Leveraging Consumers' Flexibility for the Provision of Ancillary Services

Giulia De Zotti

Agenda

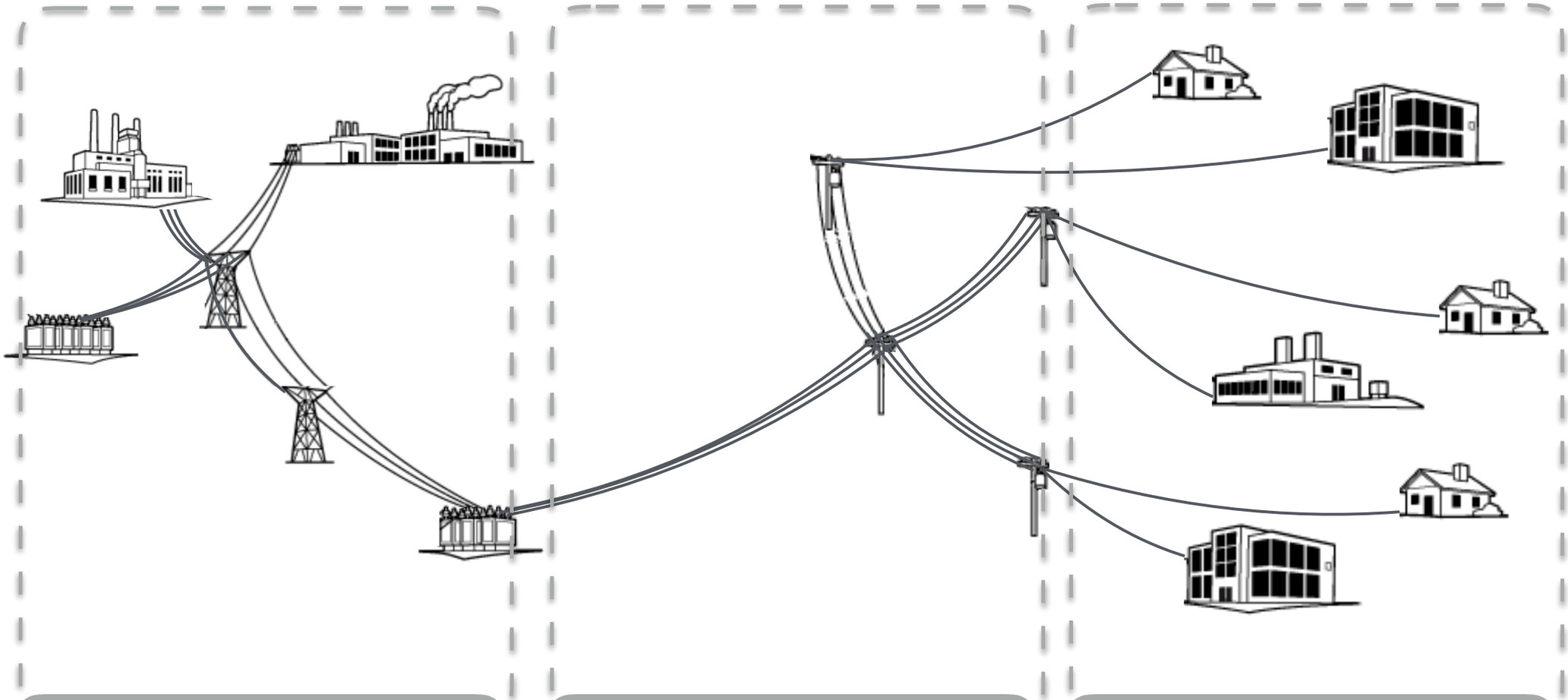
- Introduction
- Key concepts in smart power systems
- Consumers' flexibility for services provision
- Unlocking consumers' flexibility potential: an innovative framework
- Concluding remarks

Introduction
Context and motivation

Power system operation in the past

- **Conventional generation units**
- **Passive consumers**

Almost predictable and **controllable**



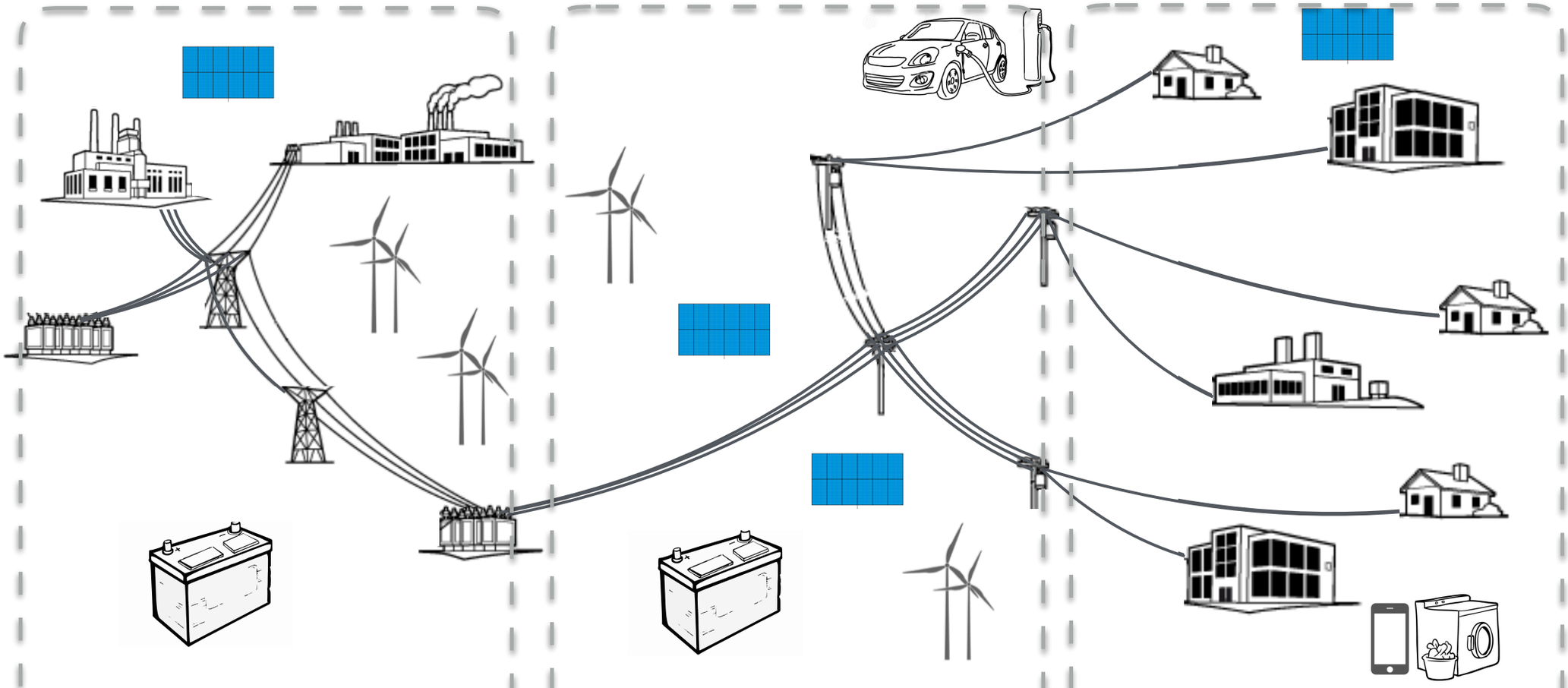
Transmission (high voltage) | Distribution (medium voltage) | Distribution (low voltage)

Introduction
Context and motivation

Power system operation today

- **Renewable energy sources**
- **Active and dynamic consumers**

Stochastic and
less controllable



Transmission (high voltage) | Distribution (medium voltage) | Distribution (low voltage)

Introduction

Context and motivation

Challenges for the power system operation

1 Increasing complexity

- **Stochasticity**
- **Non linearity**
- **Dynamics**

2 Higher need of stability

- **Higher demand of ancillary services** (AS)

3 Uncertainty in AS provision

- Operating **under rated capacity**
- Conventional generation units **retirement**

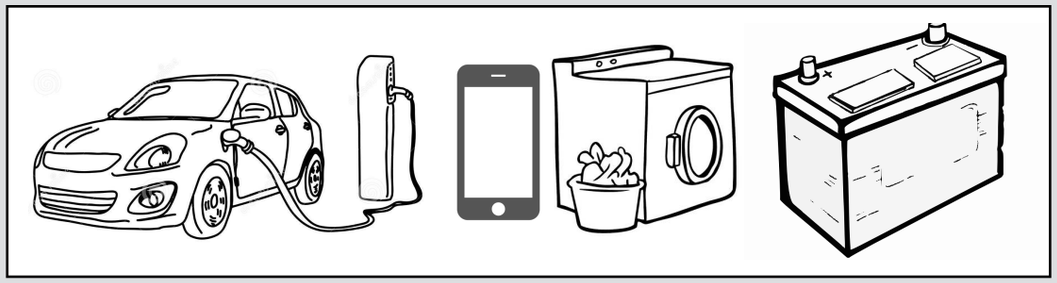
- **International targets**
- **Denmark: Strategy 2050***

* DEA, 2017

Introduction
Thesis objectives

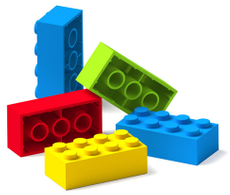
Objectives

- **Green solution for the AS provision**
- **Role** of **electrical consumers**

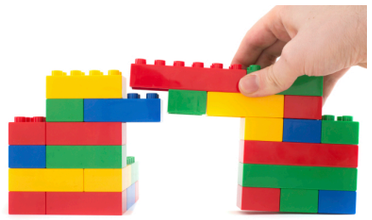


Research questions

1 How can we estimate the potential of consumers' flexibility in providing AS?



2 Which framework can help to optimally exploit consumers' flexibility for AS provision at different voltage levels?



Introduction
Contributions

Research contributions and papers

1 Consumers' flexibility potential

- **Aggregate** flexibility
- **Stochastic nature** of **consumers' behaviour**
- **Different consumers' dynamics**

Paper C

Paper D

2 Framework to leverage consumers' flexibility

- **AS4.0 hypothetical design**
- **AS4.0 modelling** and **simulations**

Paper A

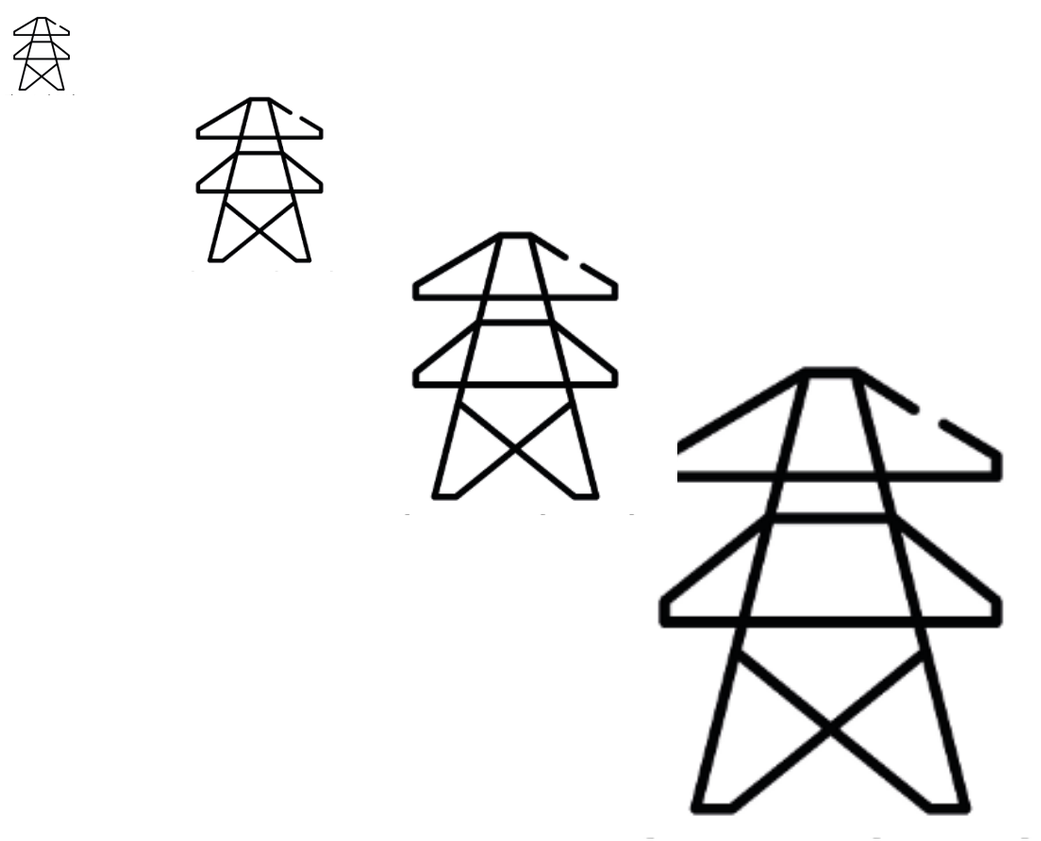
Paper B

Paper E

IEEE

IFAC
INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL

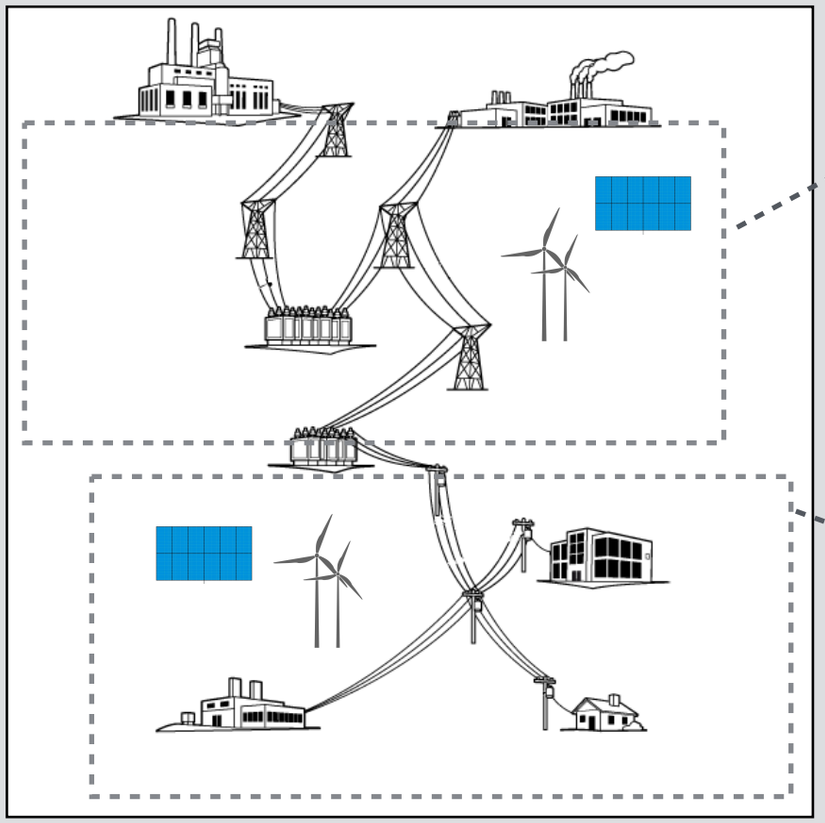
Key concepts in smart power systems



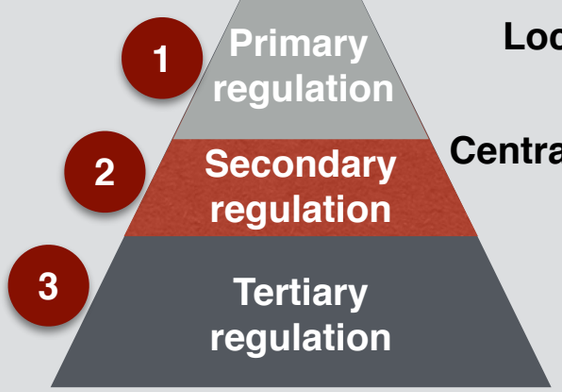
Key concepts in smart power systems
Ancillary services

Ancillary services

Ancillary services (AS) guarantee **service continuity and security** from the distribution to the transmission level.



Type / Activation time

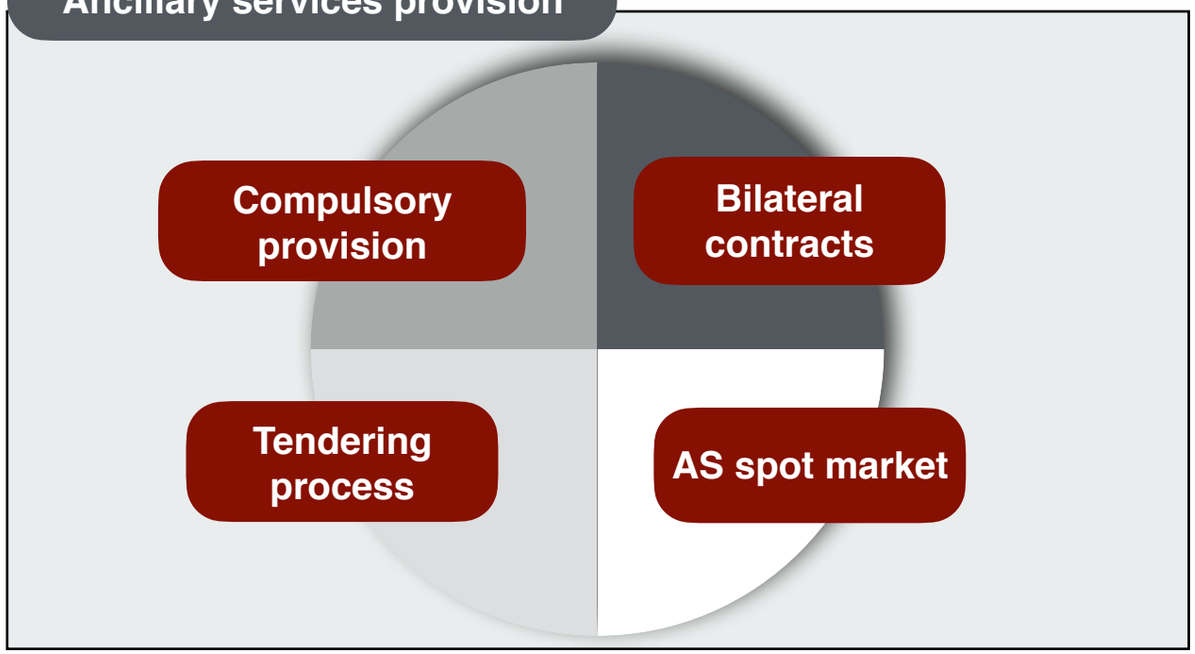


Local automatic
Seconds

Centralised automatic
Minutes

Manual
Hours

Ancillary services provision

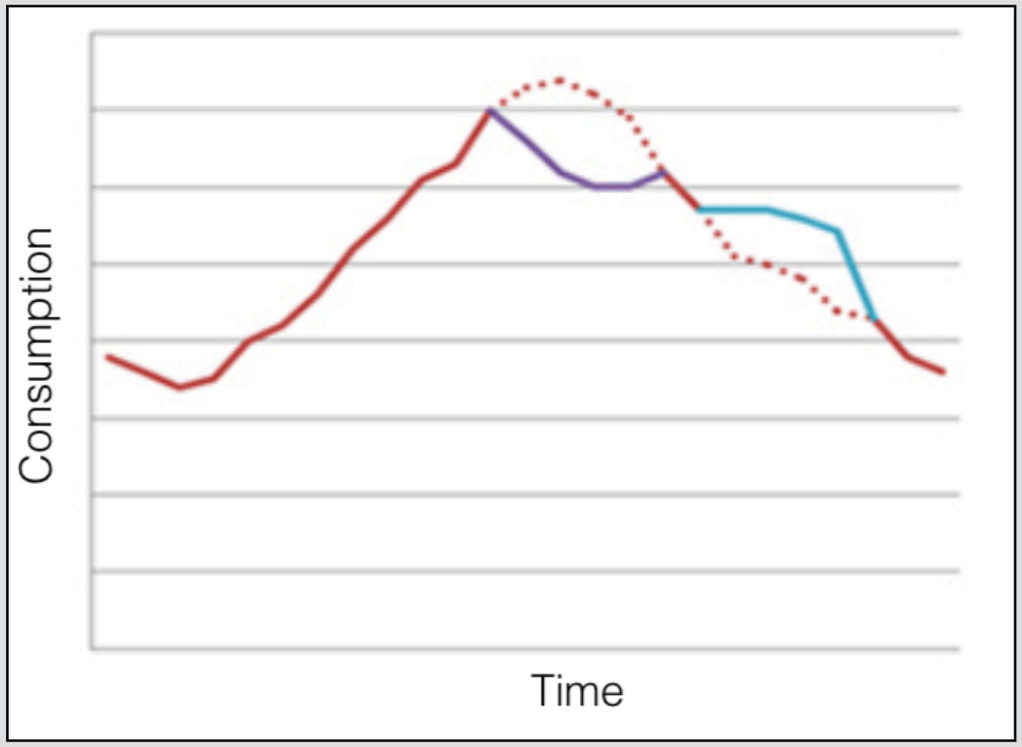


Key concepts in smart power systems

Services provision through demand response

Demand response programs

In **demand response** (DR), **consumers alter their consumption** according to the necessity of the grid.



