MULTI-MARKET REVENUE OPTIMIZATION OF INTEGRATED HYBRID ENERGY SYSTEMS IN THE NORDIC ELECTRICITY MARKETS

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LUT University

Agenda

About LUT

LUT Projects Related to Energy Storage Systems

Distributed Energy Storage Systems

Multi-Market Participation

LUT University

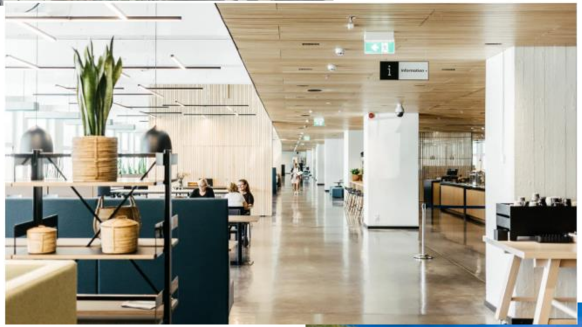
LUT University — Overview & Mission

About LUT

- Public science university in Finland with campuses in
- Lappeenranta and Lahti, founded in 1969.
- Recognized for top-30 global rankings in climate action research

Mission & Focus

- Solve global challenges via energy transition and regenerative use of natural resources
- Build infrastructure resilience through technology, business, and social sciences



Academic Structure

- Three schools: Energy Systems, Engineering Sciences, and Business
- A global science community of 8,500+ students from 100+ nationalities, 1,500 staff, 1,100+ scientific publications, and €133 million annual funding, awarding over 1,700 degrees annually.

The LUT LVDC

A Real-World Research Site Operated since 2011

Public LVDC distribution network built with Suur-Savon Sähkö Oy

Located in eastern Finland, first of its kind globally

Main Components

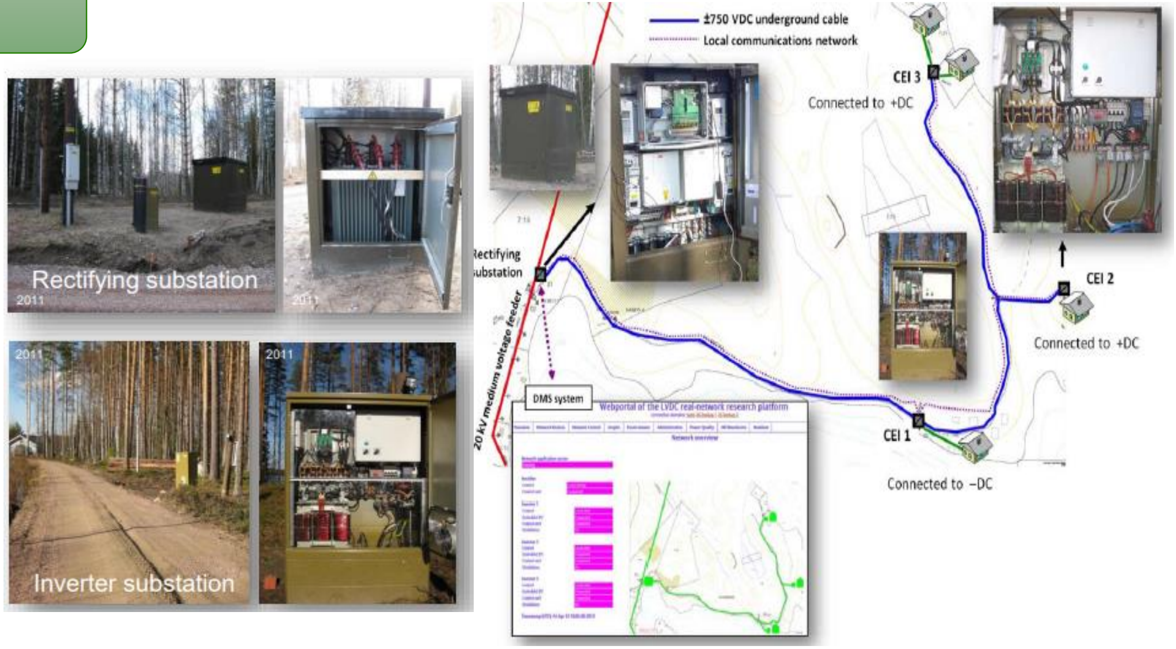
- ❑ 1× Rectifying substation (**thyristor → upgraded PWM**)
- ❑ 3× **Customer-End Inverters (CEIs)** with galvanic isolation
- ❑ Integrated **Battery Energy Storage**

System Specifications

1.7 km bipolar ±750 VDC underground network

Fed from **20 kV MV grid** via rectifying substation

Supplies **four real residential customers**



Purpose & Capabilities

Serves as LUT's full-scale LVDC testbed

- ❑ Platform for studies on converter control, protection, EMI, and system stability
- ❑ Fully equipped ICT and measurement network for remote operation
- ❑ Island operation of microgrid with BESS
- ❑ Power grid reserve; frequency control

Source: Nuutinen et al., "Research site for low-voltage direct current distribution in a utility network—structure, functions, and operation," IEEE Trans. Smart Grid, vol. 5, no. 5, pp. 2574–2582, 2014.

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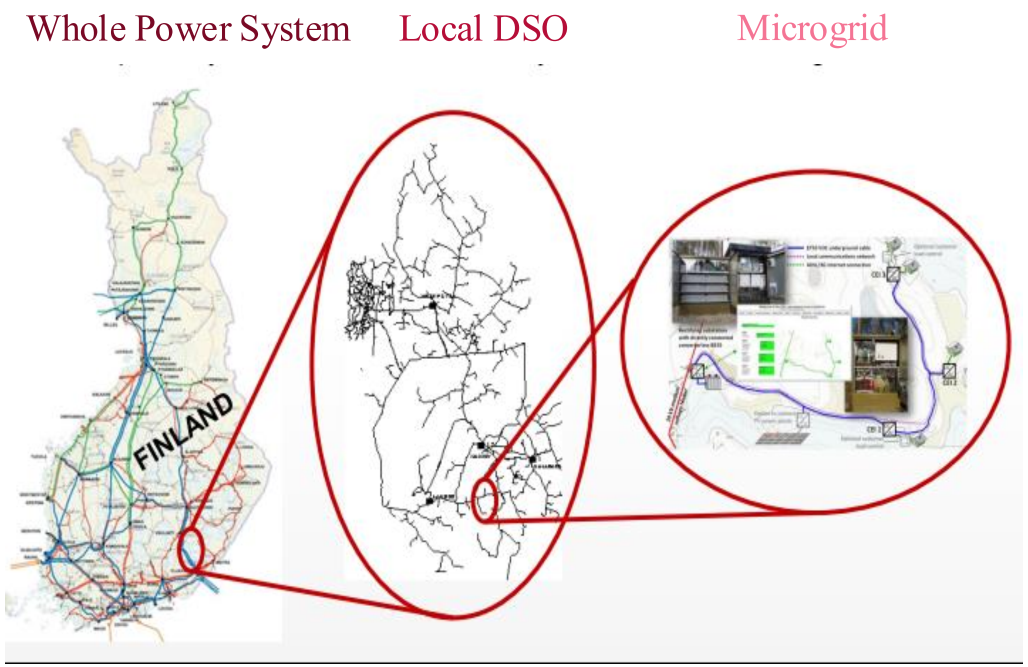
LUT LVDC Research in a Nutshell

Full Ecosystem Overview

1. **Living Lab** – ±750 VDC public pilot grid with a multi-year operational record
2. **Digital Twin (Lana)** – validated models for stability & efficiency analysis
3. **Business Playbook (Karppanen)** – framework for DSO LVDC feasibility & design
4. **Hardware Solutions (Nuutinen)** – converter control, fault protection, EMI filtering
5. **Smart Network (Pinomaa)** – power-line data communication for smart metering & control
6. **Economic Design (Mattsson)** – Life-cycle-cost design methodology that optimizes for real-world partial-load efficiency

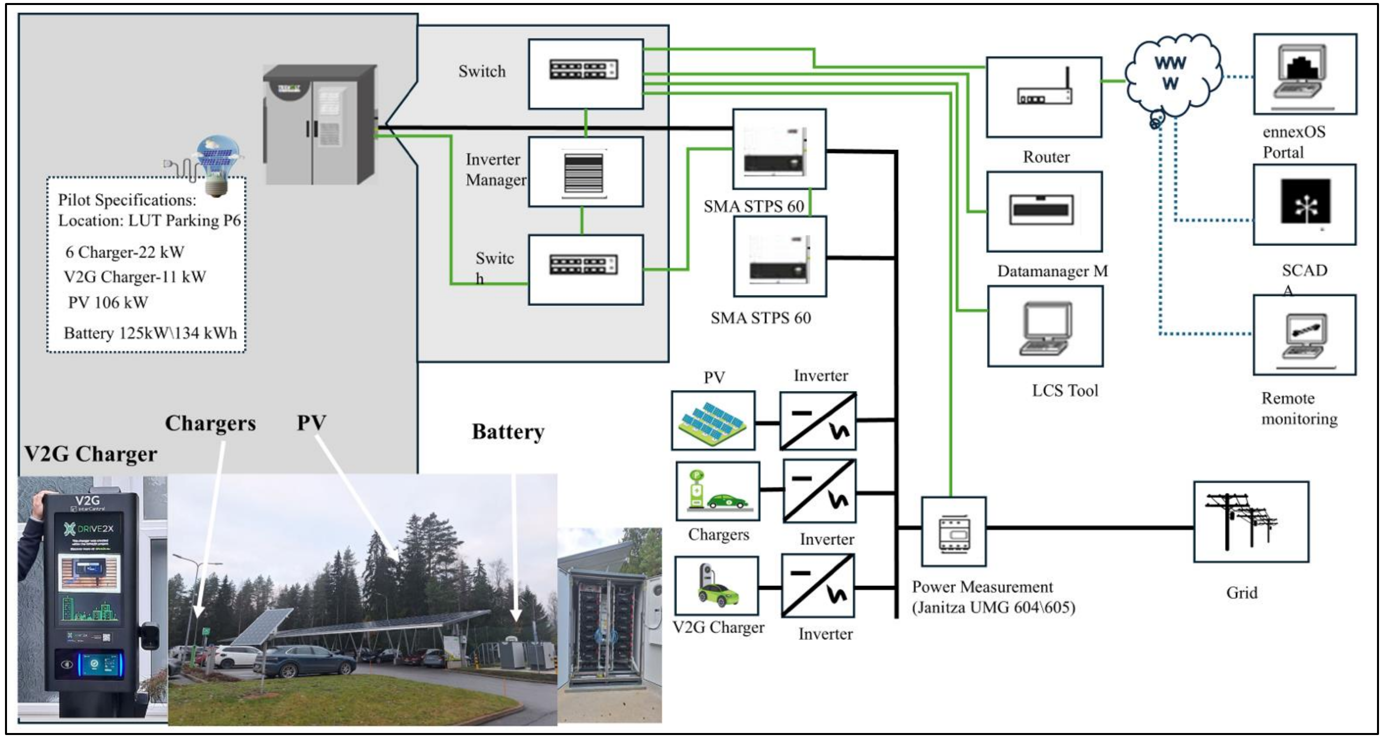


Impact

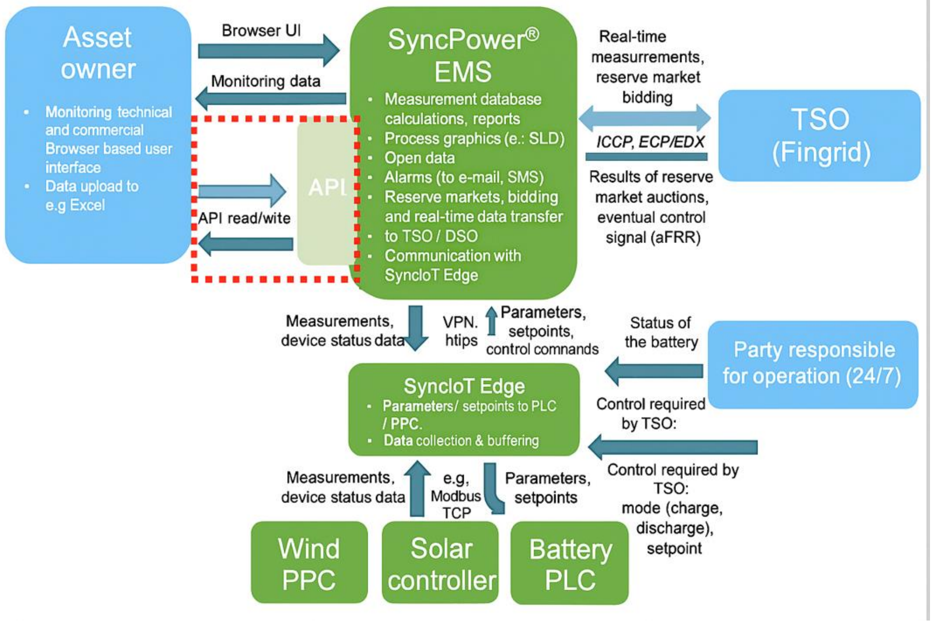
One of the first public LVDC systems worldwide
Blueprint for future hybrid AC/DC smart grids
Referenced in EU Smart Grid & IEC standardization

