Community-based & peer-2-peer electricity markets

Recent proposals and developments

Pierre Pinson

(& T. Baroche, L. Bobo, F. Moret, E. Sorin, etc.)

31761 - Lecture 12, 7 May 2018

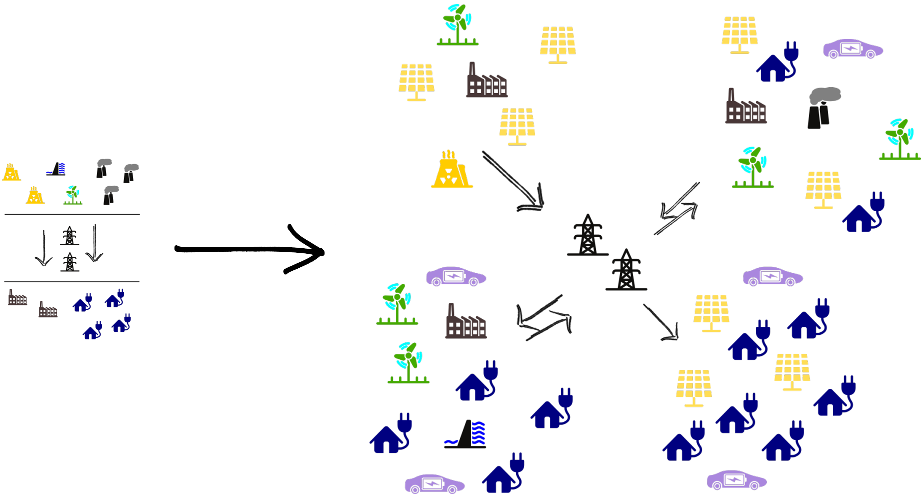
Technical University of Denmark
Centre for Electric Power and Energy
[mail: ppin@dtu.dk - webpage: www.pierrepinson.com]
Supported by "The Energy Collective" project (ForskEL 2016, 2016-1-12530)

Outline

- **A broad-audience (and short) introduction**
- **The energy collective approach**
  - Defining an energy collective
  - General exchange problem
  - Distributed optimization based approach
- **Towards full peer-to-peer electricity markets**
  - Multi-Bilateral Economic Dispatch (MBED)
  - Allowing for product differentiation
  - Consensus-based optimization
- **Re-designing network charges in a peer-to-peer market environment**
  - From uniform to differentiated network charges
  - Augmented MBED problem
  - Example application results
- **Outlook**

1. **A broad audience introduction**

From a supplier-centric model to a more decentralized setup



Eventually, electricity markets need to adapt to this new decentralized setup(!)

P. Pinson *et al.* (2017). The emergence of consumer-centric electricity markets. Available online (pdf)

Organization of consumer-centric electricity markets

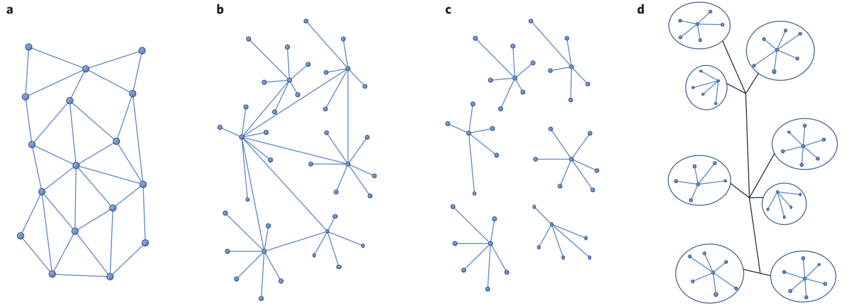


Figure 1 | Structural attributes of three prosumer markets. a, Peer-to-peer model, in which prosumers interconnect directly with each other, buying and selling energy services. **b**,**c**, More structured models involving prosumers connected to microgrids. These entail prosumer-to-interconnected microgrids, in which prosumers provide services to a microgrid that is connected to a larger grid (**b**), or prosumer-to-islanded microgrids, in which prosumers provide services to an independent, standalone microgrid (**c**). **d**, Organized prosumer group model, in which a group of prosumers pools resources or forms a virtual power plant. Dots represent prosuming agents; lines represent a transaction of prosuming service; circles represent an organized group of prosumers.

