CONTROL AND OPTIMIZATION IN SMART-GRIDS

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Course topics

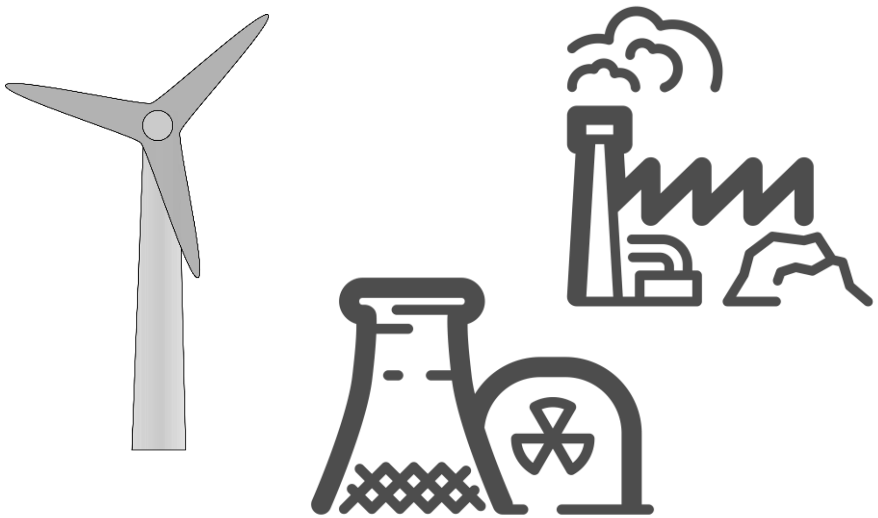
- Session 1: Introduction to Power systems
  - Context and motivation
  - Power flow analysis
  - Economic dispatch
- Session 2: Renewable sources
  - Stochastic models of variable sources
  - Dispatching random sources
- Session 3: Energy dispatch
  - Risk-limiting dispatch
  - Matlab session

Course topics

- Session 4: Incentive-based demand response
    - Modeling demand
    - Peak time rebates
    - Contract design for demand response
- **Session 5: Flexible loads**
    - **Modeling flexibility**
    - **Load dispatch**
    - **Case study: Electric vehicles**
- Session 6: Micro-grids
    - Lean energy concept
    - Joint generation and load dispatch

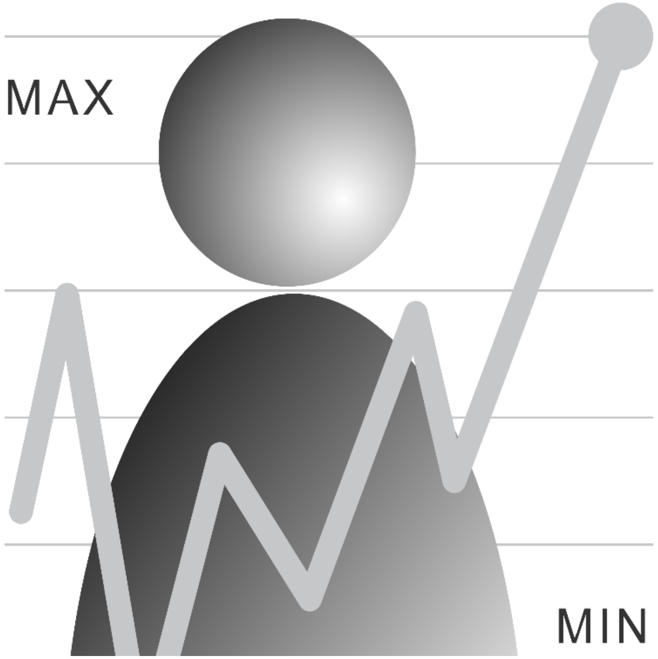
Demand Side Management

- New paradigm in grid operation
- Active consumers are responsible of grid balance
- ICT-based

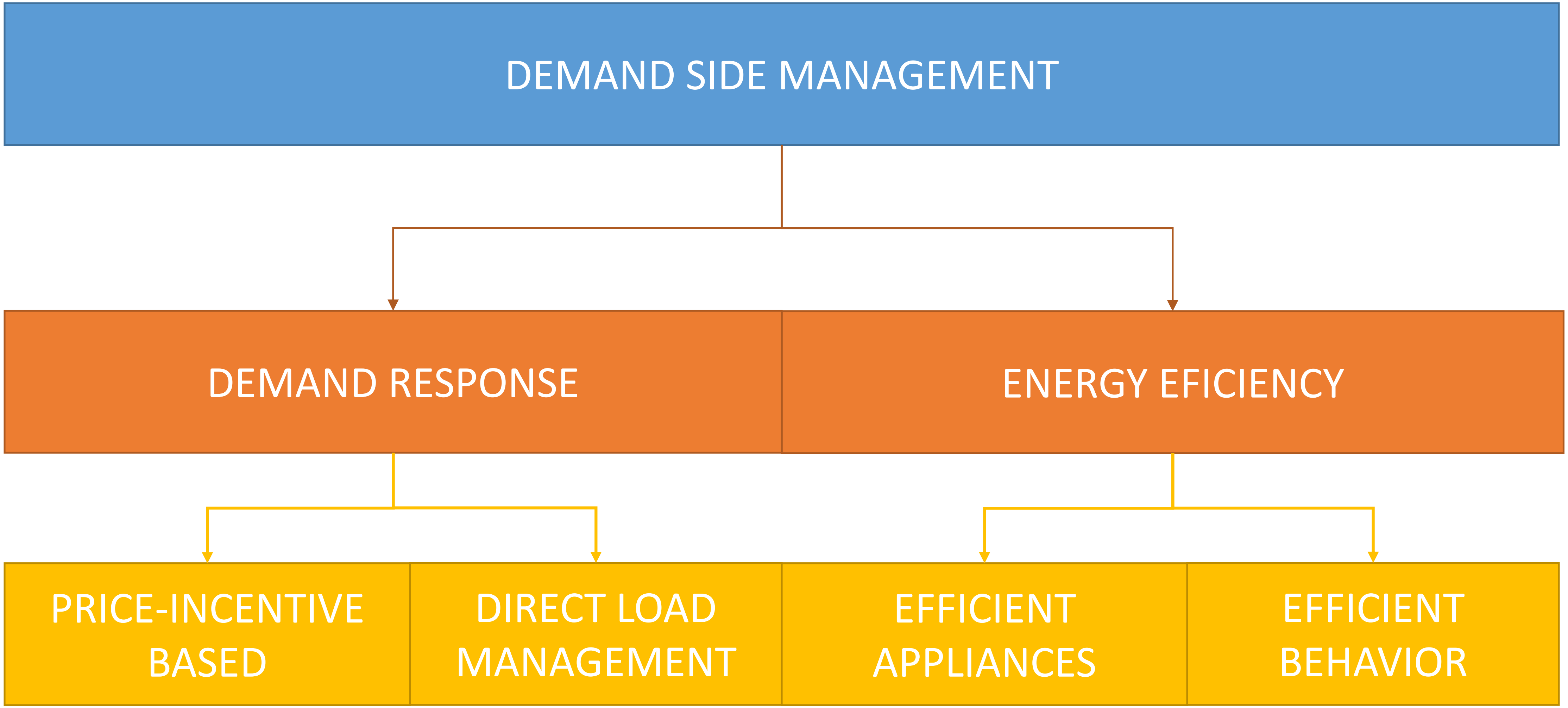


Power and Information
Bi-directional flow

PRO-SUMER



Demand Side Management



DEMAND SIDE MANAGEMENT

DEMAND RESPONSE

ENERGY EFICIENCY

PRICE-INCENTIVE BASED

DIRECT LOAD MANAGEMENT

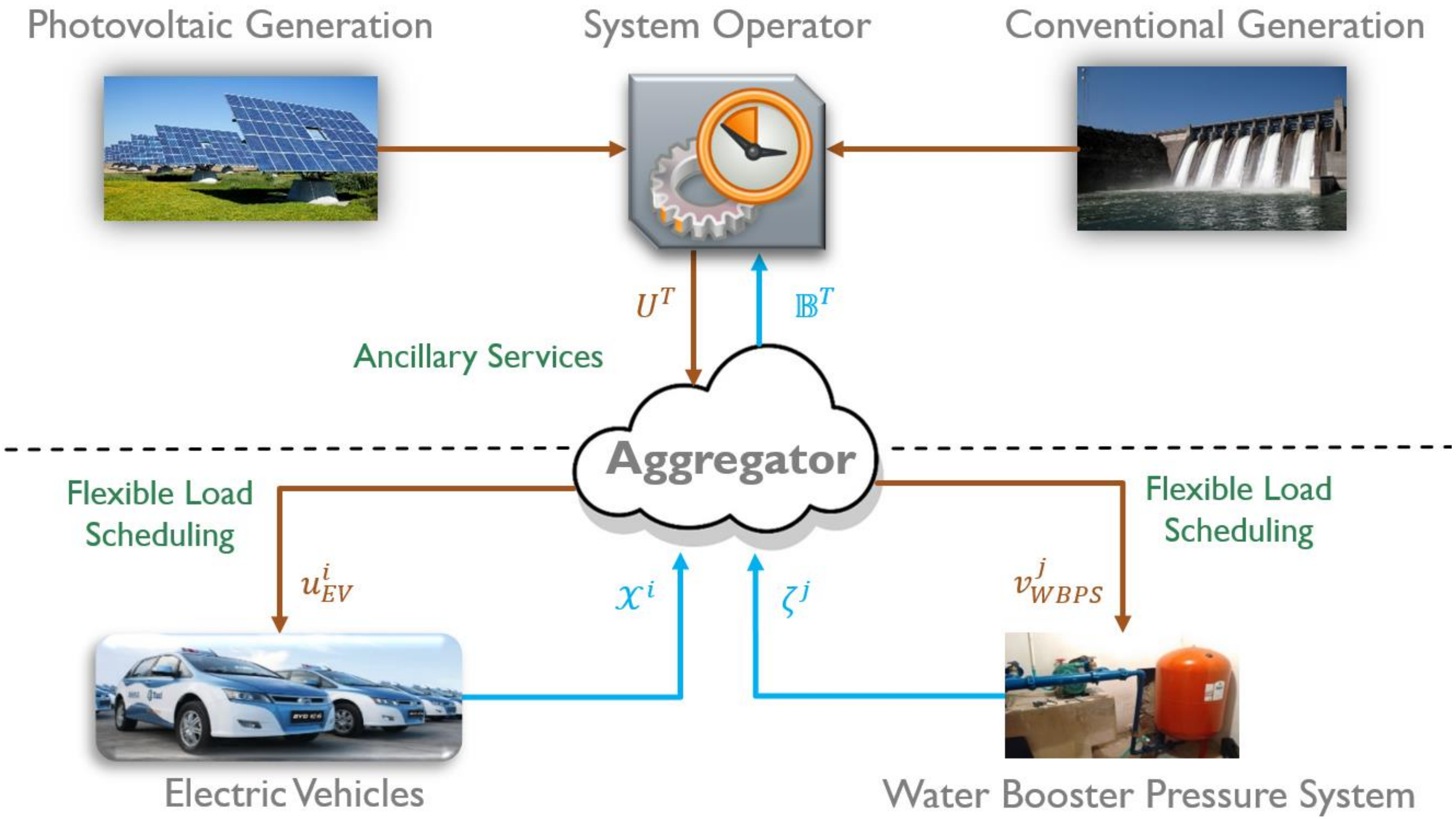
EFFICIENT APPLIANCES

EFFICIENT BEHAVIOR

Demand Response

Objective: to maintain the energy balance.

- Demand response takes advantage of flexible loads.
- To provide ancillary services to the electrical grid.



Flexible loads

What is a flexible load?

Flexible load: A load is said to be flexible if its power consumption can be modified with respect to an scheduled demand.

- Interruptible: Stop consumption
- Deferrable: Shift consumption

Baseline: Expected energy consumption of a given load when it does not provide any flexible service.

- Counterfactual model
- Critical information for operation and rewards

Flexible loads

- Is it possible to modify the power consumption of the following loads, WITHOUT heavily affecting the service they offer?

Lighting systems

- Interruptible

or

- Deferrable

Flexible loads

- Is it possible to modify the power consumption of the following loads, WITHOUT heavily affecting the service they offer?

Electric Vehicles

- Interruptible

or

- Deferrable

Flexible loads

- Is it possible to modify the power consumption of the following loads, WITHOUT heavily affecting the service they offer?

Pool Pumping Systems

- Interruptible

or

- Deferrable

Flexible loads

- Is it possible to modify the power consumption of the following loads, WITHOUT heavily affecting the service they offer?

