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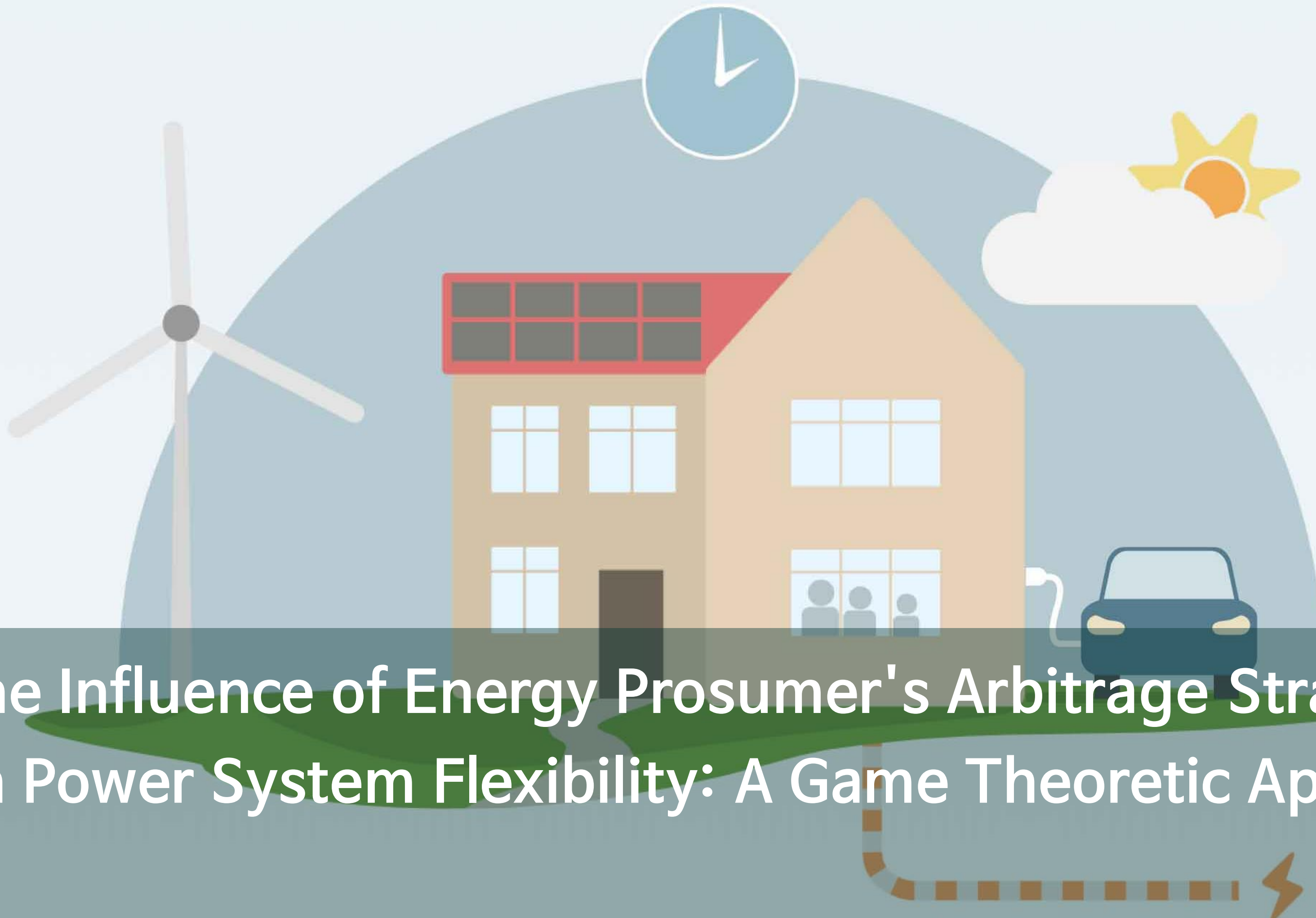

The Influence of Energy Prosumer's Arbitrage Strategy on Power System Flexibility: A Game Theoretic Approach

