Towards Decentralized Models for Day-ahead Scheduling of Energy Resources in Renewable Energy Communities

Louise Sadoine, Martin Hupez, Zacharie De Grève and Thomas Brihaye

UMONS Université de Mons
Faculté des Sciences Département de Mathématique
POLYTECH MONS
PSMR

Presentation Plan

1. Context, challenge & objectives
2. Methodology
   - Centralized No Mutualization
   - Centralized with Mutualization
   - Decentralized No Mutualization
   - Decentralized with Mutualization
3. Case study
4. Conclusion & Next steps

Introduction

Fighting climate change in the spotlight

COP21 pact : limiting temperature increase to 1,5°C and GHG emissions.

→ An energy transition towards decarbonised production is necessary !

→ Significant changes in electric power systems

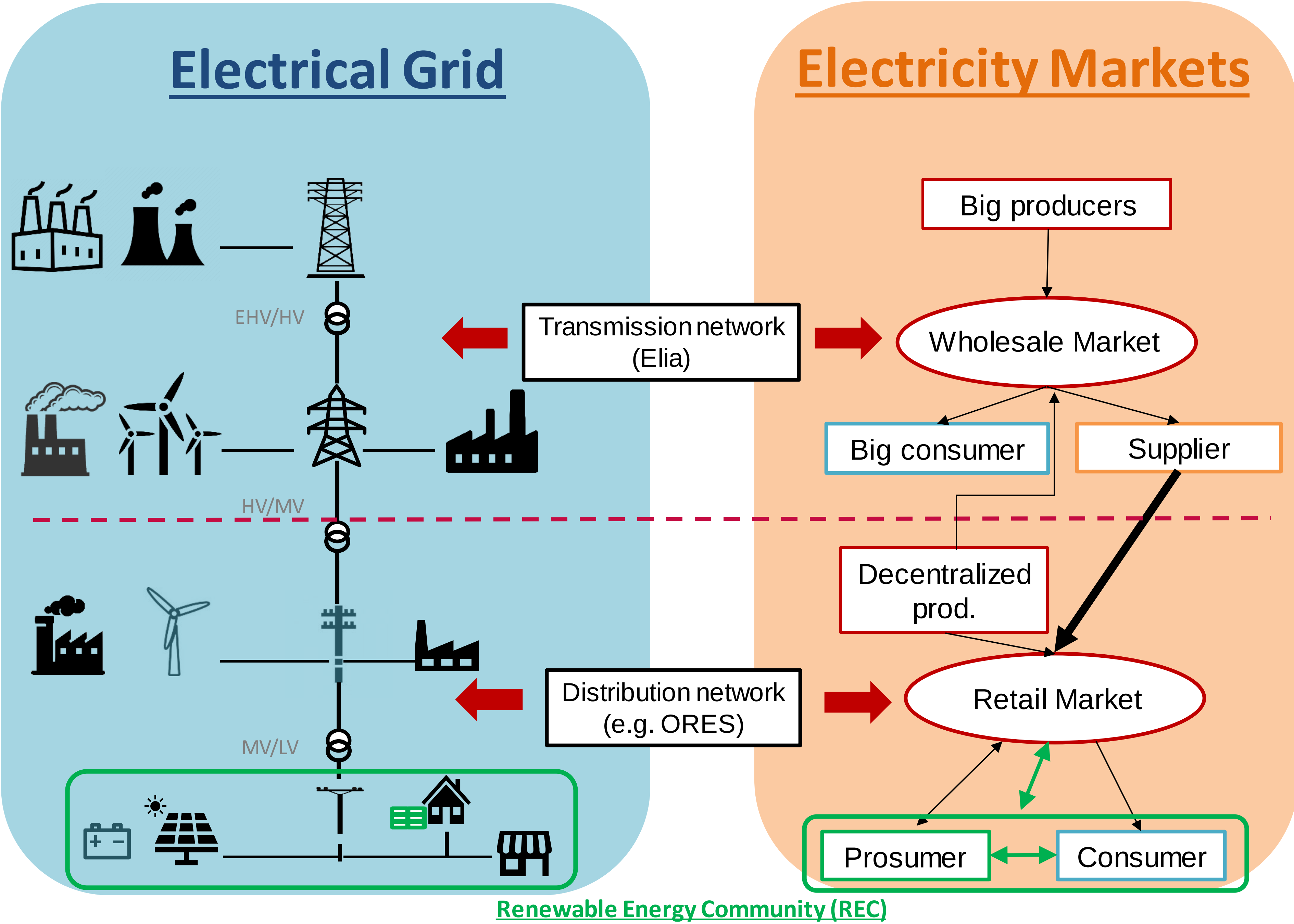
- Development of different renewable energy sources,
- Increased in distributed energy resources in the residential sector, empowering end-users.

Local generation

Flexibility systems

→ Coordination management in distributed systems

Renewable Energy Community


Electrical Grid
Electricity Markets
EHV/HV
HV/MV
MV/LV
Transmission network
(Elia)
Distribution network
(e.g. ORES)
Big producers
Wholesale Market
Big consumer
Supplier
Decentralized
prod.
Retail Market
Prosumer
Consumer
Renewable Energy Community (REC)

Renewable Energy Community

REC

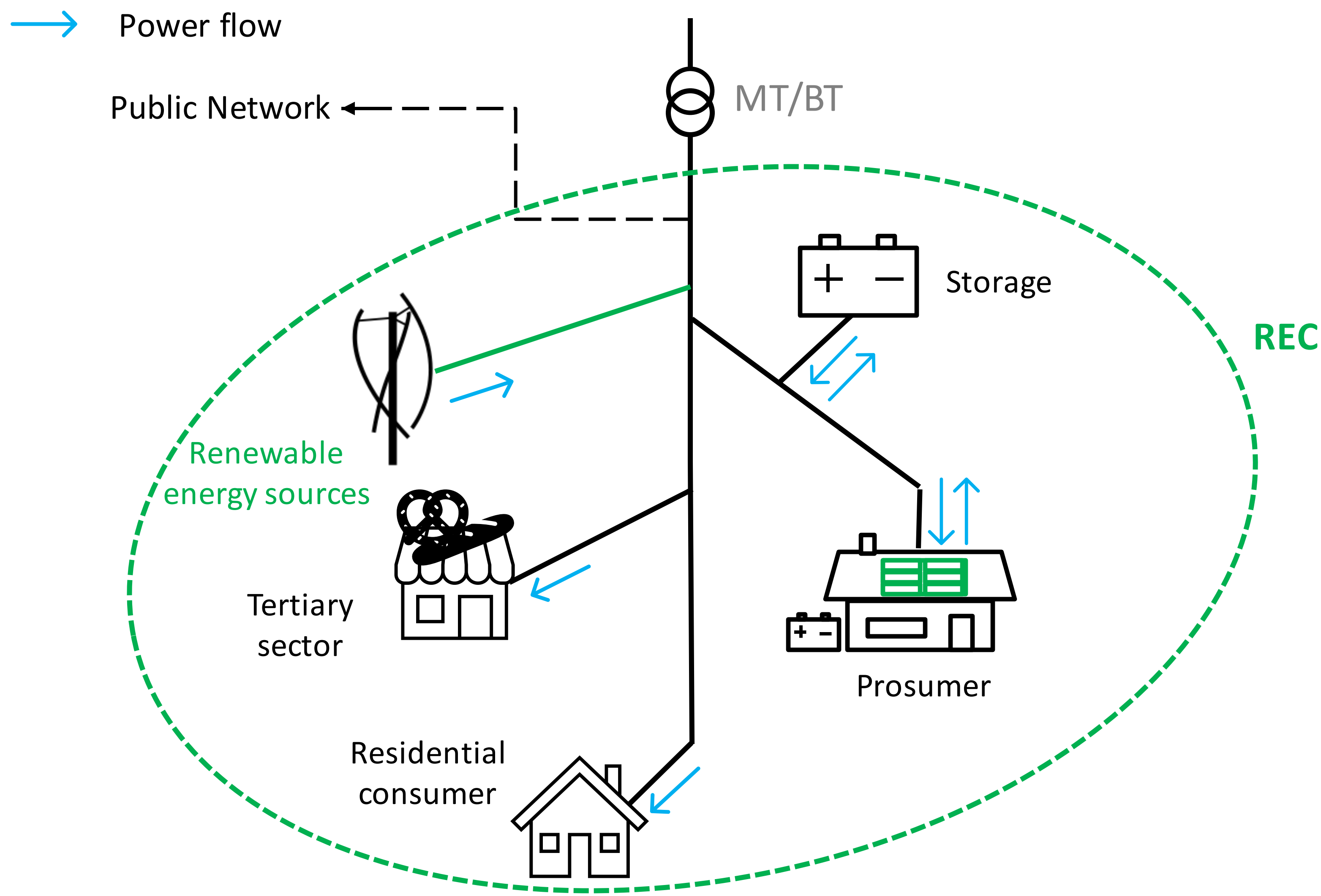
An organized entity of consumers, producers and prosumers (consumer and producer) of electricity :

- Within which exchanges of local renewable electricity production and/or stored electricity can take place,
- Freedom to contract with supplier of choice on the classical markets for consumption not covered locally,
- Possibility of reselling surplus local production on the conventional markets,
- The main purpose of a REC is to provide environmental, economic or social benefits to its members rather than to seek profit.