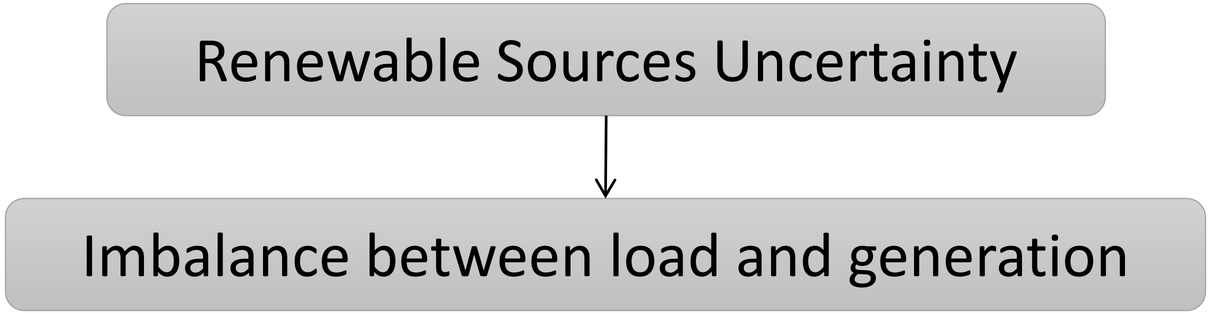
Thermostatically controlled Loads

- Interruptible

or

- Deferrable

Problem Context

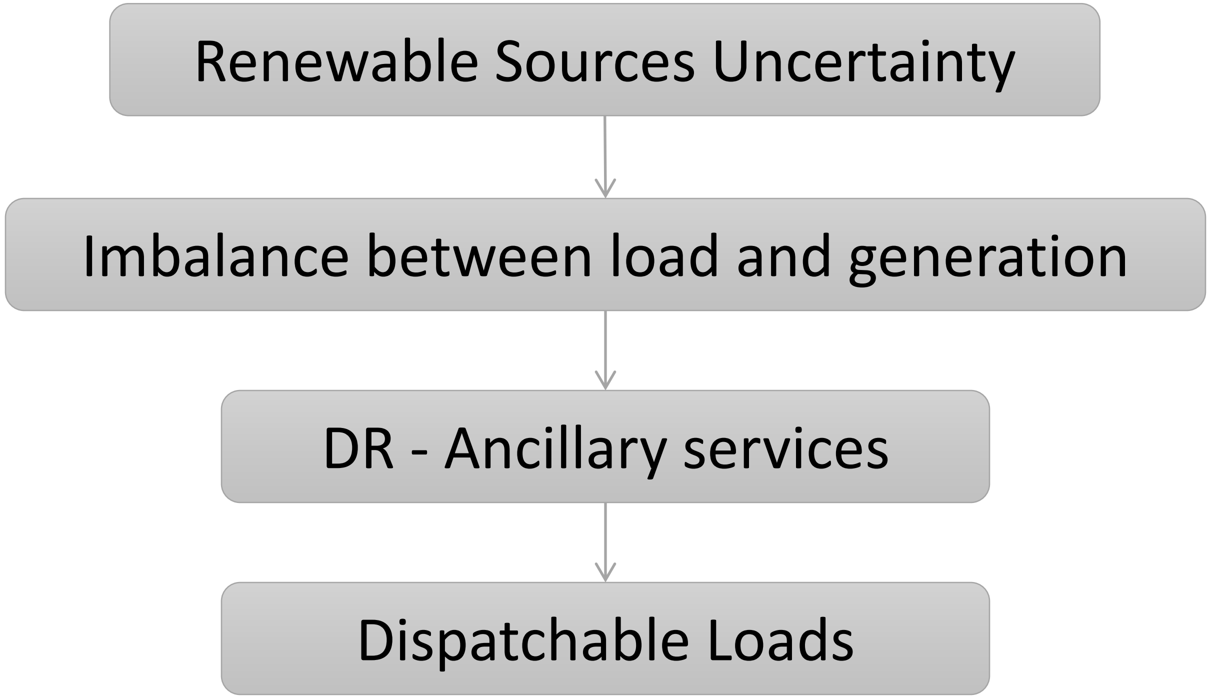


Renewable Sources Uncertainty

↓

Imbalance between load and generation

Problem Context



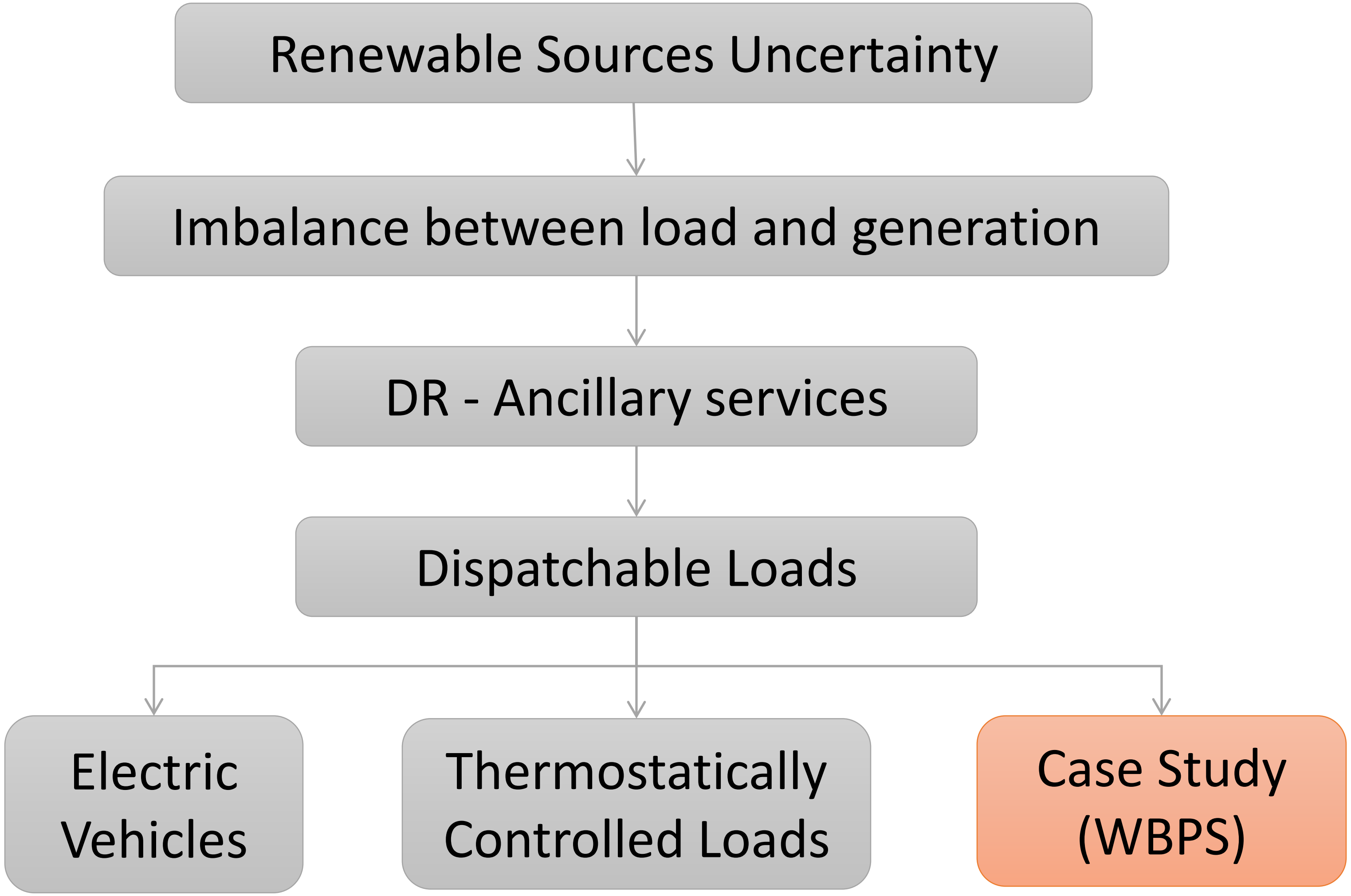
Renewable Sources Uncertainty

Imbalance between load and generation

DR - Ancillary services

Dispatchable Loads

Problem Context



Renewable Sources Uncertainty

Imbalance between load and generation

DR - Ancillary services

Dispatchable Loads

Electric Vehicles

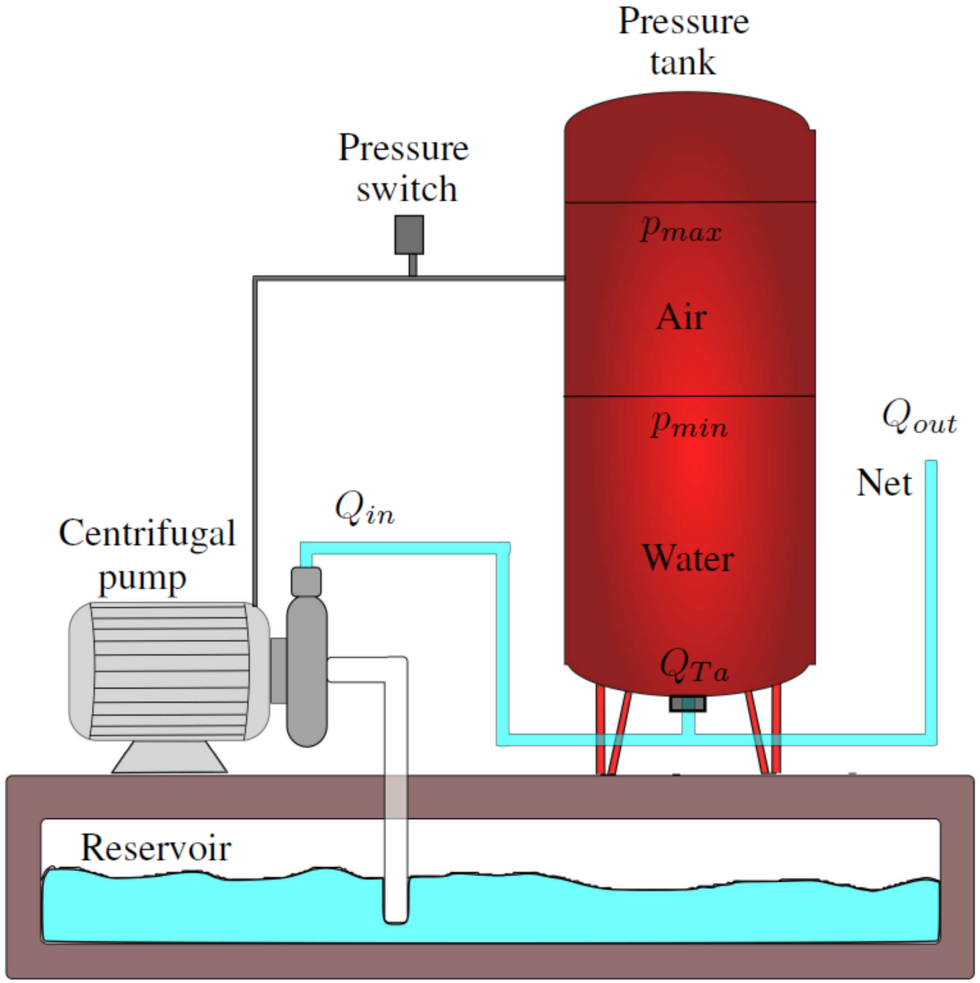
Thermostatically Controlled Loads

Case Study (WBPS)

Water Booster Pressure System

- Plenty of buildings are using these hydraulic systems.

- They are potentially useful to offer energetic services.

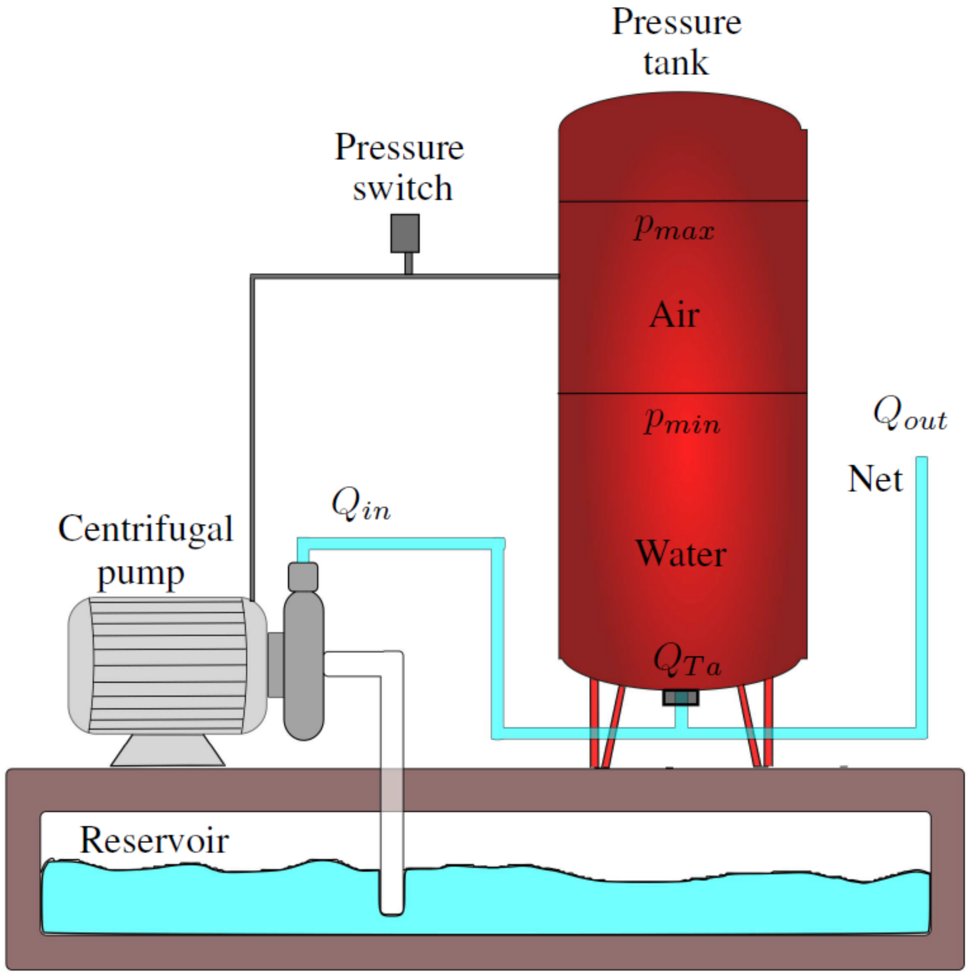


Preliminary results
Water Booster Pressure System (WBPS)

- Plenty of buildings are using these hydraulic systems.
- They are potentially useful to offer energetic services.