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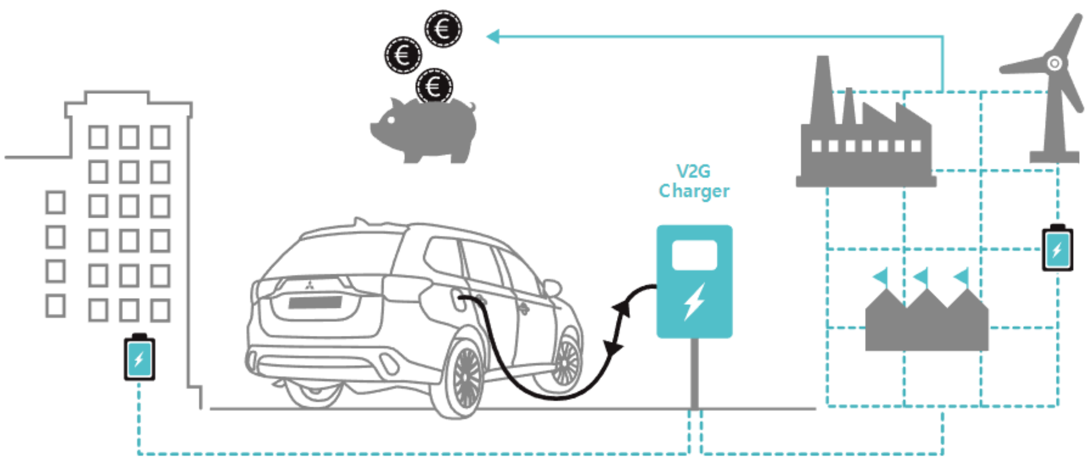
CONTENTS

Background

- The world recognizes the importance of climate change after the Paris Agreement
  - A wide variety of energy innovation technologies emerge in different industries
  - Advances in energy storage technologies such as Energy Storage System (ESS) and Vehicle-to-Grid (V2G)

    ➡ Let prosumers can charge at a low price and trade at a higher price
  - The energy prosumer market is expected to grow smoothly and continuously

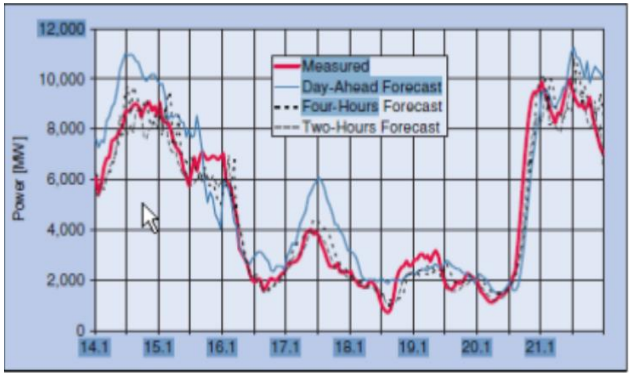


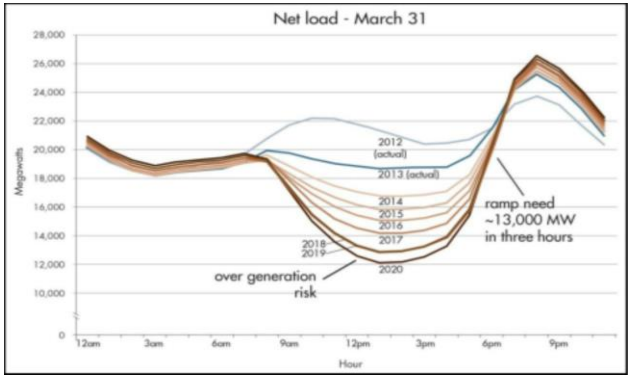
⟨The structure concept of V2G⟩

source: newmotion.com

INTRODUCTION

- Renewable energy generation expands significantly, mainly in solar and wind power
  - Variable energy generation such as solar and wind power has an intermittency problem that lowers the stability and flexibility of the power system
  - Uncertainties and fluctuations occur due to forecast errors and output variations
  - As the need for system flexibility and the number of energy prosumers are increasing, it is necessary to understand their impact on system flexibility.



