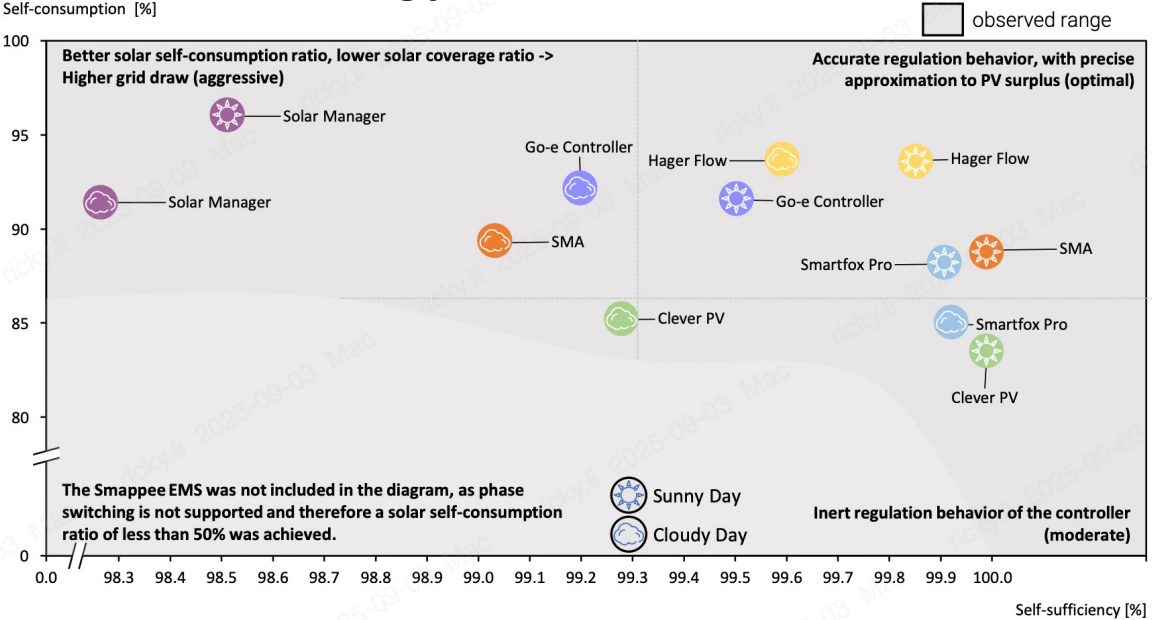
4.0 ~ 6.0 kW

Step 1 kW



month	daily load (kWh)	pv generation (kWh)	ess capacity (kWh)	original cost (\$)	cost with pv (\$)	cost with pv-ess & self-consumption (\$)	cost with pv-ess & ai-tou (\$)	pv w.r.t original (%)	pv-ess w.r.t original (%)	ai-tou w.r.t original (%)
2024-01	14.7	13.3	6	59.91	-19.1	-19.18	-33.64	131.9	132	156.1
2024-02	11	17.7	6	46.61	-32.14	-32.12	-45.57	169	168.9	197.8
2024-03	7.1	24.4	6	46.44	-44.19	-43.42	-58.05	195.1	193.5	225
2024-04	6.1	31	6	41.5	-53.08	-50.98	-67.06	227.9	222.9	261.6
2024-05	7.1	35.4	6	47.6	-54.5	-51.04	-71.08	214.5	207.2	249.3
2024-06	15	37.6	6	57.79	-47.46	-47.85	-62.6	182.1	182.8	208.3
2024-07	15	39.9	6	90.57	-21.85	-22.08	-38.44	124.1	124.4	142.4
2024-08	19.1	35.4	6	90.33	-28.84	-28.74	-45.02	131.9	131.8	149.8
2024-09	15	28.8	6	75.03	-34.95	-35.28	-50.5	146.6	147	167.3
2024-10	23.5	22.1	6	67.06	-37.4	-37.33	-53.99	155.8	155.7	180.5
2024-11	23.1	15.5	6	53.9	-28.61	-28.38	-42.25	153.1	152.7	178.4
2024-12	19.1	11.1	6	45.94	-25.31	-25.19	-39.51	155.1	154.8	186
SUM(AVG)				722.68	-427.43	-421.59	-607.71	165.59 (AVG)	164.47 (AVG)	191.88 (AVG)