Key concepts in smart power systems

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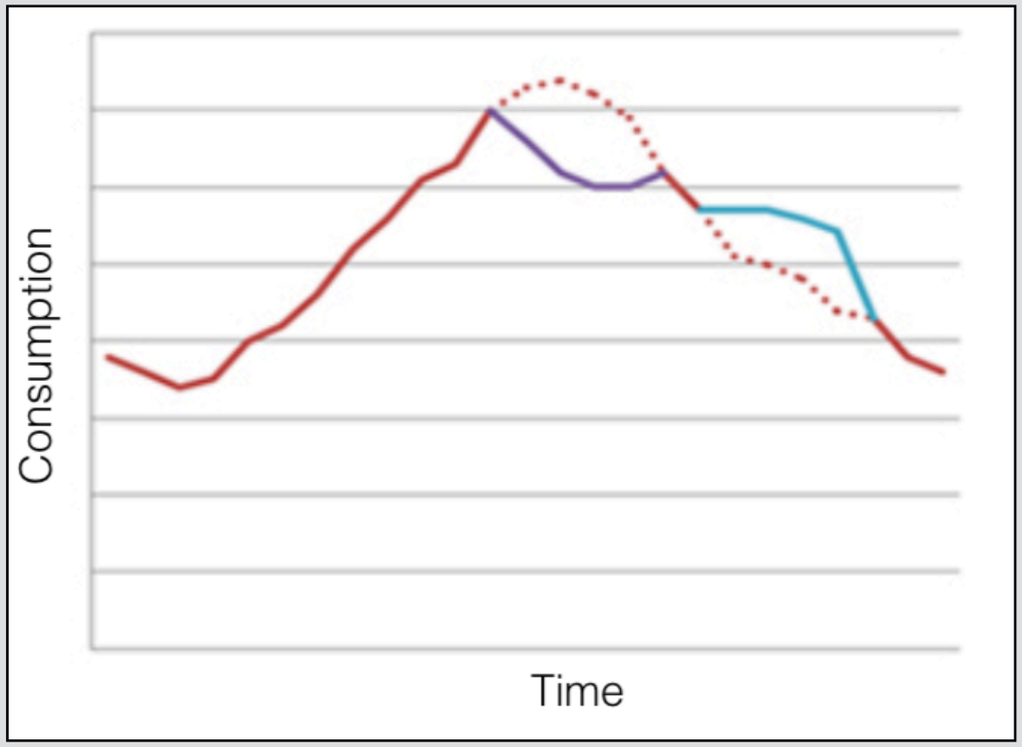
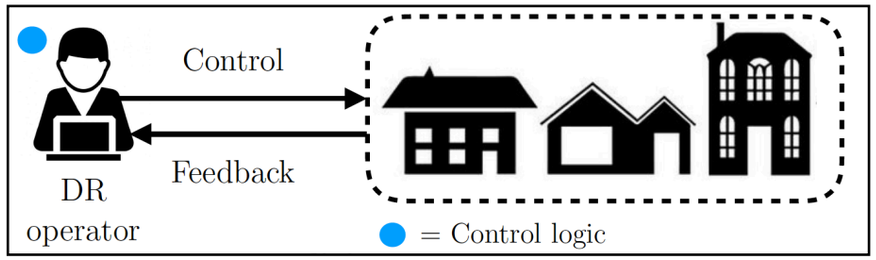


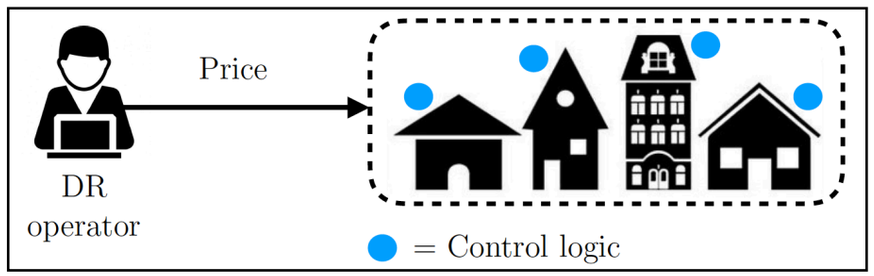
1 Explicit DR program



Two-way communication

- Minimised uncertainty
- Consumers' privacy

2 Implicit DR program

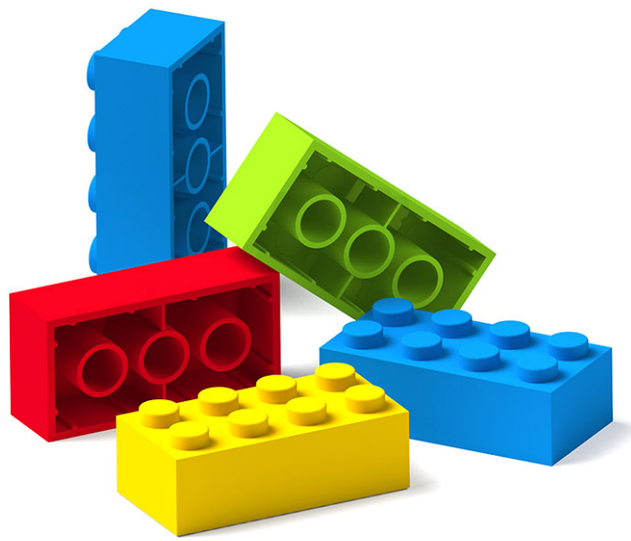


One-way communication

- Consumers' autonomy
- Proper price signals

Consumers' flexibility for services provision

1 **How can we estimate the potential of consumers' flexibility in providing AS?**



Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Consumers' flexibility potential

Assumptions

- **Different types** of **consumers**
- **Rational consumers**
- **Time varying prices**
- **One-way** communication

Cost minimisation

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

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Cost
minimisation

Model

$$\min_{L^{\alpha}_{t,j}} \sum_{t=1}^{\tau} \left(\lambda^{\text{base}} + \Delta\lambda^{u}_{t} + \Delta\lambda^{d}_{t}\right) \sum_{j=1}^{J} \left(L^{\text{base}}_{t,j} + L^{d}_{t,j} - L^{u}_{t,j}\right)$$

Consumers' flexibility for services provision

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Cost
minimisation

Comfort

Technical constraints

1. **Ramping**
2. **Rebound**
3. **Activation**
4. **Flex duration**

Model

$$\min_{L^{\alpha}_{t,j}} \sum_{t=1}^{\tau} \left(\boldsymbol{\lambda}^{\text{base}} + \boldsymbol{\Delta\lambda}^{u}_{t} + \boldsymbol{\Delta\lambda}^{d}_{t}\right) \sum_{j=1}^{J} \left(\boldsymbol{L}^{\text{base}}_{t,j} + L^{d}_{t,j} - L^{u}_{t,j}\right)$$

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minimisation

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Model

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

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

$$0 \le L^{d}_{t,j} \le u^{d}_{t,j}\left(\mathbf{L}^{\max}_{t,j} - \mathbf{L}^{\text{base}}_{t,j}\right)\mathbf{a}^{d}_{t,j} \quad \forall t, j$$

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$$\sum_{t'=(t-1)R_j+1}^{(t-1)R_j+R_j}\left(L^{d}_{t',j} - L^{u}_{t',j}\right) = 0 \quad \forall t : [t \in T, (tR_j \le \tau)], j$$

$$u^{d}_{t,j} + u^{u}_{t,j} \le 1 \qquad \forall t, j$$

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

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Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Consumers' flexibility potential

Assumptions

- **Different types** of **consumers**
- **Rational consumers**
- **Time varying prices**
- **One-way** communication

Cost minimisation

Comfort

Technical constraints

1. **Ramping** — **Provision change** is **limited** over **time**
2. **Rebound**
3. **Activation**
4. **Flex duration**

Model

$$\min_{L^{\alpha}_{t,j}} \sum_{t=1}^{\tau}\left(\boldsymbol{\lambda}^{\text{base}} + \boldsymbol{\Delta\lambda}^{u}_{t} + \boldsymbol{\Delta\lambda}^{d}_{t}\right)\sum_{j=1}^{J}\left(\boldsymbol{L}^{\text{base}}_{t,j} + L^{d}_{t,j} - L^{u}_{t,j}\right)$$

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Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Consumers' flexibility potential

Assumptions

- **Different types** of **consumers**
- **Rational consumers**
- **Time varying prices**
- **One-way** communication

Cost
minimisation

Comfort

Technical constraints

1. **Ramping**
2. **Rebound** — **Previous** and **future price reactions**
3. **Activation**
4. **Flex duration**

Model

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

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Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Consumers' flexibility potential

Assumptions

- **Different types** of **consumers**
- **Rational consumers**
- **Time varying prices**
- **One-way** communication

Cost
minimisation

Comfort

Technical constraints

1. **Ramping**
2. **Rebound**
3. **Activation** — **Amount of times flexibility is activated**
4. **Flex duration**

Model

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Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Consumers' flexibility potential

Assumptions

- **Different types** of **consumers**
- **Rational consumers**
- **Time varying prices**
- **One-way** communication

Cost
minimisation

Comfort

Technical constraints

1. Ramping
2. Rebound
3. Activation
4. **Flex duration** — **Continuous flexibility duration**

Model

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

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Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Consumers' flexibility potential

Assumptions

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- **One-way** communication

Cost minimisation

Comfort

Technical constraints

1. **Ramping**
2. **Rebound**
3. **Activation**
4. **Flex duration**

Analyses

1. Consumers' **price responsiveness**
2. **Rebound effect**
3. Outdoor **temperature**

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

1 Consumers' price responsiveness

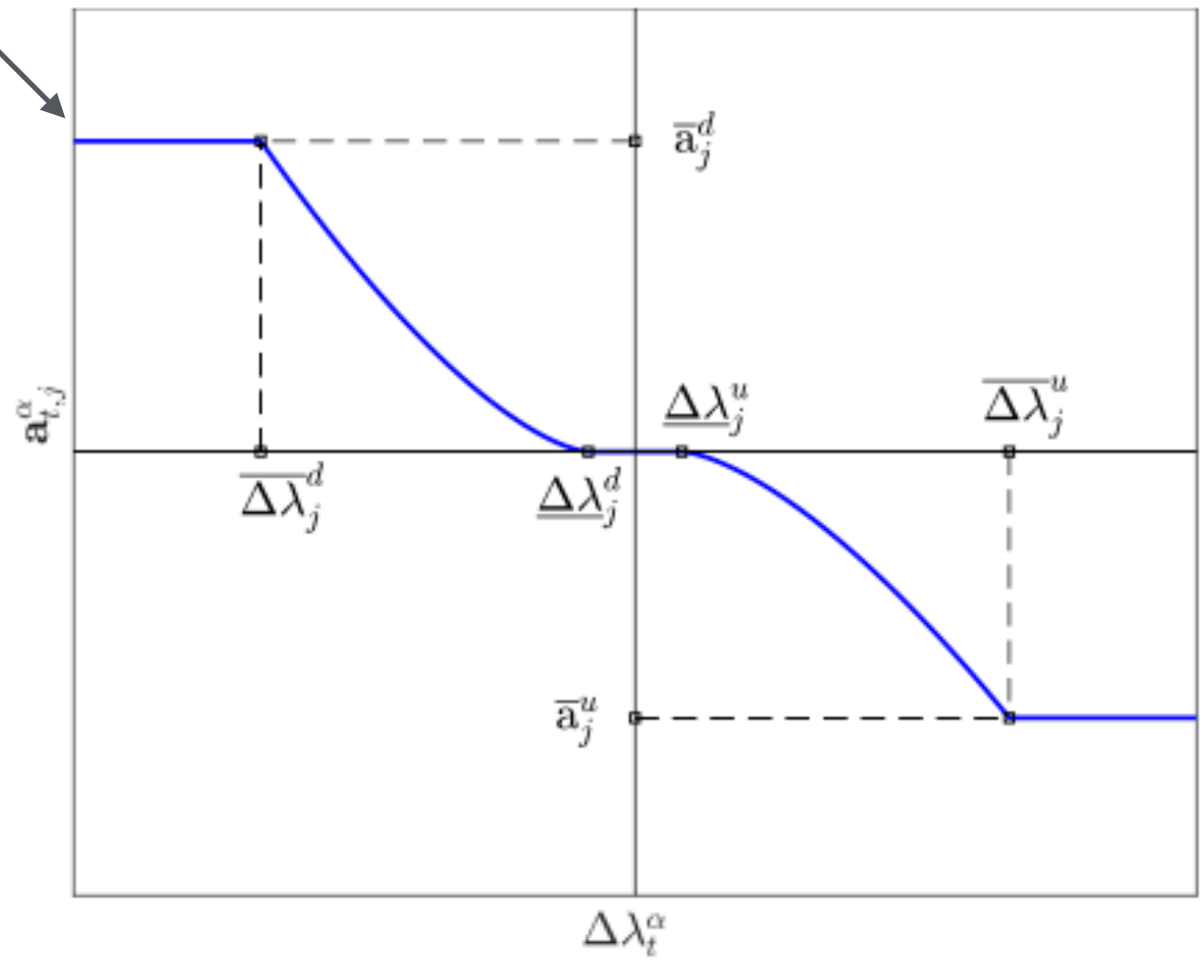
Willingness to **change consumption** for **different prices**

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

1 Consumers' price responsiveness

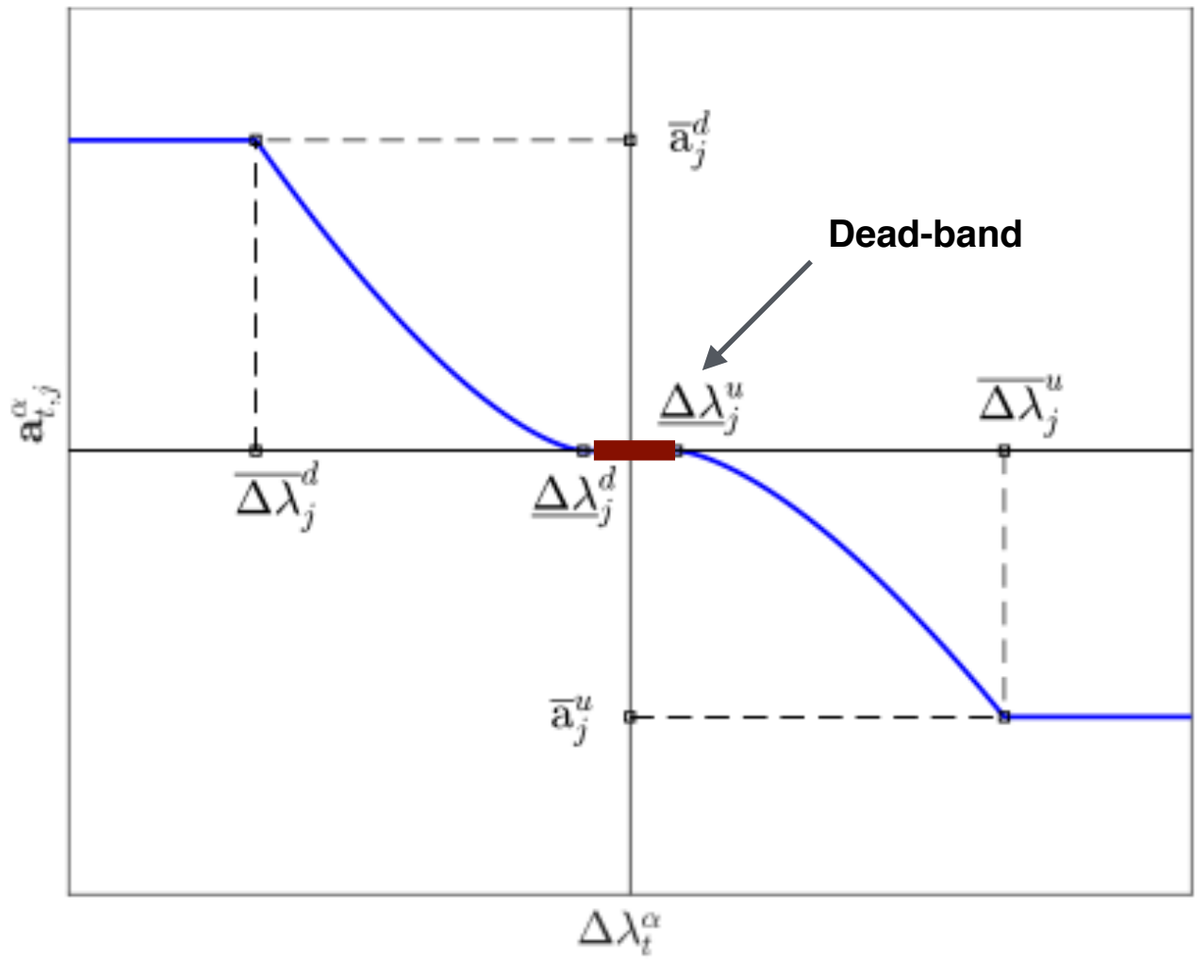
Willingness to **change consumption** for **different prices**



Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

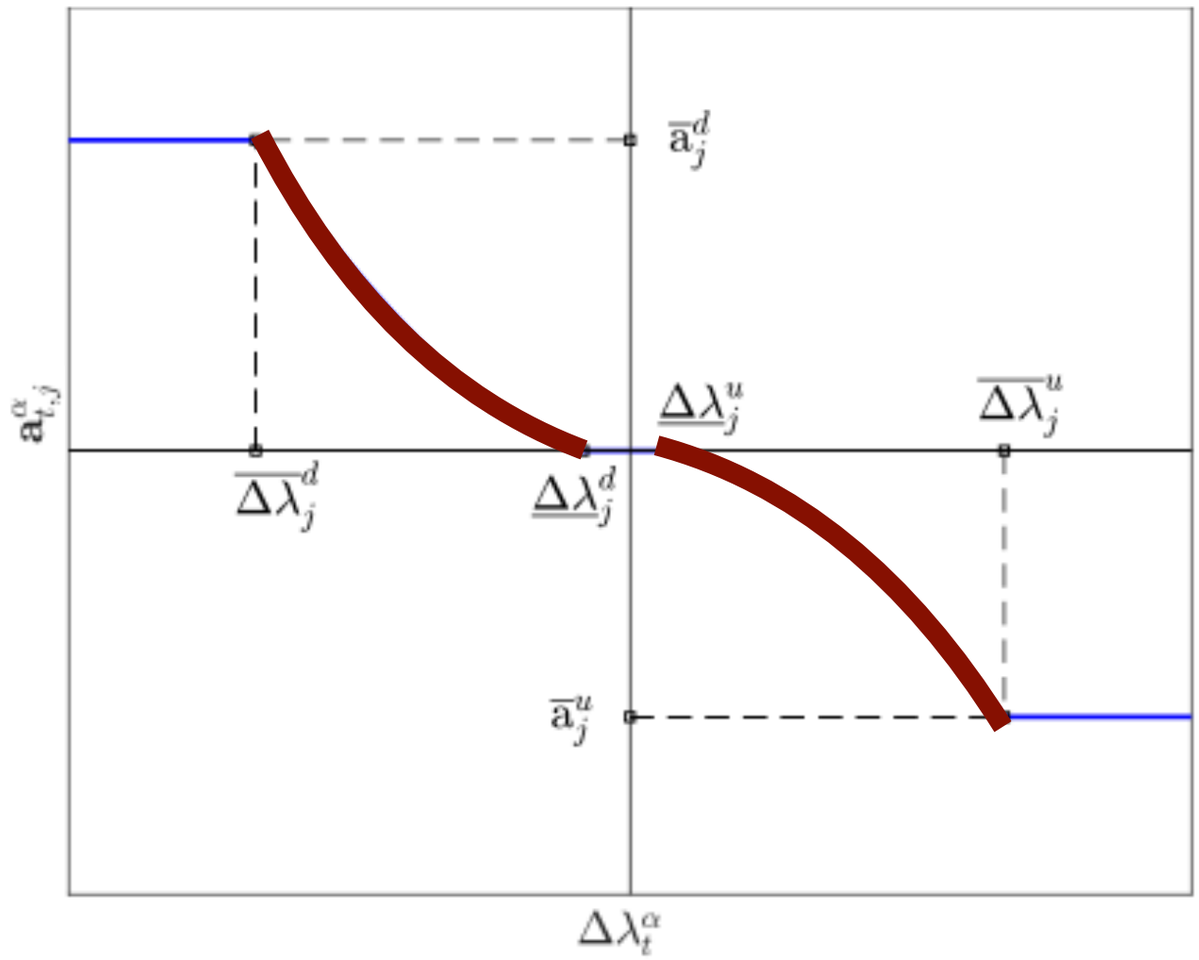
1 Consumers' price responsiveness



Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

1 Consumers' price responsiveness



Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

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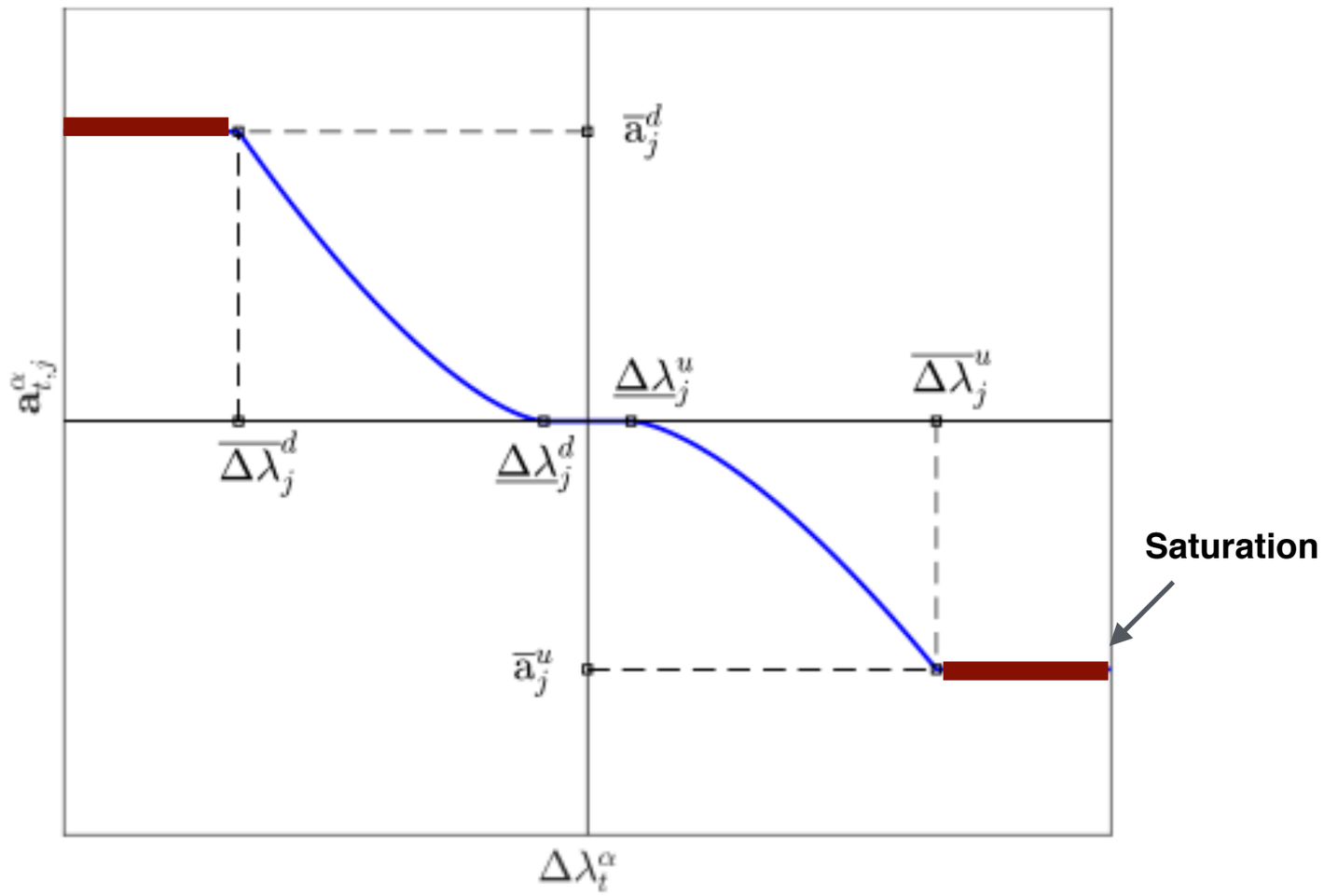