LUT ESS Living lab

LUT Hybrid Lab

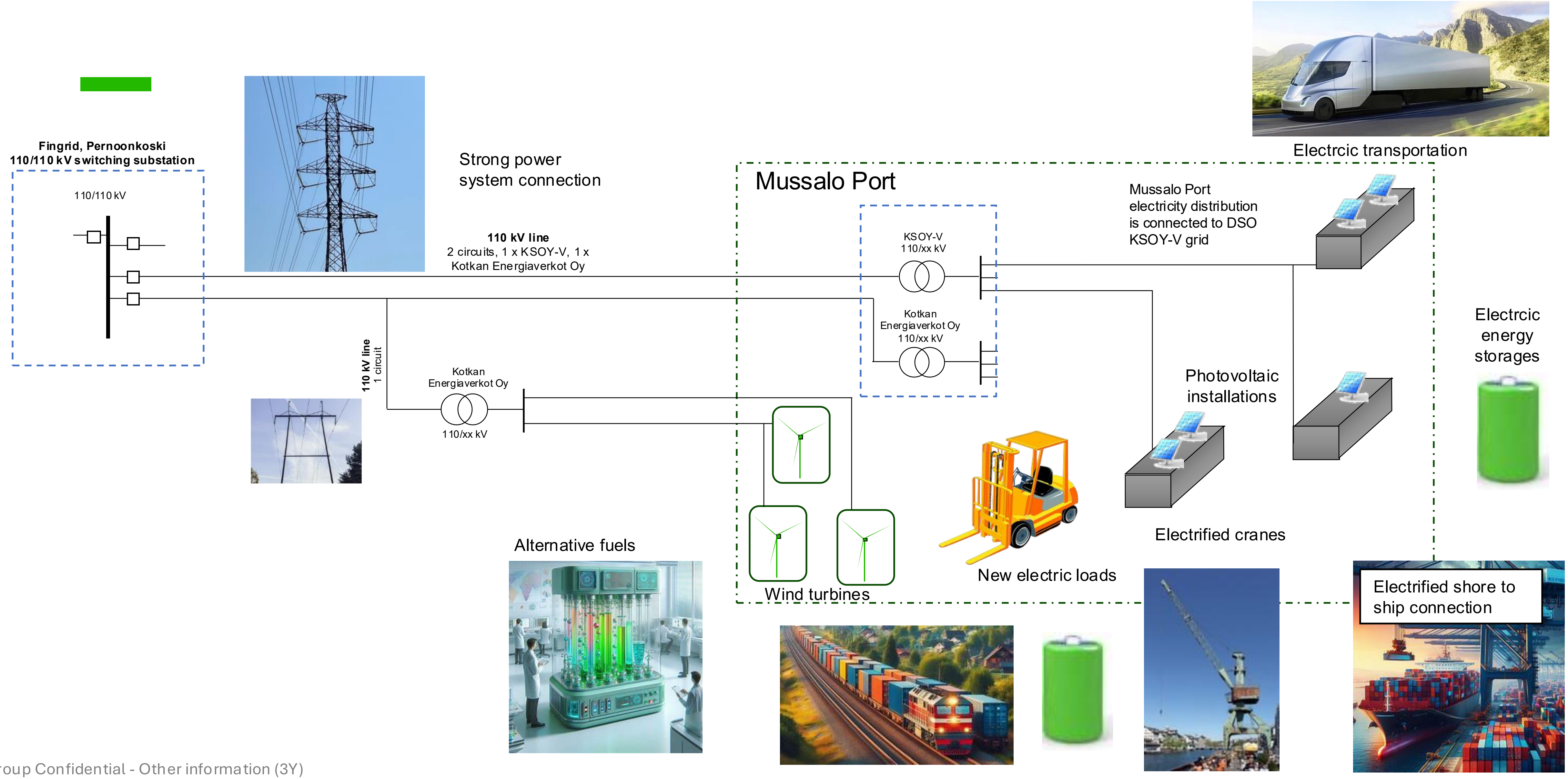


SyncPower EMS development



ONGOING PROJECTS

- Project Title: **Port of Mussalo Energy Community Pilot**
  - **<u>Objectives:</u>**
- The objective of the project is to improve the competitiveness of the local stakeholders by providing clean and affordable electricity to the participants and by helping them to meet their greenhouse gas reduction targets. The needs for regulatory changes are reported to the respective authorities and politicians.

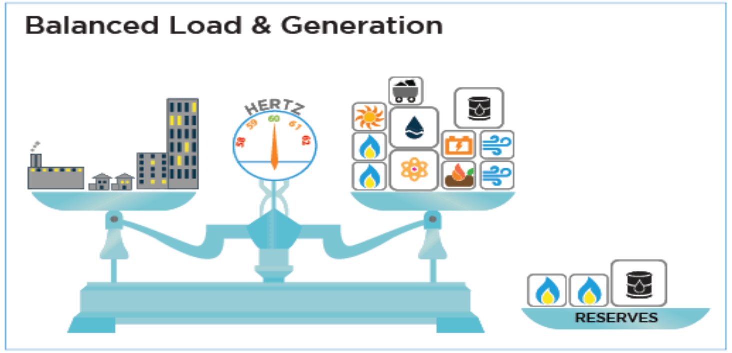

Fingrid, Pernoonkoski
110/110 kV switching substation
110/110 kV
Strong power
system connection
110 kV line
2 circuits, 1 x KSOY-V, 1 x
Kotkan Energiaverkot Oy
110 kV line
1 circuit
Kotkan
Energiaverkot Oy
110/xx kV
Mussalo Port
KSOY-V
110/xx kV
Kotkan
Energiaverkot Oy
110/xx kV
Mussalo Port
electricity distribution
is connected to DSO
KSOY-V grid
Electrcic transportation
Electrcic
energy
storages
Photovoltaic
installations
Electrified cranes
New electric loads
Wind turbines
Alternative fuels
Electrified shore to
ship connection

Why Energy Storage?