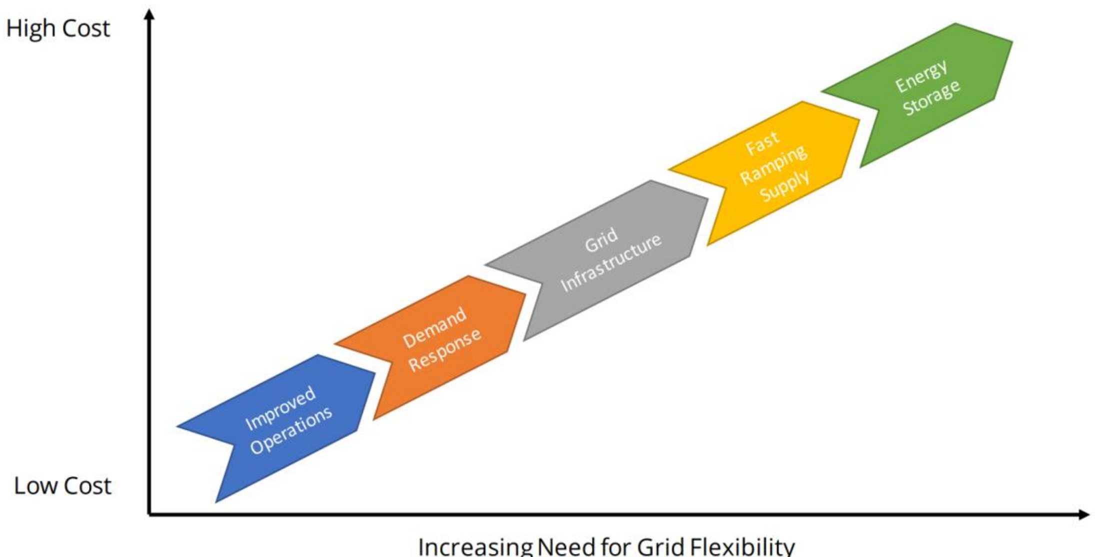


source: GE Energy (2012)　　source: CAISO (2014)

《German Wind Power Prediction Error and California Power Duck Curve》

Research Question

- Energy storage is an excellent source of flexibility, but…
  - When charging from the grid, prosumers tend to have their device charged at a lower purchase price, resulting in a higher load than usual
  - As the size of energy prosumers grows, prosumer’s profit-taking strategy can have a notable influence on system flexibility
  - Depicts how energy prosumer's arbitrage behavior affect the system flexibility under TOU pricing



source: Orvis and Aggarwal (2017)

《Flexibility Supply Curve》

Literature Review

- Studies about system flexibility and game-theoretic approach for energy prosumers

Research Topic	Literature	Summary
System flexibility	Lannoye et al. (2012)	Proposed the insufficient ramping resource expectation (IRRE) to measure power system flexibility
	Kubli et al. (2018)	Empirically show that electric car and solar PV users exhibit a higher willingness to co-create flexibility than heat pump users
	Iria et al. (2019)	Introduced a two stage stochastic optimization model including participation of energy aggregators
Game-theoretic approach for energy prosumers	Long et al. (2019)	Proposed a P2P energy trading mechanism and modeled a game theory-based decision-making process
	Tushar et al.(2019)	Devised a motivational psychology framework to increase prosumer participation
	Han et al.(2019)	Applied K-means clustering to the energy profiles of the grand coalition optimization to improve the model complexity.
	Bae and Park (2019)	Analyzed energy tradings with buyer-pricing-system and seller-pricing-system. proved they are stable and efficient.