Two-metric ranking from P3



Source: P3 Group

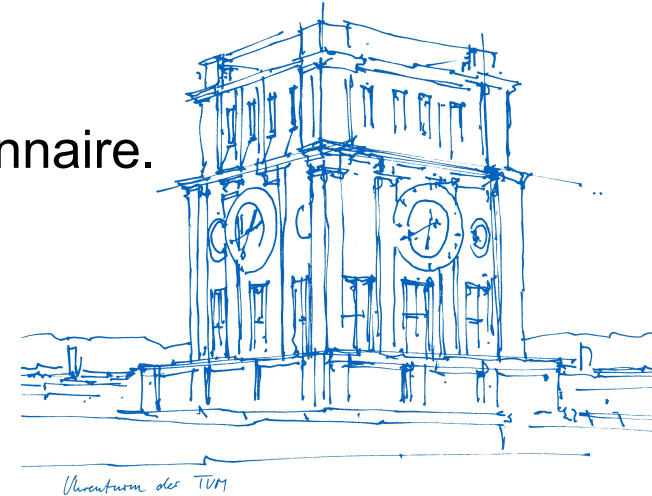
Collaboration with **HEMS Finder** is under discussion for conducting a multi-metric ranking of available HEMS on that platform.

- Metrics:
 - Cost & revenue
 - Comfort level
 - Battery degradation & LOCE



HEMS Benchmarking in Germany – story so far...

- HEMS Finder - a project to compare all available HEMS being sold in Germany
 - Second annual survey is currently out – [open-access report here](#)
 - More information can be found on the website – <https://hems-finder.org/>
- Current comparison is limited to a manufacturer survey through a questionnaire.
- A true benchmarking requires subjecting HEMS to test conditions
- But what are these conditions?



HEMS Benchmarking in Germany

- There are separate standards for benchmarking – a tale of three worlds.

	Research world	Regulations world	Real world
Motivation	What could be possible?	What should be possible?	What is currently possible?
Focus	Algorithms and forecasts	Discrimination free access, privacy by design, grid stability	Ease of implementation, converging on interoperable solutions.

- Research project PhyLFlex (2025-2028) is focused on this problem.
 - How to evaluate various HEMS strategies?
 - Can there be a universal methodology?



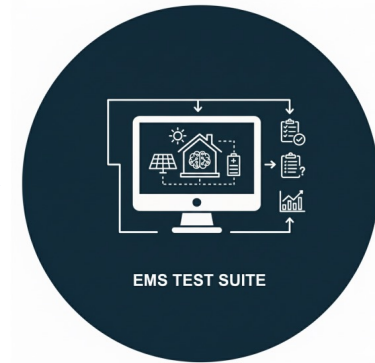
Gefördert durch:

aufgrund eines Beschlusses
des Deutschen Bundestages

PhyLFlex HEMS Benchmarking Suite

- Validation strategy for laboratory and demonstrator

CoSES Laboratory, TUM



ÜZW Grid section

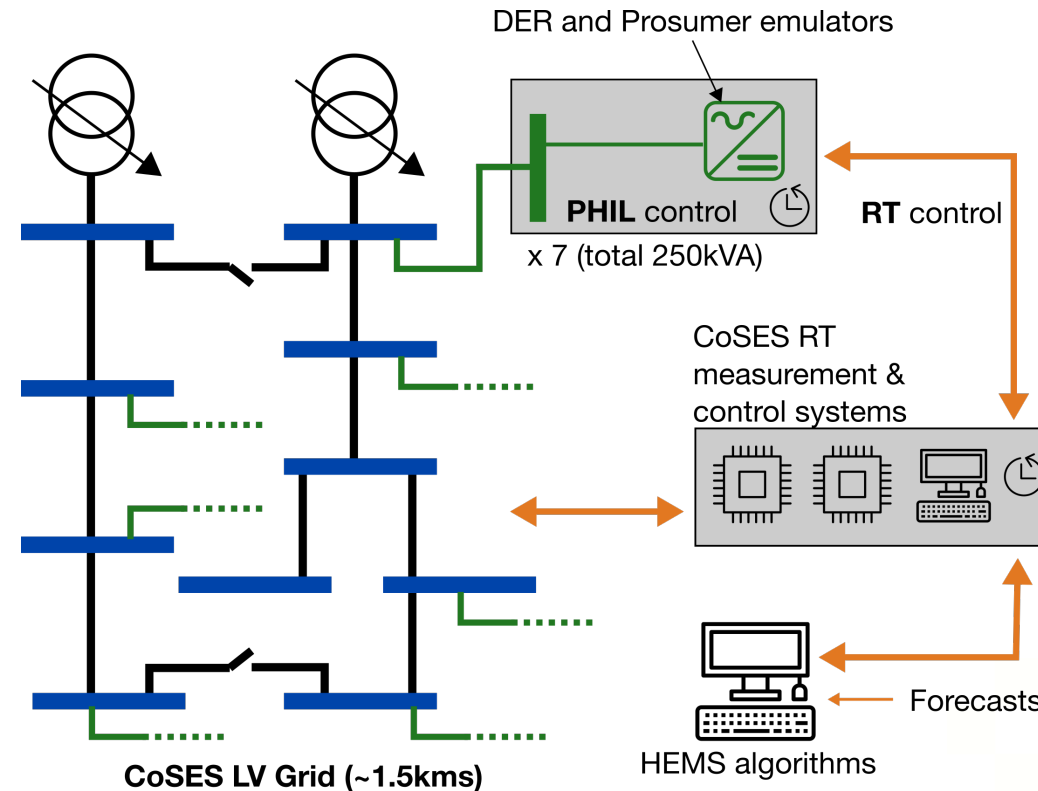


EMS benchmarking suite

1. Rule based
2. MPC
3. Reinforcement Learning
4. Physics based (combination of above)

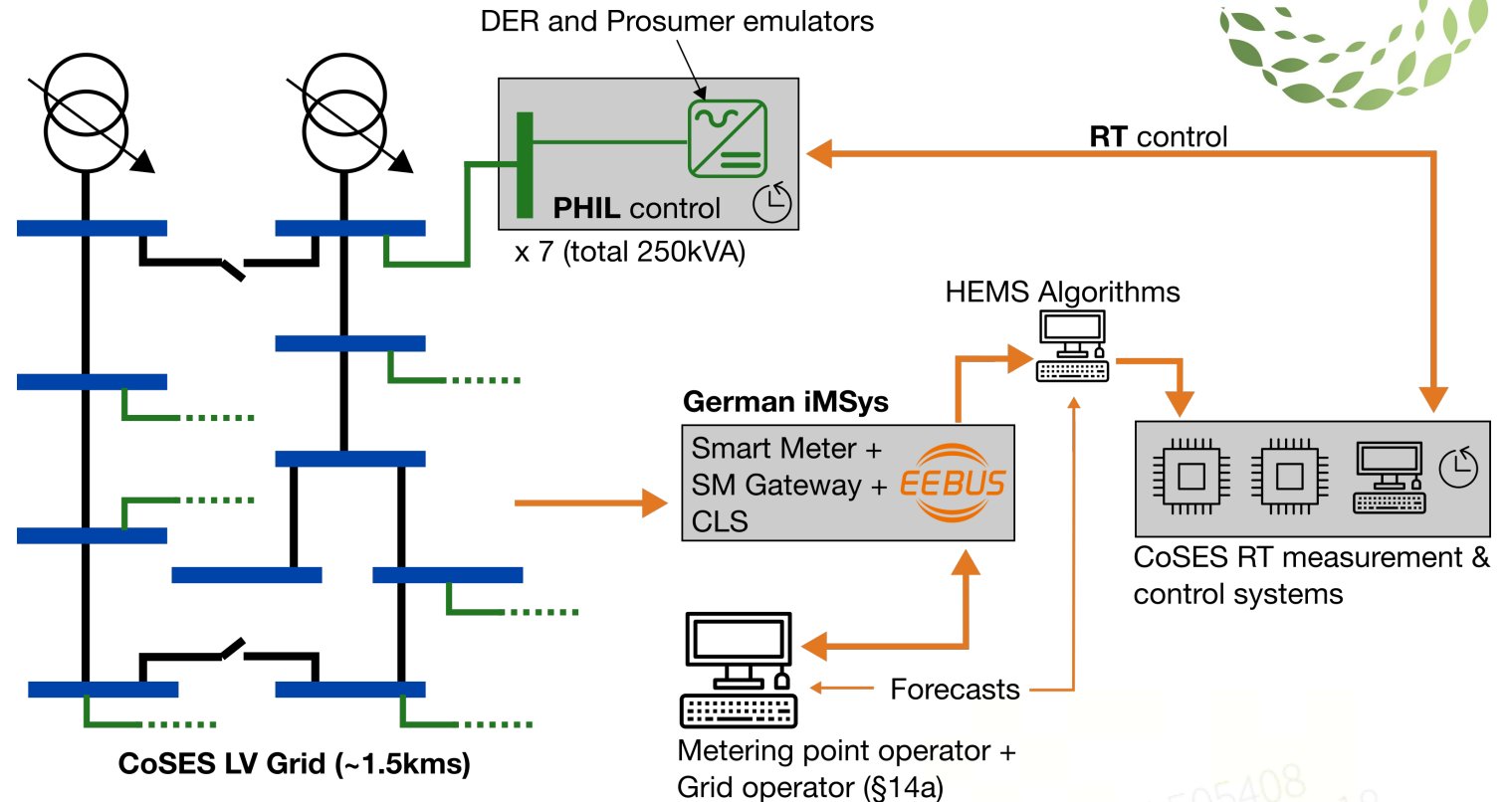
The research benchmark – What *could* be possible?

