Consumers’ Flexibility Estimation at the TSO Level for Balancing Services

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Outline

- Motivations
- Engaging the flexible resources
- Modelling the electricity consumers’ behaviour
- Chance constrained programming
- Results
- Conclusions
Engaging the energy flexibility
Consumers’ behaviour

In order to guarantee the electricity reserve, the system operator must quantify the aggregated flexibility that can be achieved from the electricity consumers.

Two-way communication

Transactive energy exploits a feedback to know the reaction of the consumers to prices. It requires significant infrastructure and might perform slowly.

One-way communication

A one-way communication fastens the process, however it is fundamental to understand the consumers' behaviour and their price response.
Estimating the available flexibility

Assumptions

How can we estimate the consumers’ behaviour at the TSO level?

We assume:

- **Time-varying electricity** prices are submitted to the consumers.

- Consumers are equipped with **energy management systems**.

The consumers’ response is statistically modelled, knowing:

- The **composition** of the aggregated pool of consumers.

- The aggregated **measurements** for each **load category**.
Estimating the available flexibility

The model

We approach a **cost minimisation** that considers the perspective of the consumers:

\[
\min_{L_{t,j}^a} \sum_{t=1}^{\tau} \left( \lambda_{t}^{\text{base}} + \Delta \lambda_{t}^{u} + \Delta \lambda_{t}^{d} \right) \sum_{j=1}^{J} \left( L_{t,j}^{\text{base}} + L_{t,j}^{d} - L_{t,j}^{u} \right)
\]

\[(5a)\]
Estimating the available flexibility

The model

We approach a **cost minimisation** that considers the perspective of the consumers:

$$
\min_{L_{t,j}^2} \sum_{t=1}^{T} \left( \lambda_{\text{base}} + \Delta \lambda_t^u + \Delta \lambda_t^d \right) \sum_{j=1}^{J} \left( L_{t,j}^\text{base} + L_{t,j}^d - L_{t,j}^u \right)
$$

where the constraints include:

The **magnitude** of the flexibility provision

\[
\begin{align*}
\text{s.t.} \quad & -r_j^\alpha \leq L_{t,j+1}^\alpha - L_{t,j}^\alpha \leq r_j^\alpha \quad \forall t, j \quad (5b) \\
& 0 \leq L_{t,j}^d \leq u_{t,j}^d \left( L_{t,j}^\text{max} - L_{t,j}^\text{base} \right) a_{t,j}^d \quad \forall t, j \quad (5c) \\
& 0 \leq L_{t,j}^u \leq u_{t,j}^u \left( L_{t,j}^\text{base} - L_{t,j}^\text{min} \right) a_{t,j}^u \quad \forall t, j \quad (5d)
\end{align*}
\]
Estimating the available flexibility

The model

We approach a **cost minimisation** that considers the perspective of the consumers:

\[
\min_{\mathcal{L}^{\alpha}_{t,j}} \sum_{t=1}^{\tau} (\lambda^{\text{base}}_t + \Delta \lambda_t^u + \Delta \lambda_t^d) \sum_{j=1}^{J} (\mathcal{L}^{\text{base}}_{t,j} + \mathcal{L}^d_{t,j} - \mathcal{L}^u_{t,j})
\]

(5a)

where the constraints include:

**The magnitude** of the flexibility provision

\[
\begin{align*}
- \zeta^\alpha_{j} &\leq L^{\alpha}_{t,j+1} - L^{\alpha}_{t,j} &\forall t, j &\text{ (5b)} \\
0 &\leq L^d_{t,j} &\leq u^d_{t,j} (L^{\text{max}}_{t,j} - L^{\text{base}}_{t,j}) &\forall t, j &\text{ (5c)} \\
0 &\leq L^u_{t,j} &\leq u^u_{t,j} (L^{\text{base}}_{t,j} - L^{\text{min}}_{t,j}) &\forall t, j &\text{ (5d)}
\end{align*}
\]