Theoretical Models

- The basic concept of game theory
  - Assume that there are i = 1,2,3, ⋯, N players taking part in the game
  - A vector x_i is used to represent the action taken by the player i
  - A collective action profile $\boldsymbol{x} = x_1, x_2, \ldots, x_N$ can be obtained when all the players make decisions simultaneously
  - The payoff function of a player i indicates the profit when a strategy space of other players is given
- Cooperative game
  - A game in which participants can negotiate strategies
  - Rather than just making a personal decision, focuses on the proper and fair conditions for players to accept the possible outcome.
- Non-cooperative game
  - A game in which each participant chooses a strategy such as Poker and Rock, Paper, Scissors
  - Focuses on how each player’s rational decision affect the outcome of the game.

Collaborative game

- Shapley value

  Revenue sharing that all the rational participants in the coalition can be satisfied, with the following four conditions

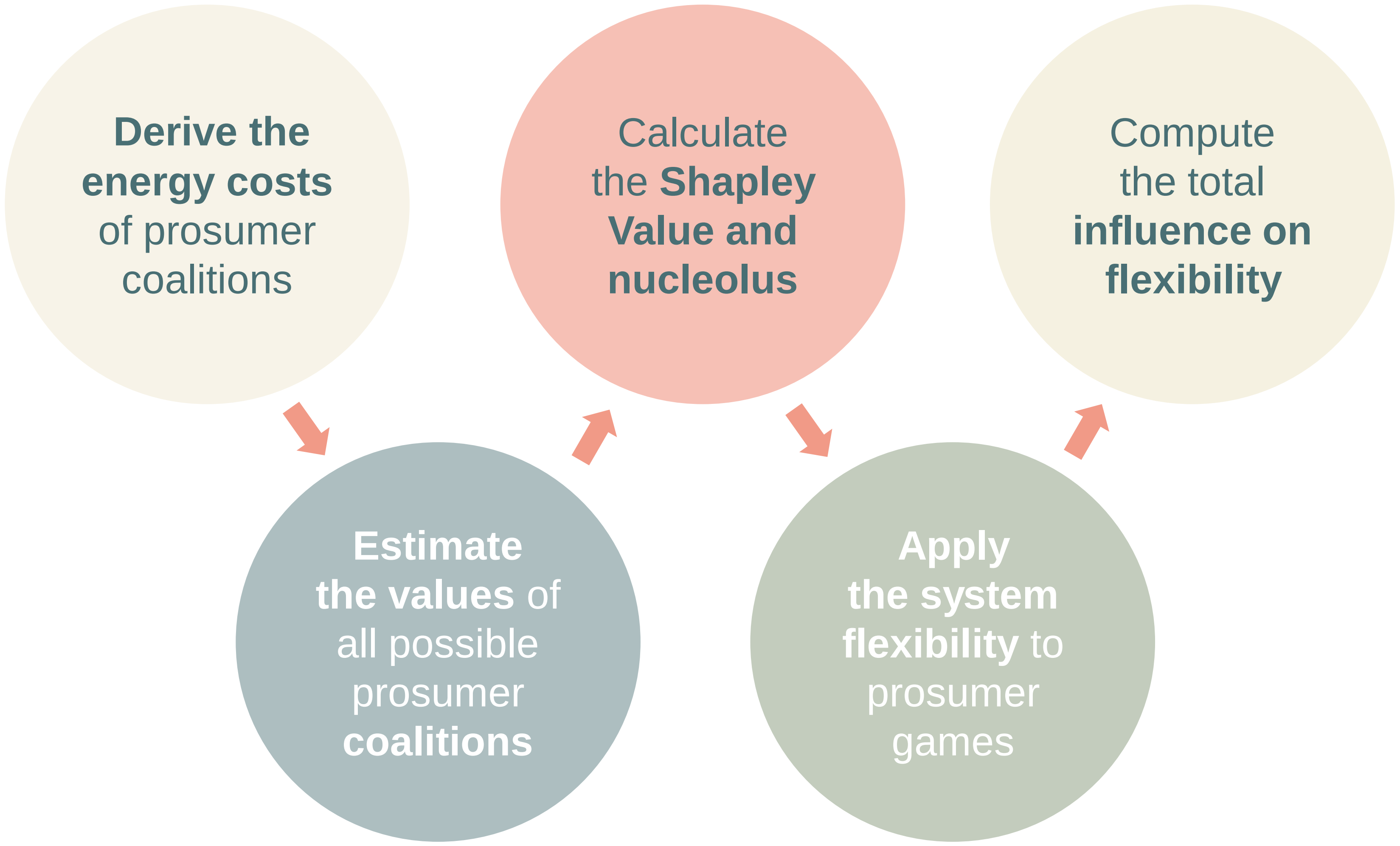
  - Efficiency: The sum of the payoff distributed to each participant equals the value of the coalition
  - Symmetry: All participants who play the same role in the coalition are equally distributed.
  - Dummy Axiom: For rational revenue sharing, each participant distributes profit as they contribute to the coalition
  - Additivity: The arbitrated value of two games played at the same time should be the sum of the arbitrated values of the games if they are played at different times.

