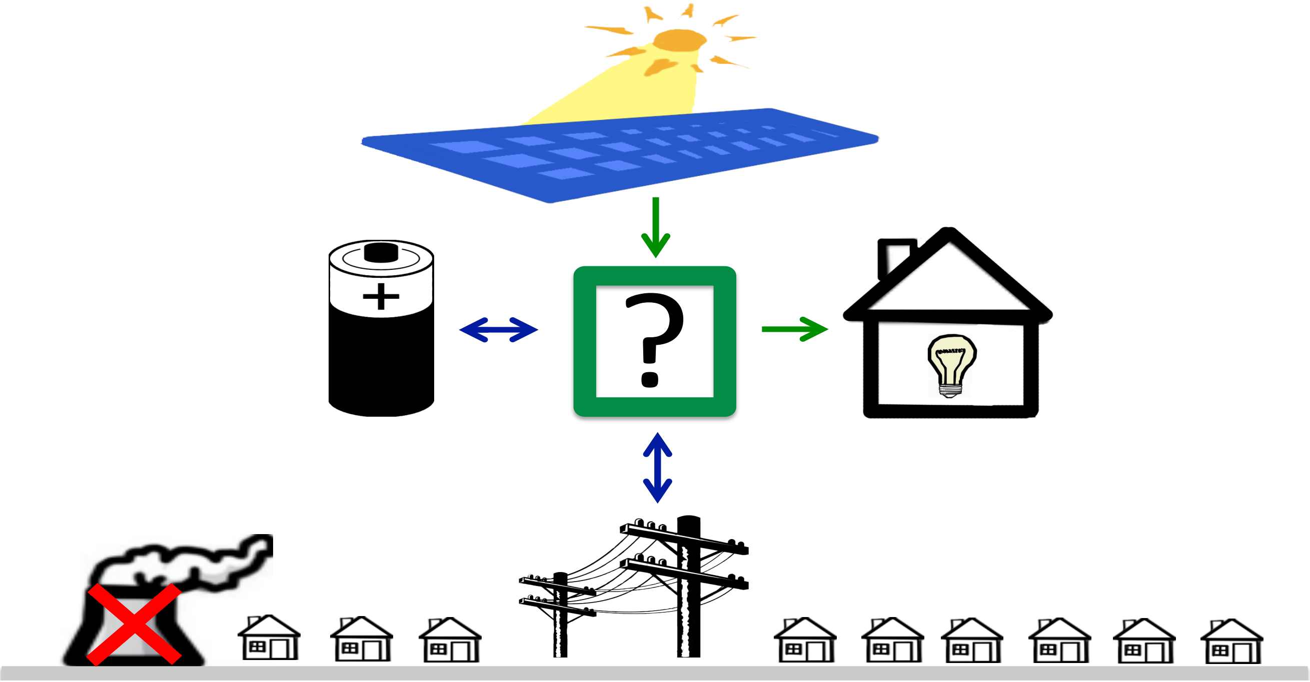
Operation of Electricity Grids



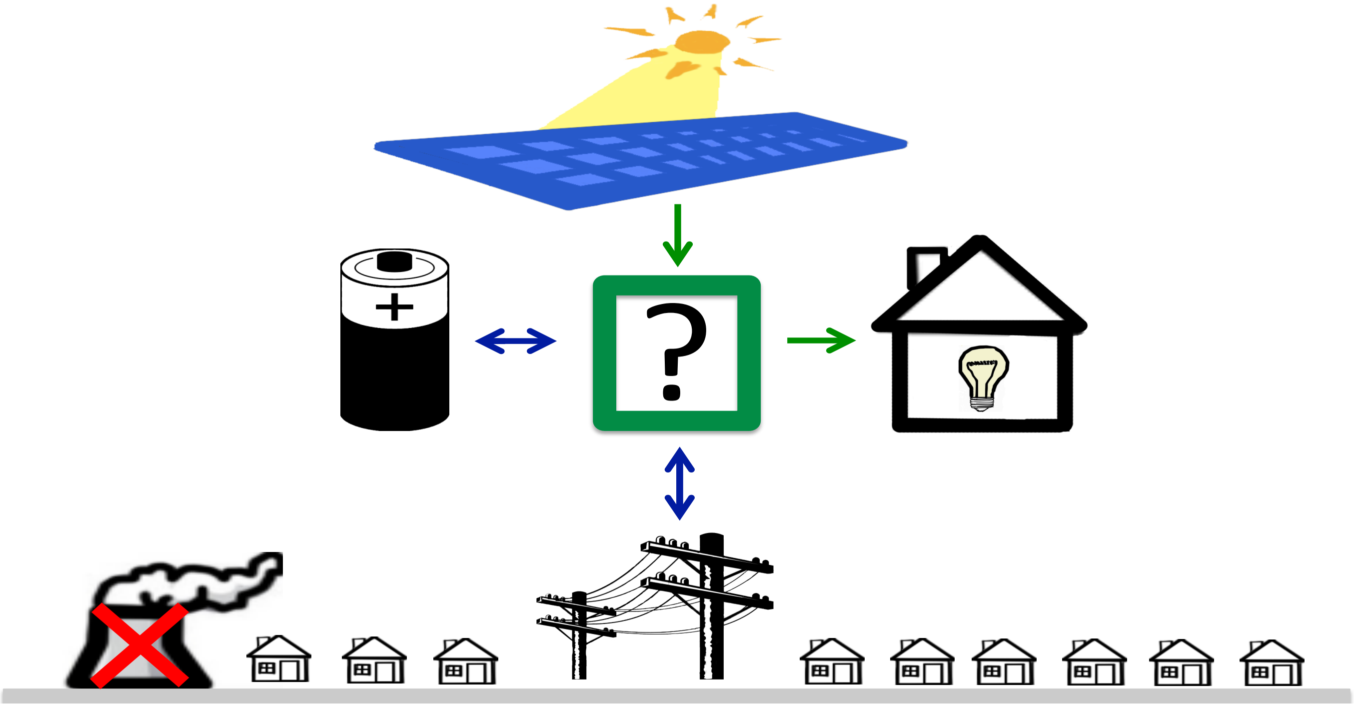
Dr. Elizabeth Ratnam, ANU FERL Fellow

The Australian National University

