Consumers' Flexibility Estimation at the TSO Level for Balancing Services

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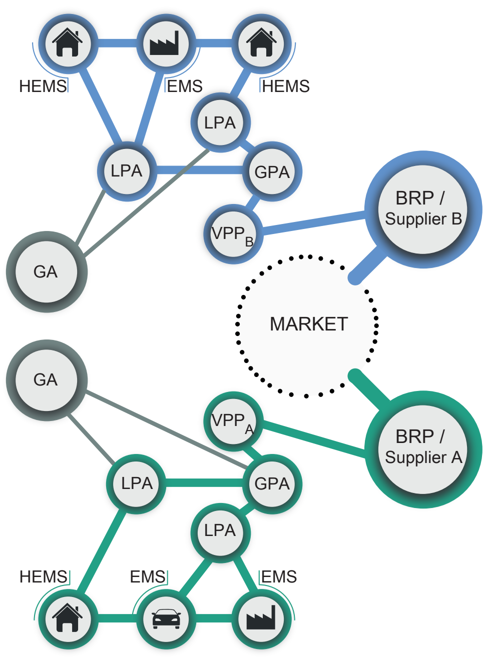
Outline

- Motivations
- Engaging the flexible resources
- Modelling the electricity consumers' behaviour
- Chance constrained programming
- Results
- Conclusions

Engaging the energy flexibility
Consumers' behaviour

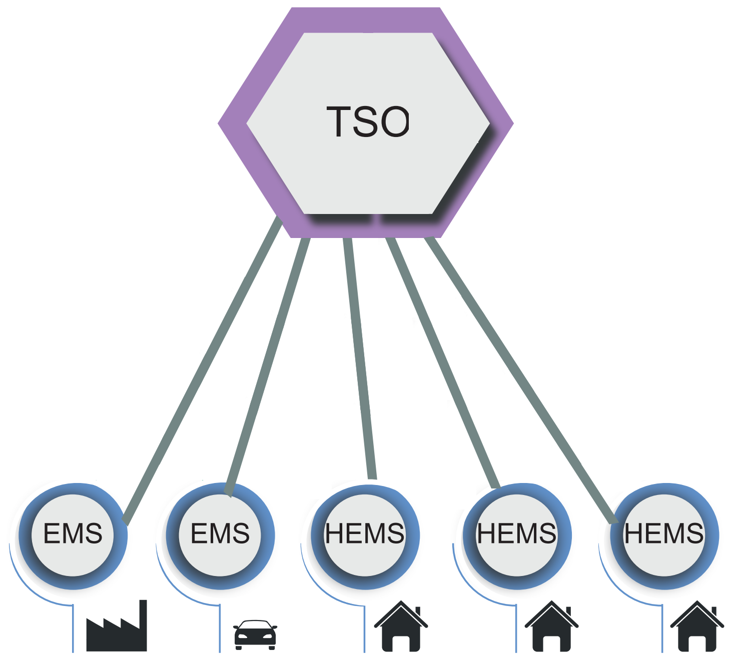
In order to guarantee the **electricity reserve**, the system operator must **quantify the aggregated flexibility** that can be achieved from the electricity consumers.

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:

$$\min_{L^{\alpha}_{t,j}} \quad \sum_{t=1}^{T} (\boldsymbol{\lambda}^{\text{base}} + \boldsymbol{\Delta\lambda}^{u}_{t} + \boldsymbol{\Delta\lambda}^{d}_{t}) \sum_{j=1}^{J} (\boldsymbol{L}^{\text{base}}_{t,j} + L^{d}_{t,j} - L^{u}_{t,j}) \tag{5a}$$

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where the constraints include:

The **magnitude** of the flexibility provision

$$\text{s.t.} \quad -\mathbf{r}^{\alpha}_{j} \leq L^{\alpha}_{t,j+1} - L^{\alpha}_{t,j} \leq \mathbf{r}^{\alpha}_{j} \qquad \forall t,j \tag{5b}$$

$$0 \leq L^{d}_{t,j} \leq u^{d}_{t,j} (\mathbf{L}^{\max}_{t,j} - \mathbf{L}^{\text{base}}_{t,j}) \mathbf{a}^{d}_{t,j} \quad \forall t,j \tag{5c}$$

$$0 \leq L^{u}_{t,j} \leq u^{u}_{t,j} (\mathbf{L}^{\text{base}}_{t,j} - \mathbf{L}^{\min}_{t,j}) \mathbf{a}^{u}_{t,j} \quad \forall t,j \tag{5d}$$

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The **duration** of the flexibility provision

$$\sum_{t=t'}^{t'+\underline{\mathbf{d}}^{\alpha}_{j}} u^{\alpha}_{t',j} \ge \underline{\mathbf{d}}^{\alpha}_{j} y^{\alpha}_{t',j} \qquad \forall t' \in \Psi, j \tag{5j}$$

$$\sum_{t=t'}^{t'+\overline{\mathbf{d}}^{\alpha}_{j}} z^{\alpha}_{t,j'} \ge y^{\alpha}_{t',j} \qquad \forall t' \in \Psi, j \tag{5k}$$

$$t' \in \Psi, t' : \left[(t + \overline{\mathbf{d}}^{d}_{j} < \tau) \cap (t + \overline{\mathbf{d}}^{u}_{j} < \tau) \right] \tag{5l}$$

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The **rebound** effect

$$\sum_{1}^{\tau}(L^{d}_{t,j} - L^{u}_{t,j}) = 0 \qquad \forall j \tag{5e}$$

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The **binary** condition

$$u^{d}_{t,j} + u^{u}_{t,j} \leq 1 \qquad \forall t,j \tag{5f}$$

$$y^{\alpha}_{t,j} - z^{\alpha}_{t,j} = u^{\alpha}_{t,j} - u^{\alpha}_{t,j-1} \qquad \forall t,j \tag{5g}$$

$$y^{\alpha}_{t,j} + z^{\alpha}_{t,j} \leq 1 \qquad \forall t,j \tag{5h}$$

Estimating the available flexibility
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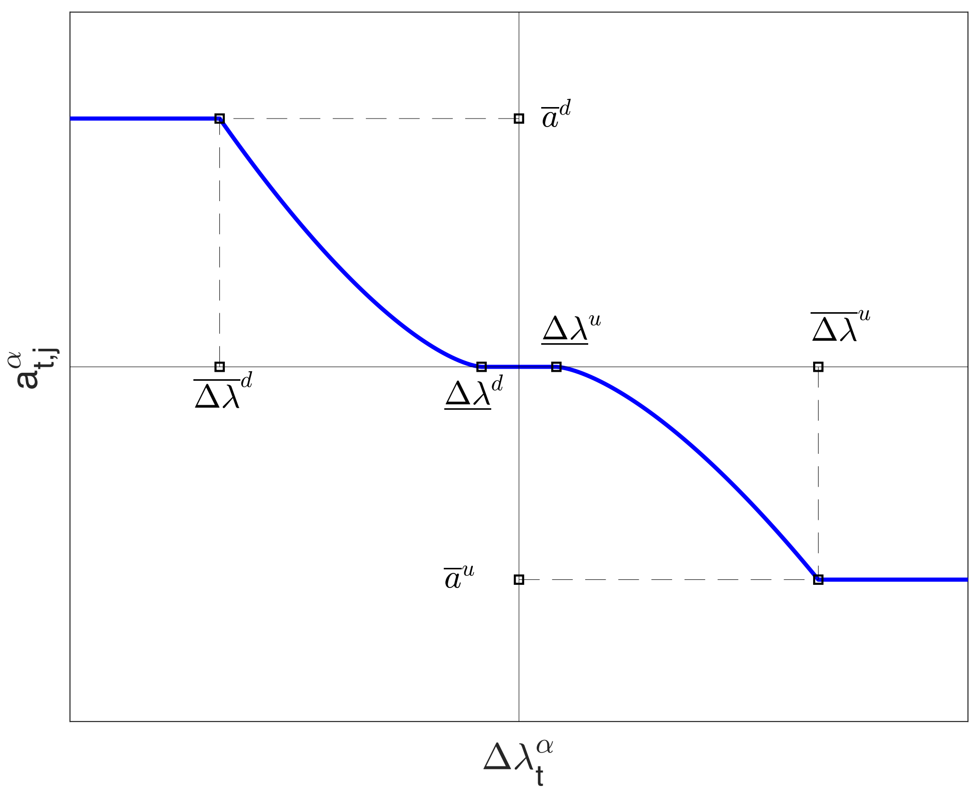
$$y^{\alpha}_{t,j} + z^{\alpha}_{t,j} \le 1 \qquad \forall t,j \qquad (5h)$$

