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京都大学 KYOTO UNIV.

Distributed Mode Scheduling for Coordinated Power Balancing

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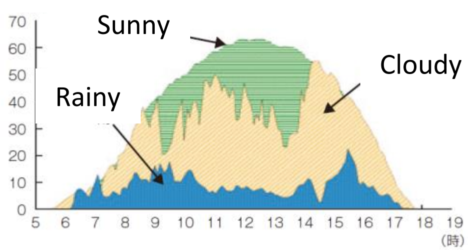
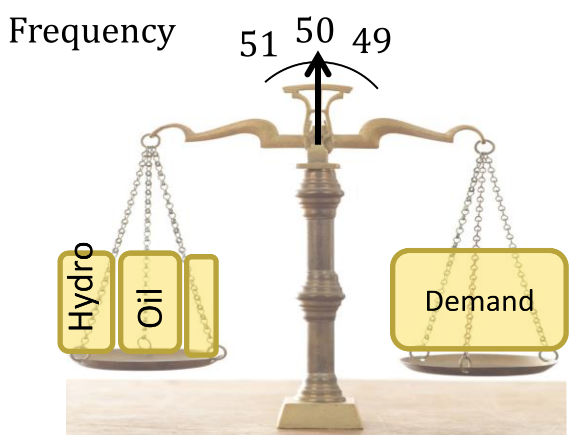
Motivation

- Volatile power supply & demand in future
  - More operating reserves (power plants)? → increase electricity price
  - How can we coordinate end users to balance/flatten the total power?

Total supply = Total demand

Solar & wind power strongly depend on weather, etc.



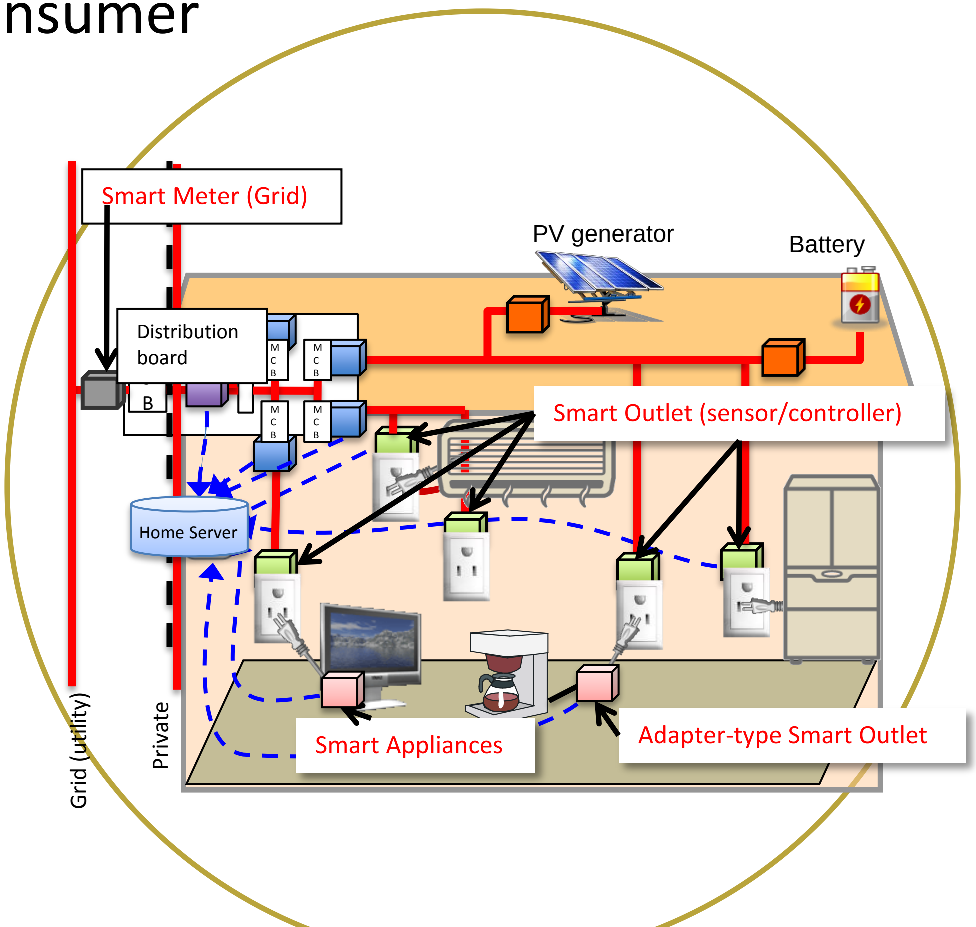


Electric Vehicle (EV) and Plugin Hybrid EV (PHEV) require several kW x several hours for everyday charging

End Users (household, office, etc.)