- Reference demand, generation profiles
- Reference objective functions
- Complete emulation
- To test:
 - Different algorithms
 - Forecasts
 - Control windows



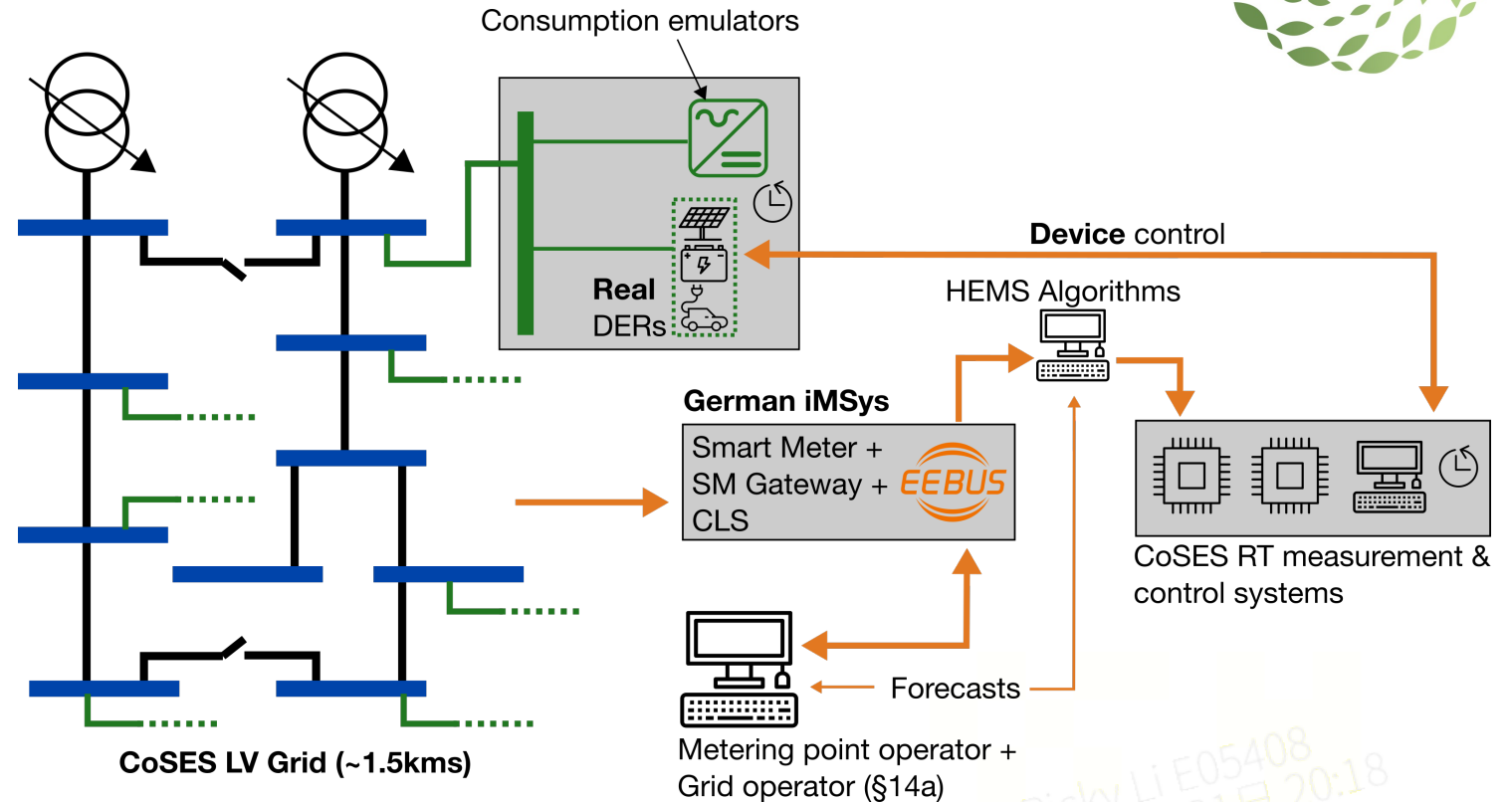
The iMSys benchmark – What *should* be possible?

