Aggregation and control of distributed energy resources

Home energy management, virtual power plants and peer-to-peer energy trading

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A/Prof Gregor Verbič
School of Electrical and Information Engineering, The University of Sydney, Australia

With contributions from:
Dr Jaysson Guerrero, Dr Daniel Gebbran, Dr Yiju Ma, Dr Sleiman Mhanna, Dr Archie Chapman

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- Background and motivation
- Management and coordination of distributed energy resources: overview
- Home energy management
- Home energy management with operating envelopes
- Virtual power plants
- Network-aware coordination: distributed optimal power flow
- Peer to peer energy trading
- Comparative analysis
- Conclusions

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Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading

Jaysson Guerrero [a,*], Daniel Gebbran [a], Sleiman Mhanna [b], Archie C. Chapman [c], Gregor Verbič [a]

[a] School of Electrical and Information Engineering, The University of Sydney, Sydney, Australia
[b] Department of Electrical and Electronic Engineering, The University of Melbourne, Melbourne, Australia
[c] School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia

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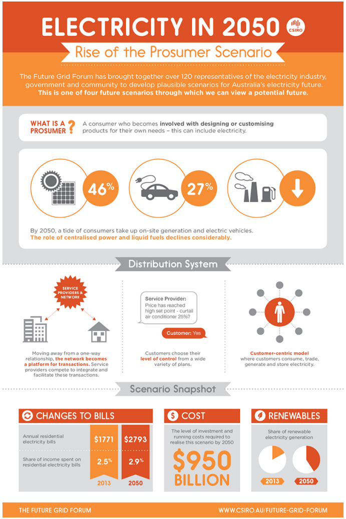
ABSTRACT

This paper reviews approaches for facilitating the integration of small-scale *distributed energy resources* (DER) into low- and medium-voltage networks, in the context of the emerging *transactive energy* (TE) concept. We focus on three general categories: (i) *uncoordinated approaches* that only consider energy management of an individual user; (ii) *coordinated approaches* that orchestrate the response of several users by casting the energy management problem as an optimization problem; and (iii) *peer-to-peer* energy trading that aims to better utilize the DER by establishing decentralized energy markets. A second separate, but important, consideration is that DER integration methods can be implemented with diverse levels of network awareness, given their capability to address

Background and motivation

Rise of the Prosumer Scenario

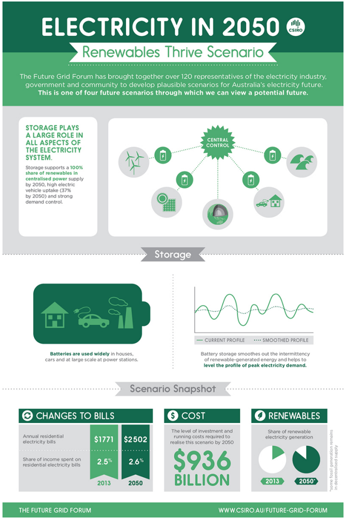
- By 2050, a tide of consumers take up on-site generation (46%) and electric vehicles (27%)
- The role of centralised power and liquid fuels declines considerably
- Customers choose their level of control from a wide variety of plans
- The network becomes a platform for transactions



Source: CSIRO Future Grid Forum, 2013.

Renewables Thrive Scenario

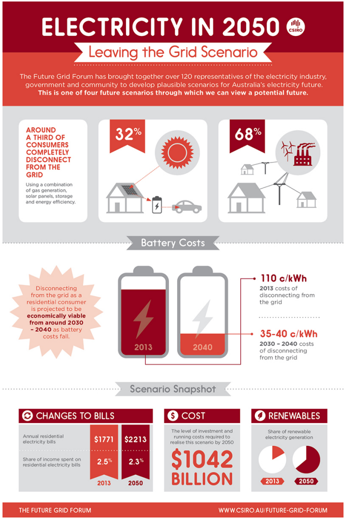
- 100% renewables in centralised power supply by 2050
- High electric vehicle uptake (37%)
- Strong demand control
- Batteries are used widely in houses, cars and at large scale at power stations



Source: CSIRO Future Grid Forum, 2013.

Leaving the Grid Scenario

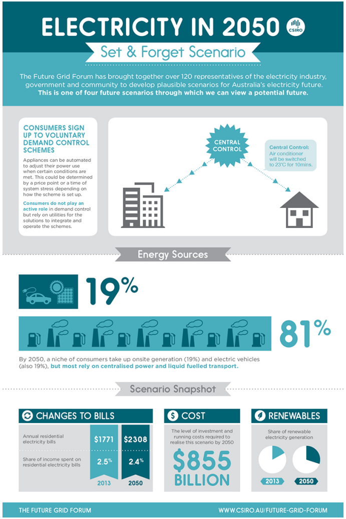
- Around a third of consumers completely disconnect from the grid
- PV and battery storage are the key technologies
- Disconnecting from the grid as a residential consumer is projected to be economically viable from around 2030-2040 as battery costs fall



Source: CSIRO Future Grid Forum, 2013.

Set and Forget Scenario

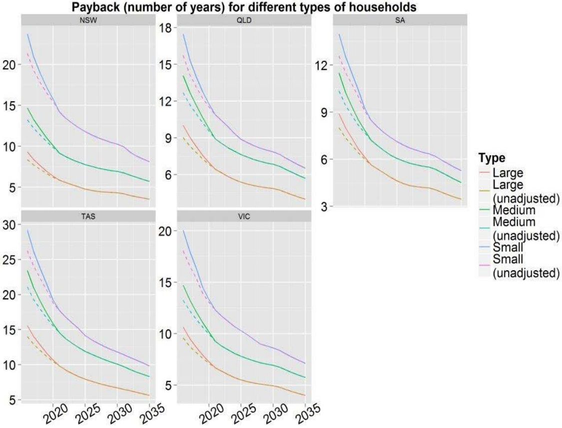
- Consumers sign up to voluntary demand control schemes
- Appliances can be automated to adjust their power use when certain conditions are met
- Dynamic pricing to incentivise users' action
- Consumers do not play an active role in demand control but rely on utilities for the solutions to integrate and operate the schemes
- Energy Sources:
    - onsite generation and EVs (19%)
    - centralised power and liquid fuelled transport (81%)

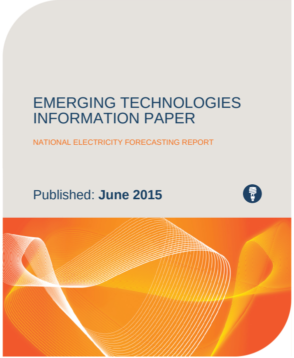


Source: CSIRO Future Grid Forum, 2013.

Technology cost is dropping

Payback period for PV-battery systems (2015)

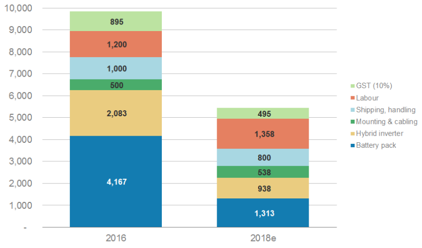




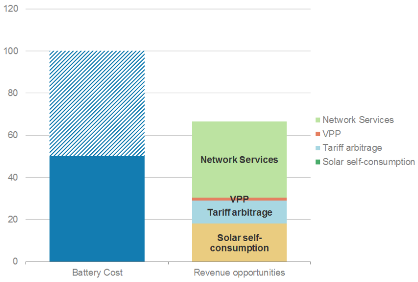
AEMO

Australian Energy Market Operator (AEMO), “Emerging Technologies Information Paper,” 2015.

Cost reduction drivers



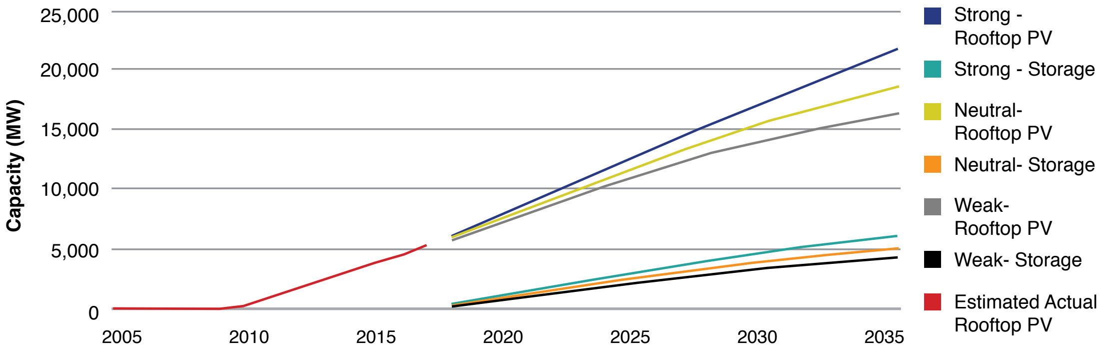
Installation costs for a generic 7 kWh battery system (A$)



Battery costs per kWh used vs. value opportunities (c/kWh)

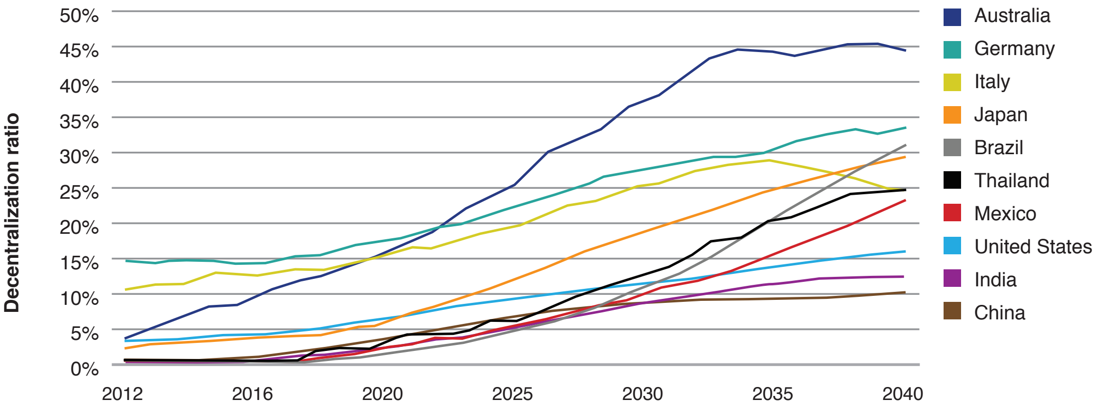
Morgan Stanley Research, “Australia Utilities Asia Insight: Solar & Batteries” 2016.

Projected installed capacity of rooftop PV and distributed battery storage in the NEM



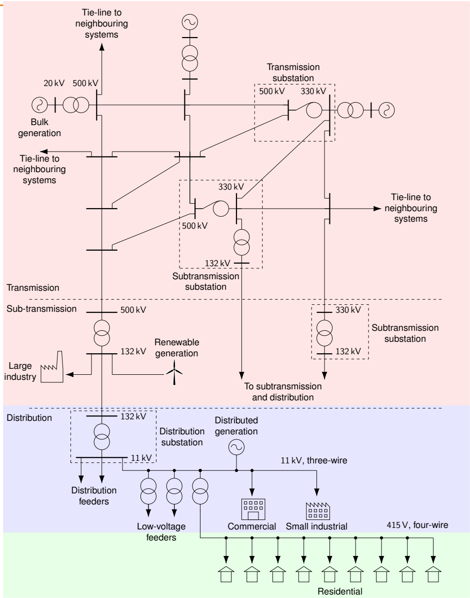
Source: AEMO ENA Open Energy Networks, 2018.

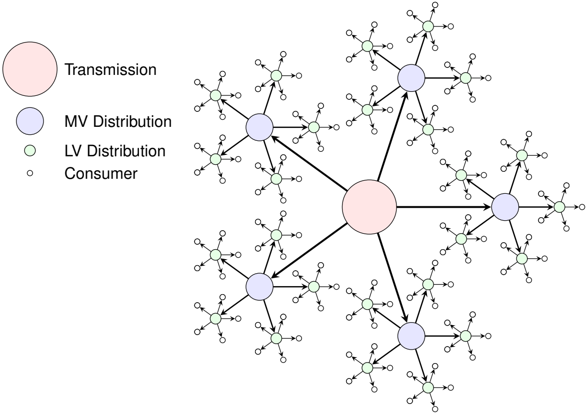
Global rate of electricity market decentralisation



Source: AEMO ENA Open Energy Networks, 2018. (from Bloomberg New Energy Finance. 2017 New Energy Outlook.)

What does that mean for the electricity network?