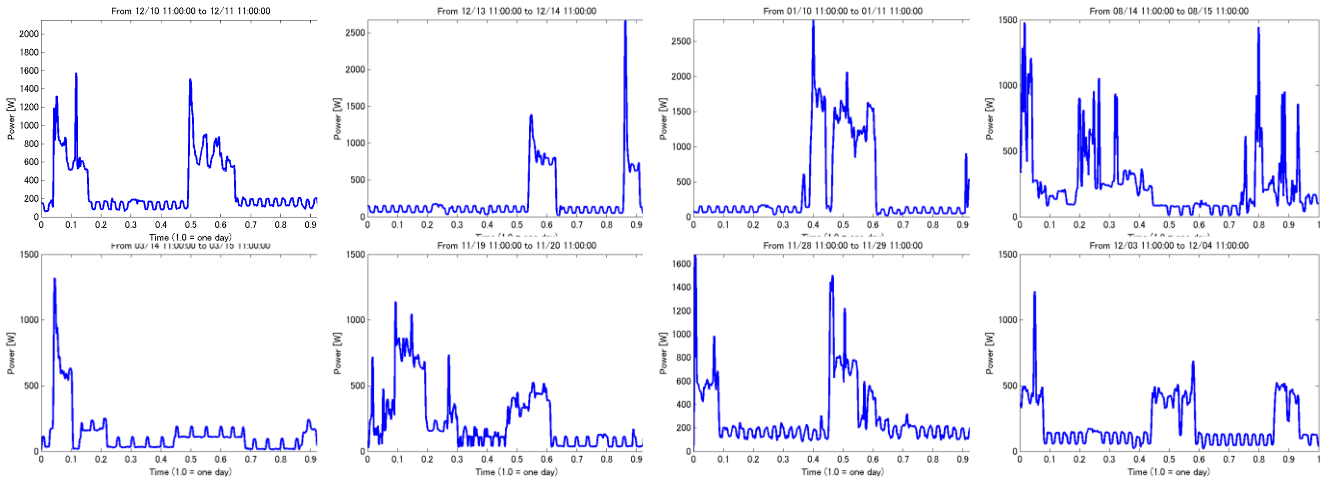
- End user: a unit of decision making for energy management
  - Household, office, factory, etc.
- Assume that Energy Management System (EMS) is installed
  - Smart meter, communication device, sensor (controller) of appliances
- Prosumer: Producer + Consumer

Eco house in Kyoto
(From http://www.kyo-ecohouse.jp))



End Users' Consumptions

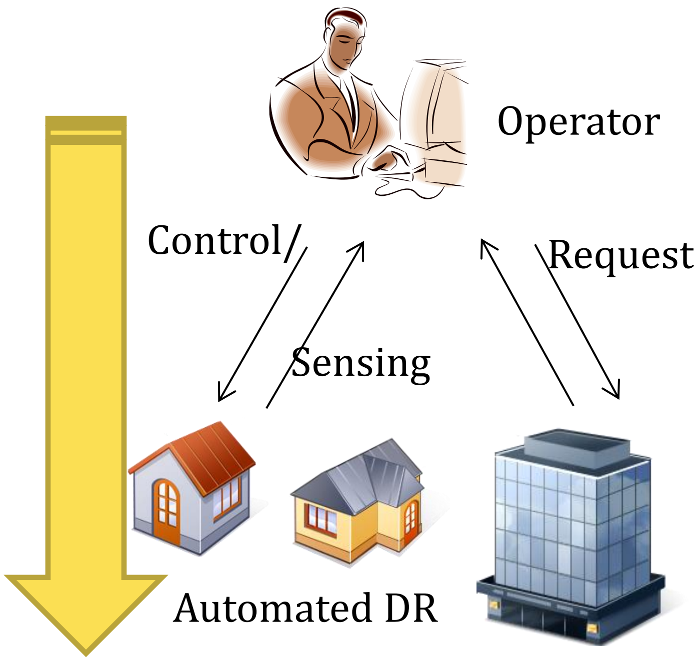
- Examples of consumption patterns of several families
  - Apartment (1 bed room) with EMS [Kato, et al. SmartGridComm11,12]
  - Affected by not only life styles but events (travel, party, etc.)



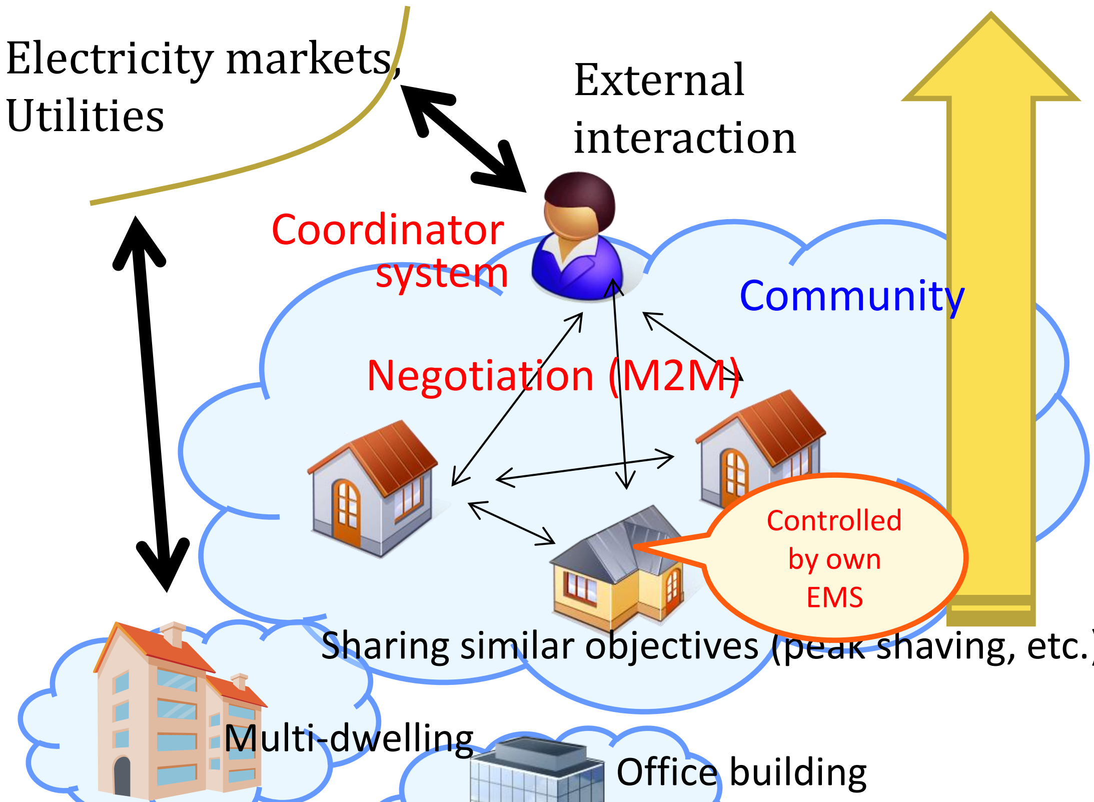
End users have their own <u>daily</u> preference and often difficult to predict from utilities