  - Variables:

Input → $Q_{in}(t)$
Output → $P_{Cp}(t)$
State → $Q_{Ta}(t)$



Dynamic Model

- WBPS Dynamics:

$$\dot{V}_f(t) = Q_{Ta}(t) = Q_{in}(t) - Q_{out}(t)$$

$$p_{air}(t) = (p_{pr} + p_a)\frac{V_T}{V_T - V_f(t)} - p_a$$

$$P_{Cp}(t) = \frac{(p_{air}(t) - p_a) * Q_{in}(t)}{c_u \eta}$$

$$Q_{in}(k\Delta t) = \begin{cases} Q_{Cp} & if \quad p_{air}(k\Delta t) \leq p_{min} \\ Q_{in}((k-1)\Delta t) & if \quad p_{min} < p_{air}(k\Delta t) < p_{max} \\ 0 & if \quad p_{air}(k\Delta t) \geq p_{max} \end{cases}$$

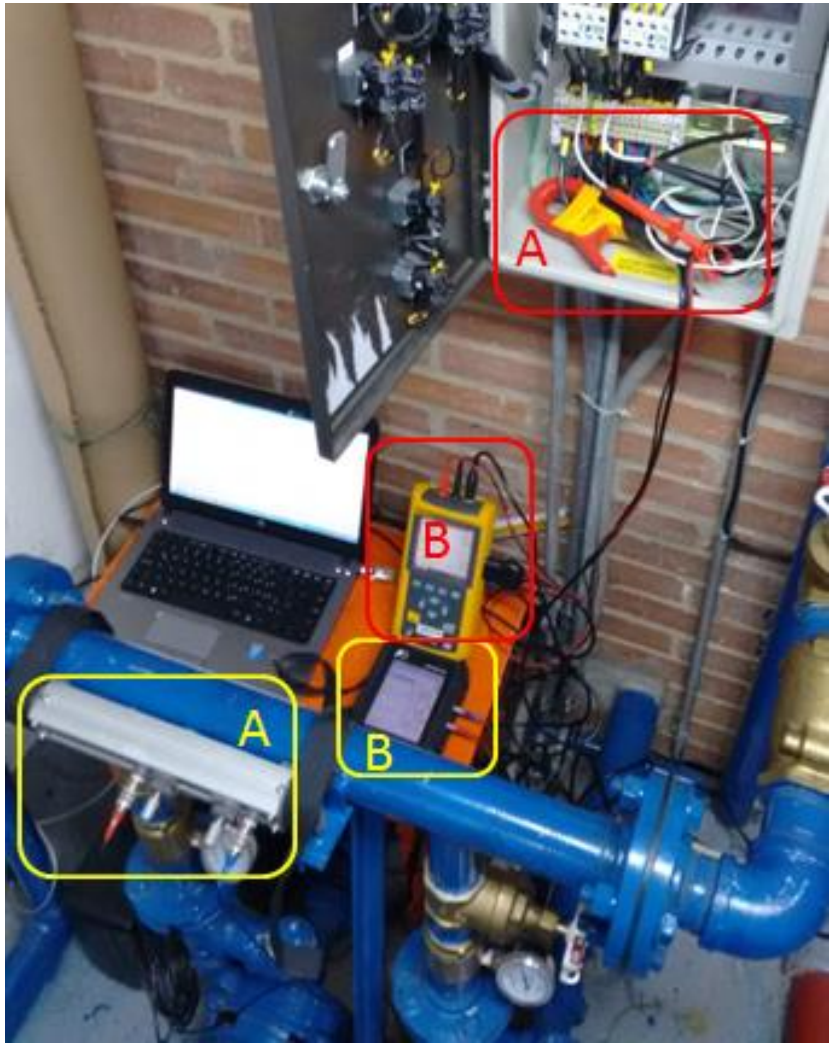
- Minimum pressure in the highest taps

$$p_{min} > \rho g h + p_{tap}$$

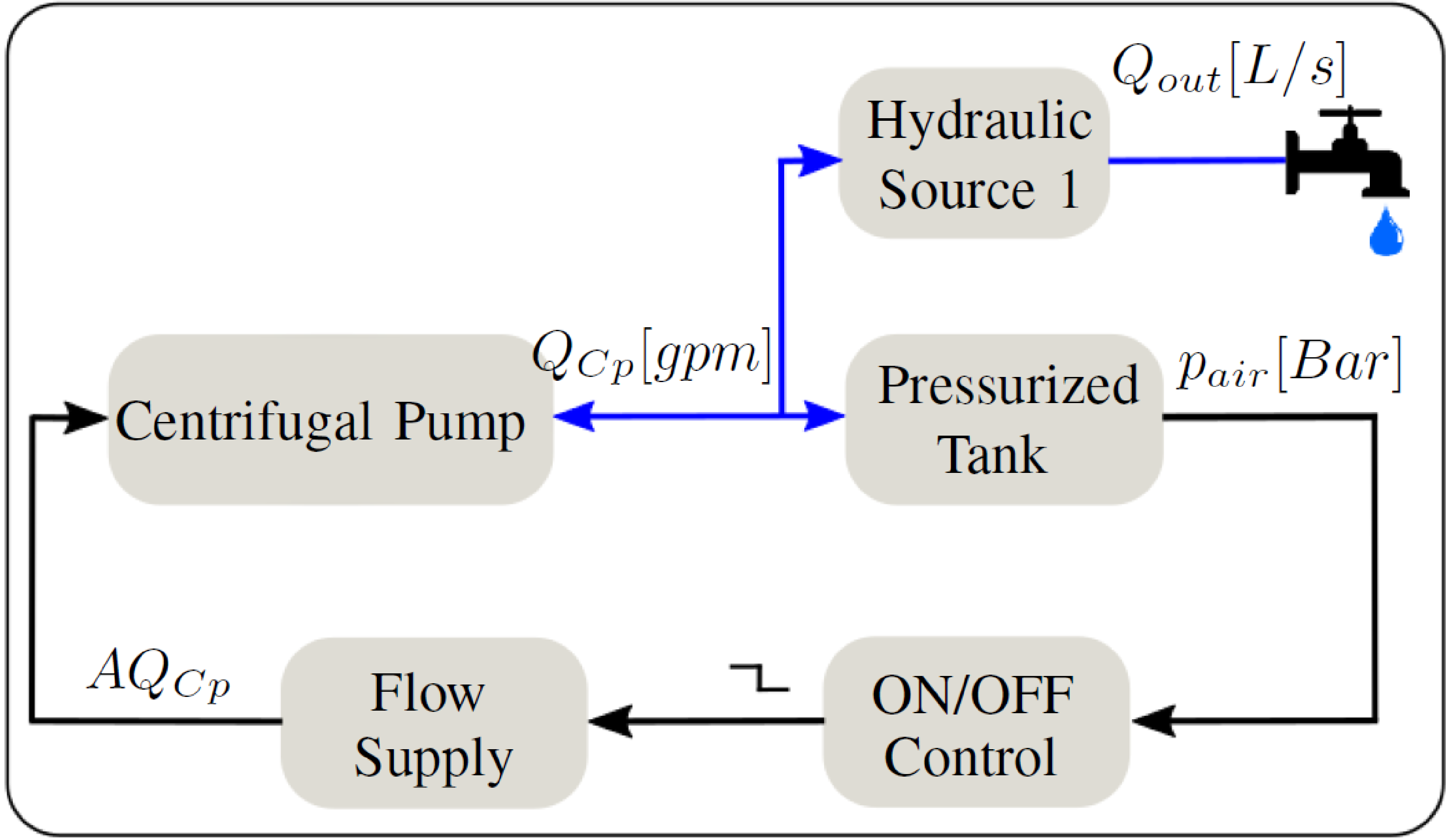
Experimental data acquisition

They were recorded from the WBPS of a 6-floor building of labs and offices.

P_{Cp} and Q_{out}, $T_s = 10s$



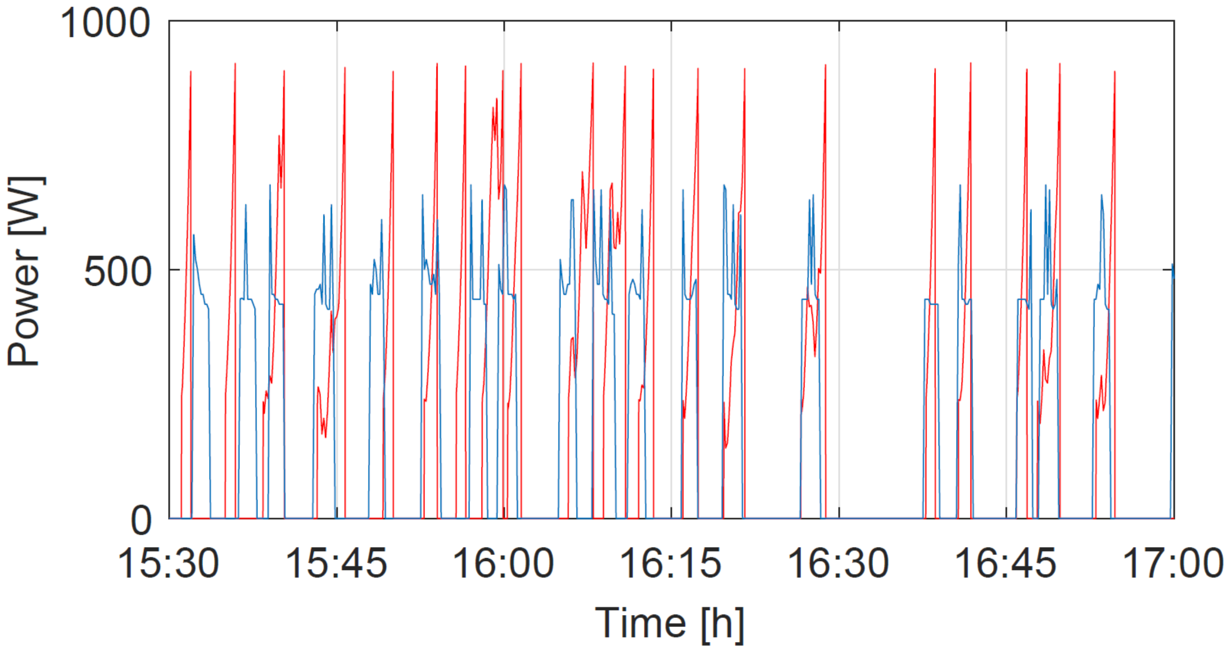
Simulation



It is performed in MATLAB® software using Simulink

Validation

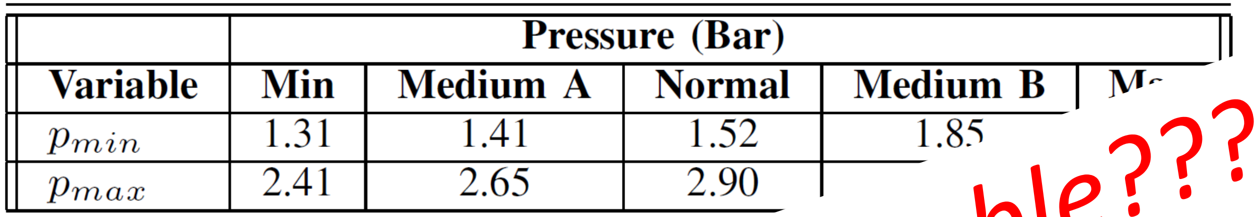
Power consumed in the experimental data (blue) and simulated (red) pump.