Why ?

- Responding to the growing desire of the end user to be placed at the center of the electrical energy supply chain,
- Encourage investment in distributed energy resources,
- Encourage the mobilization of flexibility at local level.

Renewable Energy Community

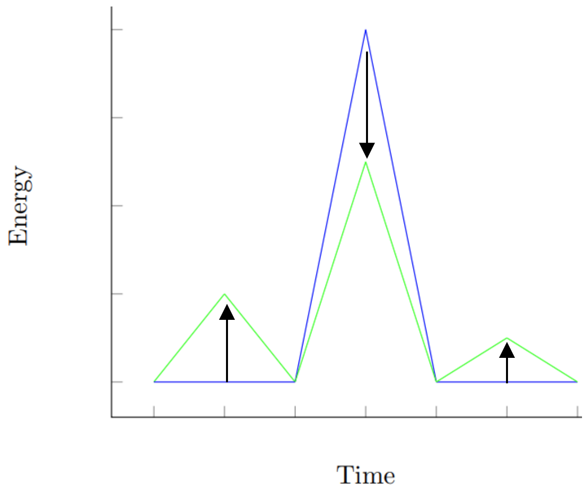


Goal REC	Provide environmental, economic or social benefits

Objectives

➢ The day-ahead scheduling of energy exchanges within a REC

Coordinate members' energy exchanges (consumption and sharing flows) using their temporal flexibility in order to adapt to generation conditions and to optimize commodity and network costs for the next day.



➢ Contributions

Extend the formalism of M. Hupez and al. in [1] and [2] by :

- Modeling the selling of local excess renewable generation to the classical market;
- Assigning a non zero price value to the energy exchanged locally

[1] Hupez, M., Toubeau, J.-F., De Grève, Z. and Vallée, F.: A New Cooperative Framework for a Fair and Cost-Optimal Allocation of Resources within a Low Voltage Electricity Community (2021).
[2] Hupez, M., Toubeau, J.-F., Atzeni, I., De Grève, Z. and Vallée, F.: Pricing Electricity in Residential Communities using Game-Theoretical Billings (under review).

Presentation Plan

1. Context, challenge & objectives

2. Methodology
   - Centralized No Mutualization
   - Centralized with Mutualization
   - Decentralized No Mutualization
   - Decentralized with Mutualization

3. Case Study

4. Conclusion & Next steps

REC Framework

- $\mathcal{N} = \{1, \ldots, N\}$ is the set of community members.
- $\mathcal{T} = \{1, \ldots, T\}$ is a set of optimization intervals for one days, each of duration Δt.

Assumptions

- Energy exchange : Cooperative Approach
- Rational agents
- No storage
- Local production and non-flexible loads are deterministic
- The REC is a « copper plate »
- A single supplier for energy not covered by local production
- Prices over the horizon
  - Price of energy imported from retail market λ^t_{imp} [€/kWh]
  - Price of energy exported to retail market λ^t_{exp} [€/kWh]
  - Cost for the upstream network α [€/kWh^2]
- Objective : to minimize the REC's billing (centralized) / individual electricity bill (decentralized)

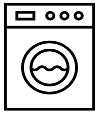
How to model a REC to compare the centralized and decentralized views ?

Prosumer profile

The energy profile of a member n is defined from the following electrical components

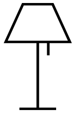
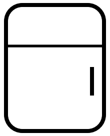
- The flexible consumption is the load for which users consent flexibility in their operation. Each of this appliance $a \in \mathcal{A}_n$ is described by

$$x_{n,a} = (x_{n,a}^1, \dots, x_{n,a}^T), \quad x_{n,a}^t \geqslant 0 \ \forall t \in \mathcal{T}$$

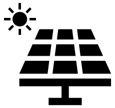
- The vector composed of the non-flexible loads :

$$d_n = (d_n^1, \dots, d_n^T), \quad d_n^t \geqslant 0 \ \forall t \in \mathcal{T}$$

- Local renewable energy production is described by

$$g_n = (g_n^1, \dots, g_n^T), \quad g_n^t \geqslant 0 \ \forall t \in \mathcal{T}$$



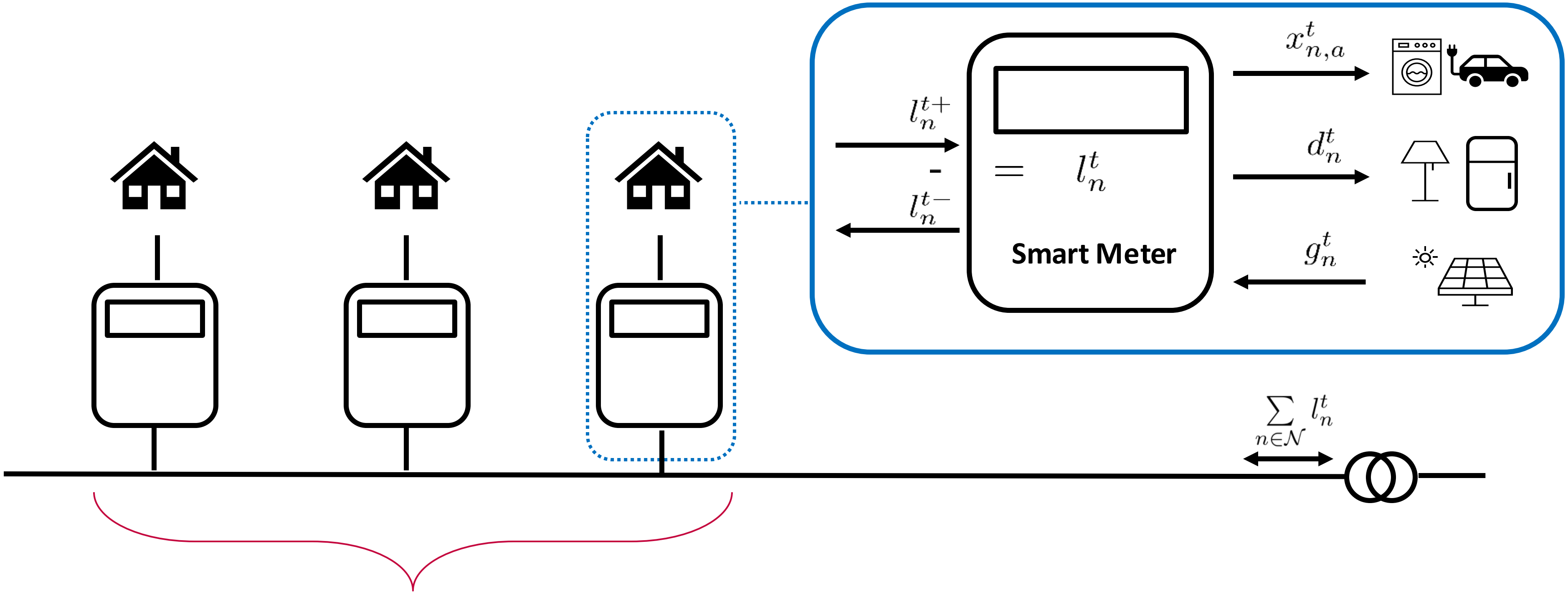

- Net load of the prosumer n is described by

$$l_n^t = \sum_{a \in \mathcal{A}_n} x_{n,a}^t + d_n^t - g_n^t, \quad \forall t \in \mathcal{T}$$

$$l_n^t = l_n^{t+} - l_n^{t-}$$

$$l_n^{t+} = \max(0, l_n^t) \longrightarrow \textbf{Lack}$$
$$l_n^{t-} = \max(0, -l_n^t) \longrightarrow \textbf{Surplus}$$

Model CNM : A « Community »



$$\text{Community bill} = \sum_{n\in\mathcal{N}} \lambda_{imp}^t l_n^{t+} - \sum_{n\in\mathcal{N}} \lambda_{exp}^t l_n^{t-} + \alpha\Big(\sum_{n\in\mathcal{N}} l_n^t\Big)^2$$