Coordination of End Users in a Community

- Demand Response



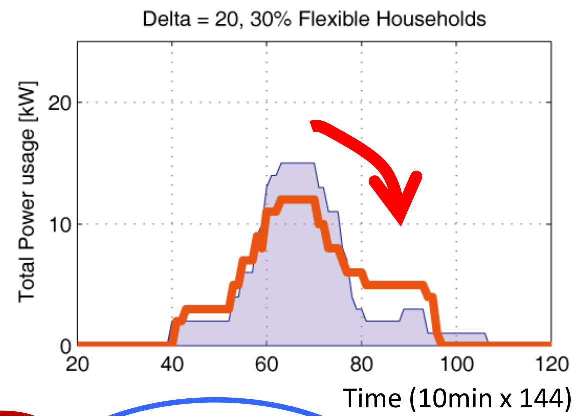
- Coordination as a community

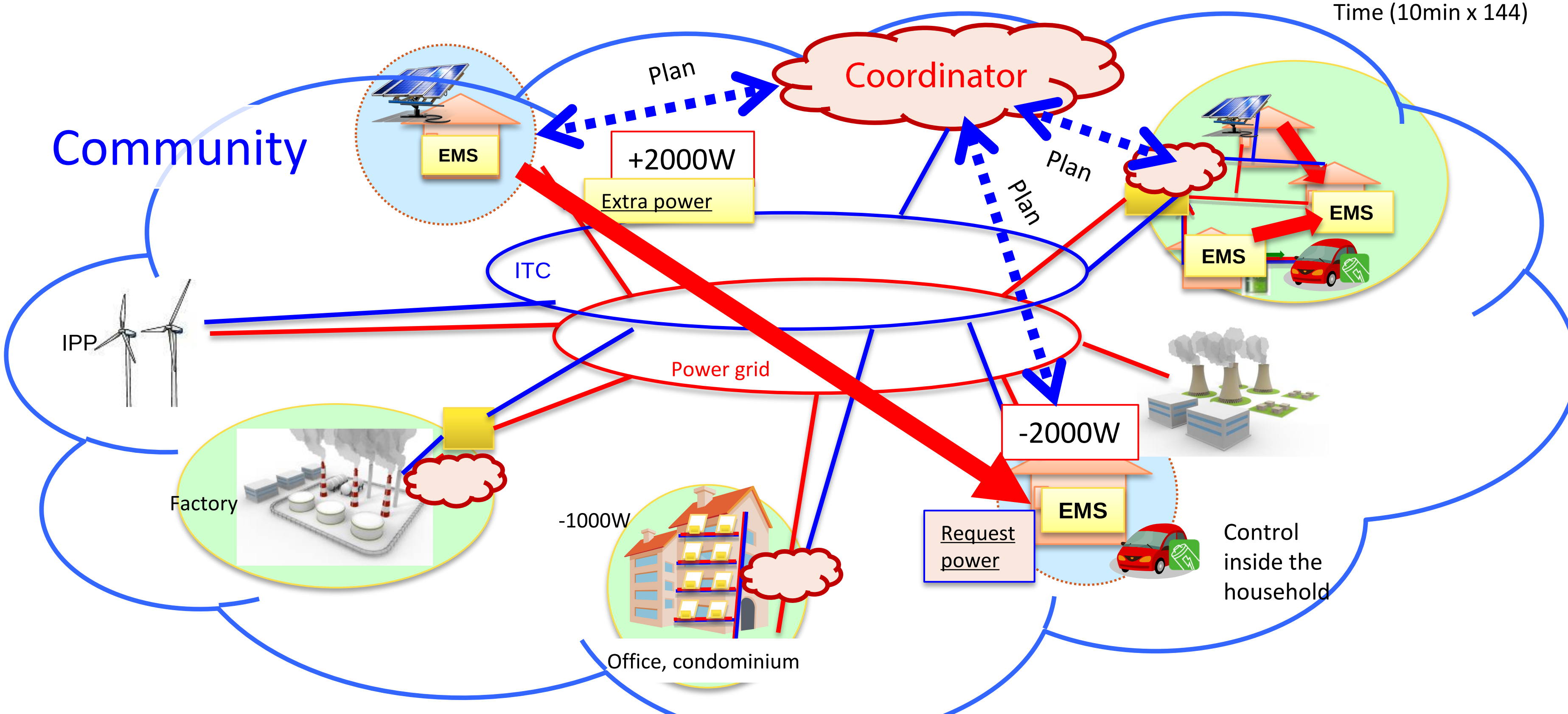


Demand-side management "from demand side"

Community-based Coordination for Flattening

- Distributed architecture
  - User has own controller (autonomous agent)
- Users negotiate their plans via coordinator
  1. Day-ahead coordination
  2. Online coordination





Outline

1. Motivation
2. Community-based architecture to coordinate users
3. Models and algorithms
    1. Distributed optimization
    2. End user’s model
4. Simulation examples
5. Conclusion