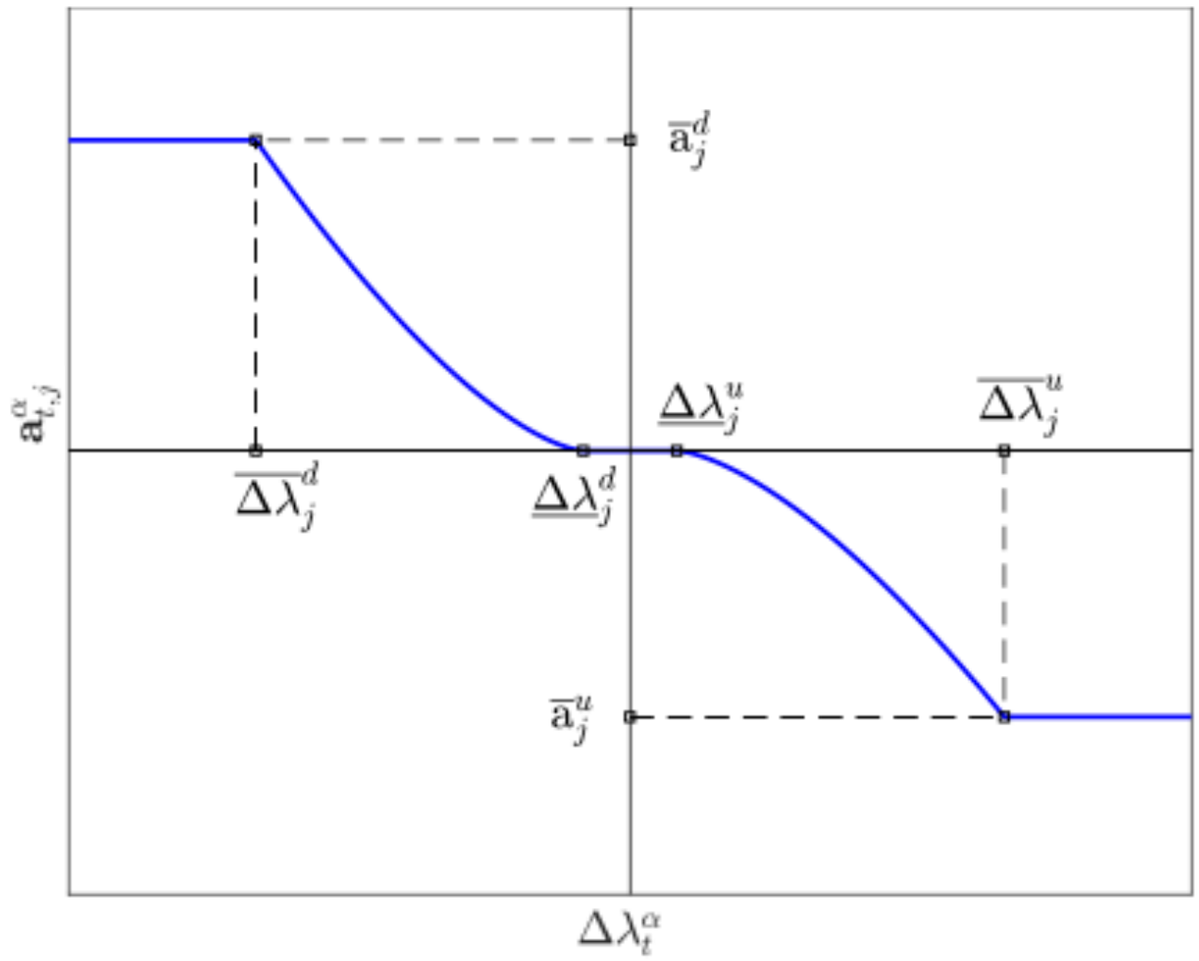
Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

1 Consumers' price responsiveness

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

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



Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

1 Consumers' price responsiveness

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

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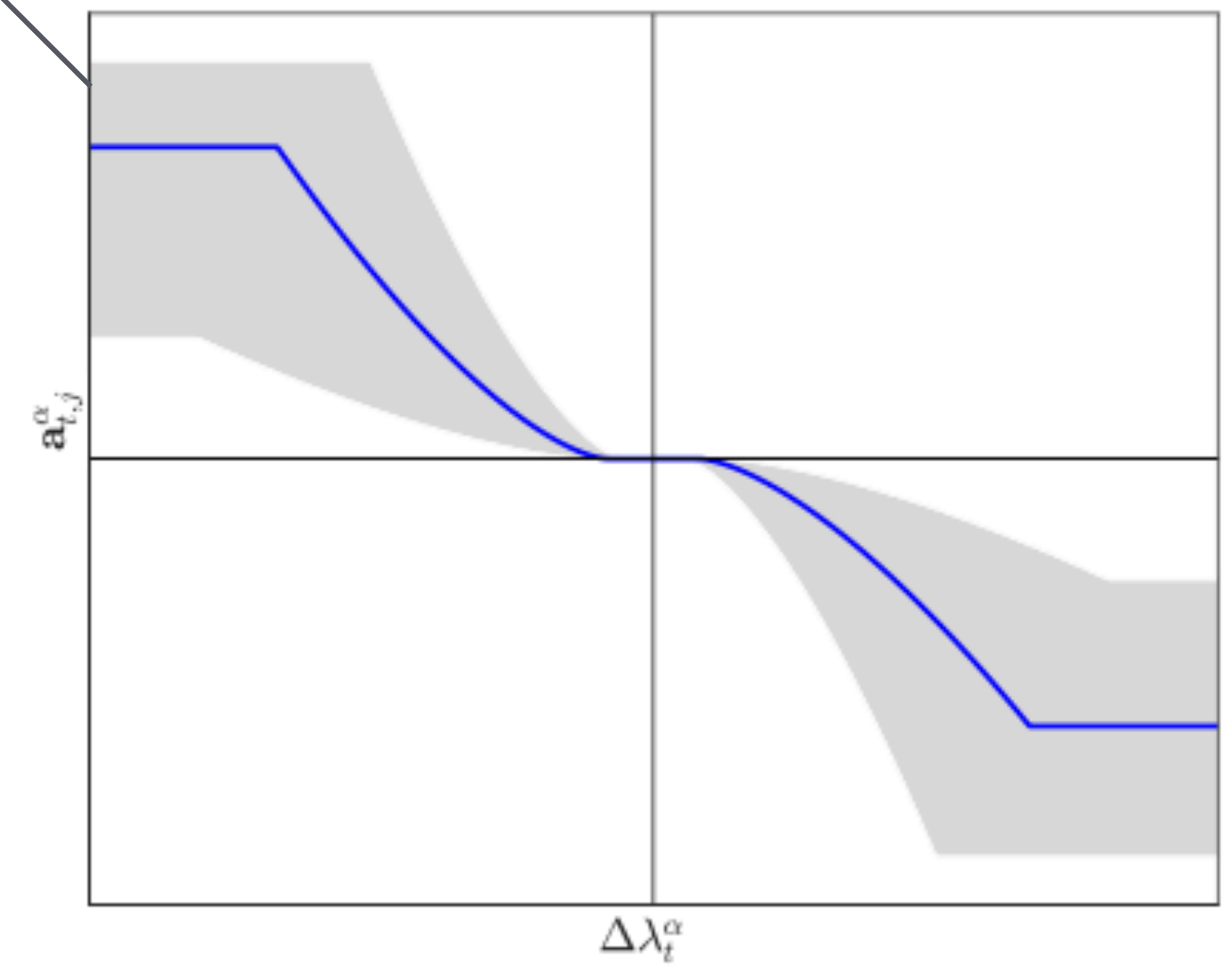

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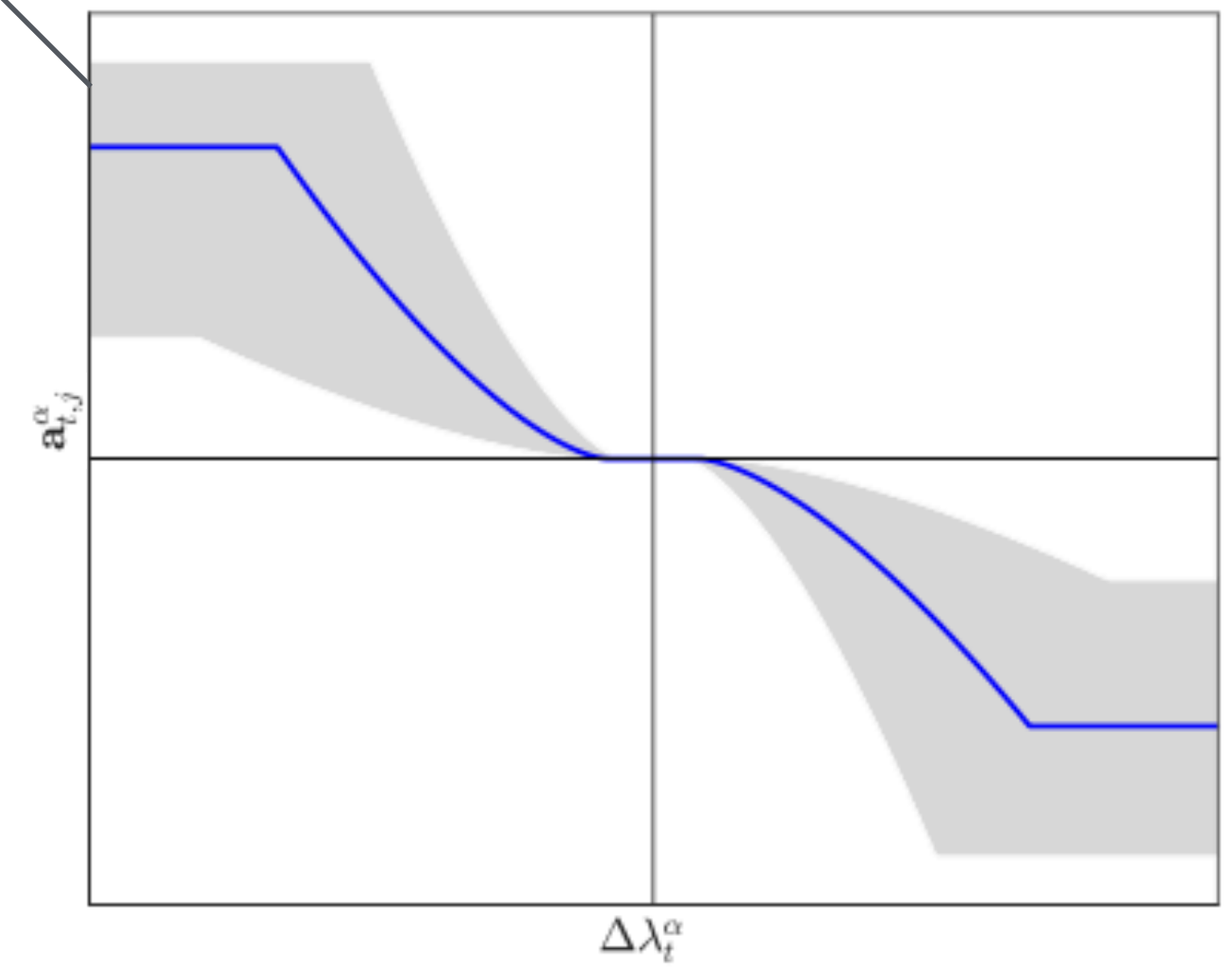

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Chance constrained programming

$$\min_{x} \; c^T x$$

subject to:

$$Ax \leq b$$

$$x \geq 0$$

$$Pr\left(Ax \leq b\right) \geq \beta$$

Confidence level

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Simulations results

- **Conservative CC case** (β=0.95) and **high-risk CC case** (β=0.50)
- **29** different **consumers**' **categories**
- Maximum load consumption: **3.85 GWh**

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

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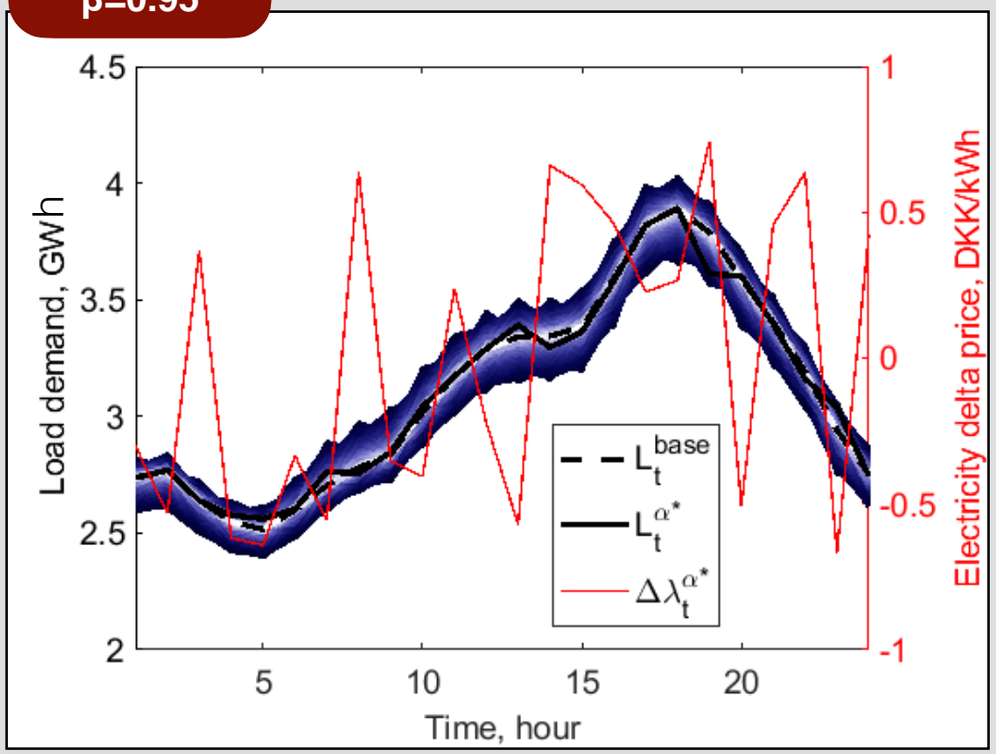
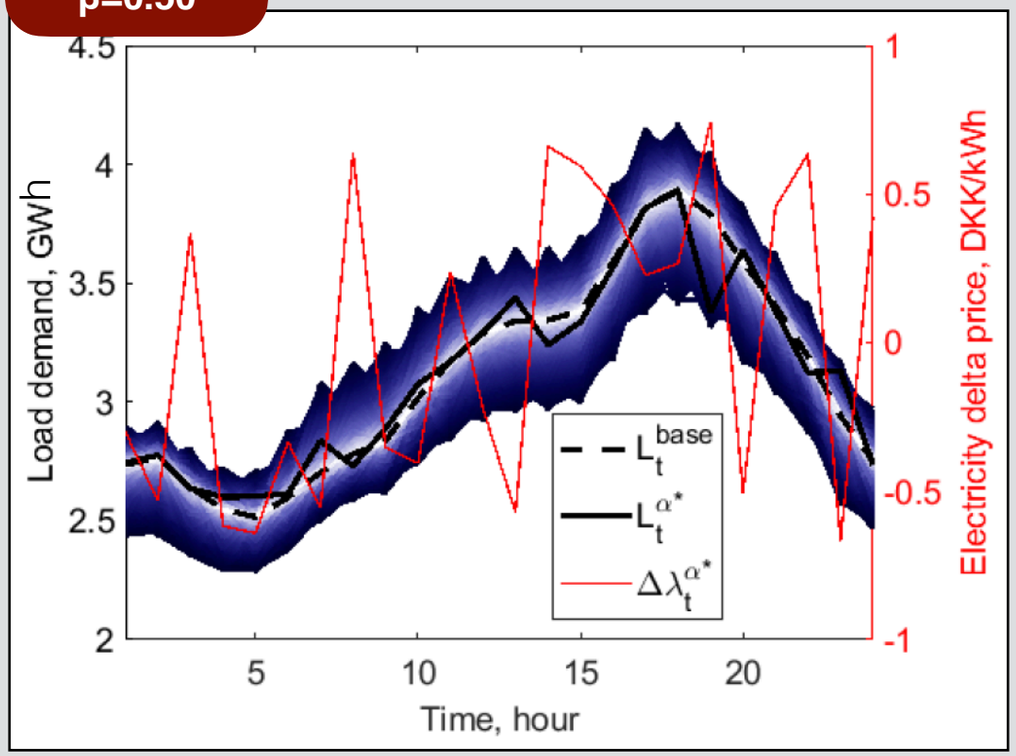
β=0.95



β=0.50



Study case	Regulation (GWh)
95 %	0.719
50 %	0.243
Difference	**-66 %**

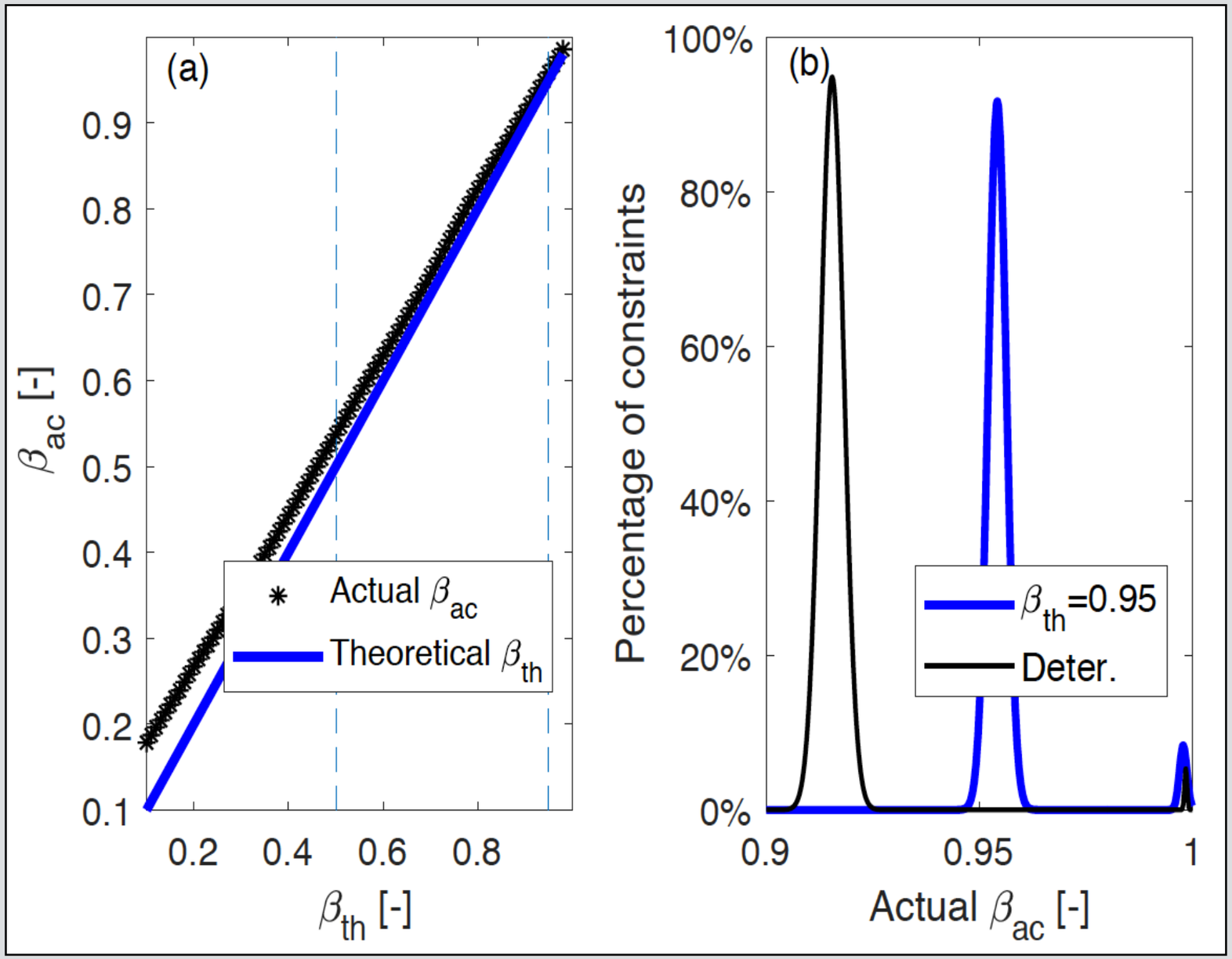
Finding

The choice of the **confidence level significantly affects** the **flexibility estimation**.

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

CC Validation



β_{th} **Theoretical** confidence level

β_{ac} **Actual** confidence level

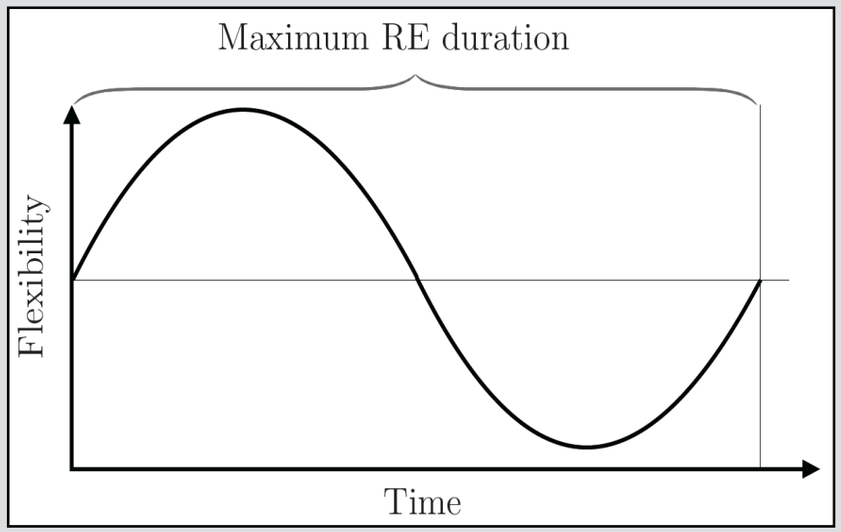
Findings

- The **actual confidence level** is **always higher** than the theoretical counterpart.

