# Competition and Coalition for Smart Energy Supply

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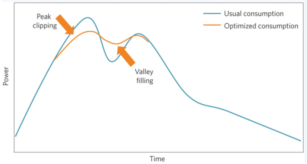
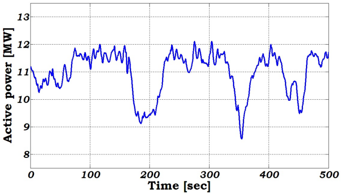
# Context: flexibility integration

- Flexibility = Deferrable/alternative loads.




- Need for flexibility: high penetration of renewables (unpredictable energy sources such as wind, solar, etc.).




(source: Margaris et al. (2011))

# Implementing flexibility

## How to implement flexibility?

- Price-based demand response (real-time pricing, critical-peak pricing, time-of-use, etc.) [Li et al. *water filling algorithm*, Vasirani et al.].
- Incentive-based demand response
  refunds [Chao et al. *menu based load increment differentiation*].
- Storage

# Context: aggregators entering the electricity market

## Aggregators (Flexibility Service Provider FSP)

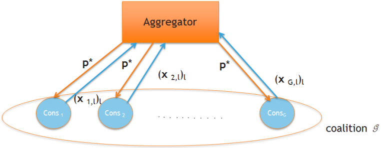
- New entrants on the electricity market
- Can group and manage flexibility of clusters of flexible consumers
- Offer demand response services to different power system participants.

Potential advantages from the consumers' perspective:

- Benefits of demand response mechanism (e.g., better service)
- A lower bill at the end of the month.

# Questions

- How should an aggregator price his services so as to reach a targeted profit?
- How should this targeted profit be defined so as to guarantee that none of his clients switches to the conventional retailer?




A Stackelberg game to model consumers (followers)-FSP (leader) interactions [Zugno et al.]

- Horizon $T > 0$ days,
- Discretization $n \in \mathbb{N}^*$ time periods per day.

# Setting the Stackelberg game

## Agents

- two suppliers in competition: aggregator vs conventional retailer,
- consumers *captive* over $nT$ time periods.

## Input

- coalition $\mathscr{G}$ fixed,
- aggregator's targeted profit $\Pi_{agg} \geq 0$,
- cost sharing mechanism chosen by the aggregator.

## Each consumer $i$ has

- a set of shiftable loads $\mathcal{L}_i$,
- a (stochastic) base load profile $\boldsymbol{d_i} = \Big(d_i(t)\Big)_{t=0}^{nT-1}$.

Shiftable loads are scheduled automatically thanks to an intelligent device.

# Consumer model

For each load $l \in \mathcal{L}_i$ consumer $i$ gives:

- intrinsic characteristics,
- priority level $k_{i,l} \in [\![1; K]\!]$.

## Reservation prices (private information)

- Maximum price the consumer is willing to pay per unit of load for each priority level.
- *Priority rule:*

$$k_{i,l} \prec k_{i,l'} \Rightarrow p_{\max,i}(k_{i,l}) > p_{\max,i}(k_{i,l'}), \forall l, l' \in \mathcal{L}_i, l \neq l'.$$

# Timing of the game - Horizon $nT$

1. **Pricing:** the aggregator determines his price profile $\boldsymbol{p}^\star = \left(p^\star(t)\right)_{t=0}^{nT-1}$ so as to reach $\Pi_{agg}$.

2. **Load scheduling:** observing $\boldsymbol{p}^\star$, each consumer $i \in \mathscr{G}$ (intelligent device) chooses the load profile $\boldsymbol{x_{i,l}} = \left(x_{i,l}(t)\right)_{t=0}^{nT-1}, \forall l \in \mathcal{L}_i$ that minimizes their bill while taking into account constraints imposed by:

   - the intrinsic characteristics of his loads,
   - (private) reservation prices.

# Scheduling the shiftable loads ($\mathcal{L}_i$)

$\mathcal{L}_i = \mathcal{B}_i \cup \mathcal{I}_i$ where $\mathcal{B}_i$ block load set and $\mathcal{I}_i$ interruptible load set.