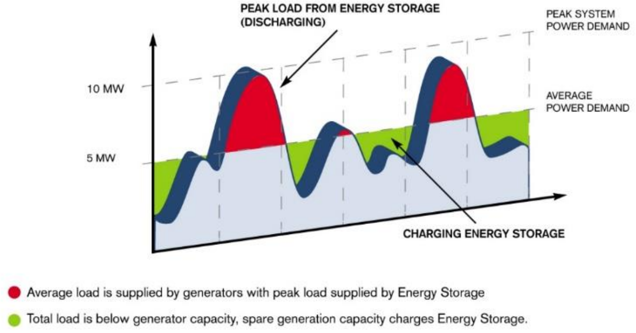
RES integration

Price arbitrage

Ancillary services



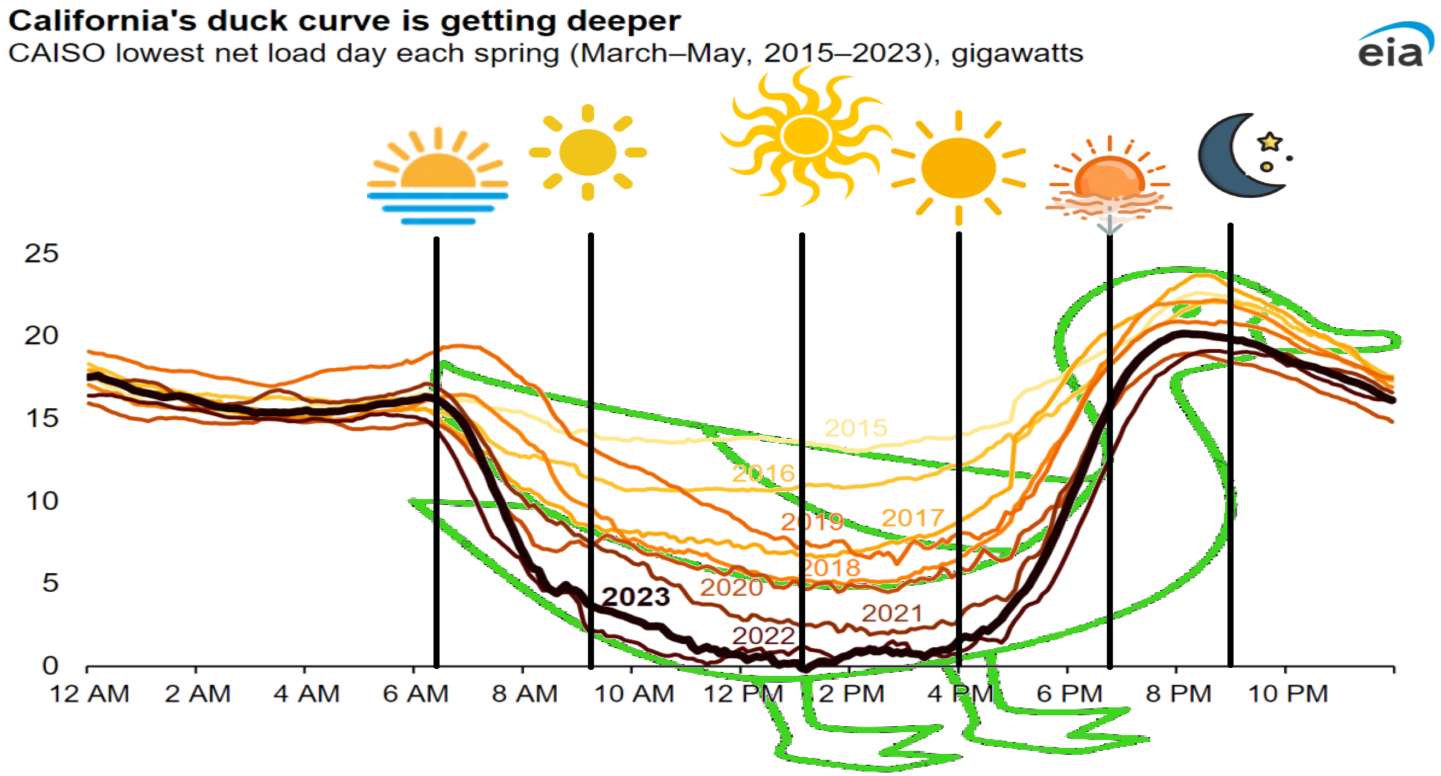
Peak shaving

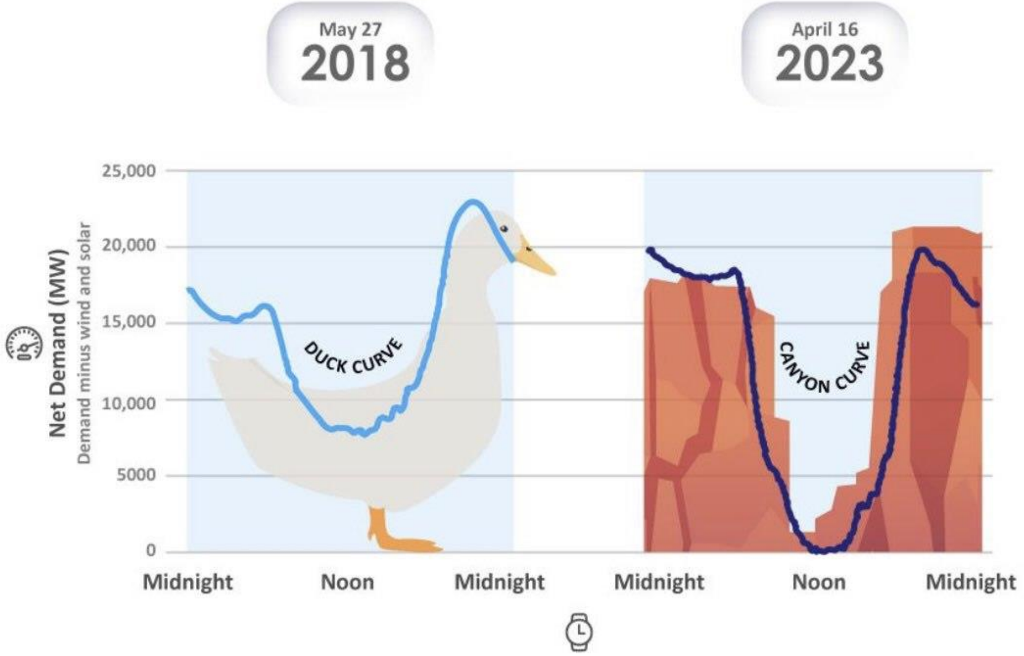


Flexibility

Electricity Cost

Renewable Energy Integration Challenges

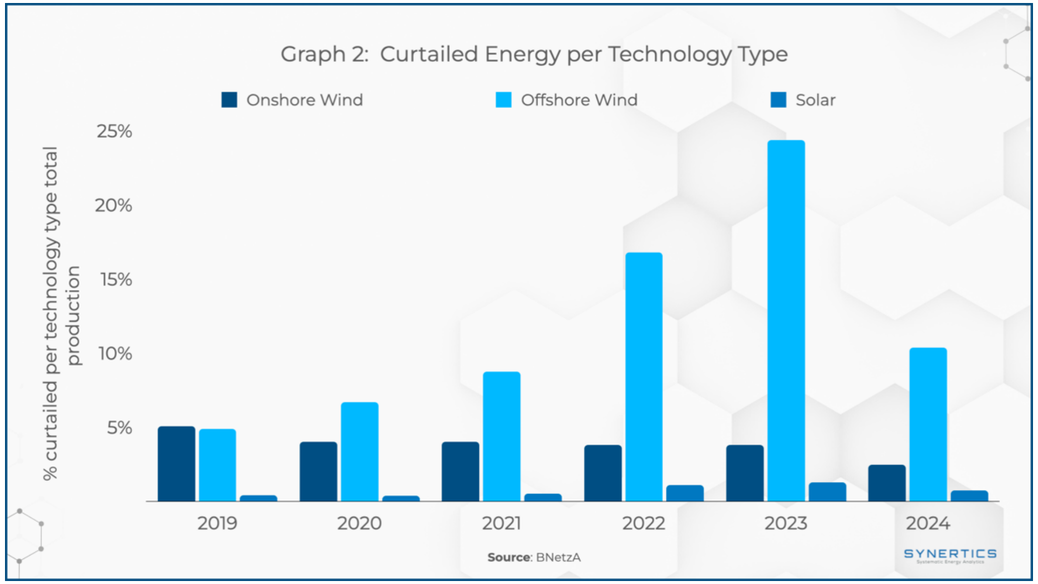




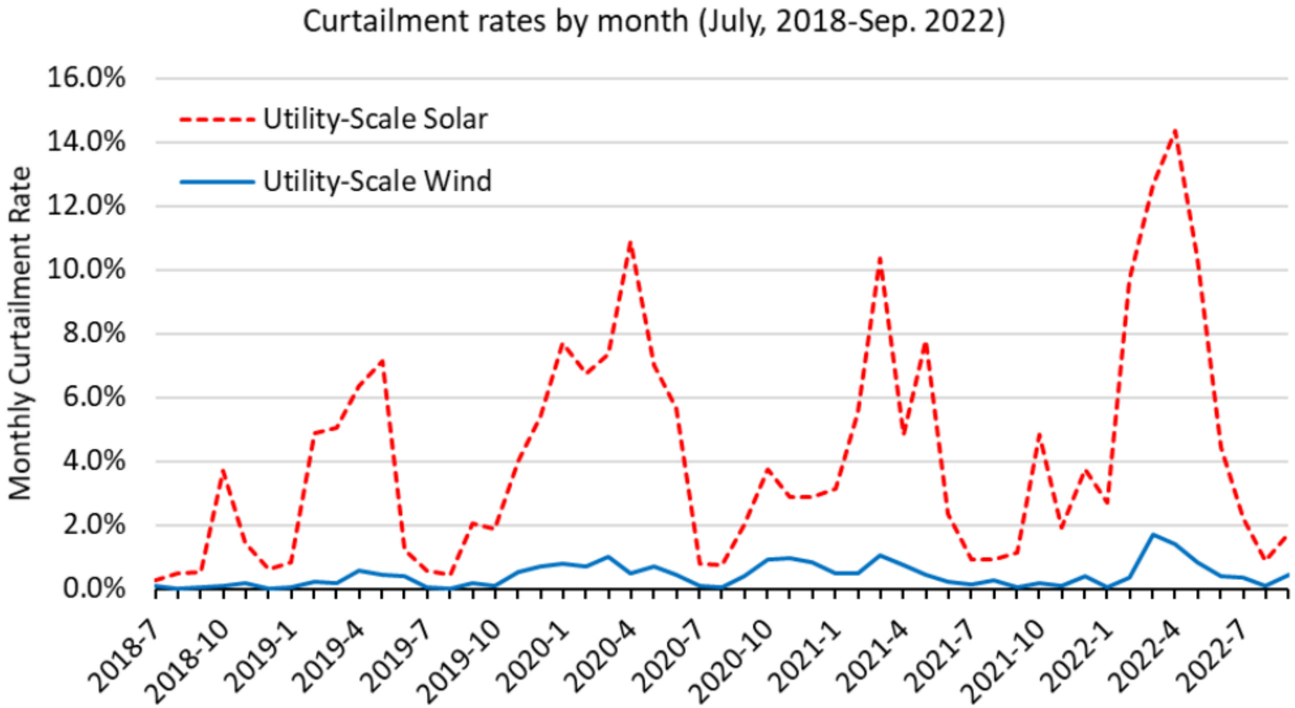
Source: *Energy Information Administration,* 2023

Renewable Energy Integration

Curtailment of Solar and Wind Energy in Germany during Redispatching-Sep 2024



Curtailments of solar-powered electricity generation have increased in the California Independent System Operator (CAISO) region, the part of the electric grid that covers most of the state.

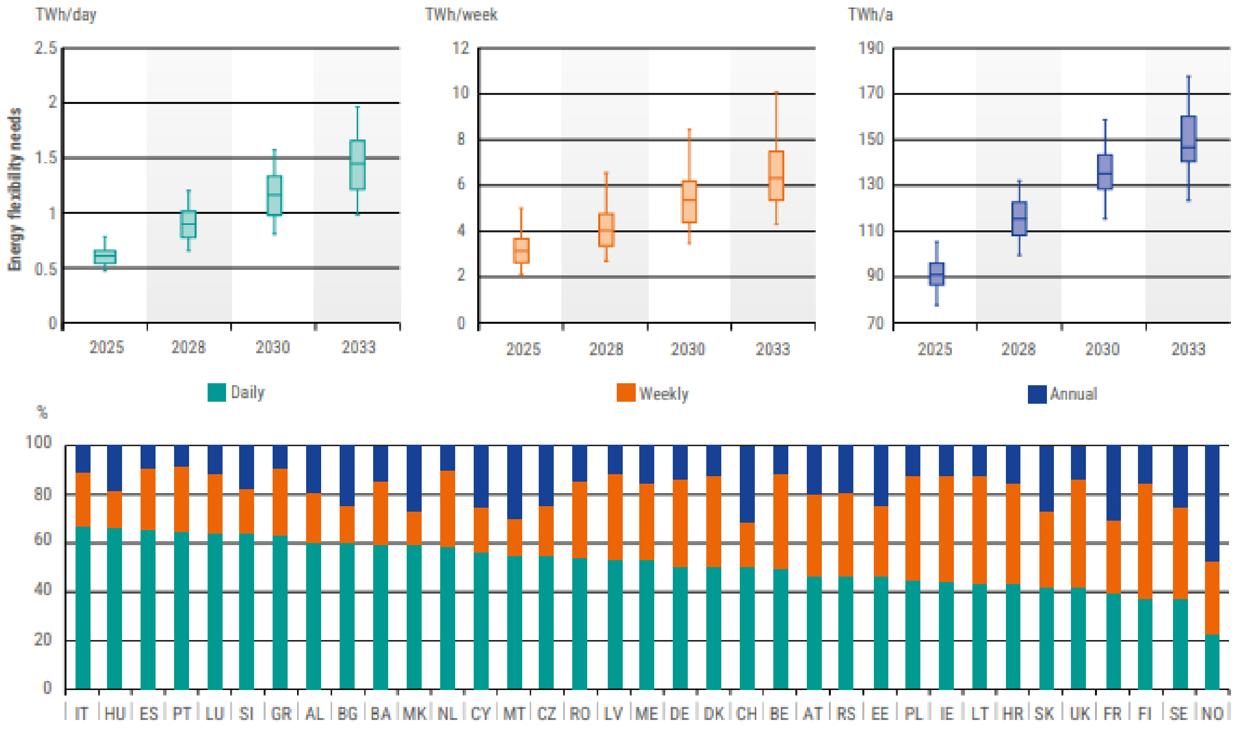


Novan K, Wang Y. Estimates of the Marginal Curtailment Rates for Solar and Wind Generation

Pan-European Flexibility Needs

Key Driver	Trend / Impact
Generation–Demand Variability	Flexibility demand ×2 (2025–2033)
Forecast Uncertainty	Short-duration flexibility need ×2 (by 2030)
Regional Effects	Stress across zones, reduced interconnection support

Pan-European flexibility needs from 2025 to 2033

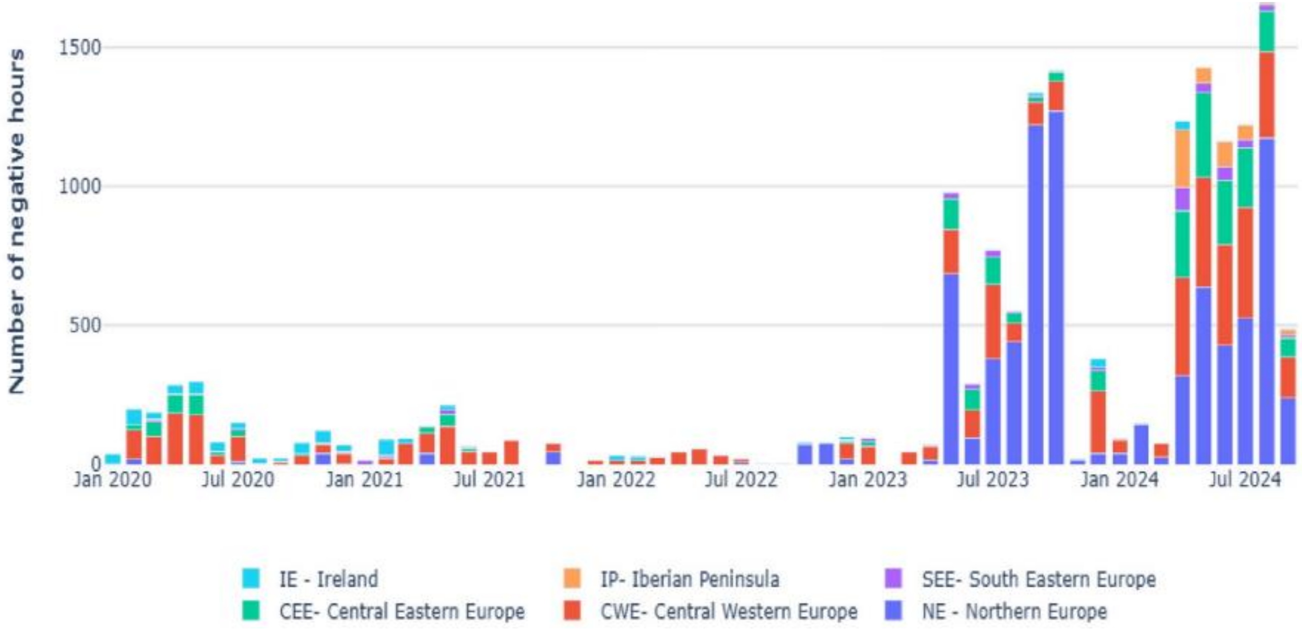


Source: ENTSO-E (2025), *Market Report 2025 – Pan-European Flexibility Needs*

Rising Frequency of Negative Price Events in European Power Markets

- 1,200 h negative prices in 2024
- Rapid RES expansion
- Need for flexibility & storage

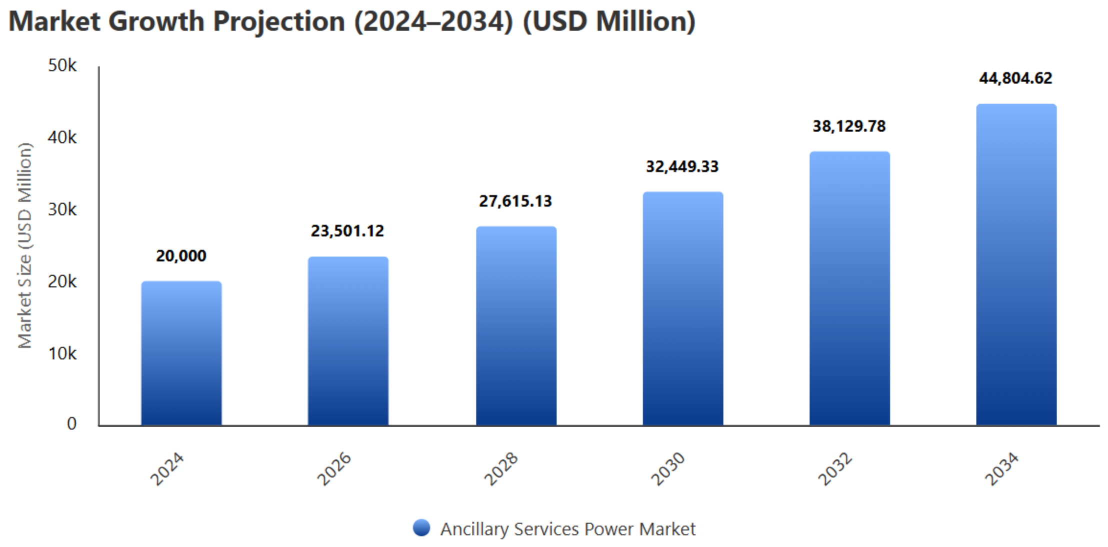
Number of negative electricity price hours across European regions (2020–2024).