**The duration** of the flexibility provision

\[
\begin{align*}
\sum_{t=t'}^{t'+d^\alpha_j} u^\gamma_{t',j} &\geq d^\alpha_j y^\alpha_{t',j} &\forall t' &\in \Psi, j &\text{ (5j)} \\
\sum_{t=t'}^{t'+d^\alpha_j} z^\gamma_{t',j} &\geq y^\gamma_{t',j} &\forall t' &\in \Psi, j &\text{ (5k)} \\
t' &\in \Psi, t' : \left[ (t + d^d_j < \tau) \land (t + d^u_j < \tau) \right] &\text{ (5l)}
\end{align*}
\]
Estimating the available flexibility

The model

We approach a **cost minimisation** that considers the perspective of the consumers:

\[
\min_{L^\alpha_{t,j}} \sum_{t=1}^{\tau} \left( \lambda^\text{base} + \Delta \lambda^u_t + \Delta \lambda^d_t \right) \sum_{j=1}^{J} \left( L^\text{base}_{t,j} + L^d_{t,j} - L^u_{t,j} \right)
\]

(5a)

where the constraints include:

The **magnitude** of the flexibility provision

\[
\begin{align*}
- r_j^\alpha & \leq L^\alpha_{t,j+1} - L^\alpha_{t,j} \leq r_j^\alpha & \forall t,j, \\
0 & \leq L^d_{t,j} \leq u^d_{t,j} (L^\text{max}_{t,j} - L^\text{base}_{t,j}) a^d_{t,j} & \forall t,j, \\
0 & \leq L^u_{t,j} \leq u^u_{t,j} (L^\text{base}_{t,j} - L^\text{min}_{t,j}) a^u_{t,j} & \forall t,j
\end{align*}
\]

(5b) (5c) (5d)

The **rebound** effect

\[
\sum_{t=1}^{\tau} \left( L^d_{t,j} - L^u_{t,j} \right) = 0 \quad \forall j
\]

(5e)

The **duration** of the flexibility provision

\[
\sum_{t=t'}^{t'+\bar{d}_j^0} u^\alpha_{t',j} \geq d_j^\alpha y_{t',j} & \forall t' \in \Psi, j
\]

(5j)

\[
\sum_{t=t'}^{t'+\bar{d}_j^0} z^\alpha_{t,j'} \geq y_{t',j} & \forall t' \in \Psi, j
\]

(5k)

\[
t' \in \Psi, t' : \left( (t + \bar{d}_j^d < \tau) \cap (t + \bar{d}_j^u < \tau) \right)
\]

(5l)
Estimating the available flexibility

The model

We approach a **cost minimisation** that considers the perspective of the consumers:

\[
\min L_{t,j}^\alpha \sum_{t=1}^{\tau} (\Delta \lambda_t^{base} + \Delta \lambda_t^{u} + \Delta \lambda_t^{d}) \sum_{j=1}^{J} (L_{t,j}^{base} + L_{t,j}^{d} - L_{t,j}^{u})
\]

where the constraints include:

The **magnitude** of the flexibility provision

\[
s.t. \quad -r_j^{u} \leq L_{t,j+1}^{\alpha} - L_{t,j}^{\alpha} \leq r_j^{u} \quad \forall t, j \quad (5b)
\]

\[
0 \leq L_{t,j}^{d} \leq u_t^{d}(L_{t,j}^{max} - L_{t,j}^{base})a_{t,j} \quad \forall t, j \quad (5c)
\]

\[
0 \leq L_{t,j}^{u} \leq u_t^{u}(L_{t,j}^{base} - L_{t,j}^{min})a_{t,j} \quad \forall t, j \quad (5d)
\]

The **rebound** effect

\[
\sum_{t=1}^{\tau} (L_{t,j}^{d} - L_{t,j}^{u}) = 0 \quad \forall j \quad (5e)
\]

The **activation** times

\[
\sum_{t=1}^{\tau} y_{t,j}^{\alpha} \leq n_j^{\alpha} \quad \forall j \quad (5i)
\]

The **duration** of the flexibility provision

\[
\sum_{t=t'}^{t'+d_{j}^{u}} u_t^{\alpha} y_{t,j}^{\alpha} \geq d_{j}^{u} y_{t,j}^{\alpha} \quad \forall t' \in \Psi, j \quad (5j)
\]

\[
\sum_{t=t'}^{t'+d_{j}^{u}} z_{t,j'} \geq y_{t,j}^{\alpha} \quad \forall t' \in \Psi, j \quad (5k)
\]

\[
t' \in \Psi, t' : \left[ (t + d_{j}^{d} < \tau) \cap (t + d_{j}^{u} < \tau) \right] \quad (5l)
\]
Estimating the available flexibility