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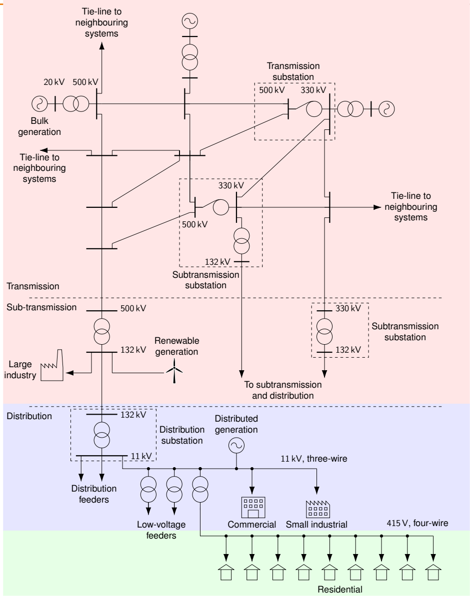
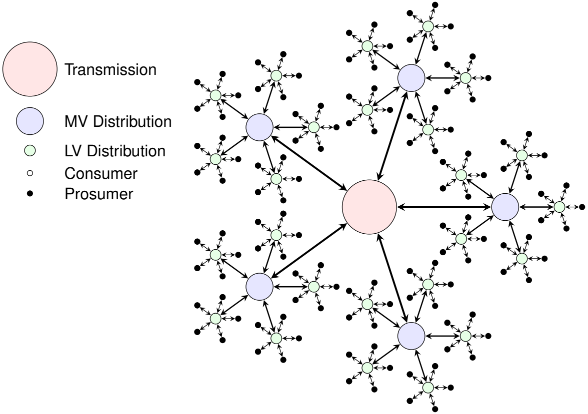
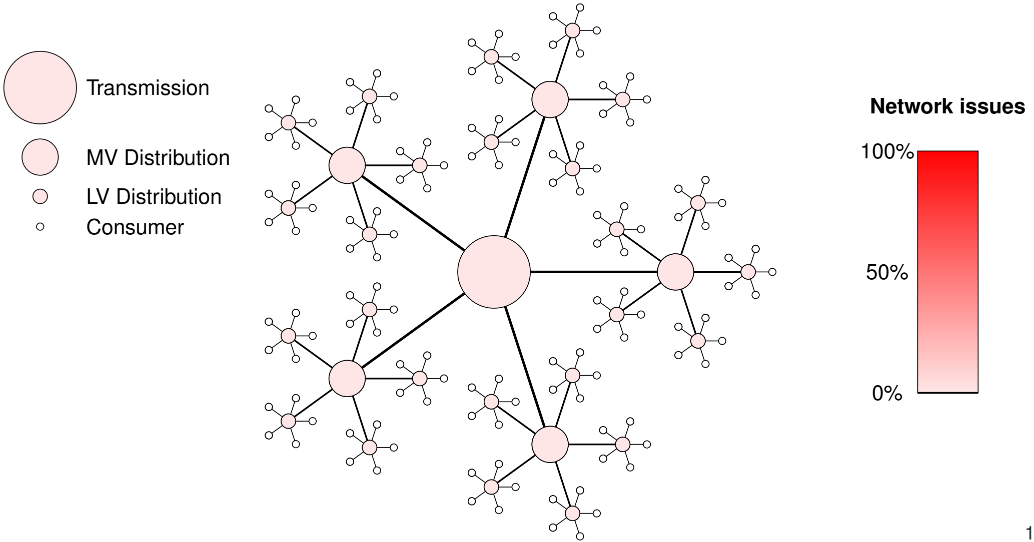




Increasing penetration of rooftop solar PV creates network problems



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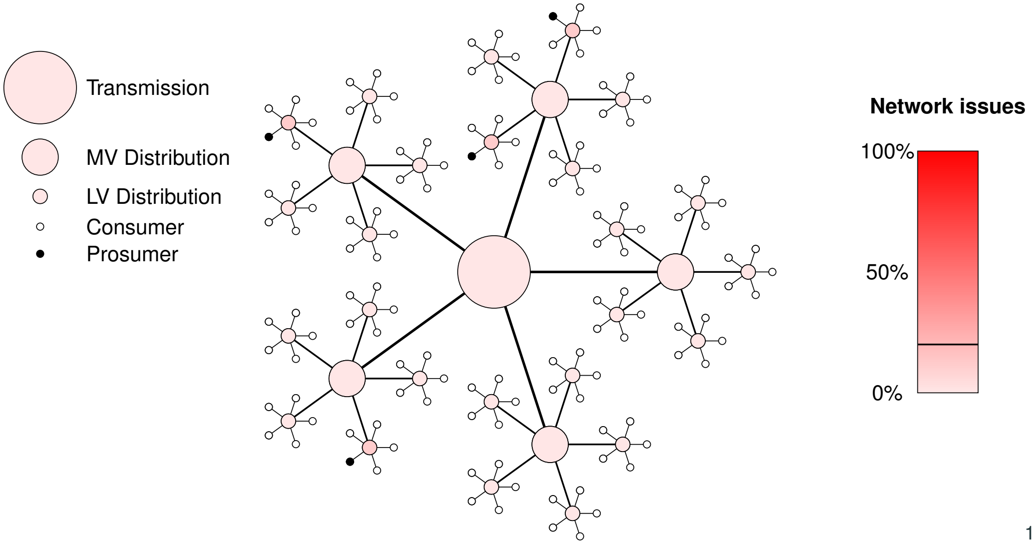

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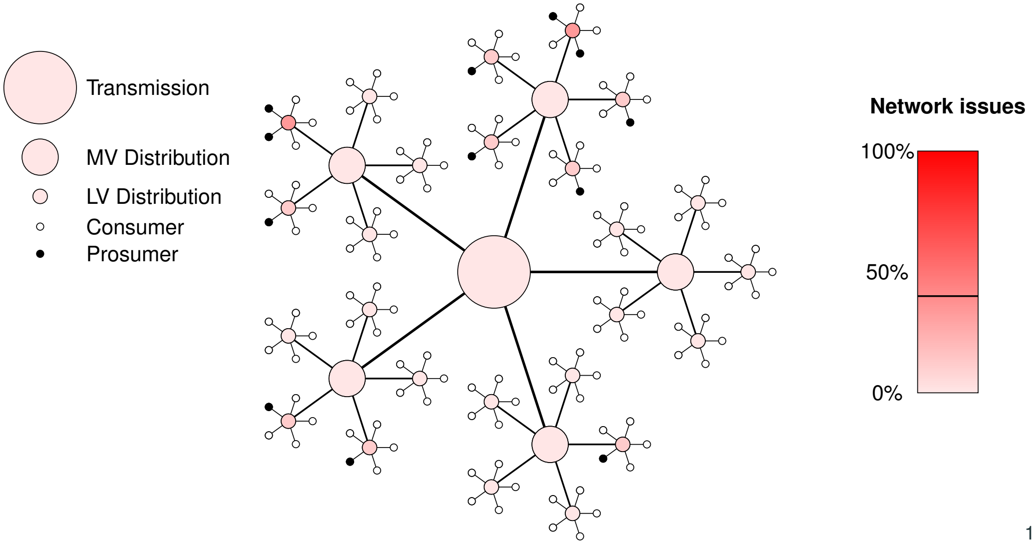

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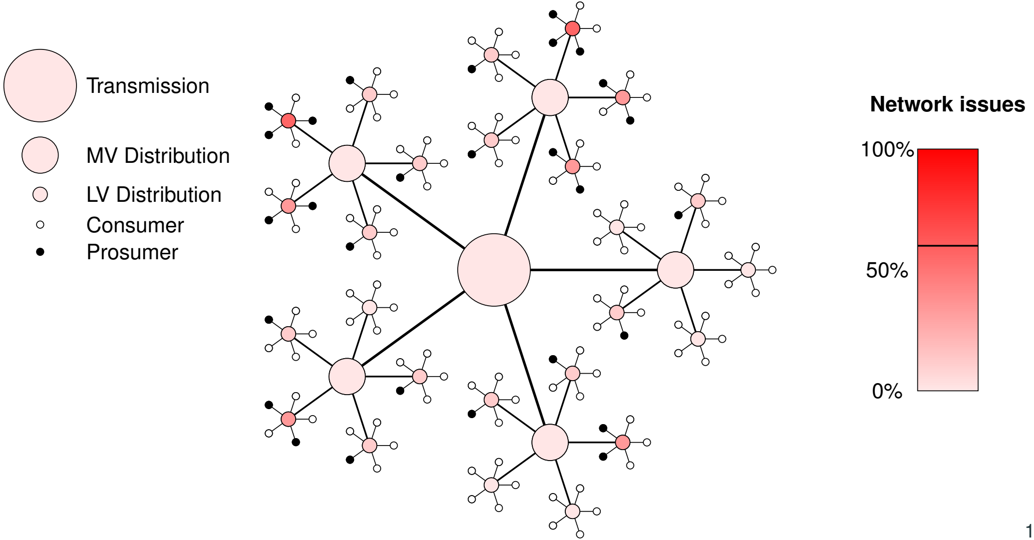

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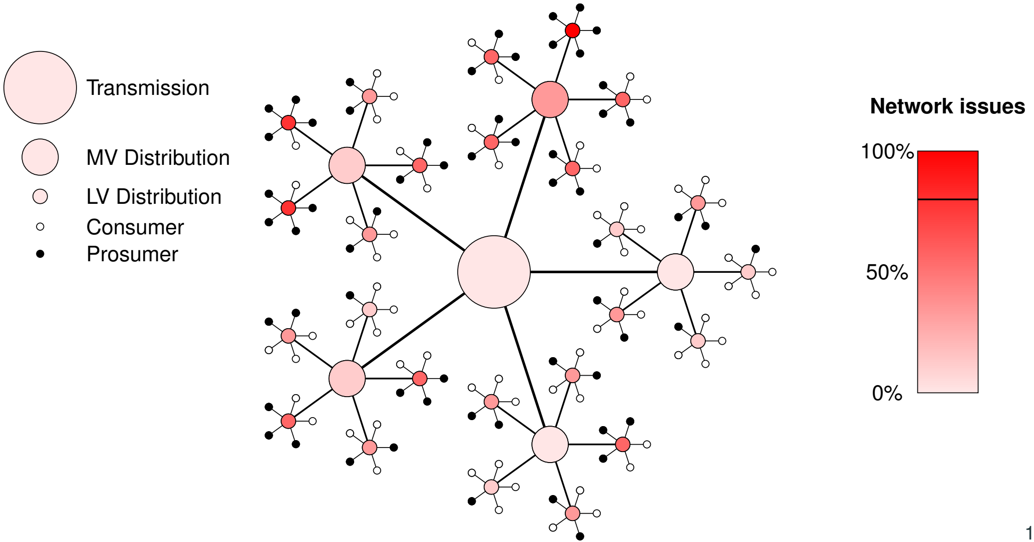

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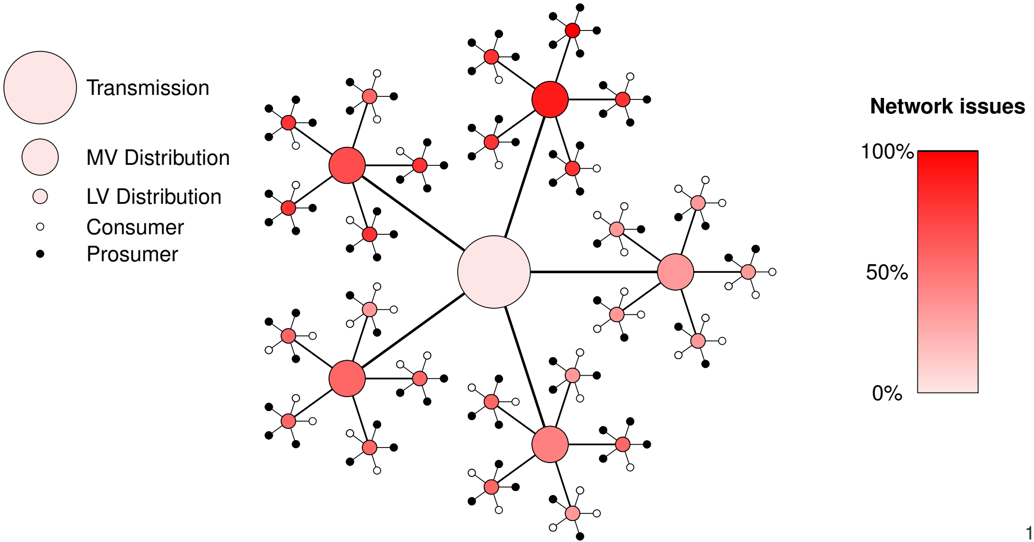


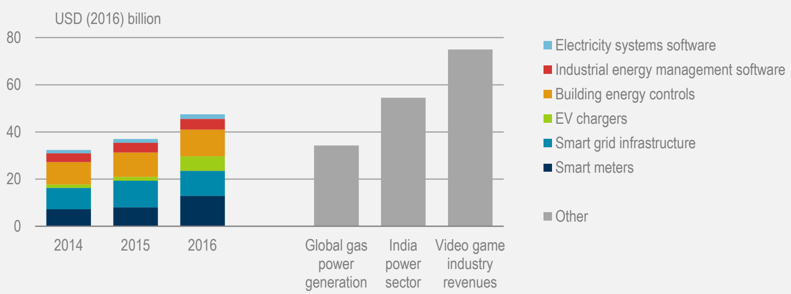
Solar exports: Should households pay for right to export more solar to the grid?

