Control-based provision of ancillary services by flexible end-users

G. De Zotti* A. Pourmousavi**
J.M. Morales *** H. Madsen*

* Technical University of Denmark
** The University of Queensland
*** University of Málaga

Agenda

- Introduction
- Reliability in power systems
- Leveraging consumers' flexibility
- Approaches to ancillary services provision: AS4.0
- Concluding remarks

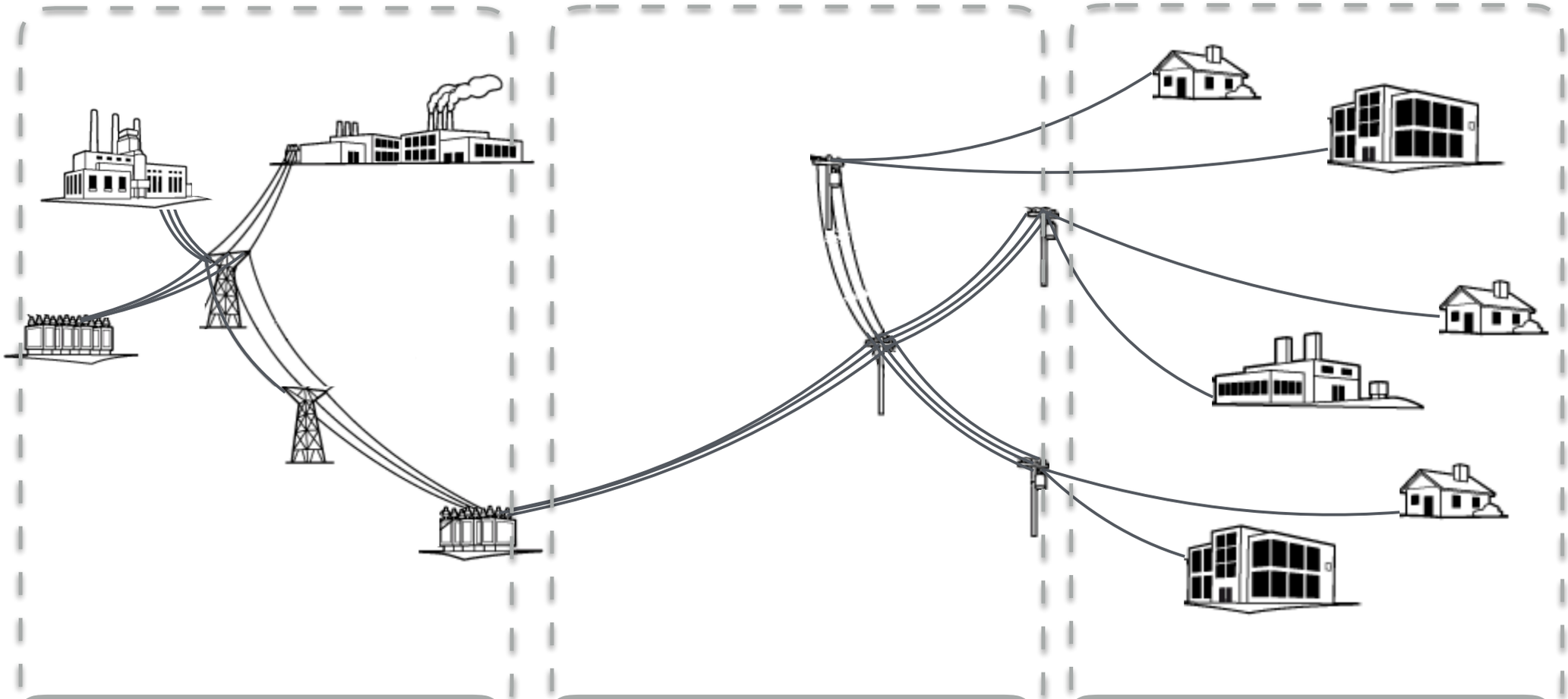
Introduction

Power system operation

Power system operation in the past

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

Almost predictable and **controllable**



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

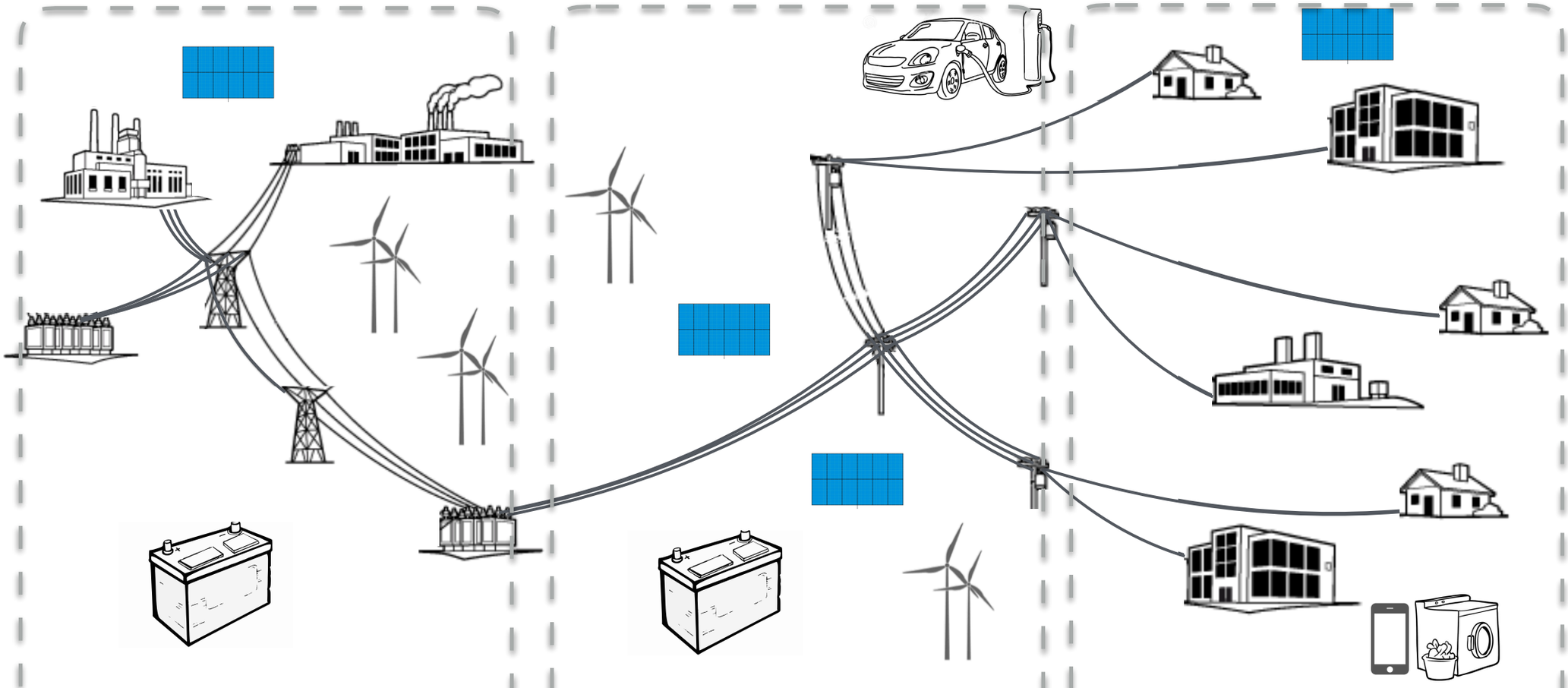
Introduction

Power system operation

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

Power system operation

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

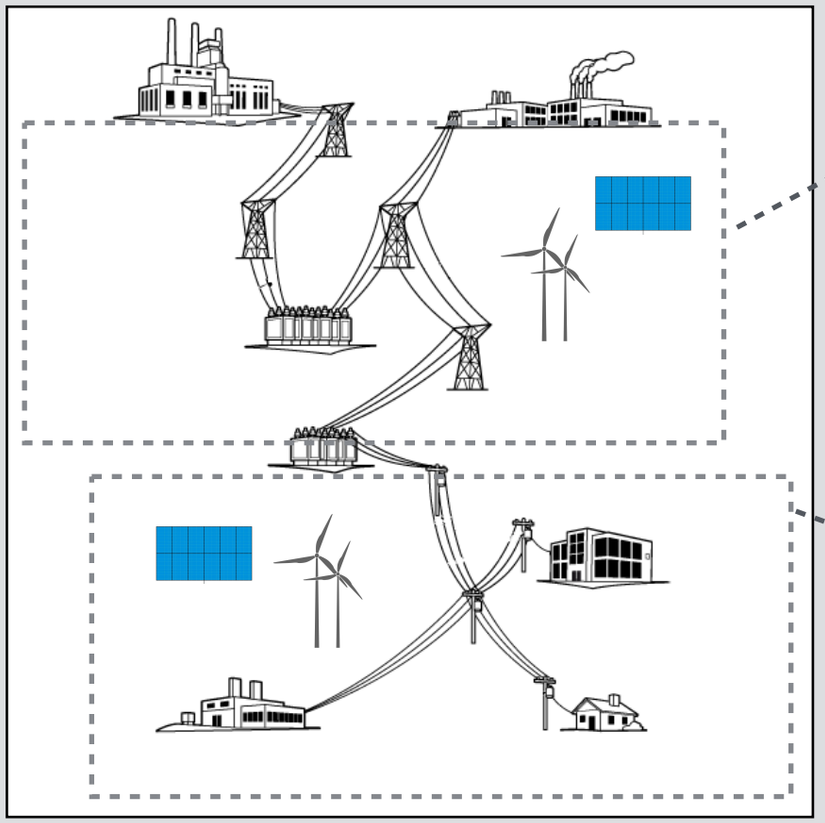
- Operating **under rated capacity**
- Conventional generation units **retirement**
- **International targets**
- **Denmark: Strategy 2050***

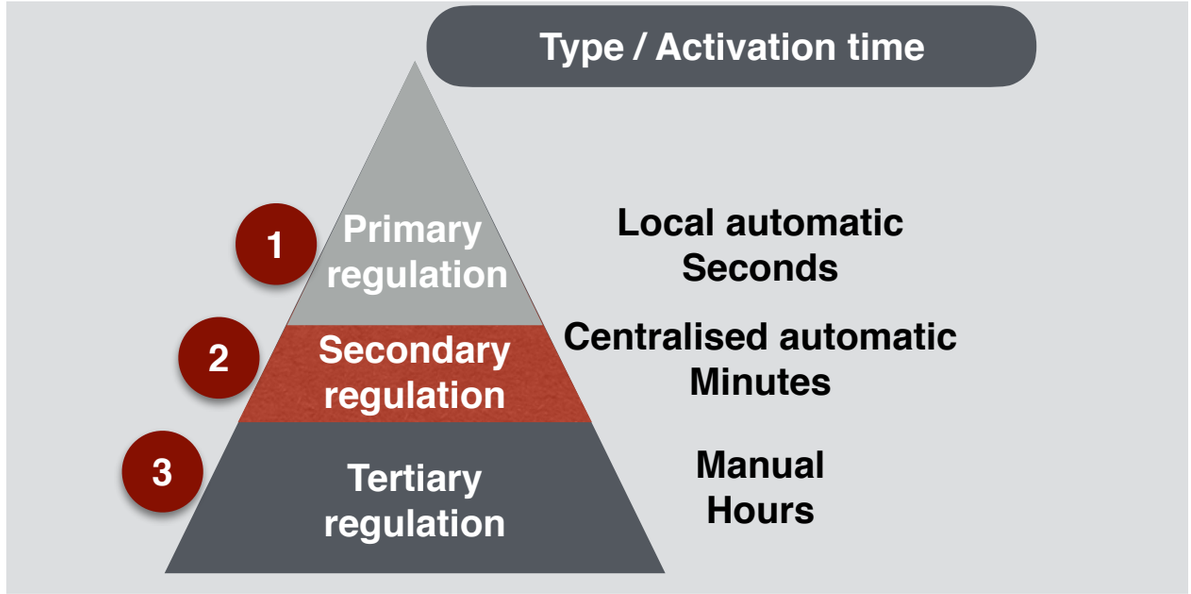
* DEA, 2017

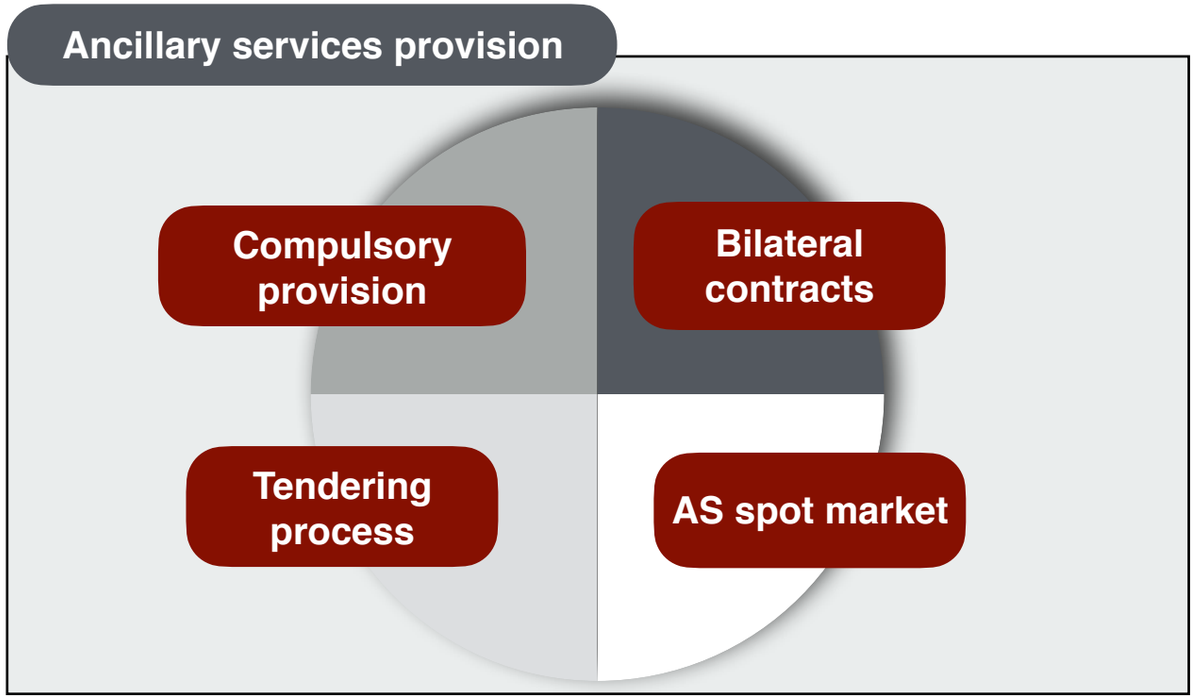
Reliability in power systems
Ancillary services

