ETH zürich

Automatic Control Laboratory

A Coalitional Stable and Fair Reward Allocation for Dynamic Virtual Power Plants

Carl von Holly-Ponientzietz

Master Thesis Presentation

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Prof. Dr. Florian Dörfler

30.04.2026

Outline

1. Introduction
2. Dynamic Ancillary Services
3. Dynamic Virtual Power Plant Control Design
4. Problem Statement and Results
5. Case Study

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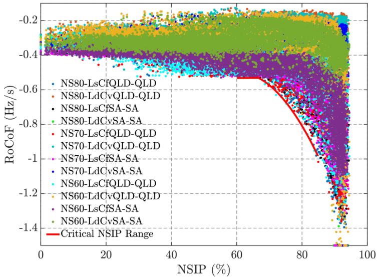
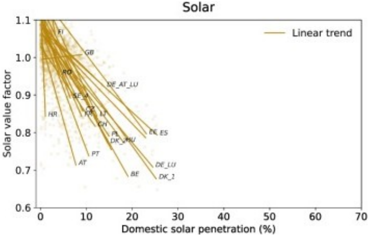
   1. Low inertia of power system
   2. Decreasing market value of renewables





From Ahmadyar et al. 2018 and Hirth 2013

Introduction

- Energy transition towards renewable, distributed energy resources (DERs)
- We tackle two challenges of the transition:
    1. Low inertia of power system
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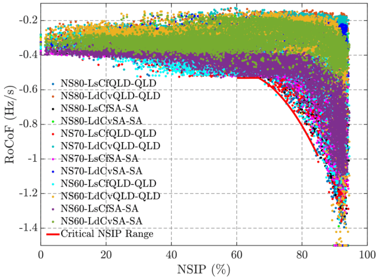
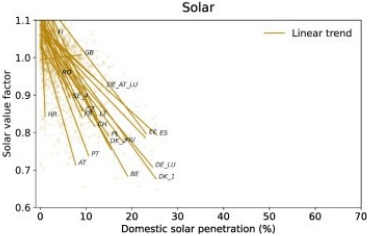
- *Proposed solution:* Enable DERs' cooperative provision of Dynamic Ancillary Services (DAS)





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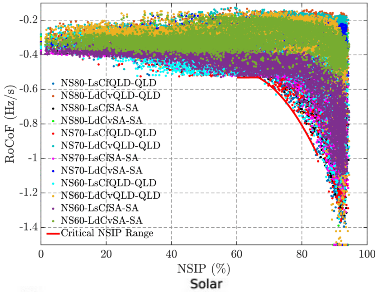
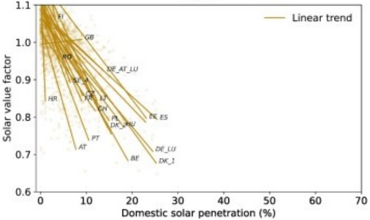
★ *Proposed solution:* Enable DERs' cooperative provision of Dynamic Ancillary Services (DAS)

- Requirements:
   - Technical feasibility *(a collection of DERs is able to provide the DAS)*
   - Economic & Cooperative feasibility *(collective DAS provision is beneficial for every DER)*





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Dynamic Ancillary Service (DAS)

- Characteristics of DAS: *fast* ancillary services
  - e.g., Fast Frequency Reserve (FFR), Frequency Containment Reserve for Disturbances (FCR-D), voltage control
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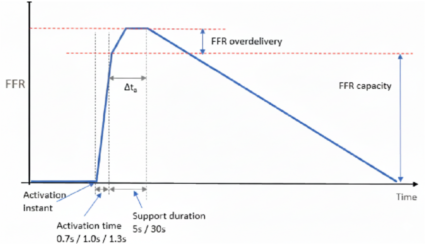

Fingrid's FFR requirements

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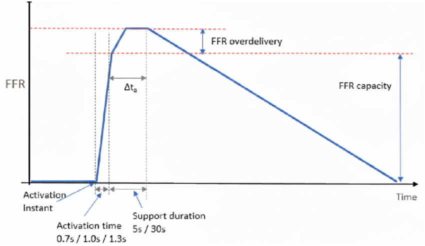
- Countries: Ireland, GB, Nordics, Australia, ...
- ✖ Individual DERs often ineffective in providing DAS
  - ★ But: Specific aggregation of DERs named *Dynamic Virtual Power Plant (DVPP)* can provide DAS [Häberle et al. 2022]



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Goal: provide DAS with a set of DERs, $i \in \mathcal{D}$.

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- Use DER-specific *Adaptive Dynamic Participation Factor (ADPF)* $m_i(s)$ to encode each DERs role in DVPP.

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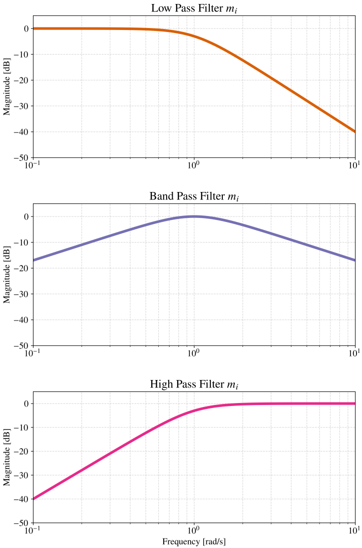