[Reproduced, with authorization, from:
Parag Y, Sovacool BJ. Electricity market design in the prosumer era. *Nature Energy* **1**, art. no. 16032, 2016]

For real (hopefully) in Denmark

[*Svalin* - a boffællesskab in Roskilde - The Energy Collective]

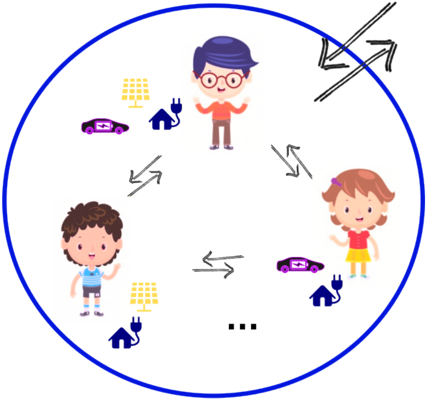
[*Nordhavn* (?) - generalizing to multi-carrier energy markets (heat and electricity, mainly)]

[*Bornholm* (?) - building on the success of the EcoGrid market and demand response experiment]

2. **The energy collective approach**

F. Moret, P. Pinson (2018). Energy Collectives: a community and fairness based approach to future electricity markets. *IEEE Transactions on Power Systems*, available online (pdf)

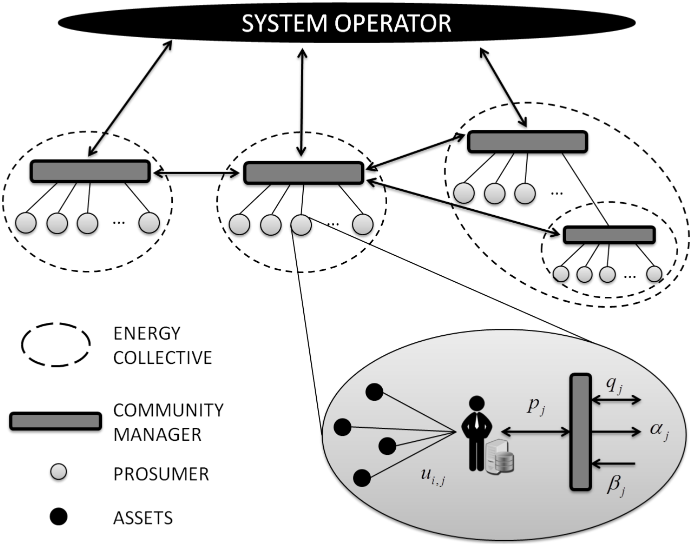
Introducing 'Energy Collectives'



[Characters designed by freepik.com]

- Lucien, Thomas, Etienne and Fabio, chose to gather in an **Energy Collective**
- They traditionally bought energy from the grid and sold their production back at a disadvantageous rate...
- Now, they work at optimally matching their production and consumption and decide on how to share costs and benefits from import/export
- Exchanges within the community do not have to be settled against monetary transactions, but e.g., against a service or simply for free (social capital
- They may also provide grid services as a community, e.g., peak shaving

Organization



Problem formulation

- Let us consider a simplified setup for our energy collective:
  - a set of generators, $j = 1, \ldots, m$ (for instance, prosumers with extra solar power generation and micro-CHPs), with generation p_j
  - a set of consumers or prosumers needing additional electric energy, $i = 1, \ldots, n$, with consumption c_i
- For a given market time unit, the optimal community dispatch is the solution of a **general exchange problem**, i.e.,

$$
\begin{aligned}
\min_{p_j, c_i} \quad & \sum_{j=1}^{m} f_j^p(p_j) - \sum_{i=1}^{n} f_i^c(c_i) - g(q_{\text{ext}}, \theta) && (1) \\
\text{s.t.} \quad & \sum_{i=1}^{n} c_i + q_{\text{ext}} - \sum_{j=1}^{m} p_j = 0 && (2) \\
& \underline{P_j} \leq p_j \leq \overline{P_j} \qquad j = 1, \ldots, m && (3) \\
& \underline{C_i} \leq c_i \leq \overline{C_i} \qquad i = 1, \ldots, n && (4) \\
& && (5)
\end{aligned}
$$

where
  - f_j^p and f_i^c are the cost functions of generators and consumers, respectively
  - q_{ext} is the import (or export) of energy for the community as a whole, with "perceived" cost $g(q_{\text{ext}}, \theta)$
- Note that this could be written with all players being prosumers (and with storage)