- Reference demand, generation profiles
- Reference objective functions
- iMSys-in-the-loop
- DERs and prosumers emulated
- To test:
 - §14a signal efficacy
 - Max. utility from iMSys + FNN
 - Grid friendly EMS



The real-world benchmark – What *is currently* possible?

- Reference demand, objective functions
- iMSys-in-the-loop
- Real DERs + Emulated consumption
- To test:
 - Device interoperability
 - HEMS → DER protocols
 - Claims vs Reality
- Further demonstrations at



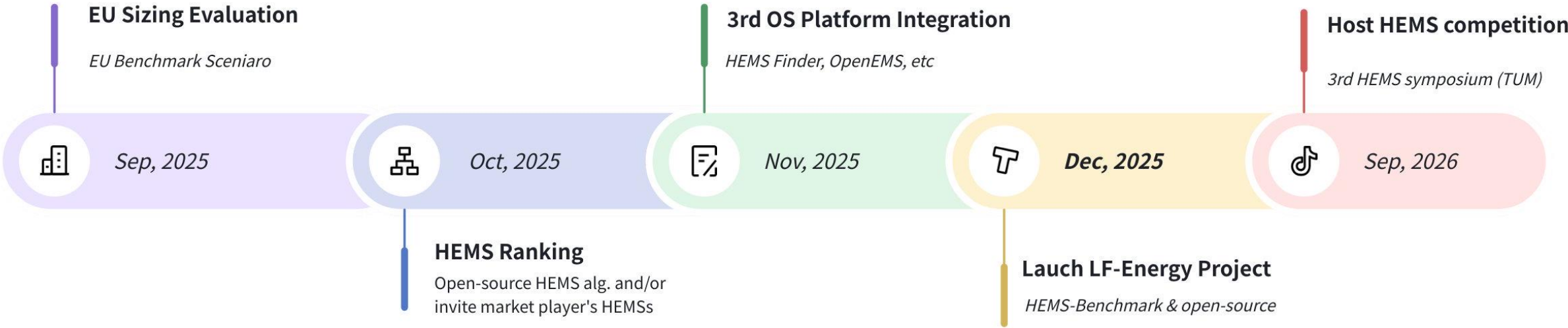
HOCHSCHULE
ANSBACH

10+ DER manufacturers

ÜZW NETZ

10 houses in ÜZW grid

CoSES LV Grid (~1.5kms)



TSG Code



Nature Energy Code



Community joint
force is **NEEDED!**

LFENERGY

LF AI & DATA

Technical Paper Open-source

Scan & Register for this Project (or sub-projects)

- Developed a **systematic prediction and optimization framework** for PV and ESS, covering lifecycle, location, sizing, HEMS, and VPP benchmarking.
- Conducted **preliminary evaluations** using open-source datasets in the US and Germany.
- Compared **AI-based** and **self-consumption** strategies for the US, Germany, and UK, with sizing benchmark results.
- Built a **benchmarking platform** for integrated results and transparent comparison.
- Ongoing **collaboration with HEMS Finder** for systematic HEMS ranking.
- Full open-source release planned for **December**.

Accelerating Transparency in Home & Community Energy Management Through Benchmarking Platforms

Thank you

Q&A

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