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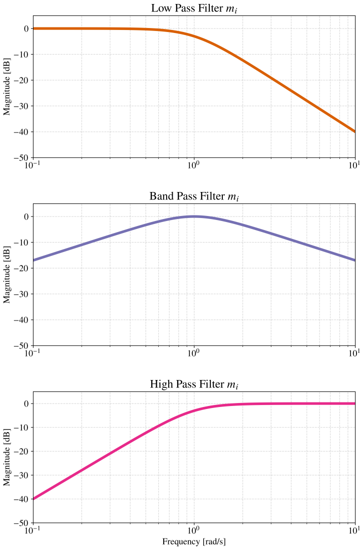
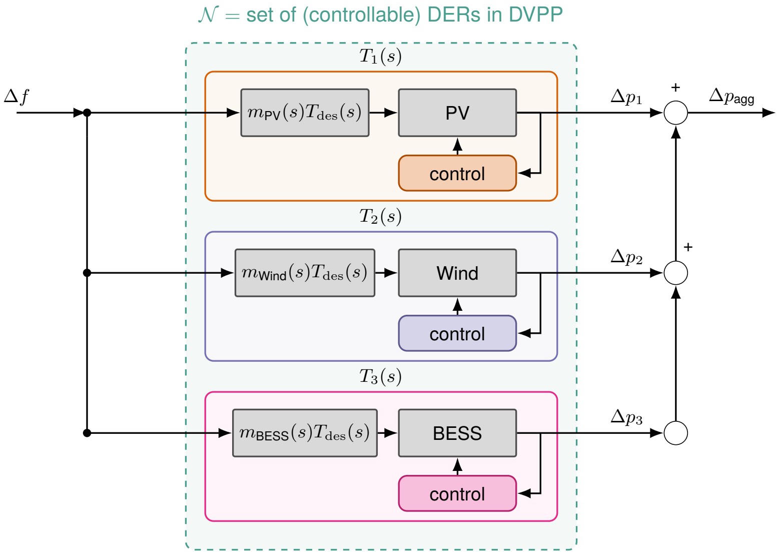
- ADPF roles: Low-pass-, Band-pass- and High-pass filters
- Important: match desired transfer function:

$$\sum_{i \in \mathcal{D}} m_i(s) \overset{!}{=} 1.$$



DVPP Control Design in Action



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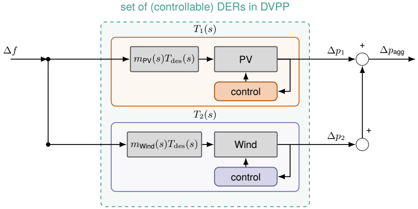
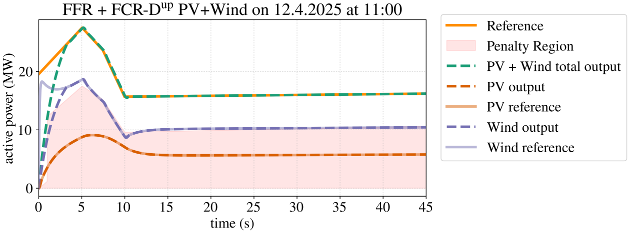


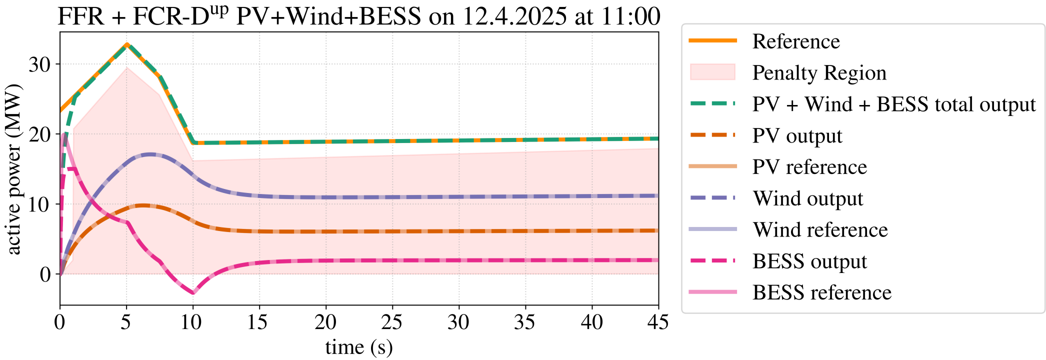
DVPP control scheme for $\mathcal{D} = \{\text{PV, Wind}\}$.



Performance of $\mathcal{D} = \{\text{PV, Wind}\}$. Reward: 632€ . Wind cannot cover HPF role satisfactory.

Technical feasibility: not efficient & only with correct forecast

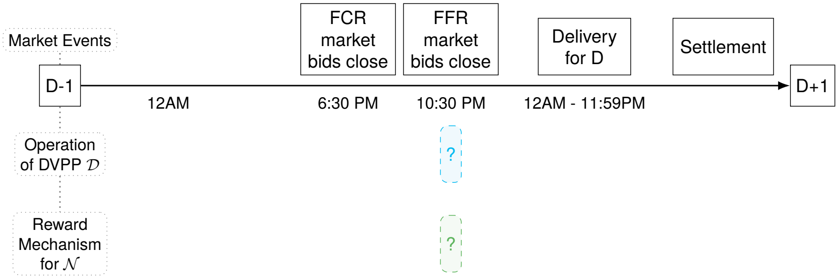
DVPP Control Design Simulation



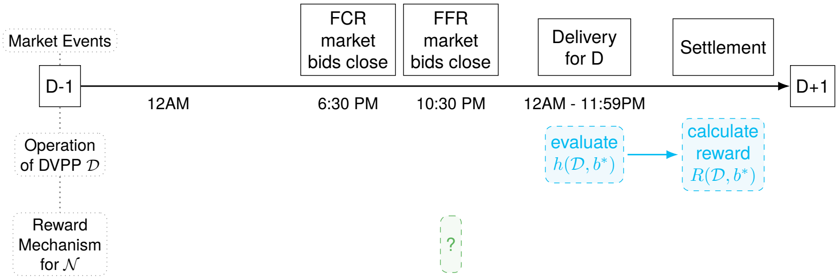
Performance of the (grand coalition) DVPP $\mathcal{D} = \mathcal{N}$. Reward: 939€ .
Technical feasibility: Yes, through the sufficient heterogeneity of DERs ✓