## Load intrinsic characteristics

- *Earliest start time period:* $\underline{t_{i,l}} \in [\![0; nT-1]\!]$,
- *Latest finish time period:* $\overline{t_{i,l}} \in [\![0; nT-1]\!]$ with $\underline{t_{i,l}} \leq \overline{t_{i,l}}$,
- *Duration of the load:* $\mu_{i,l} \in [\![0; nT]\!]$, with $0 \leq \mu_{i,l} \leq \overline{t_{i,l}} - \underline{t_{i,l}}$,
- *Power rate (kW):* $w_{i,l} \in \mathbb{R}_*^+$,
- *Priority level:* $k_{i,l} \in [\![1; K]\!]$.

## Reservation price mechanism

Each load $l \in \mathcal{L}_i$ is scheduled only if

$$\boldsymbol{p}^{\star T} \boldsymbol{x_{i,l}} \leq p_{\max,i}(k_{i,l})\mu_{i,l} w_{i,l}. \tag{1}$$

# Example: daily load scheduling

Two instances with $T = 1$, $n = 144$, $K = 3$ priority levels

- Block loads

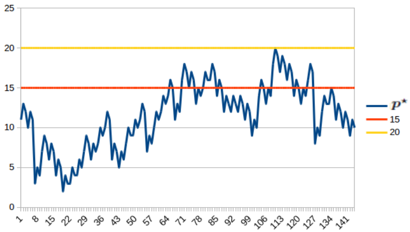
| Device | Priority | Duration | Earliest | Latest | Power |
|---|---|---|---|---|---|
| Dishwasher | 1 | 12 | 36 | 126 | 0.35 |
| Washing machine | 2 | 6 | 108 | 132 | 0.26 |
| Dryer | 3 | 3 | 132 | 144 | 0.4 |

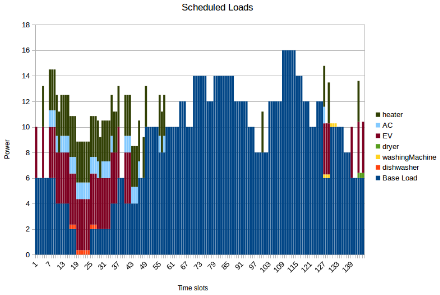
- Interruptible loads

| Device | Priority | Duration | Earliest | Latest | Power |
|---|---|---|---|---|---|
| Electric Vehicle | 1 | 42 | 0 | 144 | 4.0 |
| Heater | 2 | 48 | 0 | 144 | 3.2 |
| A/C | 3 | 36 | 0 | 144 | 1.3 |

# First instance: high reservation prices

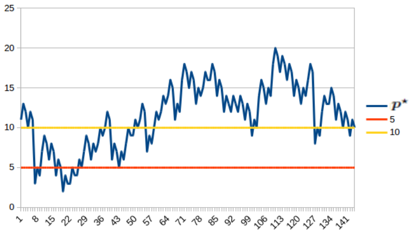
For the 3 priority levels: $p_{\max,i}(1) = 1000$, $p_{\max,i}(2) = 20$, $p_{\max,i}(3) = 15$.

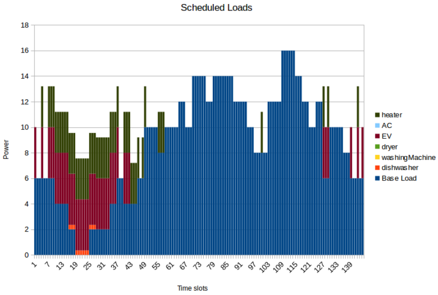


# Second instance: low reservation prices

For the 3 priority levels: $p_{\max,i}(1) = 1000$, $p_{\max,i}(2) = 10$, $p_{\max,i}(3) = 5$.



# Taking forward positions in the day-ahead market

Stochastic base load

- $d_i(t) = \hat{d}_i(t) - \epsilon_i(t), \forall i \in \mathscr{G}, \forall t \in [\![0; nT - 1]\!]$
- $\hat{d}_i(t)$ is the *forecasted* load.

Price-taker utilities

- $p^f(t)$ day-ahead market price,
- $p^+(t)$ balancing market price in case of excess power
- $p^-(t)$ in case of lack of power
- $p^+(t) < p^f(t) < p^-(t)$.

Possible price surcharge $p^f(t) \leq p^\star(t)$

- Suppliers must purchase energy in advance on the wholesale day-ahead market.
- Price surcharge justified by the risk that suppliers take.