Coordination of Households (End Users)

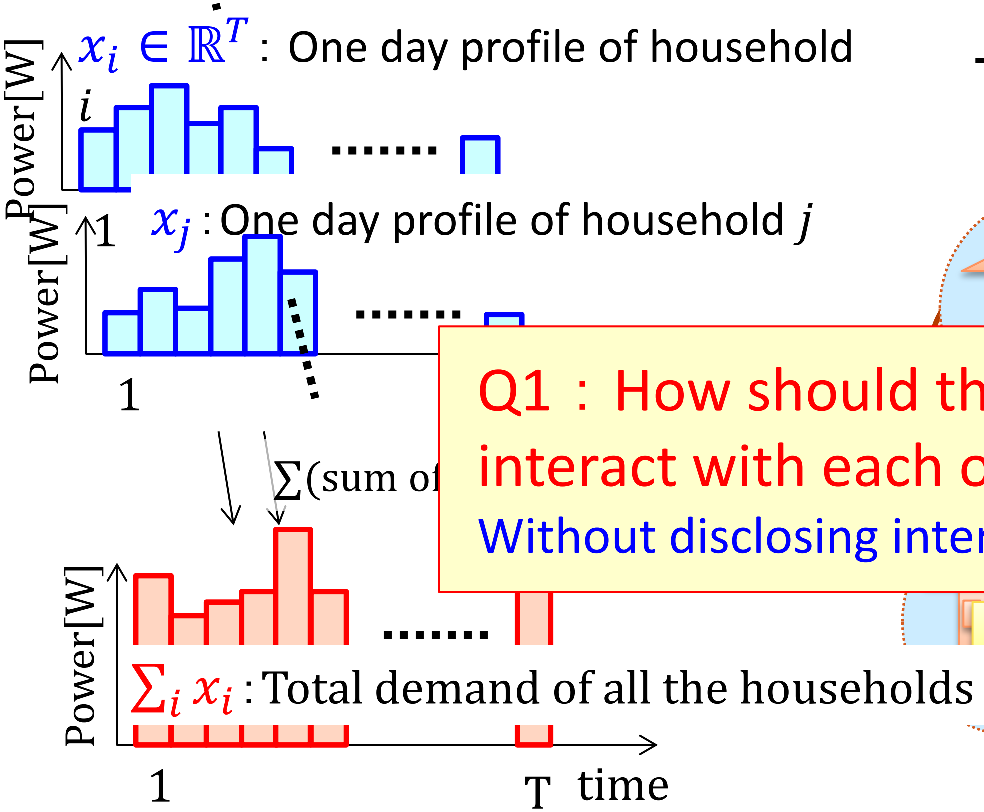
- Flatten the peak power while preserving each household's satisfaction:

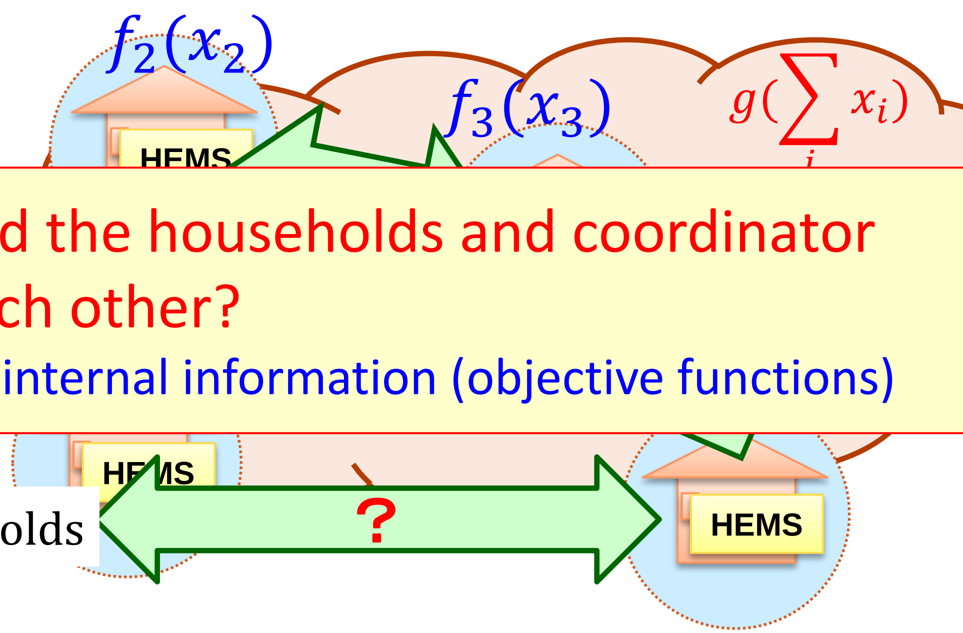
$\sum_i$ Objective of household i
$+$Objective of the community

$f_i(x_i)$ Dissatisfaction/difficulty of using power profile x_i

$g(\sum_i x_i)$ Penalty function for peak

$\rightarrow$ minimize over x_i $(i = 1, \ldots, N)$





Q1 : How should the households and coordinator interact with each other?