Outline

Timeline: Outline



Timeline: Realized Reward



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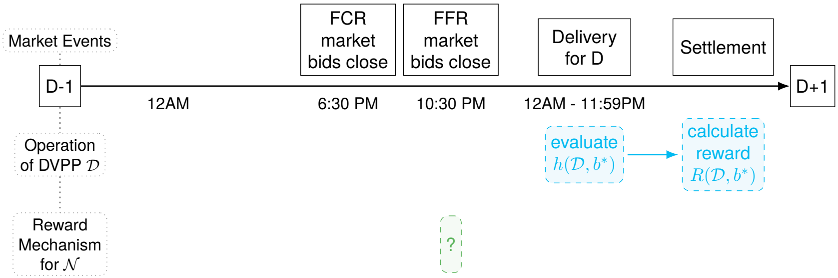


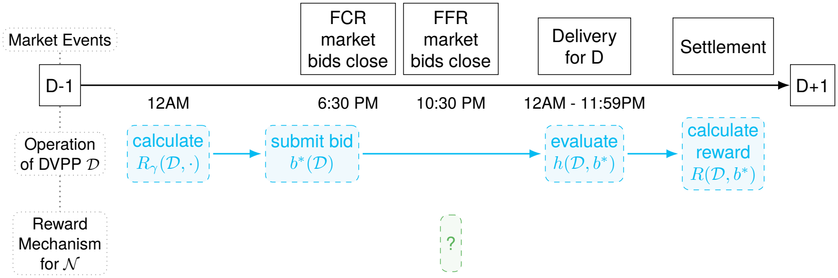
given bid b, service price π and penalty price q. The *Realized Reward:*

$$R(\mathcal{D}, b) = \begin{cases} \pi \cdot b(\mathcal{D}), & \text{if } h(\mathcal{D}, b) = \text{pass} \\ -q \cdot b(\mathcal{D}) & \text{if } h(\mathcal{D}, b) = \text{fail} \end{cases}$$

where $h(\mathcal{D}, b)$ evaluates $\mathcal{D}$'s capability:

$$h(\mathcal{D}, b) \xrightarrow{\text{simulate bid activation}} \{\text{fail, pass}\}$$

Solution Step 1: Quantify R_γ and b^*



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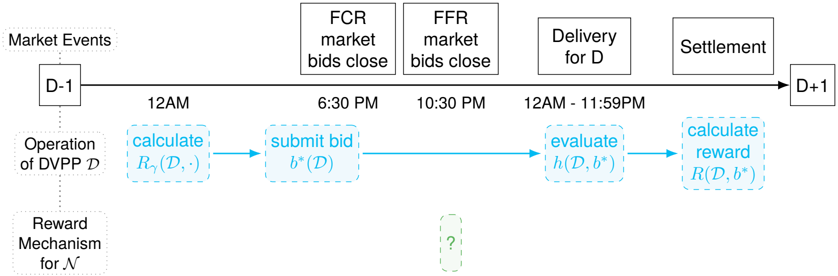

forecasted "pass" probability $\gamma_{\mathcal{D}}(b)$ & Probabilistic Reward $R_\gamma(\mathcal{D}, b)$:

$$R_\gamma(\mathcal{D}, b) = b(\mathcal{D}) \cdot [\pi \gamma_{\mathcal{D}}(b) - q(1 - \gamma_{\mathcal{D}}(b))],$$

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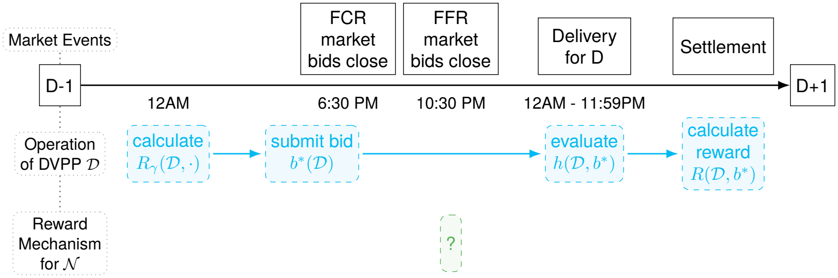

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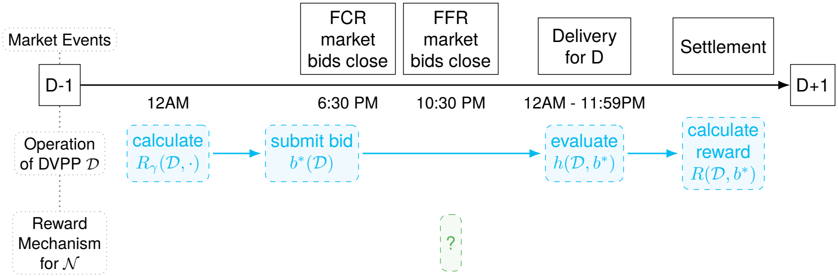
optimal bid $b^*(\mathcal{D})$:

$$b^*(\mathcal{D}) \leftarrow \arg\max_b R_\gamma(\mathcal{D},b)$$

Solution Step 2: Simulate Subcoalitions



How much is each set of DERs (coalitions) worth?