Giles Parkinson 16 July 2020 0 Comments Share

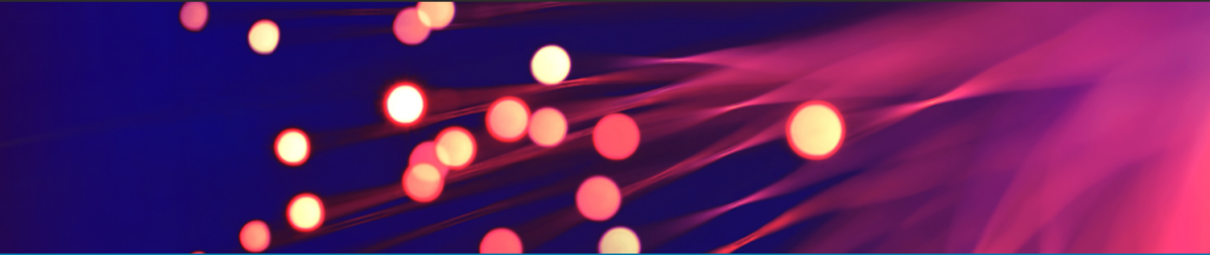
Digitalisation of the energy landscape

- Ubiquitous connectivity (Internet of Things)
- Artificial intelligence ('smart' devices)
- Blockchain (distributed energy marketplace)

Global investments in digital electricity infrastructure and software



International Energy Agency (IEA), "Digitalization & Energy", 2017.



New plan to make room on grid for more home solar and batteries

25 March 2021

View all related project documents

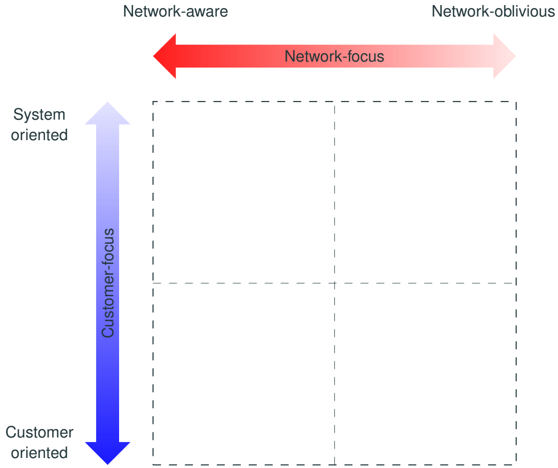
Access, pricing and incentive arrangem

Management and coordination of distributed energy resources: overview

DER coordination and management approaches

- System oriented: maximise social welfare
- Customer oriented: minimise electricity bill
- Network awareness: network impact

- Home energy management (HEM)
- Home energy management with operating envelopes (HEM-OE)
- Peer-to-peer energy trading (P2P)
- Virtual power plants (VPP)
- Network-aware virtual power plants (OPF)



[1] J. Guerrero, D. Gebbran, S. Mhanna, A. C. Chapman, and G. Verbič, "Towards a transactive energy system for integration of distributed energy resources: home energy management, distributed optimal power flow, and peer-to-peer energy trading," *Renewable and Sustainable Energy Reviews*, vol. 132, p. 110000, October 2020.

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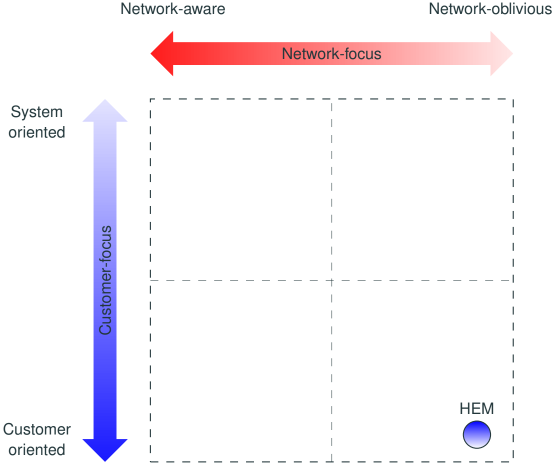

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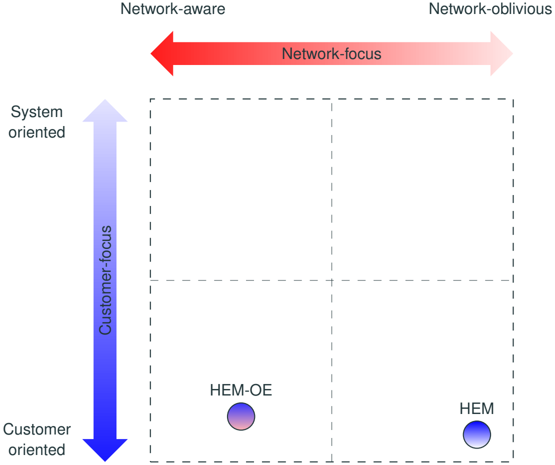

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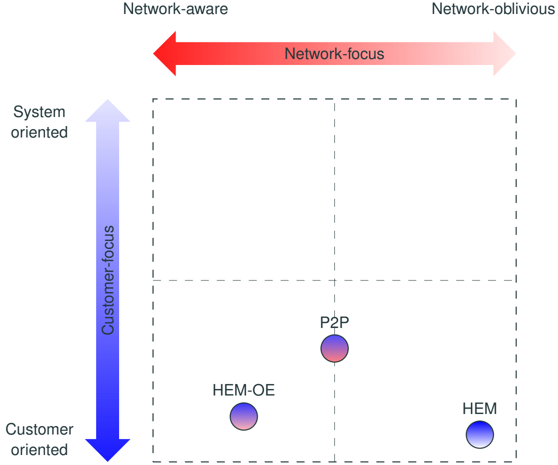

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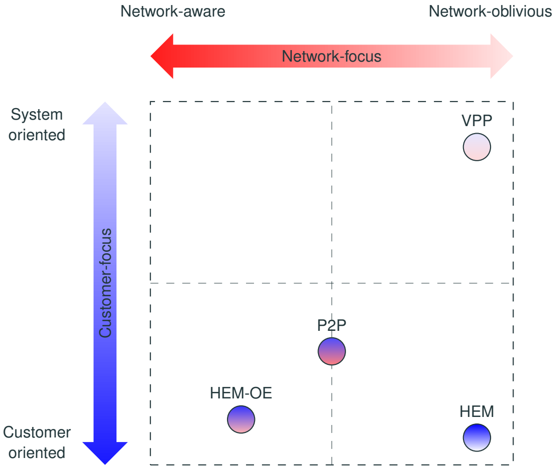

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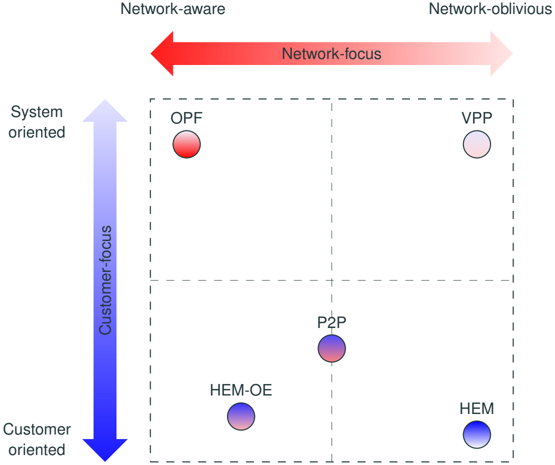

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Home energy management

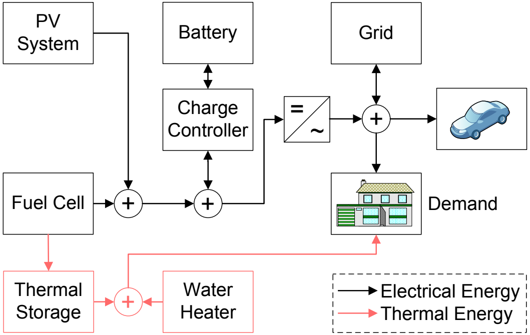
Home energy management (HEM)

Distributed energy resources (DER):

- Rooftop solar PV
- Battery storage
- Electric vehicle
- Fuel cells
- Flexible loads (thermal and shiftable)

Active DER management:

- Reduce electricity bill
- Increase PV self-consumption
- Improve comfort



[2] H. Tischer, G. Verbič, "Towards a smart home energy management system - A dynamic programming approach," in *2011 IEEE Innovative Smart Grid Technologies - Asia.*

[3] D. Azuatalam, K. Paridari, Y. Ma, M. Förstl, A. C. Chapman, and G. Verbič, "Energy management of small-scale PV-battery systems: A systematic review considering practical implementation, computational requirements, quality of input data and battery degradation," *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 555–570, September 2019.

Home energy management: Generic formulation

- Scheduling energy use over a horizon
- Typically cast as a sequential decision making problem under uncertainty:

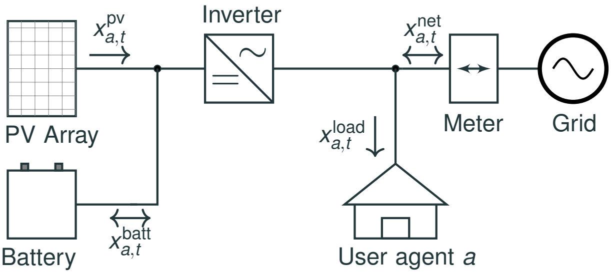
$$F^{\pi^\star} = \underset{\pi}{\text{minimise}}\, \mathbb{E} \left\{ \sum_{k=0}^{K} C_k \left(s_k, \pi(s_k), \omega(k) \right) \right\}$$

- Where C: cost, s: state, π: policy, ω: random disturbances, k: time step
- Many devices with possibly complex couplings $\rightarrow$ large state and action spaces
- Can be solved using either dynamic programming ot mathematical programming (typically mixed-integer linear programming)
- Can be computationally challenging

[4] C. Keerthisinghe, G. Verbič, and A. C. Chapman, "A Fast Technique for Smart Home Management: ADP with Temporal Difference Learning," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3291–3303, July 2018.

Home energy management: Linear programming (LP) formulation

- User demand split into appliances (e.g. pool pump, HVAC, water heater) requires MILP
- Users predict their demand and generation for time-slot $t \in \mathcal{T}$
- Net electric energy required by agent $a \neq 0$: $\boldsymbol{x}_a^{\text{net}} = \left[x_{a,t}^{\text{net}}, \ldots, x_{a,t+T-\Delta t}^{\text{net}}\right]$
- Users can feed power into the grid: $x_{a,t}^{\text{net}} = x_{a,t}^{+} - x_{a,t}^{-}$, such that $\underline{P}_a \Delta t \leq x_{a,t}^{\text{net}} \leq \overline{P}_a \Delta t$



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HEM: LP formulation

- Then, the optimization problem of a local HEMS for each user is given by:

$$\begin{aligned} \underset{\boldsymbol{x}_a \in \mathcal{X}_a}{\text{minimise}} \quad & \sum_{t \in \mathcal{T}} \sigma_t^{\text{ft/tou}} x_{a,t}^{+} - \sigma^{\text{fit}} x_{a,t}^{-} \\ \text{subject to} \quad & \text{power balance constraints} \\ & \text{DER operational constraints} \\ & \forall t \in \mathcal{T} \end{aligned}$$

- Power balance constraints:

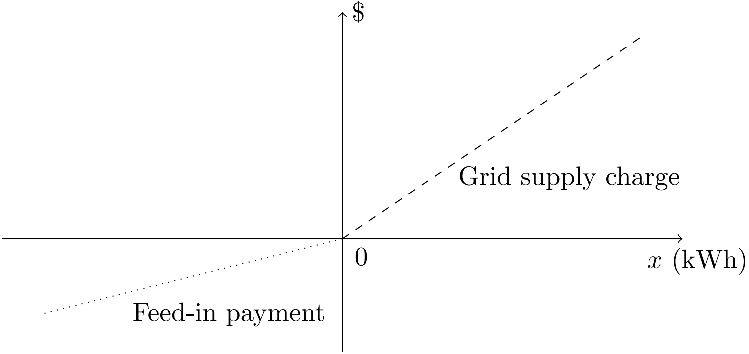
$$x_{a,t}^{+} = x_{a,t}^{\text{load}} - \eta_a^{\text{inv}} \left(x_{a,t}^{\text{batt,dem}} - x_{a,t}^{\text{batt,ch}} + x_{a,t}^{\text{pv}} \right)$$

$$x_{a,t}^{-} = \eta_a^{\text{inv}} \left(x_{a,t}^{\text{batt,grid}} + x_{a,t}^{\text{pv}} \right)$$

$$x_{a,t}^{\text{batt,dis}} = x_{a,t}^{\text{batt,dem}} + x_{a,t}^{\text{batt,grid}}$$