# Gambling on the balancing

## Consumer imbalance penalty

$$\begin{aligned} IB_i(t) &= p^-(t) \underbrace{\left(\hat{d}_i(t) - d_i(t)\right)_-}_{under-estimation} + \left(p^f(t) - p^+(t)\right) \underbrace{\left(\hat{d}_i(t) - d_i(t)\right)_+}_{over-estimation}, \\ &= p^-(t)\left(\epsilon_i(t)\right)_- + \left(p^f(t) - p^+(t)\right)\left(\epsilon_i(t)\right)_+. \end{aligned}$$

## Gambling on the balancing

- Each consumer pays the aggregator for his short/long position estimated in day-ahead.
- Aggregator may not need to cover all the positions (short positions cancelled out by long positions) although *all the consumers pay their mismatches*.

# Aggregator's utility function

Coalition cost:

$$c(\mathscr{G}, t) = p^f(t) \sum_{i \in \mathscr{G}} \Big( \sum_{l \in \mathcal{L}_i} x_{i,l}(t) + \hat{d}_i(t) \Big) + p^-(t) \Big( \sum_{i \in \mathscr{G}} (\hat{d}_i(t) - d_i(t)) \Big)_- - p^+(t) \Big( \sum_{i \in \mathscr{G}} (\hat{d}_i(t) - d_i(t)) \Big)_+$$

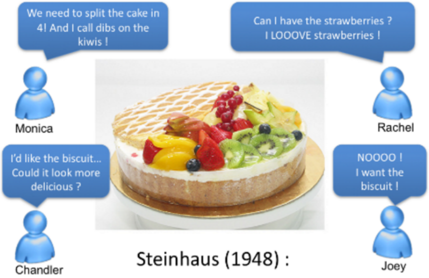
Aggregator's expected profit:

$$\Pi_{agg} = \sum_{t=0}^{nT-1} \Big\{ \underbrace{p^\star(t) \sum_{i \in \mathscr{G}} \big( \sum_{l \in \mathcal{L}_i} x_{i,l}(t) + \hat{d}_i(t) \big) + \sum_{i \in \mathscr{G}} \mathbb{E}[IB_i(t)]}_{\text{total bill paid by coalition } \mathscr{G}} - \mathbb{E}[c(\mathscr{G}, t)] \Big\}.$$

# Stability and fairness: sharing the pie?

The aggregator shares his cost $\Pi_{agg} + \sum_t \mathbb{E}[c(\mathscr{G}, t)]$ to guarantee:

- the stability of his coalition $\mathscr{G}$,
- (a certain idea of) fairness.



Steinhaus (1948) :
How do we fairly share the cake ?

## Conventional retailer cost

$c_{retailer}(i, t) = p_{retailer}(t)\Big(d_i(t) + \sum_{l \in \mathcal{L}_i} x_{i,l}(t)\Big)$ with $p_{retailer}(t)$ the conventional retailer's price at time period $t$.

# Cost-sharing mechanisms

We consider several cost-sharing mechanisms:

- Stand-alone cost:

$$y_i := \kappa_i \Big\{ \Pi_{agg} + \sum_{t=0}^{nT-1} \mathbb{E}[c(\mathscr{G}, t)] \Big\}$$

where $\kappa_i = \frac{\sum_{t=0}^{nT-1} \mathbb{E}[c_{retailer}(i,t)]}{\sum_{j \in \mathscr{G}} \sum_{t=0}^{nT-1} \mathbb{E}[c_{retailer}(j,t)]}$.

- Shapley value: computed under the assumption that the coalition is formed by entering the participants one at a time. It can be shown that

$$y_i = \frac{\Pi_{agg} + \sum_{t=0}^{nT-1} \mathbb{E}[c(\mathscr{G}, t)]}{card(\mathscr{G})}, \forall i \in \mathscr{G}.$$

# Cost-sharing mechanisms (cont.)

- Separable and non-separable costs:

$$y_i = m_i + \frac{\kappa_i}{\sum_{j \in \mathscr{G}} \kappa_j} \xi(\mathscr{G}), \forall i \in \mathscr{G}, \tag{2}$$

where $m_i = \sum_{t=0}^{nT-1} \left\{ \mathbb{E}[c(\mathscr{G}, t)] - \mathbb{E}[c(\mathscr{G} - \{i\}, t)] \right\}$ is the marginal cost of participant $i$ with respect to the coalition $\mathscr{G}$, and

$$\xi(\mathscr{G}) = \left( \Pi_{agg} + \sum_{t=0}^{nT-1} \mathbb{E}[c(\mathscr{G}, t)] \right) - \sum_{j \in \mathscr{G}} m_j, \tag{3}$$

with $\kappa_i = \frac{1}{card(\mathscr{G})} \quad \forall i \in \mathscr{G}$, or
$\kappa_i = \sum_{t=0}^{nT-1} \mathbb{E}[c_{retailer}(i, t)] - m_i \quad \forall i \in \mathscr{G}$.