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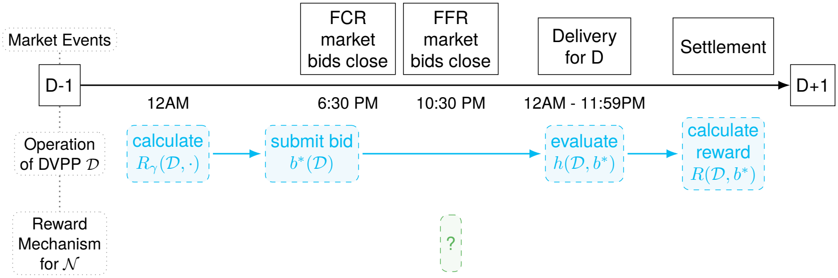

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Simulate all possible coalitions $\mathcal{S} \subseteq \mathcal{N}$:

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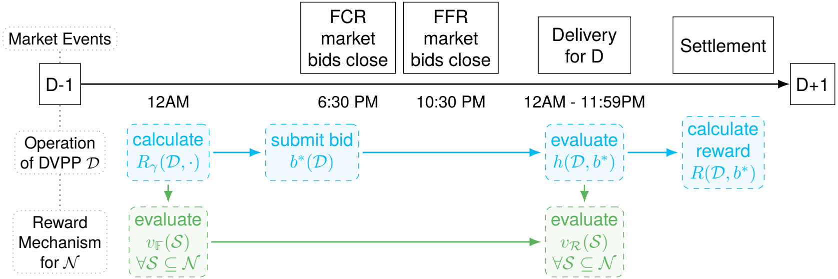

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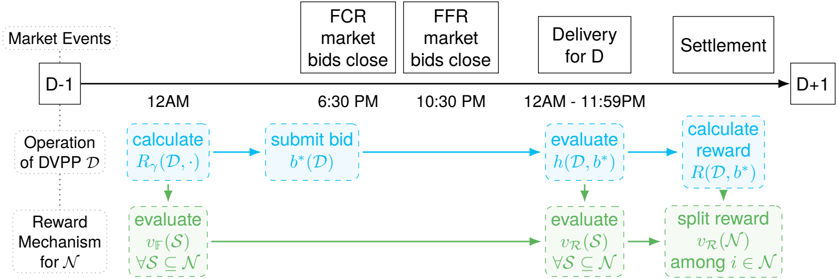
Simulate all possible coalitions $\mathcal{S} \subseteq \mathcal{N}$:

Forecasted Value $v_{\mathbb{F}}(\mathcal{S}) = \sum_{\mathcal{D} \in P^*(\mathcal{S})} R_\gamma(\mathcal{D}, b^*(\mathcal{D})$

Realized Value $v_{\mathcal{R}}(\mathcal{S}) = \sum_{\mathcal{D} \in P^*(\mathcal{S})} R(\mathcal{D}, b^*(\mathcal{D}))$

operating as optimal partitions $\mathcal{D} \in P^*(\mathcal{S})$

Solution Step 3: Allocate Reward



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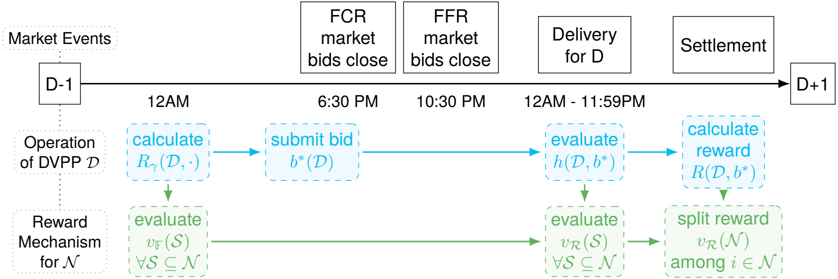
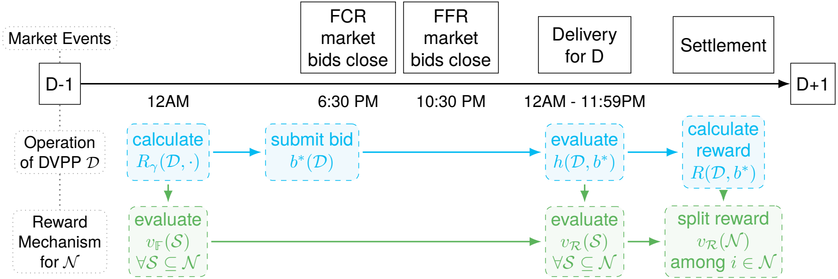


Need suitable Reward Allocation

$$A^*(\mathcal{N}) : v_{\mathcal{R}}(\mathcal{N}) \rightarrow [x_i]_{i \in \mathcal{N}}$$

to ensure cooperation. What criteria?