Home energy management: Linear programming (LP) formulation

- Since the feed-in tariff is assumed to be always less than the retail tariff, each term in the summation is convex
- Reformulating a piece-wise affine objective function can only be applied to the minimisation of a convex function



HEM: LP formulation

- Battery model:

$$
\begin{aligned}
& x_{a,t}^{\text{batt}} = x_{a,t}^{\text{batt,dis}} - x_{a,t}^{\text{batt,ch}} \\
& \underline{\gamma}_a^{\text{batt,ch}} \Delta t \leq x_{a,t}^{\text{batt,ch}} \leq \overline{\gamma}_a^{\text{batt,ch}} \Delta t \\
& \underline{\gamma}_a^{\text{batt,dis}} \Delta t \leq x_{a,t}^{\text{batt,dis}} \leq \overline{\gamma}_a^{\text{batt,dis}} \Delta t \\
& e_{a,t}^{\text{batt}} = e_{a,t-\Delta t}^{\text{batt}} + \eta_a^{\text{ch}} x_{a,t}^{\text{batt,ch}} - \frac{x_{a,t}^{\text{batt,dis}}}{\eta_a^{\text{dis}}} \\
& \underline{e}_a^{\text{batt}} \leq e_{a,t}^{\text{batt}} \leq \overline{e}_a^{\text{batt}} \\
& e_a^{\text{batt},\tau_a^{\text{batt,start}} - \Delta t} = e_a^{\text{batt,ini}} \\
& e_a^{\text{batt},\tau_a^{\text{batt,end}}} \geq e_a^{\text{batt,final}}
\end{aligned}
$$

Home energy management with operating envelopes

Home energy management with operating envelopes

- Operating envelopes determine the amount of power a prosumer can inject to the grid
- They can be obtained from the power flow Jacobian matrix:

$$J = \begin{bmatrix} \frac{\partial P}{\partial |V|} & \frac{\partial P}{\partial \theta} \\ \frac{\partial Q}{\partial |V|} & \frac{\partial Q}{\partial \theta} \end{bmatrix}$$

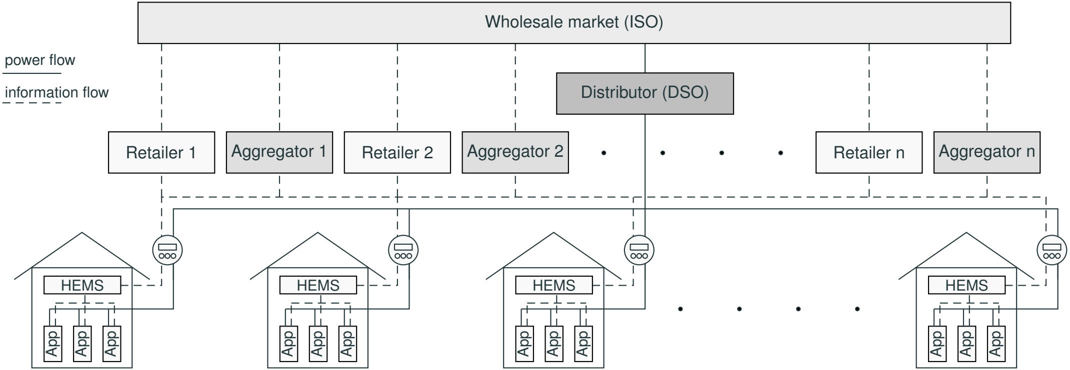
- Impact of prosumer power injection on voltage at the connection point i:

$$\Delta V_i = \left(\frac{\partial V_i}{\partial P_i}\right) \Delta P_i + \left(\frac{\partial V_i}{\partial Q_i}\right) \Delta Q_i$$

- Requires state estimation, currently not done in distribution networks
- Operating envelopes are location dependent, which raises the question of fairness

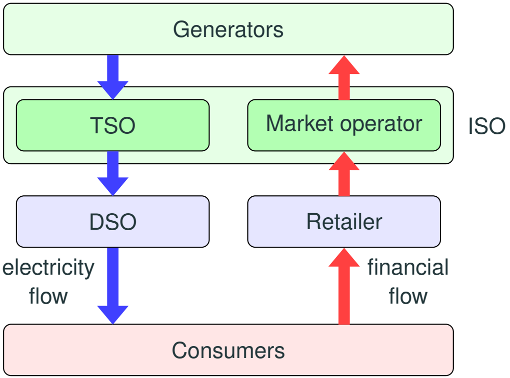
Virtual power plants

Prosumer aggregation



Market structure: Passive vs. active demand side

Deregulated



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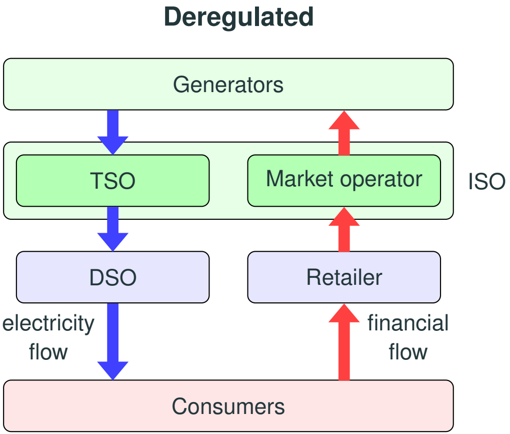

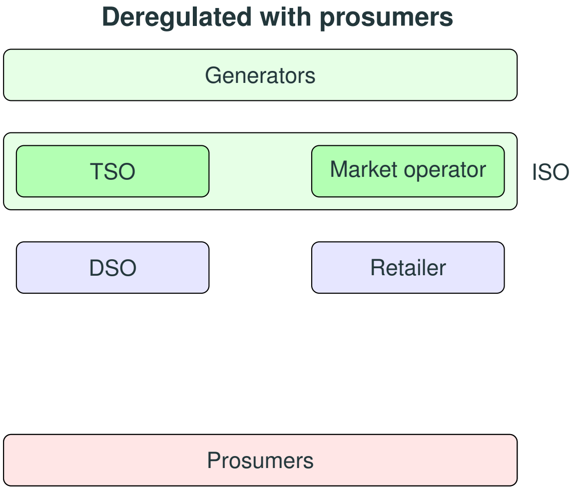

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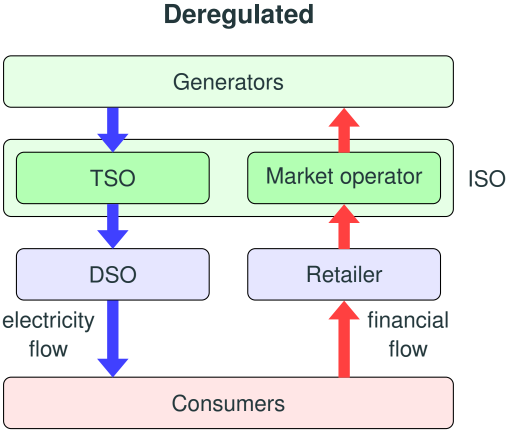
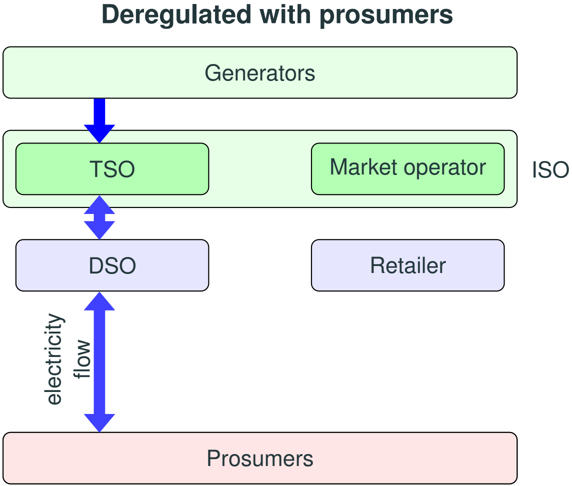
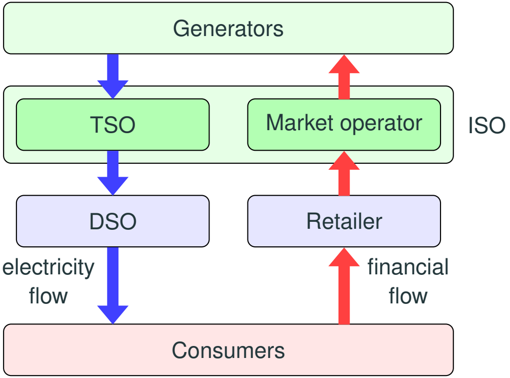


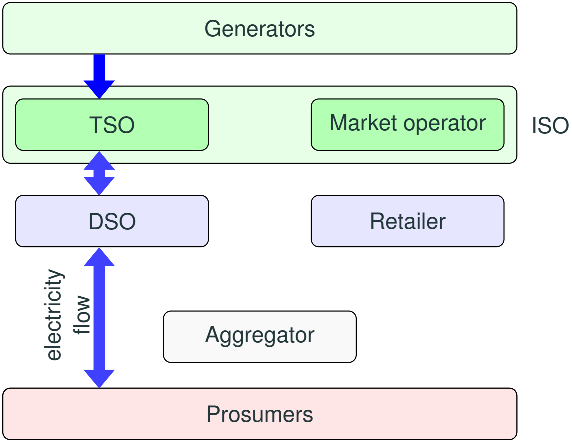


Market structure: Passive vs. active demand side

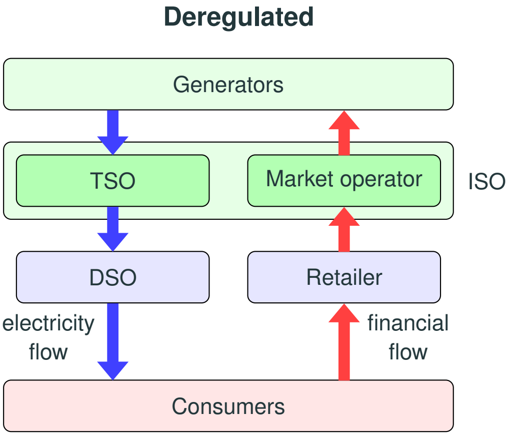
Deregulated

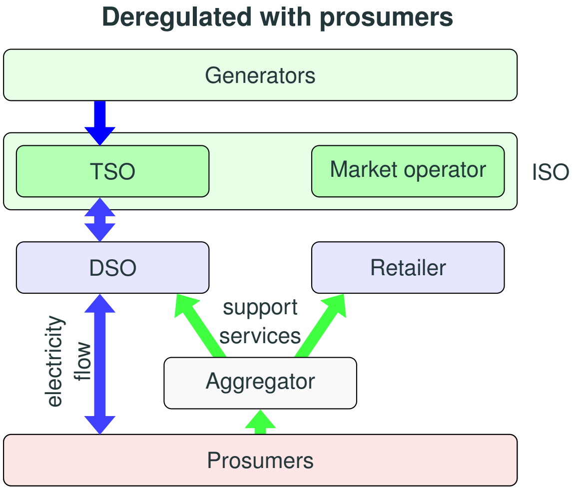


Deregulated with prosumers

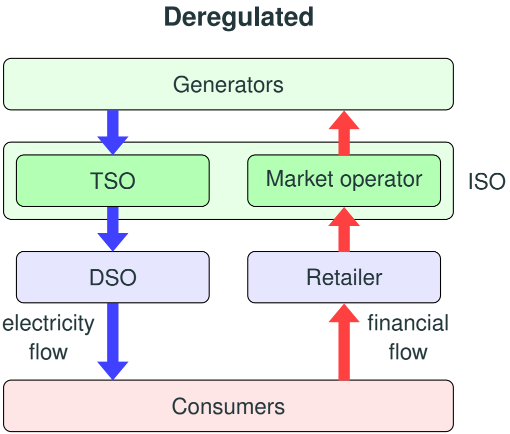


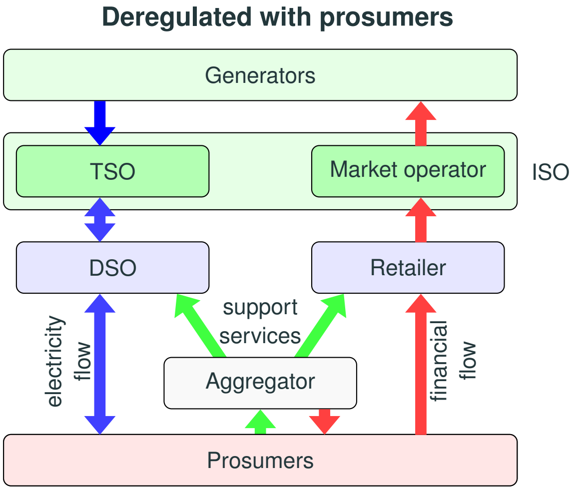
Market structure: Passive vs. active demand side