Commodity costs | **Revenue from sales** | **Upstream grid costs**

Model CNM : A « Community »

$$\min_{\Theta} \sum_{t=1}^{T} \Big[\sum_{n \in \mathcal{N}} (\lambda^t_{imp}.l^{t+}_n - \lambda^t_{exp}.l^{t-}_n) + \alpha.(\sum_{n \in \mathcal{N}} l^t_n)^2 \Big]$$

$$\text{s.t. Technical constraints of devices}$$

$$l^t_n = \sum_{a \in \mathcal{A}_n} x^t_{n,a} + d^t_n - g^t_n \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$l^t_n = l^{t+}_n - l^{t-}_n \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$0 \leqslant l^{t+}_n \leqslant l^{max}_n \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$0 \leqslant l^{t-}_n \leqslant l^{min}_n \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

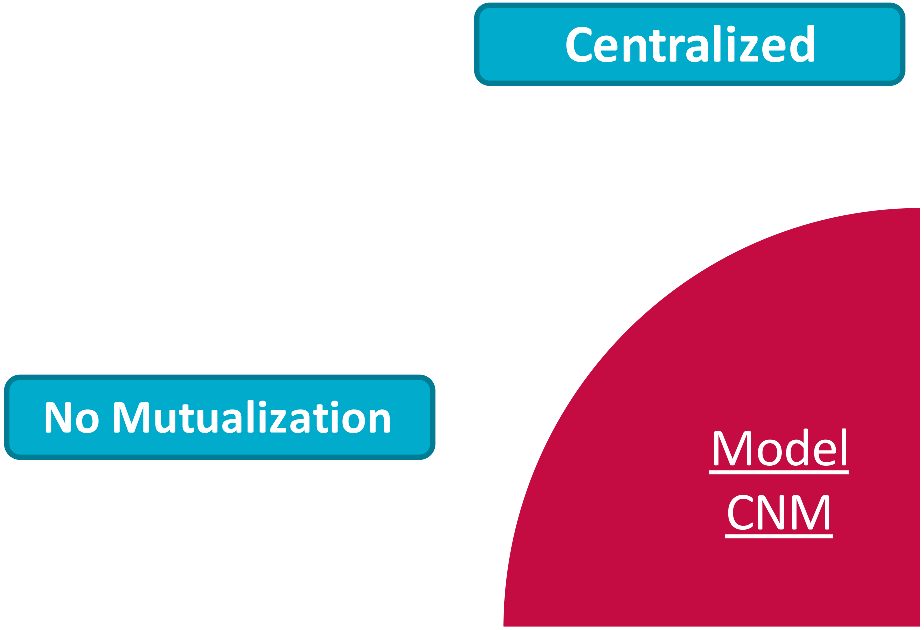
$=: \Omega$ the feasible set

Vector of decision variables
$\Theta := (x_i, l^+_i, l^-_i)^N_{i=1}$

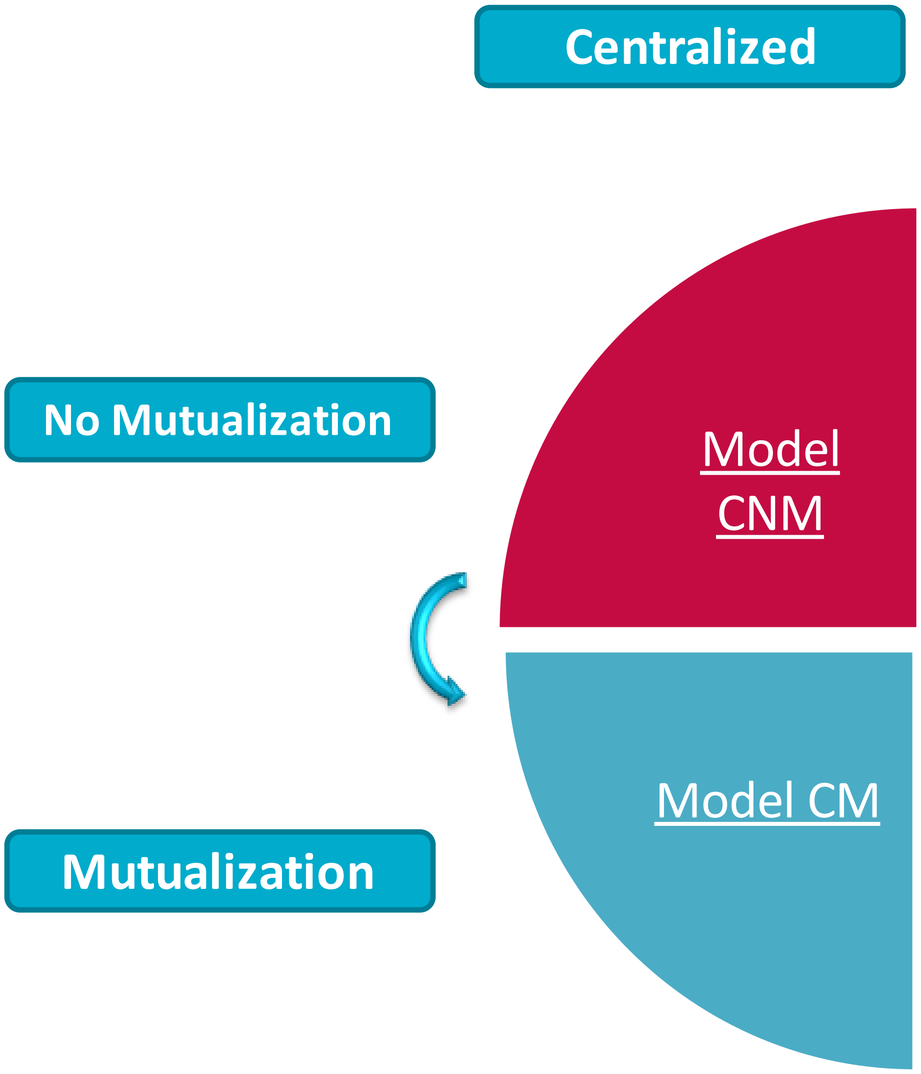
Convex optimization problem

- Quadratic programming
- The objective function is convex and of class C^2
- The feasible set is convex and compact
- All constraints are affine
- Standard algorithms