Solution Step 3.1: Cooperation Criteria



Establish criteria **C1-C5** for cooperation of DERs:

C1 **Rationality & Coalitional Stability**

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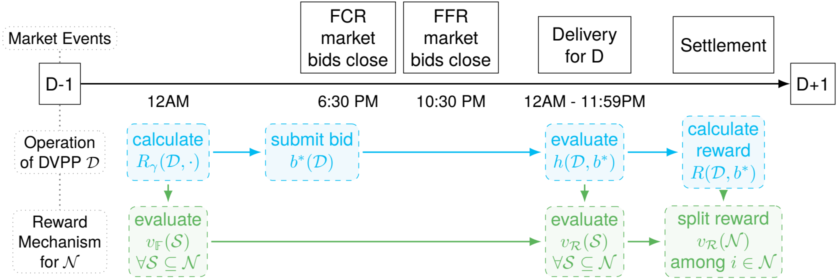

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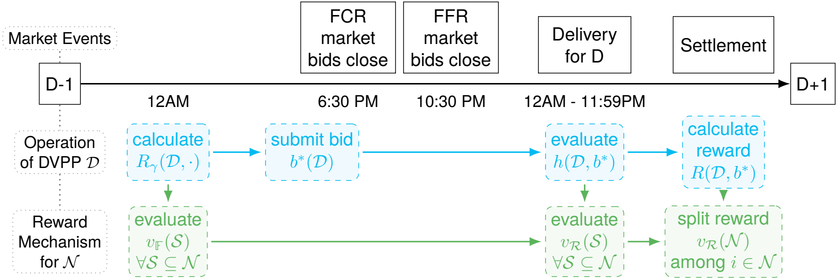

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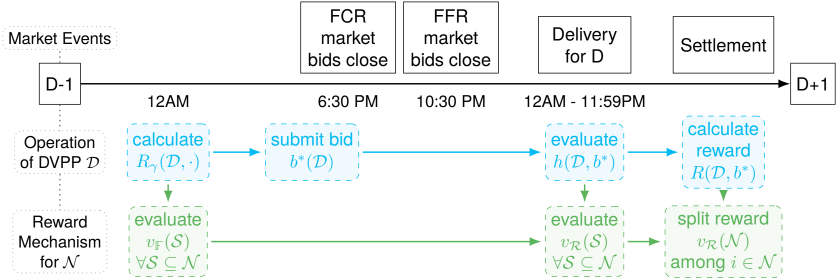

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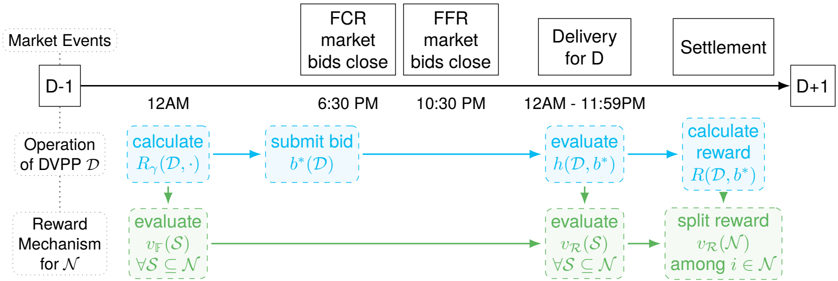

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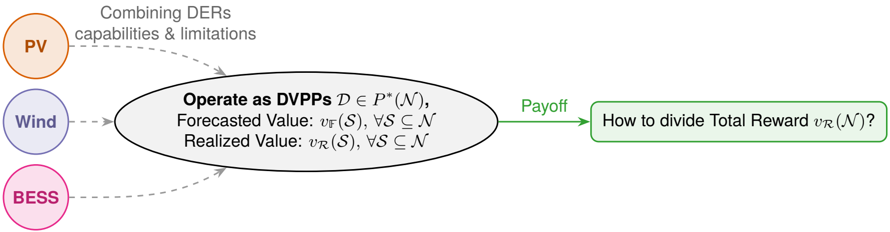
Solution Step 3.2: Reward Allocations Comparison



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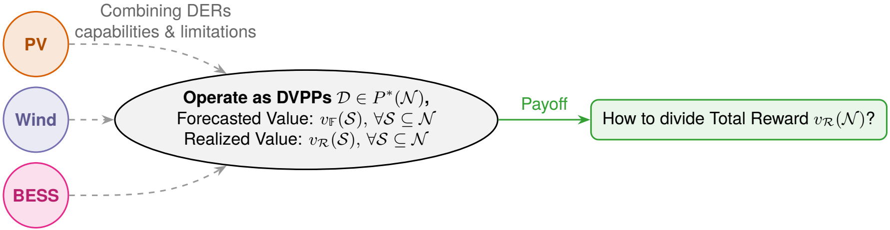
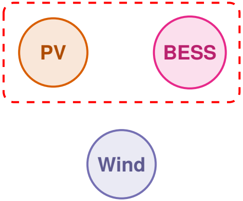


The Nucleolus $\mathbf{nc}(v)$ [Schmeidler 1969]

Threaten to leave DVPP!



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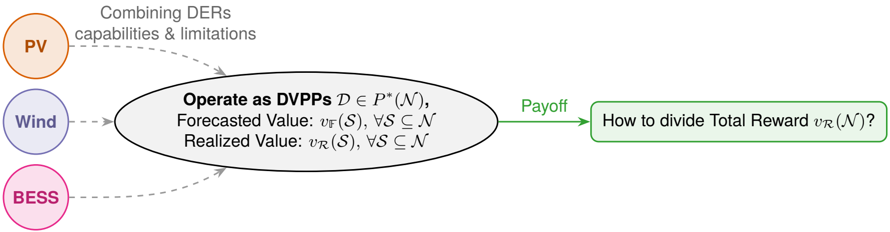

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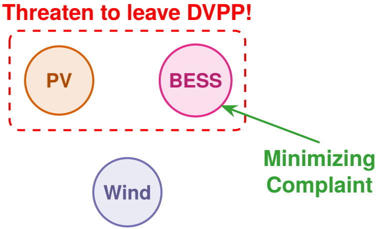