Dealing with the uncertainty
Consumers' willingness

The consumers' **willingness** to provide flexibility is modelled as an **exponential** function:



$$\mathbf{a}_{t,j}^{\alpha} = 0 \qquad |\Delta\boldsymbol{\lambda}_t^{\alpha}| < \underline{\Delta\boldsymbol{\lambda}}_j^{\alpha} \qquad (2)$$

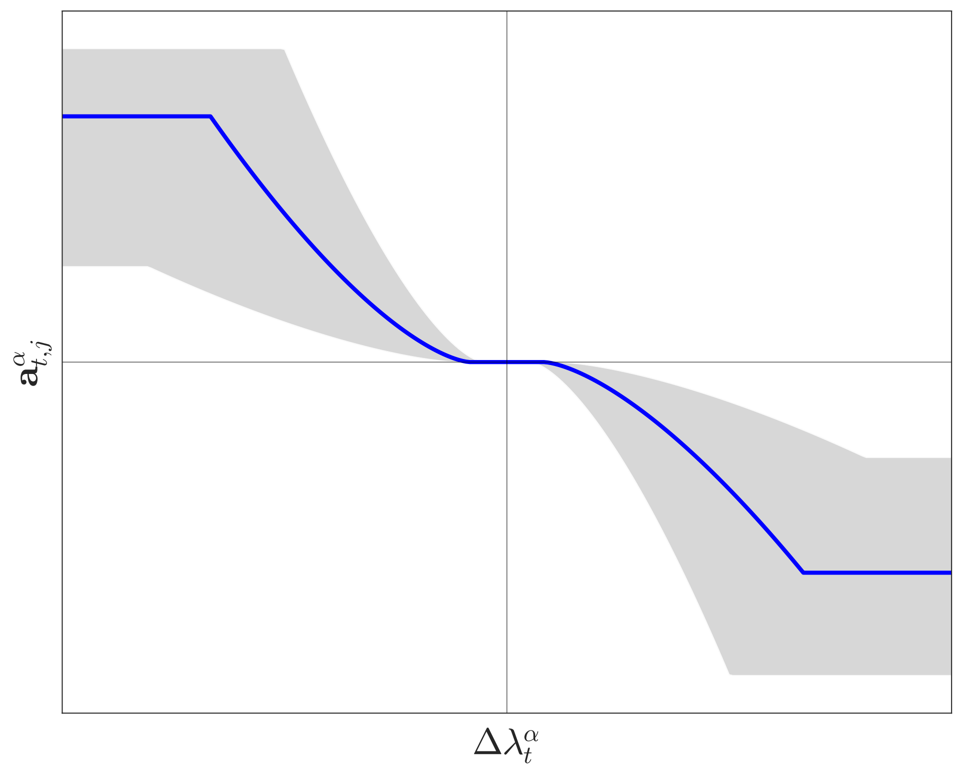
$$\mathbf{a}_{t,j}^{\alpha} = \overline{\mathbf{a}}_j^{\alpha}\left(\frac{\Delta\boldsymbol{\lambda}_t^{\alpha} - \underline{\Delta\boldsymbol{\lambda}}_j^{\alpha}}{\overline{\Delta\boldsymbol{\lambda}}_j^{\alpha} - \underline{\Delta\boldsymbol{\lambda}}_j^{\alpha}}\right)^{\gamma} \qquad \underline{\Delta\boldsymbol{\lambda}}_j^{\alpha} \leq |\Delta\boldsymbol{\lambda}_t^{\alpha}| \leq \overline{\Delta\boldsymbol{\lambda}}_j^{\alpha} \qquad (3)$$