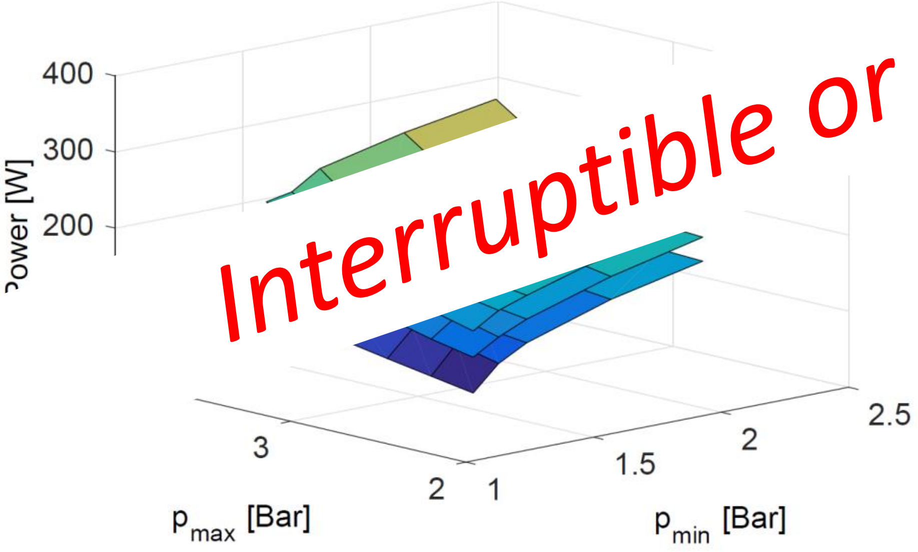
Validation	Energy consumption	Time the pump is ON
Experimental	148,6 Wh	29 min 20 s
Simulation	145 Wh	30 min 0 s

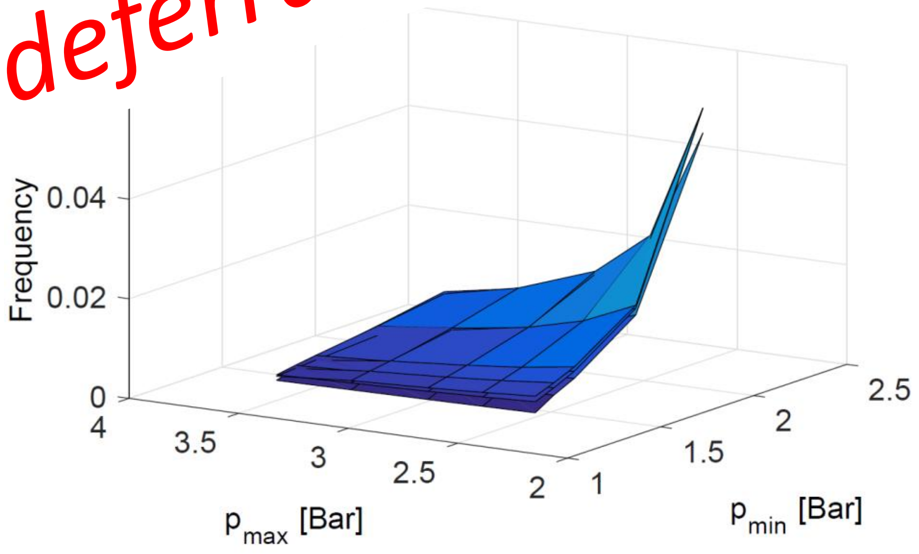
The energy error is 2,42%.

How would the power consumption be altered by varying pressures p_{min} and p_{max}?



	Pressure (Bar)				
Variable	**Min**	**Medium A**	**Normal**	**Medium B**	**Ma**
p_{min}	1.31	1.41	1.52	1.85	
p_{max}	2.41	2.65	2.90		





Interruptible or deferrable????

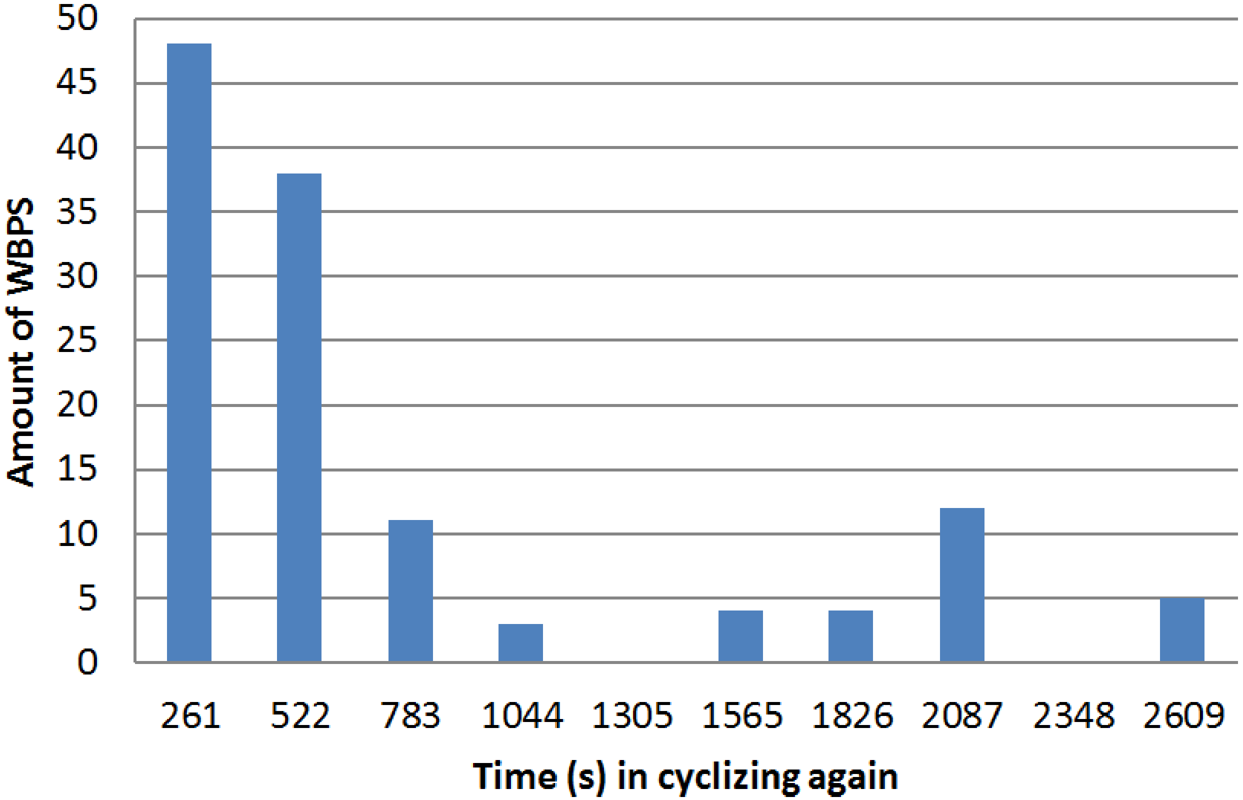
Analysis of Energy Services

Power consumption can be altered by varying pressures p_{min} and p_{max}.

- Pressure in p_{tap} is reduced 25%.
- Water supply does not stop at any moment.

The average power decrease is 27%.

Analysis of Energy Services



Approximately 70% of the systems are delayed less than 540 s (9 min) for cycling again.

Analysis of Energy Services

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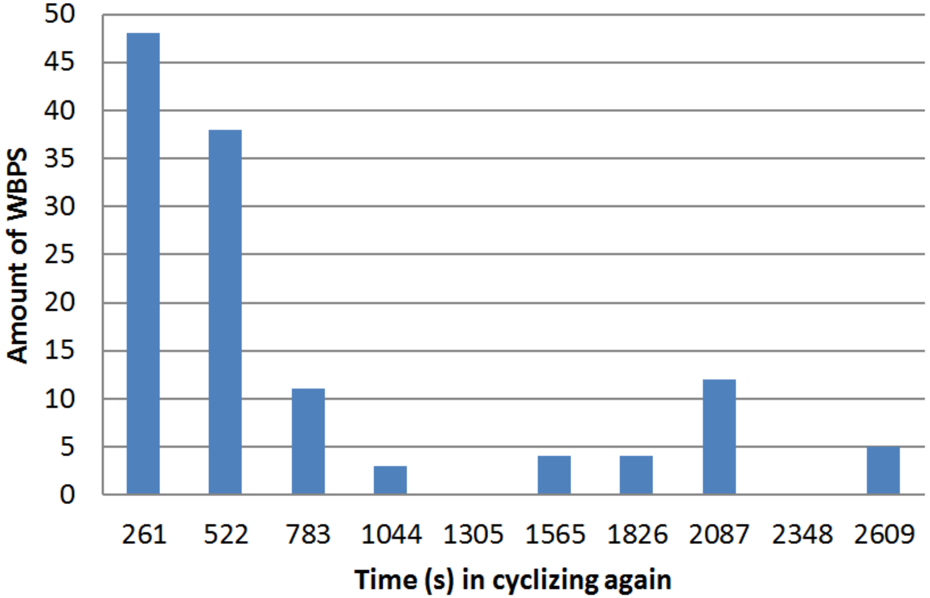

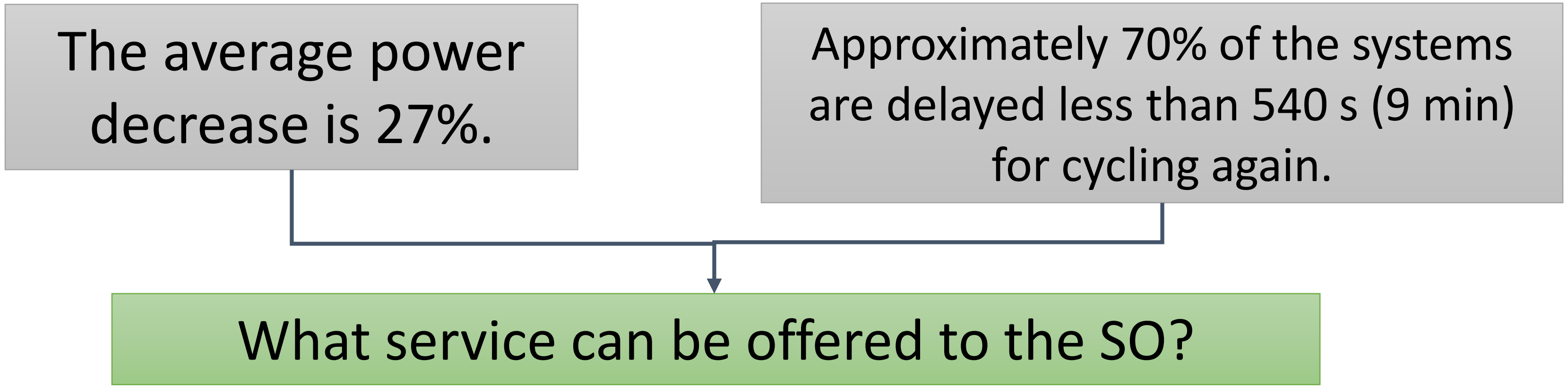

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What service can be offered to the SO?

According to the energy services usually employed by SO, which service can a WBPS provide?

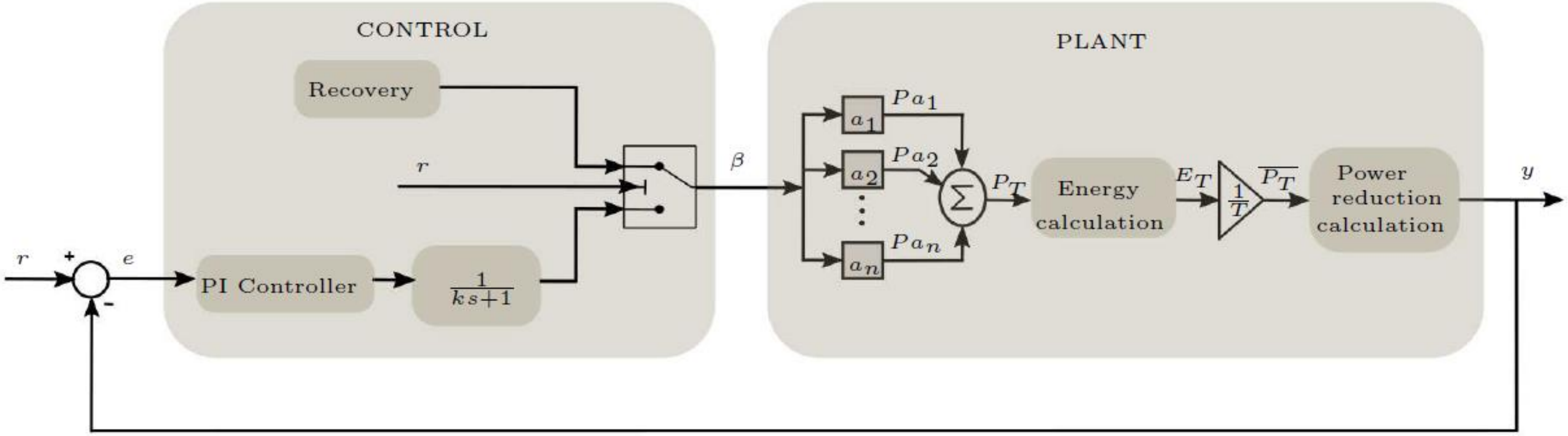
- According to the FERC (Federal Energy Regulatory Commission) definitions of reserves services are:

Reserve service	Time response (Within)	Maintained time
Regulation reserve	15 - 30 s	10 or 15 min
Spinning reserve	10 min	105 min
Non-spinning reserve	10 min	105 min
Replacement reserve	30 min	105 min

Reserve service	Valuable economically for SO
Non-spinning reserve	2 to 8 times
Replacement reserve	2 to 20 times

Aggregator Proposal

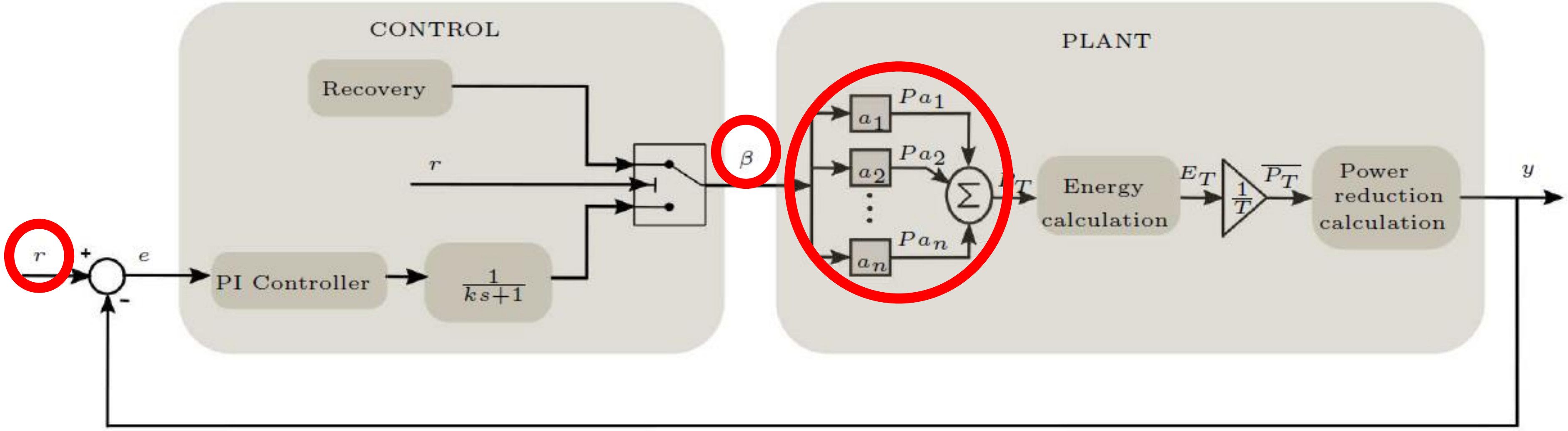
- Control strategy to provide Spinning reserve service.