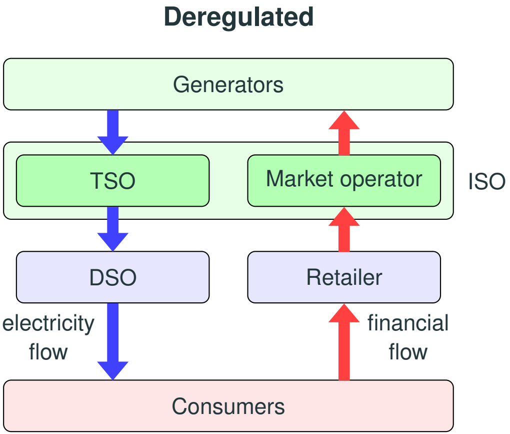


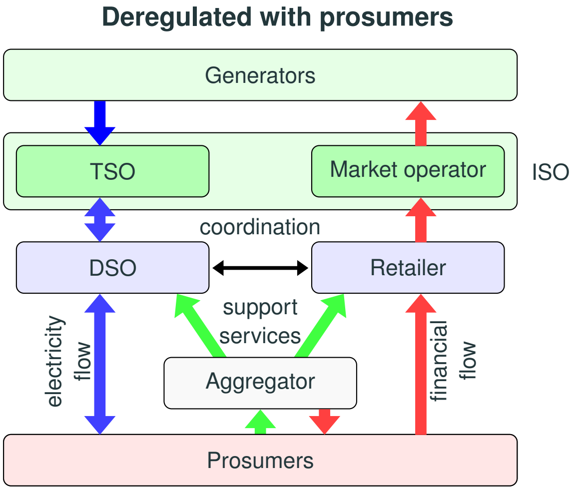
Market structure: Passive vs. active demand side





Market structure: Passive vs. active demand side



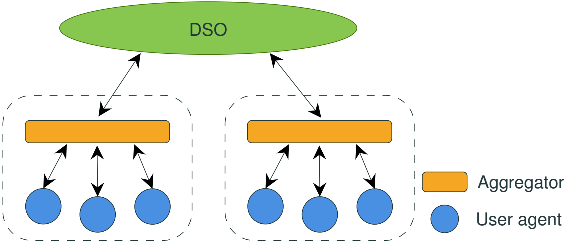


Canonical DER coordination problem

- We assume a distribution system operator (DSO) responsible for reliable and secure operation
- The DER coordination problem can be written in general form:

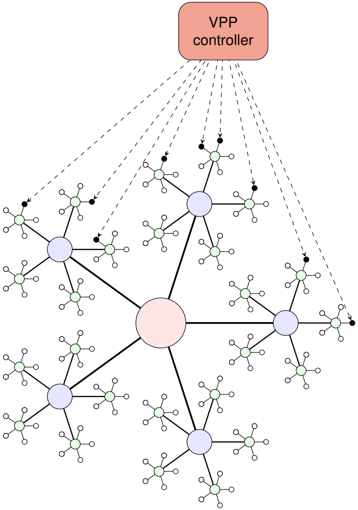
$$\text{minimise } F(\boldsymbol{x}), \quad \boldsymbol{x} \in \mathcal{X}$$

- Objective $F(\boldsymbol{x})$ depends on the framework (typically cost minimisation)
- Feasible set $\mathcal{X}$ includes aggregator, agent and network decision variables ($\mathcal{X} = \mathcal{X}_0 \cup \mathcal{X}_\mathrm{a} \cup \mathcal{X}_\mathrm{n}$)



State of the art: Retailer VPP (VPP 0.0)

- Direct load control by a retailer (no optimisation)
- Batteries used to mitigate price exposure
- Batteries located in different MV networks
- Users have no control over when VPP uses their batteries
- Battery controller (heuristic):
    - Self-consumption maximisation
    - Price arbitrage
    - Consumer demand profiles not considered
    - Suboptimal!
- Example: AGL Tesla VPP
- Demand response mechanism rule change (24 October 2021)



System-focused VPP (VPP 1.0)

- The objective of the aggregator is to minimise cost (maximise social welfare):

$$
\begin{aligned}
\underset{\boldsymbol{x}_a \in \mathcal{X}_a, \boldsymbol{x}_0 \in \mathcal{X}_0}{\text{minimise}} \quad & f(\boldsymbol{x}_0) \\
\text{subject to} \quad & \sum_{a \in \mathcal{A} \setminus 0} x_{a,t}^{\text{net}} = x_{0,t}, \qquad \forall t \in \mathcal{T}
\end{aligned}
$$

- Aggregator cost function $f(\boldsymbol{x}_0) = \sum_{t \in \mathcal{T}} C(x_{0,t})$ can represent cost of electricity in wholesale market (energy and ancillary services), system losses, or cost of auxiliary supply, e.g. diesel
- Quadratic function captures generation cost of a wide range of technologies:

$$
C(x_{0,t}) = c_2 (x_{0,t})^2 + c_1 x_{0,t} + c_0
$$

- Consumer DER are controlled by the aggregator
- Multiperiod to account for inter-temporal couplings
- Rolling-horizon approach to reduce computational burden and forecast error (akin to MPC)

Consumer-focused VPP (VPP 2.0)

- The objective of the aggregator is to minimise system and customer cost:

$$\begin{aligned} \underset{\boldsymbol{x}_a \in \mathcal{X}_a, \boldsymbol{x}_0 \in \mathcal{X}_0}{\text{minimise}} \quad & f(\boldsymbol{x}_0) + \gamma \sum_{a \in \mathcal{A} \setminus 0} g_a(\boldsymbol{x}_a) \\ \text{subject to} \quad & \sum_{a \in \mathcal{A} \setminus 0} x_{a,t}^{\text{net}} = x_{0,t}, \qquad \forall t \in \mathcal{T} \end{aligned}$$

- Term $g_a(\boldsymbol{x}_a) = \sum_{t \in \mathcal{T}} \sigma_t^{\text{ft/tou}} x_{a,t}^{+} - \sigma^{\text{fit}} x_{a,t}^{-}$ represents users' electricity cost
- Note the optimisation problem of user agents (home energy management problem):

$$\underset{\boldsymbol{x}_a \in \mathcal{X}_a}{\text{minimise}} \quad \sum_{t \in \mathcal{T}} \sigma_t^{\text{ft/tou}} x_{a,t}^{+} - \sigma^{\text{fit}} x_{a,t}^{-}$$

- Consumer preferences now also considered

Consumer-focused VPP (VPP 2.0): Solution approach

- Large-scale optimisation problem solved in a distributed fashion using dual decomposition
- Power balance constraint is ‘relaxed’ and put in the objective, which gives (partial) Lagrangian:

$$L_{\mathrm{VPP}}(\boldsymbol{x},\boldsymbol{\lambda}) := f(\boldsymbol{x}_0) + \gamma \sum_{a\in\mathcal{A}\setminus 0} g_a(\boldsymbol{x}_a) + \sum_{t\in\mathcal{T}} \lambda_t \left(\sum_{a\in\mathcal{A}\setminus 0} x^{\mathrm{net}}_{a,t} - x_{0,t} \right)$$

- Lagrange dual function: $D(\boldsymbol{\lambda}) := \underset{\boldsymbol{x}_a\in\mathcal{X}_\mathrm{a},\boldsymbol{x}_0\in\mathcal{X}_0}{\text{minimise}} \; L_{\mathrm{VPP}}(\boldsymbol{x},\boldsymbol{\lambda})$
- Lagrange dual function is separable so it can be solved in parallel:

$$D(\boldsymbol{\lambda}) := \underset{\boldsymbol{x}_a\in\mathcal{X}_\mathrm{a},\boldsymbol{x}_0\in\mathcal{X}_0}{\text{minimise}} \left(D_0(\boldsymbol{\lambda}) + \sum_{a\in\mathcal{A}\setminus 0} D_a(\boldsymbol{\lambda}) \right)$$

- Distributed optimisation using price coordination

Consumer-focused VPP (VPP 2.0): Solution approach

- User agents solve:

$$D_a(\boldsymbol{\lambda}) := \underset{\boldsymbol{x}_a \in \mathcal{X}_a}{\text{minimise}} \;\; g_a(\boldsymbol{x}_a) + \sum_{t \in \mathcal{T}} \lambda^k x^{\text{net}}_{a,t}$$

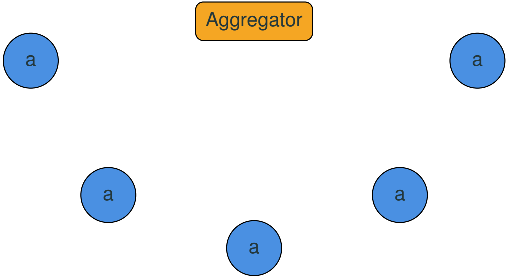
- Aggregator solves:

$$D_0(\boldsymbol{\lambda}) := \underset{\boldsymbol{x}_0 \in \mathcal{X}_0}{\text{minimise}} \;\; f(\boldsymbol{x}_0) - \sum_{t \in \mathcal{T}} \lambda^k x_{0,t}$$

- Lagrangian multiplier update:

$$\boldsymbol{\lambda}^{k+1} = \boldsymbol{\lambda}^k + \alpha^k \left(\sum_{a \in \mathcal{A} \setminus 0} \boldsymbol{x}^{\text{net}}_a - \boldsymbol{x}_0 \right)$$

- Not so straightforward if the problem contains integer variables



[5] S. Mhanna, A. C. Chapman, and G. Verbič, A fast distributed algorithm for large-scale demand response aggregation,” *IEEE Transactions on Smart Grid*, vol. 7, no. 4, pp. 2094–2107, July 2016.

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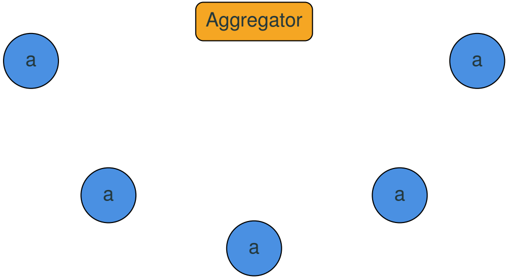

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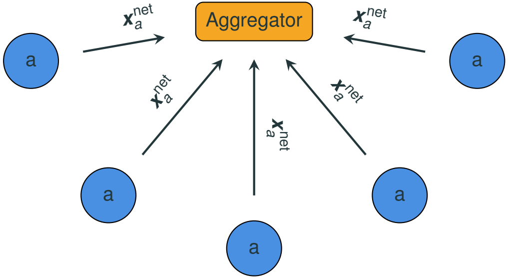

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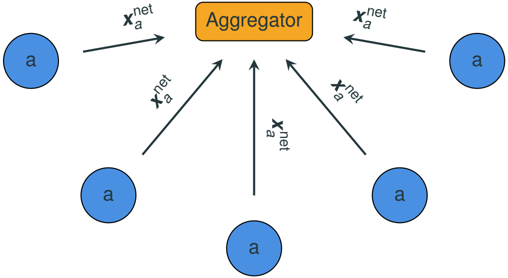

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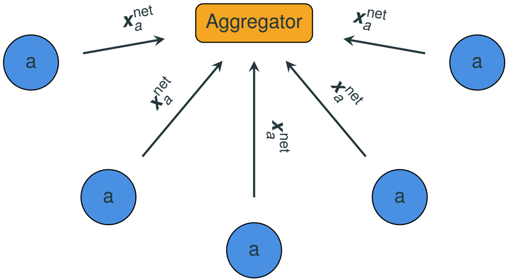

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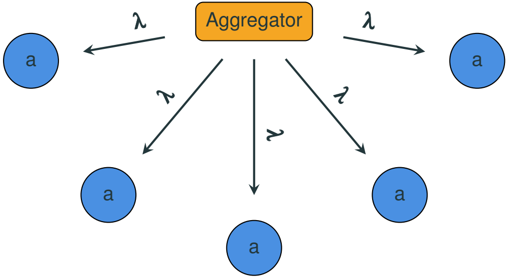

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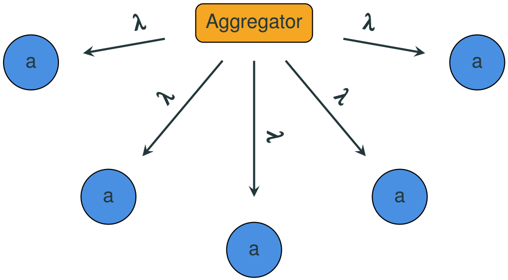