$$\mathbf{a}_{t,j}^{\alpha} = \overline{\mathbf{a}}_j^{\alpha} \qquad |\Delta\boldsymbol{\lambda}_t^{\alpha}| \geq \overline{\Delta\boldsymbol{\lambda}}_j^{\alpha} \qquad (4)$$

where the **parameters** to formulate $\mathbf{a}_{t,j}^{\alpha}$ depend on the different end-users' **categories**.

Dealing with the uncertainty
Consumers' willingness

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



$$\mathbf{a}^{\alpha}_{t,j} = 0 \qquad |\boldsymbol{\Delta\lambda}^{\alpha}_{t}| < \underline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j} \tag{2}$$

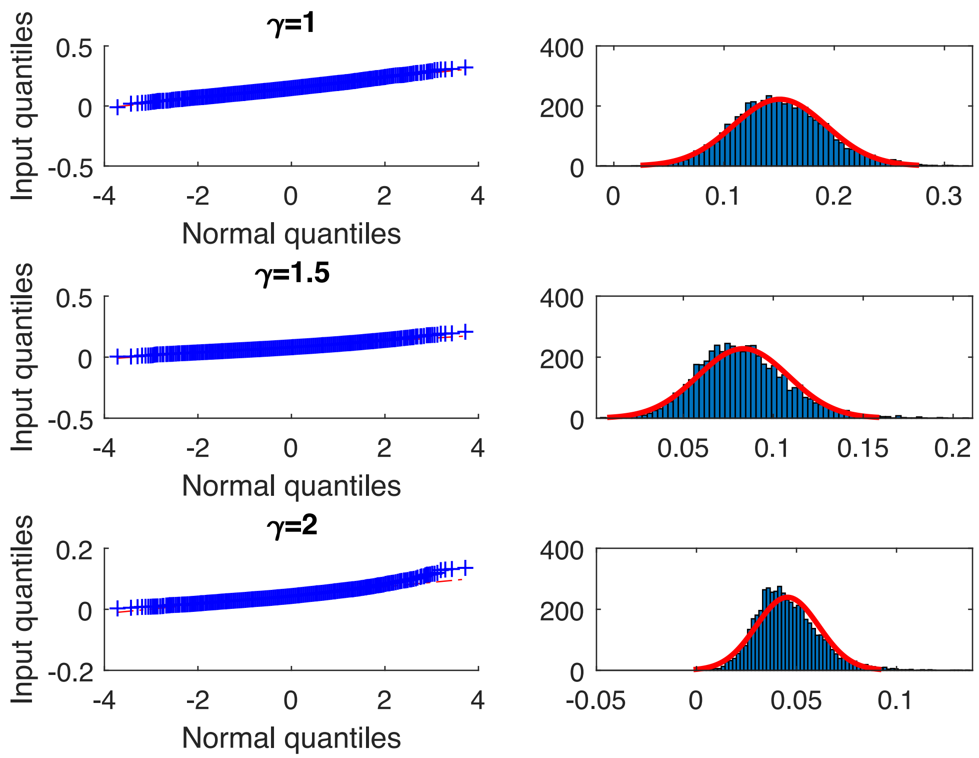
$$\mathbf{a}^{\alpha}_{t,j} = \overline{\mathbf{a}}^{\alpha}_{j}\left(\frac{\boldsymbol{\Delta\lambda}^{\alpha}_{t} - \underline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j}}{\overline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j} - \underline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j}}\right)^{\boldsymbol{\gamma}} \qquad \underline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j} \le |\boldsymbol{\Delta\lambda}^{\alpha}_{t}| \le \overline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j} \tag{3}$$

$$\mathbf{a}^{\alpha}_{t,j} = \overline{\mathbf{a}}^{\alpha}_{j} \qquad |\boldsymbol{\Delta\lambda}^{\alpha}_{t}| \ge \overline{\boldsymbol{\Delta\lambda}}^{\alpha}_{j} \tag{4}$$

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 **γ** defines the different **willingness** of consumers to respond to different **price magnitudes**.