Ancillary services

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



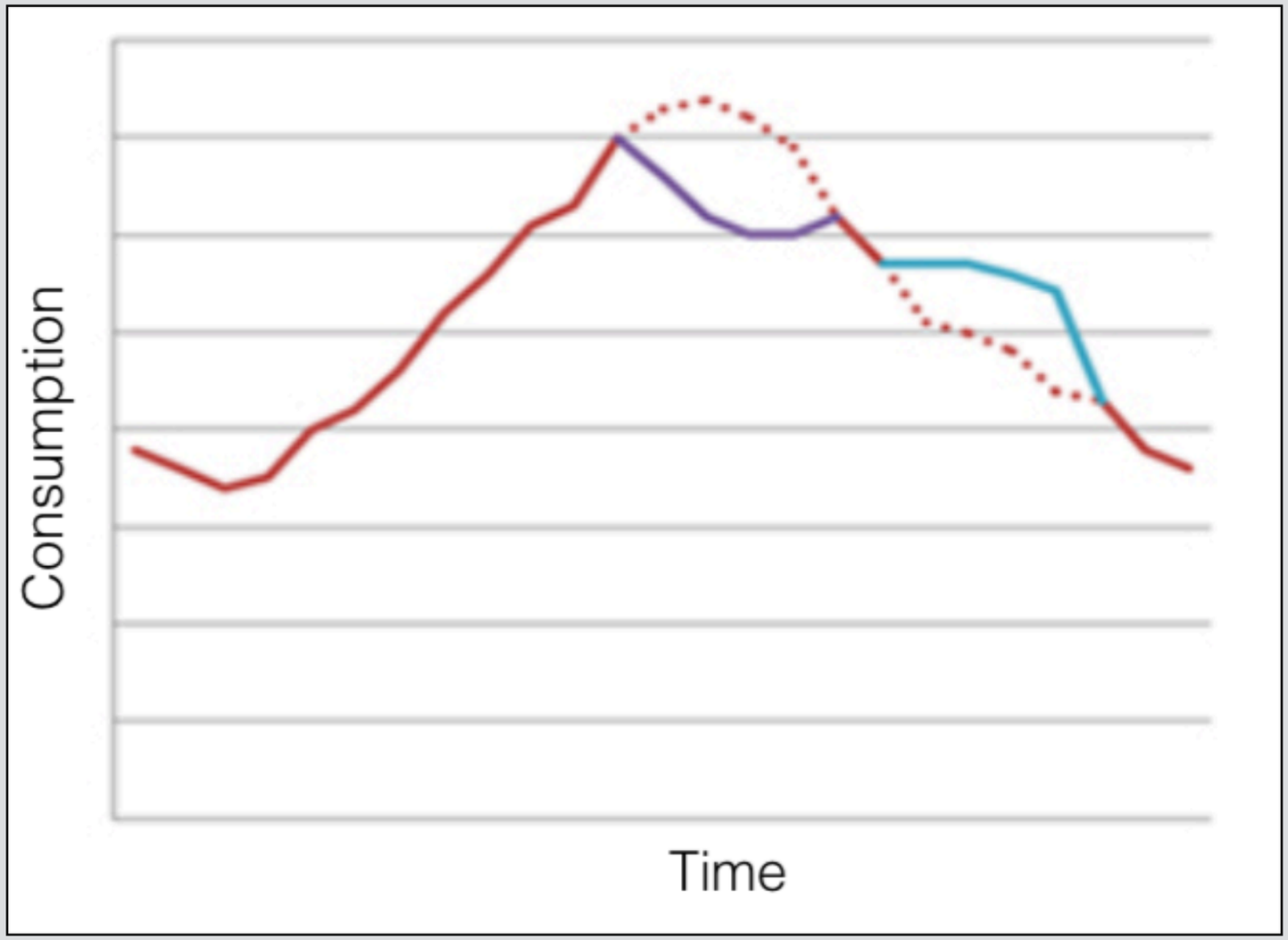




Leveraging consumers' flexibility
Demand response

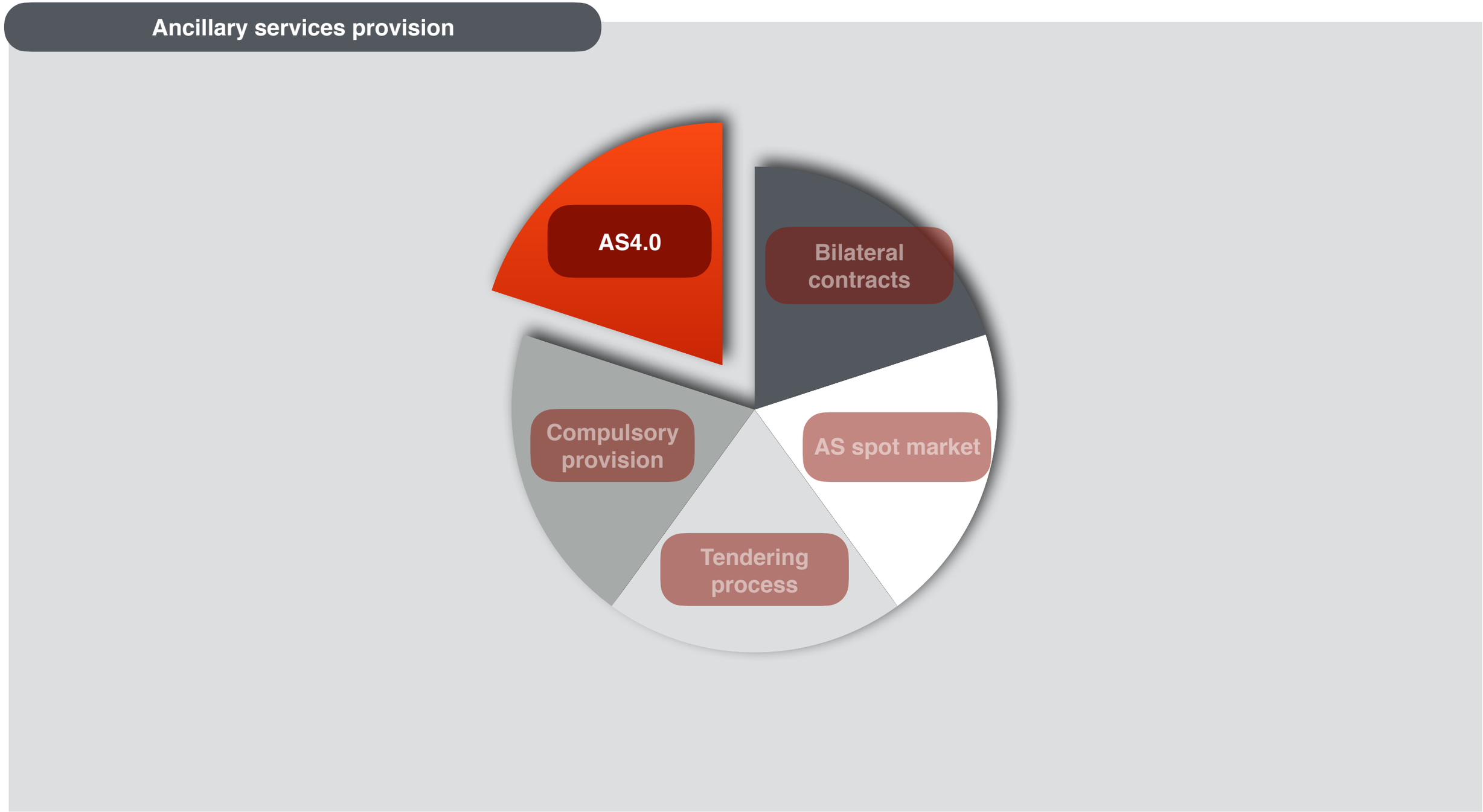
Demand response programs

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



Ancillary services provision

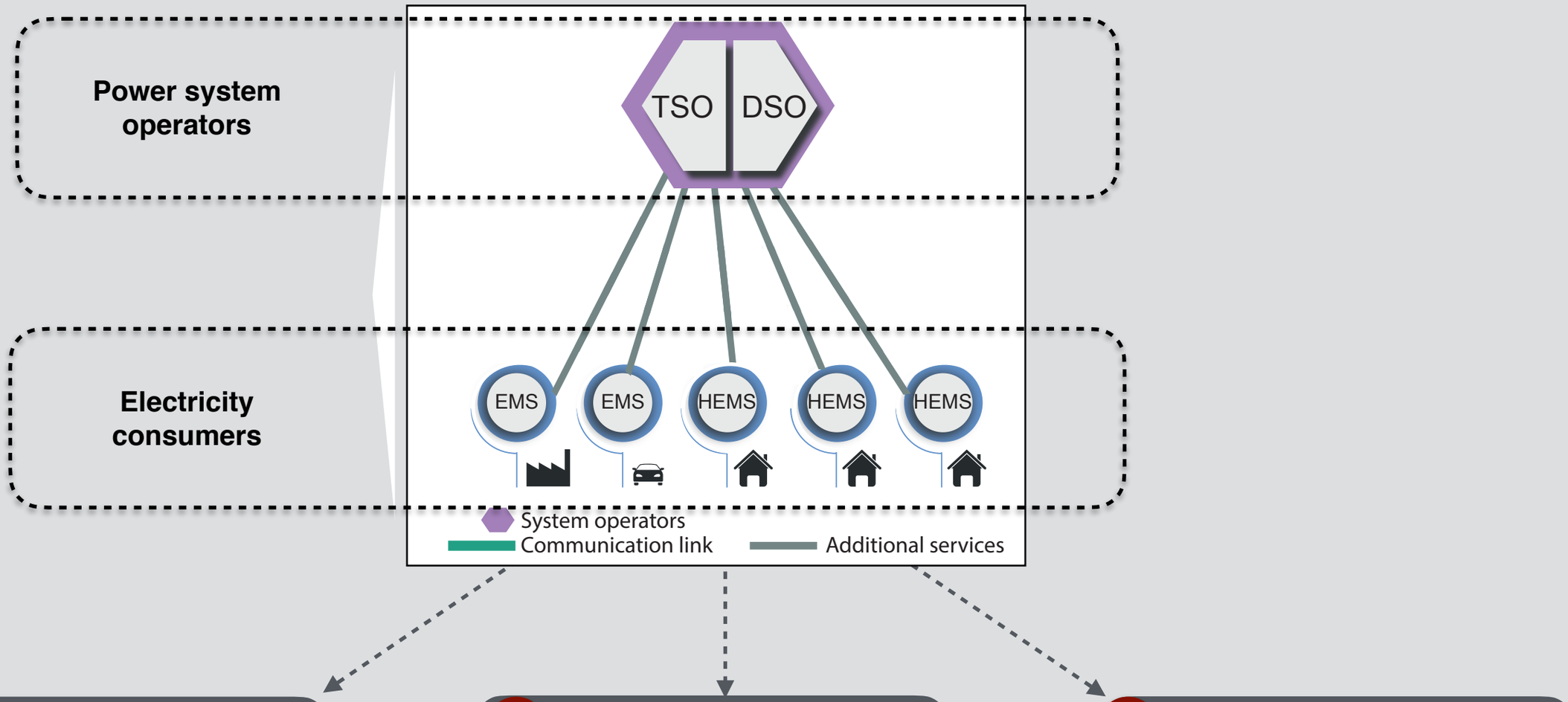
Ancillary services 4.0



Ancillary services provision

Ancillary services 4.0

AS4.0: core idea



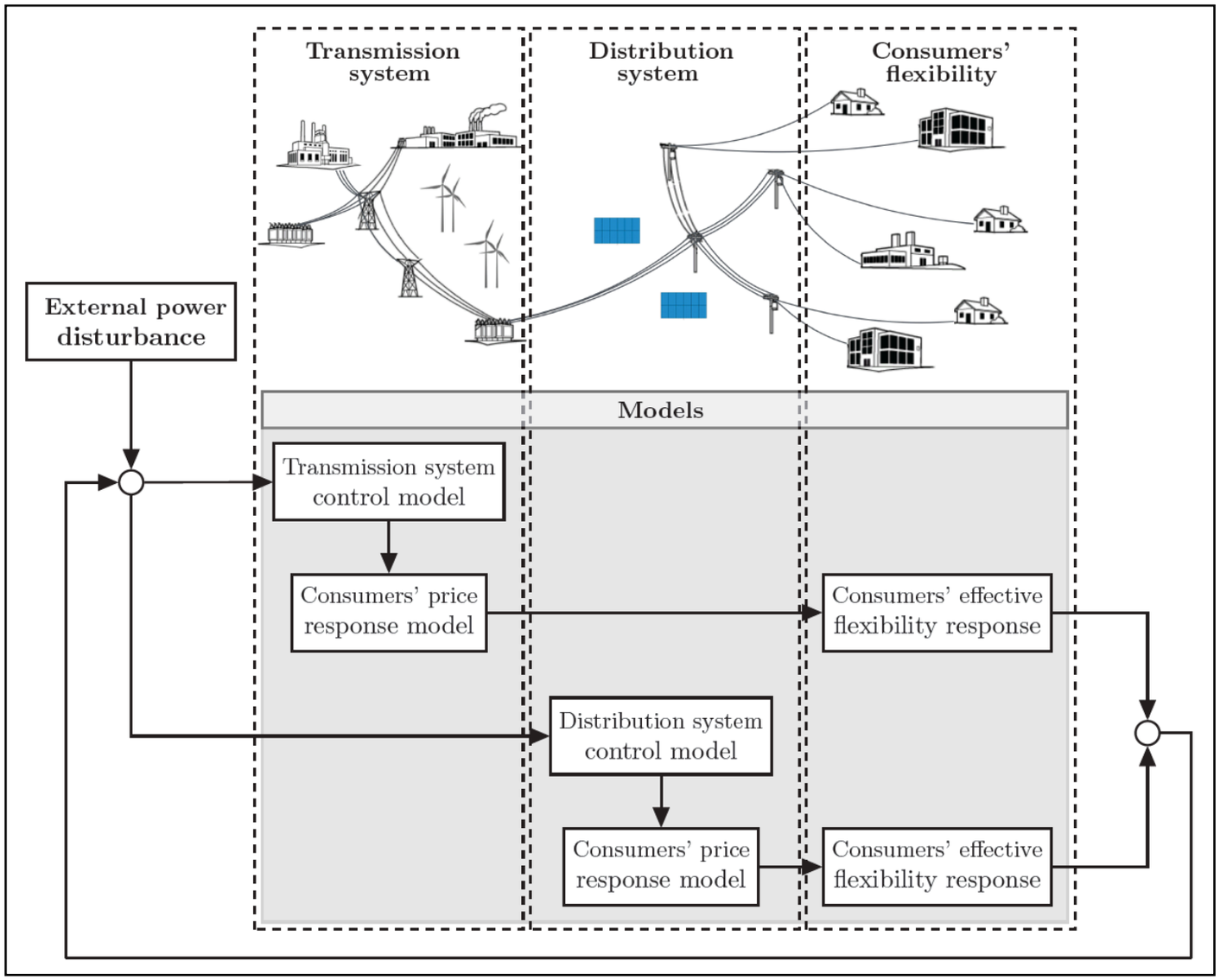
1. Time varying prices
2. Adoption of controllers
3. One-way communication