Costs functions of the various players

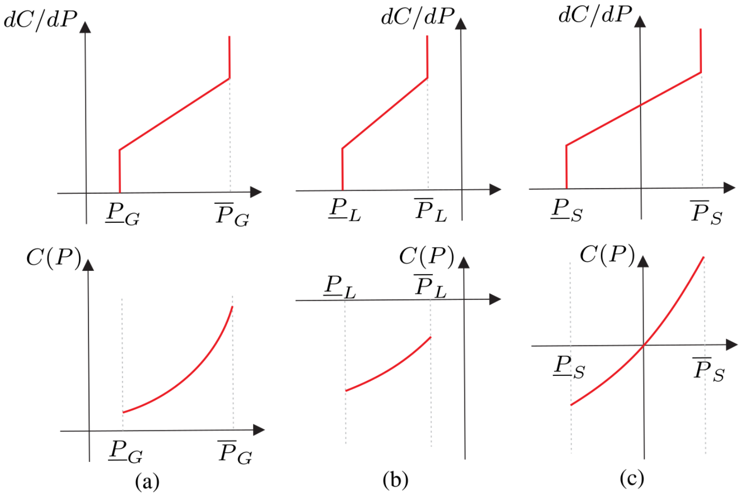


Fig. 1. Marginal cost functions dC/dP and cost functions C for (a) generator, (b) load, and (c) storage.

[taken from Hug et al. (2015)]

The interest of $g(q_{\text{ext}}, \theta)$

- $g(q_{\text{ext}}, \theta)$ result from a common agreement on how the energy collective aims at sharing costs and revenues related to import/export, and more generally the interface with the "outside" world

- Natural choices:
  - in the most simple **market-driven case**,

    $$g(q_{\text{ext}}, \theta) = \lambda_{\text{ext}} q_{\text{ext}}$$

    where λ_{ext} is the wholesale market price

  - in case the community wanted to be **as autonomous as possible**, one would naturally have

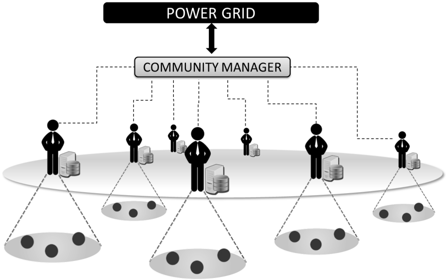
    $$g(q_{\text{ext}}) = ||q_{\text{ext}}||_l$$

    with $l = 1, 2$

  - $g(q_{\text{ext}}, \theta)$ could be augmented to **reflect grid-related costs**, to **provide grid services** (e.g., peak shaving), to **"punish" max importer**, etc.

- Considering the market setup, $g(q_{\text{ext}}, \theta)$ is to be eventually shared among the $n + m$ players. A fairness analysis is then in order...

Players are to solve their own problems



- Each player solves his own problem (though coordinated)
- Distributed optimization e.g. Alternating Direction Method of Multipliers (ADMM) is readily applicable, by iterating on
  - each player solving their individual problem (x-update),
  - a coordination node[1] ("community manager") gathering individual outcomes and updating prices (z-update)

- The coordination of community agents may allocate import costs (/export revenues) following various principles, e.g. equal share, proportional sharing, min-max protocol (L_∞ penalization), etc.
- Energy collective members **implicitly exchange energy...** while also contributing to import/export

[1] The coordination node may be removed by using e.g. Consensus ADMM

Application example

Player setup and data:

- 1 year operation
- 15 out of 300 prosumers (non-flexible/flexible consumers and PV generation) from Ausgrid dataset[2]
- Australian wholesale electricity prices and 6 extra conventional generators for backup power

Approaches:

- Benchmark, **Business As Usual** (individual trading)
  - direct trading of the prosumers in the wholesale market
  - optimized generation or load depending on the (local) PV production
- **Community-based management** with various strategies of cost/revenue allocation
  - market-based
  - autonomy
  - min-max import share
  - peak-shaving
  - geographical preferences (to be discussed later...)

[2] Ratnam *et al.*, "Residential load and rooftop PV generation: an Australian distribution network dataset", *International Journal of Sustainable Energy*

Some results

- Consideration of **costs and energy exchanges**
- But also use of **fairness** indicators
  - *Quality of Service - QoS* (Jain index): variability of energy volumes exchanged within the community
  - *Quality of Experience - QoE*: variability of perceived unit cost of energy within the community
  - *MinMax*: ratio of min vs. max individual energy import of community members