In this study, different values of **γ** 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 **γ** and we consider a value of 1.5 .

Dealing with the uncertainty
Chance constrained programming

Chance constrained programming is applied to the constraints:

$$\begin{aligned} L^d_{t,j} &\leq u^d_{t,j}(\mathbf{L}^{\max}_{t,j} - \mathbf{L}^{\text{base}}_{t,j})\mathbf{a}^d_{t,j} \quad \forall t,j \\ L^u_{t,j} &\leq u^u_{t,j}(\mathbf{L}^{\text{base}}_{t,j} - \mathbf{L}^{\min}_{t,j})\mathbf{a}^u_{t,j} \quad \forall t,j \end{aligned} \tag{6}$$

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

$$\begin{aligned} L^d_{t,j} &\leq u^d_{t,j}(\mathbf{L}^{\max}_{t,j} - \mathbf{L}^{\text{base}}_{t,j})\tilde{\mathbf{a}}^d_{t,j} \quad \forall t,j \\ L^u_{t,j} &\leq u^u_{t,j}(\mathbf{L}^{\text{base}}_{t,j} - \mathbf{L}^{\min}_{t,j})\tilde{\mathbf{a}}^u_{t,j} \quad \forall t,j \end{aligned} \tag{7}$$

The formulation can be written in a compact way:

$$\mathcal{A}^d_{t,j} \equiv u^d_{t,j}(\mathbf{L}^{\max}_{t,j} - \mathbf{L}^{\text{base}}_{t,j})\tilde{\mathbf{a}}^d_{t,j} \tag{8a}$$

$$\mathcal{A}^u_{t,j} \equiv u^u_{t,j}(\mathbf{L}^{\text{base}}_{t,j} - \mathbf{L}^{\min}_{t,j})\tilde{\mathbf{a}}^u_{t,j} \tag{8b}$$

$$L^\alpha_{t,j} \leq \mathcal{A}^\alpha_{t,j} \quad \forall t,j \tag{8c}$$

Dealing with the uncertainty
Chance constrained programming

The chance constrained condition imposes that:

$$Pr\left(L_{t,j}^{\alpha} \leq \mathcal{A}_{t,j}^{\alpha}\right) \geq \boldsymbol{\beta} \tag{9}$$

We define the **standard score** z_α :

$$Pr\left(\frac{L_{t,j}^{\alpha} - \mu_{\mathcal{A}_{t,j}^{\alpha}}}{\sigma_{\mathcal{A}_{t,j}^{\alpha}}} \leq z_\alpha\right) \geq \boldsymbol{\beta} \tag{10a}$$

$$1 - Pr\left(\frac{L_{t,j}^{\alpha} - \mu_{\mathcal{A}_{t,j}^{\alpha}}}{\sigma_{\mathcal{A}_{t,j}^{\alpha}}} \geq z_\alpha\right) \geq \boldsymbol{\beta} \tag{10b}$$