# Greediness has its limit

## Aggregator's profit maximization

$$
\begin{aligned}
(UU)\ \max \quad & \Pi_{agg}, \\
s.t. \quad & y_i = \psi_i\Big(\Pi_{agg}, \sum_{j \in \mathscr{G}} \sum_{t=0}^{nT-1} \big(x_j(t) + \hat{d}_j(t)\big)\Big), \forall i \in \mathscr{G}, \ \text{Fairness} \\
& \sum_{i \in \mathscr{G}} y_i = \Pi_{agg} + \sum_{t=0}^{nT-1} \mathbb{E}[c(\mathscr{G}, t)], \ \text{Group Rationality} \\
& y_i \le \sum_{t=0}^{nT-1} \mathbb{E}[c_{retailer}(i, t)], \forall i \in \mathscr{G}. \text{Individual Rationality}
\end{aligned}
$$

# Solving (UU)

Let $\Pi^*_{agg}$ be a solution of (UU).
$\psi_i(.)$, cost sharing mechanism (stand-alone, Shapley, separable and non-separable costs).

| Solutions | $\Pi^*_{agg}$ |
|---|---|
| Stand-alone | $\sum_{j\in\mathcal{G}}\sum_{t=0}^{nT-1}\mathbb{E}[c_{retailer}(j,t)] - \sum_{t=0}^{nT-1}\mathbb{E}[c(\mathcal{G},t)]$ |
| Shapley | $card(\mathcal{G})\min_{i\in\mathcal{G}}\left\{\sum_{t=0}^{nT-1}\mathbb{E}[c_{retailer}(i,t)]\right\} - \sum_{t=0}^{nT-1}\mathbb{E}[c(\mathcal{G},t)]$ |
| Separable and non-separable costs | $\min_{i\in\mathcal{G}}\left\{\frac{\sum_{j\in\mathcal{G}}\kappa_j}{\kappa_i}\left(\sum_{t=0}^{nT-1}\mathbb{E}[c_{retailer}(i,t)] - \sum_{j\in\mathcal{G}\setminus\{i\}}\sum_{t=0}^{nT-1}\mathbb{E}[c(\mathcal{G}\setminus\{j\},t)]\right) - \left(1-card(\mathcal{G})+\frac{\sum_{j\in\mathcal{G}}\kappa_j}{\kappa_i}\right)\sum_{t=0}^{nT-1}\mathbb{E}[c(\mathcal{G},t)]\right\}$ |

## Remark

$\Pi^*_{agg}$ depends on coalition $\mathscr{G}$ size and content.

# Computing the prices

Let $y_i$ be the bill paid by consumer $i$ over the $nT$ time period.

Aggregator price profile $\boldsymbol{p}^\star$ is solution of the system:

$$y_i - \sum_{t=0}^{nT-1} \mathbb{E}[IB_i(t)] = \sum_{t=0}^{nT-1} p^\star(t)\Big(\sum_{l\in\mathcal{L}_i} x_{i,l}(t) + \hat{d}_i(t)\Big), \forall i \in \mathscr{G}.$$

We can rewrite the system as:

$$\boldsymbol{A}\boldsymbol{p}^\star = \boldsymbol{b}, \tag{4}$$

where

- $b_i = y_i - \sum_{t=0}^{nT-1} \mathbb{E}[IB_i(t)], \forall i \in \mathscr{G},$
- $A_{i,t} = \sum_{l\in\mathcal{L}_i} x_{i,l}(t) + \hat{d}_i(t), \forall i \in \mathscr{G}, \forall t \in [\![0; nT-1]\!].$

BUT: Note that both $\boldsymbol{b}$ and $\boldsymbol{A}$ depend on $\boldsymbol{p}^\star$! (through $\boldsymbol{x}$ and $\boldsymbol{y}$)