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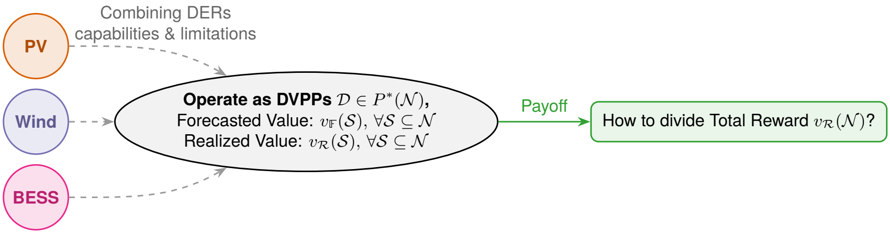

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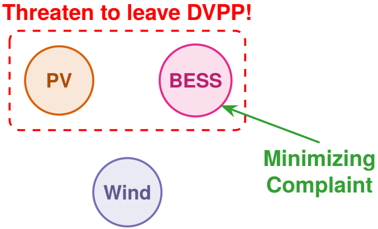
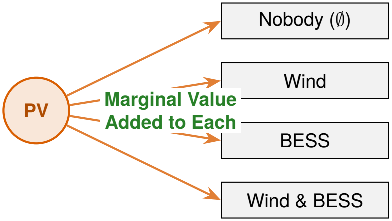


The Shapley Value $\phi(v)$ [Shapley 1951]



Solution Step 3.3: Suitable Reward Allocations $A^*(\mathcal{N}) : v_\mathcal{R}(\mathcal{N}) \to [x_i]_{i\in\mathcal{N}}$

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- Minimizes the maximum dissatisfaction over all coalitions
- Fulfills **C1-C3**

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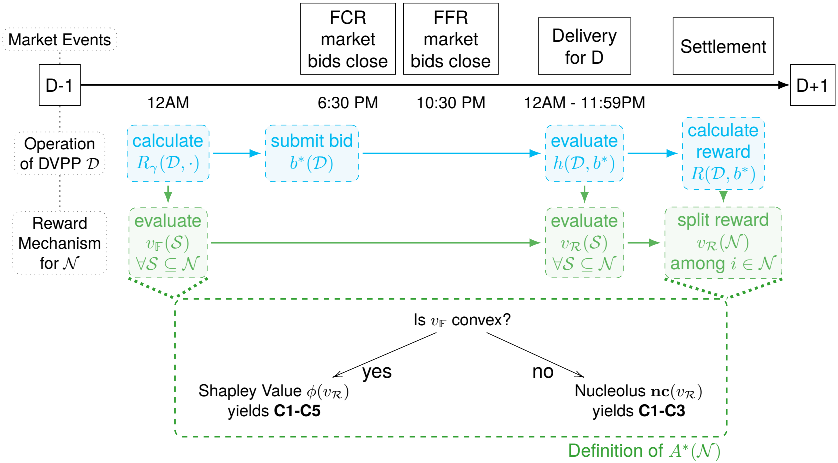
- Minimizes the maximum dissatisfaction over all coalitions
- Fulfills **C1-C3**

The Shapley Value $\phi(v)$ [Shapley 1951]

- Pay DERs based on their marginal contribution.
- If $v_{\mathbb{F}}$ is *convex*[a]: Fulfills **C1-C5**

[a] Increasing marginal contributions, like *positive network effect*

Proposed Solution Timeline

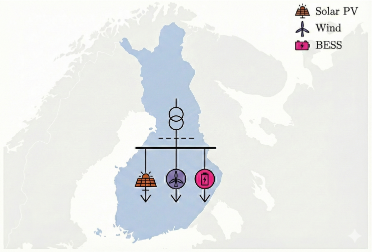


Outline

Case Study Setup: Finnish DAS Market

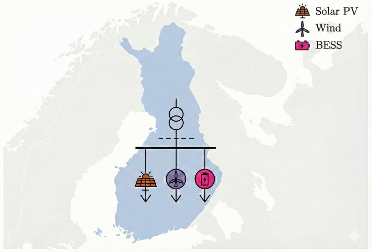
1. DERs

Wind Power Plant: 21.6 MW
Solar PV Power Plant: 15 MW
BESS: 15 MW / 5 MWh

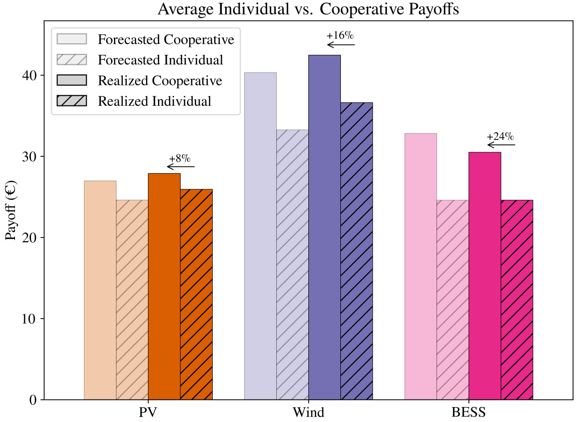


Case Study Setup: Finnish DAS Market

1. **DERs**
   Wind Power Plant: 21.6 MW
   Solar PV Power Plant: 15 MW
   BESS: 15 MW / 5 MWh
2. **Market Service & Obligation**
   - Time Period: 06.04.2025 - 12.04.2025
   - Bid Submission: 50% FFR and 50% FCR-D up (hourly procurement)
   - Activation Signal: $\Delta f = -0.4$ Hz
   - Penalty: $q = 3\pi$