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

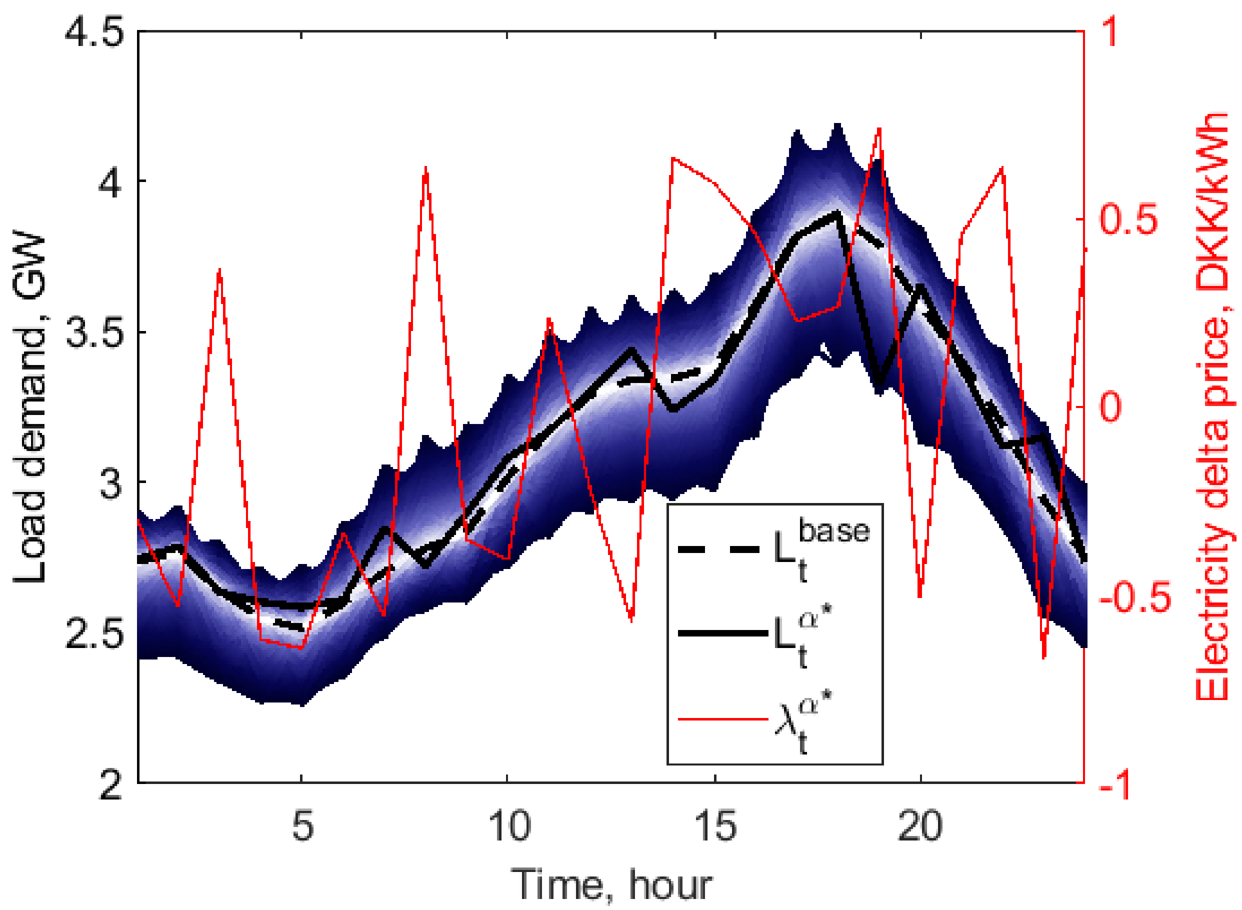
$$L_{t,j}^{d} \leq \mu_a^d u_{t,j}^d \left(\mathbf{L}_{t,j}^{\max} - \mathbf{L}_{t,j}^{\text{base}}\right) + \sigma_a^d u_{t,j}^d \left(\mathbf{L}_{t,j}^{\max} - \mathbf{L}_{t,j}^{\text{base}}\right) \Phi_{\boldsymbol{\beta}}^{-1} \tag{11a}$$

$$L_{t,j}^{u} \leq \mu_a^u u_{t,j}^u \left(\mathbf{L}_{t,j}^{\text{base}} - \mathbf{L}_{t,j}^{\min}\right) + \sigma_a^u u_{t,j}^u \left(\mathbf{L}_{t,j}^{\text{base}} - \mathbf{L}_{t,j}^{\min}\right) \Phi_{\boldsymbol{\beta}}^{-1} \tag{11b}$$