Source: ENTSO-E (2025), *Market Report 2025 – Price Formation and Negative Prices*,

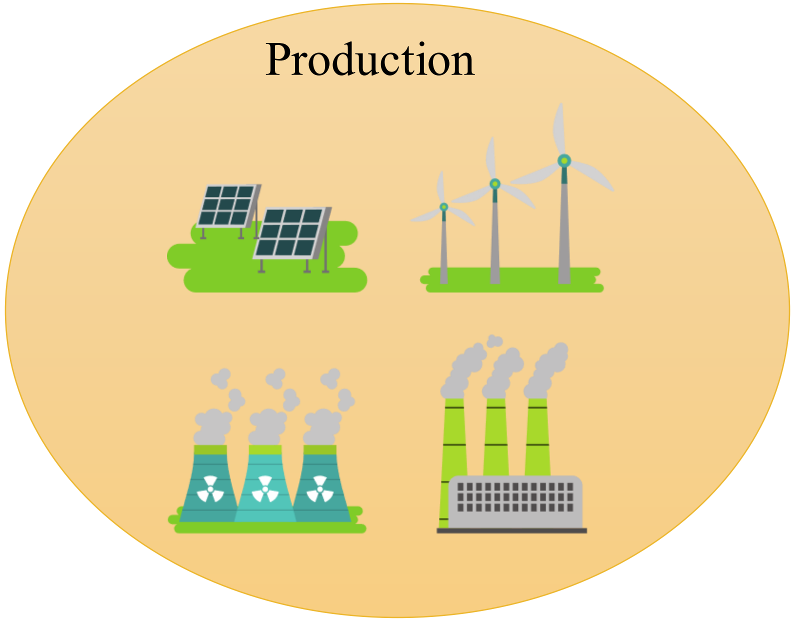
Ancillary Services Power Market Outlook

- Market size: USD 20 B (2024) → USD 45 B (2034)
- Growth rate: CAGR = 8.4 %
- Key drivers:
- Rapid renewable integration & grid stability needs
- Expansion of smart grid (+15 % /yr) & energy storage (+20 % YoY)
- Regulatory reforms and public funding

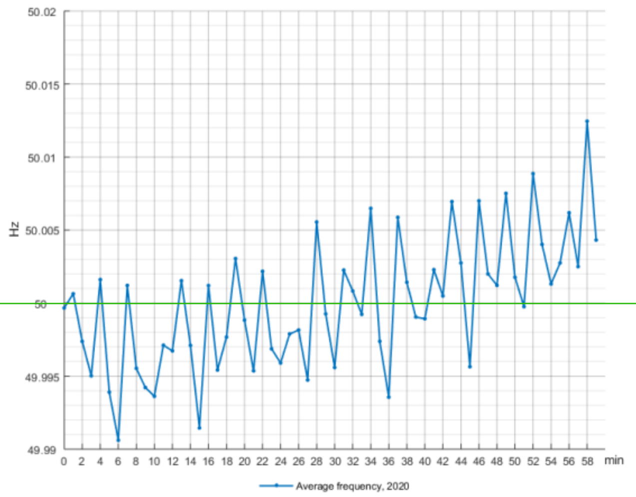


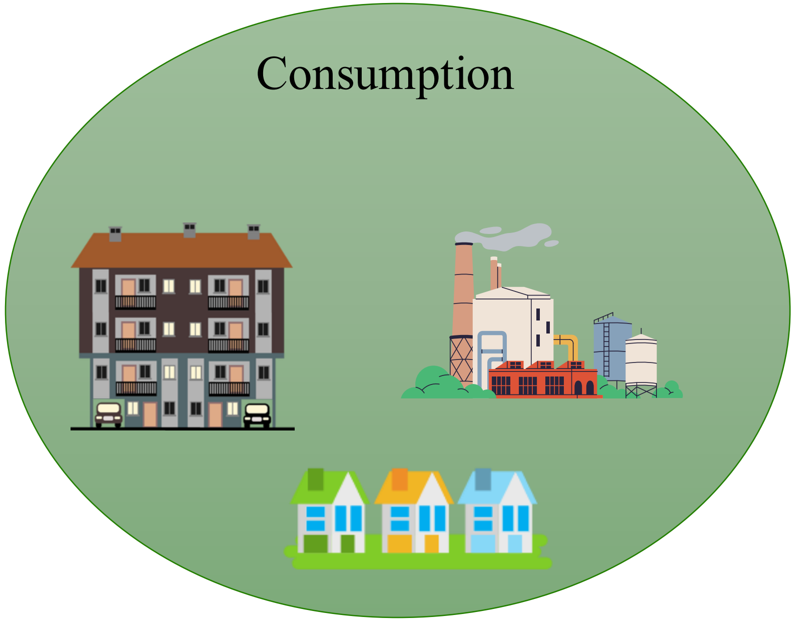
Source: *Reports and Data, "Ancillary Services Power Market – Global Industry Analysis, Trends, and Forecast 2024–2034," Reports and Data, 2024.*

Keep Balance to Preserve the Frequency



Electricity consumption and production must be in balance every moment. When balanced, grid’s frequency is 50.0 Hz.



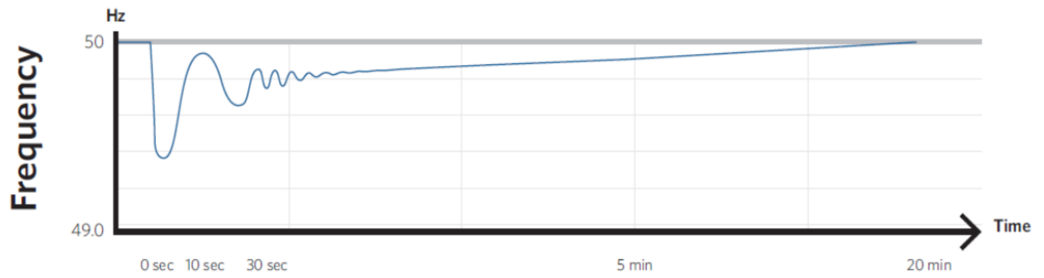


System needs Down regulation to decrease frequency

System needs Up regulation to increase frequency

Frequency Control

Power system frequency mainly depends on three factors:



- The power difference between production and consumption called imbalance
- The stored rotational energy in all synchronously connected machines
- Reserves from power generating units, consumption units and energy storage units

Types of frequency control products

➢ The frequency control reserves in the Nordic power system can be divided into three subgroups:

FFR
Fast Frequency Reserve

- FFR provides very fast power response after activation
- The reserve is utilized in situations with low levels of kinetic energy in the power system in combination with a risk of high imbalance

FCR
Frequency Containment Reserves

FCR-N
Frequency Containment Reserve for Normal Operation

FCR-D
Frequency Containment Reserve for Disturbances

- FCR is to stabilise and maintain the frequency in case of imbalances
- FCR for normal operation (FCR-N) stabilises fluctuations between production and consumption in normal operation
- FCR for disturbances (FCR-D) stabilises large power imbalances that may occur

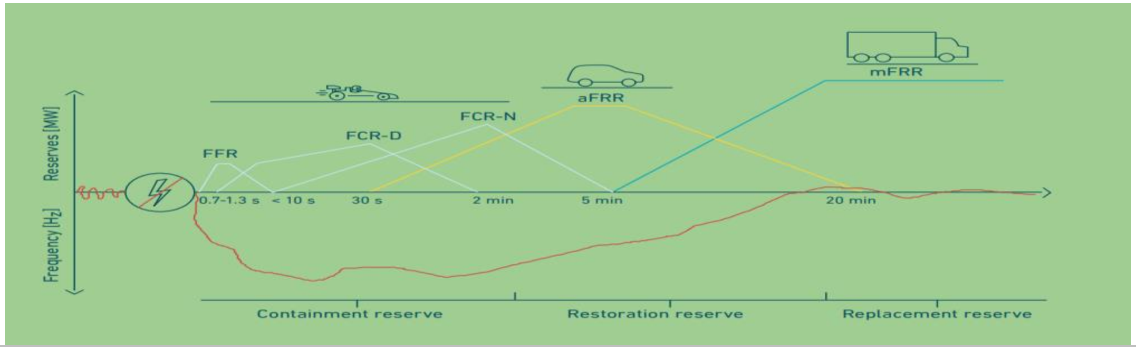
FRR
Frequency Restoration Reserves

aFRR
Automatic Frequency Restoration Reserve

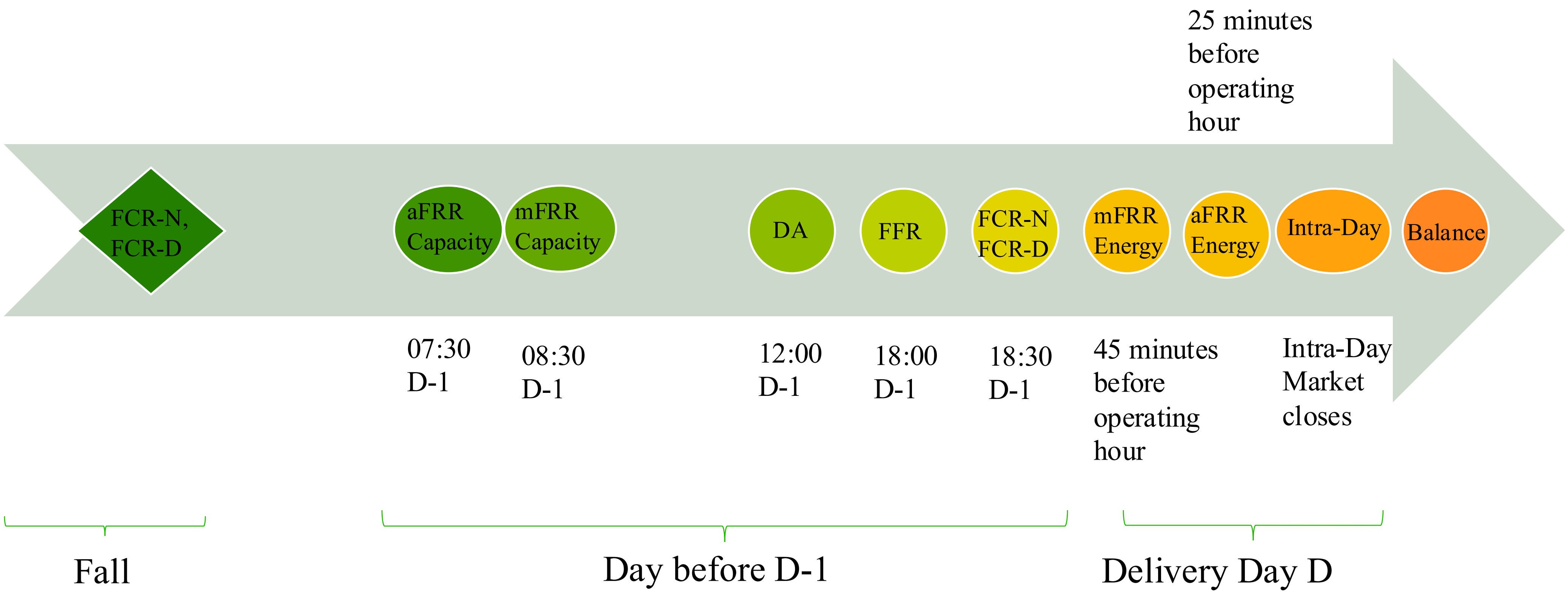
mFRR
Manual Frequency Restoration Reserve

- Relieving FCR and restoring FCR capacity since the frequency deviation will go to zero.
- The FRR is activated based on the integrated frequency deviation.
- FRR is divided into two parts, automatic FRR and manual FRR.