Trading Model	Simulations Results			QoS		QoE		MiM	
Interface model	Total costs [$]	Total import [MWh]	Total export [MWh]	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Individual Trading	5245.30	55.52	45.49	-	-	0.15	0.089	0.00	0.001
Community Trading									
Market-based	1577.43	16.71	11.77	0.54	0.096	0.95	0.112	0.00	0.005
Autonomy	4064.28	13.78	5.44	0.56	0.101	0.91	0.198	0.00	0.004
Min-max import share	1568.28	16.60	11.75	0.57	0.077	0.45	6.231	1.00	0.020
Peak-shaving	1626.01	16.65	11.73	0.53	0.114	0.93	0.155	0.01	0.058
Geographical	1836.93	18.17	13.37	0.52	0.099	0.81	0.137	0.00	0.003

3. **Peer-to-peer electricity markets**

E. Sorin, L. Bobo, P. Pinson (2018). Consensus-based approach to peer-to-peer electricity markets with product differentiation. *Arxiv preprint*, http://arxiv.org/abs/1804.03521

A good starting point...

ELSEVIER

Electrical Power and Energy Systems 21 (1999) 75–102

ELECTRICAL POWER & ENERGY SYSTEMS

Coordinated multilateral trades for electric power networks: theory and implementation [1]

Felix F. Wu, Pravin Varaiya*

Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720-1770, USA

Abstract

Recent moves to open up electric power transmission networks to foster generation competition and customer choice have touched off a debate over how the transmission system should be restructured in order to meet the goal. The opposing sides of this debate are now commonly represented by the bilateral model and the poolco model. Both models resort to conventional centralized operation in dealing with the shared resources of an integrated transmission network. The conventional operating paradigm was developed in a different era for electric utilities operated as regulated monopolies. A new operating paradigm is needed for a restructured industry that encourages efficient competition and at the same time maintains necessary coordination to guarantee a high standard of reliability. We propose a new operating paradigm in which the decision mechanisms regarding economics and reliability (security) of system operation are separated. Economic decisions are carried out by private multilateral trades among generators and consumers. The function of reliability is coordinated through the

- Great introduction to the peer-to-peer paradigm, with its advantages and caveats
- No (advanced) proposal for negotiation processes though...

Peer-to-peer exchanges

- Consider a set Ω of prosumers aiming to readily exchange electric energy, on a graph with full connectivity (to start with...)
- Write p_{nm} the energy quantity prosumer n is to sell to (> 0) or buy from (< 0) prosumer m ($m \in \Omega_{-n}$)
- The *Multi-Bilateral Economic Dispatch* (MBED) problem writes

$$
\begin{aligned}
\min_{p_{nm}} \quad & \sum_{n \in \Omega} C_n(\{p_{nm}\}) & \\
\text{s.t.} \quad & p_{nm} = -p_{mn} & \forall n \in \Omega, m \in \Omega_{-n} \\
& \underline{P_n} \leq \sum_{m \in \Omega_{-n}} p_{nm} \leq \overline{P_n} & \forall n \in \Omega \\
& p_{nm} \geq 0 & \forall n \in \Omega^p \\
& p_{nm} \leq 0 & \forall n \in \Omega^c
\end{aligned}
$$

- Note that instead of a *balance constraint*, we have a large number of *reciprocity constraints* (one per non-zero exchange)
- These will reveal the price for each and every transaction

Allowing for product differentiation

- One may generically formulate cost functions for both consumers and producers in a quadratic form (as earlier), i.e.

$$C_n(\{p_{nm}\}) = \frac{1}{2}a_n\left(\sum_{m\in\Omega_{-n}} p_{nm}\right)^2 + b_n \sum_{m\in\Omega_{-n}} p_{nm} + d_n$$

- Now, let us introduce
  - $\mathcal{G}$ the set of criteria involved in the participants' decisions (e.g. distance, type)
  - c_n^g the preference coefficient of agent n for criterion g
  - γ_{nm}^g the value of criterion g for agent m, from the perspective of agent n

- We reformulate costs functions (example of consumers) as

$$C_n(\{p_{nm}\}) = \frac{1}{2}a_n\left(\sum_{m\in\Omega_{-n}} p_{nm}\right)^2 + b_n \sum_{m\in\Omega_{-n}} p_{nm} + \sum_{g\in\mathcal{G}}\left(c_n^g \sum_{m\in\Omega_{-n|g}} (\gamma_{nm}^g p_{nm})\right) + d_n$$

hence reflecting preferences for certain (type of) trades. This translates to defining generalized and conditional utility functions.

Solution approach and insight

- Relaxed Consensus+Innovation approach[3]
- Writing KKT optimality conditions, and focusing on 1st-order ones, we make a transaction-dependent price appear, i.e.

$$\hat{\lambda}_{nm} = \lambda_{nm} - \sum_{g \in \mathcal{G}} \left(c_n^g \gamma_{nm}^g \right)$$

which allows for product differentation. In case of no preference, $\hat{\lambda}_{nm} = \lambda_{nm}$.