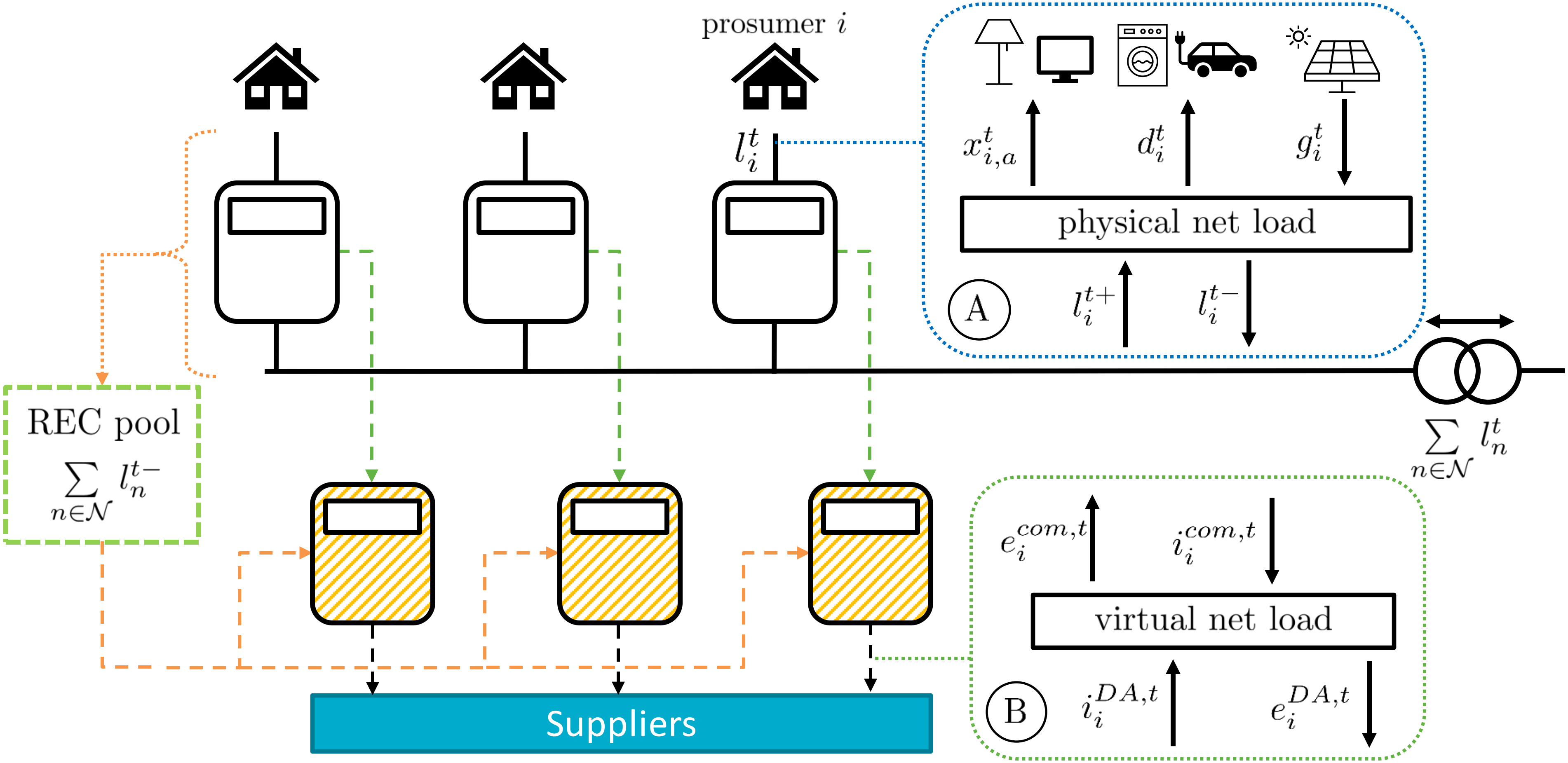
Model Centralized No Mutualization



Mutualization of excess resources



Model CM : Mutualization



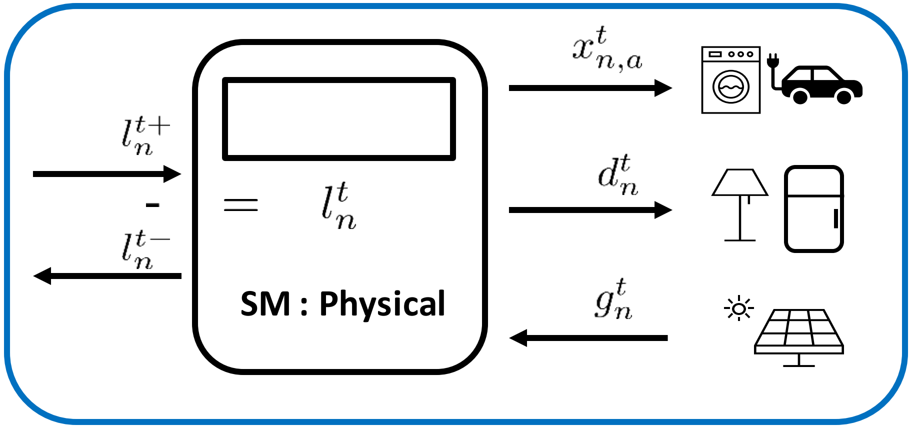
Energy exchange in CM model

Physical electrical flows

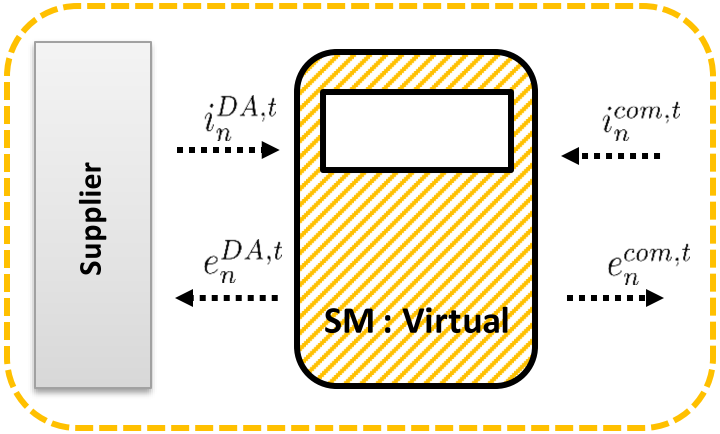
$$l_n^t = \sum_{a \in \mathcal{A}_n} x_{n,a}^t + d_n^t - g_n^t, \quad \forall t \in \mathcal{T}$$

$l_n^{t+} = \max(0, l_n^t)$ → **Net consumption**

$l_n^{t-} = \max(0, -l_n^t)$ → **Net production**



Virtual electrical flows



- Local energy imported from the REC pool : $i_n^{com,t}, \ \forall t \in \mathcal{T}$
- Local energy exported to the REC pool : $e_n^{com,t}, \ \forall t \in \mathcal{T}$
- Energy imported from the retail market : $i_n^{DA,t}, \ \forall t \in \mathcal{T}$
- Local energy exported to the retail market : $e_n^{DA,t}, \ \forall t \in \mathcal{T}$

$$l_n^{t+} = i_n^{com,t} + i_n^{DA,t}$$
$$l_n^{t-} = e_n^{com,t} + e^{DA,t}$$

Model CM

$$\min_{\Theta} \sum_{t=1}^{T} \Big[\sum_{n\in\mathcal{N}} (\lambda^t_{imp}.i^{DA,t}_n + \lambda^t_{iloc}.i^{com,t}_n - \lambda^t_{eloc}.e^{com,t}_n - \lambda^t_{exp}.e^{DA,t}_n) + \alpha.(\sum_{n\in\mathcal{N}} l^t_n)^2 \Big]$$

s.t. Technical constraints of the devices

Net load's constraints

$$i^{com,t}_n \leqslant l^{t+}_n \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$e^{com,t}_n \leqslant l^{t-}_n \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$\sum_{n\in\mathcal{N}} i^{com,t}_n \leqslant \sum_{n\in\mathcal{N}} l^{t-}_n \quad \forall t \in \mathcal{T}$$

$$\sum_{n\in\mathcal{N}} i^{com,t}_n = \sum_{n\in\mathcal{N}} e^{com,t} \quad \forall t \in \mathcal{T}$$

$$i^{DA,t}_n = l^{t+}_n - i^{com,t} \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$e^{DA,t}_n = l^{t-}_n - e^{com,t} \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$i^{com,t}_n, e^{com,t}_n, i^{DA,t}_n, e^{DA,t} \geqslant 0 \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

Vector of decision variables

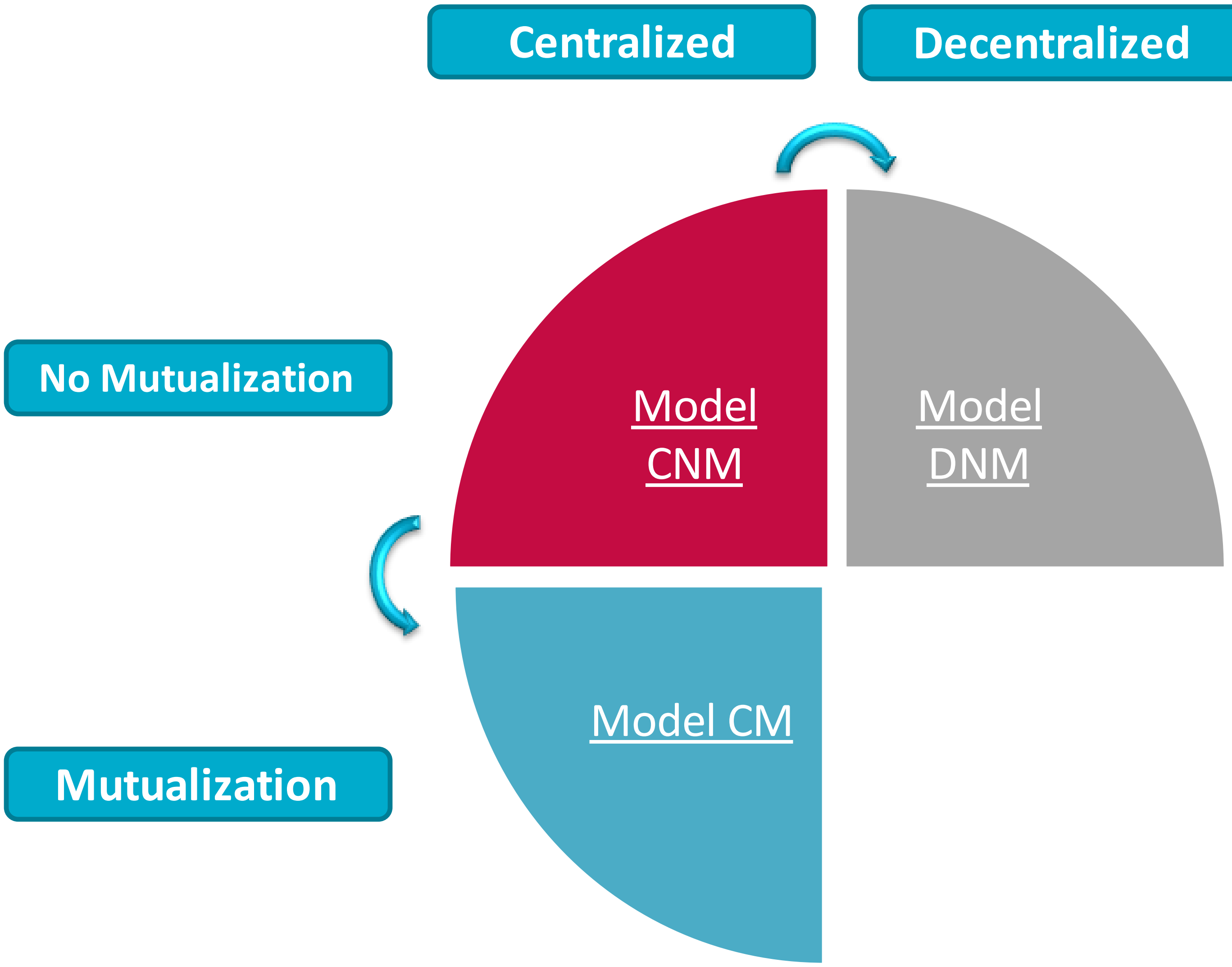
$$\Theta := (x_i, l^+_i, l^-_i, i^{com}_i, e^{com}_i, i^{DA}_i, e^{DA}_i)^N_{i=1}$$