# A bilevel mathematical program

- Upper-level: the aggregator solves

$$(\mathrm{U}) \quad \min_{\boldsymbol{p}^\star} \quad \|\boldsymbol{A}\boldsymbol{p}^\star - \boldsymbol{b}\|, \qquad s.t. \quad p^\star(t) \geq 0, \forall t \in [\![0; nT-1]\!],$$

- Lower-level: each consumer $i \in \mathscr{G}$ solves

$$(\mathrm{L}_i) \quad \min_{\left(\boldsymbol{x_{i,l}}\right)_{l \in \mathcal{L}_i} \in \mathcal{X}_{i,l}} \quad \sum_{l \in \mathcal{L}_i} \boldsymbol{p}^{\star T} \boldsymbol{x_{i,l}}, \qquad s.t. \quad \mathscr{C}_i\left(\left(\boldsymbol{x_{i,l}}\right)_{l \in \mathcal{L}_i}, \boldsymbol{p}^\star\right) \leq 0.$$

with $\mathcal{X}_{i,l}$ a discrete decision space and $\mathscr{C}_i(.)$ a set of constraints on the shiftable loads of consumer $i$, $\left(\boldsymbol{x_{i,l}}\right)_{l \in \mathcal{L}_i}$.

$\rightsquigarrow$ A non-convex mixed-integer program with discrete decision variables in $(\mathrm{L}_i)$.

# Solving the bilevel program

Problem: No closed-form expression for the response function connecting $(L_i)$ with $(\mathrm{U})$.

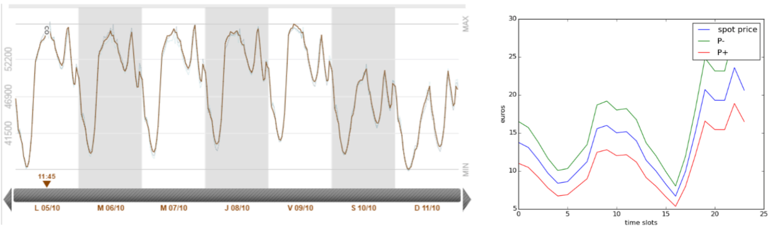
Some ideas:

- Use a derivative-free global optimization method to solve $(\mathrm{U})$ with $\boldsymbol{b} = \boldsymbol{b}(\boldsymbol{p}^\star)$ and $\boldsymbol{A} = \boldsymbol{A}(\boldsymbol{p}^\star)$
- Find the best $\boldsymbol{p}^\star$ from among a not very large number of fixed *price profiles*.
- Note that we need to deal with the issue of private information [similar in Ruiz & Conejo,Gonzalez & Andersson for MPECs]; so, the aggregator needs to estimate $\hat{p}_{\max,i}(k_{i,l})$.

# A case study

We tested our model on a database containing the power consumption of French residential consumers (RTE).

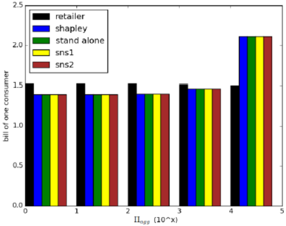
- The aggregated power consumption for France is monitored every hour on a 4 year basis.
- The market price profile in day ahead and on the balancing are simulated based on RTE data market.



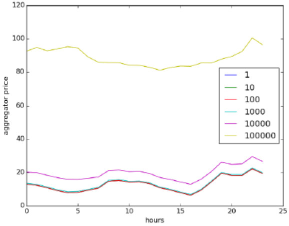

(a) (b)

Figure 2: Aggregated weekly power consumption profile (kW) for French residential consumers in (a), between October 5-th and October 11-th. Daily market price profiles on the balancing and day-ahead markets in (b).

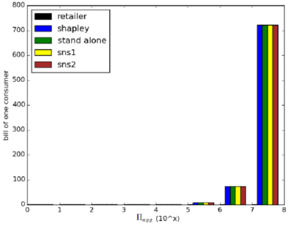
# Consumer's bill and aggregator's daily price profile



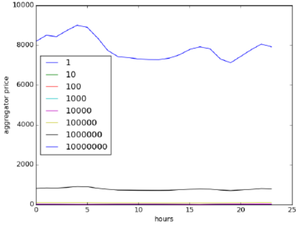

(a)




(b)



