Prosumer-centric electricity markets

energy collectives and peer-to-peer exchanges

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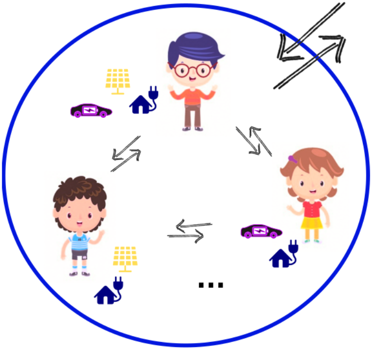

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Outline

- **A broad-audience introduction**
  - Motivations and enablers
  - Organizational scenarios
  - Practical and methodological aspects
- **The energy collective approach**
  - Defining an energy collective
  - Distributed optimization based approach
  - Ongoing extensions
- **Towards full peer-to-peer electricity markets**
  - Building on a consensus+innovation approach
  - Allowing for product differentiation
  - A working example
- **Outlook**

1. **A broad audience introduction**

Sharing is caring...

[Taken from moneycrashers.com, Brian Martucci]

- *Sharing* is part of human nature and a source of happiness
- *Sharing* is a basis for the development of new business models (*'access economy'* and *'collaborative commons'*)
  - crowdfunding
  - crowdsourcing
  - car pooling, shared property, etc.

Sharing is caring...

DTU

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There are things we might never have thought of sharing... e.g., **electric energy (!)**

Why would you think one might share electric energy?

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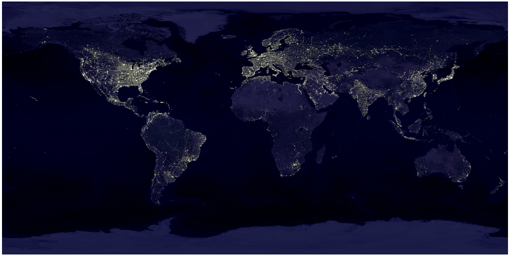
We tend to *interconnect* ourselves through *electric power networks*



[Credits to Nasa Visible Earth]

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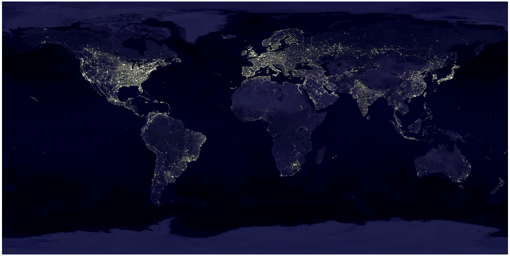


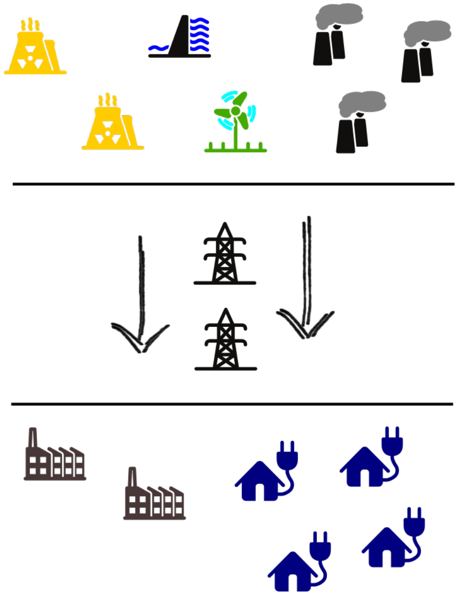
[Credits to Nasa Visible Earth]

The Internet of Things (IoT – cloud-based, blockchain) gives the promise of *remote sensoring and actuating* in a smart energy future...