The model

We approach a cost minimisation that considers the perspective of the consumers:

$$\min_{L_{t,j}} \sum_{t=1}^{\tau} (\lambda_{t,j}^{\text{base}} + \Delta \lambda_{t,j}^{u} + \Delta \lambda_{t,j}^{d}) \sum_{j=1}^{J} (L_{t,j}^{\text{base}} + L_{t,j}^{d} - L_{t,j}^{u})$$

(5a)

where the constraints include:

The magnitude of the flexibility provision

$$\text{s.t. } -r_{j}^{\alpha} \leq L_{t,j+1}^{\alpha} - L_{t,j}^{\alpha} \leq r_{j}^{\alpha} \quad \forall t,j$$

(5b)

$$0 \leq L_{t,j}^{d} \leq u_{t,j}^{d} \left( L_{t,j}^{\max} - L_{t,j}^{\text{base}} \right) a_{t,j} \quad \forall t,j$$

(5c)

$$0 \leq L_{t,j}^{u} \leq u_{t,j}^{u} \left( L_{t,j}^{\text{base}} - L_{t,j}^{\min} \right) a_{t,j} \quad \forall t,j$$

(5d)

The rebound effect

$$\sum_{t=1}^{\tau} (L_{t,j}^{d} - L_{t,j}^{u}) = 0 \quad \forall j$$

(5e)

The activation times

$$\sum_{t=1}^{\tau} y_{t,j}^{\alpha} \leq n_{j}^{\alpha} \quad \forall j$$

(5i)

The duration of the flexibility provision

$$\sum_{t=t'}^{t'+d_{j}^{d}} u_{t',j}^{u} \geq d_{j}^{\alpha} y_{t',j}^{\alpha} \quad \forall t' \in \Psi, j$$

(5j)

$$\sum_{t=t'}^{t'+d_{j}^{u}} z_{t',j}^{\alpha} \geq y_{t',j}^{\alpha} \quad \forall t' \in \Psi, j$$

(5k)

$$t' \in \Psi, t' : \left( (t + d_{j}^{d} < \tau) \cap (t + d_{j}^{u} < \tau) \right)$$

(5l)

The binary condition

$$u_{t,j}^{d} + u_{t,j}^{u} \leq 1 \quad \forall t,j$$

(5f)

$$y_{t,j}^{\alpha} - z_{t,j}^{\alpha} = u_{t,j}^{\alpha} - u_{t,j-1}^{\alpha} \quad \forall t,j$$

(5g)

$$y_{t,j}^{\alpha} + z_{t,j}^{\alpha} \leq 1 \quad \forall t,j$$

(5h)
Estimating the available flexibility

The model

We approach a **cost minimisation** that considers the perspective of the consumers:

\[
\min_{L_{t,j}^\alpha} \sum_{t=1}^{\tau} \left( \lambda_{t,j}^{\text{base}} + \Delta \lambda_{t,j}^u + \Delta \lambda_{t,j}^d \right) \sum_{j=1}^{J} \left( L_{t,j}^{\text{base}} + L_{t,j}^d - L_{t,j}^u \right)
\]

(5a)

where the constraints include:

The **magnitude** of the flexibility provision

\[
s.t. \quad -r_j^\alpha \leq L_{t,j+1}^{\alpha} - L_{t,j}^{\alpha} \leq r_j^\alpha \quad \forall t, j \quad (5b)
\]

\[
0 \leq L_{t,j}^d \leq u_{t,j}^d \left( L_{t,j}^{\max} - L_{t,j}^{\text{base}} \right) a_{t,j}^d \quad \forall t, j \quad (5c)
\]

\[
0 \leq L_{t,j}^u \leq u_{t,j}^u \left( L_{t,j}^{\text{base}} - L_{t,j}^{\min} \right) a_{t,j}^u \quad \forall t, j \quad (5d)
\]

The **rebound** effect

\[
\sum_{t=1}^{\tau} \left( L_{t,j}^d - L_{t,j}^u \right) = 0 \quad \forall j \quad (5e)
\]