Without disclosing internal information (objective functions)

Idea 1: Profile-based Distributed Coordination

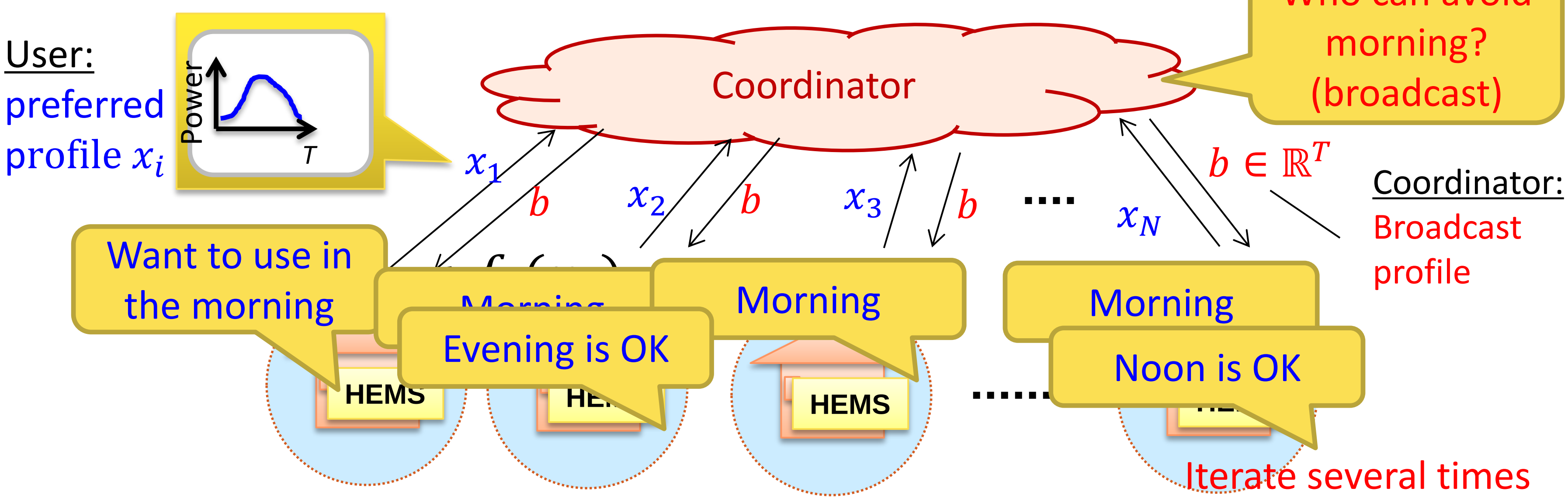
- Flatten the peak power while preserving each household's satisfaction :

$$\underset{x_1,\ldots,x_N}{\text{minimize}} \quad \sum_i f_i(x_i) + g\left(\sum_i x_i\right)$$

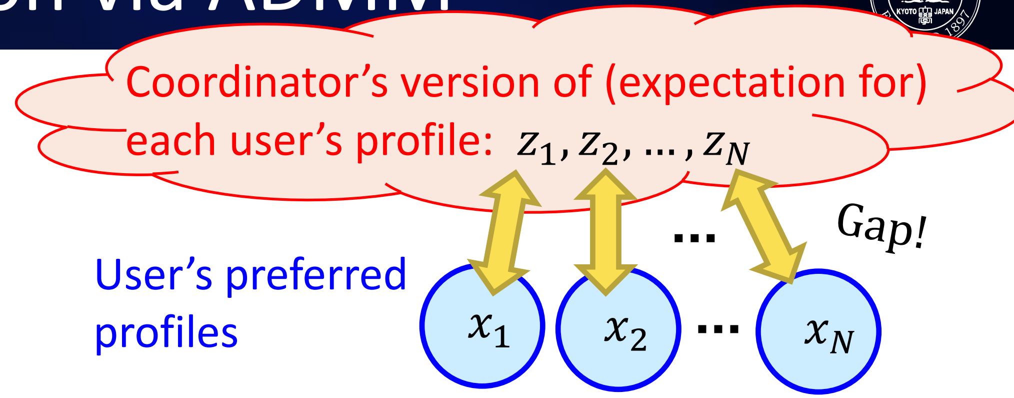
Difficulty/dissatisfaction of using x_i — Penalty function for peak

- Coordination of distributed controllers (autonomous agents)
  - Each user does not disclose their objective functions f_i
  - ☺ Can avoid privacy issues / integrate different types of EMS (allow heterogeneity)

Profile-based negotiation to find best plan $x_i (i = 1, \ldots, N)$



Distributed Optimization via ADMM



Sharing Problem:

$$\min_{x_1,\dots,x_N} \quad L(x) \triangleq \sum_{i\in\mathcal{N}} f_i(x_i) + g\Big(\sum_{i\in\mathcal{N}} x_i\Big)$$

Dual decomposition with Augmented Lagrangian

Subject to $x_i = z_i$

$$L_\rho(x, z, \lambda) \triangleq \sum_{i\in\mathcal{N}} f_i(x_i) + g\Big(\sum_{i\in\mathcal{N}} z_i\Big) + \sum_{i\in\mathcal{N}} \lambda_i^\top (x_i - z_i) + \frac{\rho}{2}\sum_{i\in\mathcal{N}} ||x_i - z_i||^2$$

Alternating Direction Method of Multipliers (ADMM):

End-users $(i = 1, \dots, N)$

$$x_i^{(k+1)} := \operatorname*{argmin}_{x_i} \left(f_i(x_i) + \frac{\rho}{2}||x_i - x_i^{(k)} + b^{(k)}||^2 \right)$$