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Network-aware coordination: distributed optimal power flow

OPF: Problem formulation (VPP 3.0)

- OPF DER aggregation problem is formulated as ($\mathcal{X} = \mathcal{X}_\mathrm{a} \cup \mathcal{X}_\mathrm{n}$, $x_0 \in \mathcal{X}_\mathrm{n}$):

$$\underset{\boldsymbol{x}_n \in \mathcal{X}_\mathrm{n}, \boldsymbol{x}_a \in \mathcal{X}_\mathrm{a}}{\text{minimise}} \quad f(\boldsymbol{x}_0) + \gamma \sum_{a \in \mathcal{A} \setminus 0} g_a(\boldsymbol{x}_a)$$

- Feasible set $\mathcal{X}_\mathrm{n}$ of network variables $\boldsymbol{x}_n \in \mathcal{X}_\mathrm{n}$, $\forall t \in \mathcal{T}$ is defined by:
  - Power balance constraints $\forall i \in \mathcal{N}$, $p_{\mathrm{g},i} = q_{\mathrm{g},i} = 0 \;\; \forall i \in \mathcal{N} \setminus 0$:

$$p^\mathrm{g}_{i,t} - p^\mathrm{d}_{i,t} = v_{i,t} \sum_{j \in \mathcal{N}} v_{j,t} (g_{ij} \cos\theta_{ij,t} + b_{ij} \sin\theta_{ij,t})$$

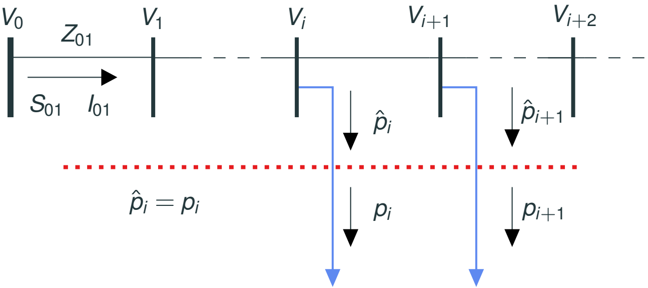
$$q^\mathrm{g}_{i,t} - q^\mathrm{d}_{i,t} = v_{i,t} \sum_{j \in \mathcal{N}} v_{j,t} (g_{ij} \sin\theta_{ij,t} - b_{ij} \cos\theta_{ij,t})$$

  - Voltage and power constraints: $\underline{v} \leq v_{i,t} \leq \overline{v}$, $\underline{p} \leq p_t \leq \overline{p}$, $\underline{q} \leq q_t \leq \overline{q}$
- Problem is not decomposable because $p^\mathrm{d}_{i,t} = p^\mathrm{net}_{a,t}$ appears both in $\mathcal{X}_\mathrm{n}$ and $\mathcal{X}_\mathrm{a}$

OPF: Decomposition approach

- To decompose the problem, we create two copies of powers injected, p_i, at each bus i where agent a is located, and introduce the following coupling constraints:

$$\hat{p}_{i,t} = p_{i,t}, \quad \{\forall a \in \mathcal{A} \setminus 0 | \mathcal{A} \subseteq \mathcal{N}\}, \forall t \in \mathcal{T}$$



OPF: Decomposition approach

- OPF problem in a general form:

$$\begin{aligned}\underset{\boldsymbol{x}_n\in\mathcal{X}_\mathrm{n},\boldsymbol{x}_a\in\mathcal{X}_\mathrm{a}}{\text{minimise}} \quad & f(\boldsymbol{x}_0)+\gamma\sum_{a\in\mathcal{A}\setminus 0} g_a(\boldsymbol{x}_a)\\ \text{subject to} \quad & \boldsymbol{p}_a=\hat{\boldsymbol{p}}_a,\quad \forall a\in\mathcal{A}\end{aligned}$$

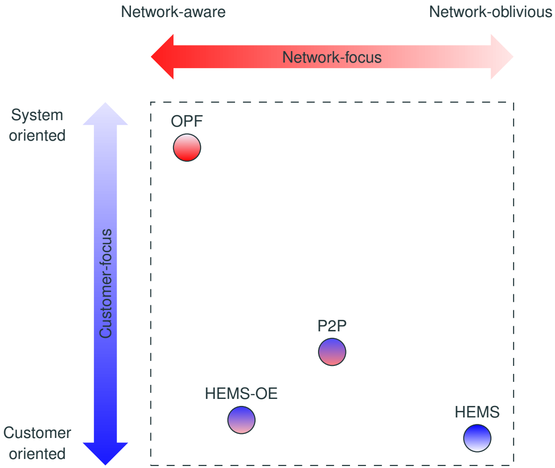
- Augmented Lagrangian:

$$L(\boldsymbol{x}_n,\boldsymbol{x}_a,\boldsymbol{\lambda}_a) := f(\boldsymbol{x}_n)+\sum_{a\in\mathcal{A}\setminus 0} g_a(\boldsymbol{x}_a)+\sum_{t\in\mathcal{T}}\left(\lambda_{a,t}(p_{a,t}-\hat{p}_{a,t})+\frac{\rho}{2}(p_{a,t}-\hat{p}_{a,t})^2\right)$$

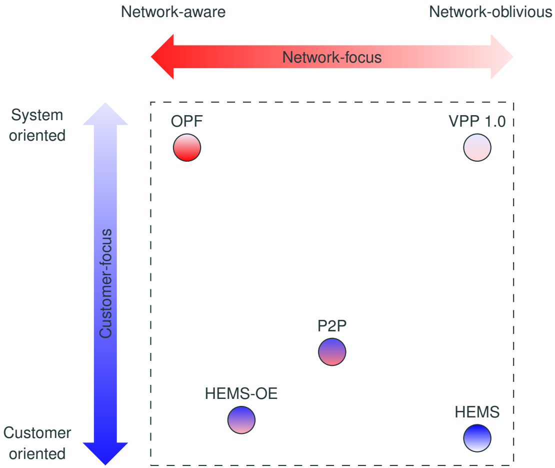
- Solution using Alternating Direction of Multipliers Method (ADMM):

$$\begin{aligned}\boldsymbol{x}_n^{k+1} &:= \underset{\boldsymbol{x}_n\in\mathcal{X}_\mathrm{n}}{\arg\min}\; L(\boldsymbol{x}_n,\boldsymbol{x}_a^k,\boldsymbol{\lambda}_a^k)\\ \boldsymbol{x}_a^{k+1} &:= \underset{\boldsymbol{x}_a\in\mathcal{X}_a}{\arg\min}\; L(\boldsymbol{x}_n^{k+1},\boldsymbol{x}_a,\boldsymbol{\lambda}_a^k) && \forall a\in\mathcal{A}\setminus 0\\ \boldsymbol{\lambda}_a^{k+1} &:= \boldsymbol{\lambda}_a^k+\rho(\boldsymbol{p}_a^{k+1}-\hat{\boldsymbol{p}}_a^{k+1}) && \forall a\in\mathcal{A}\setminus 0\end{aligned}$$

VPP evolution



VPP evolution



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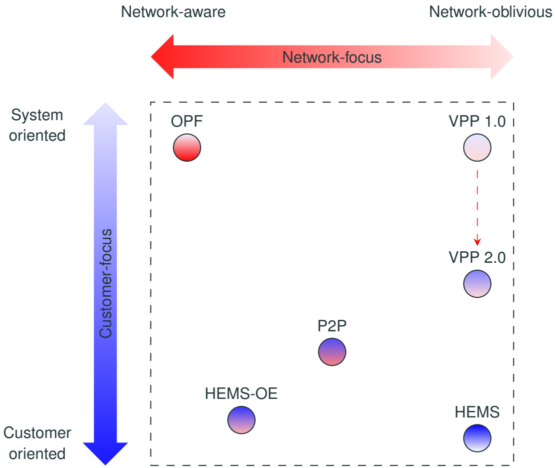

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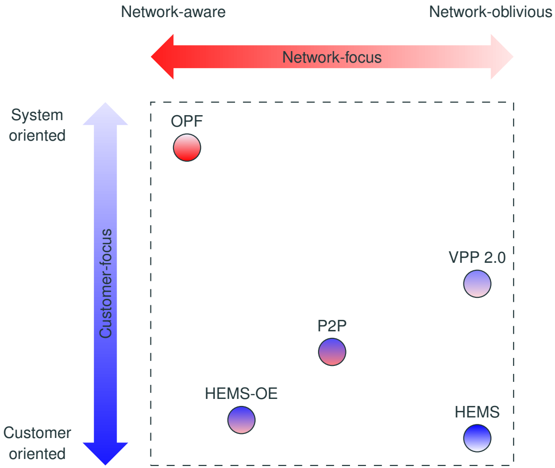

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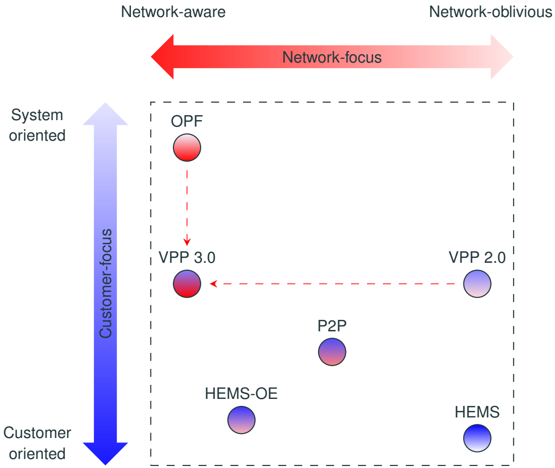

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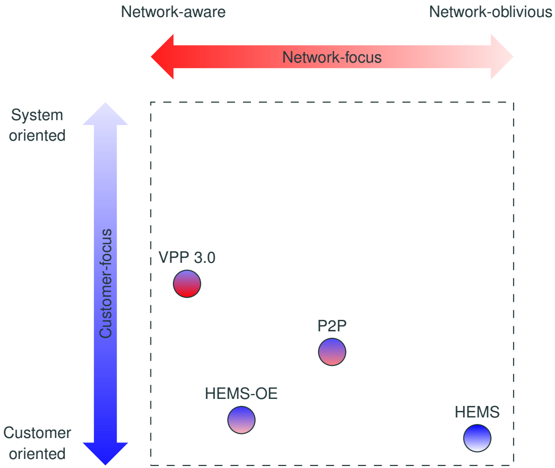
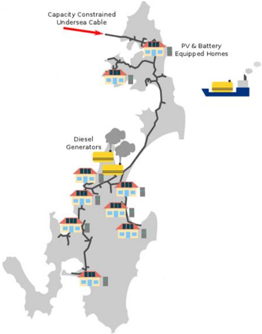


CONSORT
Bruny Island Battery Trial

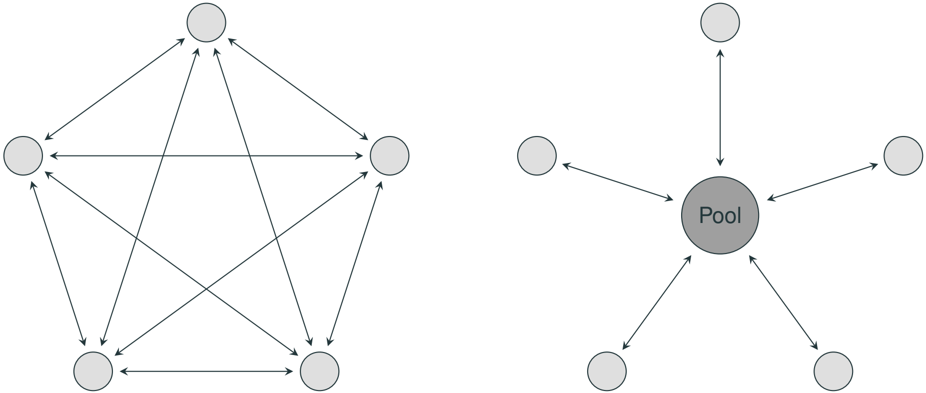
- $4.2M project ($2.9M ARENA)
- 2016-2019, 5 partners
- 32 PV-battery systems to solve a network congestion problem
- Network-aware coordination
- Reward structures (non-linear pricing)
- Social science research (customer acceptance)



ARENA Australian Government Australian Renewable Energy Agency · Australian National University · TasNetworks Delivering your power · reposit · UNIVERSITY of TASMANIA · THE UNIVERSITY OF SYDNEY