- λ and Π updates are given by (simplified here, since overlooking the relaxation of negotiation ranges)

$$\lambda_{nm}^{k+1} = \lambda_{nm}^{k} - \beta^k \left(\lambda_{nm}^{k} - \lambda_{mn}^{k} \right) - \alpha^k \left(p_{nm}^{k} + p_{mn}^{k} \right)$$

$$\Pi_{nm}^{k+1} = f_{nm}^{k} \left(\frac{\hat{\lambda}_{nm}^{k+1} - b_n}{a_n} - \sum_{l \in \Omega_{-n}} p_{nl}^{k} \right) + p_{nm}^{k}$$

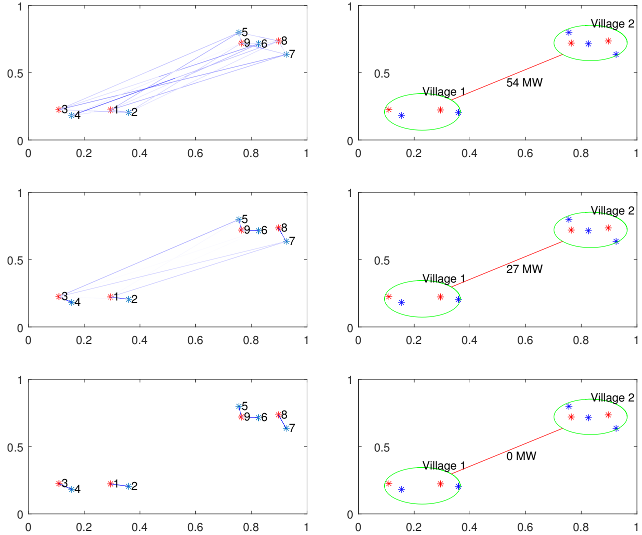
- The iterative process uses primal and dual stopping criteria

$$\sum_{n \in \Omega} \sum_{m \in \Omega_{-n}} |\lambda_{nm}^{k+1} - \lambda_{nm}^{k}| < \epsilon_\lambda \qquad \text{and} \qquad \sum_{n \in \Omega} \sum_{m \in \Omega_{-n}} |p_{nm}^{k+1} - p_{nm}^{k}| < \epsilon_P$$

[3] Here again, Consensus ADMM could be used, allowing for a unified formulation of energy collectives and

An illustrative example

- Let us consider distance between actors as a criterion (local production, local consumption!), for simplicity with a fixed unitary cost c_n^g



- $c_n^g = 0$
- $c_n^g = \frac{1}{2}$
- $c_n^g = \frac{3}{2}$

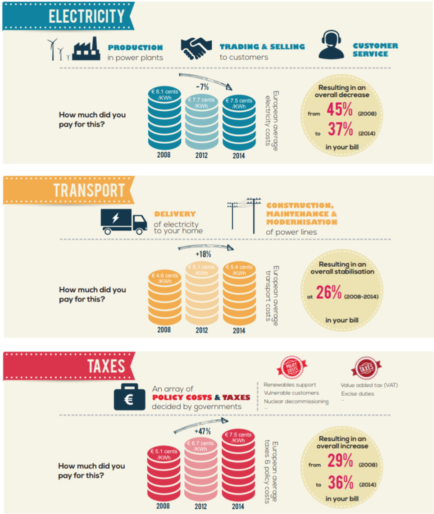
Impact of the distance-related criterion on bilateral exchange on the left, and on the exchanges between the two villages on the right

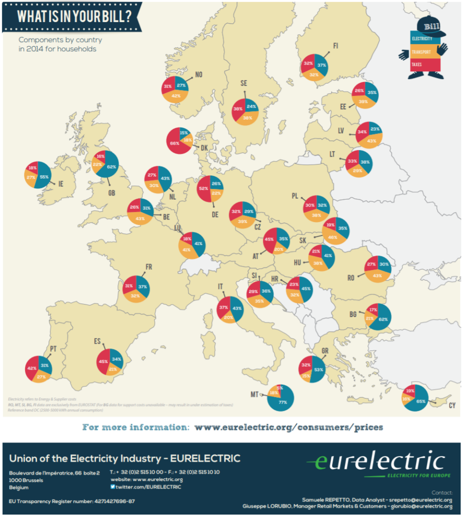
Play yourself at `https://p2psystems.shinyapps.io/ShinyApp_Project`

5. **Re-designing network charges**

T. Baroche, P. Pinson, R. Le Goff Latimier, H. Ben Ahmed (2018). Exogenous approach to grid cost allocation in peer-to-peer electricity markets. *Arxiv preprint*, http://arxiv.org/abs/1803.02159

What are network charges?