$x_i^{(k+1)}$ $(i = 1, \dots, N)$

$b^{(k)} \in \mathbb{R}^T$

$$\bar{z}^{(k+1)} := \operatorname*{argmin}_{\bar{z}} \left(g(N\bar{z}) + \frac{N\rho}{2}||\bar{z} - (\bar{x}^{(k+1)} + \eta^{(k)})||^2 \right)$$

$$\eta^{(k+1)} := \eta^{(k)} + \bar{x}^{(k+1)} - \bar{z}^{(k+1)}$$

$$b^{(k+1)} := \bar{x}^{(k+1)} - \bar{z}^{(k+1)} + \eta^{(k+1)}$$

Coordinator

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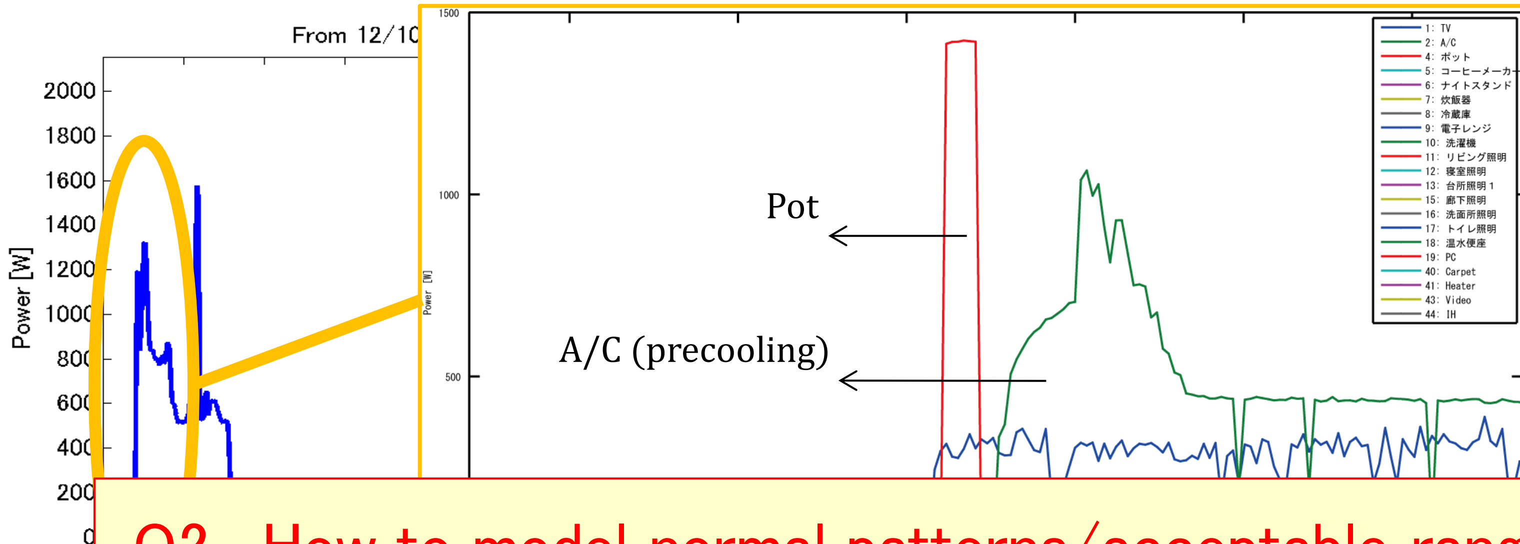
Control in a Household

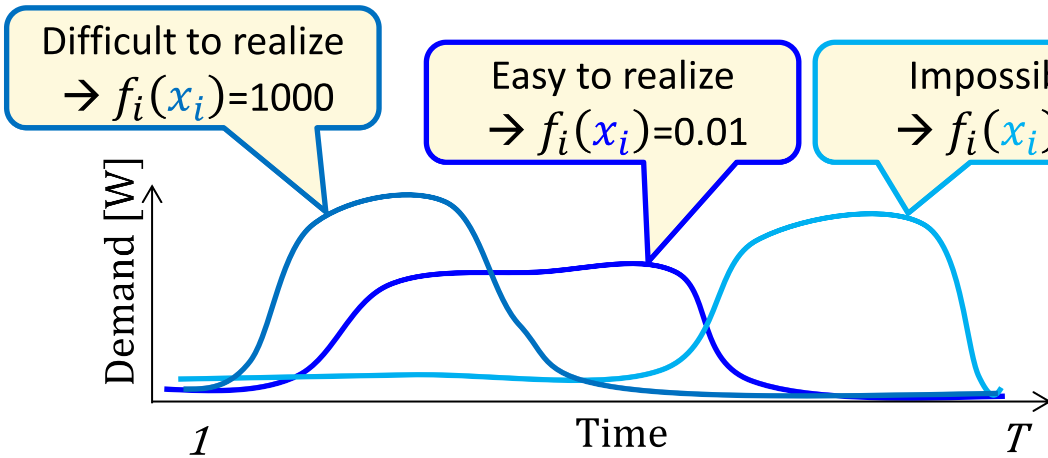
- Change of device usage: time-shift, reduction
- We focus on time-shift (scheduling) of appliance usage in a household as it has a large effect in power flattening
  - (Ex.) EV charging, A/C, dryer, dish washer, rice cooker



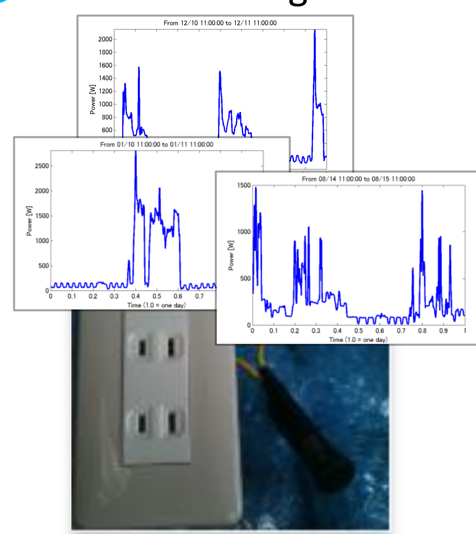
Q2. How to model normal patterns/acceptable range of each household?