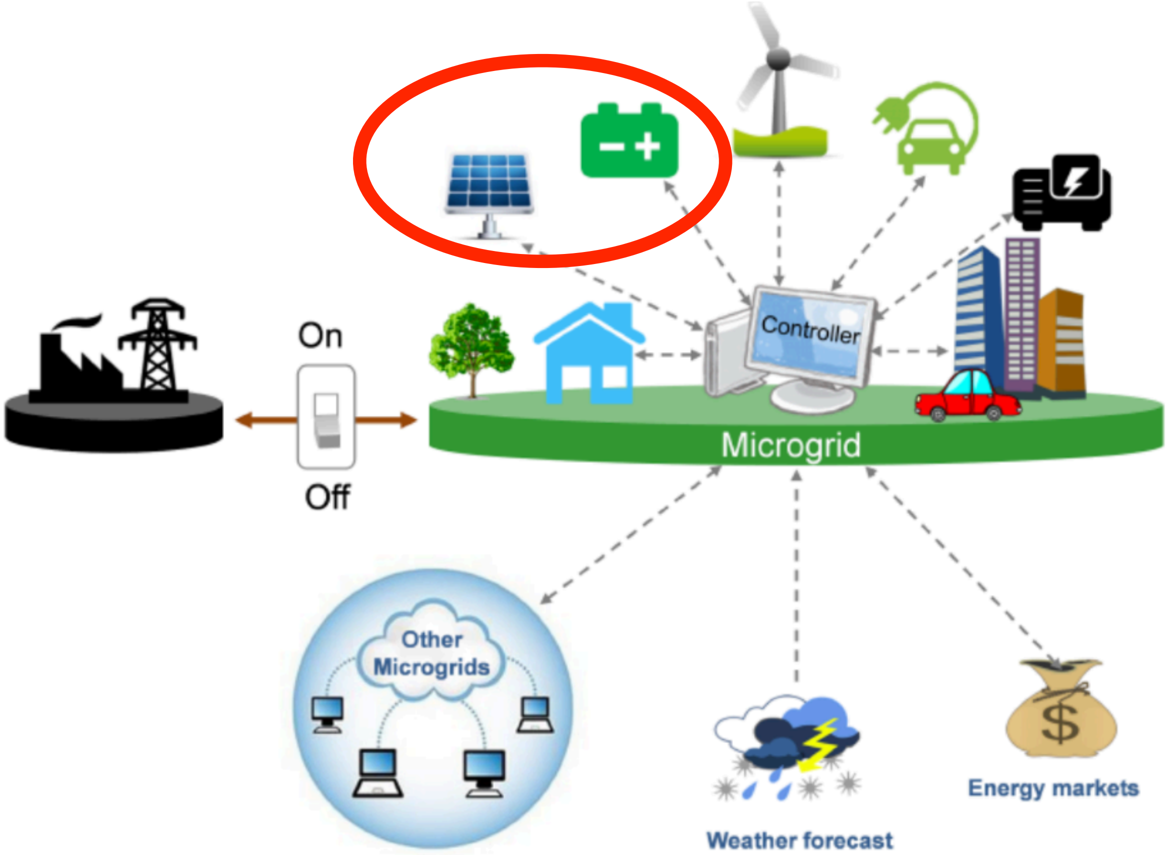
elizabeth.ratnam@anu.edu.au

ETP executive training program May 2022

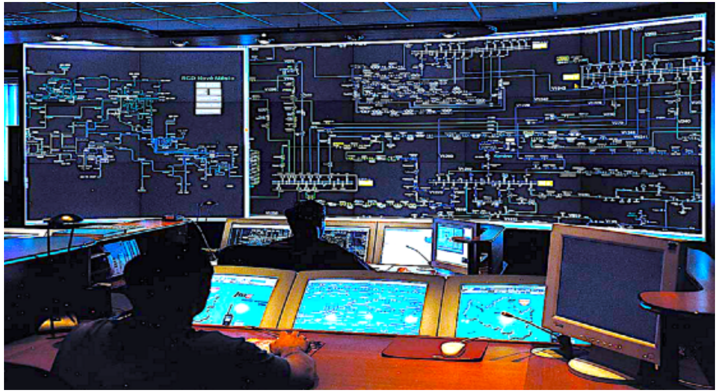
Short Overview

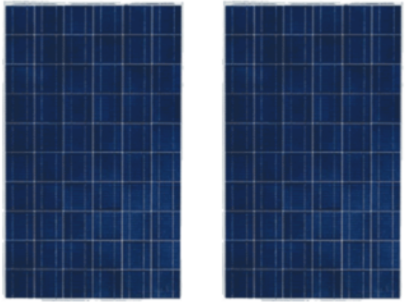