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

2 Rebound effect (RE)

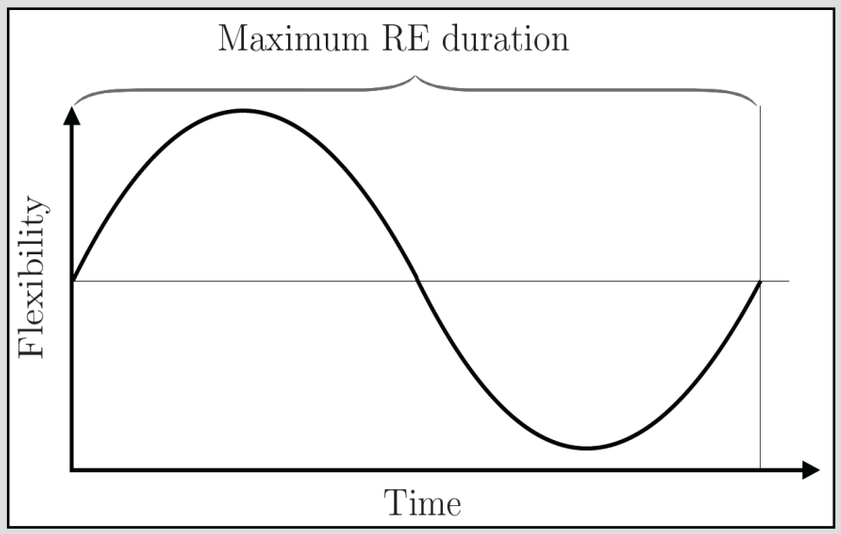


Perfect rebound

Consumers' flexibility for services provision

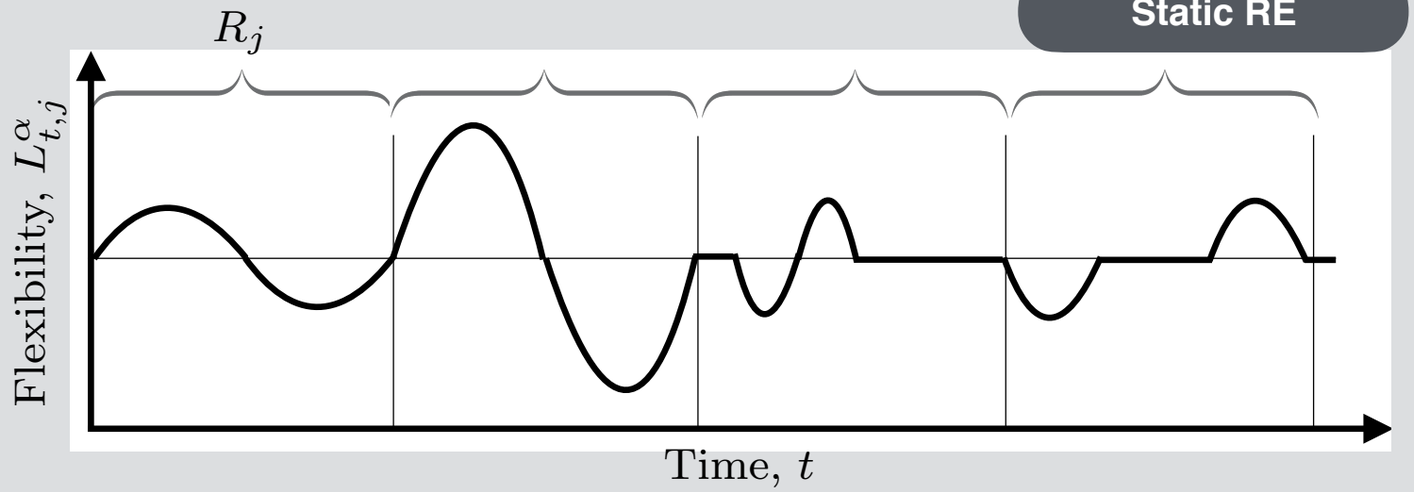
Analysis of the factors influencing consumers' response

2 Rebound effect (RE)



Perfect rebound

Static RE

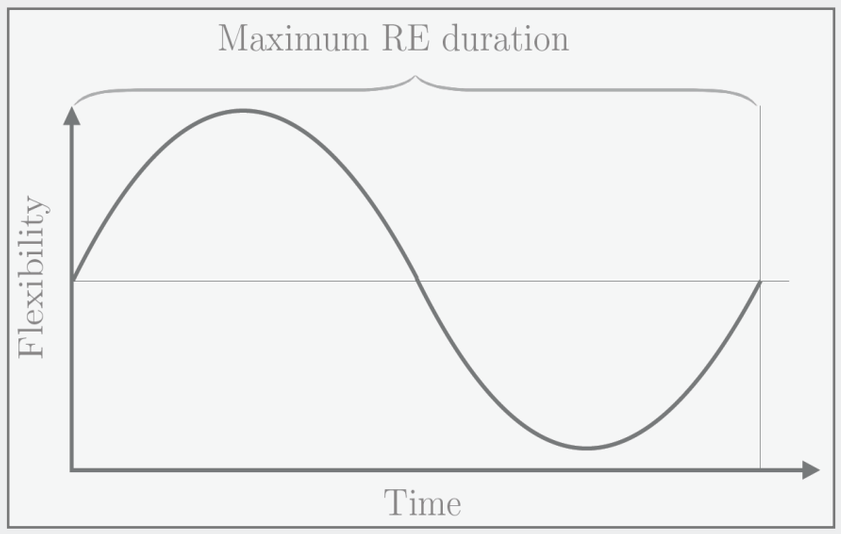


Specific time intervals

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

2 Rebound effect (RE)



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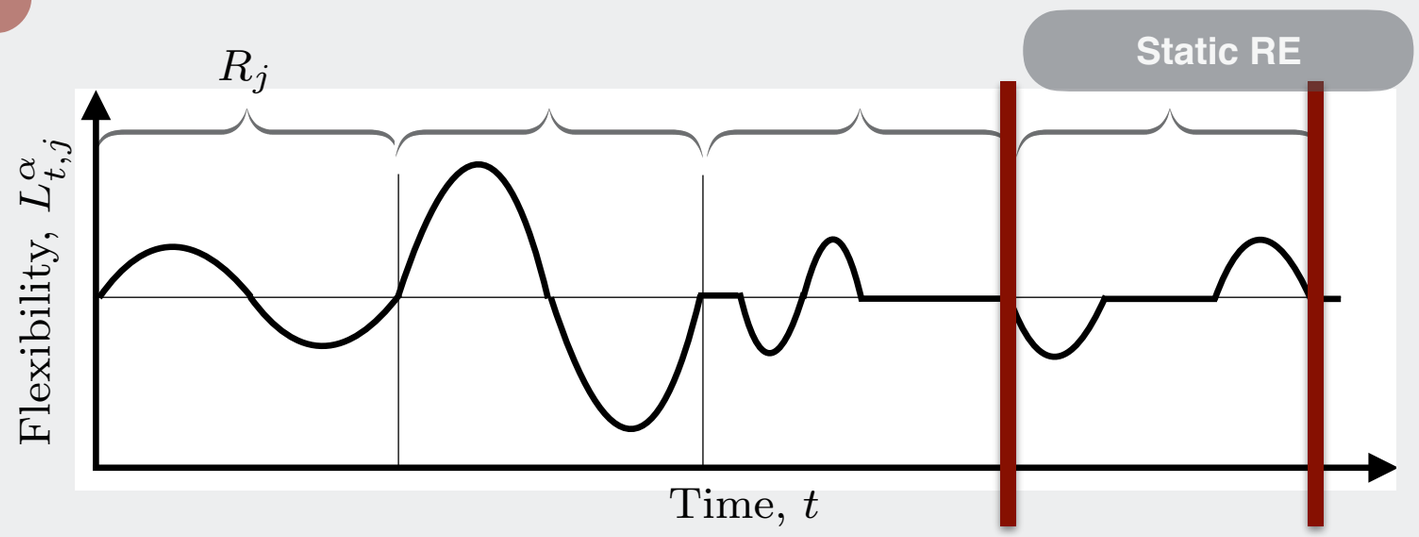

	5	10
Specific time intervals		

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

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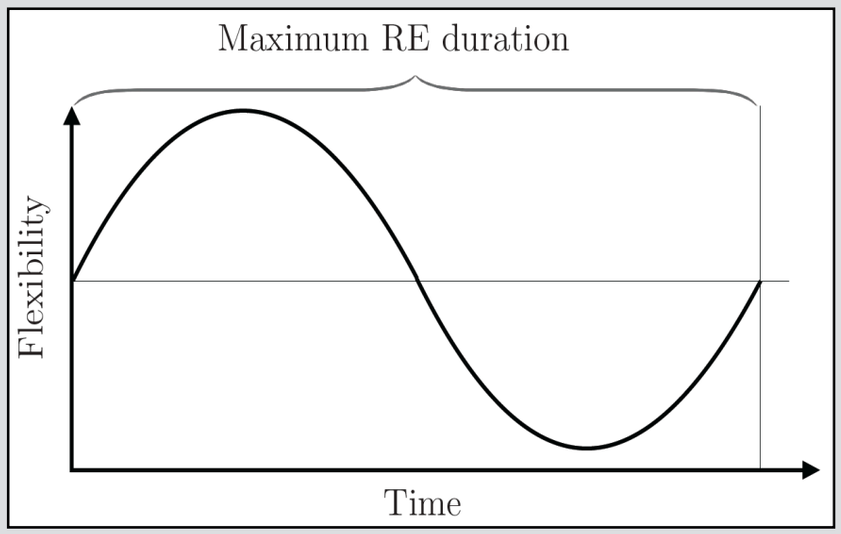

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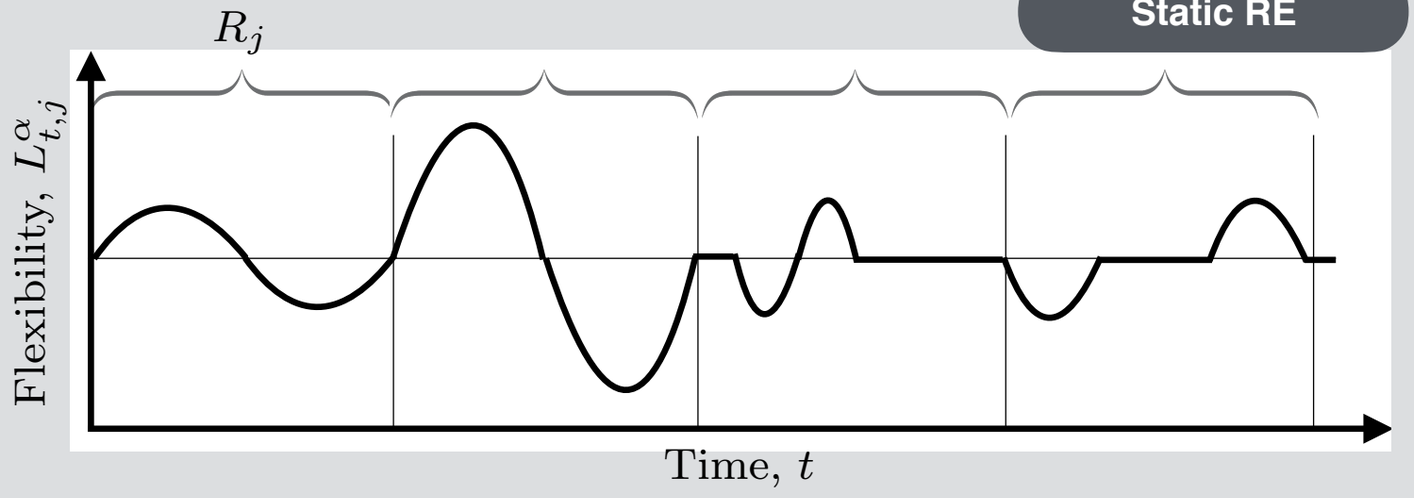
Static RE



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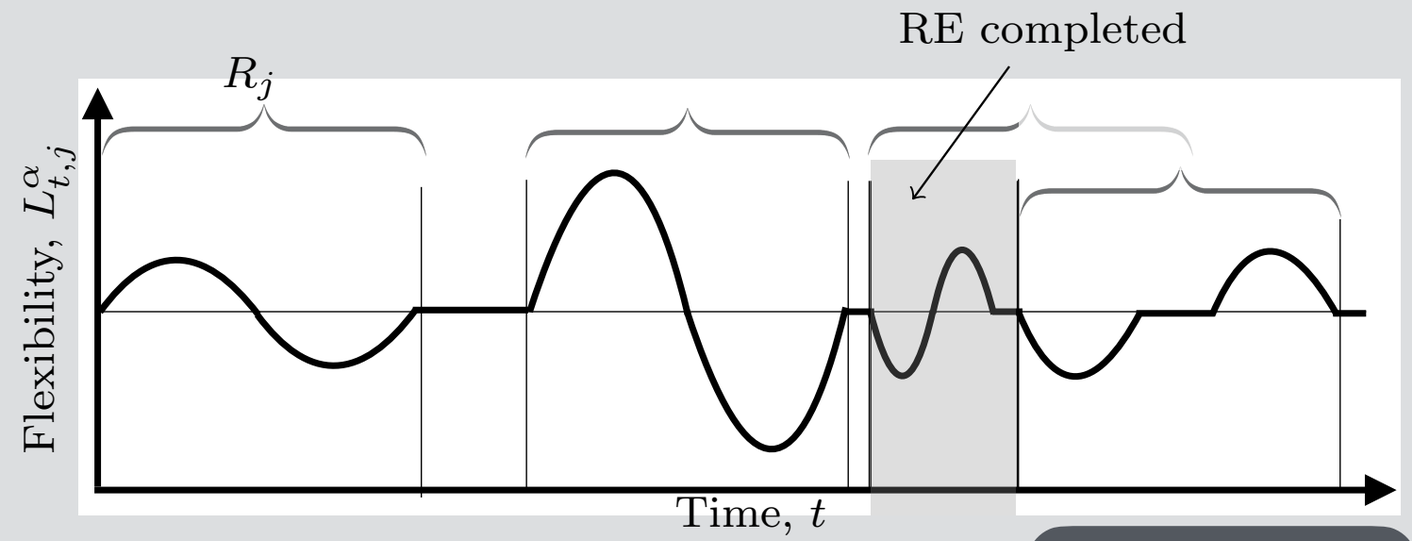


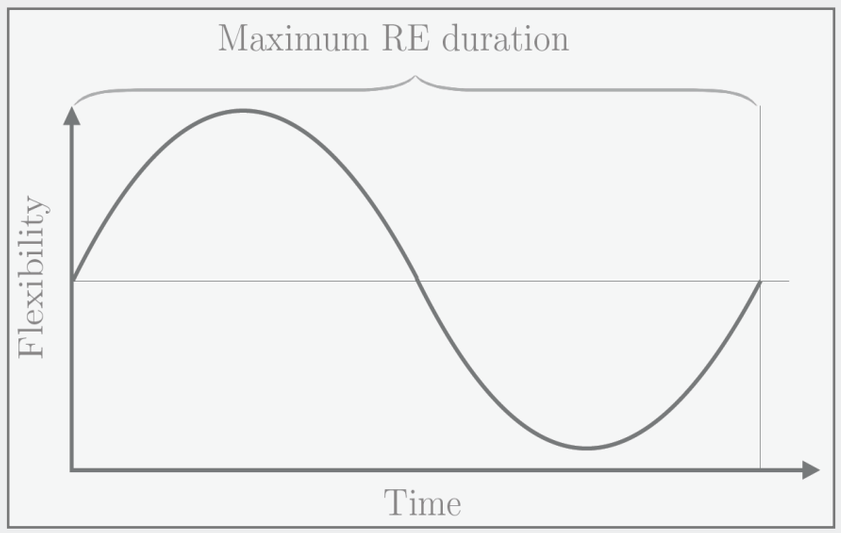
Maximum RE duration

Dynamic RE

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

2 Rebound effect (RE)



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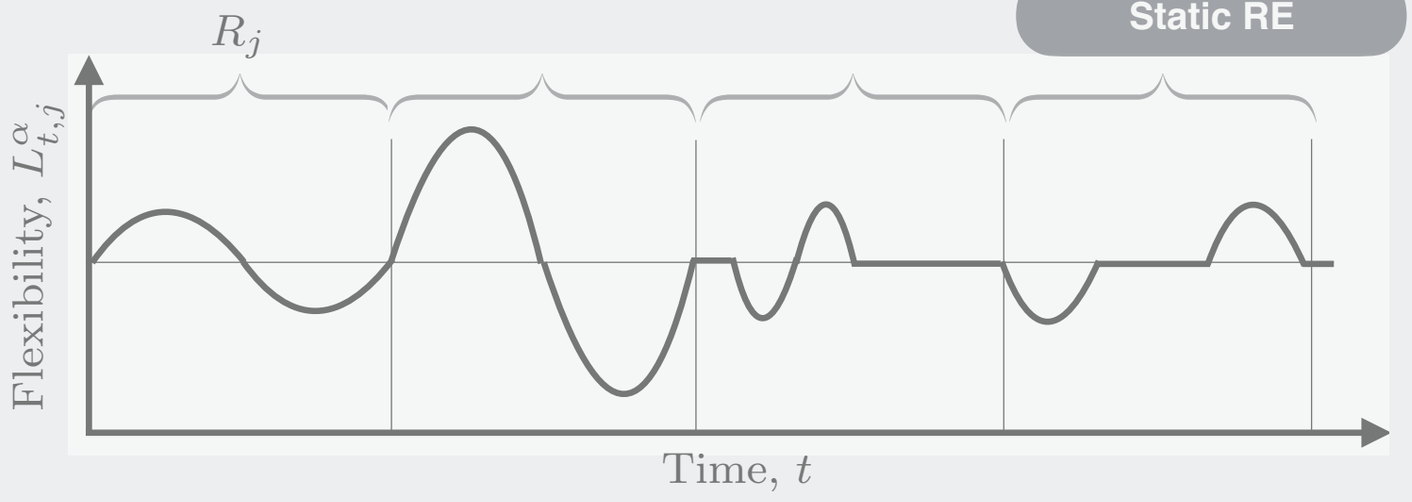
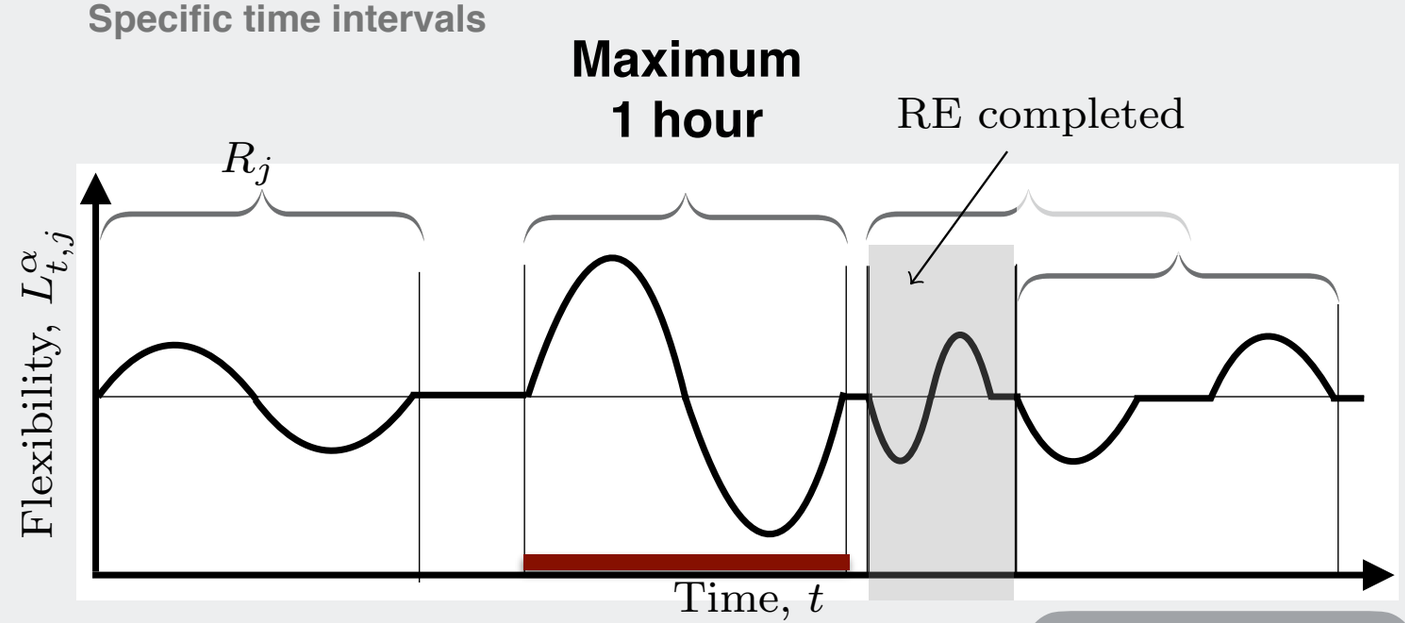


Specific time intervals



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Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

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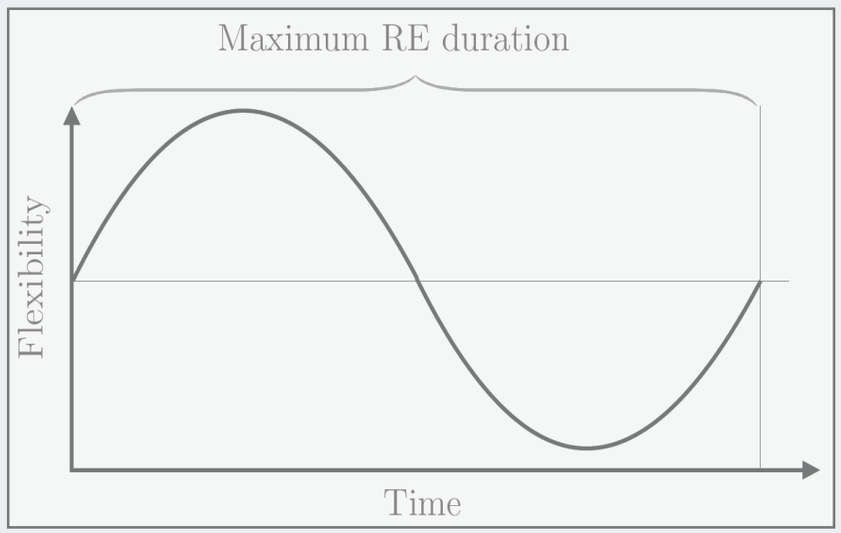