Reward Allocation Comparison



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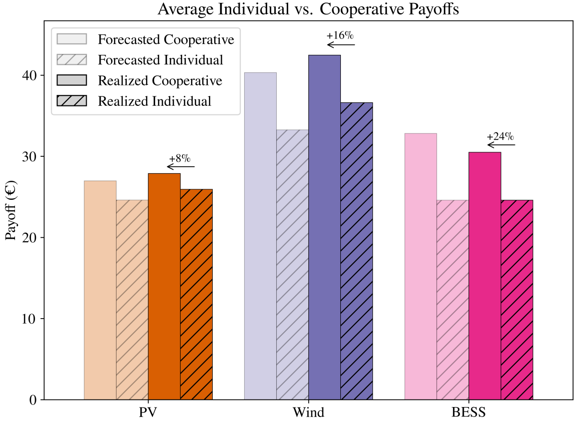

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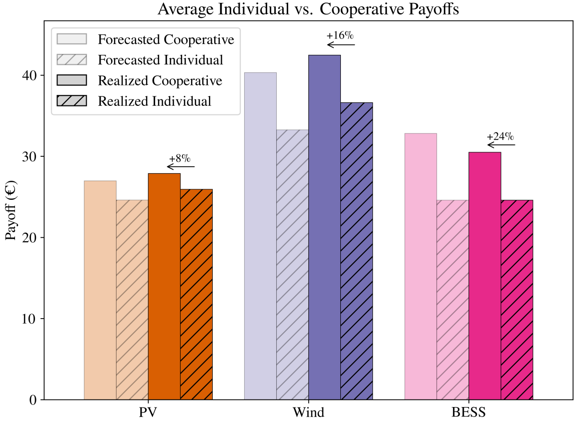

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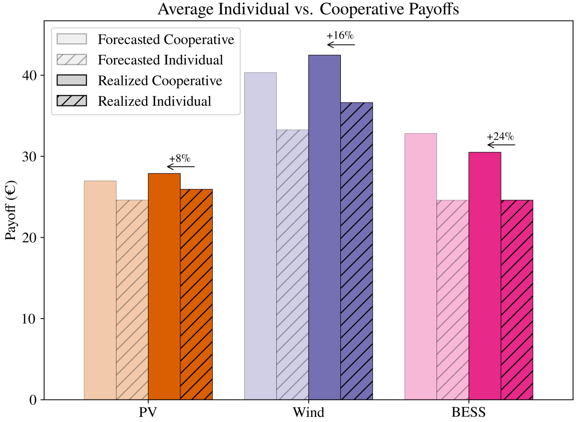

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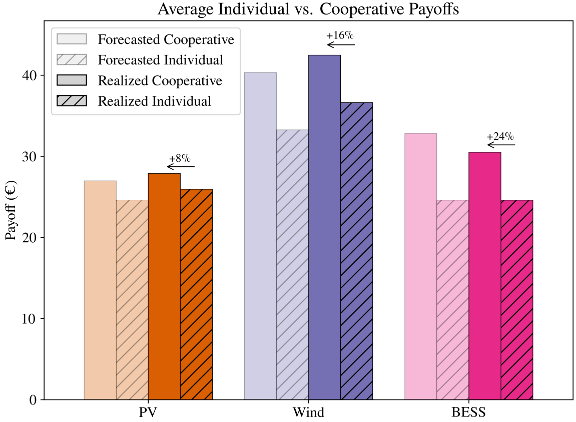

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⭐ Fulfilled requirements:
✓ Technical
✓ Economic & Cooperative

ETH zürich

Thank You for your attention.

I want to sincerely thank my supervisors Dr. Verena Häberle and Dr. Saverio Bolognani for their cooperation and wonderful feedback for this Master Thesis and the PowerUp 2026 paper submission. I have no regrets entering the coalition

$$\{\text{Verena, Saverio, Carl}\}$$

for this project. My payoff $x(\text{Carl})$ has increased tremendously in contrast to standalone operation $v(\text{Carl})$.

AUTOMATIC CONTROL LABORATORY

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Outline

Case Study Further Results

Type of game and number of times Nucleolus / Shapley Value was applied:

	Shapley Value (convex)	Nucleolus (nonempty Core)	Nucleolus (empty Core)
$\mathcal{G}_{\mathbb{F}}$	161	1	0
$\mathcal{G}_{\mathcal{R}}$	138	11	13

Cooperative Game Theory: Fundamentals

- **Objective:** Achieve *desired aggregated behavior* (DAS provision) rather than focusing on individual strategic play.
- **Game Definition:** A pair $(\mathcal{N}, v)$
  - $\mathcal{N}$: The *grand coalition* of all participating DERs.
  - $v(S)$: The value function quantifying the monetary worth of coalitions $S \subseteq \mathcal{N}$.
- **Key game-theoretic Properties:**
  - **Superadditivity:** Merging disjoint coalitions is always beneficial or neutral ($v(S_1 \cup S_2) \geq v(S_1) + v(S_2)$).
  - **Convexity:** Characterized by increasing marginal returns; joining a larger coalition yields a greater or equal contribution than joining a smaller one.

Allocations and The Core

- **Reward Allocation (x):** Vector distributing the total payoff among DERs.
  - *Feasibility:* The exact value of the grand coalition is distributed ($x(\mathcal{N}) = v(\mathcal{N})$).
  - *Rationality:* No DER accepts less than their standalone value ($x_i \geq v(\{i\})$).

- **The Core (Coalitional Stability):**

Definition

The set of all allocations where no subcoalition S has an incentive to defect:
$\sum_{i \in S} x_i \geq v(S), \quad \forall S \subseteq \mathcal{N}$

- **Existence:** The Bondareva-Shapley Theorem states that the Core is nonempty if and only if the game is *balanced*.