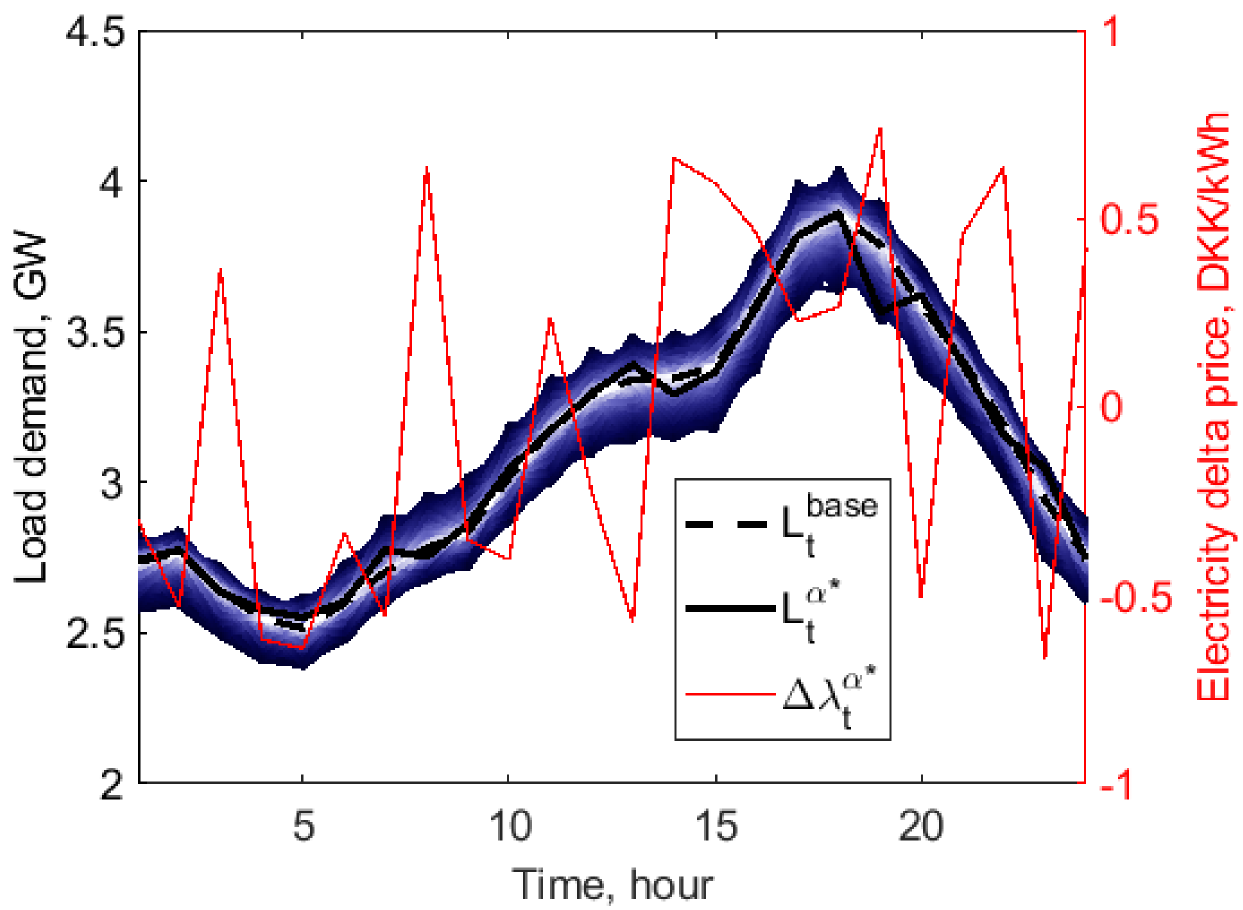
Results
Aggregated electricity flexibility

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.