  ➡ The value distributed to a participant i, which is calculated from the characteristic function, is the Shapley Value

Collaborative game

- Nucleolus
  - The idea comes from how to reduce dissatisfaction by prioritizing the most dissatisfied unions
  - Introduced the concept of excess to indicate the level of dissatisfaction
  - A similar concept, surplus, is positive because it is a surplus number, whereas excess is negative because it is short.
  - The nucleolus is the point where the difference between the value of the coalition and the total sum of the payoff of each player distributed is minimal
  - It is a compensation set for a point where the dissatisfaction for each coalition will be the smallest.

Stages of Analysis



Stages of Analysis

- Data
  - Number of prosumers, load and generation information for each prosumer, energy storage, supply capacity
  - Purchase price, selling price and grid allowable load according to seasonal and hourly electricity rate
  - System Flexibility: Start-up time and time availability of units, net system load
- Energy cost function of energy prosumer coalitions

$$F(\mathfrak{B}, Q^S) = \underbrace{\mathrm{P}_\mathrm{b}^\mathrm{T}[(\mathfrak{B} + Q^S)1^N]^+}_{\text{Energy Purchase Cost}} + \underbrace{\mathrm{P}_\mathrm{s}^\mathrm{T}[(\mathfrak{B} + Q^S)1^N]^-}_{\text{Energy Sales Revenue}}$$

  - $\mathrm{P}_\mathrm{b}^\mathrm{T}, \mathrm{P}_s^\mathrm{T}$: Transpose matrix of purchase price and sale price
  - $\mathfrak{B}$: Energy storage variable matrix
  - Q^S : net energy load of the coalition

Stages of Analysis

- Value of the coalition

$$v(S) = \sum_{i \epsilon S} \mathrm{C}_{\{i\}}\left(\mathfrak{B}^{\langle\{i\}\rangle *}\right) - \mathrm{C}_S\left(\mathfrak{B}^{\langle S\rangle *}\right)$$

  - $\mathrm{C}_{\{i\}}(\mathfrak{B})$: minimum energy cost function of a prosumer, i
  - $\mathrm{C}_S(\mathfrak{B})$: minimum energy cost function of the coalition

- Shapley Value calculation: considering the weight and marginal contribution of i for each possible coalition

$$\phi(v) = \sum_{S \epsilon 2^{\mathcal{N}}, i \epsilon S} \frac{(|S|-1)!\,(N-|S|)!}{N!}\left[v(S) - v(S\backslash\{i\})\right]$$

  - N: Grand Coalition
  - $|S|$: The number of participants in the coalition, S
  - $S\backslash\{i\}$: The coalition without a participant, i

Calculation of Nucleolus

$$LP_1\colon\ \varepsilon_1 = \min_{x,\varepsilon} \varepsilon$$

$$s.t. \quad \sum_{\forall i \epsilon \mathcal{N}} x_i = v(\mathcal{N})$$: Efficiency criterion

$$v(S) - \sum_{\forall i \epsilon S} x_i \le \varepsilon, \forall S \notin \{\emptyset, \mathcal{N}\}$$: Minimize ε for all coalitions