The **activation** times

\[
\sum_{t=1}^{\tau} y_{t,j}^{\alpha} \leq n_j^\alpha \quad \forall j \quad (5i)
\]

The **duration** of the flexibility provision

\[
\sum_{t=t'} t' + d_{j}^\alpha \geq d_{j}^\alpha y_{t',j}^{\alpha} \quad \forall t' \in \Psi, j \quad (5j)
\]

\[
\sum_{t=t'} t' + d_{j}^\alpha \geq y_{t',j}^{\alpha} \quad \forall t' \in \Psi, j \quad (5k)
\]

\[
t' \in \Psi, t' : \left[ (t + d_{j}^d < \tau) \cap (t + d_{j}^u < \tau) \right] \quad (5l)
\]

The **binary** condition

\[
u_{t,j}^d + u_{t,j}^u \leq 1 \quad \forall t, j \quad (5f)
\]

\[
y_{t,j}^{\alpha} - z_{t,j}^{\alpha} = u_{t,j}^{\alpha} - u_{t,j-1}^{\alpha} \quad \forall t, j \quad (5g)
\]

\[
y_{t,j}^{\alpha} + z_{t,j}^{\alpha} \leq 1 \quad \forall t, j \quad (5h)
\]
Dealing with the uncertainty
Consumers’ willingness

The consumers’ \textit{willingness} to provide flexibility is modelled as an \textit{exponential} function:

\[
a_{t,j}^{\alpha} = \begin{cases} 
0 & |\Delta \lambda_t^{\alpha}| < \Delta \lambda_j^{\alpha} \\
\bar{a}_j^{\alpha} \left( \frac{\Delta \lambda_t^{\alpha} - \Delta \lambda_j^{\alpha}}{\Delta \lambda_j^{\alpha} - \Delta \lambda_j^{\alpha}} \right)^\gamma & |\Delta \lambda_t^{\alpha}| \leq |\Delta \lambda_j^{\alpha}| \leq \bar{\Delta} \lambda_j^{\alpha} \\
\bar{a}_j^{\alpha} & |\Delta \lambda_t^{\alpha}| \geq \bar{\Delta} \lambda_j^{\alpha}
\end{cases}
\]

where the \textbf{parameters} to formulate \( a_{t,j}^{\alpha} \) depend on the different end-users’ \textbf{categories}.
Dealing with the uncertainty
Consumers’ willingness

To account for the **stochasticity** and **diversity** of the consumes, these parameters are treated as **normally** distributed:

\[
\begin{align*}
\alpha_{t,j}^\alpha & = 0 & |\Delta \lambda_t^\alpha| & < \Delta \lambda_j^\alpha \\
\alpha_{t,j}^\alpha & = \bar{a}_j^\alpha \left( \frac{\Delta \lambda_t^\alpha - \Delta \lambda_j^\alpha}{\Delta \lambda_j^\alpha} \right)^\gamma & \Delta \lambda_j^\alpha & \leq |\Delta \lambda_t^\alpha| \leq \bar{\Delta \lambda_j^\alpha} \\
\alpha_{t,j}^\alpha & = \bar{a}_j^\alpha & |\Delta \lambda_t^\alpha| & \geq \bar{\Delta \lambda_j^\alpha}
\end{align*}
\]

Such a choice is justified as several phenomena related to the **human behaviour** follow normal distribution.
Dealing with the uncertainty
Normality condition

The selection of $\gamma$ defines the different willingness of consumers to respond to different price magnitudes.

In this study, different values of $\gamma$ are considered and the normality of the consumers’ willingness parameter is tested for each value.