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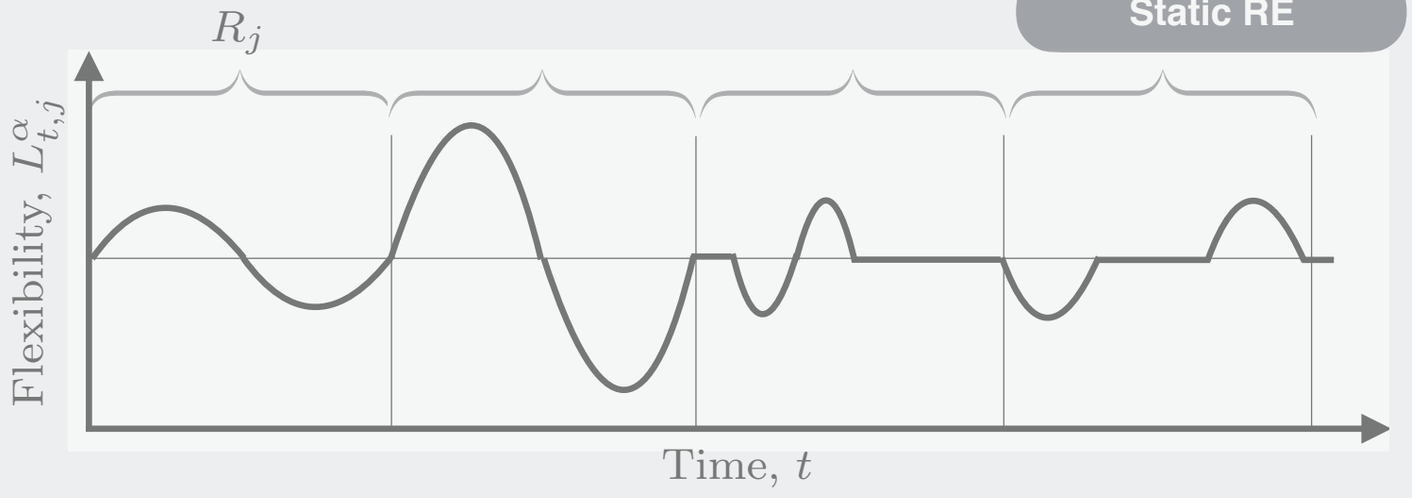
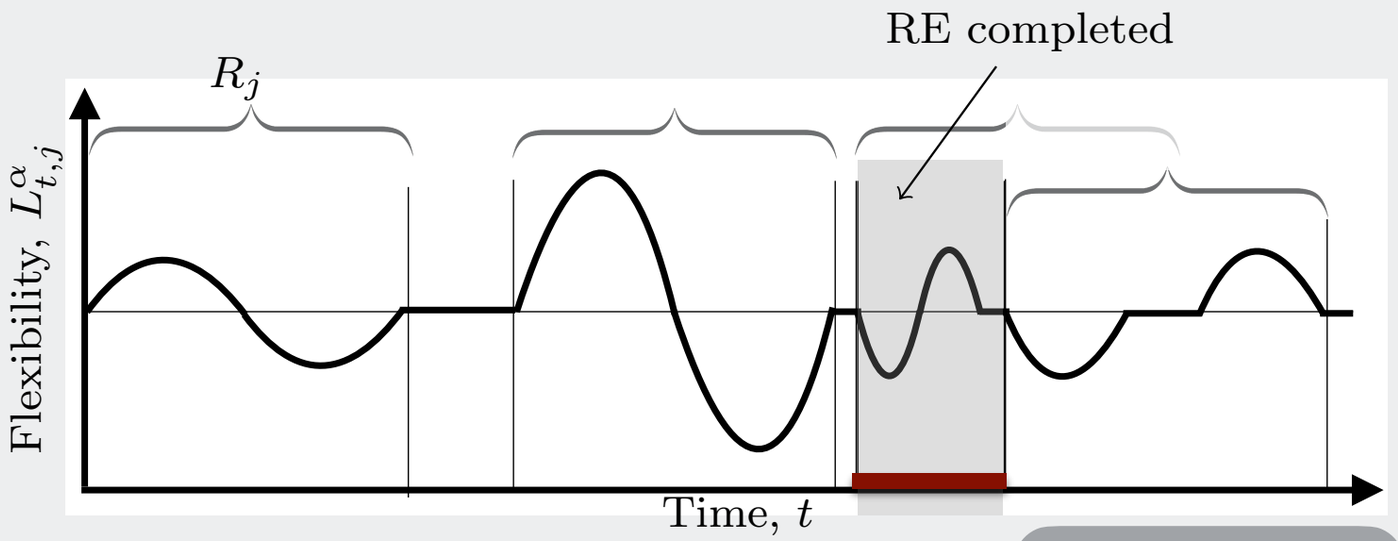


Specific time intervals



Maximum RE duration

Dynamic RE

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

Simulations and results

- **Conservative CC case**
- **29** different **consumers**' **categories**
- **Two days** simulations

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

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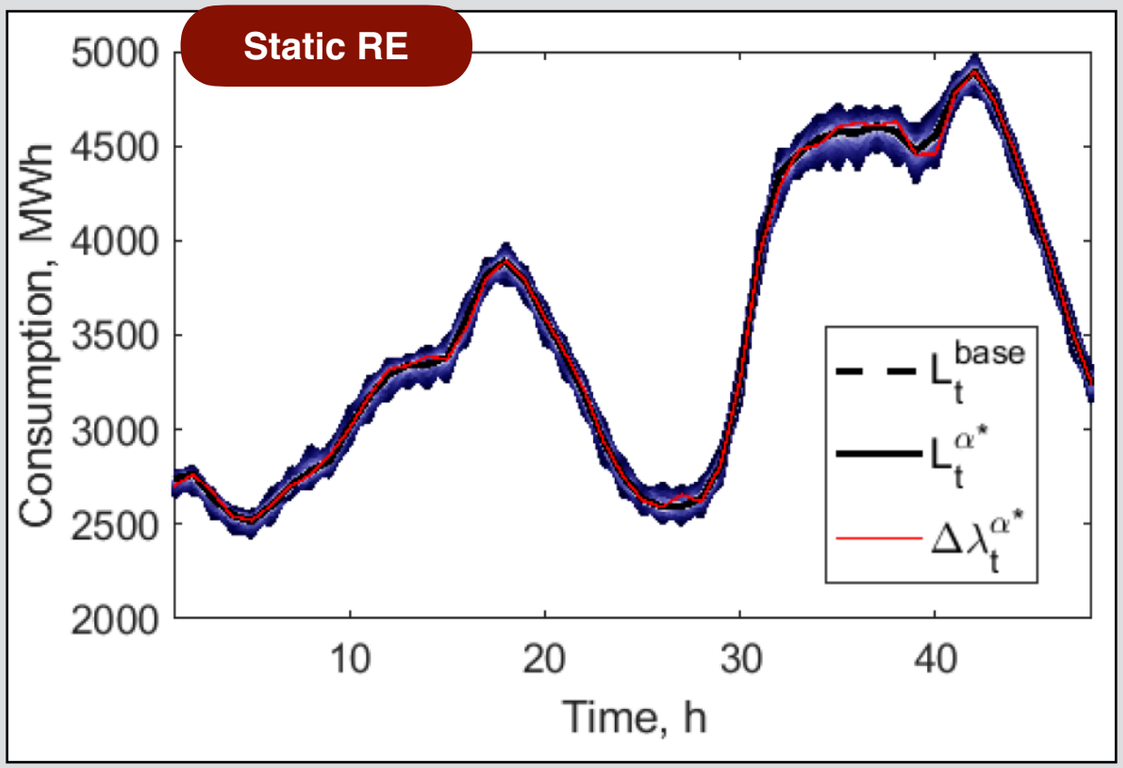

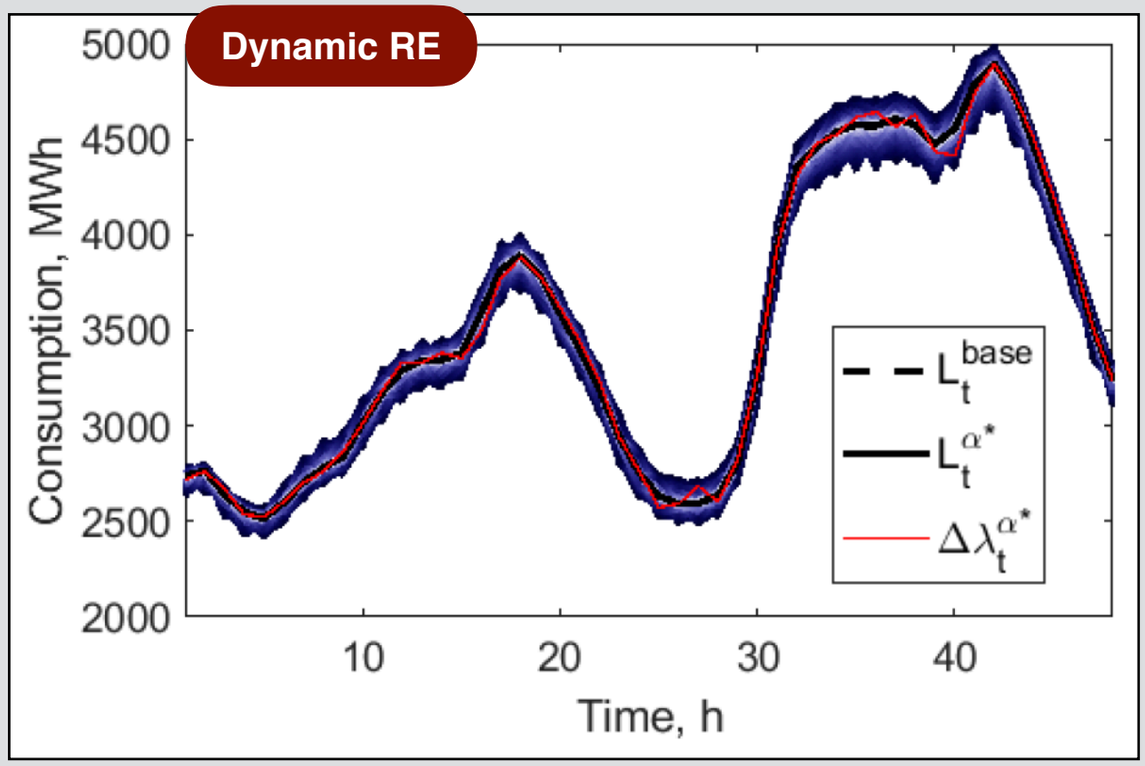

Study case	Regulation (MWh)
Static rebound	600
Dynamic rebound	874
Difference	**45 %**

Finding

It is fundamental for operators to **understand which RE dynamics are most likely to happen** on the consumers' side.

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

3 Outdoor temperature

ν

The **price responsiveness** is multiplied by a **correcting parameter**.

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

3 Outdoor temperature

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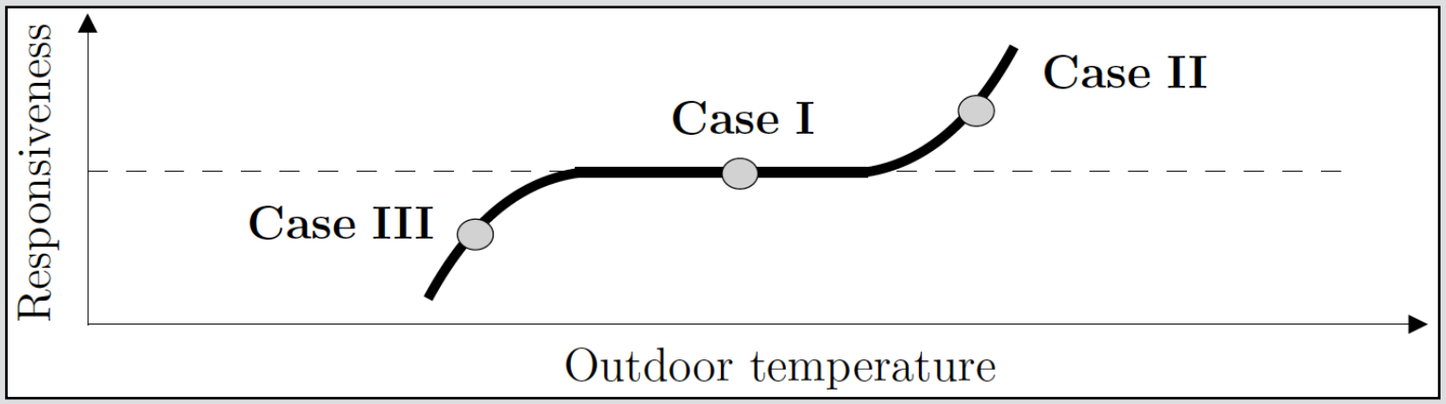

Case study

- **Summer season**

ν
Case I = 1
Case II = 1.1
Case III = 0.9

Consumers' flexibility for services provision

Analysis of the factors influencing consumers' response

3 Outdoor temperature

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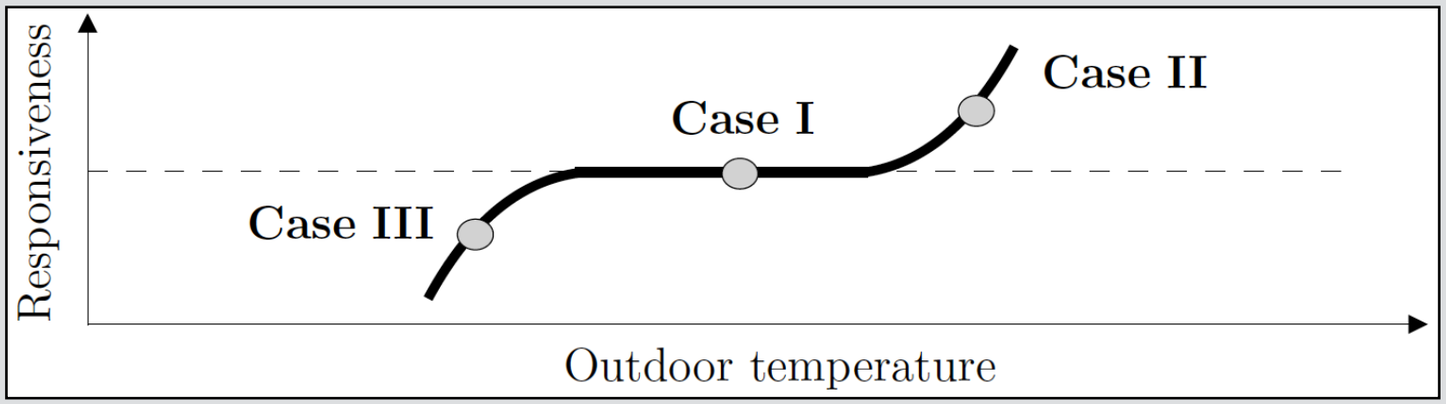


RE model	Outdoor temperature case	Regulation (GWh)
Static	I	0.600
	II	0.714
	III	**0.482**
Dynamic	I	0.874
	II	**1.032**
	III	0.714

Case study

- **Summer season**

ν **Case I** = 1
Case II = 1.1
Case III = 0.9

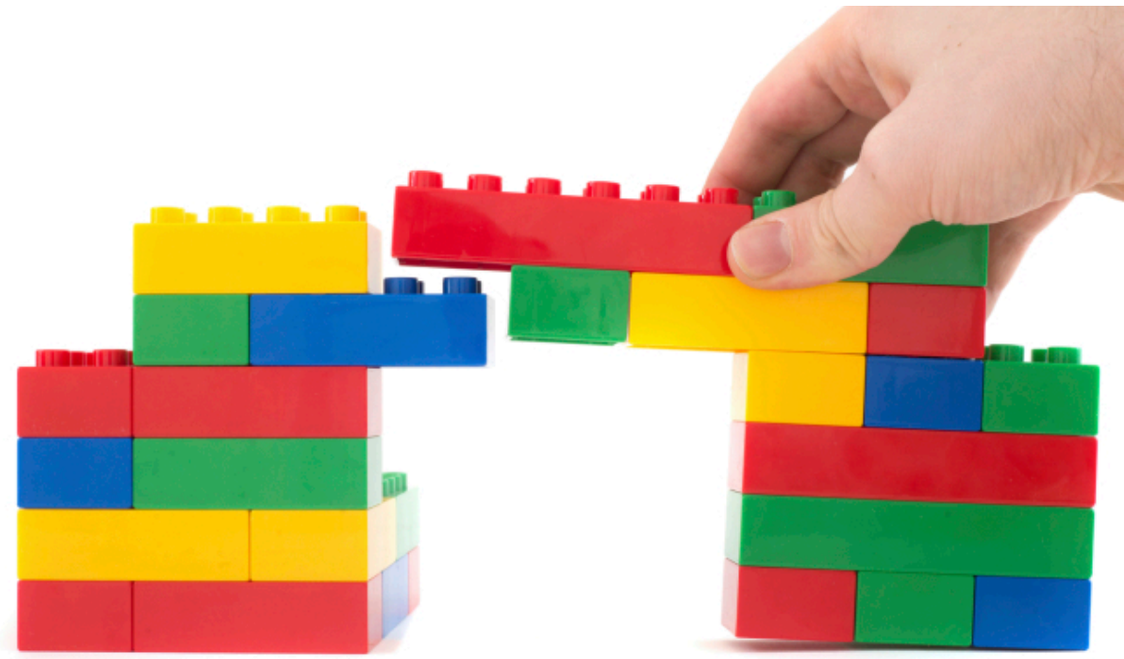
- **Static and dynamic RE** models
- **Conservative CC case**

Finding

Operators might account for weather conditions in estimating consumers' flexibility provision.

Unlocking consumers' flexibility potential

2 **Which framework can help to optimally exploit consumers' flexibility for AS provision at different voltage levels?**



Unlocking consumers' flexibility potential

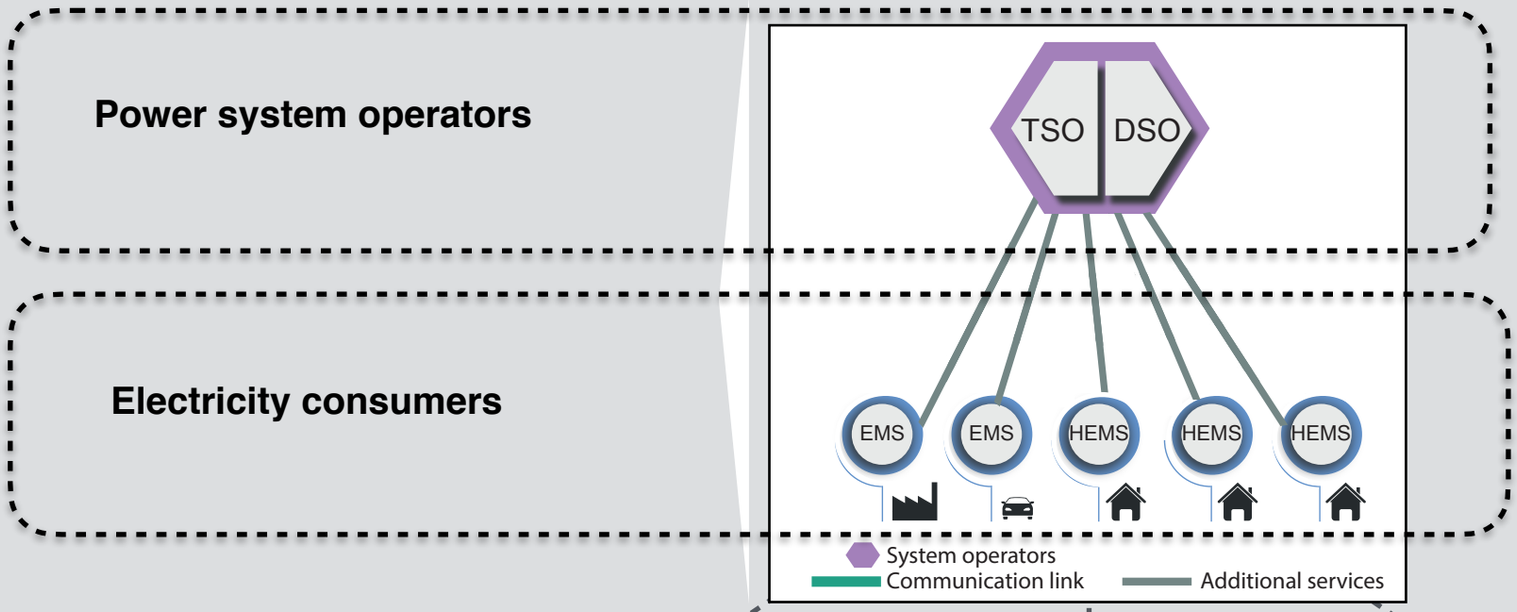
General framework for AS provision

Ancillary services provision

Unlocking consumers' flexibility potential

General framework for AS provision

AS4.0: core idea



1 Time varying prices

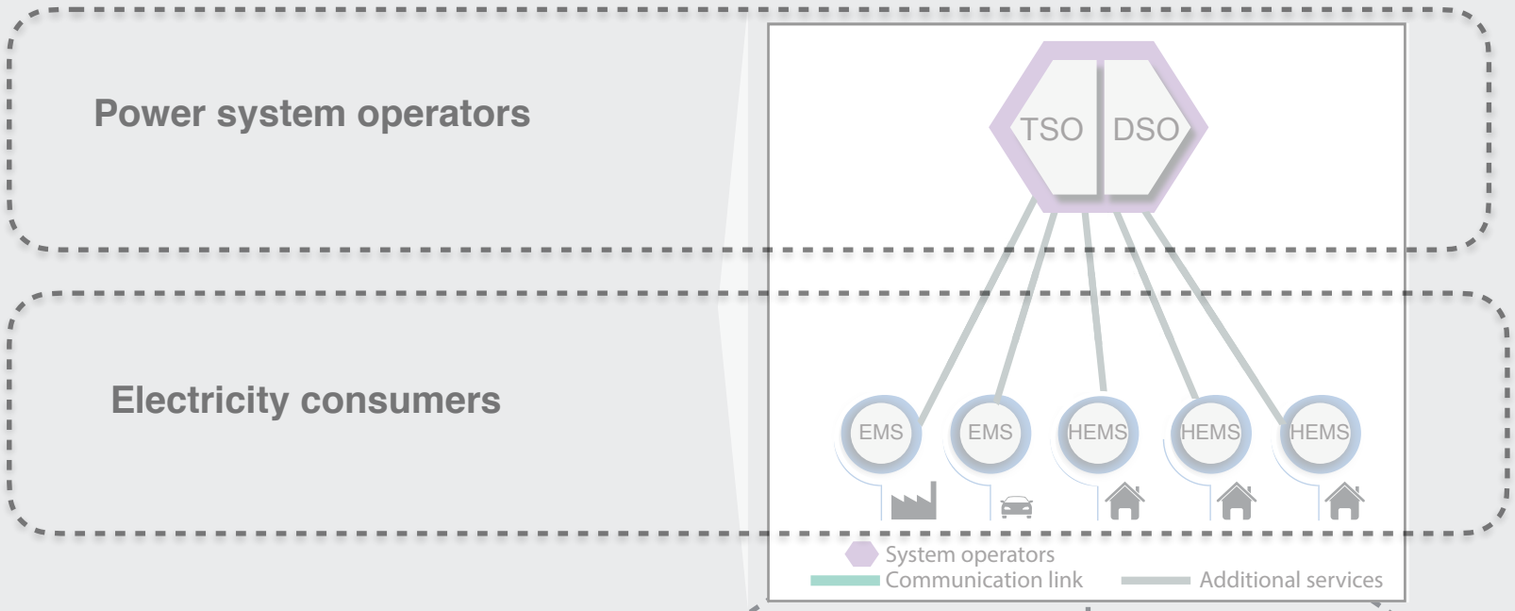
2 Adoption of controllers

3 One-way communication

Unlocking consumers' flexibility potential

General framework for AS provision

AS4.0: core idea



Requirements

- Dynamics
- Non linearity
- Stochasticity
- Services at TSO and DSO
- Fast
- Cost effective
- Consumers' autonomy and privacy
- Scalable