Ancillary services provision

Ancillary services 4.0

Required models for AS4.0

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

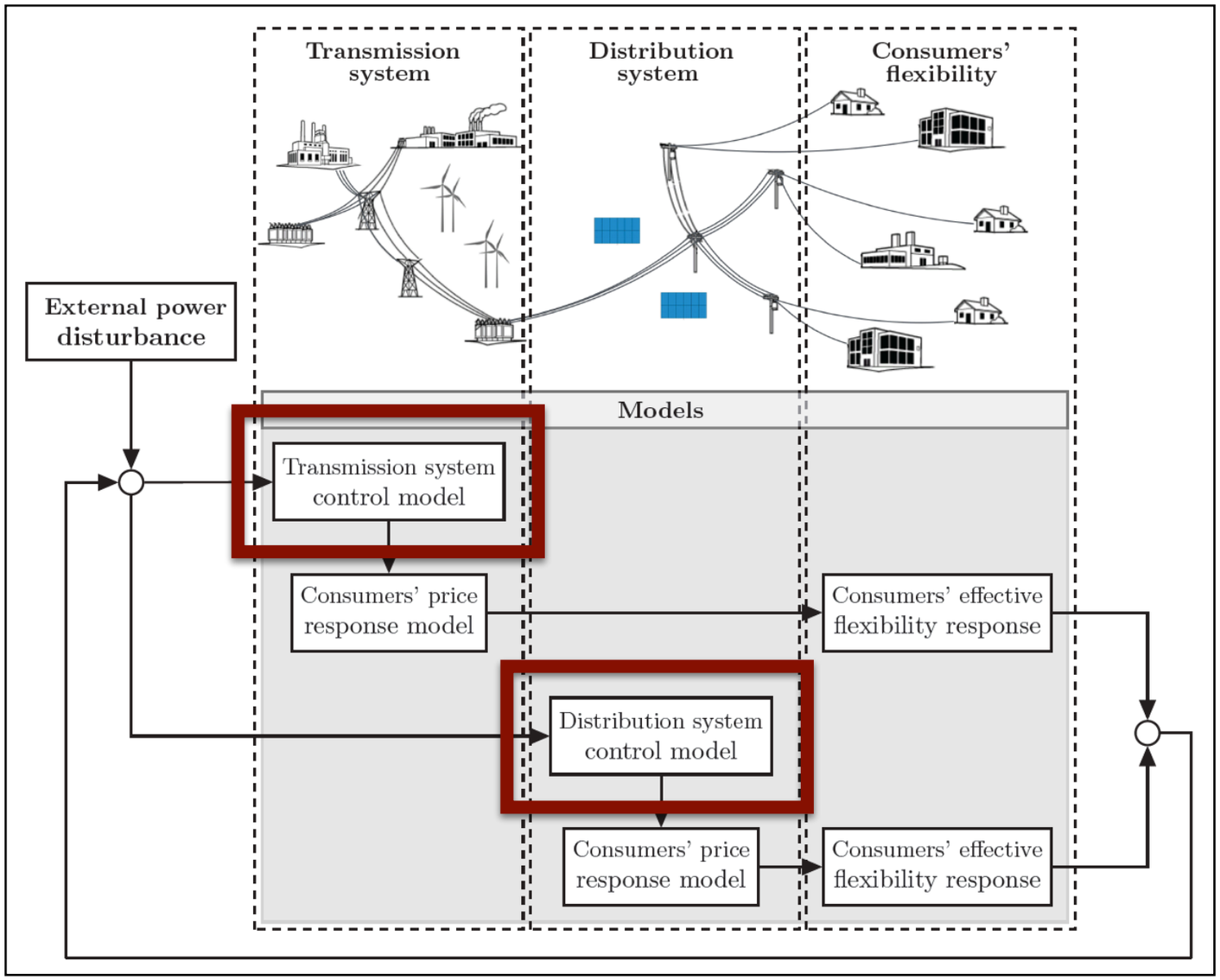


Ancillary services provision

Ancillary services 4.0

Required models for AS4.0

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



1 Power system control models

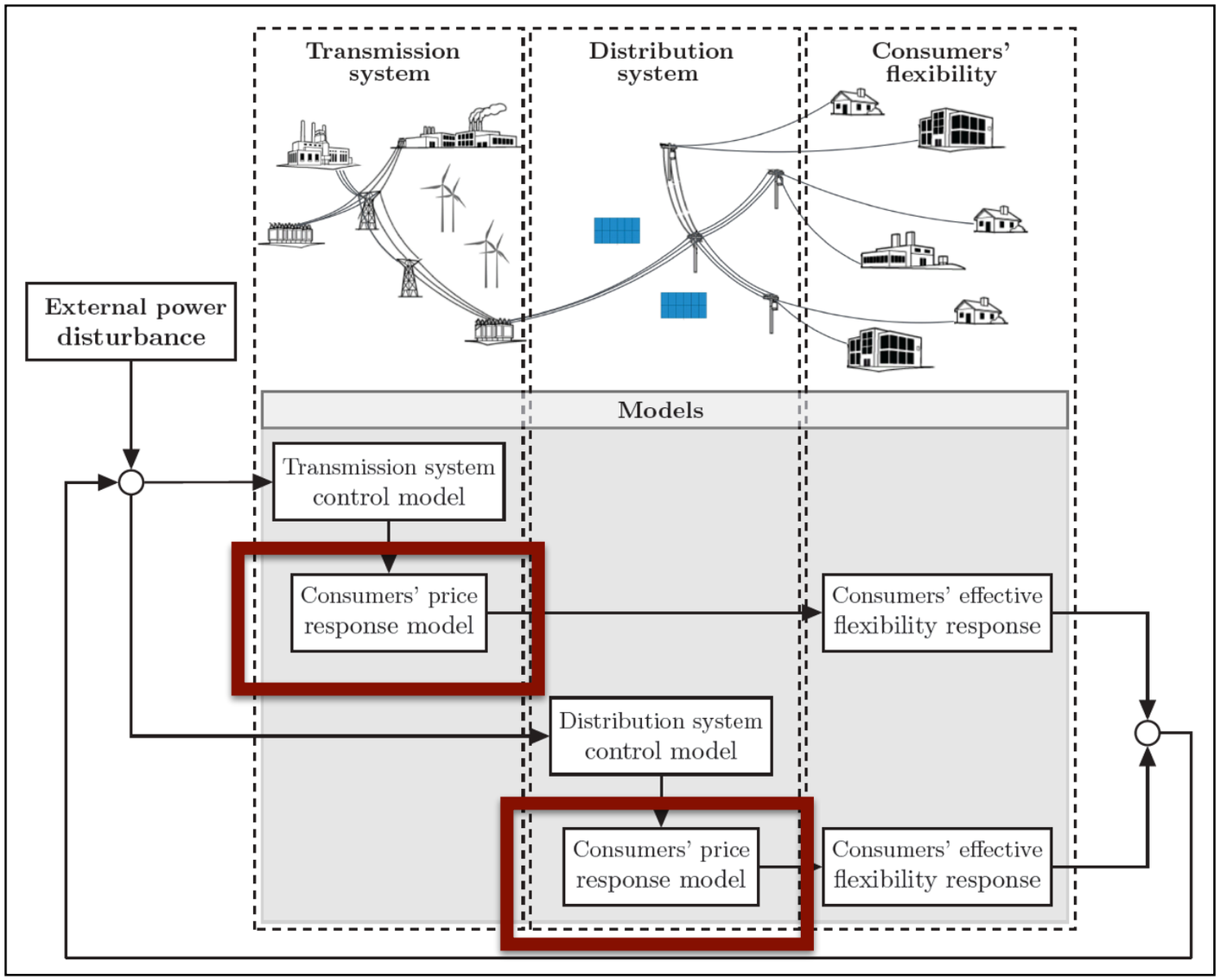
Effect on frequency/ voltage → **Needed flexibility**

Ancillary services provision

Ancillary services 4.0

Required models for AS4.0

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



1 Power system control models

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

2 Consumers' price response models

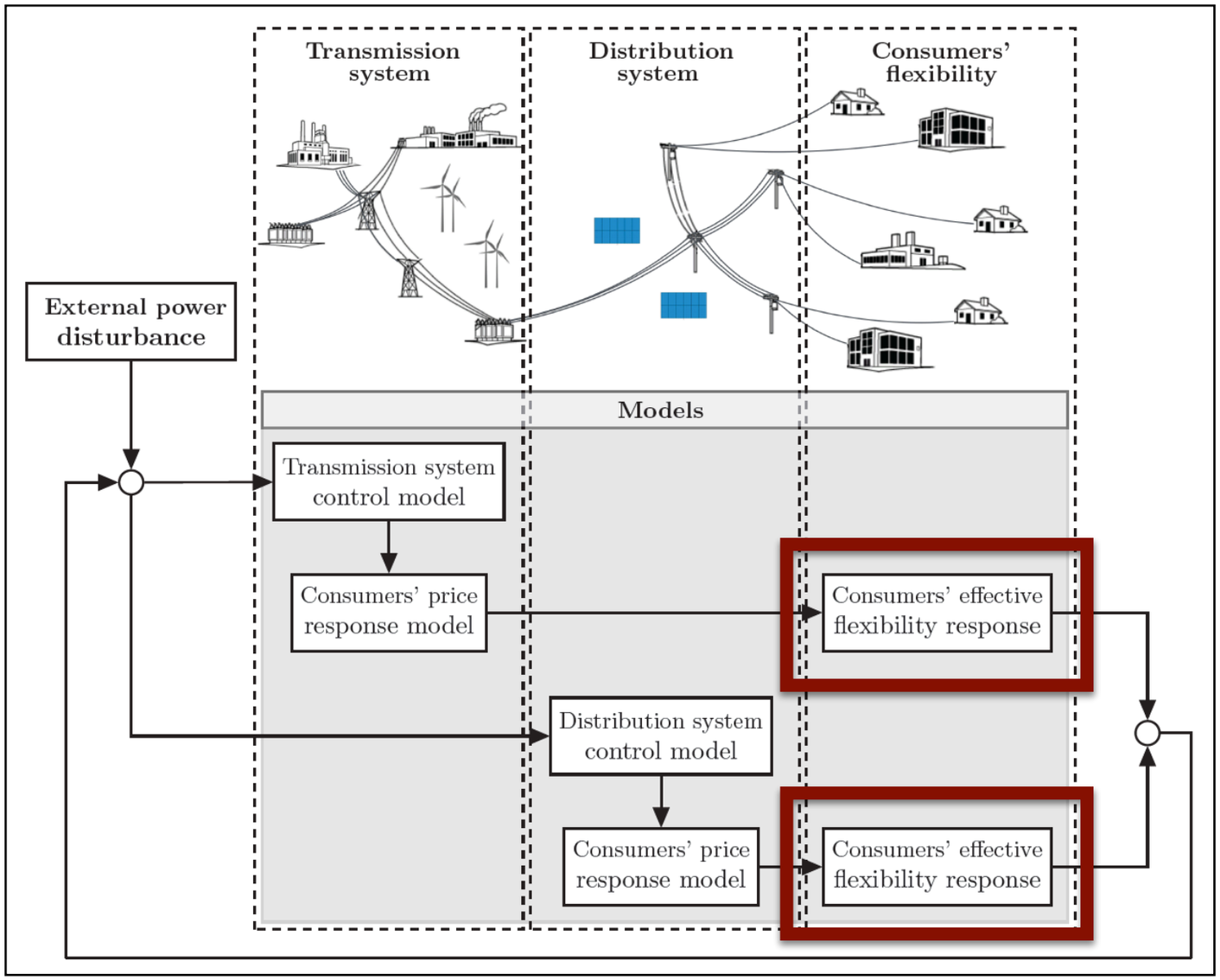
Consumers' responsiveness toward prices → **Proper price signals**