- Price of energy imported from REC λ^t_{iloc} [€/kWh]
- Price of energy exported to REC λ^t_{eloc} [€/kWh]

Convex optimization problem

- Quadratic programming
- Convex objective function and of class C^2
- The feasible set is convex and compact
- All constraints are affine
- Standard algorithms

Towards a decentralized system



Model DNM

Cost allocation

- Continuous proportional billing
- Net load proportional billing
- Marginal cost billing (VCG)

User i

Vector of i's decision variables

$\Theta_i := (x_i, l_i^+, l_i^-)$

$$\min_{\Theta_i} \; b_i(\Theta_i, \Theta_{-i})$$

$$\left.\begin{aligned} \text{s.t. } & \text{Technical constraints of } i\text{'s devices} \\ & l_i^t = \sum_{a \in \mathcal{A}_i} x_{i,a}^t + d_i^t - g_i^t \quad \forall t \in \mathcal{T} \\ & l_i^t = l_i^{t+} - l_i^{t-} \quad \forall t \in \mathcal{T} \\ & 0 \leqslant l_i^{t+} \leqslant l_i^{max} \quad \forall t \in \mathcal{T} \\ & 0 \leqslant l_i^{t-} \leqslant l_i^{min} \quad \forall t \in \mathcal{T} \end{aligned}\right\} =: \Omega_i$$

Nash Equilibrium Problem (NEP)

- Players: $\mathcal{N} = \{1, \ldots, N\}$
- Strategies : $\Theta \in \Omega = \prod_{i \in \mathcal{N}} \Omega_i$
- Player i's bill given the rivals' strategies Θ_{-i} : $b_i(\Theta_i, \Theta_{-i})$

A strategy profile $\Theta^* \in \Omega$ is a Nash equilibrium or simply a NEP solution, if for any $i \in \mathcal{N}$:

$$b_i(\Theta_i^*, \Theta_{-i}^*) \leqslant b_i(\Theta_i, \Theta_{-i}^*) \quad \forall \Theta_i \in \Omega_i$$

Model DNM

Agent 1

$$\min_{\Theta_1} b_1(\Theta_1, \Theta_{-1})$$
$$\text{s.t. } \Theta_1 \in \Omega_1$$

...

Agent N

$$\min_{\Theta_N} b_N(\Theta_N, \Theta_{-N})$$
$$\text{s.t. } \Theta_N \in \Omega_N$$

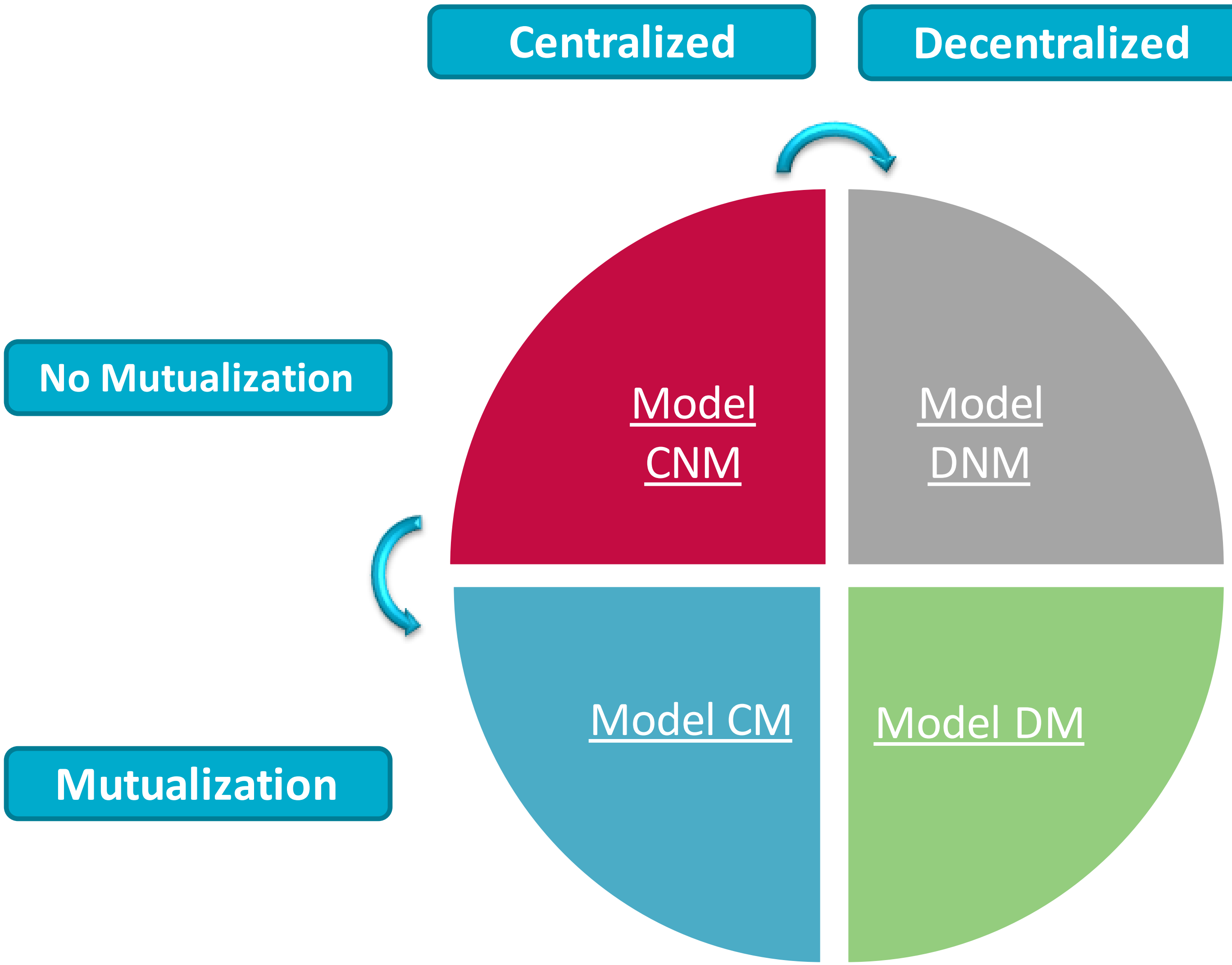
Community bill

$$\sum_{i \in \mathcal{N}} b_i(\Theta_i^*, \Theta_{-i}^*)$$

- All N optimization problems are linked, and should be solved all together
- Variational inequalities Theory
- Distributed algorithms (e.g., Proximal Decomposition Algorithm [3])

[3] Scutari, G., Facchinei, F., Pang, J.-S. and Palomar, D. P.: Real and Complex Monotone Communication Games (2014)

Towards a decentralized system



Model DM

User i

$$\min_{\Theta_i} b_i(\Theta_i, \Theta_{-i})$$

s.t. i's individual constraints

$$\sum_{n\in\mathcal{N}} i_n^{com,t} \leqslant \sum_{n\in\mathcal{N}} l_n^{t-} \quad \forall t \in \mathcal{T}$$

$$\sum_{n\in\mathcal{N}} i_n^{com,t} = \sum_{n\in\mathcal{N}} e^{com,t} \quad \forall t \in \mathcal{T}$$

$=: \Omega_i(\Theta_{-i})$

Shared constraints

Cost allocation

- Continuous proportional billing
- Two keys
- Marginal cost billing (VCG)

Vector of i's decision variables

$$\Theta_i := (x_i, l_i^+, l_i^-, i_i^{com}, e_i^{com}, i_i^{DA}, e_i^{DA})$$

Generalized Nash Equilibrium Problem (GNEP)

- Players: $\mathcal{N} = \{1, \ldots, N\}$
- Player i's strategy set can depend on the rivals' strategies $\Theta_{-i} : \Omega_i(\Theta_{-i})$.
- Player i's bill given the rivals' strategies $\Theta_{-i} : b_i(\Theta_i, \Theta_{-i})$

A strategy profile $\Theta^* \in \Omega$ is a generalized Nash equilibrium or simply a GNEP solution, if for any $i \in \mathcal{N}$:

$$b_i(\Theta_i^*, \Theta_{-i}^*) \leqslant b_i(\Theta_i, \Theta_{-i}^*) \quad \forall \Theta_i \in \Omega_i(\Theta_{-i}^*)$$

Model DM

Agent 1

$$\min_{\Theta_1} b_1(\Theta_1, \Theta_{-1})$$
$$\text{s.t.} \;\; \Theta_1 \in \Omega_1(\Theta_{-1})$$

...