- $\varepsilon_1, \mathfrak{S}_1$: optimal solution of Grand Coalition, $\mathcal{N}$

$$LP_j\colon\ \varepsilon_j = \min_{x,\varepsilon} \varepsilon$$: $j > 2$

$$s.t. \quad \sum_{\forall i \epsilon \mathcal{N}} x_i = v(\mathcal{N})$$

Fix ε from the previous constraint : $$\sum_{\forall i \epsilon S} x_i = v(S) - \varepsilon_l, \forall S \in \mathfrak{S}_l, \forall l \in [1, j-1]$$

Minimize ε for all : coalitions at LP_j $$v(S) - \sum_{\forall i \epsilon S} x_i \le \varepsilon, \forall S \notin \{\emptyset, \mathfrak{S}_l, \mathcal{N}\}, \forall l \in [1, j-1]$$

- x^* : nucleolus of prosumer cooperative game

Optimization for energy systems

$$\min_{\substack{\mathfrak{B}_+,\mathfrak{B}_-,\\ \mathrm{L}_+,\mathrm{L}_-}} \mathrm{P}_\mathrm{b}^\mathrm{T}\left(L_+\mathbf{1}^N\right) + P_s^T\left(L_-\mathbf{1}^N\right)$$

$$\begin{aligned}
s.t.\quad & \mathfrak{B}_+, \mathfrak{B}_-, L_+, L_- \in \mathbb{R}^{K\times N} \\
& 0 \le L_+ \\
& \mathfrak{B}_+ + \mathfrak{B}_- + Q^S \le L_+ \\
& \mathfrak{B}_+ + \mathfrak{B}_- + Q^S = L_+ + L_- \\
& 0 \le \mathfrak{B}_+ \le \overline{B}^S \\
& \underline{B}^S \le \mathfrak{B}_- \le 0 \\
& E^S\underline{SoC} \le E^S\mathrm{SoC} + A^K(\mathfrak{B}_+\eta^I + \mathfrak{B}_-\eta^O) \\
& \qquad \le E^S\overline{SoC}
\end{aligned}$$

- $\mathfrak{B}$: energy storage variable matrix
- $L_- = min\{0, \mathfrak{B}_+ + \mathfrak{B}_- + Q^S\}$, $L_+ = max\{0, \mathfrak{B}_+ + \mathfrak{B}_- + Q^S\}$
- E: energy storage capacity
- Q: net energy load
- SoC: energy storage state of charge

Applying system flexibility into the game

- Calculation of IRRE (Insufficient Ramping Resource Expectation)

$$NLR_{t,i} = NL_t - NL_{t-i}$$

: **Net Load Ramp**

$$Flex_{t,u,i,+} = RR_{u,+} - NL_{t-i}$$

: **Minimize ε for all coalitions**

$$Flex_{t,SYSTEM,i,+/-} = \sum_{\forall u} Flex_{t,u,i,+/-}$$

: **System flexibility time series**

Applying system flexibility into the game

$AFD_{i,+/-}(X)$

The probability that X MW or less, of flexible resource available during time i

: AFD function
Available Flexibility Distribution

$$IRRP_{t,i,+/-} = AFD_{i,+/-}(NLR_{t,i,+/-} - 1)$$

: Insufficient ramping resource **probability**

$$IRRE_{i,+/-} = \sum_{\forall t \epsilon T_{+/-}} IRRP_{t,i,+/-}$$

: Insufficient ramping resource **expectation**

Further Research

- Empirical validation by applying data to a flexible game model
  - Scenario analysis based on the penetration rate of ESS and EV and the number of energy prosumers
  - Derive solutions that maximize system flexibility without compromising the profitability of prosumers
- Application of non-cooperative game theory
  - Calculate how prosumers' behavior affects the system flexibility when prosumers do not participate in a cooperative game
- Comparing Peer-to-Peer transactions and transmission to the grid
  - Conduct a comparative study with the P2P transactions based on blockchain technology and when transaction through the grid.

THANK YOU FOR YOUR ATTENTION

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