1 Time varying prices

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3 One-way communication

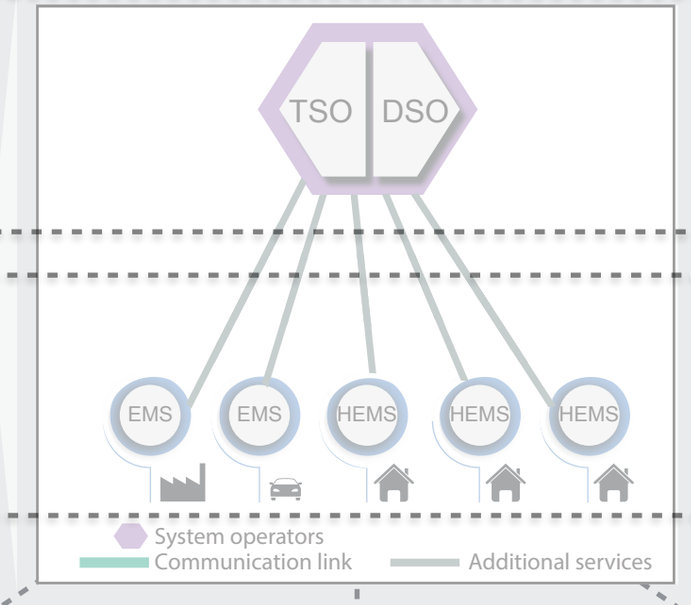
Unlocking consumers' flexibility potential

General framework for AS provision

AS4.0: core idea

Power system operators

Electricity consumers



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Unlocking consumers' flexibility potential

General framework for AS provision

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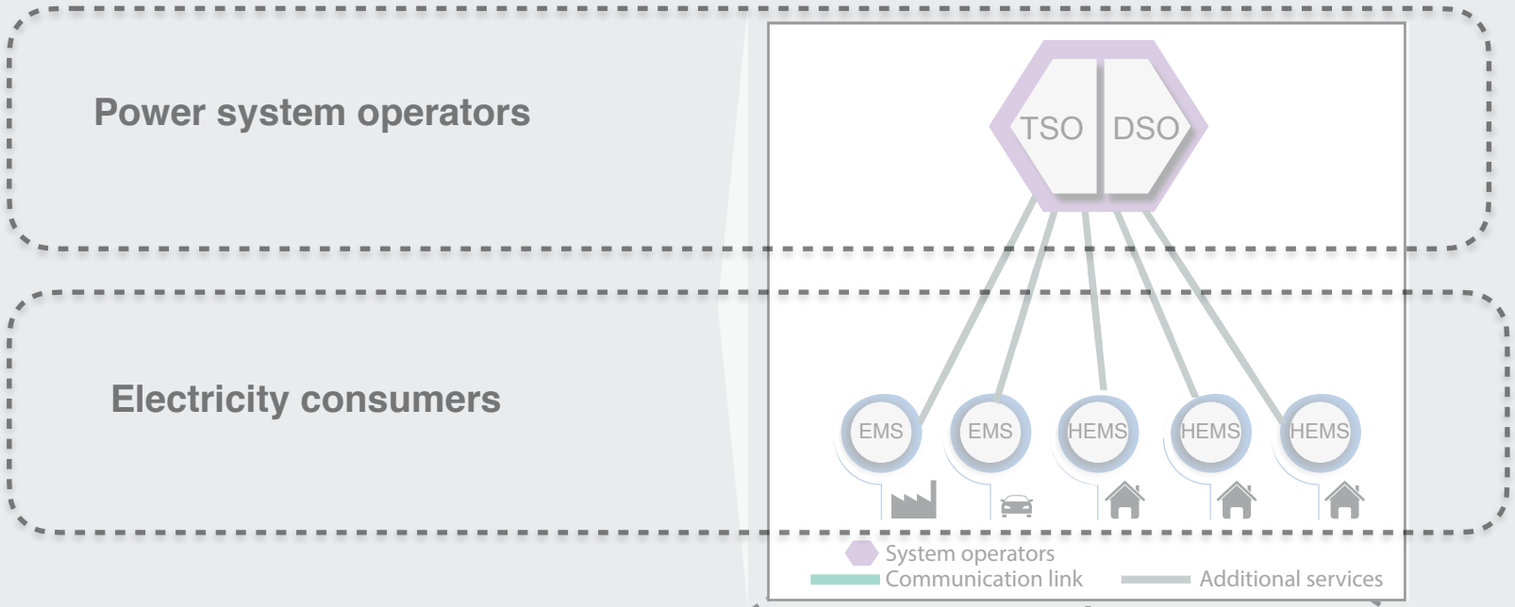

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General framework for AS provision

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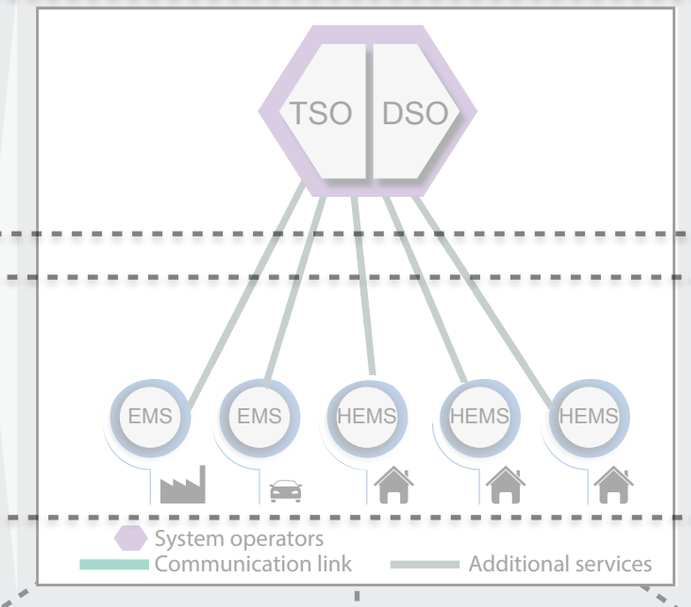

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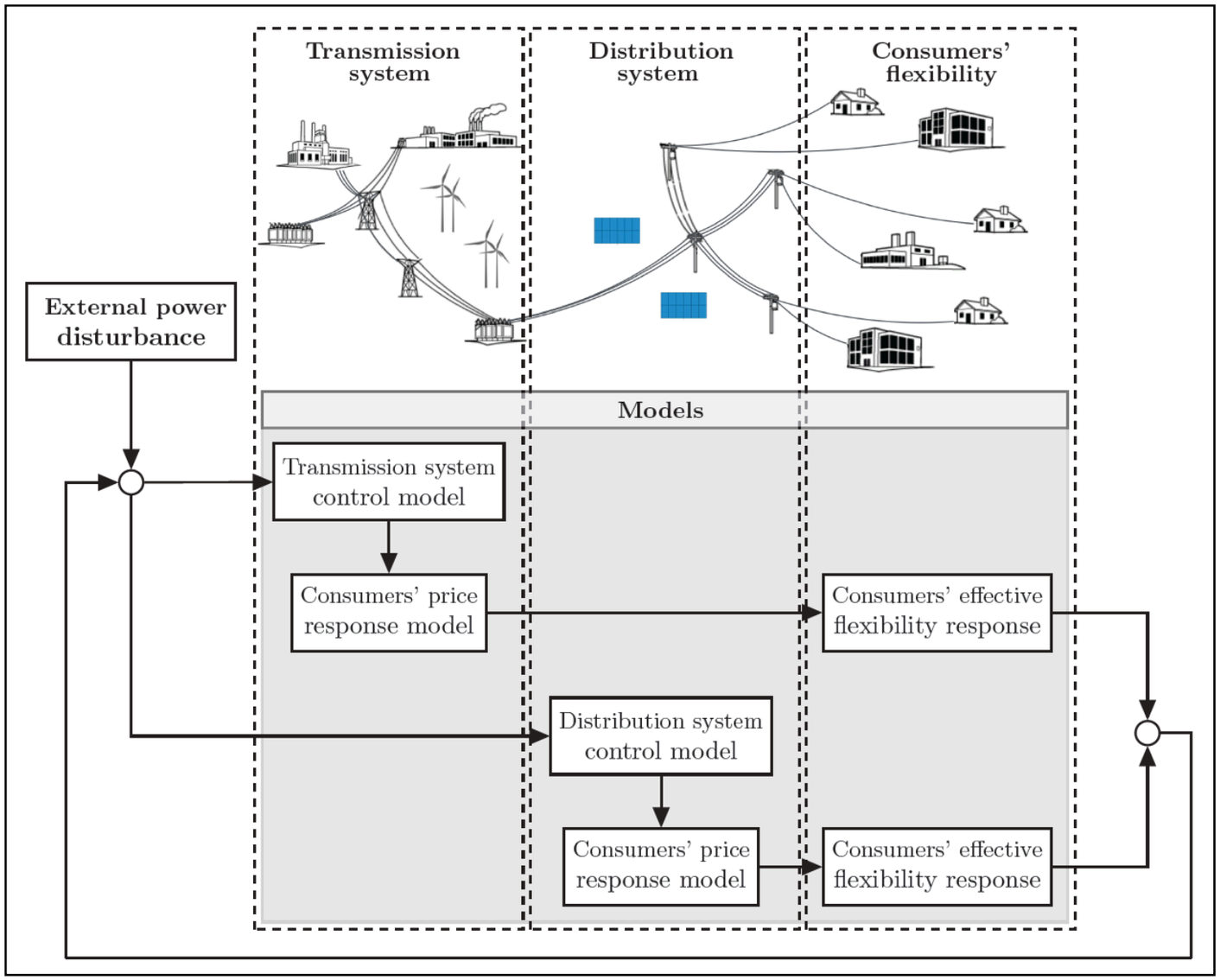
Unlocking consumers' flexibility potential

General framework for AS provision

Required models for AS4.0

Three types of **models** are needed to formulate AS4.0.



Unlocking consumers' flexibility potential

General framework for AS provision

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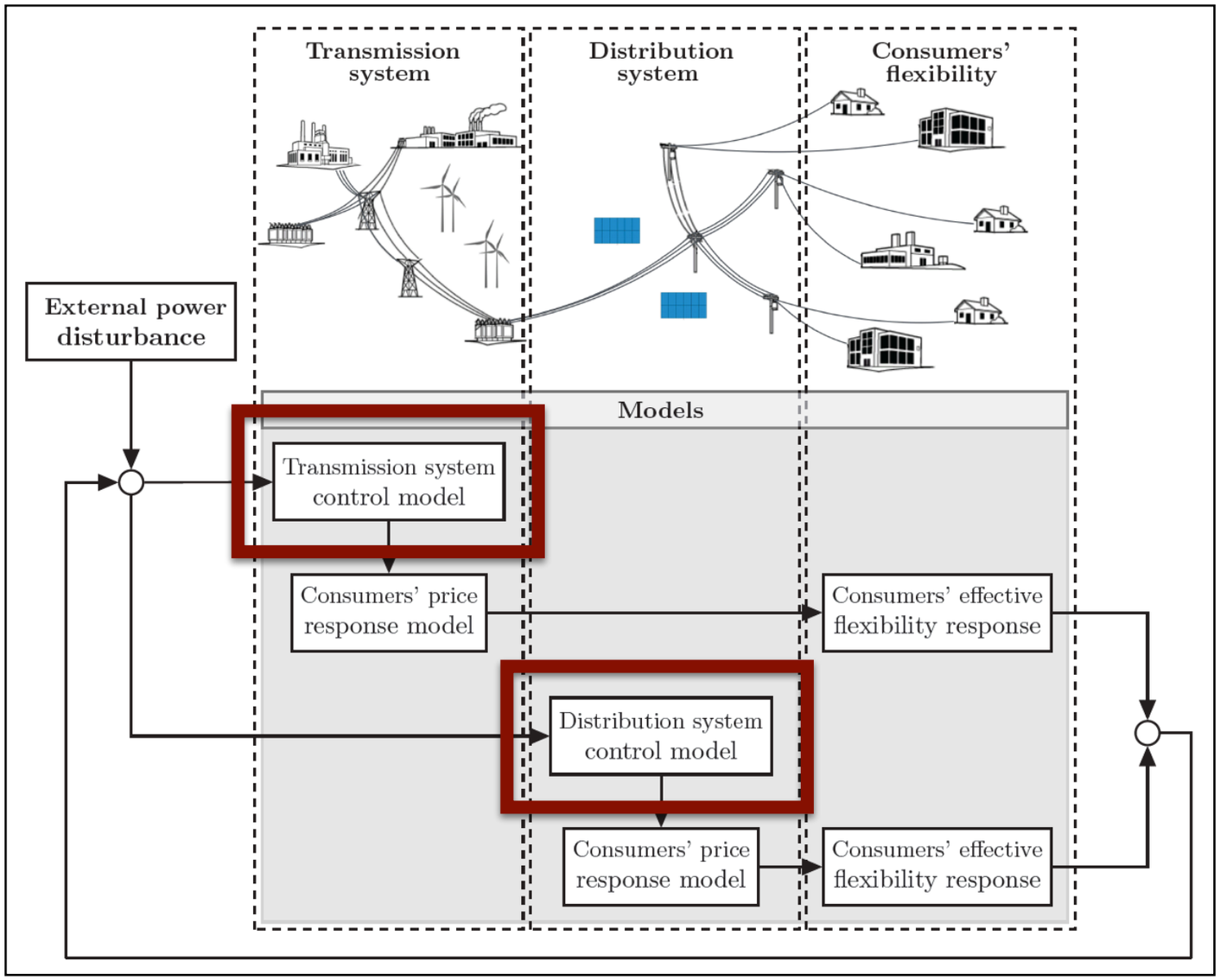

1 Power system control models

Effect on frequency/ voltage → **Needed flexibility**

Unlocking consumers' flexibility potential

General framework for AS provision

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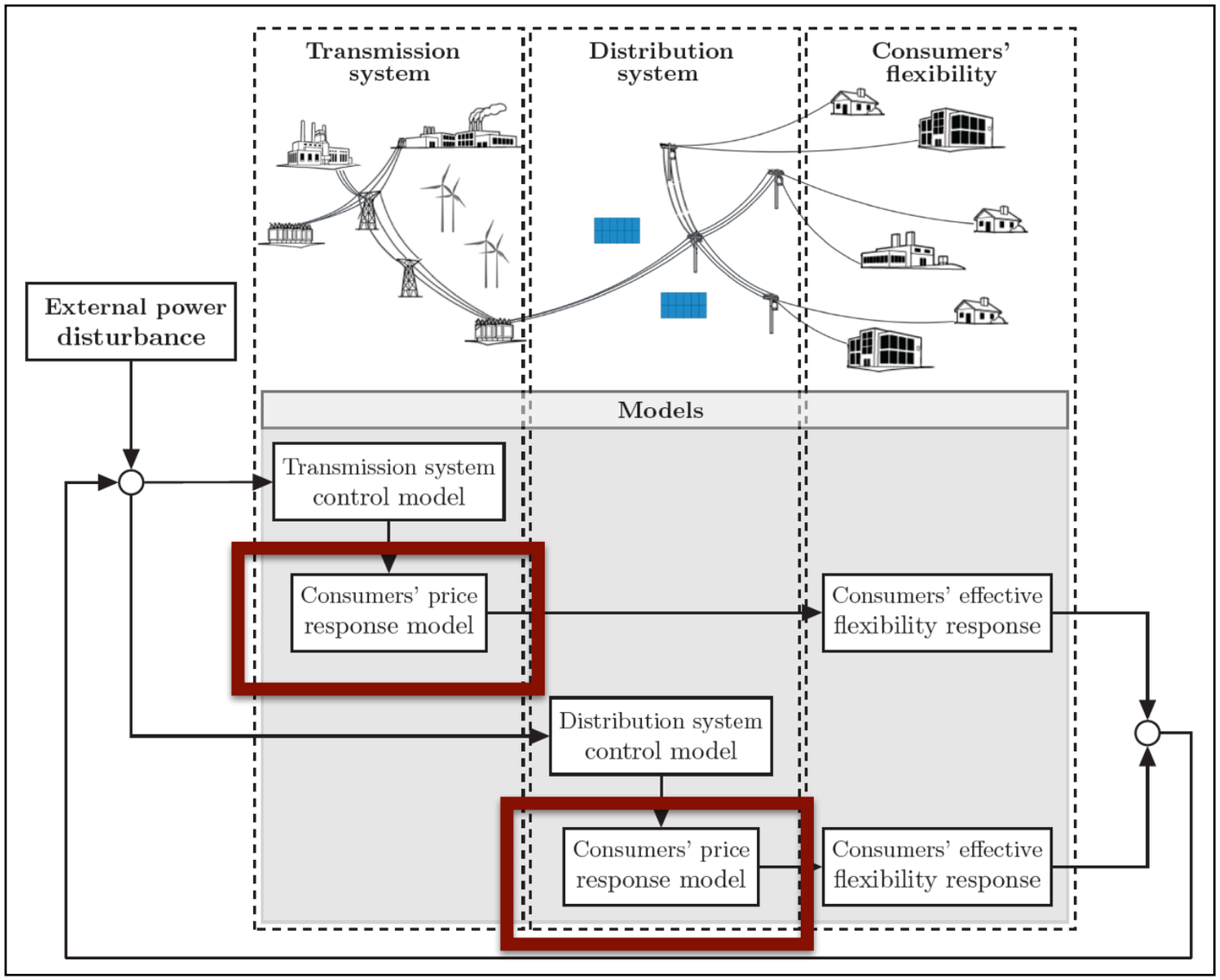

1 Power system control models

Effect on frequency/ voltage → **Needed flexibility**

2 Consumers' price response models

Consumers' responsiveness toward prices → **Proper price signals**

Unlocking consumers' flexibility potential

General framework for AS provision

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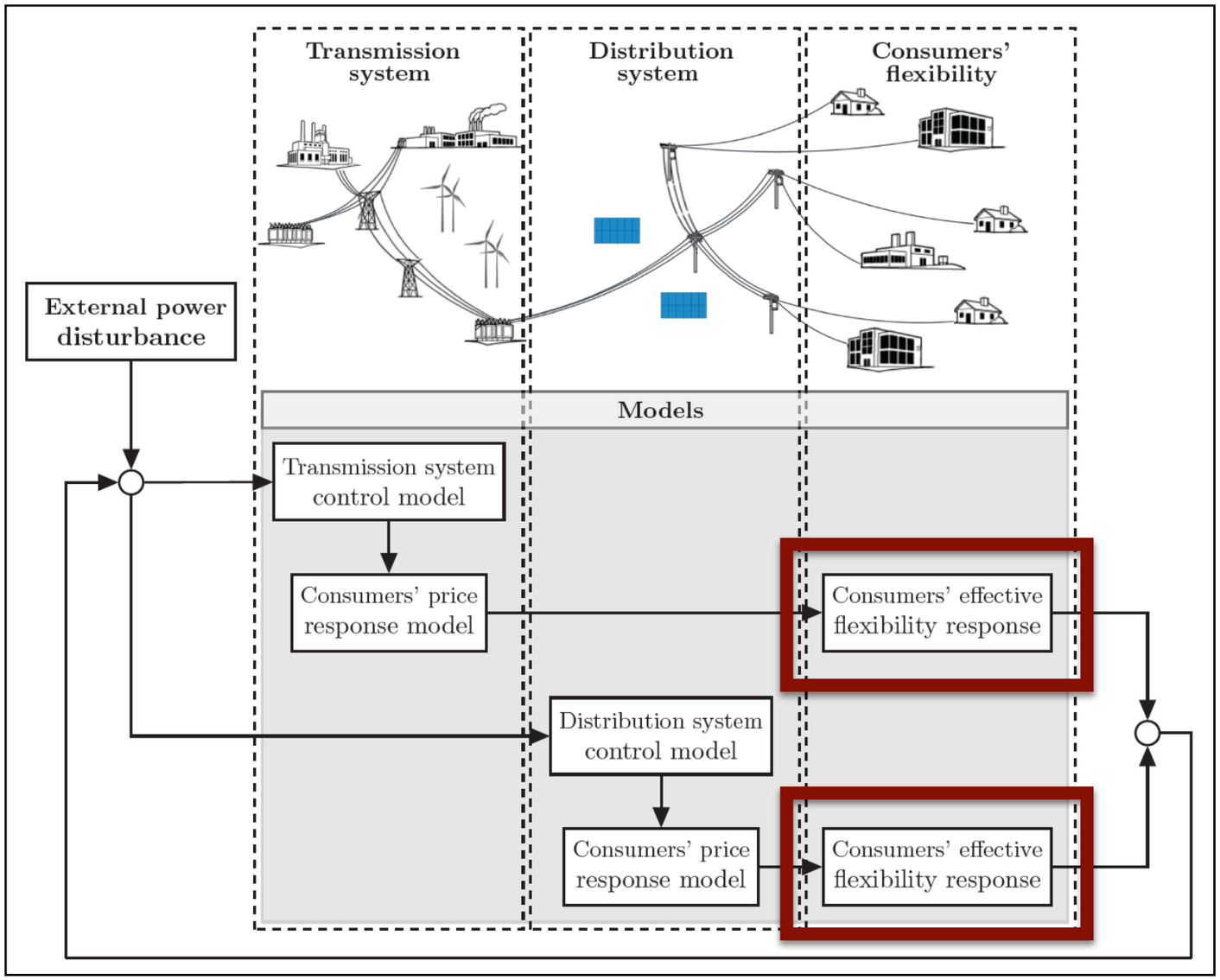