Idea 2: Objective Function of Households

- Objective function $f_i(x_i)$
  - Difficulty/dissatisfaction of realizing profile x_i by household i



Training data



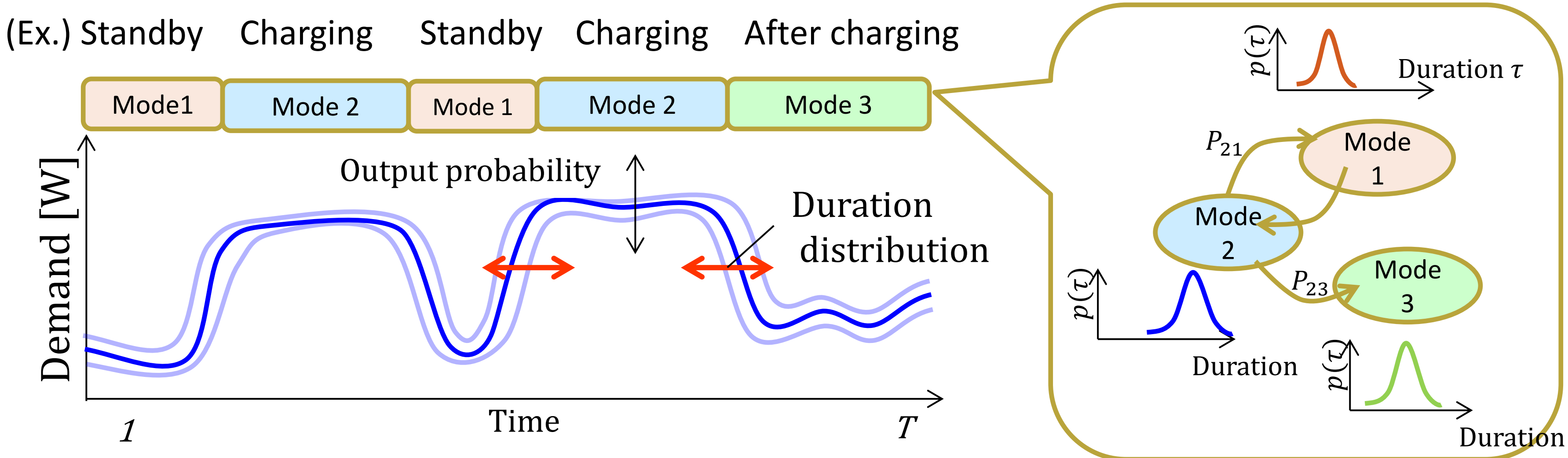
Smart tap
(smart plug)

Many profiles are infeasible, i.e., $f_i(x_i)$=∞
Can we learn the function $f_i(x_i)$ from data?

➡ We can use a probabilistic model of time series used in speech/gesture recognition

Probabilistic Model of Time Series

- Hidden Semi-Markov Model
  - Assume that each device has its “internal modes” (discrete states)
  - Power consumption is determined by the control of modes
  - All the model parameters can be learned from daily usage data



$$f(x_i) \triangleq -\log \max_{s_{i,1},\dots,s_{i,T}} P(s_{i,1},\dots,s_{i,T},x_i)$$

Replace user-side optimization over x_i by ”mode scheduling”

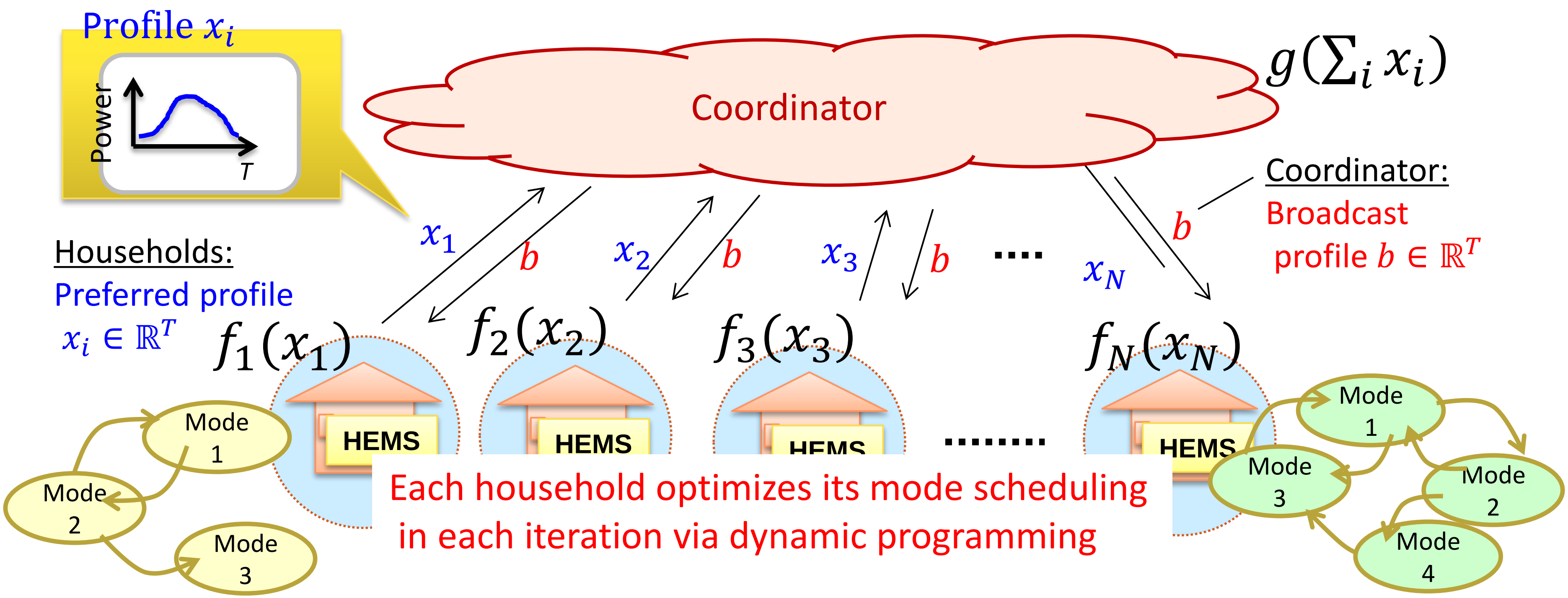
Take into account temporal constraints (duration, order) on power levels