Agent N

$$\min_{\Theta_N} b_N(\Theta_N, \Theta_{-N})$$
$$\text{s.t.} \;\; \Theta_N \in \Omega_N(\Theta_{-N})$$

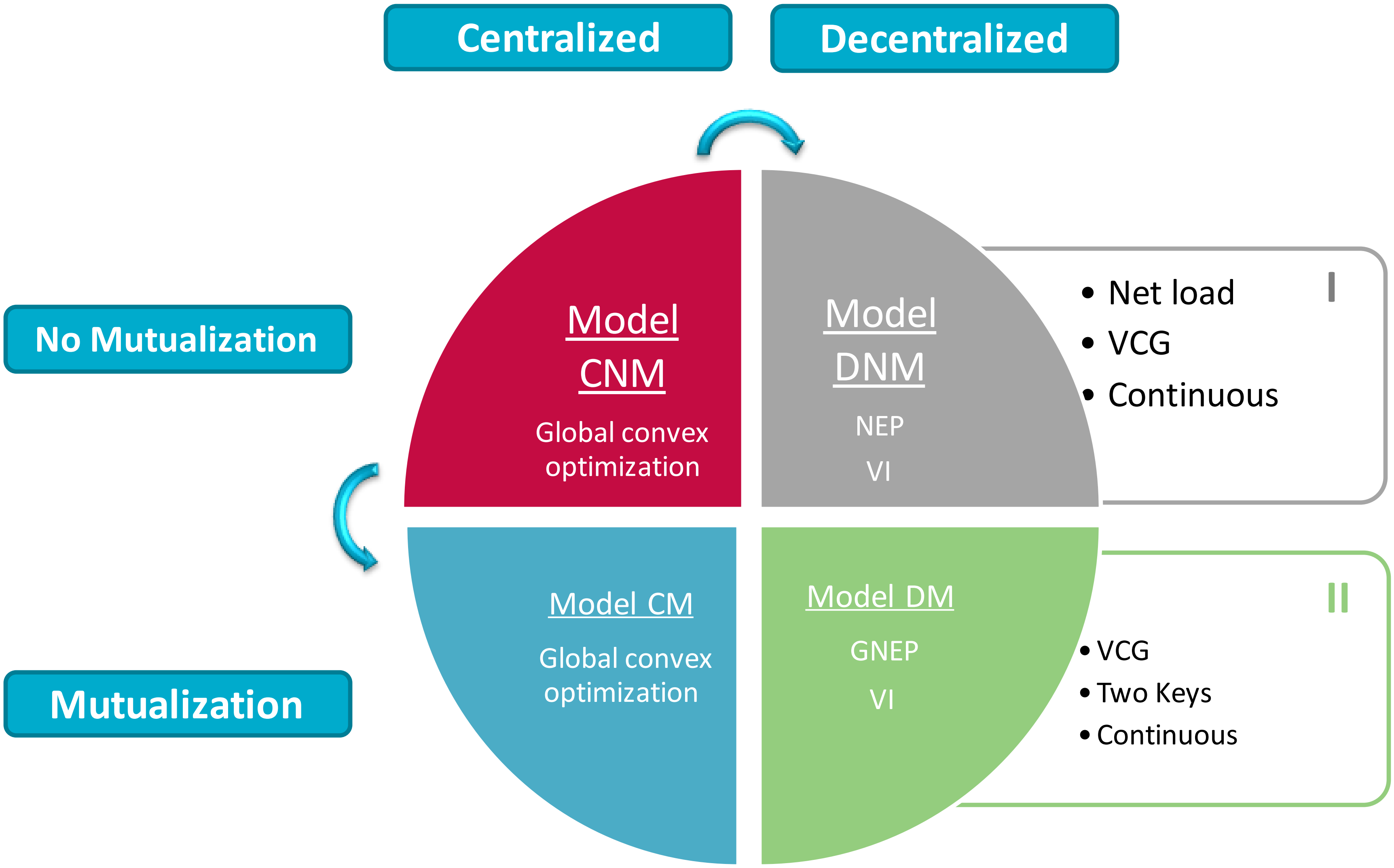
Community bill

$$\sum_{i \in \mathcal{N}} b_i(\Theta_i^*, \Theta_{-i}^*)$$

- All N optimization problems are linked, and should be solved all together
- The variability of the strategy sets makes GNEPs more complicated to solve than NEPs.
- Variational inequalities Theory
- Distributed algorithms (e.g., PDA with shared constraints [3])

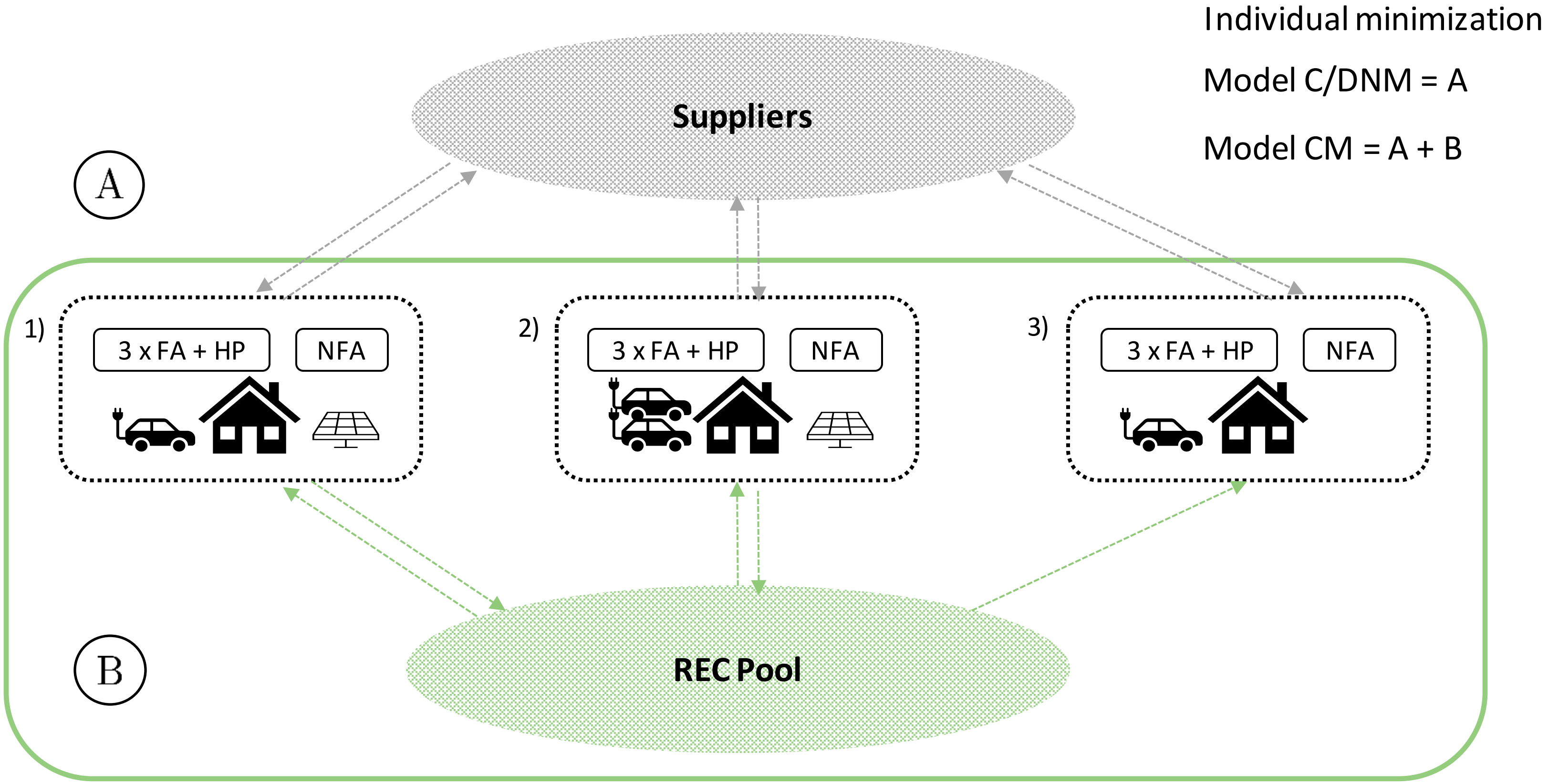
[3] Scutari, G., Facchinei, F., Pang, J.-S. and Palomar, D. P.: Real and Complex Monotone Communication Games (2014)