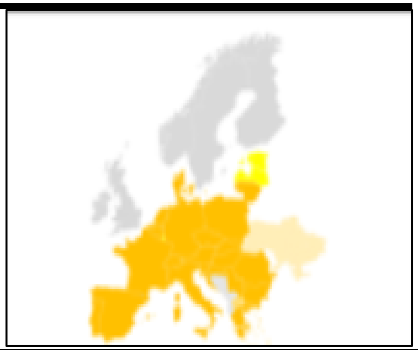
one second — seconds — minutes — 15 minute



Reserve markets' time table

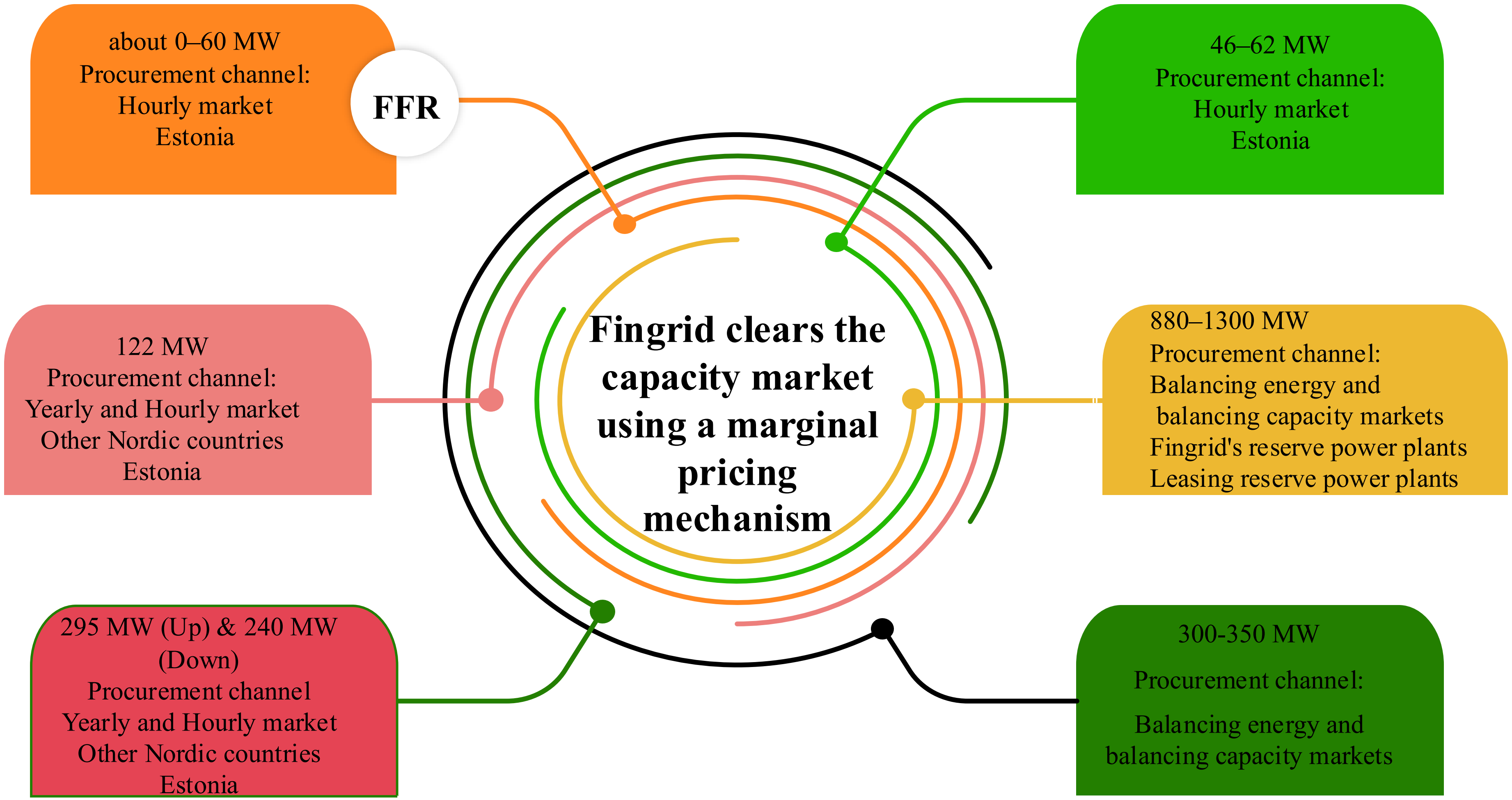


Key Projects in Europe's Ancillary Services Market

	FCR Cooperation	PICASSO	MARI	TERRE	IGCC
Balancing Services	-	aFRR	mFRR	RR	IN
Participants					
Highlights	-	Economic surplus: 170 M€ in 2024	Economic surplus: 11.7 M€ in 2024	Economic surplus: 450 M€ in 2024	Economic surplus: 814 M€ in 2024
Objective	Cost minimisation, cross-border FCR, harmonisation	Imbalance netting, efficiency, reduced activation	aFRR integration, coordination, standardisation	mFRR exchange, interoperability, reliability	RR trading, long-term balancing, market harmonisation

Sources: Mapping Europe's Battery Storage Potential for 2025.
REGlobal. (2025, June 11). "European Ancillary Services Markets: Critical role of FCR and other cross-border balancing platforms

Fingrid's Reserve Obligations and Procurement Sources in 2024

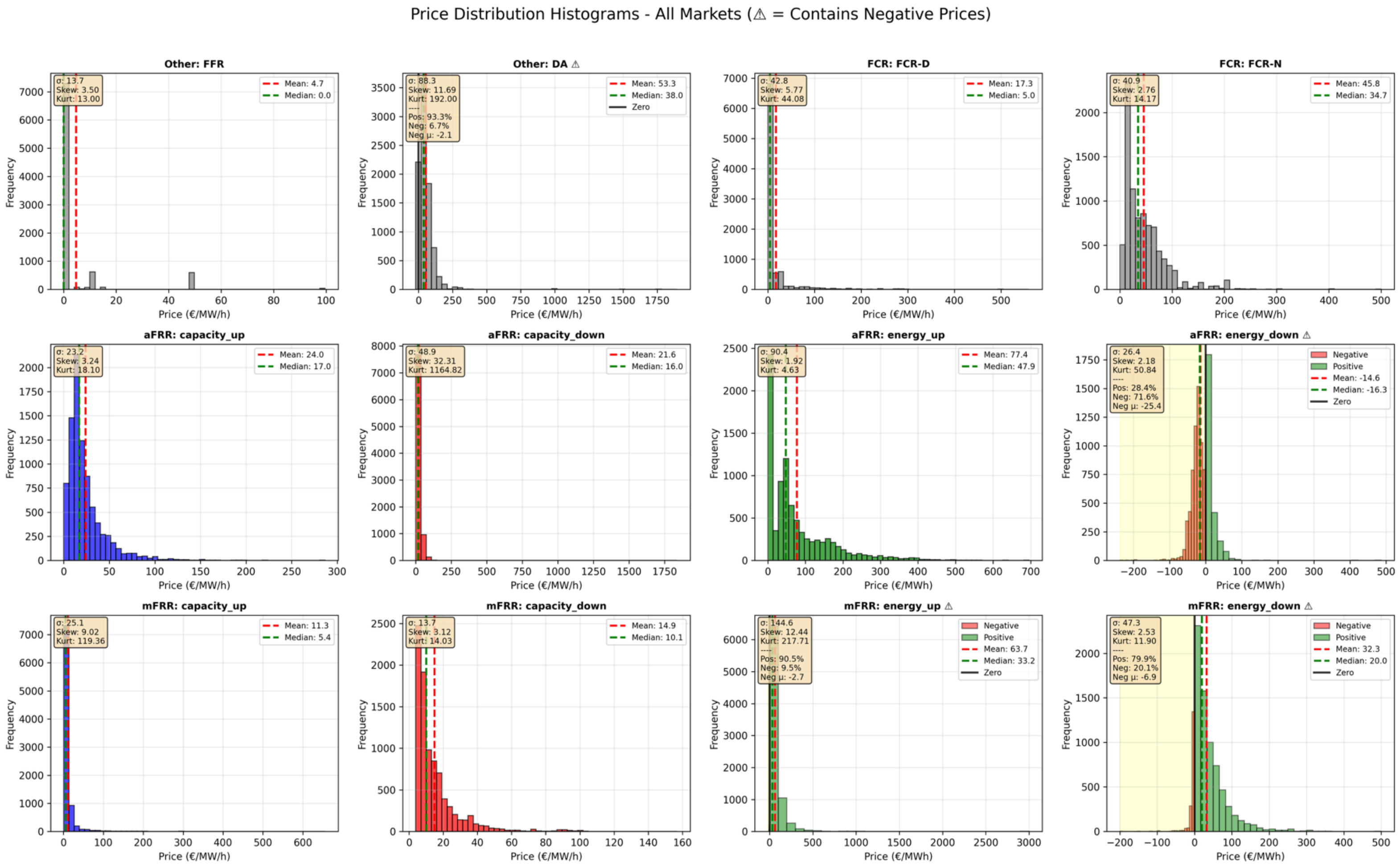


Market Price Distributions in Finland, 2024

Descion Maker?????

Bid Limits

Market	Min	Max
FCR-N	0.1 MW	5 MW
FCR-D	0.1 MW	10 MW
FFR	1 MW	10 MW
aFRR (Capacity)	1 MW	50 MW
aFRR (Energy)	5 MW	-
mFRR (Capacity)	1 MW	50
mFRR (Energy)	1 MW	200



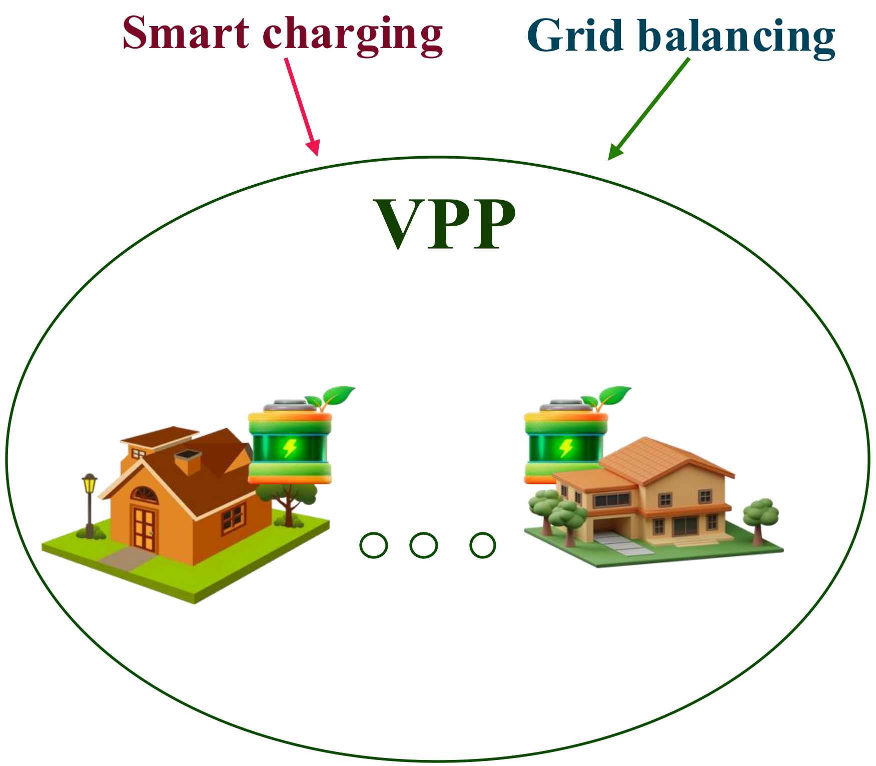
Home Energy Storage Service by Elisa (Finland)

Company & Concept

- Elisa (Telecom → Energy Service Provider)
- “Kotiakku” smart home battery system
- Integrated system: battery + smart control + installation
- Smart charging: low-price hours / solar surplus
- Smart discharging: peak-price hours
- Integration into Virtual Power Plant (VPP)
- Grid balancing & flexibility market participation

Customer Benefits

- 30–50 % bill reduction
- Energy independence & resilience
- Support for clean-energy transition



Source: Elisa Corporation (2025) – Press Release

Multi-market bidding key stages

1. Forecasting
   - Price
   - Renewable Energy Generation
   - Demand Forecasting
   - Ancillary Services Needs
2. Optimization
   - Revenue Maximization
   - Resource Allocation
   - Technical Constraints
   - Simultaneous Participation
3. Market Bidding
   - Bid Preparation
   - Submission
4. Real-Time Operation and Adjustments
   - Monitoring Market Results
   - Intraday Adjustments
   - Balancing Actions

Optimization Framework for Energy Storage in Ancillary and Energy Markets

Revenue Components

Revenue from individual ancillary services:

- FFR capacity revenue calculation
- FCR-N revenue (capacity + activation)
- FCR-D capacity revenue
- mFRR revenue and aFRR capacity revenue

Energy market revenue:

- Day-ahead market
- mFRR and aFRR Energy payments

Cost Components

System operation and market participation costs:

- Day-ahead purchase costs
- Operational costs
- Down regulation activation costs

Objective Function:

Max $\sum$ Revenue Components - $\sum$ Cost Components

Multi-Market Optimization Model: Key Constraints

Constraints

- Power balance constraints: Ensures total generation + imports = load + exports + charging demand
- Operational limits: Boundaries on SoC, charge/discharge rates, and efficiency.
- Market-specific limits: Capacity offers per market (FFR, FCR, aFRR).
- Activation Constraints: Link capacity offers with available energy and market activation ratios.
- Coupled capacity limits: Shared BESS capacity across markets.
- Degradation constraints (Calendar and Cycle life)
- Market rule constraints:
- **FCR-N** — symmetric up/down capacity required
- **FFR** — up-regulation only
- **aFRR and mFRR** — separate capacity and energy markets.