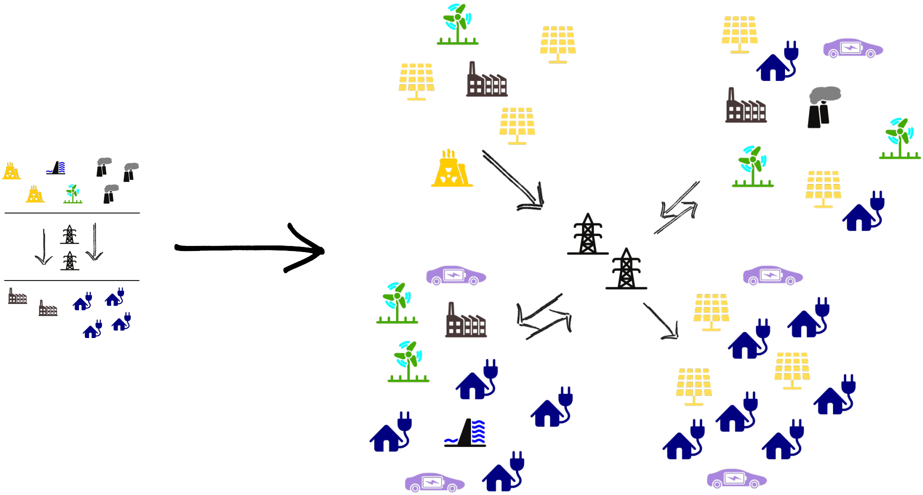
[Taken from www.telecomstechnews.com]

From a supplier-centric model...

Actors of the electric power network are traditionally organized in a *hierarchical* and *supplier-centric* manner



From a supplier-centric model to a more decentralized setup



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

Organization of consumer-centric electricity markets

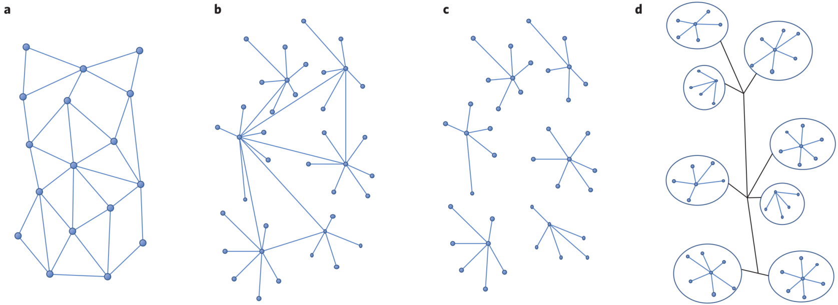


Figure 1 | Structural attributes of three prosumer markets. a, Peer-to-peer model, in which prosumers interconnect directly with each other, buying and selling energy services. **b**,**c**, More structured models involving prosumers connected to microgrids. These entail prosumer-to-interconnected microgrids, 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]

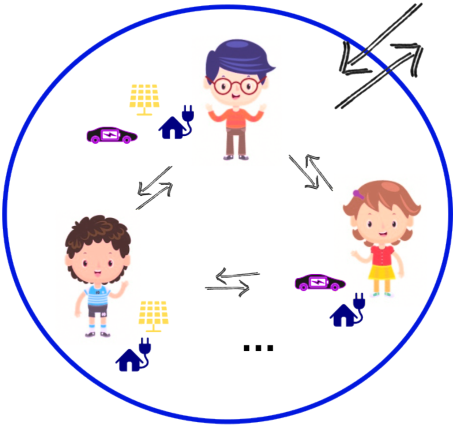
For real in Denmark

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

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

[*København NV* - social experiment - EnergyBlock]

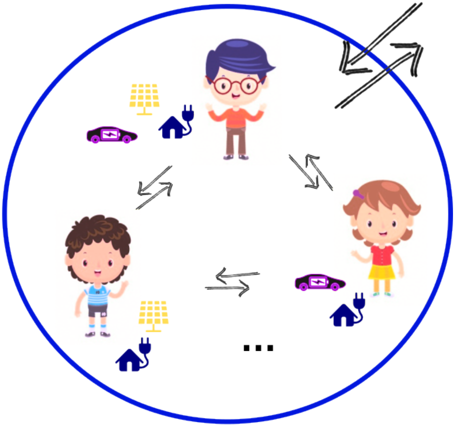
Introducing ‘Energy Collectives’