Summary


Centralized
Decentralized
No Mutualization
Mutualization
Model CNM
Global convex optimization
Model DNM
NEP
VI
Model CM
Global convex optimization
Model DM
GNEP
VI
I
• Net load
• VCG
• Continuous
II
• VCG
• Two Keys
• Continuous

Presentation Plan

Case study



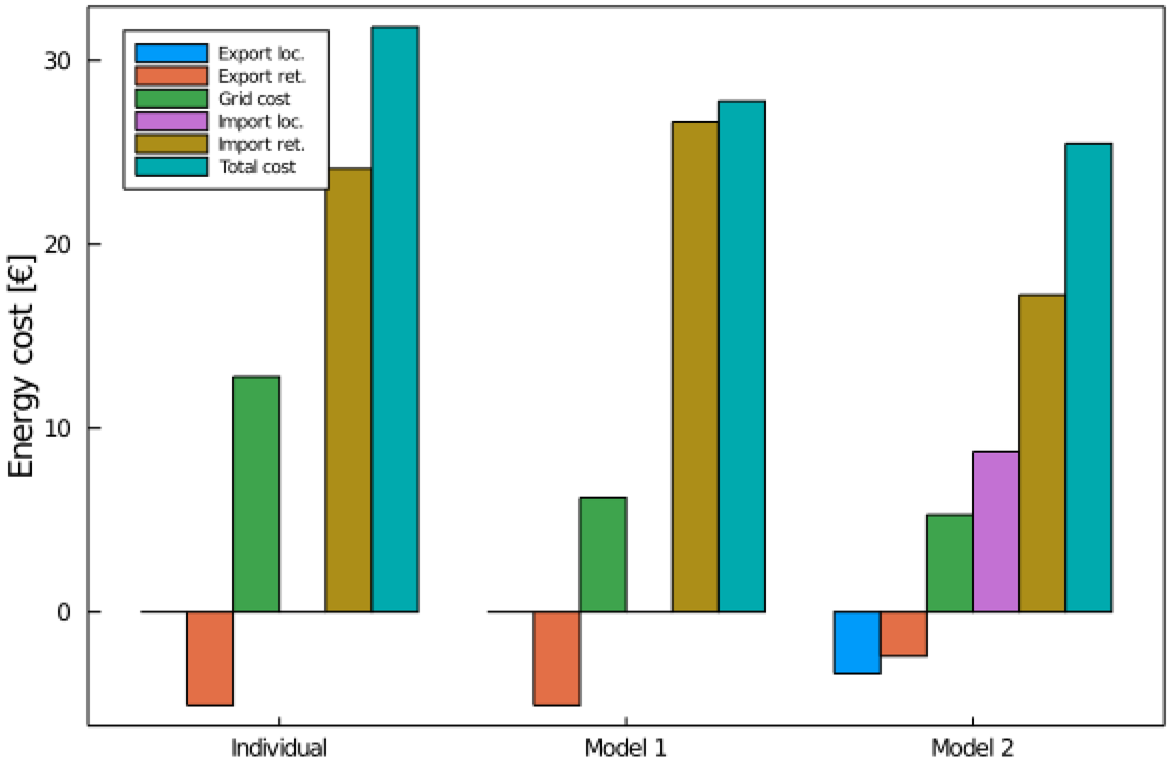
	5h-20h	21h-4h	
Import DA	0,16	0,08	[€/kWh]
Export DA	0,04	0,02	[€/kWh]
Import local	0,13	0,065	[€/kWh]
Export local	0,05	0,032	[€/kWh]
Grid	0,00109488 [€/kWh^2]		

- 2 prosumers and 1 consumer
- 24 times steps
- Implemention on JuliaPro with JuMP library and the Gurobi solver

Devices	Min P [kW]	Max P [kW]	Total E [kWh]	Quantity
Electric car	0	20	30	4
Heat pump	0	8	70	3
Flexible appliance	0	5	5	9

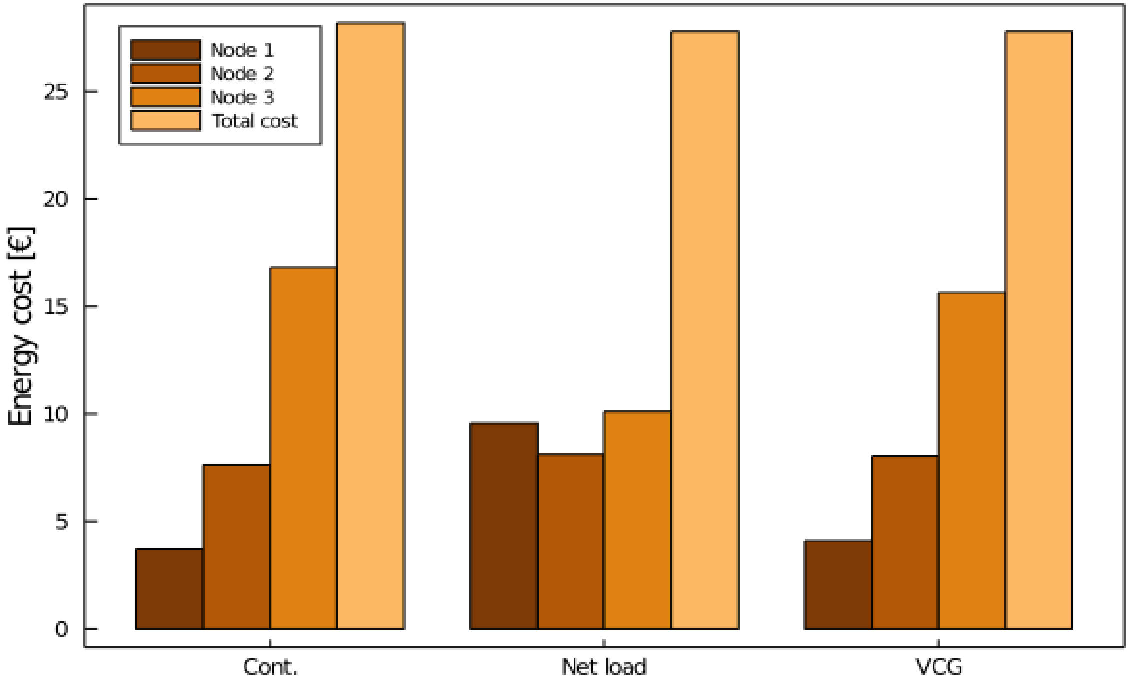
[4] Pecan Street Inc. (2020) Residential data New York 15 min.

Promoting cooperation and sharing



	Export local	Export retail	Grid cost	Import local	Import retail	Total cost	PAR
Individual	0 €	-5,087 €	12,793 €	0 €	24,116 €	**31,822 €**	5,608
Model 1 : CNM	0 €	-5,086 €	6,212 €	0 €	26,655 €	**27,781 €**	2,218
Model 2 : CM	-3,535 €	-2,404 €	5,278 €	8,717 €	17,235 €	**25,473 €**	2,033

Cost allocation in DNM



	User 1 Bill	User 2 Bill	User 3 Bill	Social cost
Continuous	3,731 €	7,632 €	16,81 €	**28,173 €**
Net load	9,569 €	8,109 €	10,103 €	**27,781 €**
VCG	4,1 €	8,042 €	15,639 €	**27,781 €**

Continuous:
- Some inefficiency
- Negotiation power
- Flexibility is higher incentivized

Net load:
- Egalitarian
- Efficient
- Strategy proofness
- Flexibility is poorly incentivized

VCG:
- Efficient
- Strategy proofness
- Flexibility is more or less incentivized

Presentation Plan

1. Context, challenge & objectives
2. Methodology
   - Centralized No Mutualization
   - Centralized with Mutualization
   - Decentralized No Mutualization
   - Decentralized with Mutualization
3. Case study
4. Conclusion & Next steps

Conclusion & Next steps

- Two market design for the day-ahead scheduling of energy resources in RECs based on a cooperative framework.
  i. Global optimization problem
  ii. (Generalized) Nash equilibrium problem with different billing methods.