Source: Aghamohammadloo, H., Mohammadi-Ivatloo, B., Safdarian, A., Tikka, V., Aghaei, J., & Mendes, G. P. P. (2026). *Multi-market revenue optimization for integrated wind and hybrid energy storage systems. Applied Energy, 402,* 126773. https://doi.org/10.1016/j.apenergy.2025.126773

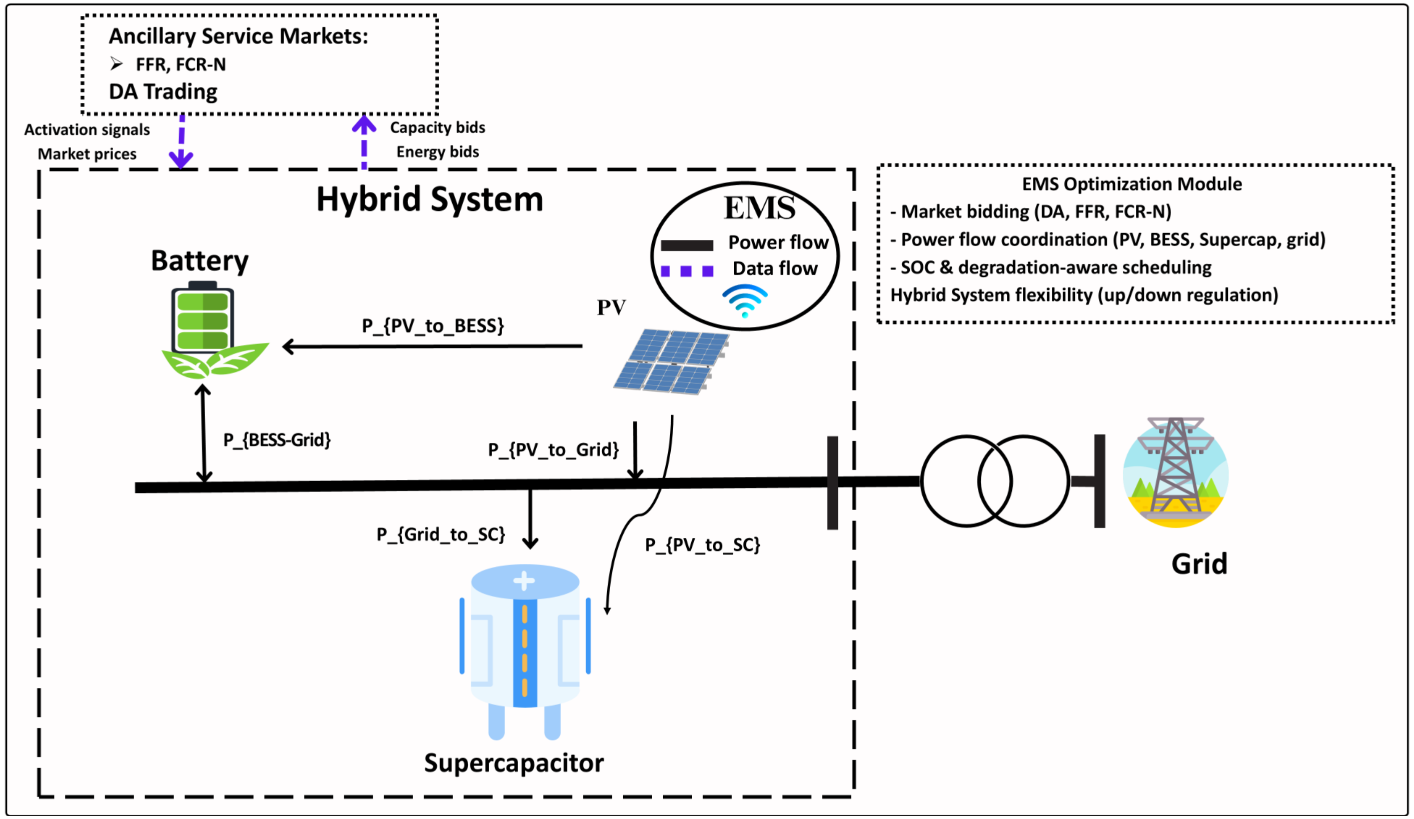
Case Study: PV-Integrated Hybrid Energy Storage System (HESS) in Finland

System Components:

- Photovoltaic (PV) system: 3 MW capacity
- ancillary services
- Battery Energy Storage System: 4 MWh
- Supercapacitor: 15 kWh

Why HESS → Battey + SC?

SC: fast response, FFR support → reduces battery cycling, extends lifetime

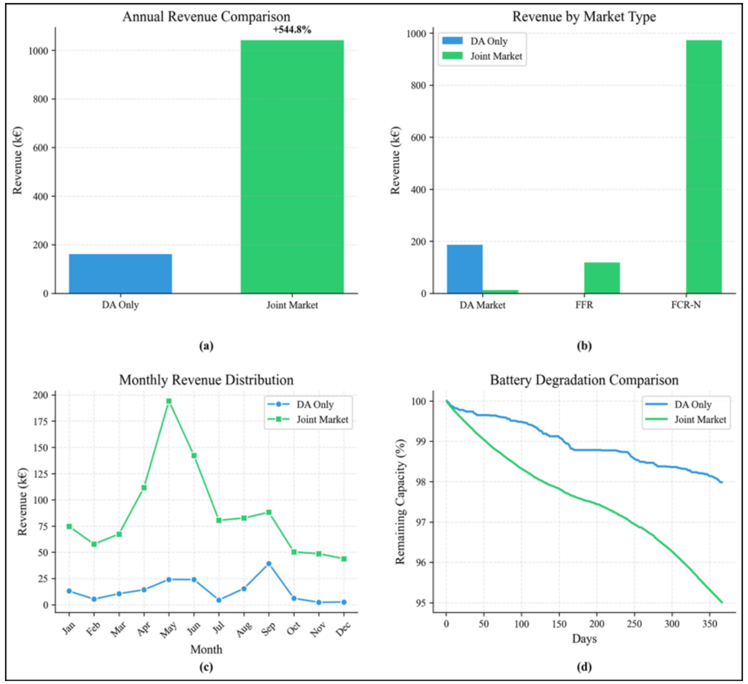


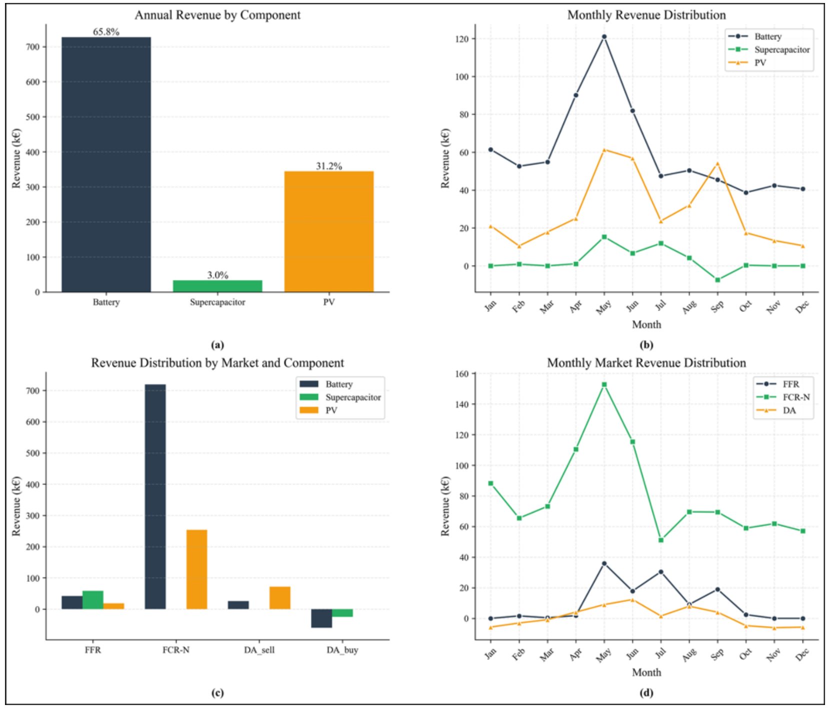
Objective:

Evaluate the multi-market participation of a PV-integrated hybrid system in DA, FFR, and Frequency FCR-N markets

Simulation Results

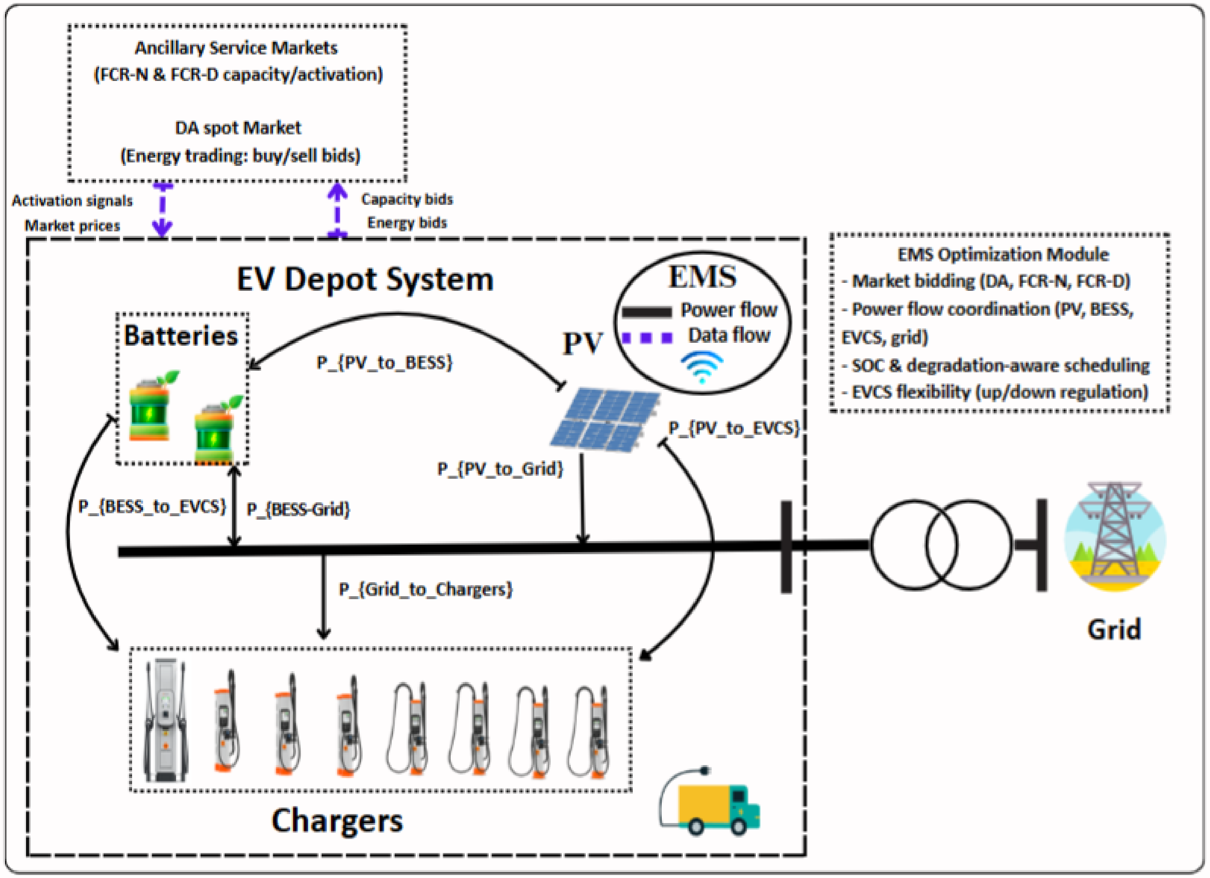
- Joint participation in energy and frequency regulation markets increases annual revenue by 544.8%
- Significant revenue peak in May due to higher solar radiation and increased PV production
- High renewable generation in May leads a greater need for FFR and FCR-N services to maintain frequency stability.
- The BES degradation is 3% higher in the joint market scenario compared to the DA-only case but the higher revenues compensate.
- Battery dominates monthly revenue
- PV contribution rises during summer