Solution Concepts: Nucleolus vs. Shapley Value

The Nucleolus $\mathbf{nc}(v)$

- *Goal:* Maximize coalitional stability.
- Lexicographically minimizes the dissatisfaction (excess) of the most unhappy coalitions.
- *Stability:* Unique allocation that is **always** in the Core (if the Core is nonempty).
- Highly resistant to fragmentation.
- $\mathbf{nc}(v) = x^* \in X(v), \quad$ s.t. $\nexists y \in X(v)$ s.t. $\theta(y) \succ_{lex} \theta(x^*)$

The Shapley Value $\phi(v)$

- *Goal:* Distribute rewards based on average marginal contributions.
- Grounded in 4 axioms: Symmetry, Efficiency, Linearity, and Dummy Player.
- *Stability:* Guaranteed to be in the Core **if** the game is convex.
- $\phi_i(v) = \sum_{\substack{S \ni i, \\ S \subseteq \mathcal{N}}} \underbrace{\frac{(n - |S|)!(|S| - 1)!}{n!}}_{\text{contribution factor}} \underbrace{[v(S) - v(S \setminus \{i\})]}_{\text{marginal contribution}}$

Advanced System Properties

- **Fairness (Balanced Contributions Property):** Ensures an equitable playing ground. Individual effort is proportionally rewarded; the mutual impact of any two DERs joining/leaving is balanced.
- **Ex-Post Consistency:** Addresses uncertainty (e.g., power production). Ensures the expected realized payoffs align with the forecasted payoffs, adjusted for systemic bias.
- **Bayesian Incentive Compatibility:** Ensures DERs have no incentive to manipulate or hide private information (like state-of-charge or generation forecasts), assuming others also act truthfully.

Bayesian Incentive Compatibility Definition

Bayesian Incentive Compatibility

Consider a triple of a reward allocation $A^* : (\mathcal{N}, v) \to [x_i]_{i \in \mathcal{N}}$, an ex-ante game $(\mathcal{N}, v_{\mathbb{F}})$ and an ex-post game $(\mathcal{N}, v_{\mathcal{R}})$.
The triple is *Bayesian Incentive Compatible* if it is individual rational, i.e., $x_i(v_{\mathcal{R}}) \geq v_{\mathcal{R}}(\{i\})$, for each DER $i \in \mathcal{N}$ to reveal their private information $\mathcal{I}_i$ truthfully in the ex-ante stage, under the assumption that the other DERs $j \in \mathcal{N} \setminus i$ act truthfully as well.

Fairness Definition

Balanced Contributions Property (BCP) *Myerson*

A reward allocation $A^*(\mathcal{N}, v)$ with payoffs $x_i(\mathcal{N}, v)$ fulfills BCP if for any $(\mathcal{N}, v)$ and $i, j \in \mathcal{N}, i \neq j$ it holds that:

$$x_i(\mathcal{N}, v) - x_i(\mathcal{N} \setminus j, v) = x_j(\mathcal{N}, v) - x_j(\mathcal{N} \setminus i, v)$$

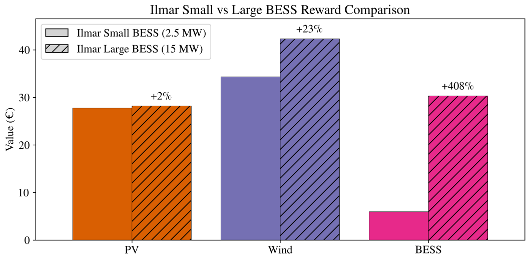
Ex-Post Consistency Definition

Ex-Post Consistency

Assume an ex-ante and ex-post game with value functions $v_{\mathbb{F}}$ and $v_{\mathcal{R}}$, respectively. Further, let μ denote the bias of the ex-ante game, i.e., $\mathbb{E}[v_{\mathbb{F}}(S)] + \mu(S) = \mathbb{E}[v_{\mathcal{R}}(S)]$, $\forall S \subseteq \mathcal{N}$.
A reward allocation $A^*(\mathcal{N}, v)$ with payoffs $x_i(\mathcal{N}, v)$ (**??**) is called *ex-post consistent* if it fulfills for all $i \in \mathcal{N}$:

$$\mathbb{E}[x_i(\mathcal{N}, v_{\mathcal{R}})] = \mathbb{E}[x_i(\mathcal{N}, v_{\mathbb{F}})] + x_i(\mathcal{N}, \mu)$$

Sensitivity Analysis



DERs average hourly reward comparison of small (2.5 MW) vs. large (15 MW) BESS. Reward gains increase non-linear.

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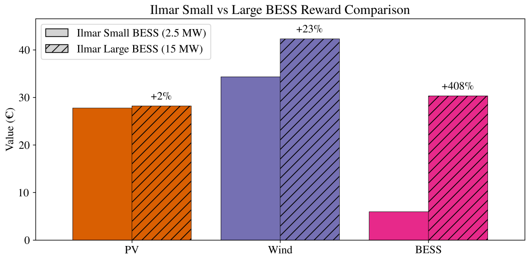

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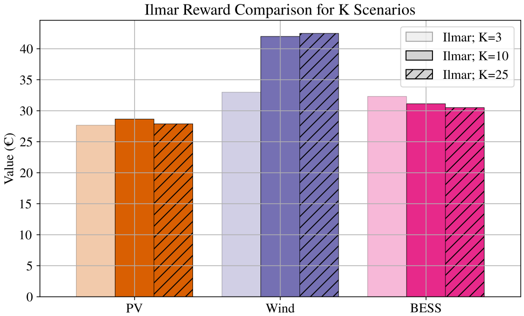

DERs average hourly reward comparison for different number of forecasts used K. DERs have different k (i.e., forecast accuracy) preferences.

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