It emerges graphically that the normality condition is not significantly affected by the choice of $\gamma$ and we consider a value of 1.5.
Dealing with the uncertainty
Chance constrained programming

Chance constrained programming is applied to the constraints:

\[
\begin{align*}
L^d_{t,j} &\leq u^d_{t,j} (L^\text{max}_{t,j} - L^\text{base}_{t,j}) a^d_{t,j} \quad \forall t, j \\
L^u_{t,j} &\leq u^u_{t,j} (L^\text{base}_{t,j} - L^\min_{t,j}) a^u_{t,j} \quad \forall t, j
\end{align*}
\]      (6)

\[
\begin{align*}
L^d_{t,j} &\leq u^d_{t,j} (L^\text{max}_{t,j} - L^\text{base}_{t,j}) \tilde{a}^d_{t,j} \quad \forall t, j \\
L^u_{t,j} &\leq u^u_{t,j} (L^\text{base}_{t,j} - L^\min_{t,j}) \tilde{a}^u_{t,j} \quad \forall t, j
\end{align*}
\]      (7)

where \( a^u_{t,j}, a^d_{t,j} \) are treated as random variables with normal distribution, \( \tilde{a}^u_{t,j}, \tilde{a}^d_{t,j} \):

\[
\begin{align*}
L^d_{t,j} &\leq u^d_{t,j} (L^\text{max}_{t,j} - L^\text{base}_{t,j}) \tilde{a}^d_{t,j} \quad \forall t, j \\
L^u_{t,j} &\leq u^u_{t,j} (L^\text{base}_{t,j} - L^\min_{t,j}) \tilde{a}^u_{t,j} \quad \forall t, j
\end{align*}
\]      (8a)

\[
\begin{align*}
\mathcal{A}^d_{t,j} &\equiv u^d_{t,j} (L^\text{max}_{t,j} - L^\text{base}_{t,j}) \tilde{a}^d_{t,j} \\
\mathcal{A}^u_{t,j} &\equiv u^u_{t,j} (L^\text{base}_{t,j} - L^\min_{t,j}) \tilde{a}^u_{t,j}
\end{align*}
\]      (8b)

\[
\begin{align*}
L^\alpha_{t,j} &\leq \mathcal{A}^\alpha_{t,j} \quad \forall t, j
\end{align*}
\]      (8c)
Dealing with the uncertainty
Chance constrained programming

The chance constrained condition imposes that:

\[ Pr\left(L_{t,j}^\alpha - A_{t,j}^\alpha \leq \beta \right) \geq \beta \]  
(9)

We define the **standard score** \( z_\alpha \):

\[ Pr\left(\frac{L_{t,j}^\alpha - \mu A_{t,j}^\alpha}{\sigma A_{t,j}^\alpha} \leq z_\alpha \right) \geq \beta \]  
(10a)

\[ 1 - Pr\left(\frac{L_{t,j}^\alpha - \mu A_{t,j}^\alpha}{\sigma A_{t,j}^\alpha} \geq z_\alpha \right) \geq \beta \]  
(10b)

The **final constraints** are re-written as:

\[ L_{t,j}^{d} \leq \mu_{a} u_{t,j}^{d} \left(L_{t,j}^{\max} - L_{t,j}^{\min}\right) + \sigma_{a} u_{t,j}^{d} \left(L_{t,j}^{\max} - L_{t,j}^{\min}\right) \Phi_{\beta}^{-1} \]  
(11a)

\[ L_{t,j}^{u} \leq \mu_{a} u_{t,j}^{u} \left(L_{t,j}^{\max} - L_{t,j}^{\min}\right) + \sigma_{a} u_{t,j}^{u} \left(L_{t,j}^{\max} - L_{t,j}^{\min}\right) \Phi_{\beta}^{-1} \]  
(11b)
Results

Aggregated electricity flexibility

A Monte Carlo simulation is approached, investigating the available flexibility for different price sets. The chance constrained program is solved for a risky and a conservative security level.

\[ \beta = 50\% \]

\[ \beta = 95\% \]
Results
Method validation

We validate the method, comparing the theoretical security levels with the achieved level. Moreover, the additional value of adopting the chance constrained program is quantified:

**Actual $\beta$**

**Deterministic versus CC**
Conclusions

We present a planning-based tool for estimating the flexibility achievable from the electricity consumers at the transmission system operator level.

Such a method supports the system operator to understand the consumers’ behaviour, evaluating the flexibility for different types of consumers. It facilitates to guarantee the electricity reserve for addressing ancillary services. Aggregated measurements of different types of consumers are applied.

In order to handle the uncertainty of consumers’ behaviour, chance constrained programming is used for the consumers’ willingness to provide flexibility. Afterwards, the method is validated.

In the future, we will implement a stricter rebound in the model and evaluate additional uncertainty of the consumers’ behaviour.
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Thank you!