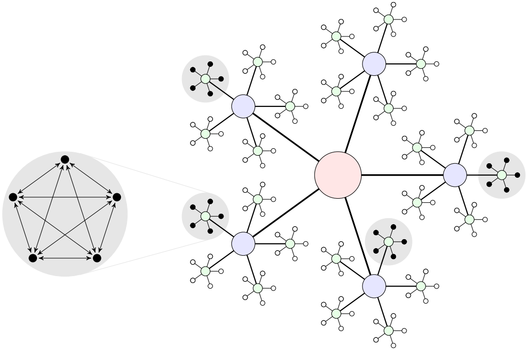
Peer-to-peer energy trading

P2P vs pool market



P2P energy market

- Prosumer form a local energy market
- Excess energy is shared with neighbours
- Limited to a single LV network
- Trades can be facilitated by a third party



P2P energy trading: Multi-bilateral economic dispatch

- Problem formulation:

$$
\begin{aligned}
\underset{\boldsymbol{p}^{\mathrm{s}},\boldsymbol{p}^{\mathrm{b}}}{\text{maximise}} \quad & \sum_{a\in\mathcal{S}} w_a^{\mathrm{s}} + \sum_{a\in\mathcal{B}} w_a^{\mathrm{b}} \\
\text{subject to} \quad & p_{ij} \geq 0 && \forall i \in \mathcal{S},\ j \in \mathcal{B} \\
& p_{ij} \leq 0 && \forall i \in \mathcal{B},\ j \in \mathcal{S} \\
& \underline{p}_a^{\mathrm{s}} \leq p_a^{\mathrm{s}} \leq \overline{p}_a^{\mathrm{s}} && \forall a \in \mathcal{S} \\
& \underline{p}_a^{\mathrm{b}} \leq p_a^{\mathrm{b}} \leq \overline{p}_a^{\mathrm{b}} && \forall a \in \mathcal{B} \\
& p_{ij} = p_{ji} && \forall (i,j) \in (\mathcal{S},\mathcal{B}),\ \forall (j,i) \in (\mathcal{B},\mathcal{S})
\end{aligned}
$$

- Welfare of seller $i \in \mathcal{S}$: $w_i^{\mathrm{s}} = \sum_{j\in\mathcal{B}} \pi_{ij} p_{ij} - c_i^{\mathrm{s}}\left(p_i^{\mathrm{s}}\right)$
- Welfare of buyer $j \in \mathcal{B}$: $w_j^{\mathrm{b}} = u_j^{\mathrm{b}}(p_j^{\mathrm{b}}) - \sum_{i\in\mathcal{S}} \pi_{ji} p_{ji}$

[6] E. Sorin, L. Bobo, and P. Pinson, “Consensus-Based Approach to Peer-to-Peer Electricity Markets with Product Differentiation,” *IEEE Transactions on Power Systems*, vol. 34, no. 2, Mar. 2019.

P2P energy trading: Multi-bilateral economic dispatch

- Sellers' production cost: $c(p^s) = \frac{1}{2}\alpha^s (p^s)^2 + \beta^s p^s + \gamma^s$
- Buyers' utility $\left(\frac{du}{dp} \geq 0, \quad \frac{d^2u}{dp^2} \leq 0, \quad u(0) = 0\right)$:

$$u(p^b) = \begin{cases} \beta p - \frac{\alpha}{2}(p^b)^2 & \text{if } 0 \leq p^b \leq \frac{\beta}{\delta} \\ \frac{\beta^2}{2\delta} & \text{if } \frac{\beta}{\delta} \leq p^b \end{cases}$$

- The reciprocity constraint $p_{ij} = p_{ji}$ implies: $\sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{B}} \pi_{ij} p_{ij} = \sum_{j\in\mathcal{B}}\sum_{i\in\mathcal{S}} \pi_{ji} p_{ji}$
- The objective becomes:

$$\underset{\boldsymbol{p}^s,\boldsymbol{p}^b}{\text{maximise}} \quad \sum_{a\in\mathcal{B}} u_a^b\left(p_a^b\right) - \sum_{a\in\mathcal{S}} c_a^s\left(p_a^s\right) + \sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{B}} c_{ij} p_{ij}$$

- Product differentiation can be imposed by adding transaction cost $\sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{B}} c_{ij} p_{ij}$

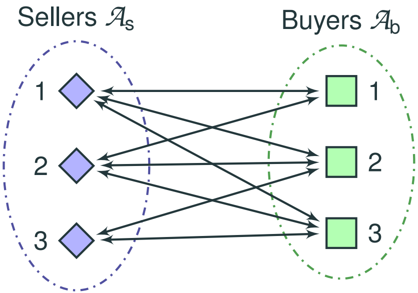
Auction-based P2P energy trading: Preliminary concepts

- Many-to-many market (cf. one-to-one and one-to-many)
- Set of agents $\mathcal{A} = \mathcal{A}_b \cup \mathcal{A}_s$:
  - Buyers $\mathcal{A}_b$, $b = 1, 2, \ldots, N_b$
  - Sellers $\mathcal{A}_s$, $s = 1, 2, \ldots, N_s$
- Trade $\omega \in \Omega$: $\langle b, s, \alpha_\omega, \pi_\omega \rangle$, where α_ω is transaction price and π_ω is amount of traded energy
- Buyers' utility:

$$u_b(d_b) \triangleq \begin{cases} v_b(d_b) - \sum_{\omega \in \Omega_b} \alpha_\omega \pi_\omega & \text{if } \Omega_b \notin \varnothing \\ 0 & \text{otherwise} \end{cases}$$

- Sellers' utility:

$$u_s(g_s) \triangleq \begin{cases} \sum_{\omega \in \Omega_s} \alpha_\omega \pi_\omega - v_s(g_s) & \text{if } \Omega_s \notin \varnothing \\ 0 & \text{otherwise} \end{cases}$$



Auction-based P2P energy trading: Continuous double auction (CDA)

- CDA is a many-to-many auction, with multiple buyers and sellers (e.g. eBay)
- Buyers and sellers can make offers at any time during the trading period
- Requires an auctioneer, which can be an automated software agent
- Seller' bids and buyers' asks can be stored in a distributed ledger (e.g. Blockchain), resulting in a fully decentralized marketplace
- Bid $o_b = \langle b, \alpha_b, \pi_b, t \rangle$: offer from buyer b to purchase quantity π_b at a maximum unit price α_b
- Ask $o_s = \langle s, \alpha_s, \pi_s, t \rangle$: offer from seller s to sell quantity π_s at a minimum unit price α_s
- Thin market: finding an 'optimal' bidding strategy impossible
- Automated zero intelligence plus (ZIP) traders use an adaptive mechanism, which can give performance very similar to that of human traders in stock markets
- Limit prices forbid the trader to buy or sell at a loss (ToU for buyers, FiT for sellers)

Auction-based P2P energy trading: Continuous double auction (CDA)

- Bids and asks are queued and published in an order book
- The current best (uncleared) bid/ask called the outstanding bid/ask $o_b^\star / o_s^\star$
- Matching between new bid/ask and outstanding ask/bid results in a trade $\omega = \langle b, s, \alpha_\omega, \pi_\omega \rangle$

Auction-based P2P energy trading: Matching theory

- Decentralised matching mechanism based on stable matching theory
- Agents bid in the market and choose bids/asks that maximise their utility
- Let $\Omega^\star := \bigcup_{\omega \in \Omega} (\Omega_b^\star \cap \Omega_s^\star)$ be the set of all optimal matches
- The set of trades $\Omega_b^\star \subseteq \Omega$ that maximises the utility of buyers is given by

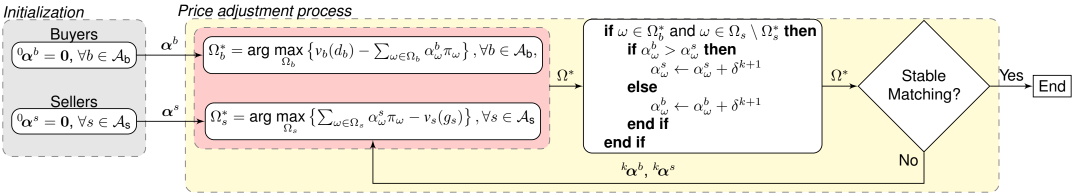
$$\Omega_b^\star = \arg\max_{\Omega_b} \left\{ v_b(d_b) - \sum_{\omega \in \Omega_b} \alpha_\omega^b \pi_\omega \right\}, \quad \forall b \in \mathcal{A}_\mathrm{b}$$

- The set of trades $\Omega_s^\star \subseteq \Omega$ that maximises the utility of sellers is given by

$$\Omega_s^\star = \arg\max_{\Omega_s} \left\{ \sum_{\omega \in \Omega_s} \alpha_\omega^s \pi_\omega - v_s(g_s) \right\}, \quad \forall s \in \mathcal{A}_\mathrm{s}$$

Matching theory-based P2P energy trading: Price adjustment

- Ascending auction: prices in the bidding can only increase
- Steps in each iteration: price adjustment, proposals, acceptance/rejection
- At each iteration k, let ${}^{k}\boldsymbol{\alpha}^{b} = [\alpha_1^b, \alpha_2^b, \ldots, \alpha_{|\Omega|}^b]$ denotes the $|\Omega| \times 1$ vector of bid prices from each buyer $b \in \mathcal{A}_b$ for each a trade $\omega \in \Omega$
- For each seller, $s \in \mathcal{A}_s$, let ${}^{k}\boldsymbol{\alpha}^{s} = [\alpha_1^s, \alpha_2^s, \ldots, \alpha_{|\Omega|}^s]$ be the $|\Omega| \times 1$ vector of its ask prices for each trade $\omega \in \Omega$



Auction-based P2P energy trading: Network permission structure

- Network impact of bilateral transactions estimated through sensitivity coefficients
- Voltage sensitivity coefficients (VSC)

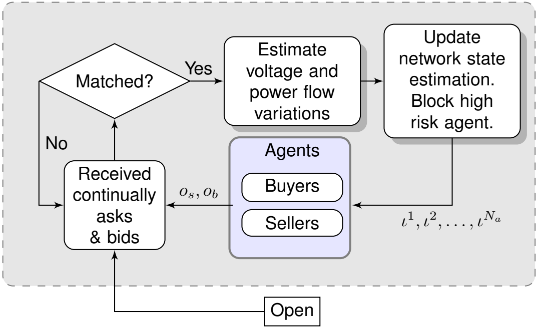
$$\Delta |V_i| = \frac{\Delta P_n}{|V_i|} \mathrm{Re}\left(V_i^* \frac{\partial V_i}{\partial P_n} \right)$$

- Power transfer distribution factors (PTDF)

$$\Phi_{nl}^{ij} = \Psi_{nl}^{i} - \Psi_{nl}^{j} = \frac{\Delta P_{nl}^{i}}{\Delta P_i} - \frac{\Delta P_{nl}^{j}}{\Delta P_j}$$

- Loss sensitivity factors (LSF)

$$\frac{\partial P_{\text{loss}}}{\partial P_n} = 2\mathrm{Re}\left[\mathbf{V}^{*\top} G \frac{\partial \mathbf{V}}{\partial P_n} \right]$$

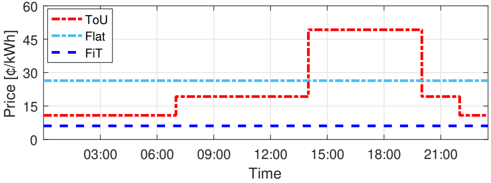


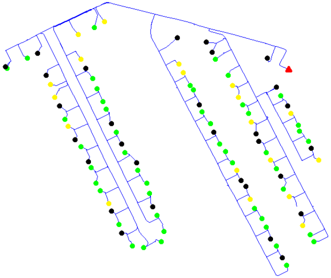
[7] J. Guerrero, A. C. Chapman, and G. Verbič, "Decentralized P2P energy trading under network constraints in a low-voltage network," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, Sep. 2019.