- Determine adequate parameters to apply the algorithm to our GNEP. Characterization of GNEs.
- The continuous proportional billing provides more space for strategy. Interesting to see with heterogeneous preferences or non-rationality of prosumers.
- Incorporating storage systems and their mutualization could help to further reduce import and upstream grid costs.
- Incorporating uncertainty of renewable production and non-flexible consumption.

Thank you
Danke

Typology of community model

No mutualization (NM)

- Cooperative demand management scheme
- Local production surplus exported on the retail market

Mutualization (M)

- **Allow** mutualization of excess resources among members
- Local production **can be** exported on the retail market

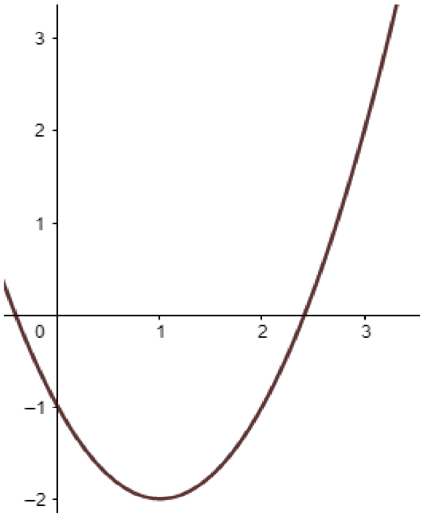
Centralized model (C)

- 1 Optimization
- Convex optimization
- Optimal but idealistic resolution
- REC's billing

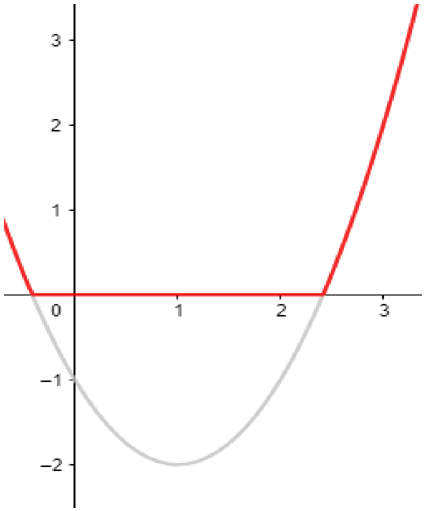
Decentralized model (D)

- N-Optimizations
- Non-cooperative game
- More realistic
- Individual electricity bill
- Privacy

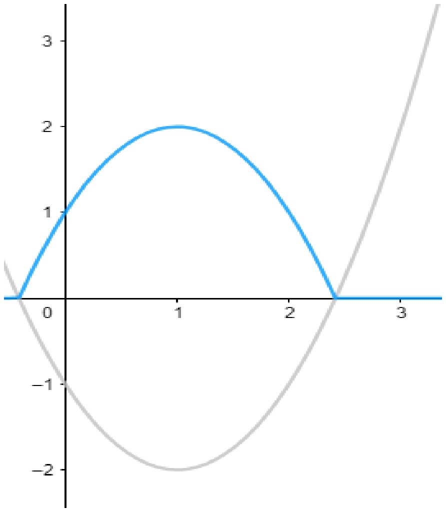
$$l_n^t$$



$$l_n^{t+} = \max(0, l_n^t)$$

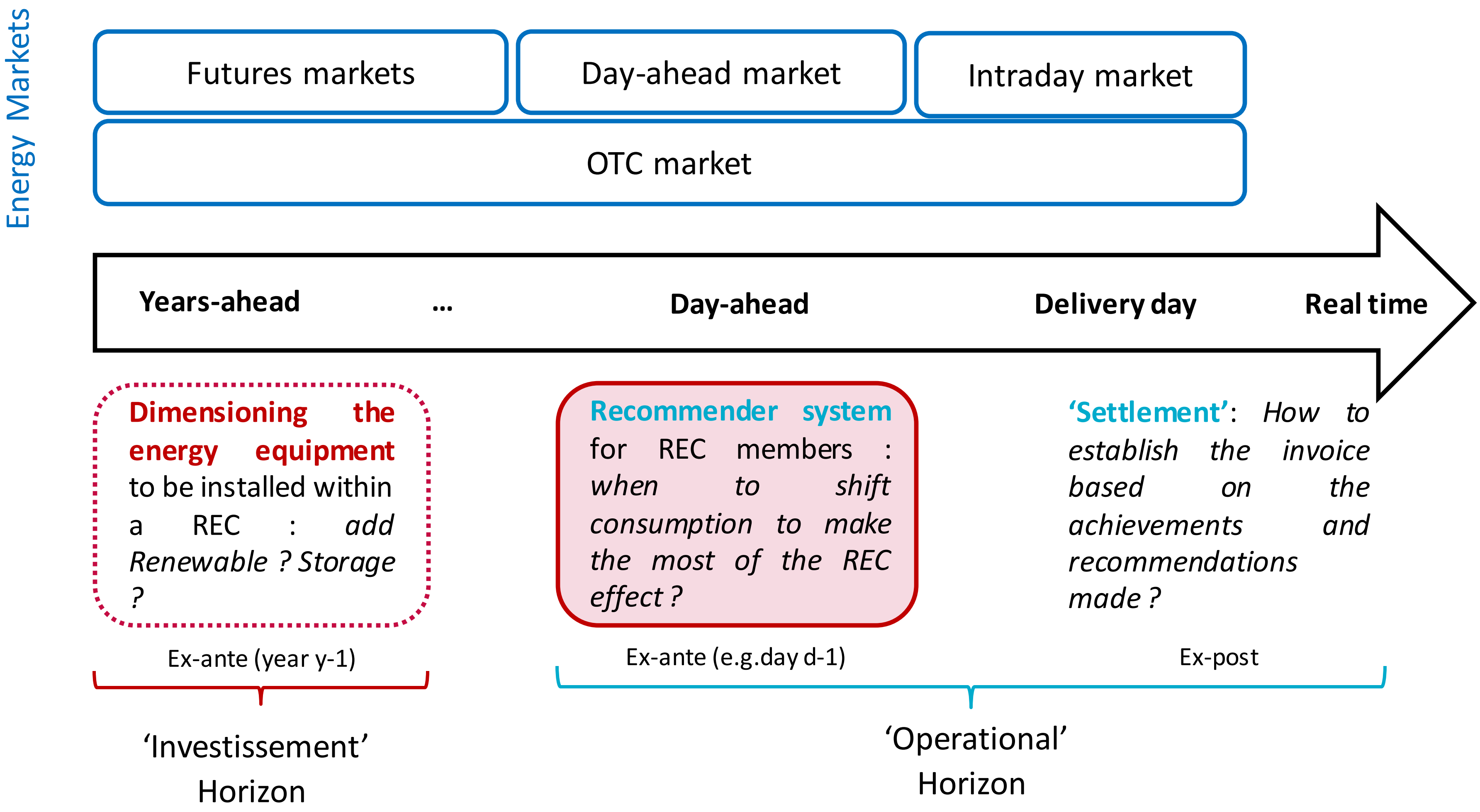


$$l_n^{t-} = \max(0, -l_n^t)$$



$$l_n^t = l_n^{t+} - l_n^{t-}$$
$$|l_n^t| = l_n^{t+} + l_n^{t-}$$

RECs modeling



Towards a decentralized system

Centralized (1 Optimization)

Decentralized (N-Optimizations)

Daily Billing		Continuous Billing
Net	**VCG**	**Continuous Variant**
• Efficiency • Strategy proofness • Privacy	• Efficiency • Favors real flexibility • Strategy proofness • Budget balanced	• Favors real flexibility • Empowerment • Privacy
$\frac{\sum_{t\in\mathcal{T}} \lvert l_i^t\rvert}{\sum\limits_{t\in\mathcal{T}}\sum\limits_{j\in\mathcal{N}} \lvert l_j^t\rvert} f(\Theta)$	$\frac{C^*_{\mathcal{N}} - C^*_{\mathcal{N}\setminus i}}{\sum\limits_{j\in\mathcal{N}} (C^*_{\mathcal{N}} - C^*_{\mathcal{N}\setminus j})} f(\Theta)$	$\sum\limits_{t\in\mathcal{T}} [\lambda_{imp} l_i^{t+} - \lambda_{exp} l_i^{t-} + \alpha . l_i^t . (l_i^t + L_{-i})]$

Towards a mutualization of energy

No mutualization

↓

Mutualization of surplus production

N -Optimizations problems

↓

Decentralized

Daily Billing		Continuous Billing
VCG	Two key • Commodity cost • Grid cost	Continuous variant