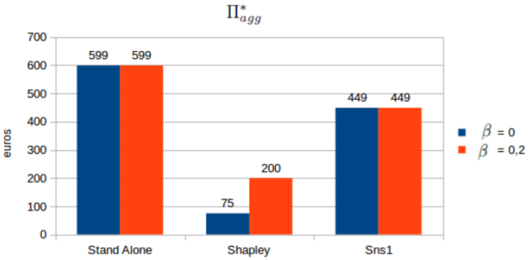

(c)



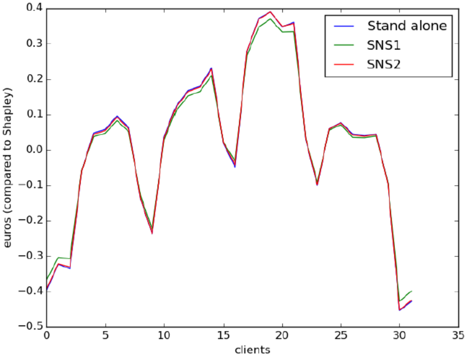

(d)

# Comparing $\Pi^*_{agg}$ for various cost sharing mechanisms

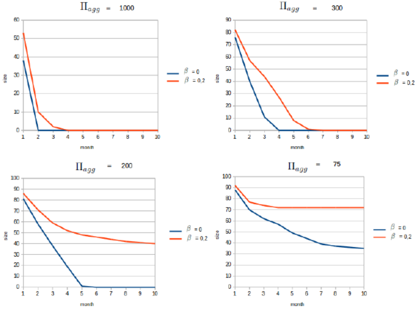
Let $\beta \in [0; 1]$ be the probability of inertia.



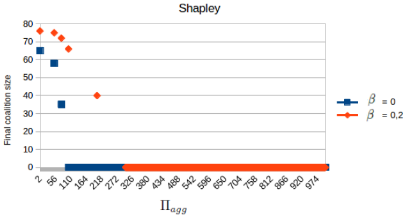
# Shapley vs stand-alone and separable and non-separable costs



# Coalition dynamics under Shapley

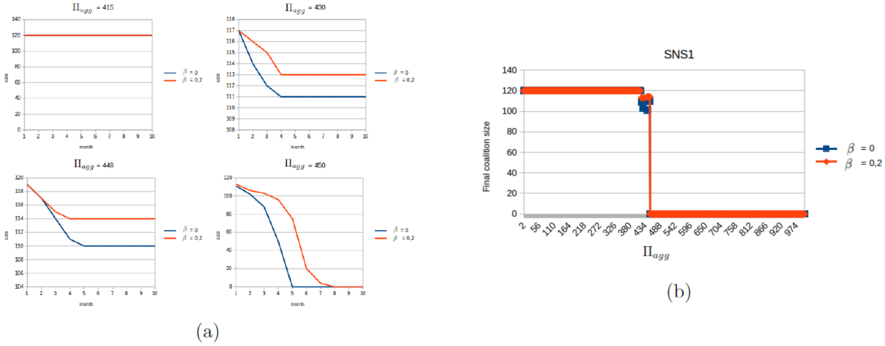



(a)

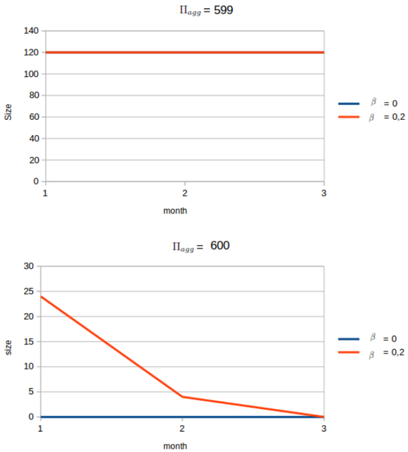



(b)

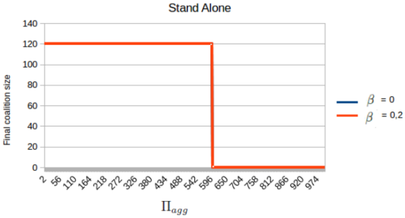
# Coalition dynamics under separable and non-separable costs



# Coalition dynamics under stand-alone cost




(a)




(b)

# Conclusions

- Coalition schemes can be useful and beneficial to consumers, provided that the aggregator limits its profits to keep the consumers in the coalition.
- The general case, where flexible loads are scheduled depending on the price, is very challenging from an algorithmic perspective, as it requires solving a bilevel model with integer variables.
- The choice of cost-sharing mechanism matters, both for the consumers as well as for the aggregator.