[Characters designed by freepik.com]

- Aidan, Eamonn, Niamh, etc., chose to gather in an *Energy Collective*
- They traditionally bought energy from the grid and sold their production back at a disadvantageous rate...
- They work at optimally matching their production and consumption
- They 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

Generalizing to peer-to-peer exchanges



[Characters designed by freepik.com]

- The base concept relies on p2p exchanges
- One ends up with a negotiation problem on a network, of potentially very large dimension
- In pratice, consensus-based optimization and Lagrangian relaxation-decomposition techniques can be used
- The negotiation problems can be made sparse by market design (russian doll principle for energy collectives) or through trading bots accounting for preferences
- Many mathematical challenges ahead of us, but direct applications also readily possible!

2. **The energy collective approach**

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.,

$$\min_{p_j, c_i} \quad \sum_{j=1}^{m} f_j^p(p_j) - \sum_{i=1}^{n} f_i^c(c_i) - g(q_{\text{ext}}, \theta) \tag{1}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} c_i + q_{\text{ext}} - \sum_{j=1}^{m} p_j = 0 \tag{2}$$

$$P_j^{\min} \leq p_j \leq P_j^{\max}, \qquad j = 1, \ldots, m \tag{3}$$

$$C_i^{\min} \leq c_i \leq C_i^{\max}, \qquad i = 1, \ldots, n \tag{4}$$

$$\tag{5}$$

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 storage)

Costs functions of the various players

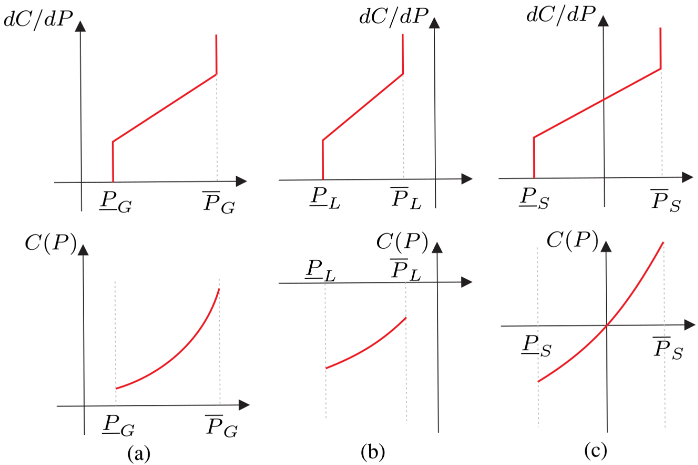


Fig. 1. Marginal cost functions dC/dP and cost functions C for (a) generator, (b) load, and (c) storage.

[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

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

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

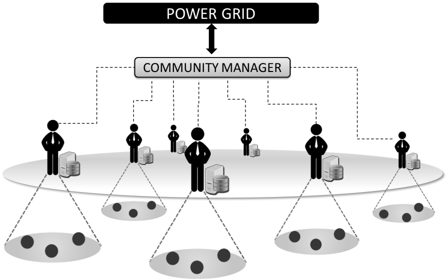
    where λ_{ext} is the wholesale market price
  - in case the community wanted to be as autonomous as possible, one would naturally have

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

    with $l = 1, 2$
  - $g(q_{\text{ext}}, \theta)$ **could be augmented to reflect grid-related costs**

- Considering the market setup, $g(q_{\text{ext}}, \theta)$ is to be eventually shared among the $n + m$ players, using cost attribution and fairness principles

Players are to solve their own problems



- In our prosumer context, we assume 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 ("community manager") gathering individual outcomes and updating prices (z-update)
- The coordination node may allocate import costs (/export revenues) following various principles (yielding modified x-updates), e.g. equal share, proportional sharing, "worst" player, etc.
- Energy collective members **implicitly exchange energy...**

Our working example

Player setup and data:

- 300 prosumers (non-flexible/flexible consumers and PV generation) from Ausgrid dataset [1]
- Australian wholesale electricity prices
- Extra assets: 15 mini-CHP generators, 5 of which are modelled as peak generators (small size and higher marginal costs)

Approaches:

- Benchmark, **Business As Usual** (BAU)
  - 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
  - no allocation
  - equally divided allocation
  - allocation proportional to the power consumed/produced
  - and others, but skipped here

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

Quick illustrative results

- One day simulation with 30 minutes intervals
- Minimisation of community procurement costs (and maximization of revenues)

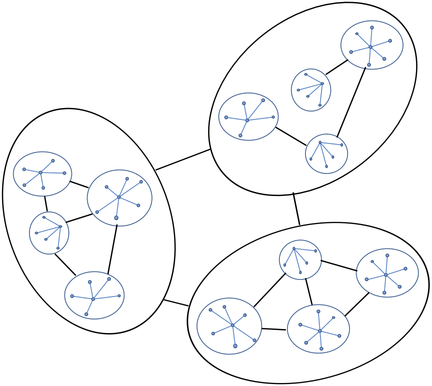
Total costs for the community:

Approach	Total costs
BAU	55.38
Community-based - no allocation	47.12
Community-based - equal allocation	45.27
Community-based - power proportional	46.81

- With the sharing setup, overall costs are decreased thanks to implicit exchanges within the community
- Allocation schemes impact individual dispatch and costs/revenues

Towards nested approaches

- Generalizing this idea to a complete setup would require some form of nesting, and eventually interfacing to current market



- Nested distributed optimization approaches may not be so difficult to develop from a mathematical point of view... but would that be really practical? (e.g., communication issues)

3. **Peer-to-peer exchanges**

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]

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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 (so far...)
- Write P_{nm} the energy quantity prosumer n is to send to (> 0) or receive from (< 0) prosumer m ($m \in \Omega_{-n}$)
- The *Multi-Bilateral Economic Dispatch* (MBED) writes

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

- 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.

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

- 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

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

hence reflecting preferences for certain (type of) trades. This translates to defining type-dependent utility functions.

Solution approach and insight

- We use a Consensus+Innovation approach for solving our MBED in a decentralized manner
- Writing stationarity conditions, we make a transaction-dependent price appear, i.e.

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

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

- λ and Π updates are given by

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

  and

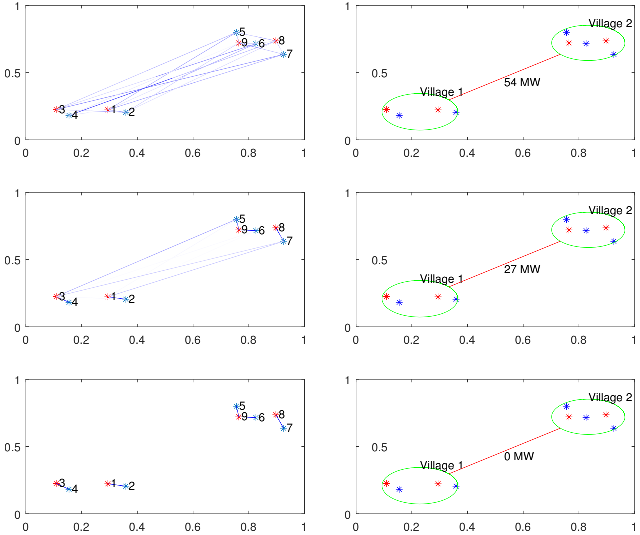
$$\Pi_{nm}^{k+1} = f_{nm}^{k} \left(\frac{\hat{\lambda}_{nm}^{k+1} - b_n}{a_n} - \sum_{l \in \Omega_{-n}} P_{nl}^{k} \right) + P_{nm}^{k}$$

- The iterative process uses primal and dual stopping criteria

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

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

4. **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
  - a wealth of new business models(!)
  - 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
  - embed grid operation costs, reliability consideration, etc. in either exogenous or endogenous manners
  - propose and validate mixed market designs

Thanks for your attention!