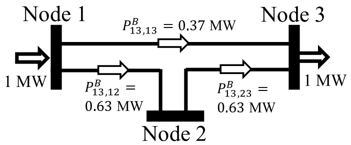


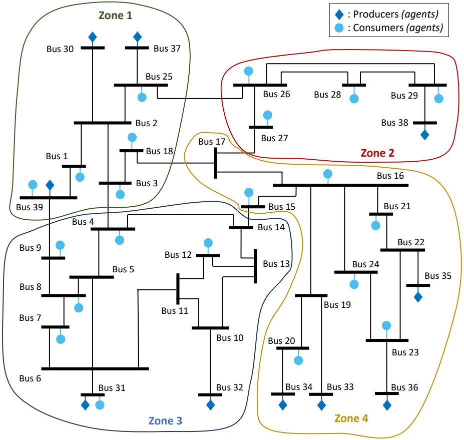


- In Denmark, 85% of the electricity costs relates to grid costs and taxes(!)
- Redesigning and modulating those will certainly be more efficient than price-based demand-response based on energy price only

- instead preferences, let us rethink the *cost structure*
- network charges may be a function of the network needs of each and every trade
- some form of *electric distance* can be used as a proxy (others may also be relevant)

- Ex: fully socialized (as of today in most markets)
- Ex: zonal approach (right)
- Ex: Thevenin and PTDF-based electric distance (below)





(IEEE 39-bus New England system, also used as a case-study in the following)

Cost allocation policies

- For a trade between agents m and n, the associated price $\tilde{\lambda}_{nm}$ accounting for network charges is

$$\tilde{\lambda}_{nm} = \lambda_{nm} \pm \gamma_{nm} \ ,$$

  where λ_{nm} is the energy price negotiated through the peer-to-peer mechanism while γ_{nm} is for the network charges ($\pm$ is for the case of buying, resp. selling, agents)

- γ_{nm} may be defined in various ways:
  - **Socialized**:

$$\gamma_{nm} = \frac{u^{\text{fixed}}}{2},$$

  - **Zonal**:

$$\gamma_{nm} = \frac{u^{\text{zonal}} N_{nm}}{2} \ , \quad N_{nm}\text{: minimum number of zones to cross,}$$

  - **Electric distance (Thevenin)**:

$$\gamma_{nm} = \frac{u^{\text{dist}} d^{\text{thev}}_{nm}}{2} \ , \quad d^{\text{thev}}_{nm}\text{: Thevenin electric distance,}$$

  - **Electric distance (PTDF)**:

$$\gamma_{nm} = \frac{u^{\text{dist}} d^{\text{PTDF}}_{nm}}{2} \ , \quad d^{\text{PTDF}}_{nm}\text{: PTDF electric distance}$$

A peer-to-peer market with network charges

- The basic set-up is similar (agents, cost functions, etc. no product differentiation though)

- The *Augmented Multi-Bilateral Economic Dispatch* writes

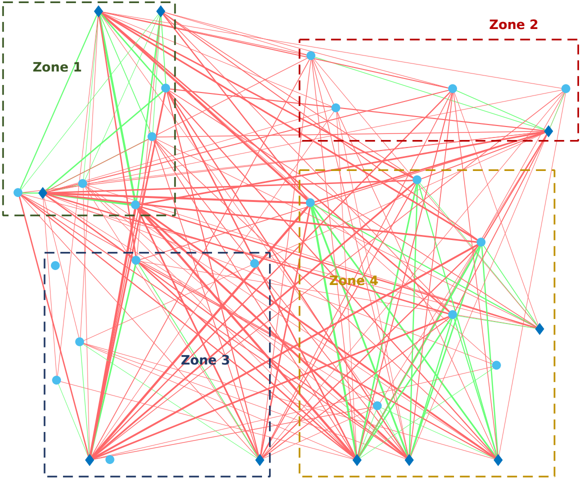
$$
\begin{aligned}
\min_{P_{nm}} \quad & \sum_{n \in \Omega} C_n(\{p_{nm}\}) + \sum_{n \in \Omega, m \in \Omega_{-n}} \gamma_{nm} p_{nm} & \\
\text{s.t.} \quad & p_{nm} = -p_{mn} & \forall n \in \Omega, m \in \Omega_{-n} \\
& \underline{P_n} \leq \sum_{m \in \Omega_{-n}} p_{nm} \leq \overline{P_n} & \forall n \in \Omega \\
& p_{nm} \geq 0 & \forall n \in \Omega^p \\
& p_{nm} \leq 0 & \forall n \in \Omega^c
\end{aligned}
$$