Ancillary services provision

Ancillary services 4.0

Required models for AS4.0

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



1 Power system control models

Effect on frequency/ voltage	→	Needed flexibility

2 Consumers' price response models

Consumers' responsiveness toward prices	→	Proper price signals

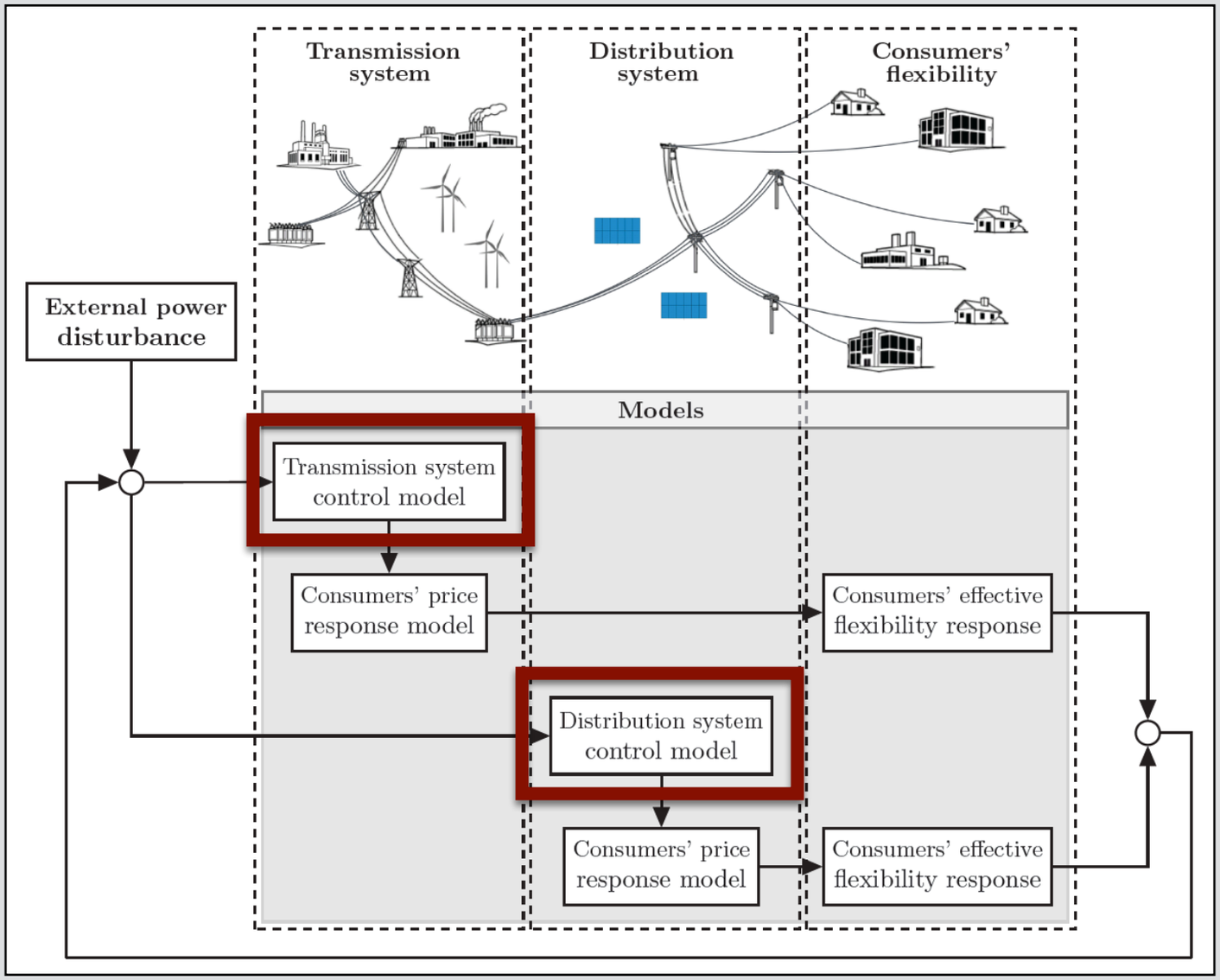
3 Effective flexibility response models

Actual consumers' behaviour	→	Achieved flexibility

Ancillary services provision

Ancillary services 4.0

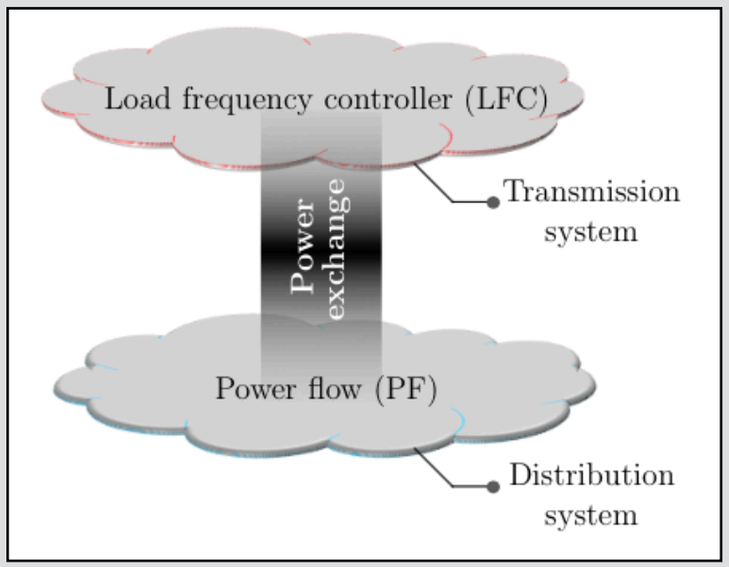
Power system control models



Ancillary services provision

Ancillary services 4.0

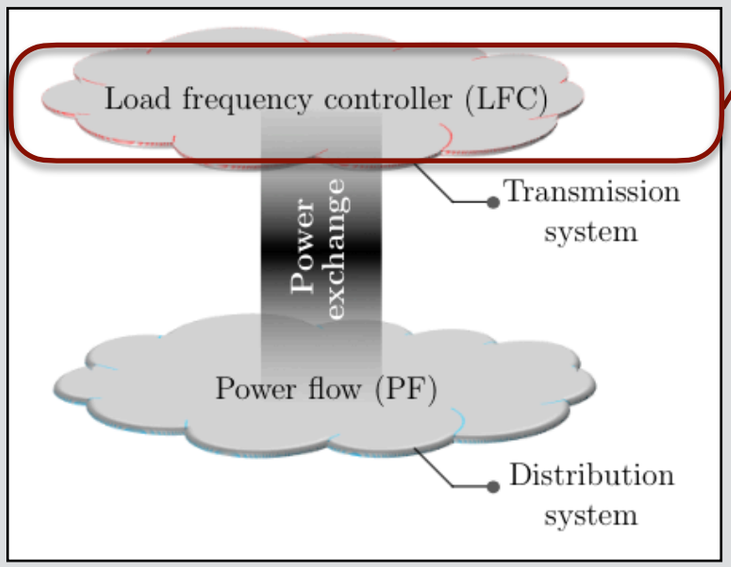
Power system control models



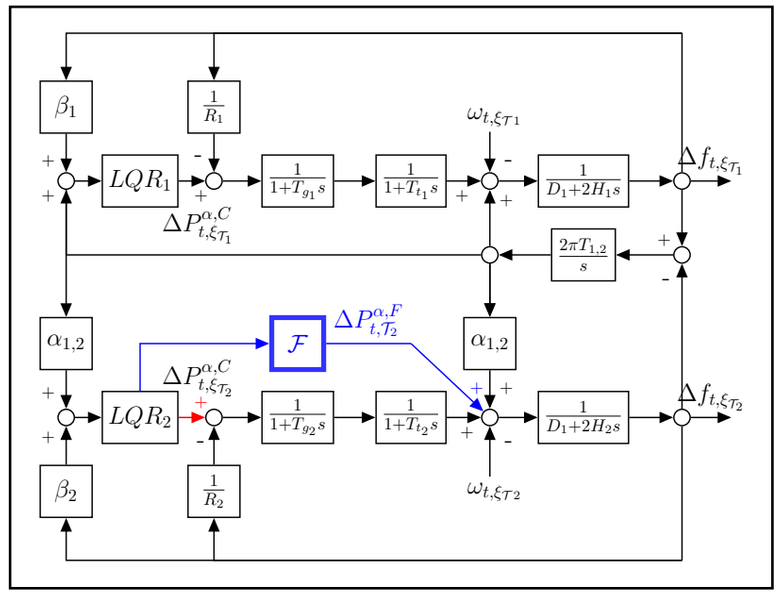
Ancillary services provision

Ancillary services 4.0

Power system control models



At the transmission level



Two-area LFC

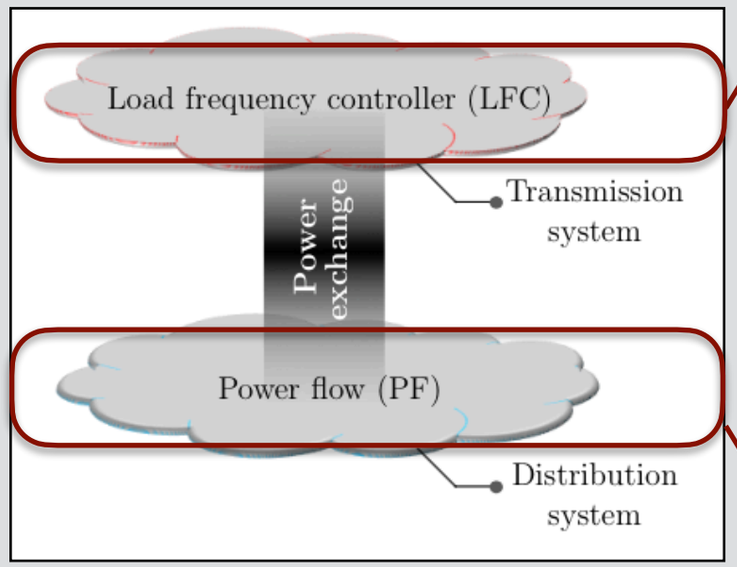
Study cases:

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

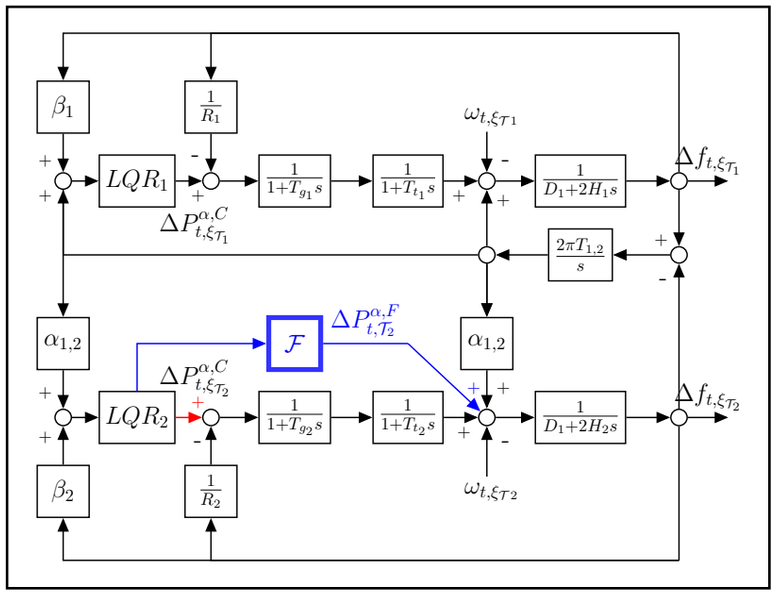
Ancillary services provision

Ancillary services 4.0

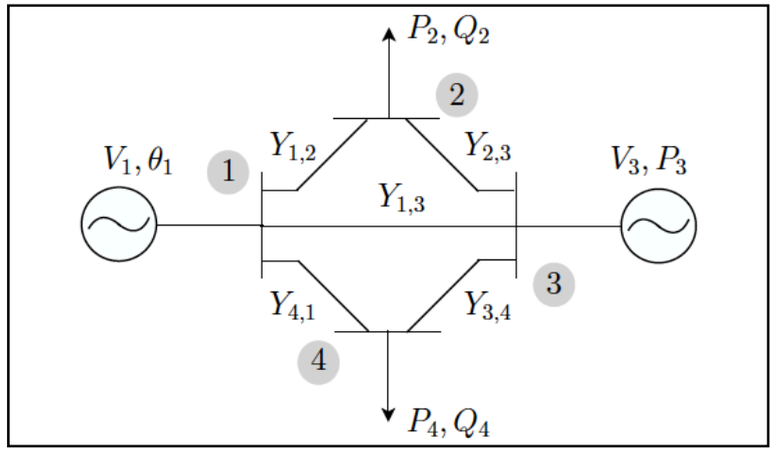
Power system control models



At the transmission level



At the distribution level



Two-area LFC

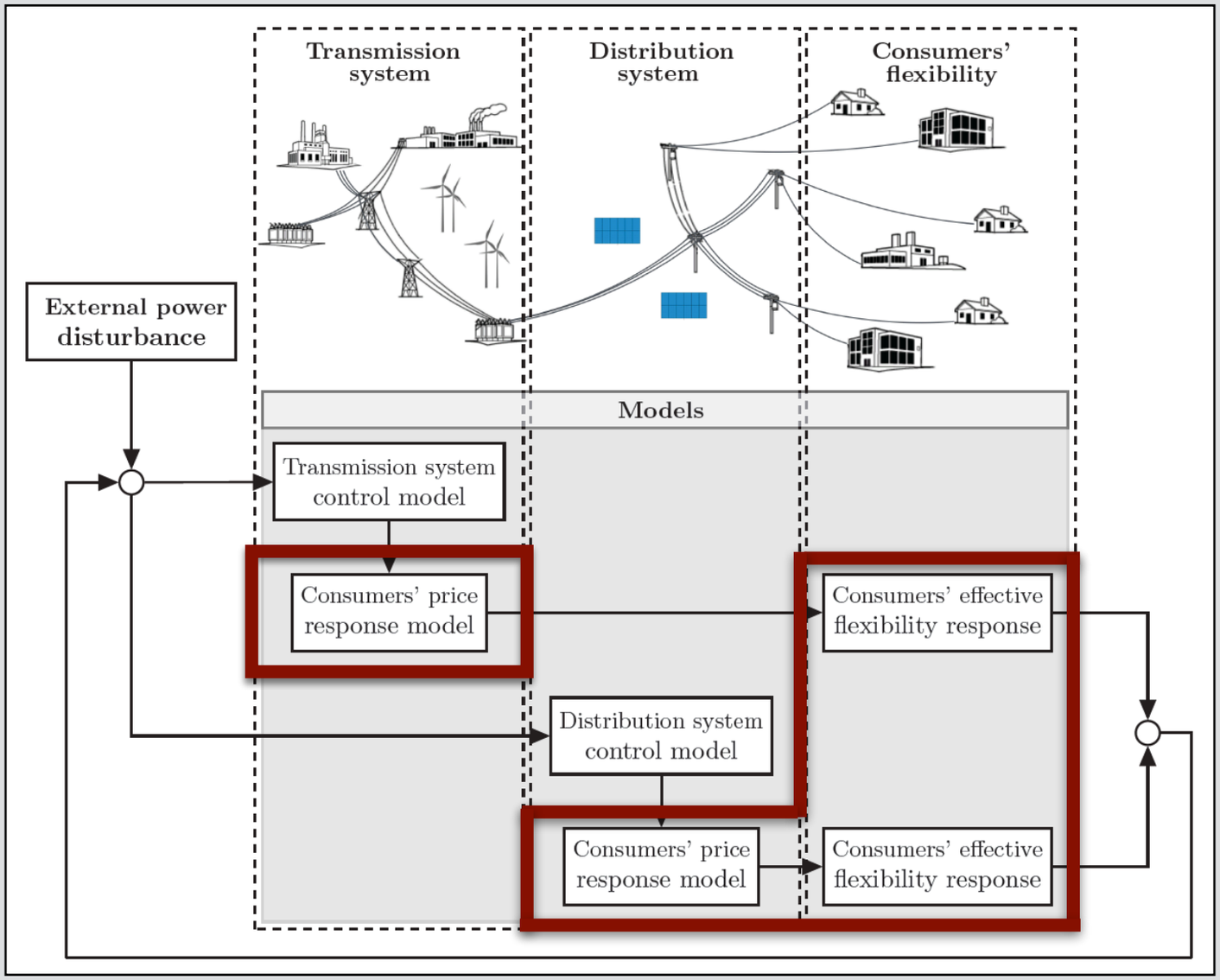
Study cases:

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

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

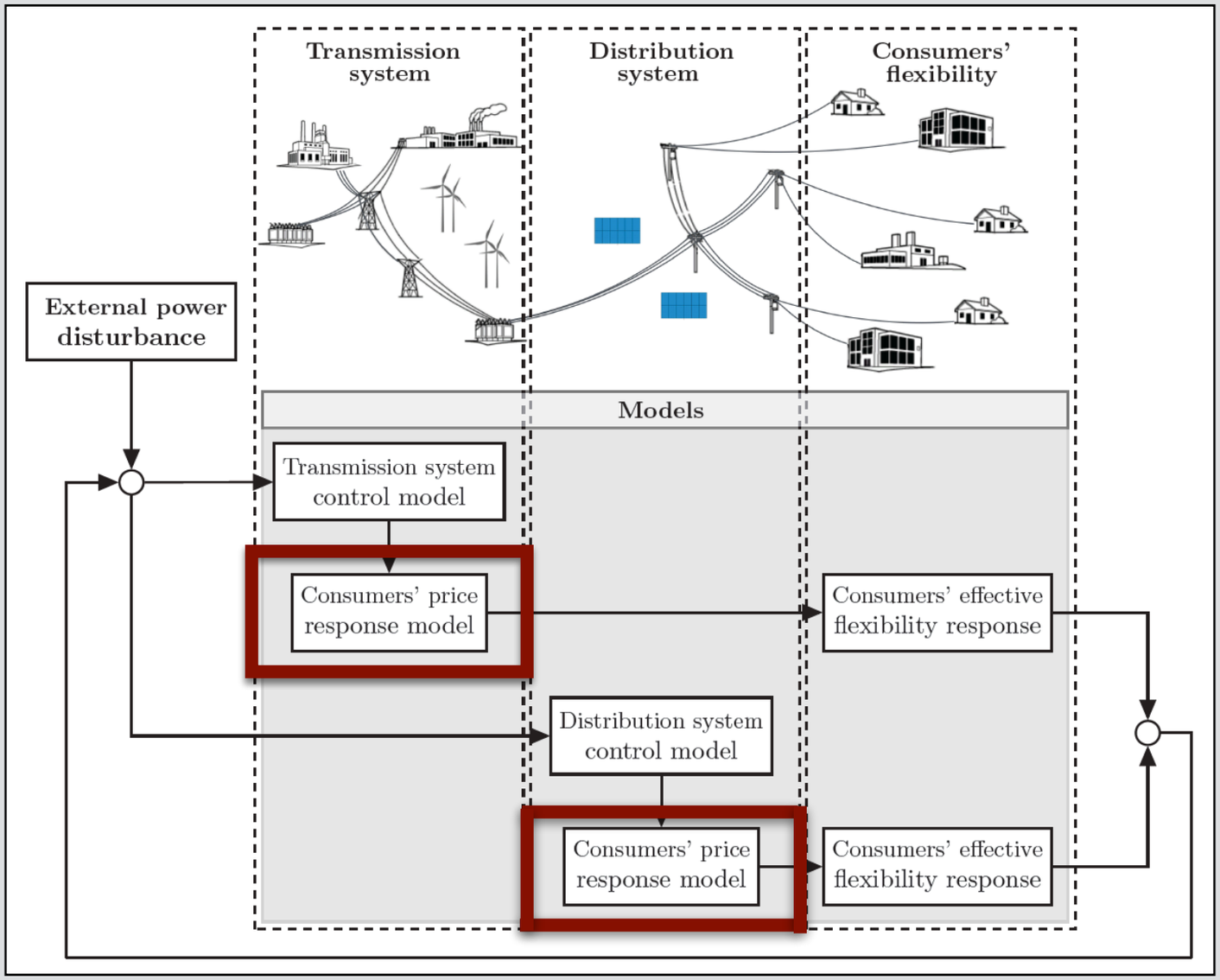


Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

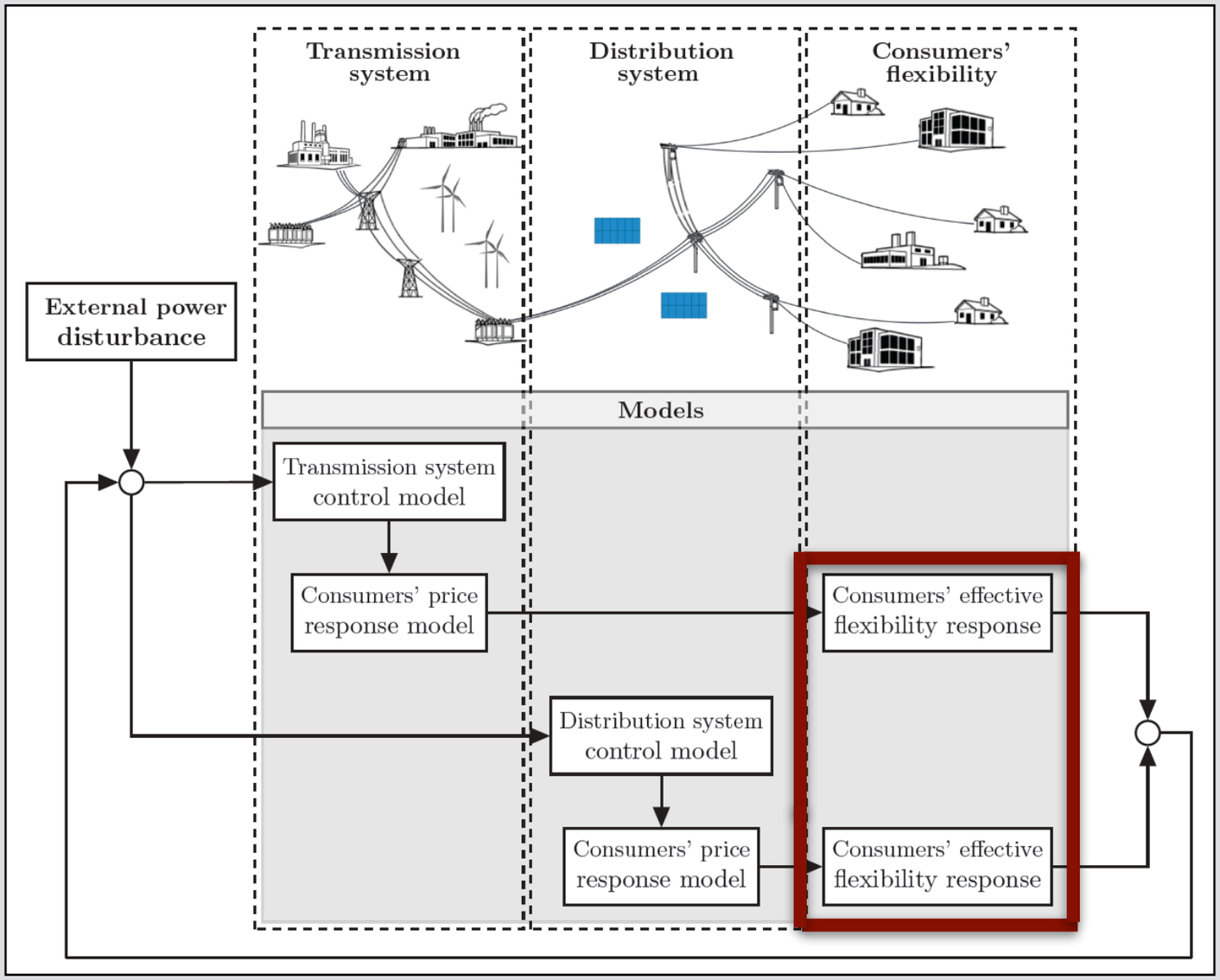
Time varying price formulation



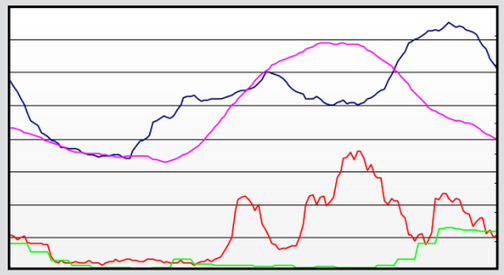
Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response



Realised consumers' response

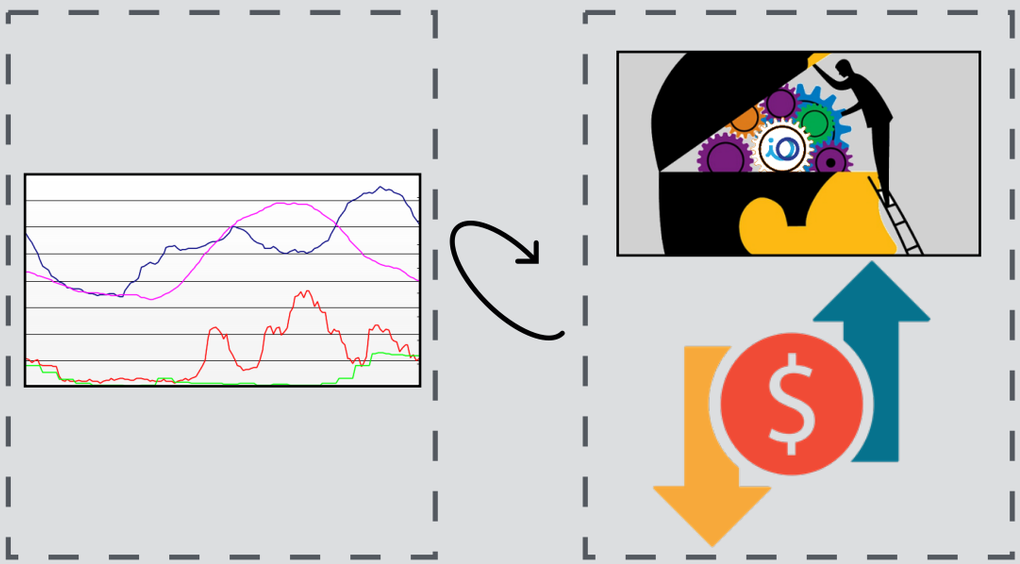


Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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

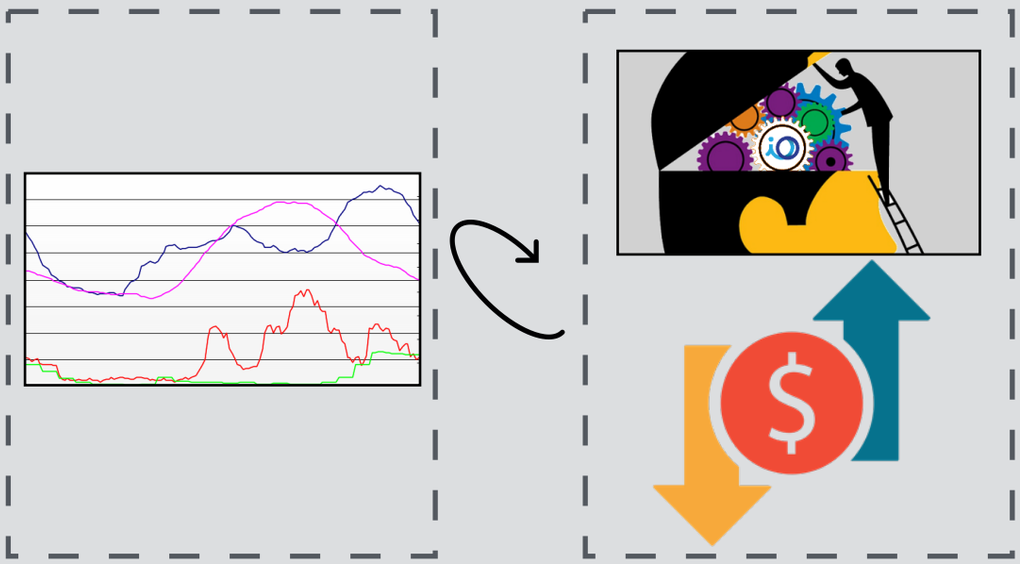


Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



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

Different models at transmission and distribution levels:

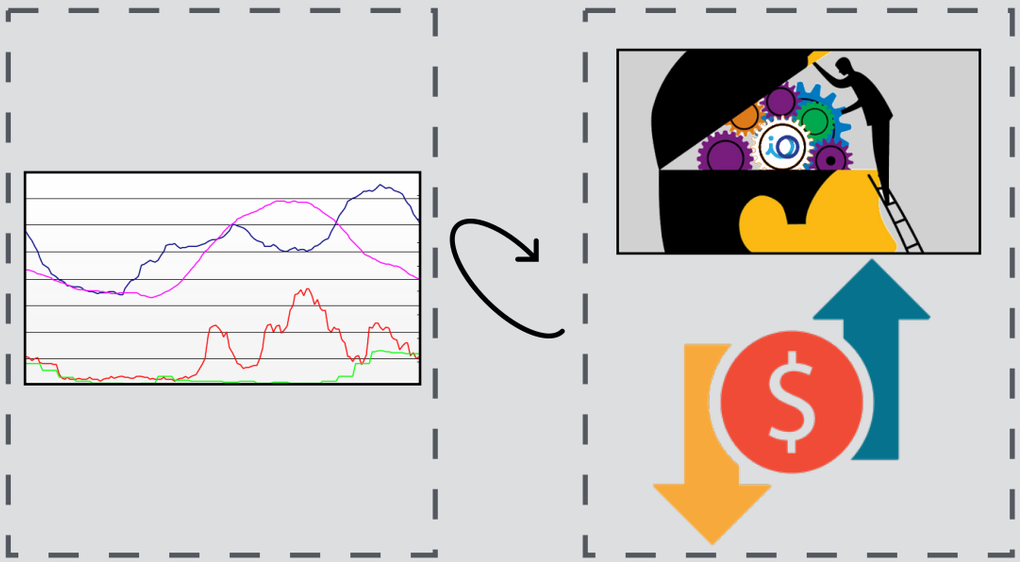
- Size
- Consumers' composition

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



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

Different models at transmission and distribution levels:

- Size
- Consumers' composition

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

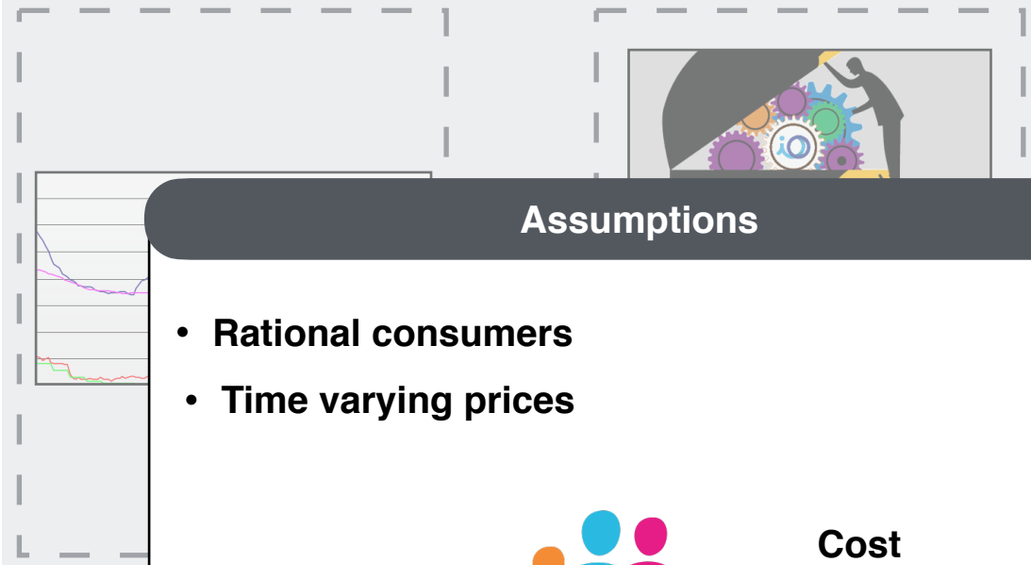
1 **Model**

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

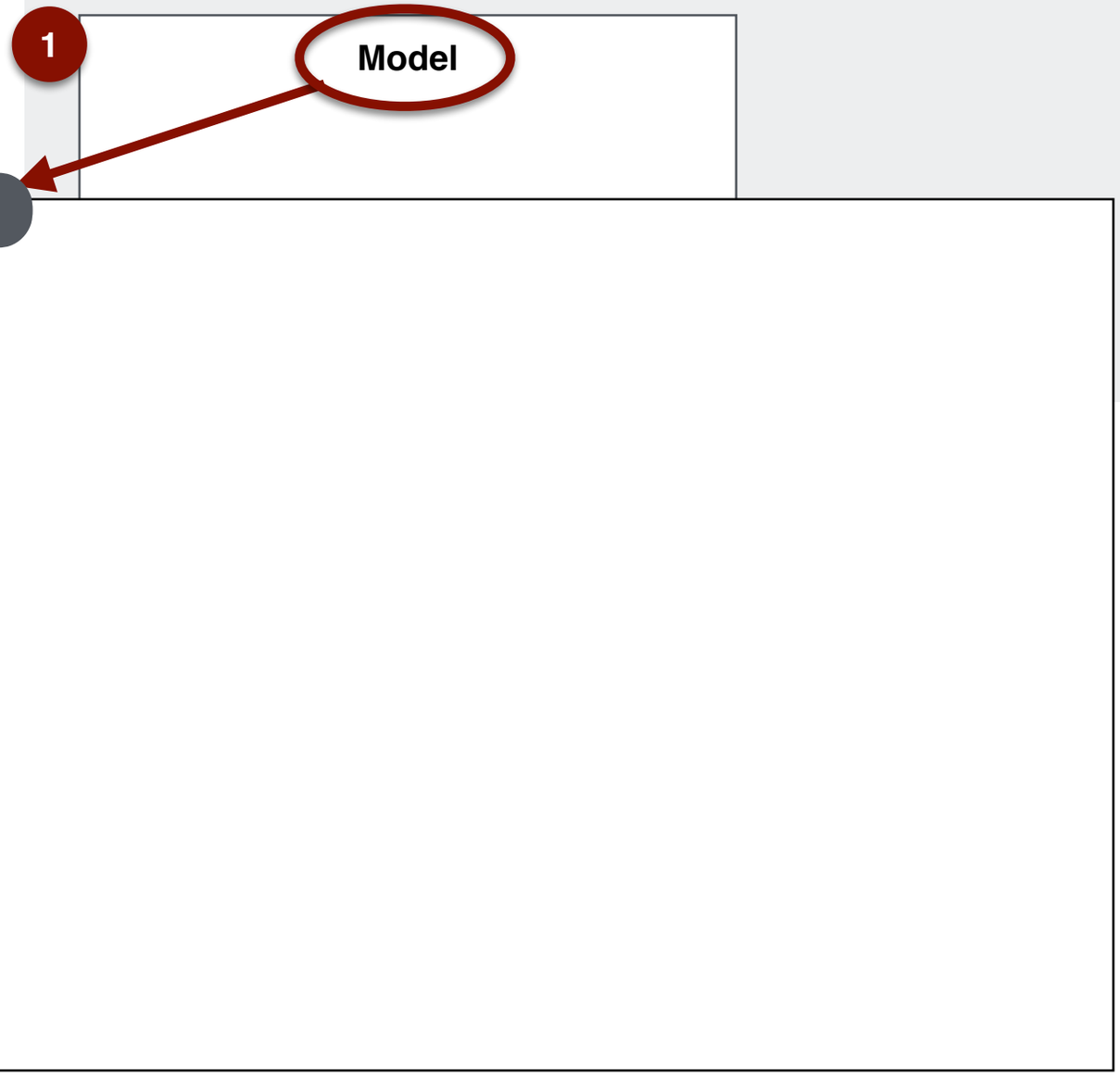
Differe

- Size
- Con

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

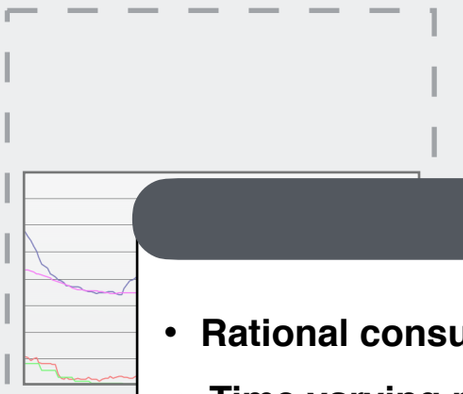


Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



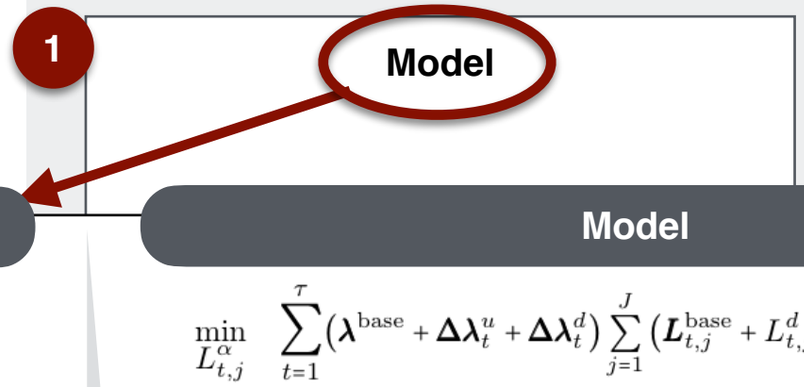
Due to

Differe

- Size
- Con

At the transmission level

Frequency is **not a local issue** → **Aggregate** consumers' flexibility



Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

Model

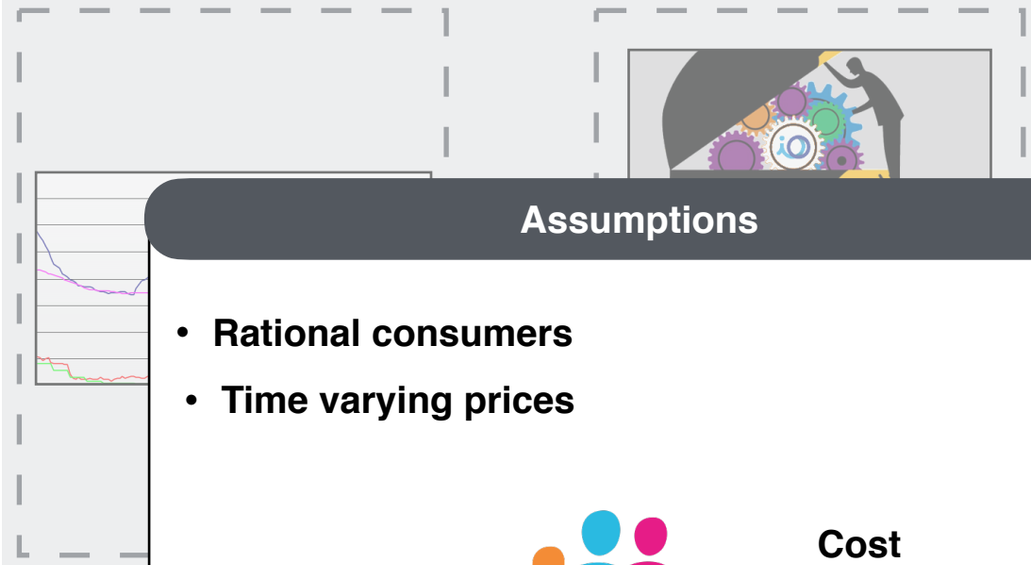
$$\min_{L^{\alpha}_{t,j}} \quad \sum_{t=1}^{\tau}\left(\boldsymbol{\lambda}^{\text{base}} + \boldsymbol{\Delta\lambda}^{u}_{t} + \boldsymbol{\Delta\lambda}^{d}_{t}\right)\sum_{j=1}^{J}\left(\boldsymbol{L}^{\text{base}}_{t,j} + L^{d}_{t,j} - L^{u}_{t}\right.$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

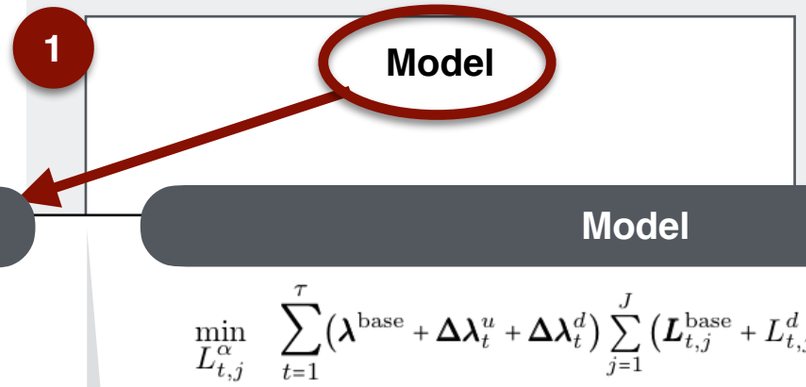
Differe

- Size
- Con

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility



Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

Comfort

Model

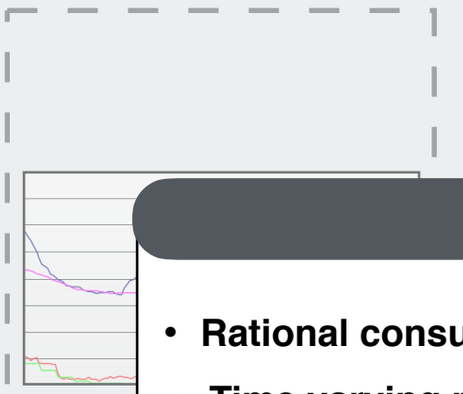
$$\min_{L^{\alpha}_{t,j}} \quad \sum_{t=1}^{\tau} \left(\boldsymbol{\lambda}^{\text{base}} + \boldsymbol{\Delta\lambda}^{u}_{t} + \boldsymbol{\Delta\lambda}^{d}_{t}\right) \sum_{j=1}^{J} \left(\boldsymbol{L}^{\text{base}}_{t,j} + L^{d}_{t,j} - L^{u}_{t}\right.$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