- Controlled variable: y, a power reduction of the set of WBPSs.
- Manipulated variable: β, number of systems that should be enabled or disabled. Each system receives a binary signal.
- Reference signal: r, power reduction sent by the SO.

Aggregator Proposal

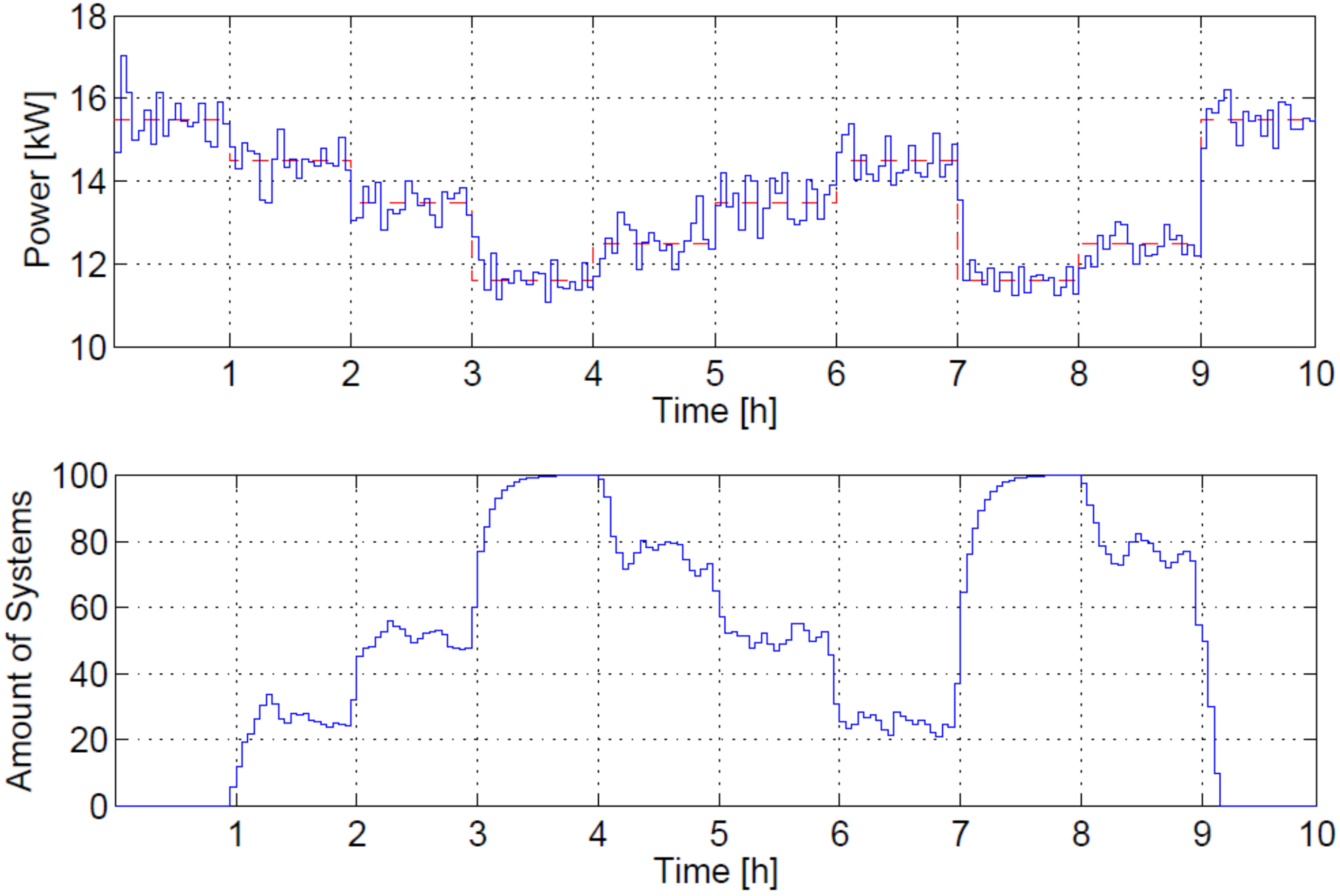
- Control strategy to provide Spinning reserve service.



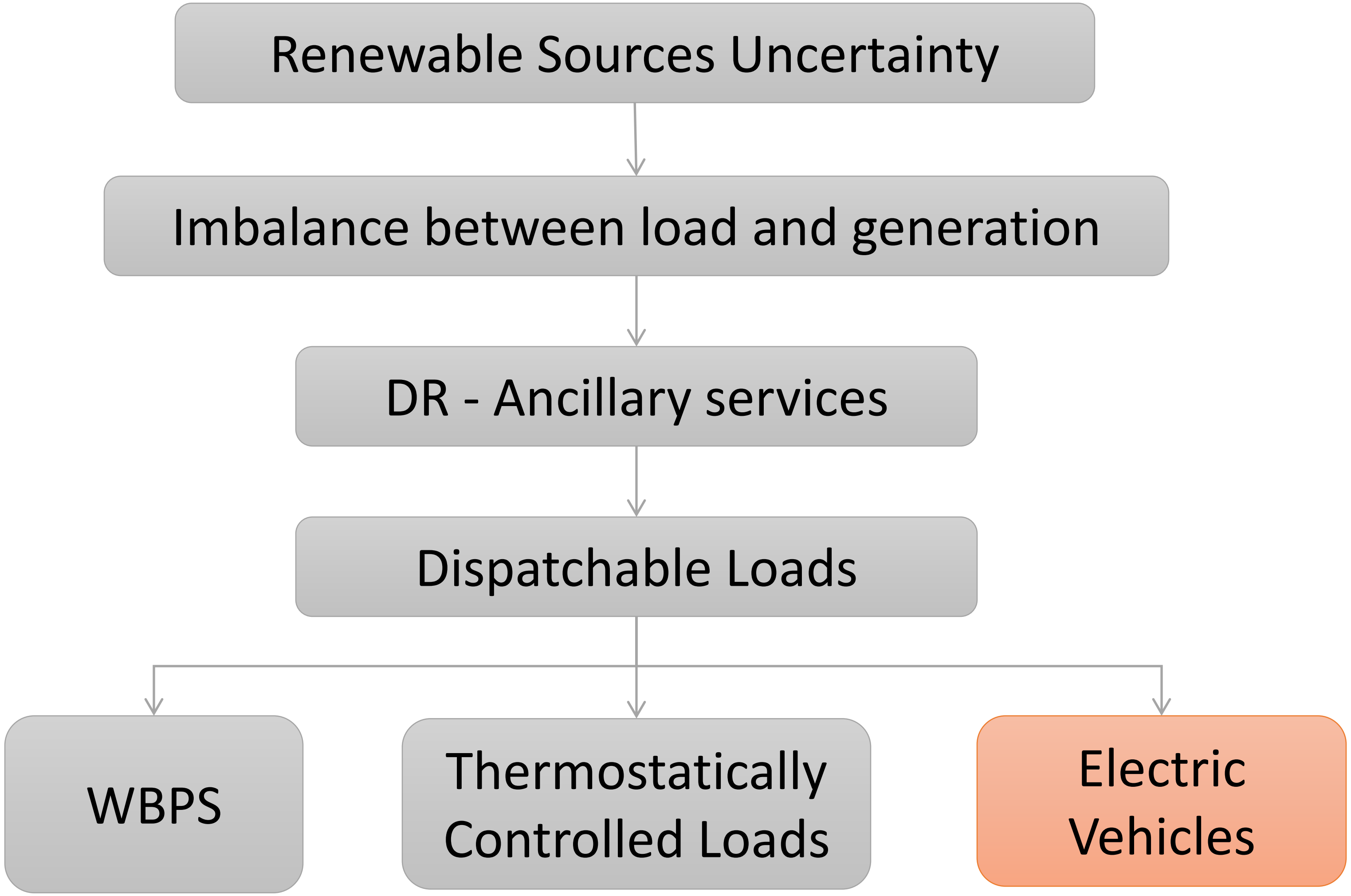
- ➢ <u>Controlled variable</u>: y, a power reduction of the set of WBPSs.
- ➢ <u>Manipulated variable</u>: β, number of systems that should be enabled or disabled. Each system receives a binary signal.
- ➢ <u>Reference signal</u>: r, power reduction sent by the SO.

Aggregator Proposal

- ➢A Gain-Scheduled (GS) controlled is proposed.
- ➢The aggregator follow time-varying reduction signals (red) requested by the system operator.