Comparative analysis

LV distribution test system

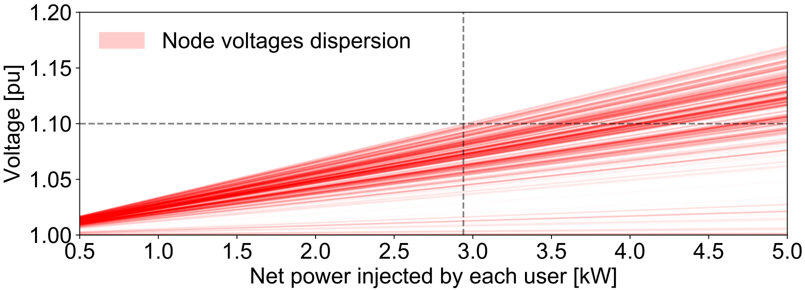
- 30 consumers (black)
- 20 prosumers with only 5 kW PV (yellow)
- 50 prosumers with 5 kW PV and 5 kW/9.8 kWh battery (green)
- Distribution transformer (red)
- Ausgrid Solar Home Electricity Data demand profiles
- Flat, ToU and FiT tariffs



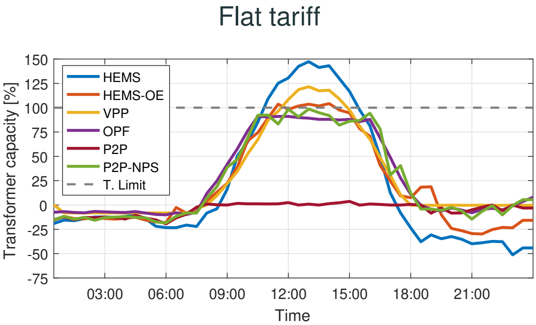


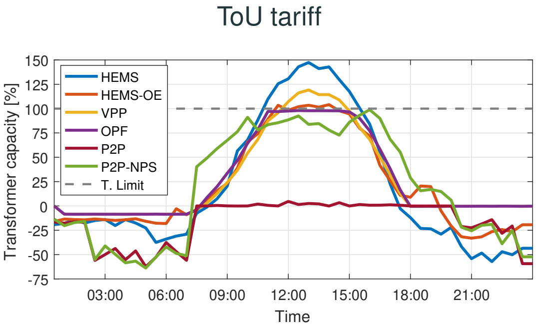
Voltage variation without mitigation

- Voltage at each connection point as a function of net power injection
- Serves as an input to HEMS-OE

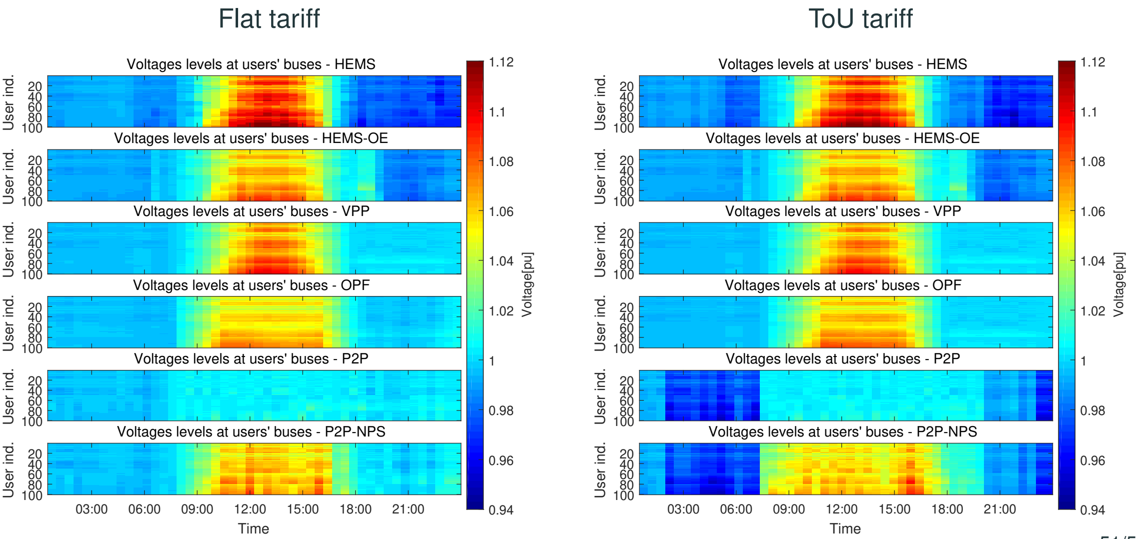


Network congestion (transformer capacity): Flat vs. ToU tariff

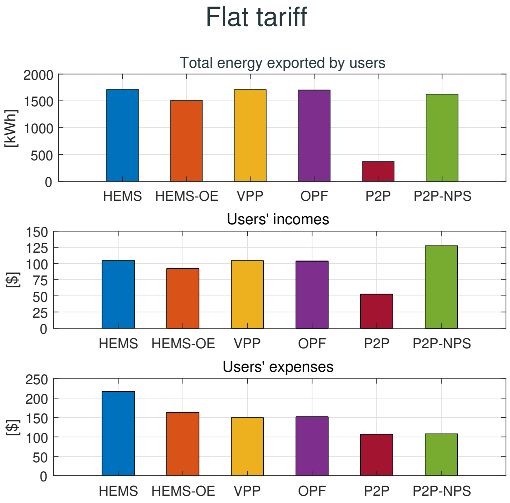


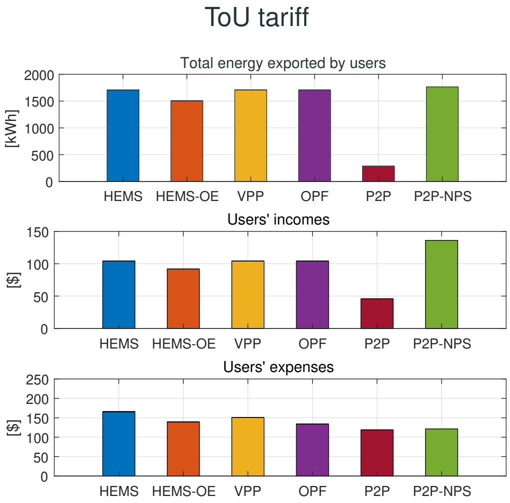


Network voltages: Flat vs. ToU tariff



Exported energy and cash flows: Flat vs. ToU tariff

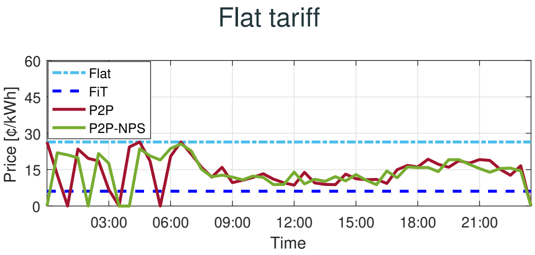


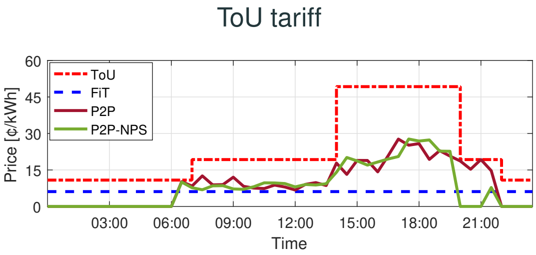


Cash flow comparison

			Flat tariff			
	HEMS	**HEMS-OE**	**VPP**	**OPF**	**P2P**	**P2P-NPS**
Income [$]	104.29	91.85	104.24	103.77	52.71	127.38
Expenses [$]	-217.83	-164.02	-150.59	-151.66	-107.31	-107.95
Net balance [$]	-113.54	-72.17	-46.35	-47.89	-54.6	19.43
			ToU tariff			
	HEMS	**HEMS-OE**	**VPP**	**OPF**	**P2P**	**P2P-NPS**
Income [$]	104.29	91.85	104.35	104.3	45.9	136.13
Expenses [$]	-165.63	-139.61	-151.1	-134.23	-119.12	-121.39
Net balance [$]	-61.34	-47.76	-46.75	-29.93	-73.22	14.74

P2P transaction prices: Flat vs. ToU tariff

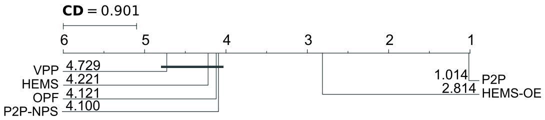




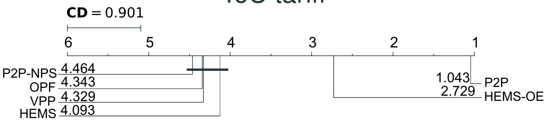
Critical difference analysis

Energy exported

Flat tariff

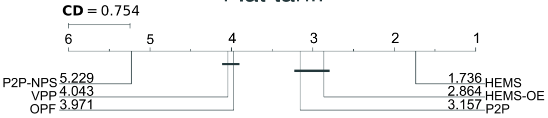


ToU tariff

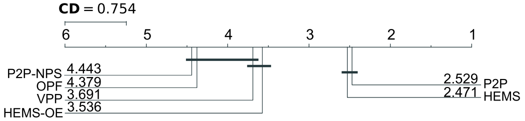


Net cash flow balance

Flat tariff



ToU tariff



Conclusions

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Conclusions

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  - Easily incorporated into existing market framework
  - Require DSO to ensure network constraints are not violated

Conclusions

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- Active network management is required to avoid network problems (DSO)
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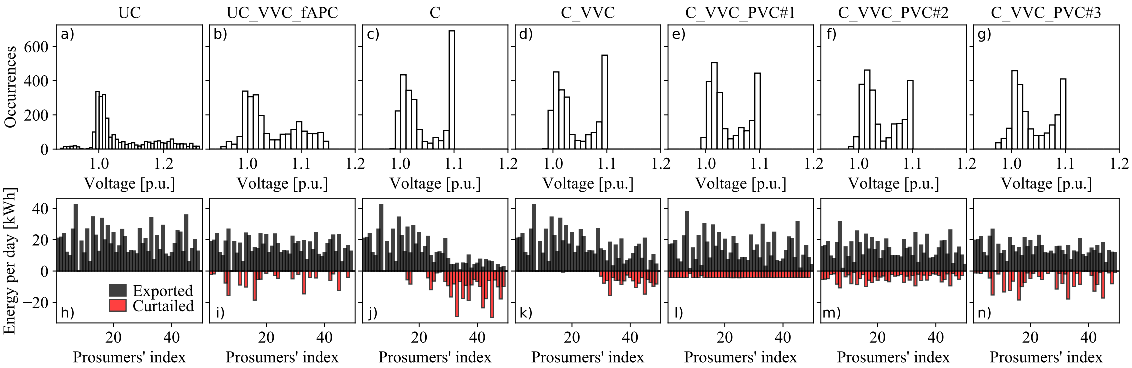
- P2P approaches:
  - Easily incorporated into existing market framework
  - Require DSO to ensure network constraints are not violated
- PV curtailment depends on electrical distance (can be unfair)

Fair DER Coordination with Volt-Var Control and PV Curtailment

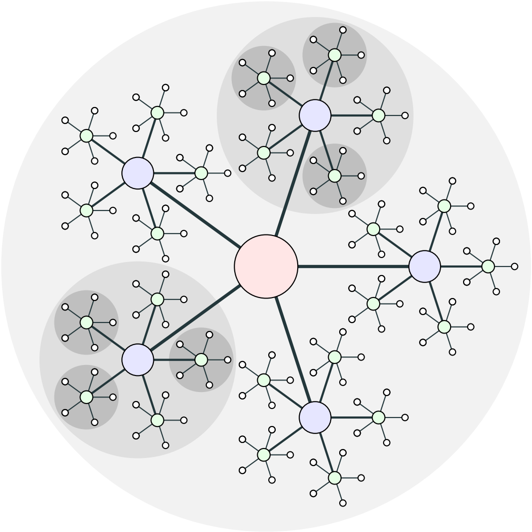


[8] D. Gebbran, S. Mhanna, Y. Ma, A. C. Chapman, and G. Verbič, “Fair coordination of distributed energy resources with Volt-Var control and PV curtailment,” *Applied Energy*, vol. 286, p. 116546, Mar. 2021.

Hierarchical distributed power supply

Future digital grid

- New technologies: DER, power electronics
- New structures: microgrids, VPPs
- New Markets
- Big data



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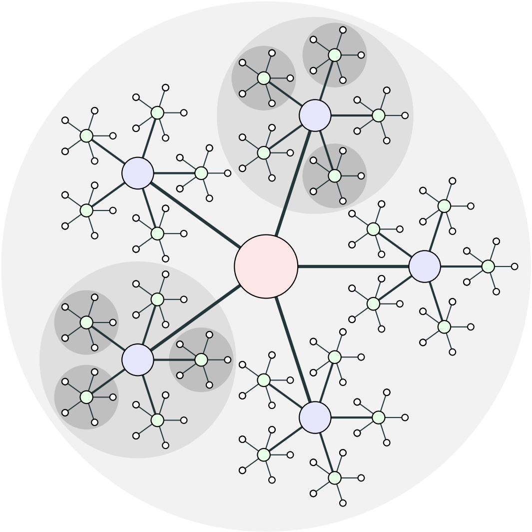
Underpinning science

- Communication
- Computation
- Artificial intelligence
- Data science
- Optimisation and control
- Cyber security



Questions?

Gregor Verbič | Associate Professor
Centre for Future Energy Networks
School of Electrical & Information Engineering
Faculty of Engineering & IT

THE UNIVERSITY OF SYDNEY
Room 307, Electrical Engineering Building, J03
The University of Sydney | NSW | 2006
T +61 2 9351 8136 | **F** +61 2 9351 3847
E gregor.verbic@sydney.edu.au
W http://sydney.edu.au/engineering/electrical