1 Power system control models

Effect on frequency/ voltage → **Needed flexibility**

2 Consumers' price response models

Consumers' responsiveness toward prices → **Proper price signals**

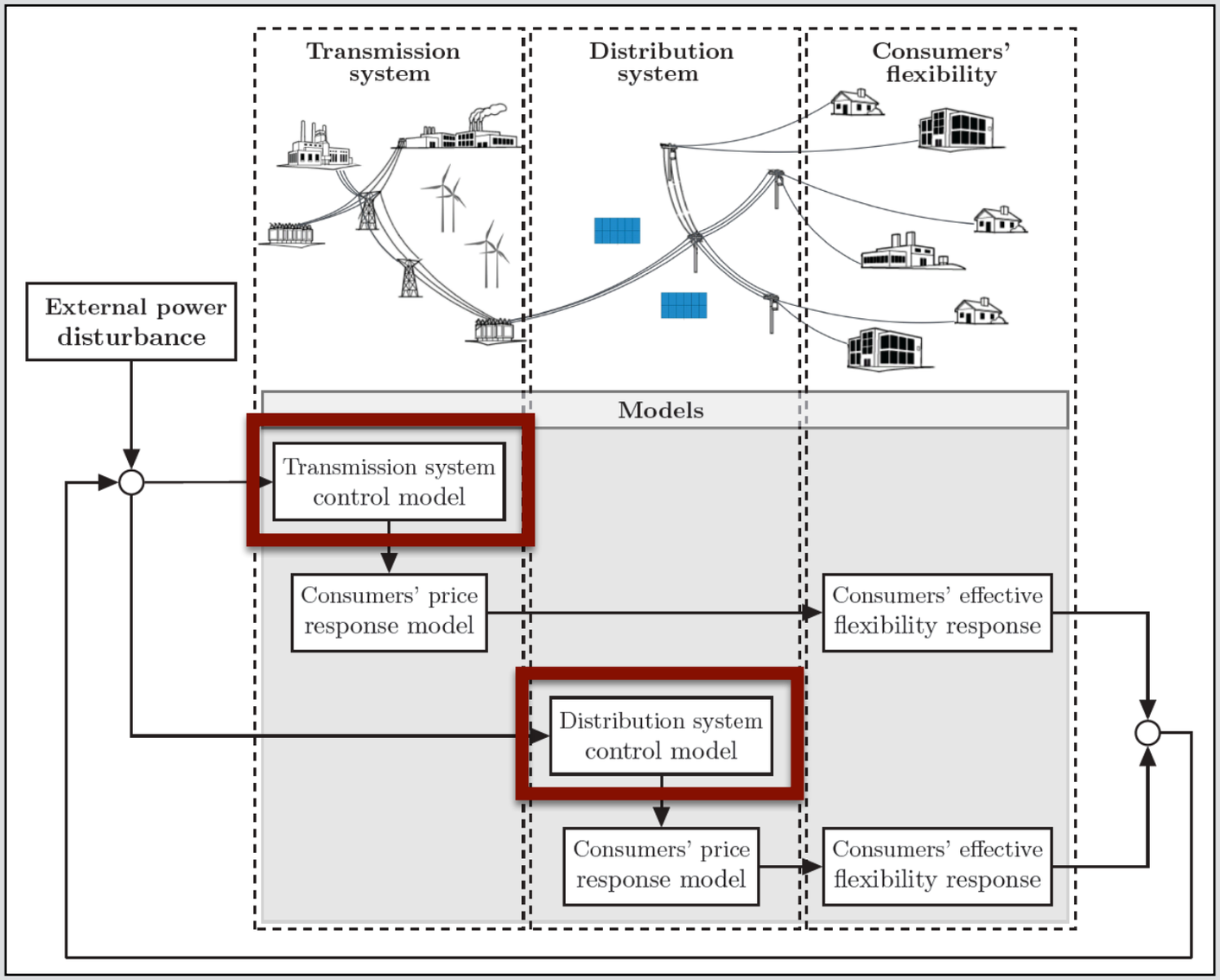
3 Effective flexibility response models

Actual consumers' behaviour → **Achieved flexibility**

Unlocking consumers' flexibility potential

General framework for AS provision

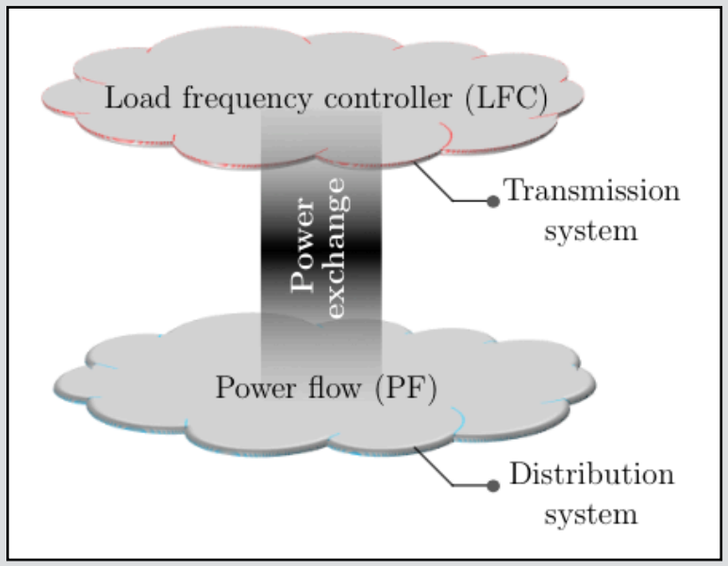
Power system control models



Unlocking consumers' flexibility potential

General framework for AS provision

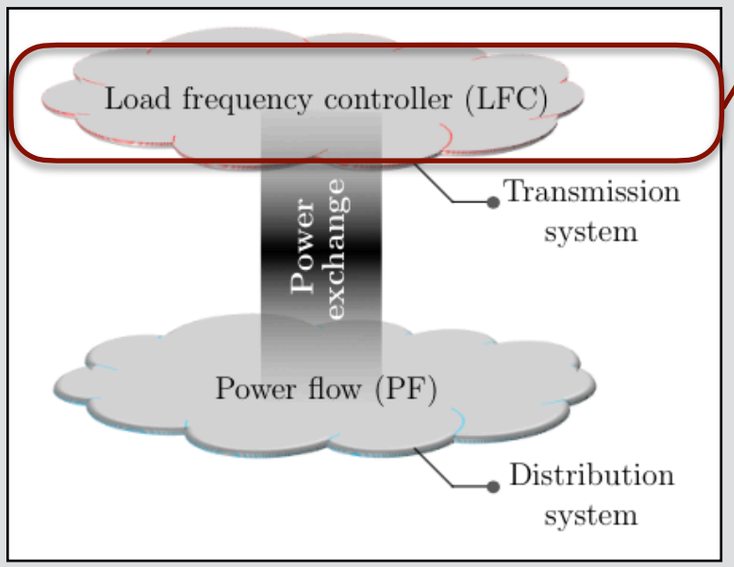
Power system control models



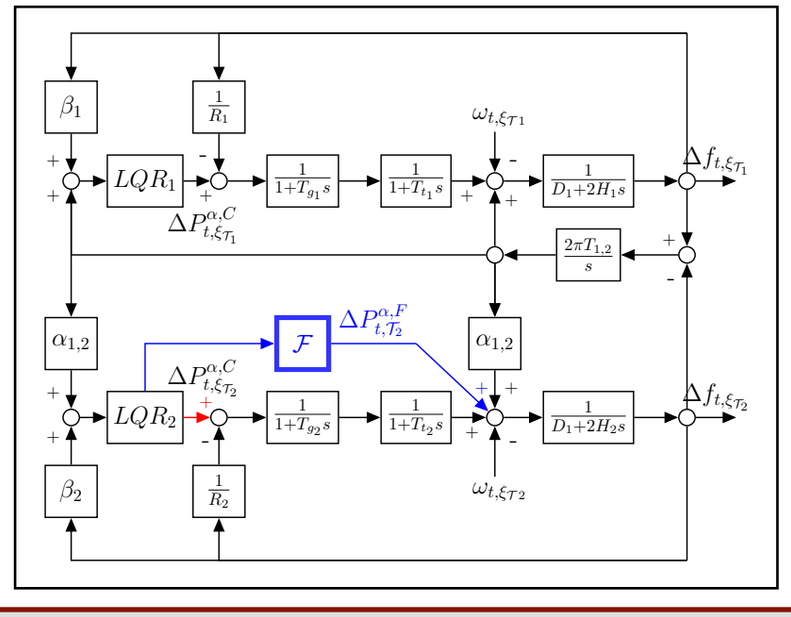
Unlocking consumers' flexibility potential

General framework for AS provision

Power system control models



At the transmission level



Two-area LFC

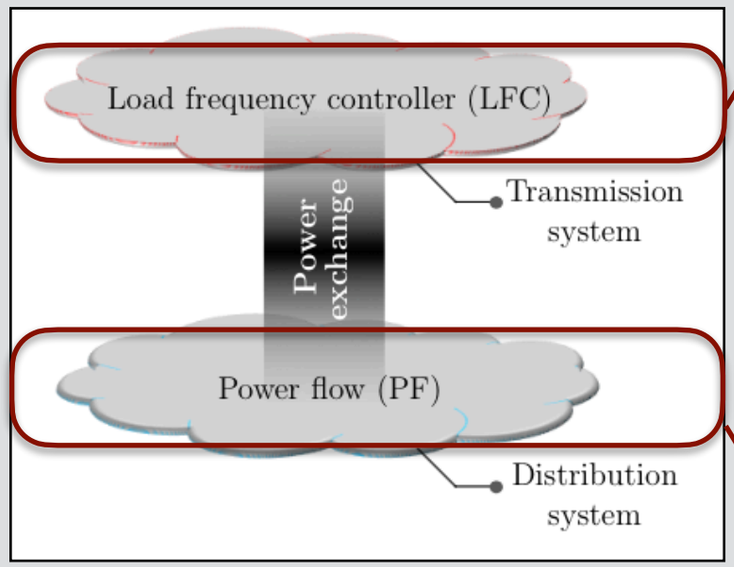
Study cases:

- **Conventional generation units**
- **AS4.0**

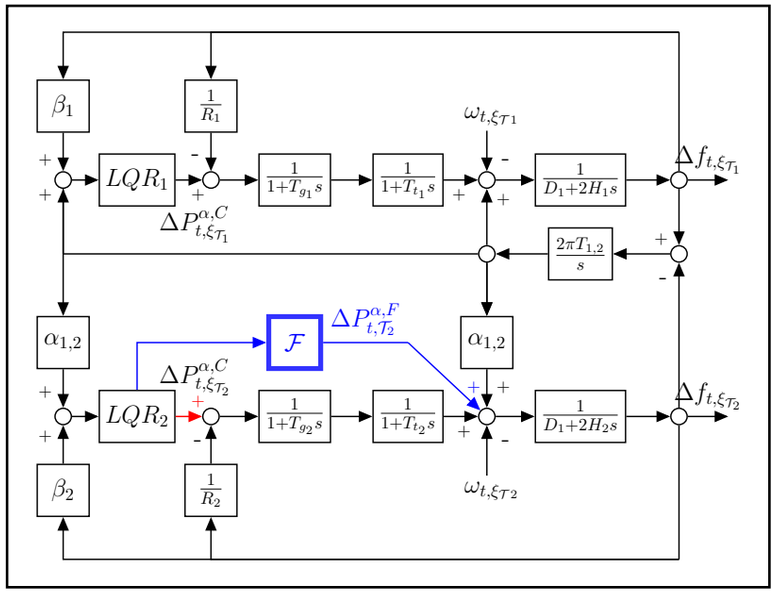
Unlocking consumers' flexibility potential

General framework for AS provision

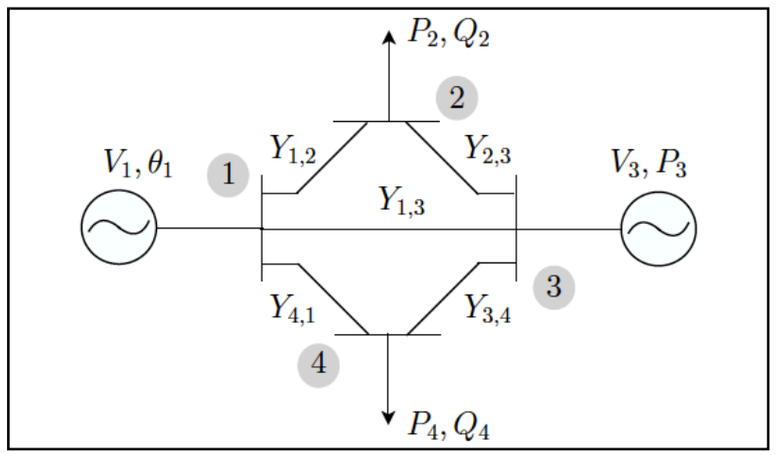
Power system control models



At the transmission level



At the distribution level



Two-area LFC

Study cases:

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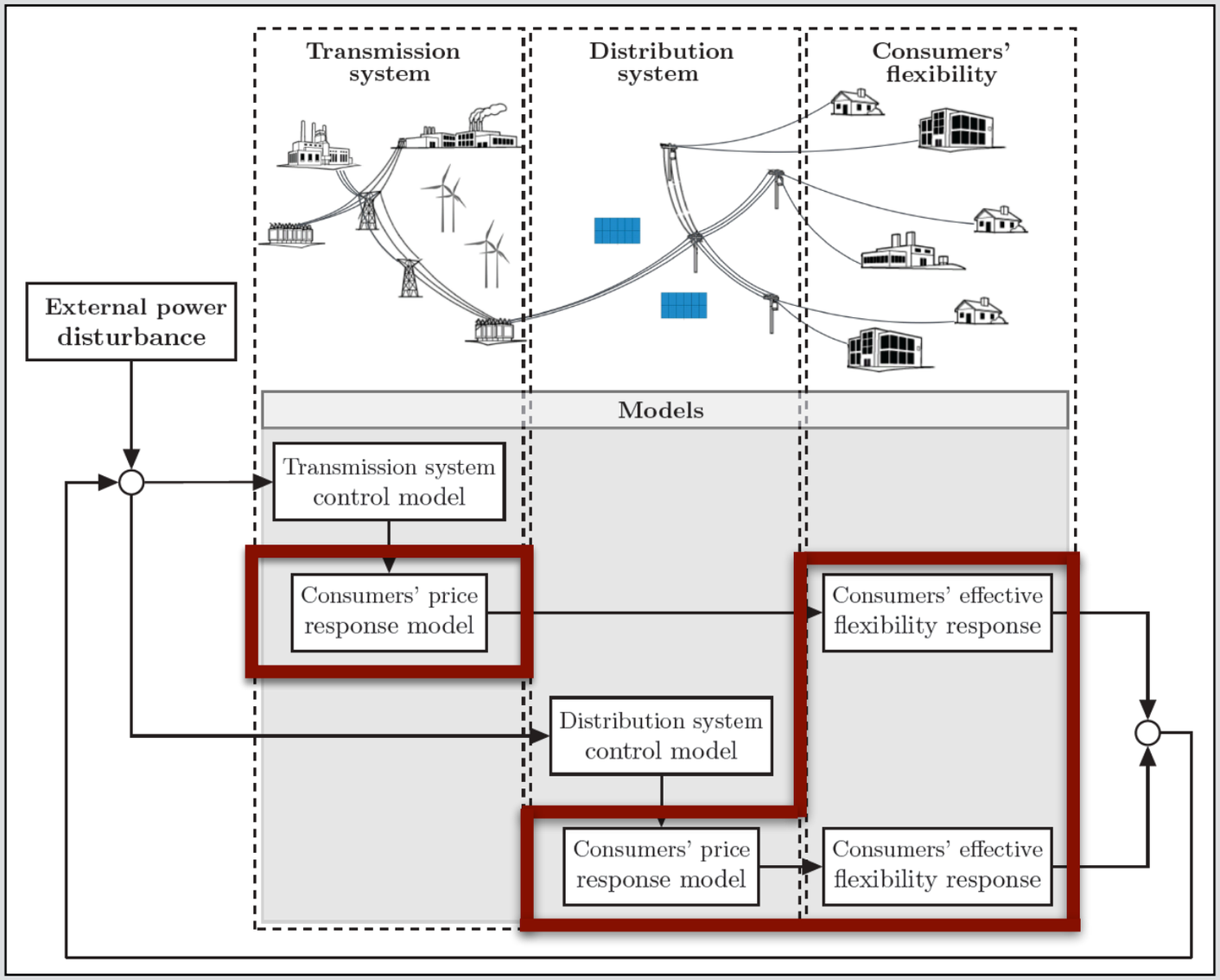
Unlocking consumers' flexibility potential