Distributed Mode Scheduling

- Flatten the peak power while preserving each household's satisfaction

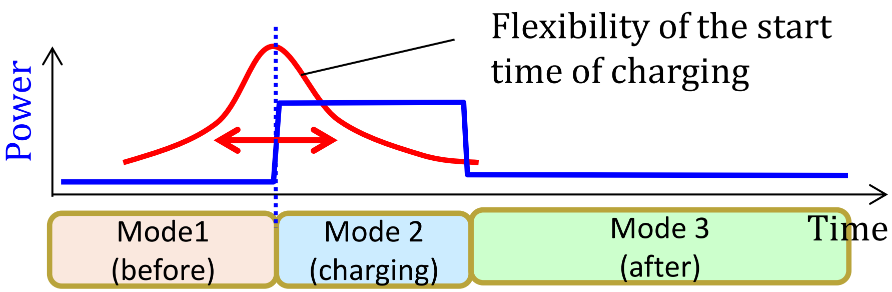
$$\underset{x_1,\ldots,x_N}{\text{minimize}} \sum_i f_i(x_i) + g(\textstyle\sum_i x_i)$$

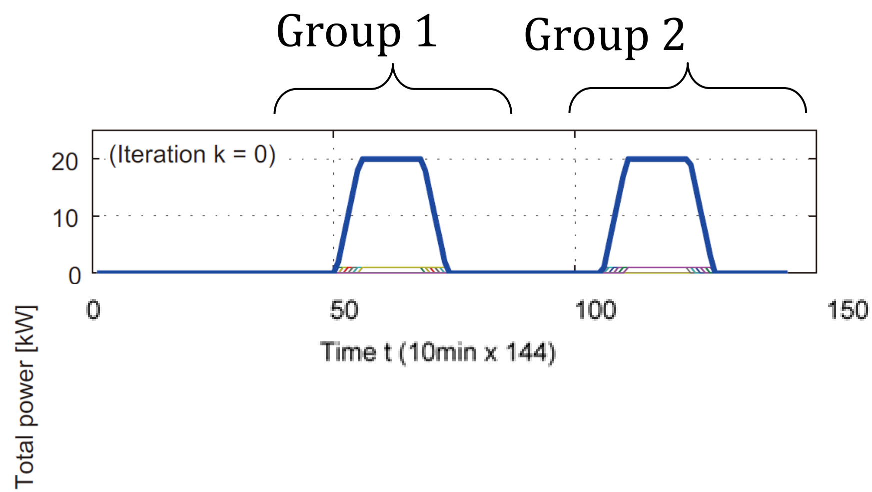
- Household need to send only their profiles
  - The coordinator do not need to know each objective function



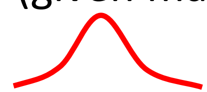
Simulation (Day-ahead Scheduling)

- PHEV charging
  - 1kW x 3hours in a day

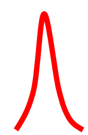




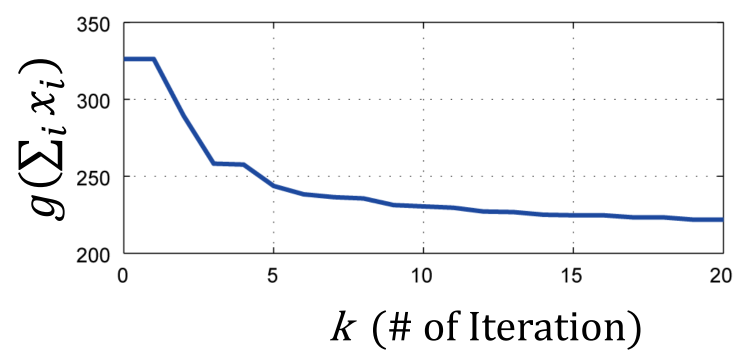
- Two groups with different flexibility (given manually)
  - Group 1 (20 households)
    - Large flexibility of changing the start time



  - Group 2 (20 households)
    - Small flexibility



- Result
  - Almost converge with in 20 iterations
  - Realize group objective (peak shaving) while taking into account users' flexibility



Conclusion: Distributed Mode Scheduling

- Coordination of user-side controllers (autonomous agents)
  ☺ Profile-based negotiation (ex. different types of EMS can be integrated)
  ☺ Negotiation is done by the coordinator's broadcast signal (simple)

- Hidden-semi Markov model for users' objective functions
  ☺ Model can be learned from daily consumption patterns
  ☺ User-side optimization becomes "mode scheduling" and solved efficiently

- Future work
  - Economic design of objective functions
  - Generators and batteries (charging/discharging)
  - Online negotiation (Users do not always follow the schedule)