Differe

- Size
- Con

Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

Comfort

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

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

Model

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

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

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

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

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

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

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

$$y^{\alpha}_{t,j} + z^{\alpha}_{t,j} \le 1 \qquad \forall t,j,\alpha$$

$$\sum_{t=1}^{\tau} y^{\alpha}_{t,j} \le \mathbf{n}^{\alpha}_{j} \qquad \forall j,\alpha$$

$$\sum_{t'=t}^{t+\underline{\mathbf{d}}^{\alpha}_{j}} u^{\alpha}_{t',j} \ge \underline{\mathbf{d}}^{\alpha}_{j} y^{\alpha}_{t,j} \qquad \forall t : [t \in T, (t + \underline{\mathbf{d}}^{\alpha}_{j} < \tau)], j, \alpha$$

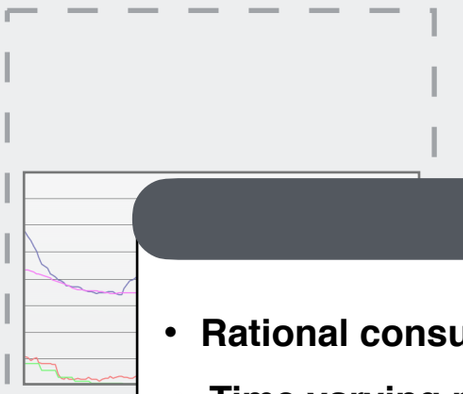
$$\sum_{t'=t}^{t+\overline{\mathbf{d}}^{\alpha}_{j}} z^{\alpha}_{t',j} \ge y^{\alpha}_{t,j} \qquad \forall t : [t \in T, (t + \overline{\mathbf{d}}^{\alpha}_{j} < \tau)], j, \alpha$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

Differe

- Size
- Con

Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

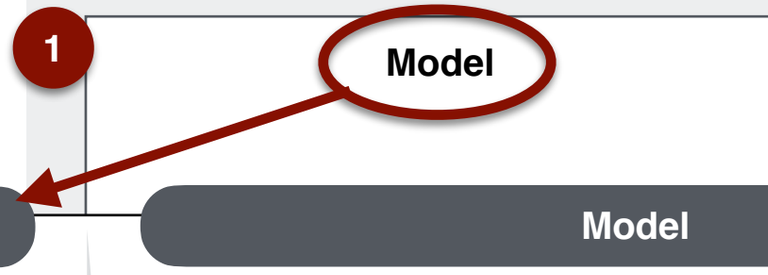
Comfort

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

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility



Model

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

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

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

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

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

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

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

$$y^{\alpha}_{t,j} + z^{\alpha}_{t,j} \le 1 \qquad \forall t,j,\alpha$$

$$\sum_{t=1}^{\tau} y^{\alpha}_{t,j} \le \mathbf{n}^{\alpha}_{j} \qquad \forall j,\alpha$$

$$\sum_{t'=t}^{t+\underline{\mathbf{d}}^{\alpha}_{j}} u^{\alpha}_{t',j} \ge \underline{\mathbf{d}}^{\alpha}_{j} y^{\alpha}_{t,j} \qquad \forall t : [t \in T, (t + \underline{\mathbf{d}}^{\alpha}_{j} < \tau)], j, \alpha$$

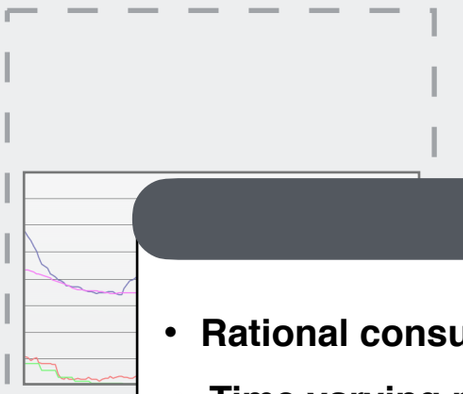
$$\sum_{t'=t}^{t+\overline{\mathbf{d}}^{\alpha}_{j}} z^{\alpha}_{t',j} \ge y^{\alpha}_{t,j} \qquad \forall t : [t \in T, (t + \overline{\mathbf{d}}^{\alpha}_{j} < \tau)], j, \alpha$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

Differe

- Size
- Con

Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

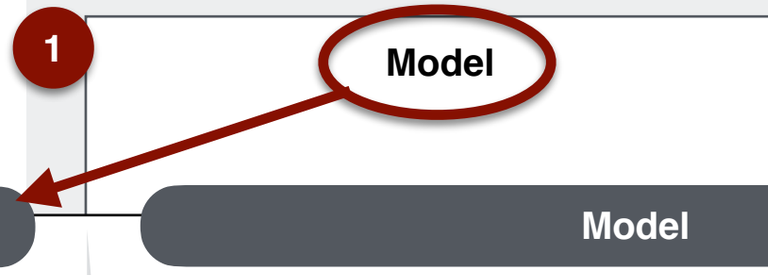
Comfort

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

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility



Model

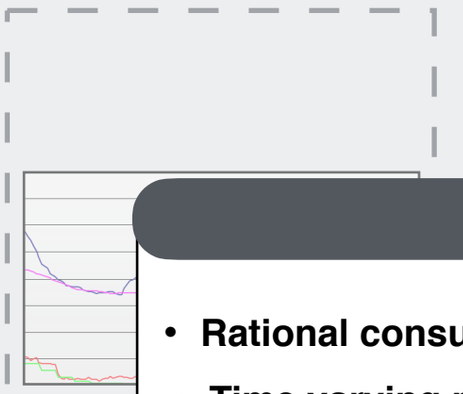
$$
\begin{aligned}
\min_{L^{\alpha}_{t,j}} \quad & \sum_{t=1}^{\tau}\left(\boldsymbol{\lambda}^{\text{base}}+\boldsymbol{\Delta\lambda}^{u}_{t}+\boldsymbol{\Delta\lambda}^{d}_{t}\right)\sum_{j=1}^{J}\left(\boldsymbol{L}^{\text{base}}_{t,j}+L^{d}_{t,j}-L^{u}_{t}\right.\\
\text{s.t.} \quad & -\mathbf{r}^{\alpha}_{j}\le L^{\alpha}_{t+1,j}-L^{\alpha}_{t,j}\le \mathbf{r}^{\alpha}_{j} && \forall t,j,\alpha\\
& 0\le L^{d}_{t,j}\le u^{d}_{t,j}\left(\mathbf{L}^{\max}_{t,j}-\mathbf{L}^{\text{base}}_{t,j}\right)\mathbf{a}^{d}_{t,j} && \forall t,j\\
& 0\le L^{u}_{t,j}\le u^{u}_{t,j}\left(\mathbf{L}^{\text{base}}_{t,j}-\mathbf{L}^{\min}_{t,j}\right)\mathbf{a}^{u}_{t,j} && \forall t,j\\
& \sum_{t'=(t-1)R_j+1}^{(t-1)R_j+R_j}\left(L^{d}_{t',j}-L^{u}_{t',j}\right)=0 && \forall t:[t\in T,(tR_j\le\tau)],j\\
& u^{d}_{t,j}+u^{u}_{t,j}\le 1 && \forall t,j\\
& y^{\alpha}_{t,j}-z^{\alpha}_{t,j}=u^{\alpha}_{t,j}-u^{\alpha}_{t-1,j} && \forall t,j,\alpha\\
& y^{\alpha}_{t,j}+z^{\alpha}_{t,j}\le 1 && \forall t,j,\alpha\\
& \sum_{t=1}^{\tau}y^{\alpha}_{t,j}\le \mathbf{n}^{\alpha}_{j} && \forall j,\alpha\\
& \sum_{t'=t}^{t+\underline{\mathbf{d}}^{\alpha}_{j}}u^{\alpha}_{t',j}\ge \underline{\mathbf{d}}^{\alpha}_{j}y^{\alpha}_{t,j} && \forall t:[t\in T,(t+\underline{\mathbf{d}}^{\alpha}_{j}<\tau)],j,\alpha\\
& \sum_{t'=t}^{t+\overline{\mathbf{d}}^{\alpha}_{j}}z^{\alpha}_{t',j}\ge y^{\alpha}_{t,j} && \forall t:[t\in T,(t+\overline{\mathbf{d}}^{\alpha}_{j}<\tau)],j,\alpha
\end{aligned}
$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

Differe

- Size
- Con

Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

Comfort

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

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

1 Model

Model

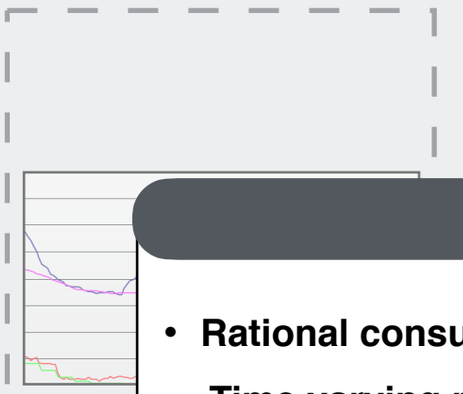
$$
\begin{aligned}
\min_{L^{\alpha}_{t,j}} \quad & \sum_{t=1}^{\tau}\left(\boldsymbol{\lambda}^{\text{base}}+\boldsymbol{\Delta\lambda}^{u}_{t}+\boldsymbol{\Delta\lambda}^{d}_{t}\right)\sum_{j=1}^{J}\left(\boldsymbol{L}^{\text{base}}_{t,j}+L^{d}_{t,j}-L^{u}_{t}\right.\\
\text{s.t.} \quad & -\mathbf{r}^{\alpha}_{j}\le L^{\alpha}_{t+1,j}-L^{\alpha}_{t,j}\le \mathbf{r}^{\alpha}_{j} && \forall t,j,\alpha\\
& 0\le L^{d}_{t,j}\le u^{d}_{t,j}\left(\mathbf{L}^{\max}_{t,j}-\mathbf{L}^{\text{base}}_{t,j}\right)\mathbf{a}^{d}_{t,j} && \forall t,j\\
& 0\le L^{u}_{t,j}\le u^{u}_{t,j}\left(\mathbf{L}^{\text{base}}_{t,j}-\mathbf{L}^{\min}_{t,j}\right)\mathbf{a}^{u}_{t,j} && \forall t,j\\
& \sum_{t'=(t-1)R_j+1}^{(t-1)R_j+R_j}\left(L^{d}_{t',j}-L^{u}_{t',j}\right)=0 && \forall t:[t\in T,(tR_j\le\tau)],j\\
& u^{d}_{t,j}+u^{u}_{t,j}\le 1 && \forall t,j\\
& y^{\alpha}_{t,j}-z^{\alpha}_{t,j}=u^{\alpha}_{t,j}-u^{\alpha}_{t-1,j} && \forall t,j,\alpha\\
& y^{\alpha}_{t,j}+z^{\alpha}_{t,j}\le 1 && \forall t,j,\alpha\\
& \sum_{t=1}^{\tau}y^{\alpha}_{t,j}\le \mathbf{n}^{\alpha}_{j} && \forall j,\alpha\\
& \sum_{t'=t}^{t+\underline{\mathbf{d}}^{\alpha}_{j}}u^{\alpha}_{t',j}\ge \underline{\mathbf{d}}^{\alpha}_{j}y^{\alpha}_{t,j} && \forall t:[t\in T,(t+\underline{\mathbf{d}}^{\alpha}_{j}<\tau)],j,\alpha\\
& \sum_{t'=t}^{t+\overline{\mathbf{d}}^{\alpha}_{j}}z^{\alpha}_{t',j}\ge y^{\alpha}_{t,j} && \forall t:[t\in T,(t+\overline{\mathbf{d}}^{\alpha}_{j}<\tau)],j,\alpha
\end{aligned}
$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