General framework for AS provision

Aggregate consumers' price response

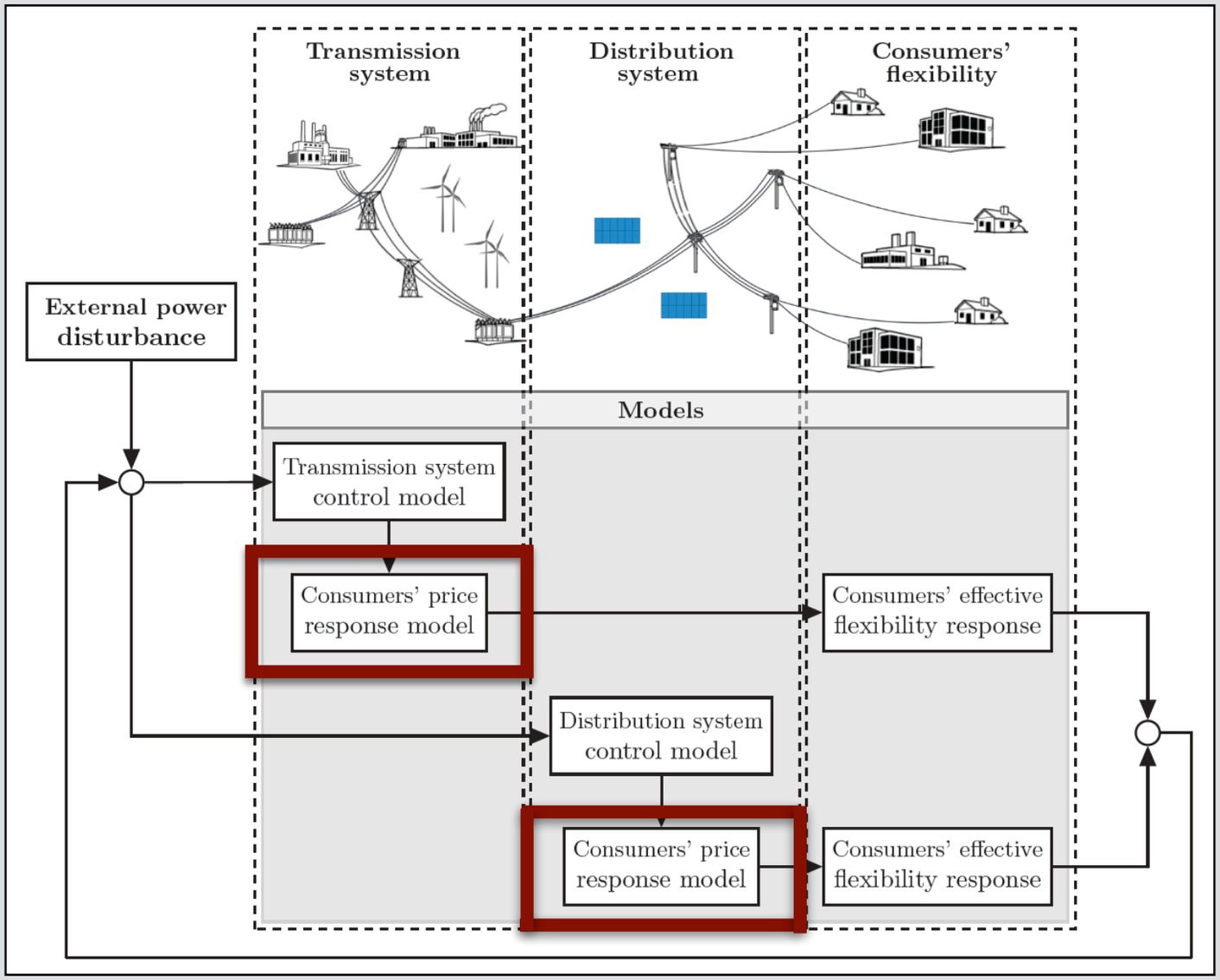


Unlocking consumers' flexibility potential

General framework for AS provision

Aggregate consumers' price response

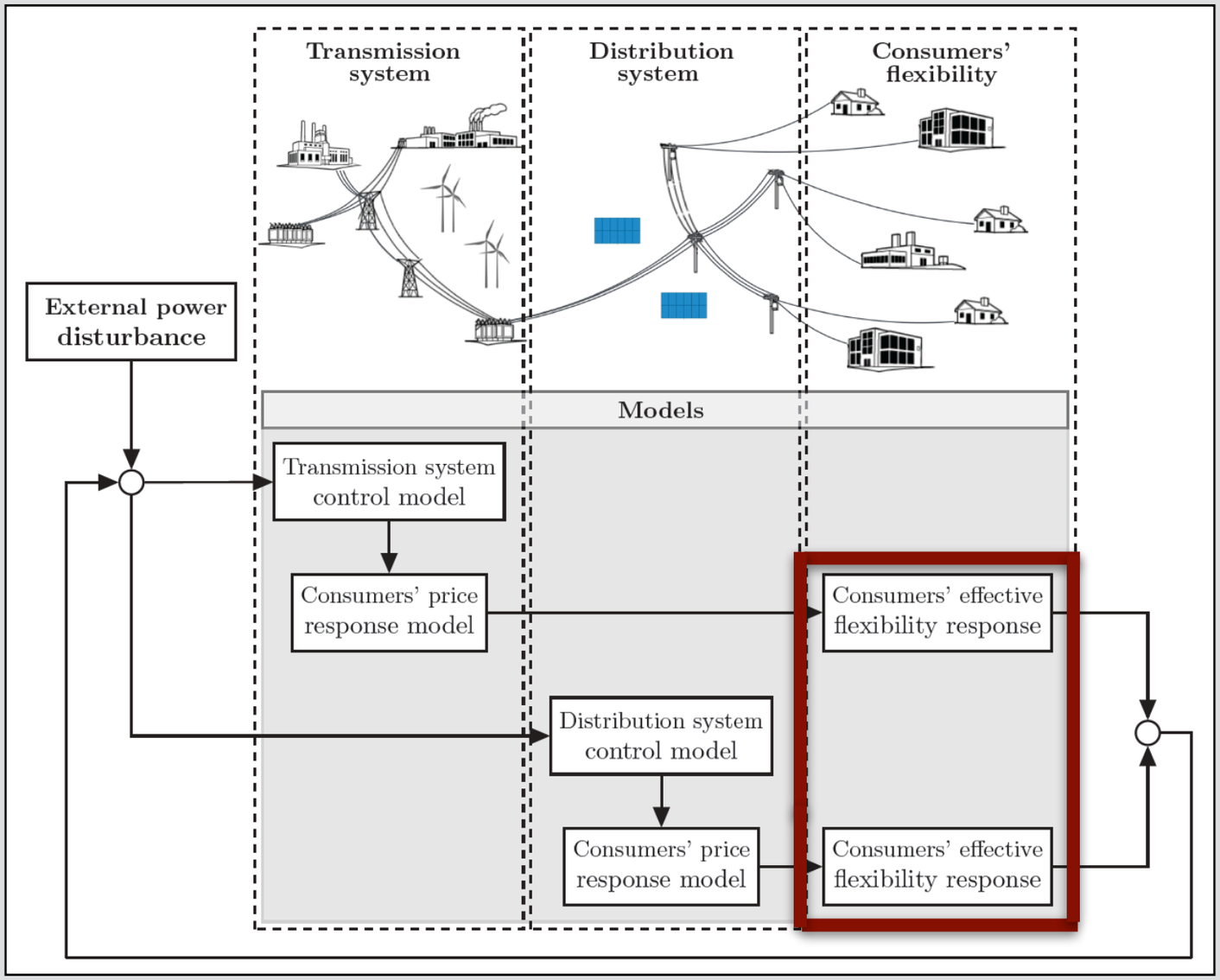
Time varying price formulation



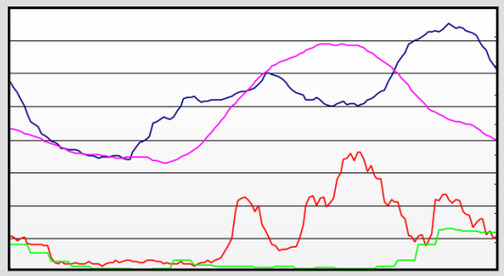
Unlocking consumers' flexibility potential

General framework for AS provision

Aggregate consumers' price response



Realised consumers' response

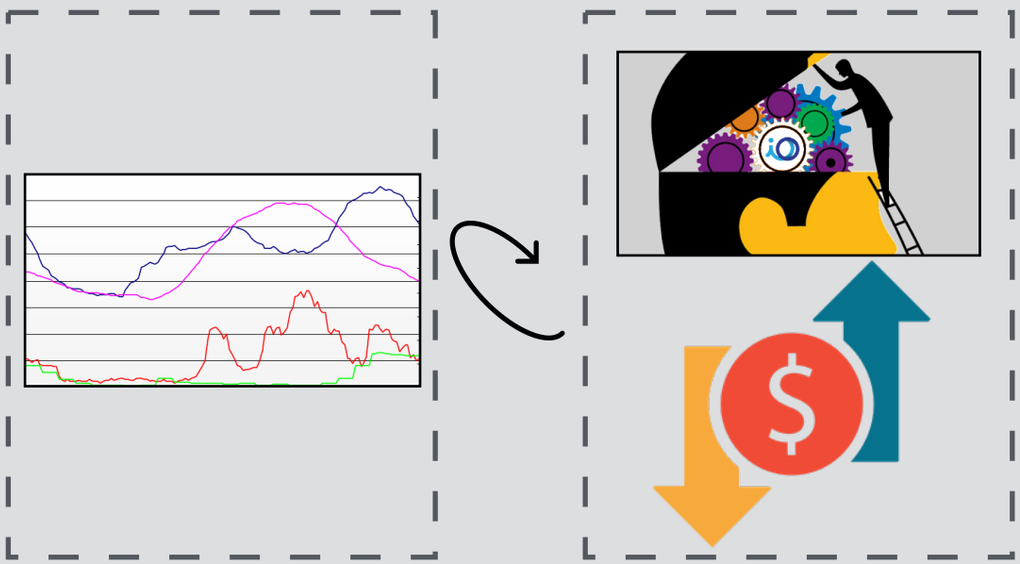


Unlocking consumers' flexibility potential

General framework for AS provision

Aggregate consumers' price response

Data can be used to model consumers' reaction toward prices.



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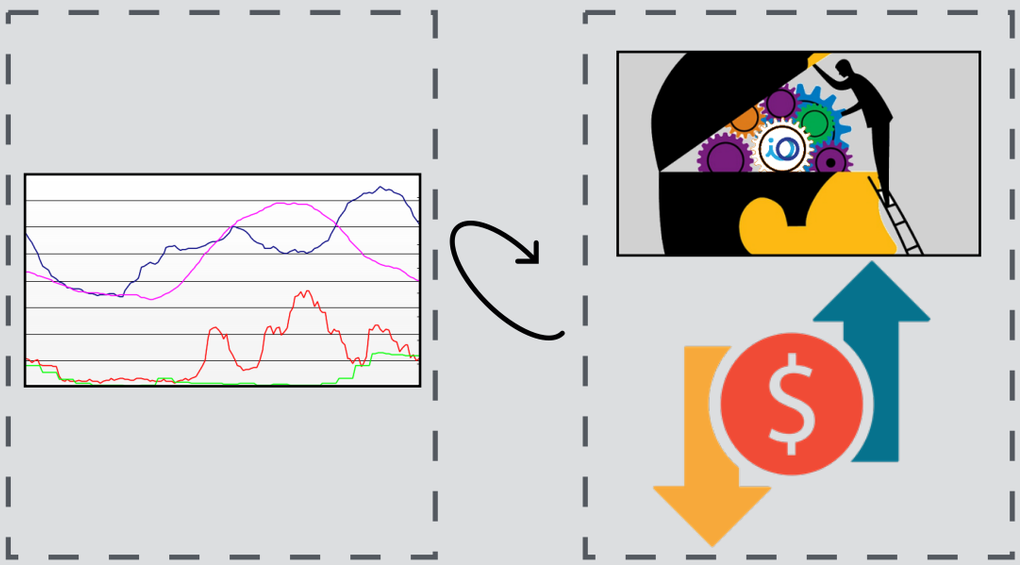

Due to **data scarcity**, models are adopted.

Different models at transmission and distribution levels:

- Size
- Consumers' composition

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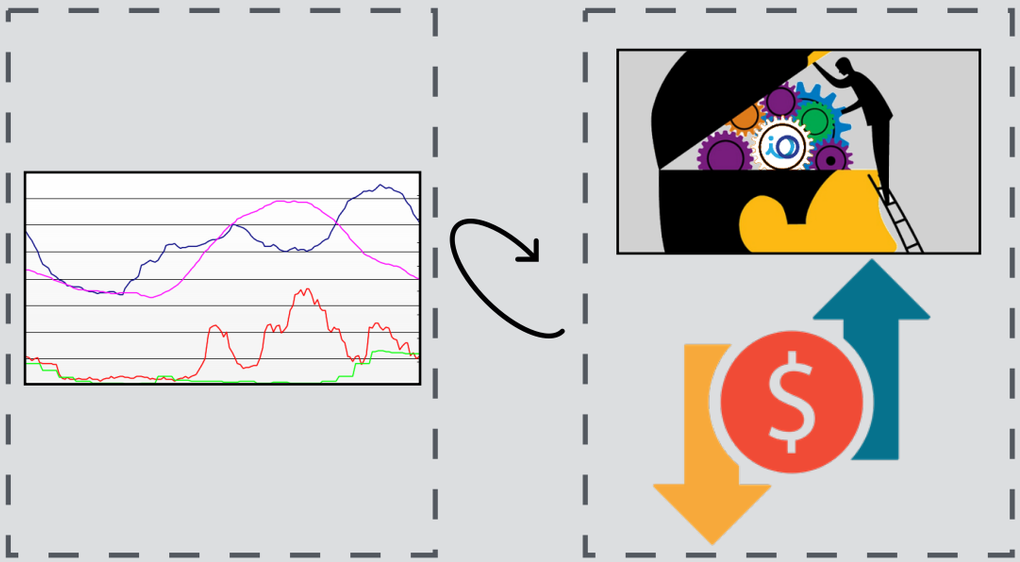

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Different models at transmission and distribution levels:

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At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

1. **Model**
   - Consumers' **composition**
   - **Time varying prices**
   - Cost minimisation
2. **Montecarlo simulation**
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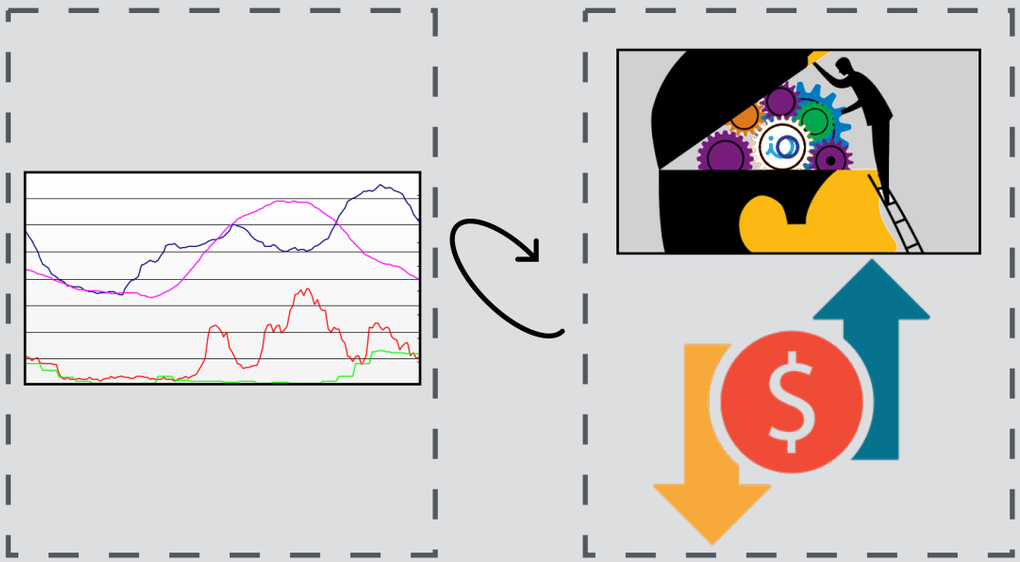

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At the distribution level

Voltage is a **local issue**

Flexibility at each **DSO bus**

To make it scalable, we cluster DSO buses

1. **Model**
   - Electricity **price**
   - consumers' **willingness**
2. **PI controller**
   - **Voltage** deviation

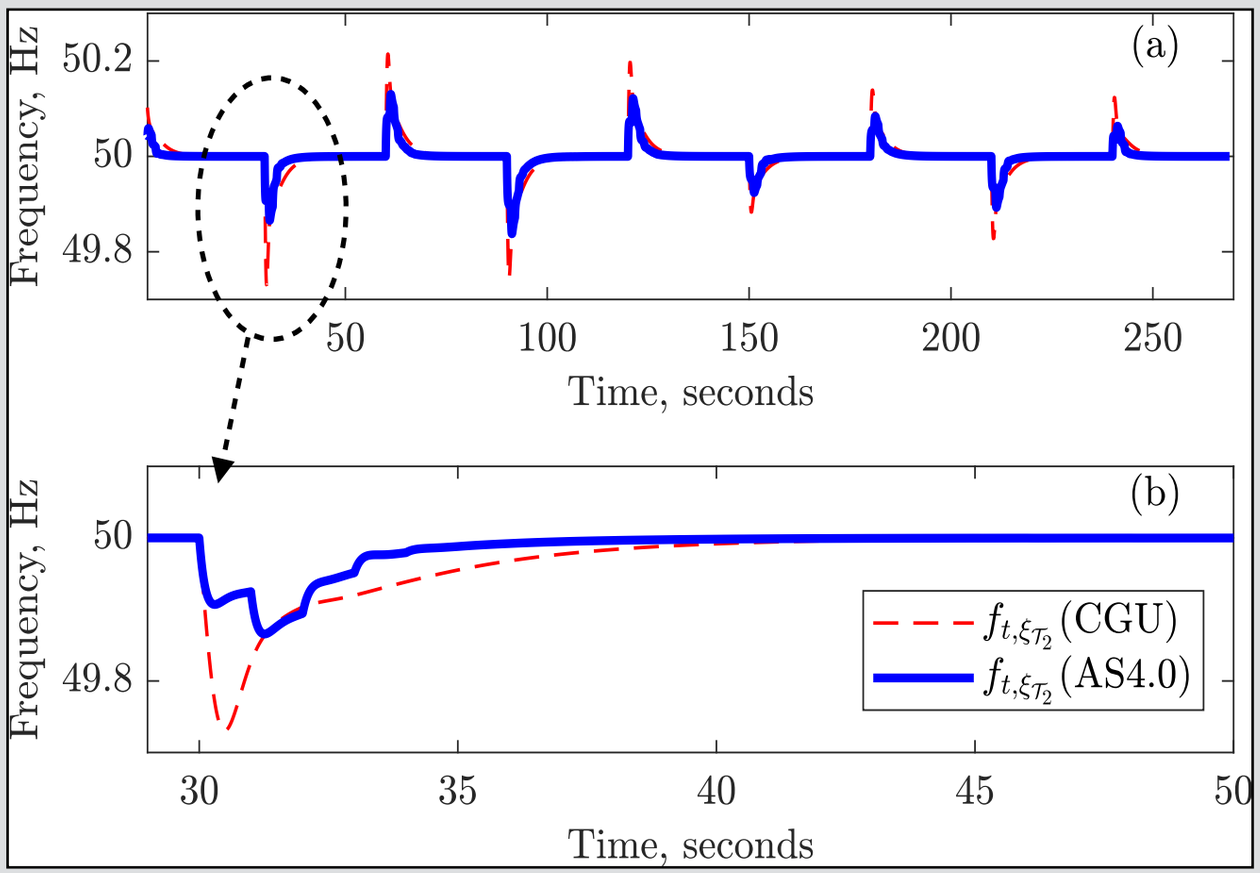
Unlocking consumers' flexibility potential

General framework for AS provision

Simulations results

Frequency at the transmission level

AS4.0 **reduces** the **frequency deviation** by around **50%** compared to the conventional method.



Time and disturbance injected, (sec, MW)	Maximum frequency deviation, Hz		Deviation reduction, %
	CGUs-based AS	AS4.0	
[1,1000]	0.10	0.06	40 %
[30,350]	-0.27	-0.13	52 %
[60, 852]	0.21	0.13	38 %
[90, 500]	-0.26	-0.16	38 %
[120, 1148]	0.20	0.12	40 %
[150, 1000]	-0.12	-0.08	33 %
[180, 1300]	0.14	0.08	42 %
[210, 1056]	-0.17	-0.11	35 %
[240, 1500]	0.12	0.07	41 %

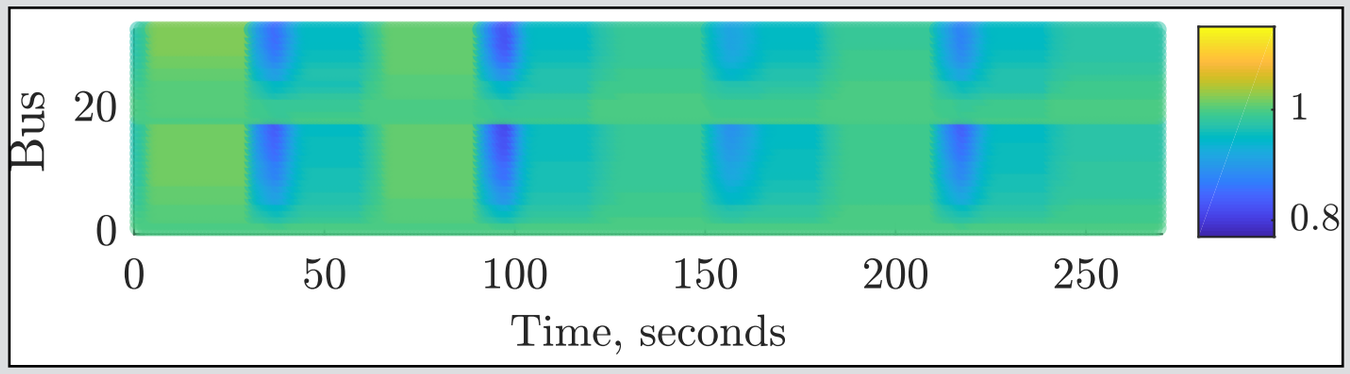
Unlocking consumers' flexibility potential

General framework for AS provision

Simulations results

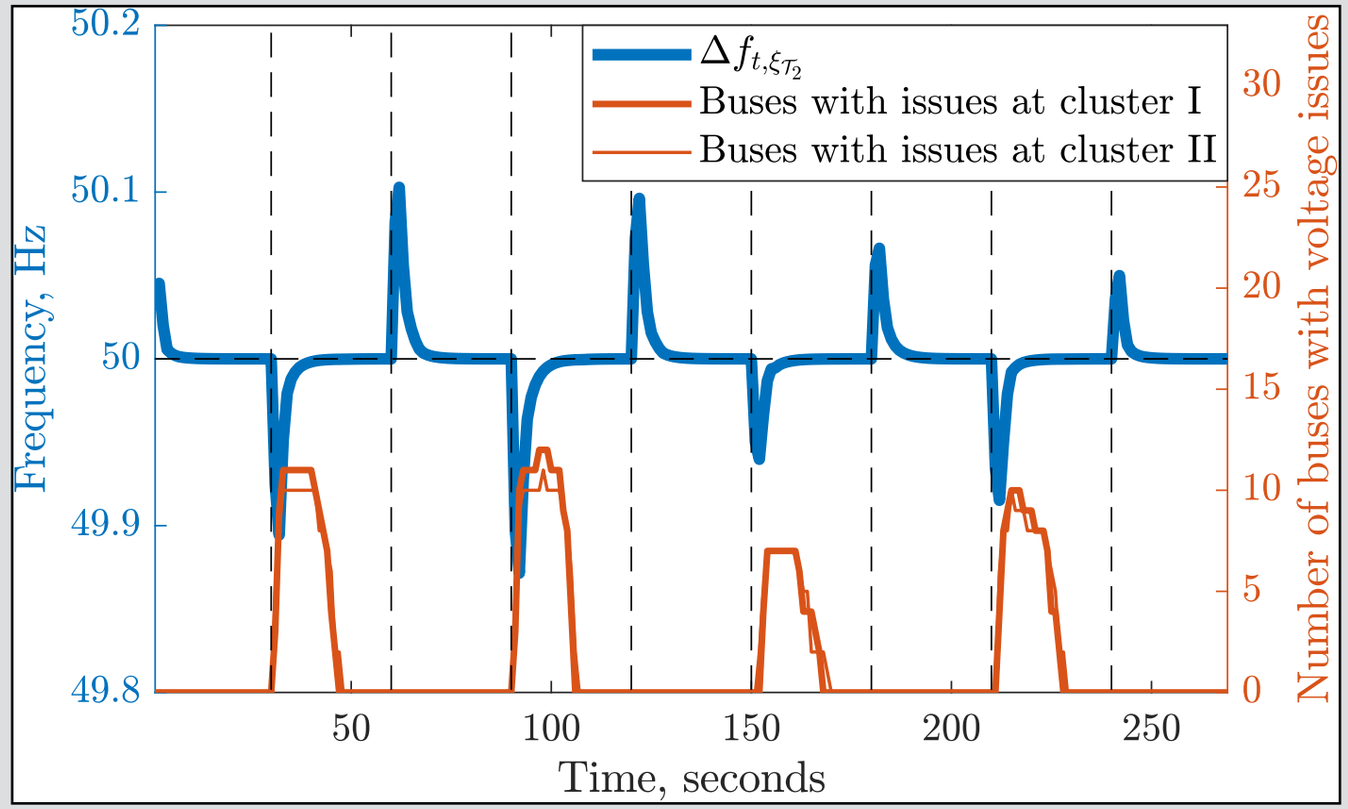
Voltage at the distribution level

AS4.0 manages to **mitigate** the **voltage** issues at the DSO buses.



Operational issues at TSO and DSO levels

The **number of buses** with voltage issues **decreases** over time.



Concluding remarks

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Conclusions and perspectives for future work

Conclusions

A **new approach to AS provision** based on:

- **time varying electricity prices**
- **one-way communication**
- **control techniques**

It **successfully handled** the operational **issues** at TSO and DSO level

Better performance than the conventional generation units-based method

Perspectives for future work

1. **Including additional factors** that influence the price responsiveness of consumers (such as type of **day**, **household income**, **on-site generation** and **storage**)

2. **Modelling power system operation** in a more **realistic manner.**

3. **Collecting high resolution data** of consumers' price-responsiveness.

Thank you!