β = 50%



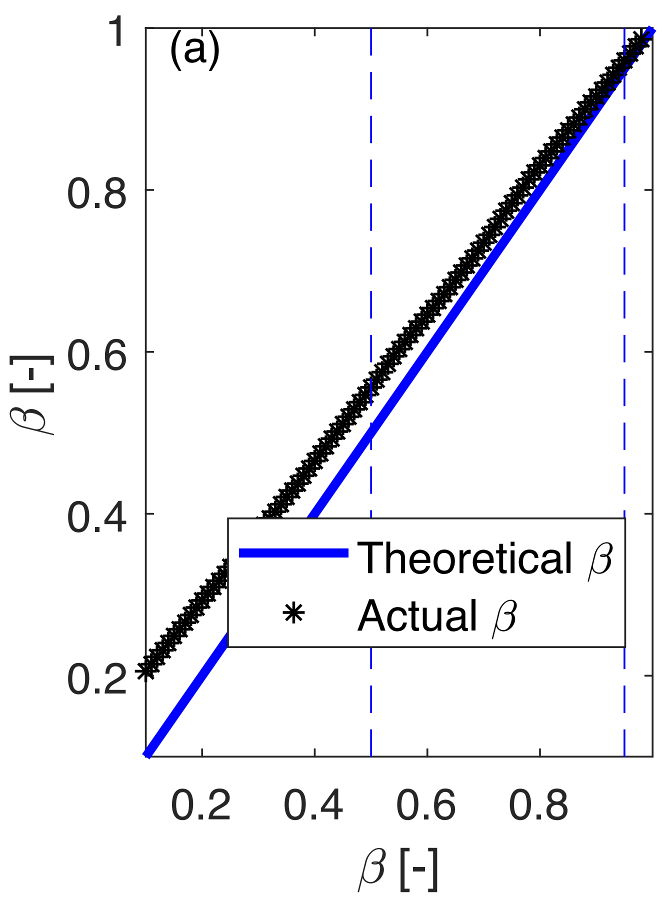
β = 95%



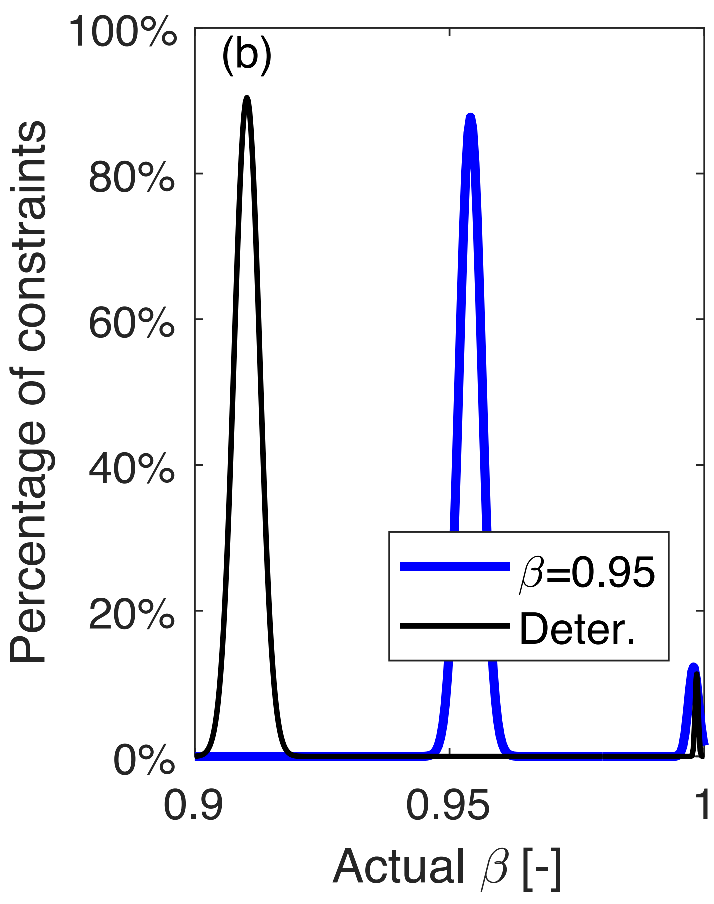
Results
Method validation

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 β



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!