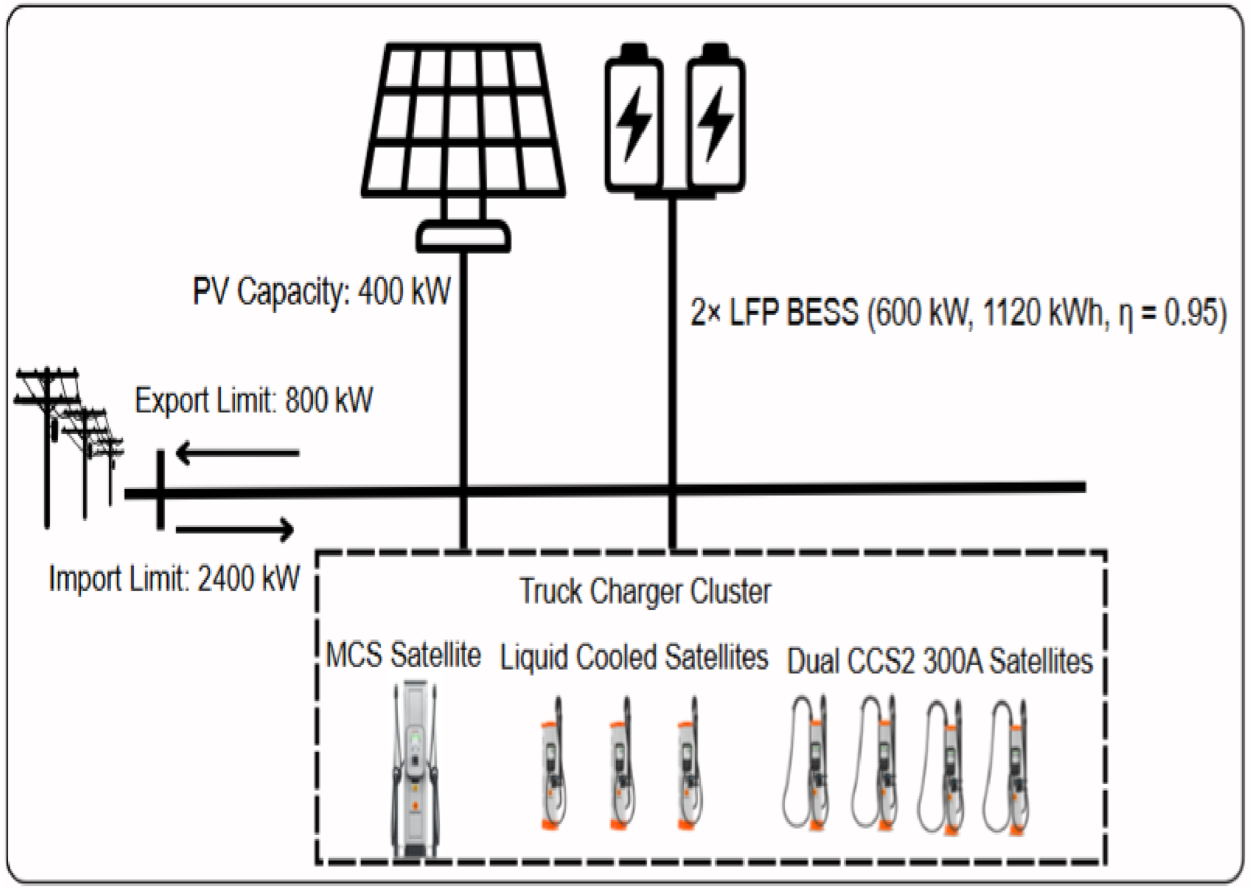


Case Study: Real-World Heavy-Duty EV Charging Depot (SE3 Zone, Sweden)

System overview and market interactions.

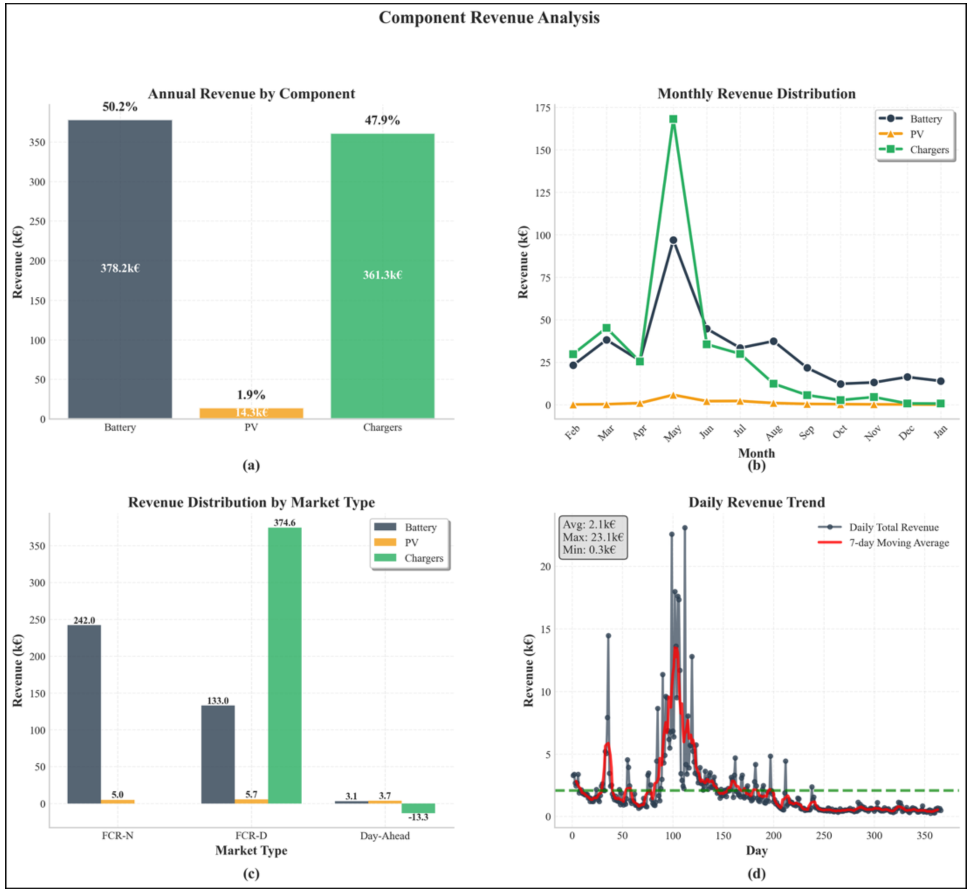


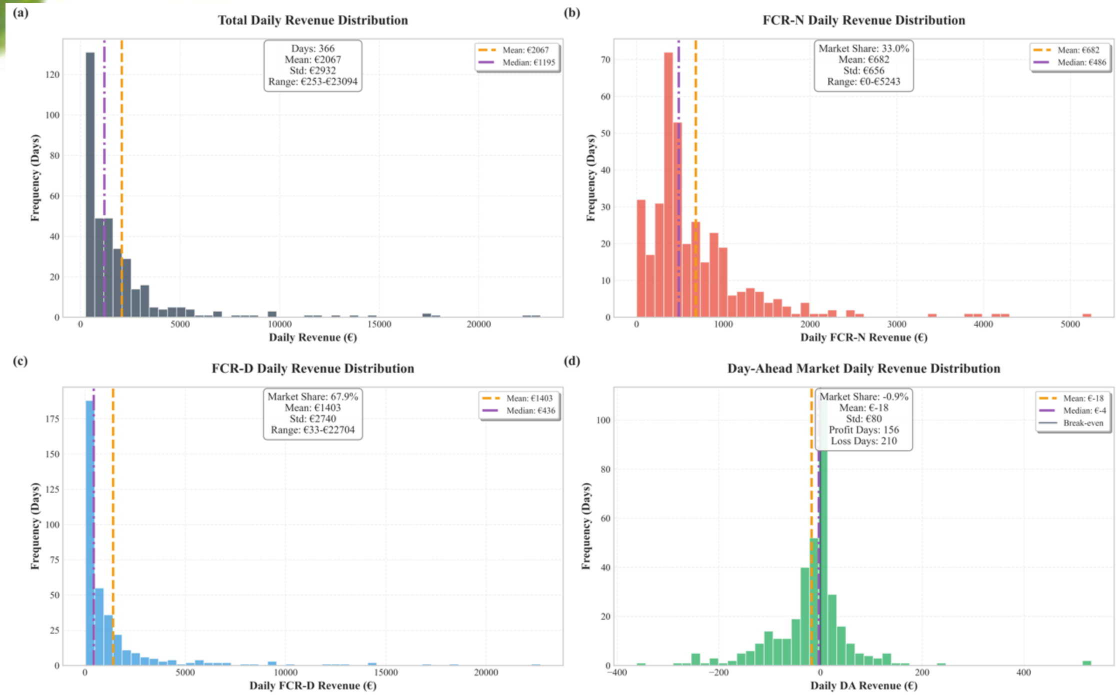
Physical configuration and technical specifications.



Simulation Results

With Fleet-Enabled Down-Regulation



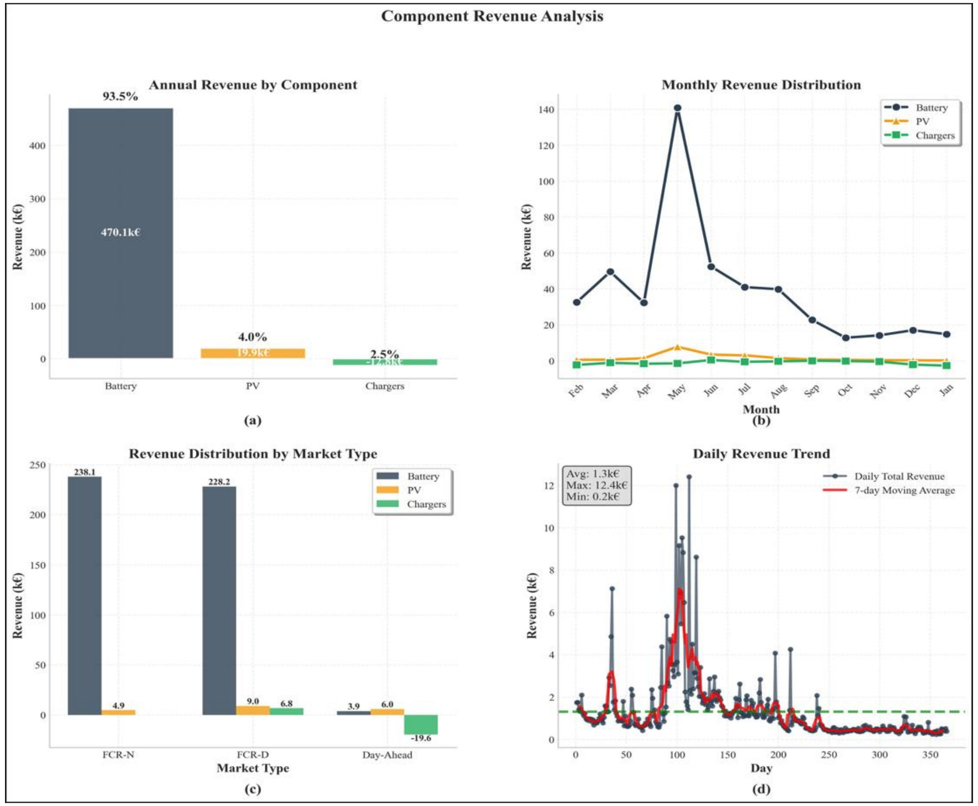


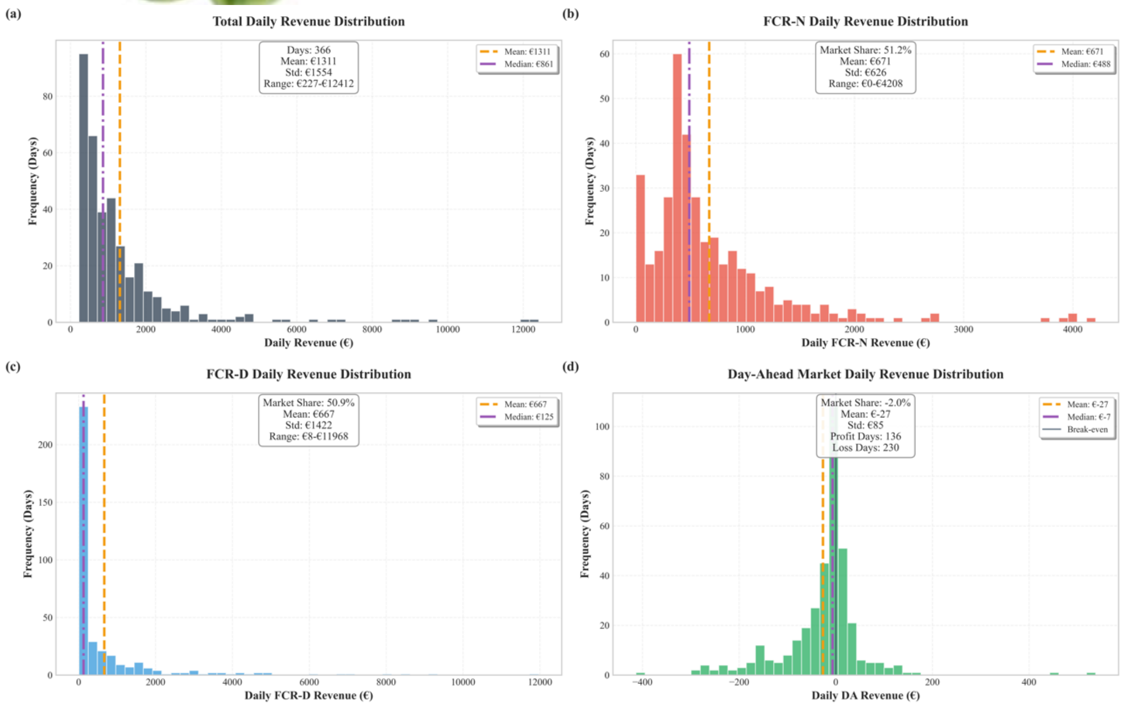
Key Findings

- **Total annual revenue:** ≈ €750 k — dominated by **FCR-D (≈ 68%)**, followed by **FCR-N (≈ 33%)**.
- **Chargers:** Major contributor through **fleet-enabled down-regulation** in the **FCR-D market**.
- **Component shares: Battery 50%**, **Chargers 48%**, **PV < 2%**.
- **Market behavior: FCR-D** ensures stable high revenue; **FCR-N** shows moderate volatility; **DA** market yields near break-even or negative results.