Due to

Differe

- Size
- Con

Assumptions

- **Rational consumers**
- **Time varying prices**

Cost minimisation

Comfort

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

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

1 **Model**

Model

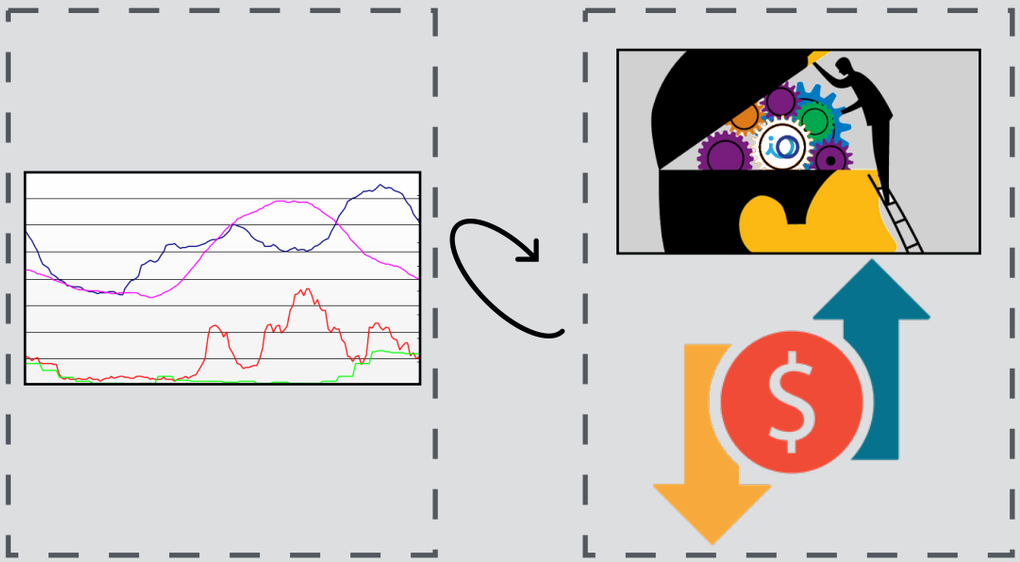
$$
\begin{aligned}
\min_{L^{\alpha}_{t,j}} \quad & \sum_{t=1}^{\tau}\left(\boldsymbol{\lambda}^{\text{base}}+\boldsymbol{\Delta\lambda}^{u}_{t}+\boldsymbol{\Delta\lambda}^{d}_{t}\right)\sum_{j=1}^{J}\left(\boldsymbol{L}^{\text{base}}_{t,j}+L^{d}_{t,j}-L^{u}_{t}\right.\\
\text{s.t.} \quad & -\mathbf{r}^{\alpha}_{j}\le L^{\alpha}_{t+1,j}-L^{\alpha}_{t,j}\le \mathbf{r}^{\alpha}_{j} && \forall t,j,\alpha\\
& 0\le L^{d}_{t,j}\le u^{d}_{t,j}\left(\mathbf{L}^{\max}_{t,j}-\mathbf{L}^{\text{base}}_{t,j}\right)\mathbf{a}^{d}_{t,j} && \forall t,j\\
& 0\le L^{u}_{t,j}\le u^{u}_{t,j}\left(\mathbf{L}^{\text{base}}_{t,j}-\mathbf{L}^{\min}_{t,j}\right)\mathbf{a}^{u}_{t,j} && \forall t,j\\
& \sum_{t'=(t-1)R_j+1}^{(t-1)R_j+R_j}\left(L^{d}_{t',j}-L^{u}_{t',j}\right)=0 && \forall t:[t\in T,(tR_j\le\tau)],j\\
& u^{d}_{t,j}+u^{u}_{t,j}\le 1 && \forall t,j\\
& y^{\alpha}_{t,j}-z^{\alpha}_{t,j}=u^{\alpha}_{t,j}-u^{\alpha}_{t-1,j} && \forall t,j,\alpha\\
& y^{\alpha}_{t,j}+z^{\alpha}_{t,j}\le 1 && \forall t,j,\alpha\\
& \sum_{t=1}^{\tau} y^{\alpha}_{t,j}\le \mathbf{n}^{\alpha}_{j} && \forall j,\alpha\\
& \sum_{t'=t}^{t+\underline{\mathbf{d}}^{\alpha}_{j}} u^{\alpha}_{t',j}\ge \underline{\mathbf{d}}^{\alpha}_{j}\,y^{\alpha}_{t,j} && \forall t:[t\in T,(t+\underline{\mathbf{d}}^{\alpha}_{j}<\tau)],j,\alpha\\
& \sum_{t'=t}^{t+\overline{\mathbf{d}}^{\alpha}_{j}} z^{\alpha}_{t',j}\ge y^{\alpha}_{t,j} && \forall t:[t\in T,(t+\overline{\mathbf{d}}^{\alpha}_{j}<\tau)],j,\alpha
\end{aligned}
$$

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



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

Different models at transmission and distribution levels:

- Size
- Consumers' composition

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

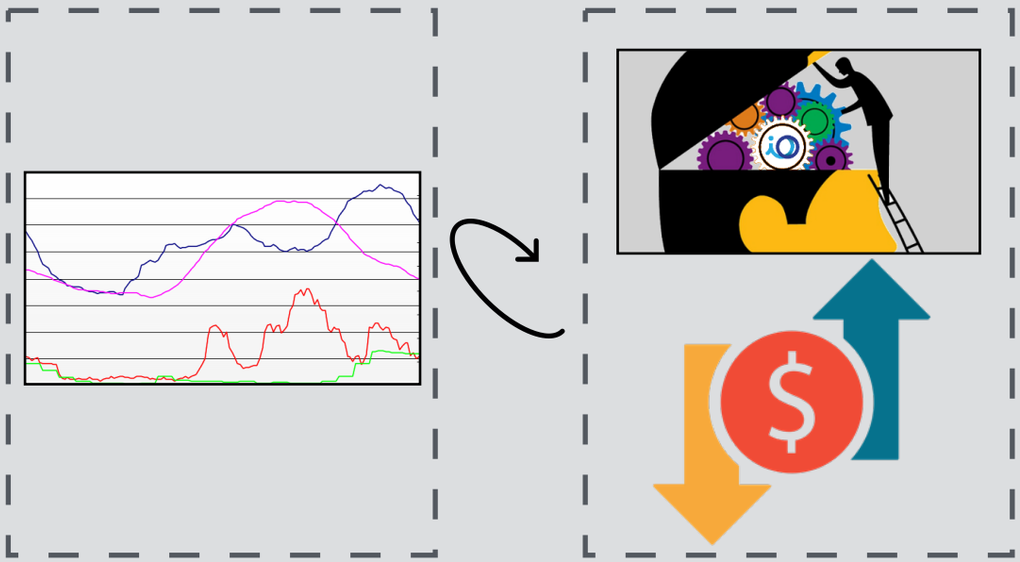
1. **Model**
2. **Montecarlo simulation** → • Aggregate **flexibility**
3. **Neural network** → • Time varying **prices**

Ancillary services provision

Ancillary services 4.0

Aggregate consumers' price response

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



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

Different models at transmission and distribution levels:

- Size
- Consumers' composition

At the transmission level

Frequency is **not a local issue**

Aggregate consumers' flexibility

1. **Model**
2. **Montecarlo simulation** → • Aggregate **flexibility**
3. **Neural network** → • Time varying **prices**

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

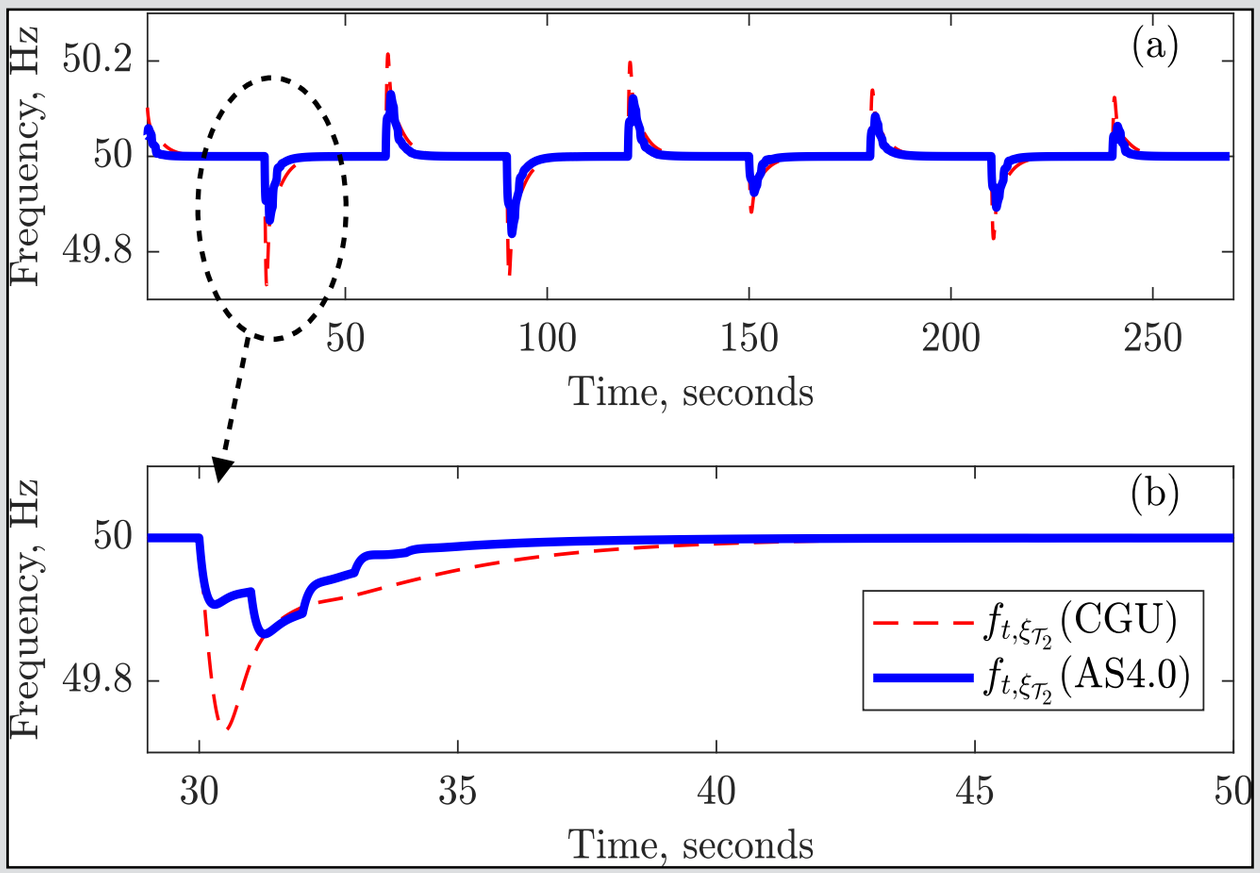
Ancillary services provision

Ancillary services 4.0

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 %

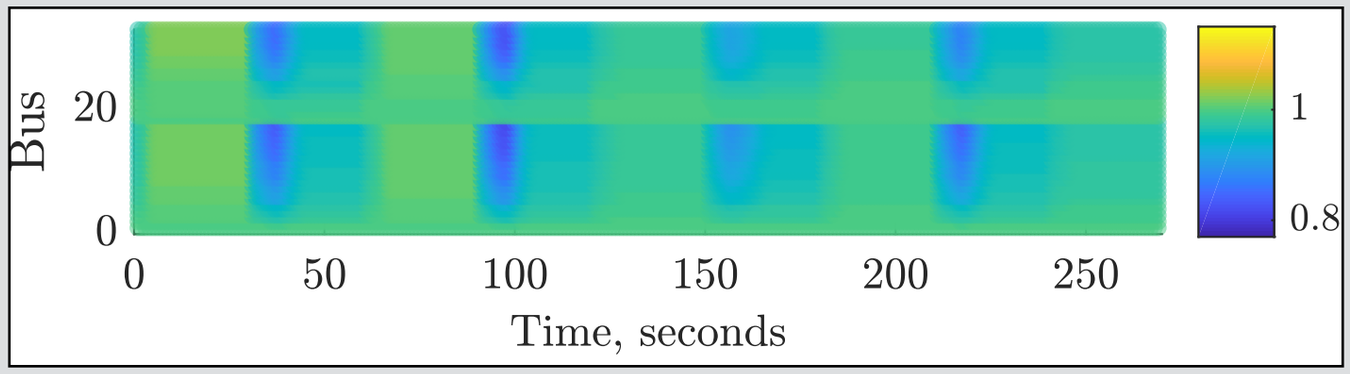
Ancillary services provision

Ancillary services 4.0

Simulations results

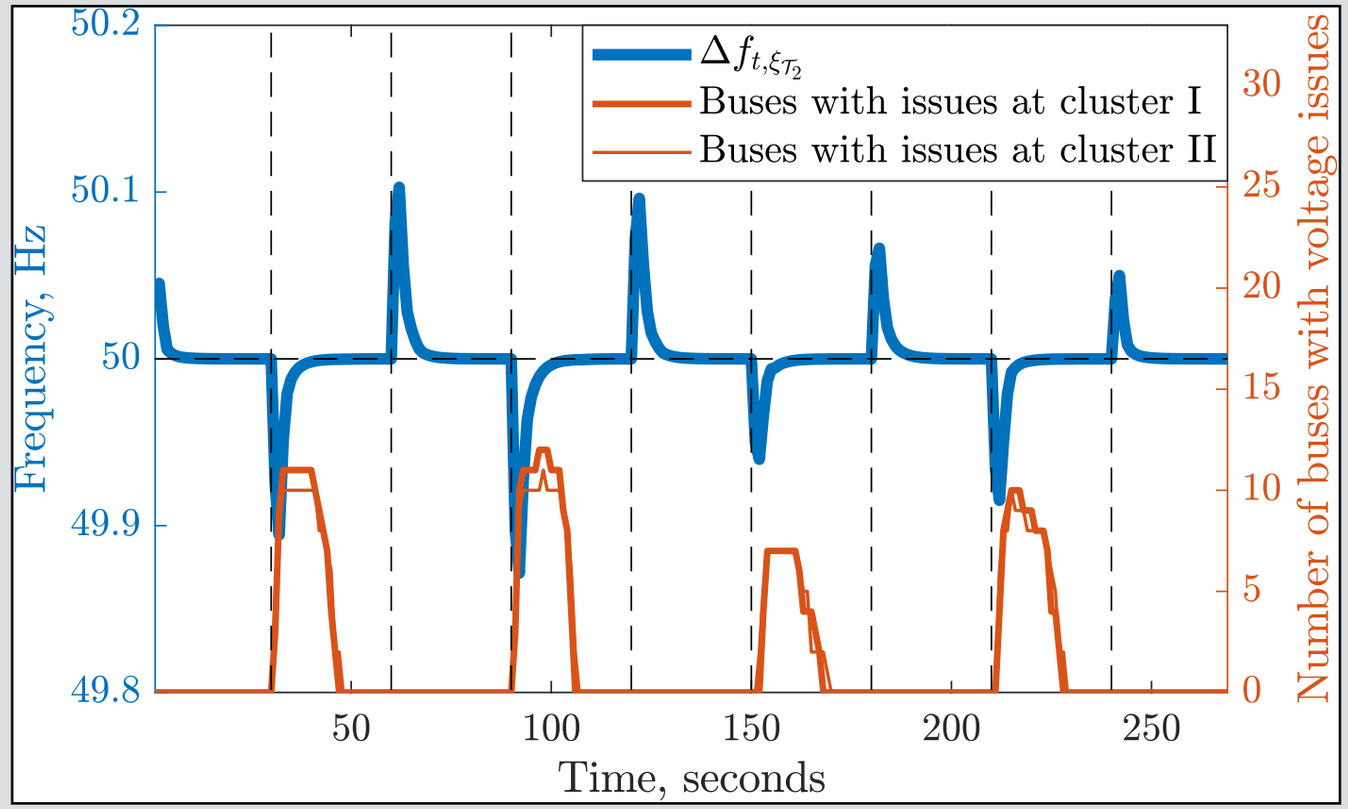
Voltage at the distribution level

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

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

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

Contacts

- Giulia De Zotti (gizo@dtu.dk)
- Seyyed Ali Pourmousavi Kani (a.pour@uq.edu.au)
- Juan Miguel Morales Gonzalez (juan.morales@uma.es)
- Henrik Madsen (hmad@dtu.dk)

Thank you!