- This can also be seen as a general exchange problem, except that with our definition of network charges, the resulting $g(\{p_{nm}\}, \theta) = \sum_{n \in \Omega, m \in \Omega_{-n}} \gamma_{nm} p_{nm}$ is separable

- There again, Consensus ADMM can be used after a little reformulation

Application example (1)

- This is what happens on the IEEE 39-bus New England system if clearing a peer-to-peer electricity market with socialized (uniform) network charges

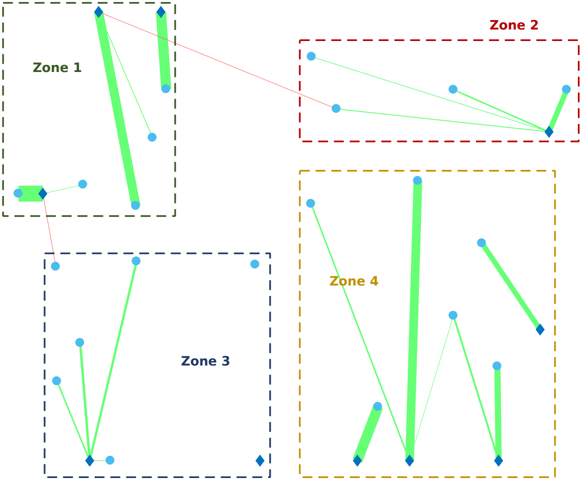


Red lines are for inter-zonal exchanges and green lines for intra-zonal ones

- It does not provide any incentive to account for network usage in the trades(!)

Application example (2)

- Now using network charges proportional to an electric distance

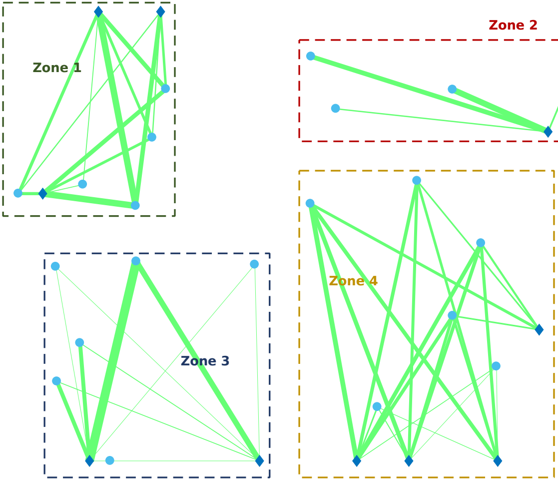


Red lines are for inter-zonal exchanges and green lines for intra-zonal ones

- It seems to work, though possibly inducing too much stress on energy exchanges

Application example (3)

- Now using network charges using the zonal principle



Red lines are for inter-zonal exchanges and green lines for intra-zonal ones

- Possibly the most interesting option if having identified relevant zones and sensitive links

5. **Outlook**

A few concluding thoughts

- Current centralized market and proposed decentralized approaches **may co-exist in the near future**

- A number of interesting **potential advantages**:
  - a true consumer-centric approach to electricity market design and operation (yielding, e.g., crowfunding of shared generation capacities)
  - increased awareness and commitments of all players down to residential customers
  - new paradigm for electricity exchanges allowing for product differentiation and differentiated network charges (not only time-dependent)
  - a wealth of new business models (C2C, B2B and B2C)
  - etc.

- From the **scientific point of view**:
  - need to develop scalable negotiation algorithms on graphs (mixing distributed and decentralized paradigms)
  - find ways to reveal and maintain sparsity
  - generalize to account for forecast uncertainty
  - embed grid operation costs, reliability consideration, etc. in either exogenous or endogenous manners
  - propose and validate mixed market designs

Thanks for your attention!

References

F. Moret, P. Pinson (2018). Energy Collectives: a community and fairness based approach to future electricity markets. *IEEE Transactions on Power Systems*, available online (pdf)

P. Pinson, T. Baroche, F. Moret, T. Sousa, E. Sorin, S. You (2017). The emergence of consumer-centric electricity markets. Available online (pdf) also in Chinese(!)