Simulation Results

Without Fleet-Enabled Down-Regulation





Key Findings

- **Total annual revenue:** ≈ €503 k — lower compared to the fleet-enabled **case.**
- **Battery-dominated income:** 93.5% of total revenue; limited charger participation.
- **Market split:** FCR-N (51%) and FCR-D (49%); no meaningful DA market contribution.
- **Lack of down-regulation support:** Chargers underutilized → reduced system flexibility and total earnings.

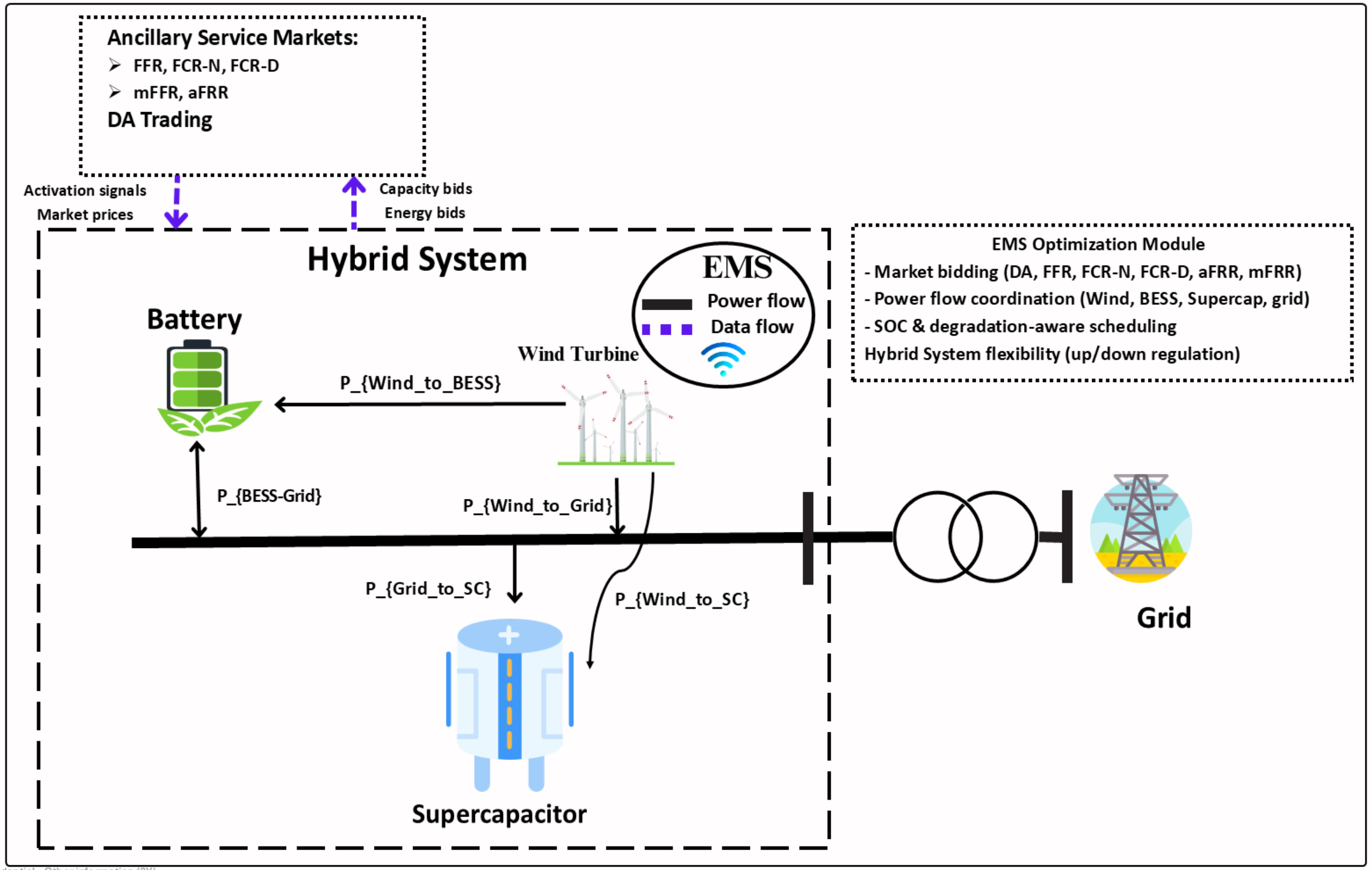
Case Study: Wind-HESS Multi-Market Participation in Finland

System configuration:

- Wind power: 5 MW
- BESS: 6 MWh
- Supercapacitor: 4 kWh

Objective:

Maximize annual revenue while respecting technical and market constraints.



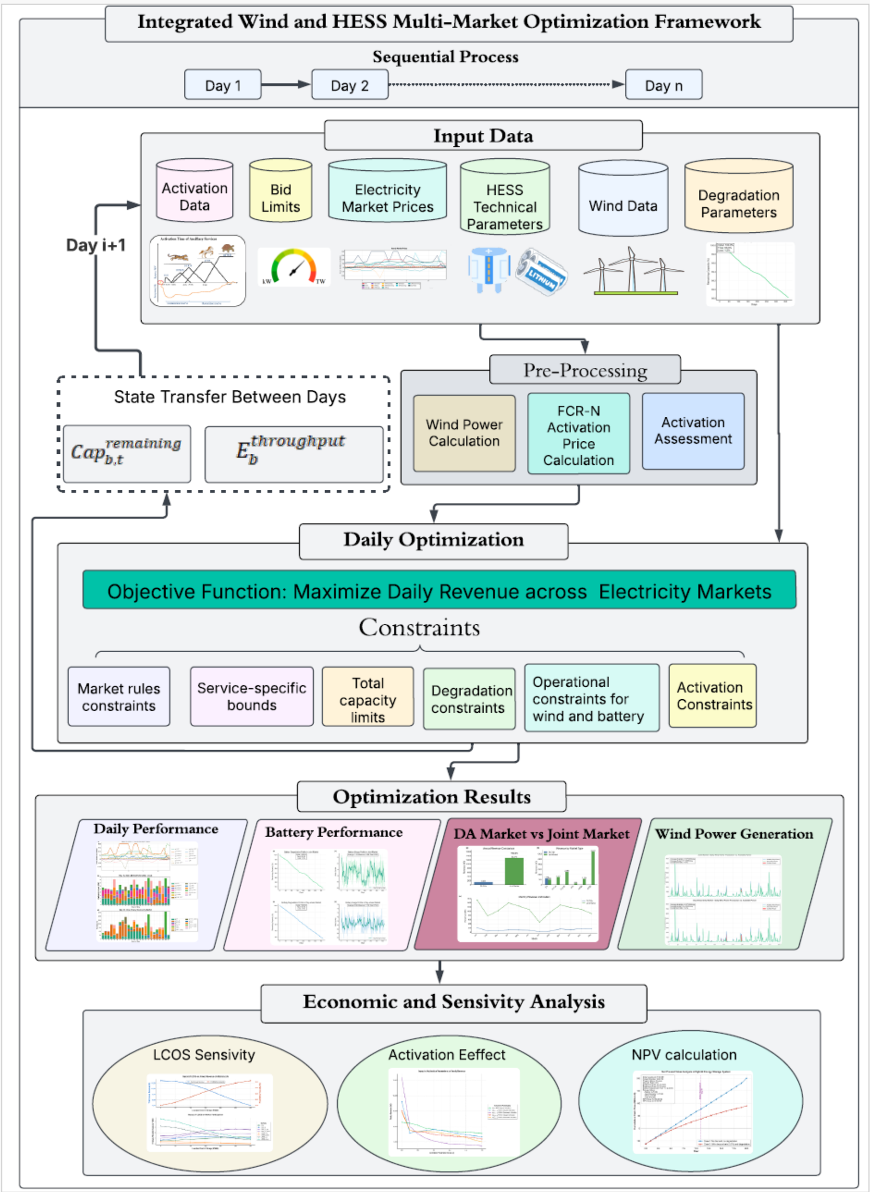
nfidential - Other information (3Y)

Source: Aghamohammadloo, H., Mohammadi-Ivatloo, B., Safdarian, A., Tikka, V., Aghaei, J., & Mendes, G. P. P. (2026). *Multi-market revenue optimization for integrated wind and hybrid energy storage systems. Applied Energy, 402,* 126773. https://doi.org/10.1016/j.apenergy.2025.126773

Contribution and Methodology

- MILP optimization across DA + multiple ancillary services
- Hybrid flexibility model: BES (energy) + SC (power)
- Explicit battery degradation cost in objective

- Sequential day-by-day optimization
- Inputs: market prices, activation data, wind forecast, HESS specs
- Objective: maximize revenues – DA costs – degradation costs
- Outputs: optimal schedules, revenues



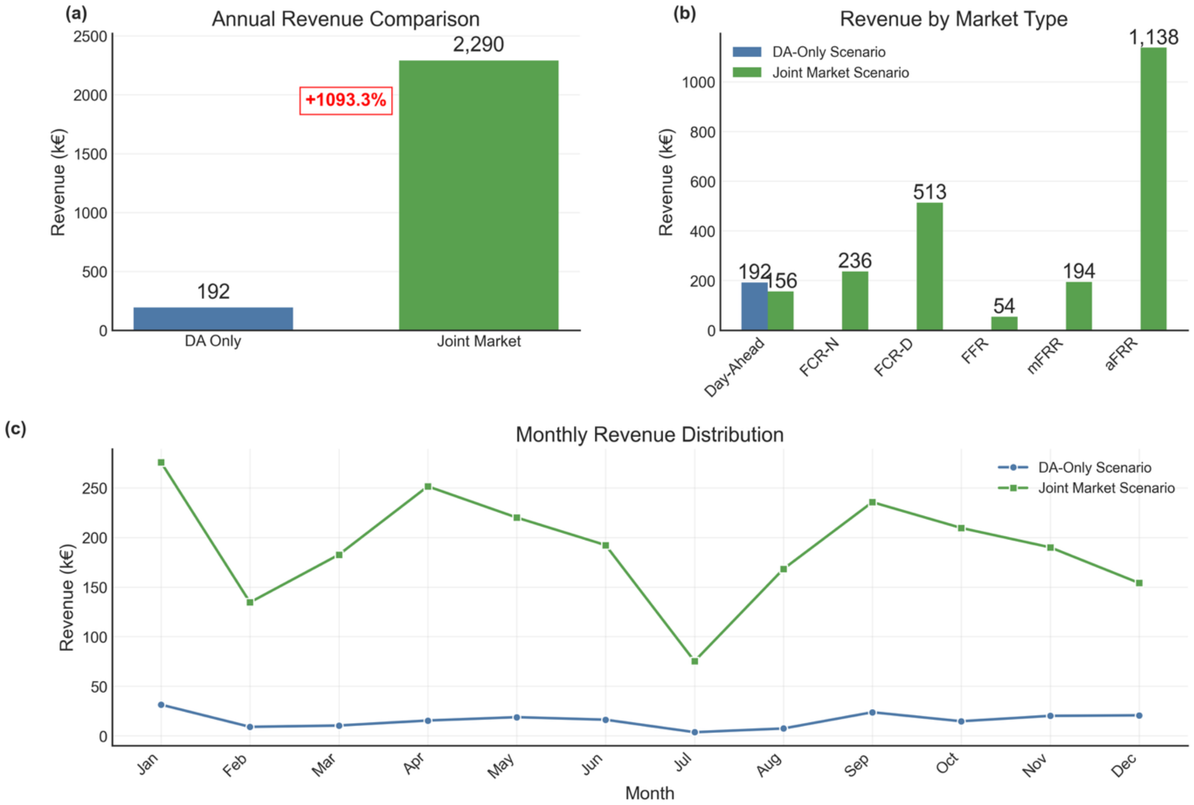
Economic Performance of Multi-Market Participation

Joint market = +1093% revenue vs DA-only

aFRR largest share

DA-only = flat & low

Joint market = fluctuates, higher in winter months



Key Insights from Optimization Results

Revenue potential is high but reported results represent an upper bound:

- Price-taker assumption (no price impact).
- Perfect foresight of prices, activations, and wind.
- Market saturation risk (limited ancillary capacity).
- Frequency regulation dominates → higher value than DA arbitrage.
- Multi-market participation outperforms single-market strategies.

Conclusion

- Flexibility is the cornerstone of a renewable-dominated European power system.
- Energy storage systems provide fast, accurate, and reliable balancing across multiple timescales.
- Multi-market participation significantly enhances both system reliability and economic returns.
- Optimization-based modeling enables realistic evaluation of technical constraints (SoC, efficiency, degradation, non-simultaneous up/down activation).
- Coordinated market design and appropriate remuneration mechanisms are essential to unlock full flexibility potential.

Future work: extend modeling to long-duration storage, uncertainty-aware optimization, and aggregated distributed flexibility (e.g., EVs, residential batteries).

LAND OF THE CURIOUS

Thank you

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