Problem Context



Renewable Sources Uncertainty

Imbalance between load and generation

DR - Ancillary services

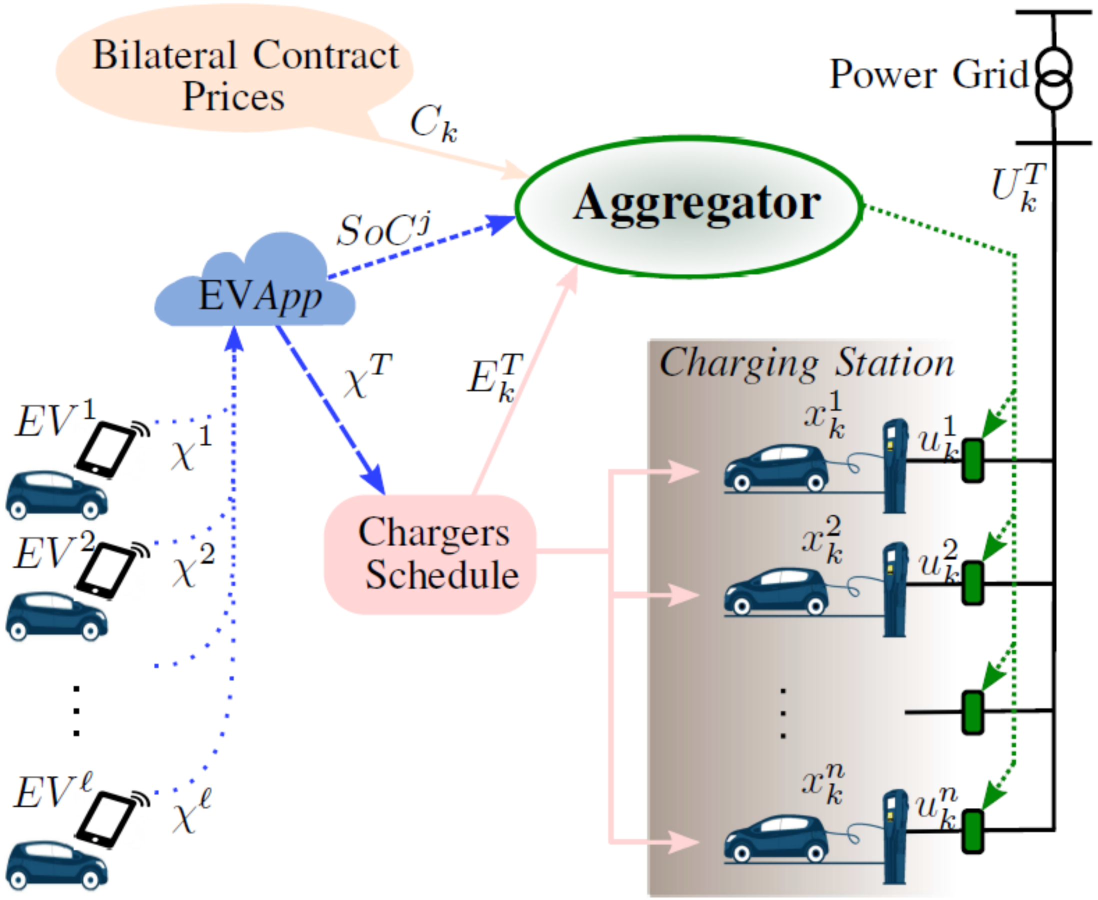
Dispatchable Loads

WBPS

Thermostatically Controlled Loads

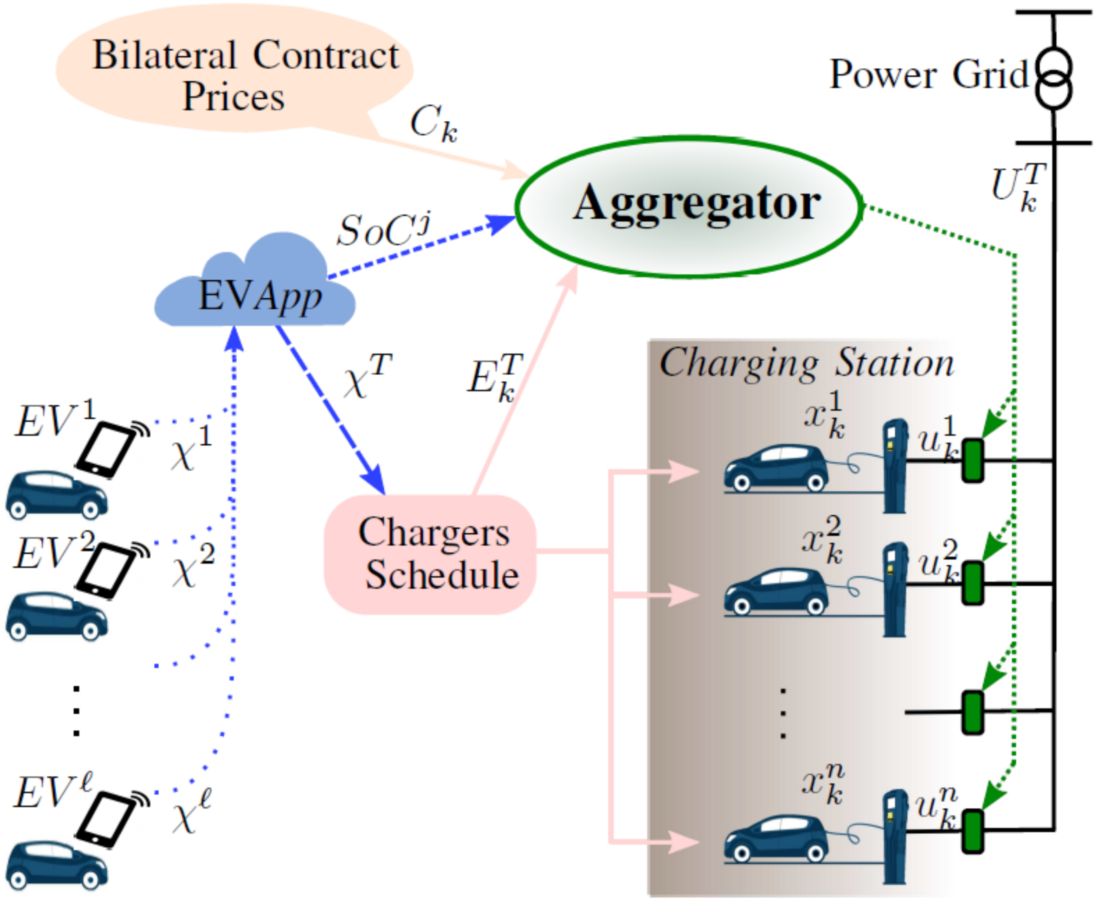
Electric Vehicles

Aggregator for an Electric Vehicle Charging Station



- EV batteries can behave as flexible loads.
  - Varying the charging power.
- The EV need to be charged up to a required SoC.
- 3 charging strategies are analyzed
  - Standard
  - MPC with complete information
  - MPC with uncertainty in the EV arrival SoC
- The aggregator (MPC) decides the power to charge EV depending on:
  - Energy price
  - Time spent by EVs at the charging station

Aggregator for an Electric Vehicle Charging Station



- How can we model the SoC evolution (dynamic model)?
- What happens when a car arrives or leaves the Charging station?
- Do we need to consider the discharge process while the car moves around?
- NOVEL APPROACH:
  - The system that evolves in time is the Charger NOT the Car.
  - A charger can handle multiple cars in one day
  - The SoC of the plugged car evolves with the battery dynamics
  - When a car leaves, the charger can not act as a flexible load
  - When a car arrives, the system state "jumps" to the car SoC.

Aggregator for an Electric Vehicle Charging Station

- Economic dispatch problem taking into account chargers:

$$\min_{u} \quad J = \Delta t \sum_{k=1}^{N} \left(C_k \sum_{i=1}^{n} u_k^i \right)$$

$$\text{s.t.} \quad x_{k+1}^i = \begin{cases} x_k^i + \Delta t u_k^i & \text{if} \quad E_k^i = 1, \quad k \neq a^j \\ SoC_0^j & \text{if} \quad E_k^i = 1, \quad k = a^j \\ 0 & \text{if} \quad E_k^i = 0 \end{cases}$$

$$x_{d^j}^i = SoC_F^j$$

$$0 \leq x_k^i \leq x_{max}^i$$

$$0 \leq u_k^i \leq u_{max}$$

$$\forall\ k = 1, 2, ..., N, \quad i = 1, 2, ..., n \quad j = 1, 2, ..., \ell$$

$$E_k^i = \begin{cases} 1 & \text{if} \quad x^i \text{ has an EV connected at } k \\ 0 & \text{if} \quad x^i \text{ has not an EV connected at } k \end{cases}$$

- Dealing with Uncertainty:
  - The optimal power injection sequence *u(1),… u(N),* does not take into account variation in arrival times, initial SoC, ….
  - A feedback strategy is needed to counteract uncertain events.
  - MPC solution!

Aggregator for an Electric Vehicle Charging Station

- Economic dispatch problem taking into account chargers: dynamics

$$\min_{u} \qquad J = \Delta t \sum_{k=1}^{N} \left(C_k \sum_{i=1}^{n} u_k^i \right)$$

$$\text{s.t.} \qquad x_{k+1}^i = \begin{cases} x_k^i + \Delta t u_k^i & \text{if} \quad E_k^i = 1, \quad k \neq a^j \\ SoC_0^j & \text{if} \quad E_k^i = 1, \quad k = a^j \\ 0 & \text{if} \quad E_k^i = 0 \end{cases}$$

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- MPC solution:
  - Optimization problem solved at every sample time *Δt*.
  - Only the first simple of the optimal power injection sequence *u(1),… u(N)* is applied.
  - The SoC of connected vehicles is MEASURED at *t+ Δt,* and
  - Optimization problem is solved again.

Aggregator for an Electric Vehicle Charging Station

- Economic dispatch problem taking into account chargers dynamics

$$\min_{u} \quad J = \Delta t \sum_{k=1}^{N} \left(C_k \sum_{i=1}^{n} u_k^i \right)$$

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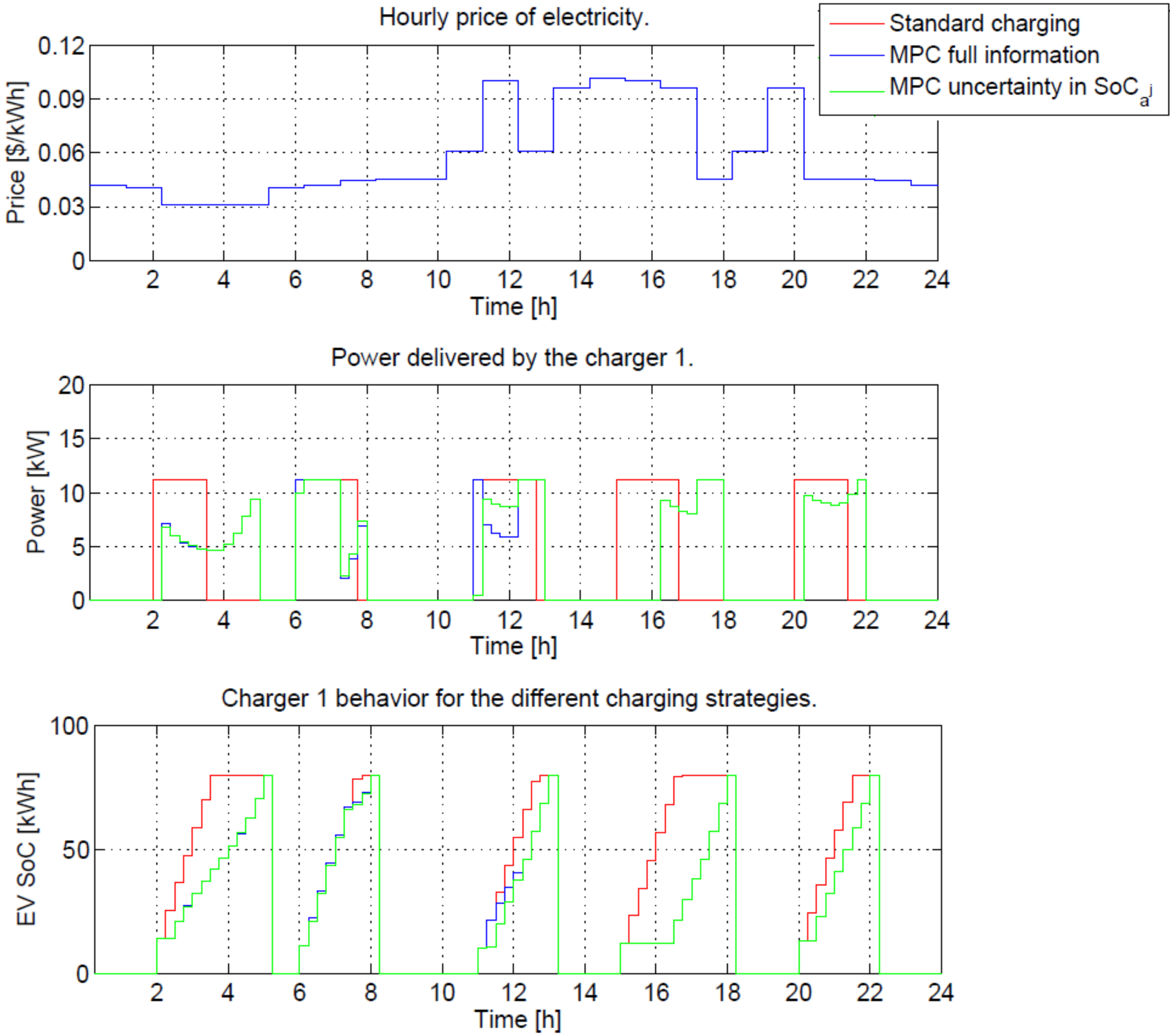
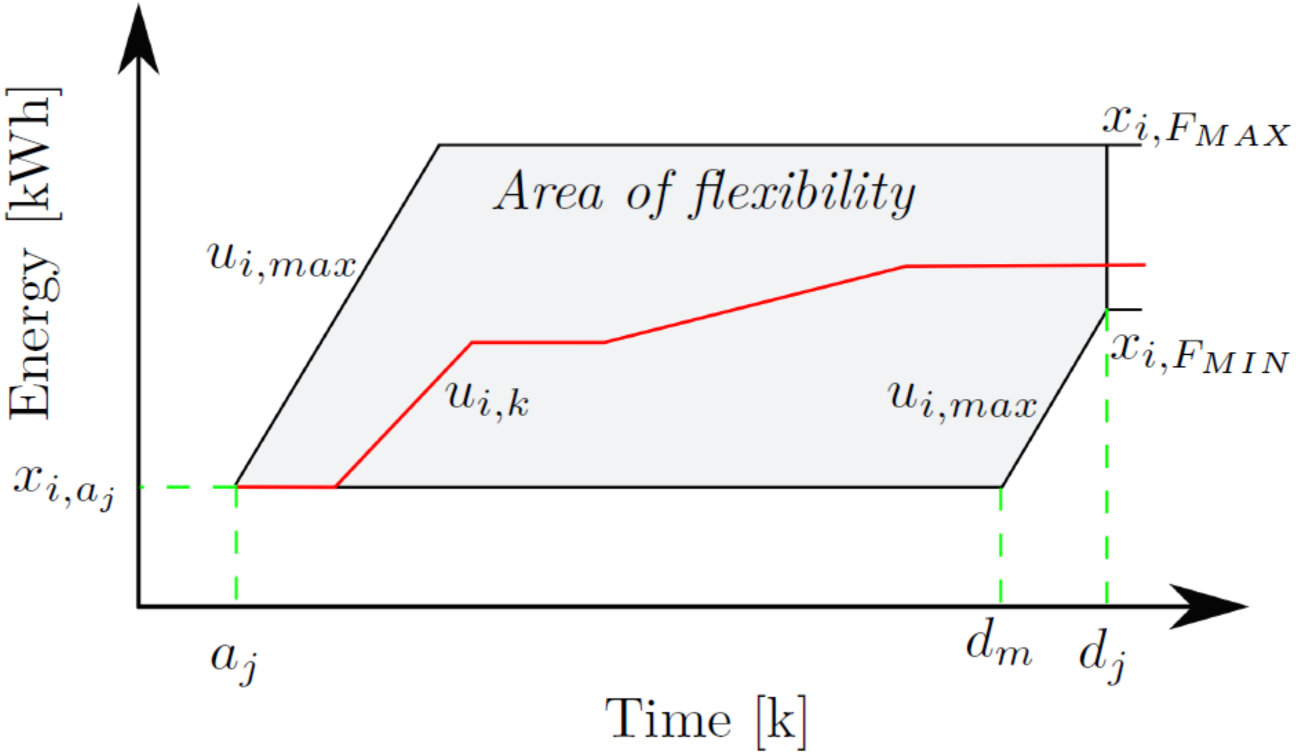


EV Charger as Flexible Load

Flexibility: Power capacity that the charging station can deviate from the optimal scheduling, WITHOUT violating constraints.