F. Moret, T. Baroche, P. Pinson, E. Sorin (2018). Negotiation algorithms for peer-to-peer electricity markets: Computational properties. *Power System Computation Conference 2018*, Dublin, Ireland, (pdf)

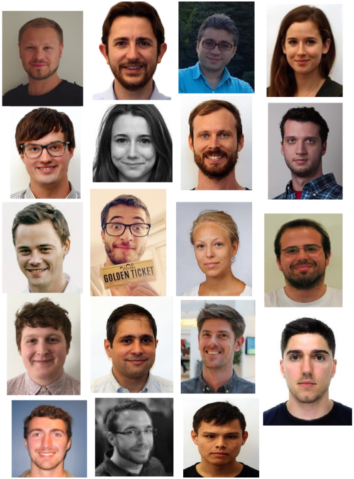
T. Baroche, P. Pinson, R. Le Goff Latimier, H. Ben Ahmed (2018). Exogenous approach to grid cost allocation in peer-to-peer electricity markets. *Arxiv preprint*, http://arxiv.org/abs/1803.02159

E. Sorin, L. Bobo, P. Pinson (2018). Consensus-based approach to peer-to-peer electricity markets with product differentiation. *Arxiv preprint*, http://arxiv.org/abs/1804.03521

Ackn.: Characters of the title page designed by `freepik.com`

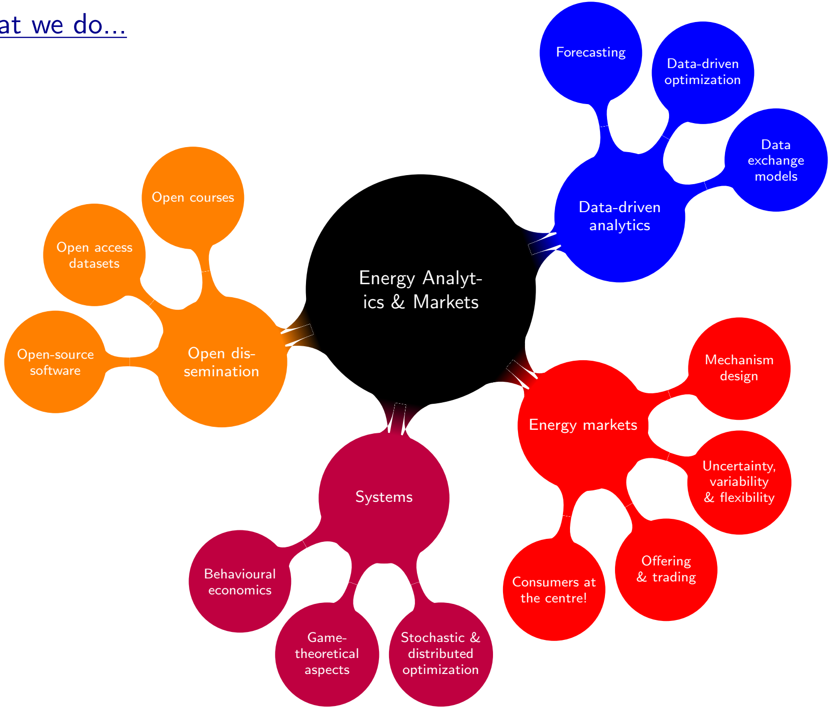
Who are we? - The Energy Analytics & Markets group

- One of the 5 groups of the Center for Electric Power and Energy, Dpt. of Electrical Engineering



- **Resources:** ($\sim$11 nationalities)
  - *Faculty:* 1 Prof, 2 Assist. Profs.
  - *Junior:* 3 post-doc fellows, 10 Ph.D. students (+2/3 not at DTU), 2 research assistants
  - + student helpers, and Ph.D. guests from, e.g., China, Brazil, US, Spain, France, Italy, The Netherlands, Germany, etc.
- **Projects** (examples, active in 2018):
  - **EU:** BestPaths
  - **Danish:** MULTI-DC, 5s, EcoGrid 2.0, The Energy Collective, CITIES, EnergyLab Nordhavn, CORE
- **Education:** Various courses on analytics, optimization, forecasting, game theory, renewables and electricity markets
- (hopefully) recognized leading expertise in energy analytics and markets

What we do...


Energy Analyt-
ics & Markets
Data-driven
analytics
Forecasting
Data-driven
optimization
Data
exchange
models
Energy markets
Mechanism
design
Uncertainty,
variability
& flexibility
Offering
& trading
Consumers at
the centre!
Systems
Behavioural
economics
Game-
theoretical
aspects
Stochastic &
distributed
optimization
Open dis-
semination
Open courses
Open access
datasets
Open-source
software