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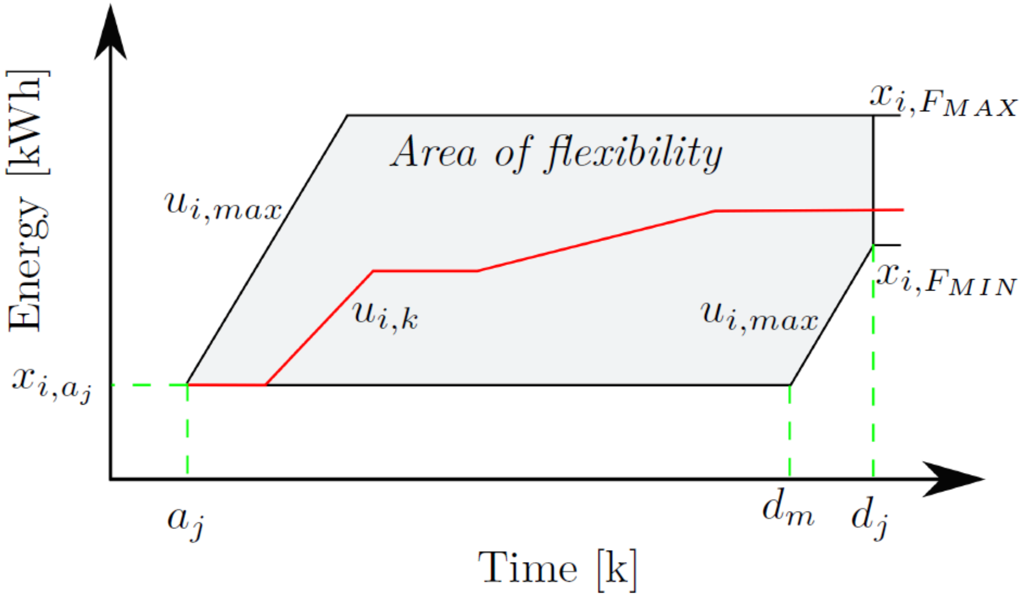


$$F_k = \sum_{i=1}^{n} Up_{i,k}^{Flex} - Down_{i,k}^{Flex}$$

$$Up_{i,k}^{Flex} = \begin{cases} u_{max} - u_{i,k} & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \& \ k < d_m \\ 0 & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \& \ k \geq d_m \\ 0 & \text{if} \quad x_{i,k} = x_{i,max} \text{ or } x_{i,k} = 0 \end{cases}$$

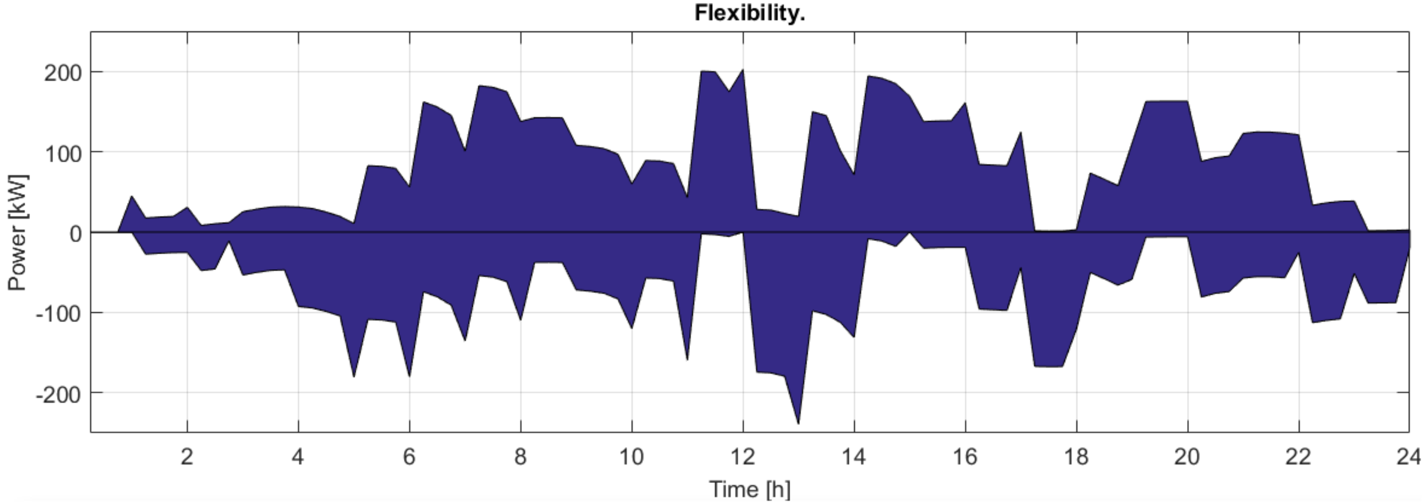
$$Down_{i,k}^{Flex} = \begin{cases} -u_{i,k} & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \& \ k < d_m \\ 0 & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \& \ k \geq d_m \\ 0 & \text{if} \quad x_{i,k} = x_{i,max} \text{ or } x_{i,k} = 0 \end{cases}$$

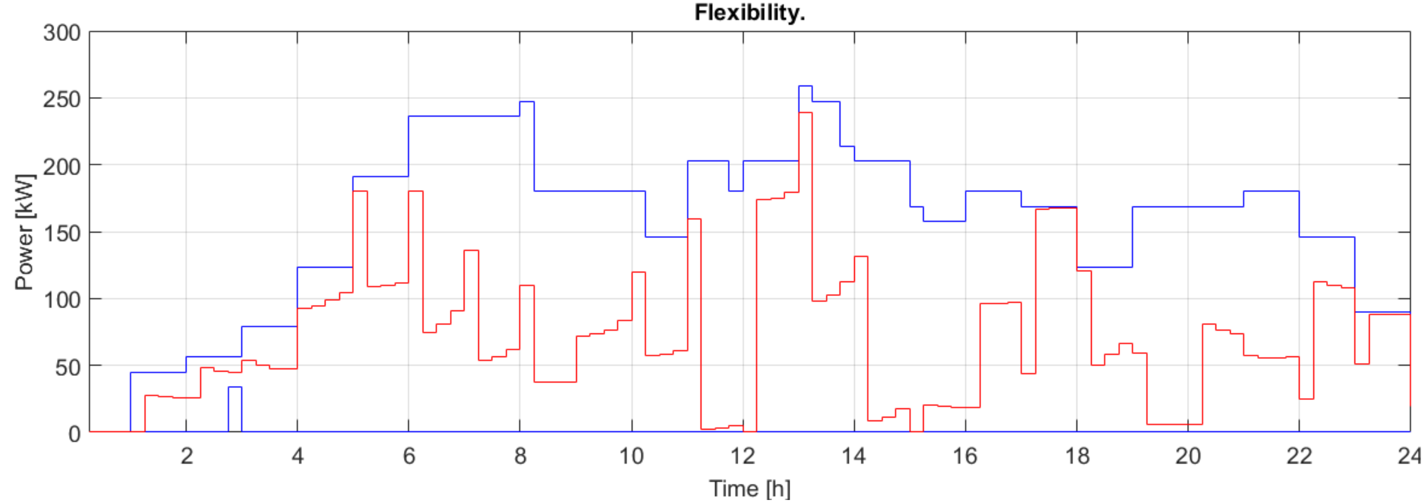
EV Charger as Flexible Load

Flexibility of a dispatch:

- ➢Evaluated after the dispatch problem is solved
- ➢It is not symmetric
- ➢Varies with prices

¿Can we modify the dispatch to guarantee some flexibility capacity?





Maximizing flexibility

Economic MPC with combined objective:

$$\min_{u,F} \quad J_F = \Delta t \sum_{k=1}^{N} \left(C_k \sum_{i=1}^{n} u_{i,k} - P_k \sum_{i=1}^{n} F_{i,k} \right)$$

$$\text{s.t.} \quad x_{i,k+1} = \begin{cases} x_{i,k} + \Delta t u_{i,k} & \text{if} \quad E_{i,k} = 1, \quad a_j < k < d_j \\ SoC_{j,a_j} & \text{if} \quad E_{i,k} = 1, \quad k = a_j \\ 0 & \text{if} \quad E_{i,k} = 0 \end{cases}$$

$$x_{i,d_j} = SoC_{j,F}$$

$$F_{i,k} \leq u_{i,k} \leq E_{i,k}(u_{i,max} - F_{i,k})$$

$$0 \leq F_{i,k} \leq u_{i,max}$$

$$0 \leq x_{i,k} \leq x_{i,max}$$

$$\forall\ k = 1, 2, ..., N, \quad i = 1, 2, ..., n \quad j = 1, 2, ..., \ell$$

$$F_k = \sum_{i=1}^{n} F_{i,k} = Up_{i,k}^{Flex} = Down_{i,k}^{Flex}$$

- Guaranteed final SOC
- Balance between Min charging cost and Ancillary service return

$$F_k = \sum_{i=1}^{n} Up_{i,k}^{Flex} - Down_{i,k}^{Flex}$$

Where,

$$Up_{i,k}^{Flex} = \begin{cases} u_{max} - u_{i,k} & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \&\ k < d_m \\ 0 & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \&\ k \geq d_m \\ 0 & \text{if} \quad x_{i,k} = x_{i,max} \text{ or } x_{i,k} = 0 \end{cases}$$

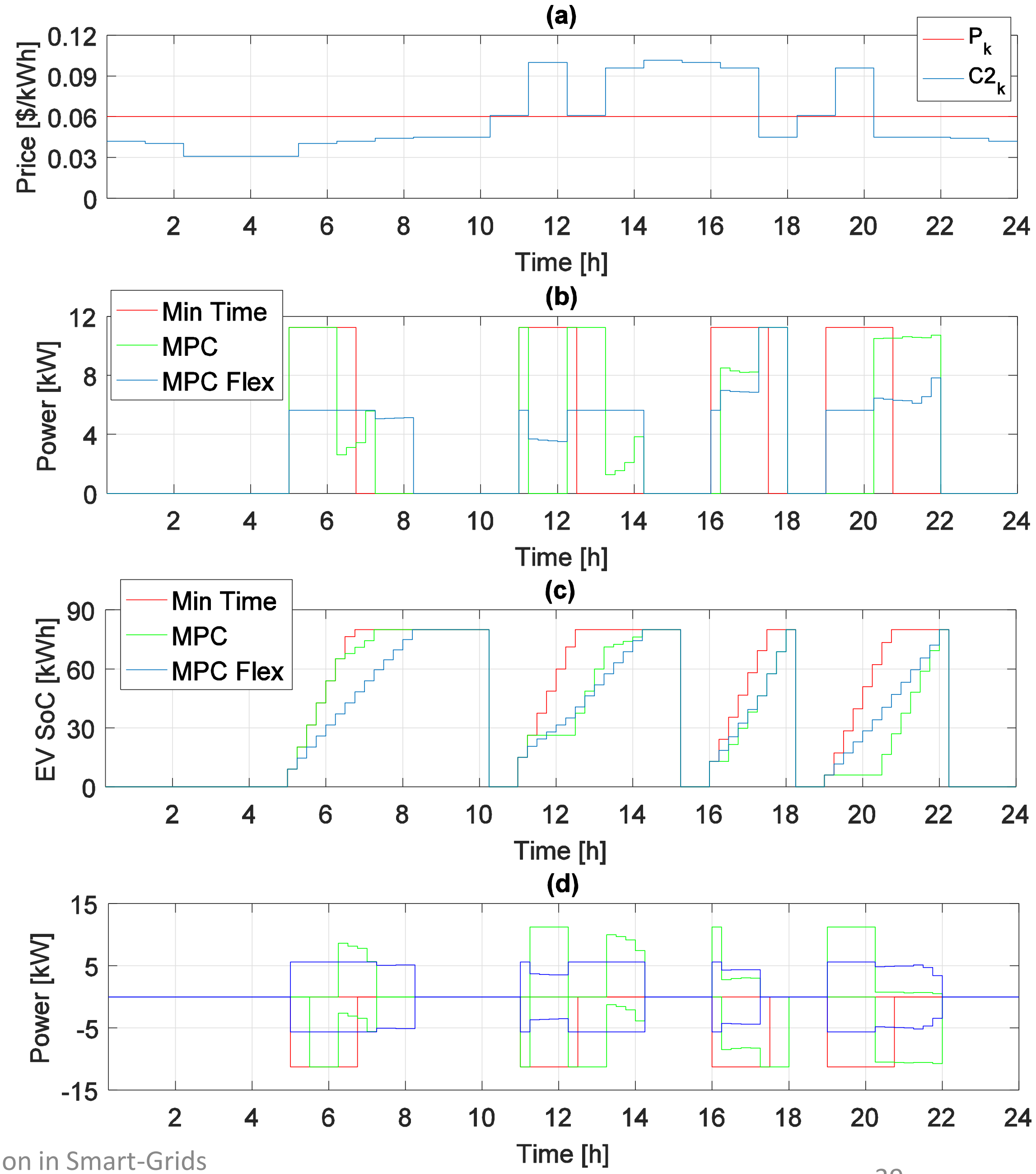
$$Down_{i,k}^{Flex} = \begin{cases} -u_{i,k} & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \&\ k < d_m \\ 0 & \text{if} \quad 0 < x_{i,k} < x_{i,max} \ \&\ k \geq d_m \\ 0 & \text{if} \quad x_{i,k} = x_{i,max} \text{ or } x_{i,k} = 0 \end{cases}$$

Case Study

- 10 EV y 3 Chargers

EV_j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
a_j	1	5	8	11	11	12	15	16	19	19
d_j	5	10	13	15	13	15	20	18	22	21
Charger #	1	**2**	1	**2**	3	-	1	**2**	**2**	3

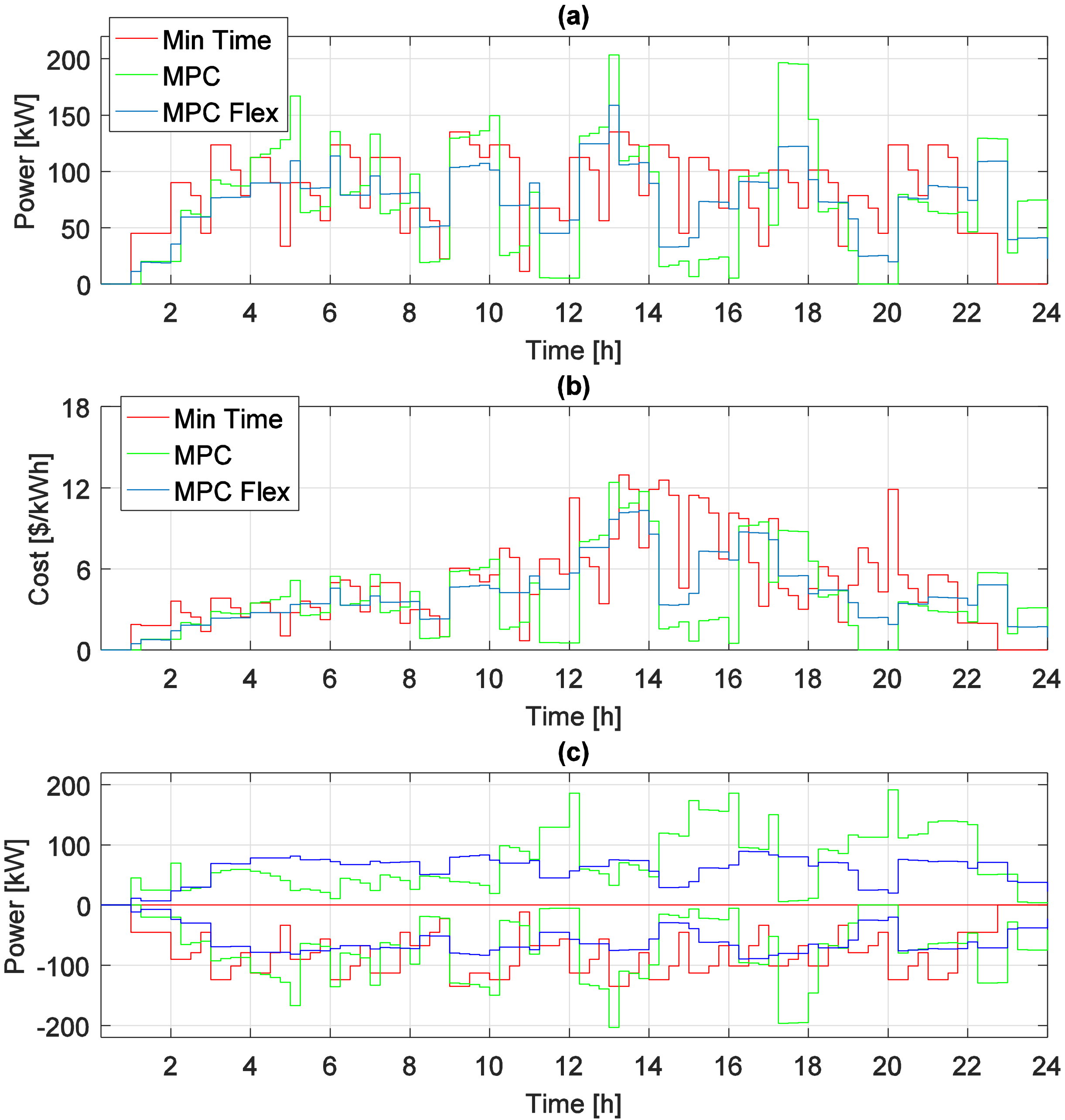
Charge Strategy	**Cost [$]**	**Savings [%]**
Minimum Time	46.73	-
Economic MPC	34.24	26.74
MPC - Flexibility Maximization	43.18	7.61



Case Study

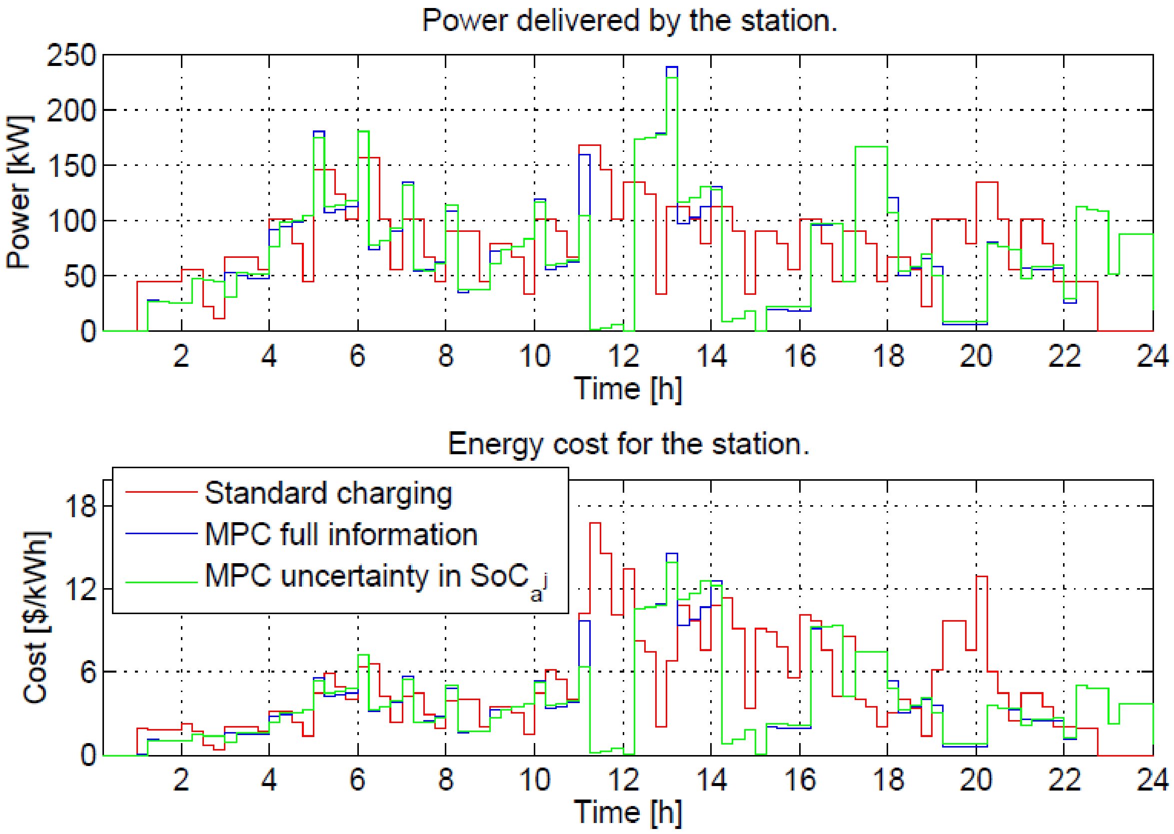
- 100 EV y 25 Chargers

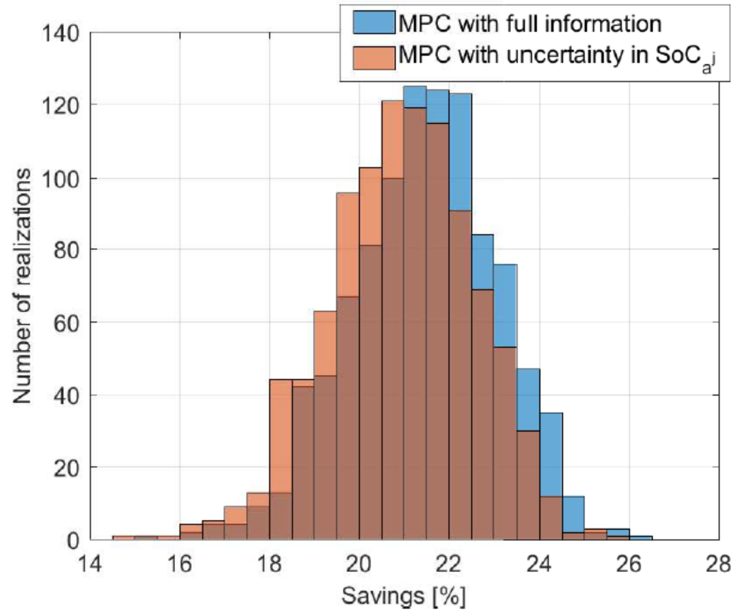
Charge Strategy	Cost [$]	Savings [%]
Minimum Time	454.35	-
Economic MPC	356.19	21.61
MPC - Flexibility Maximization	392.38	13.64



Case Study

- A Monte Carlo simulation is performed with 1000 realizations.
- There are used 25 chargers and 100 EVs



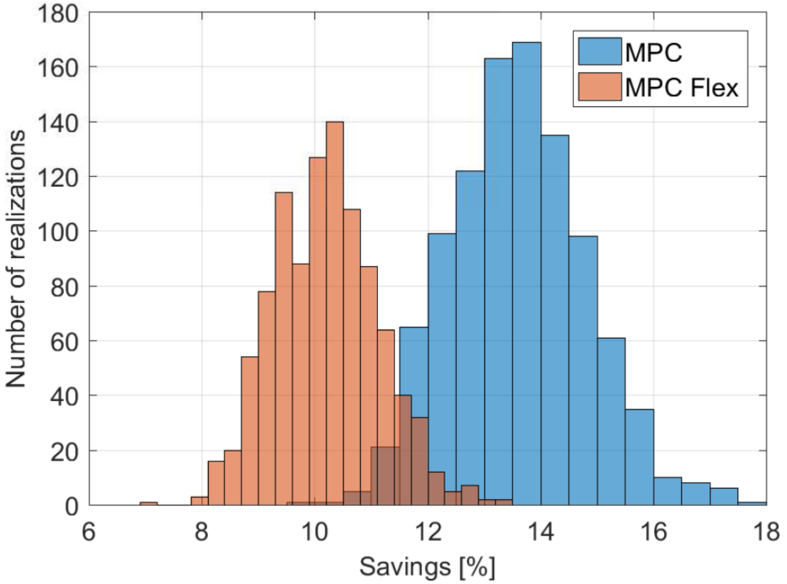


Average saving: 21%

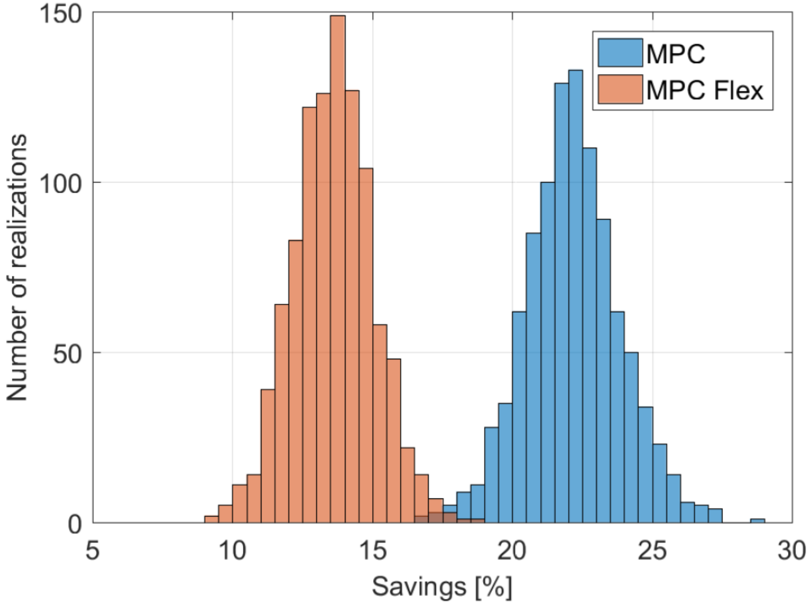
Case Study

1000 iterations, randomizing EV arrival and departure time and Arrival SoC.

Price 1



Price 2



Charge Strategy	Average Cost [$]	Minimum Saving	Average Savings	Maximum Saving
Minimum Time	456.07	-	-	-
Economic MPC	394.06	9.80%	13.59%	17.91%
MPC - Flex Max	409.51	7.01%	10.20%	13.27%

Charge Strategy	Average Cost [$]	Minimum Saving	Average Savings	Maximum Saving
Minimum Time	433.80	-	-	-
Economic MPC	337.67	16.57%	22.15%	28.73%
MPC - Flex Max	374.75	9.14%	13.60%	18.63%

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