Elements of a carbon neutral electricity grid



PV Generation - How do we grid-integrate PV?

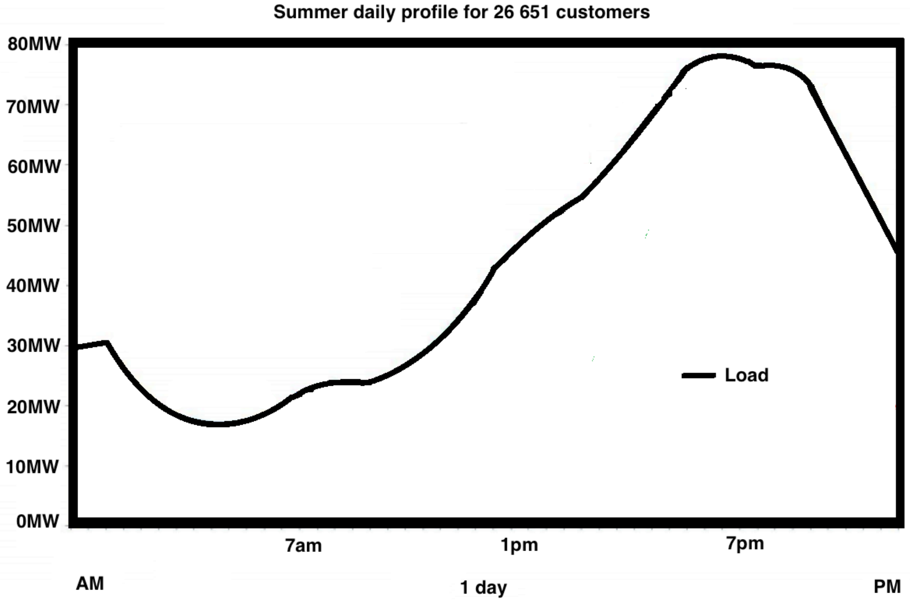




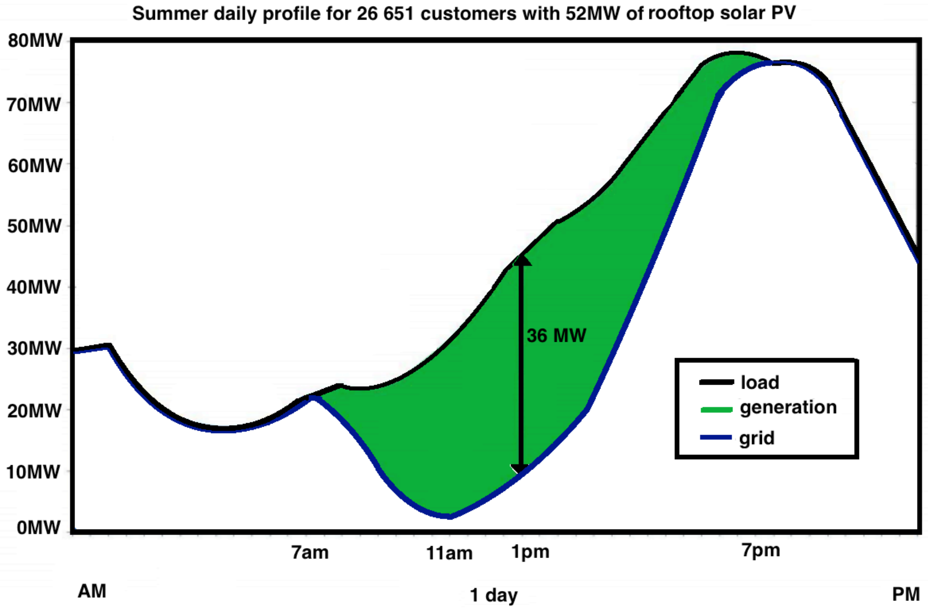
3.8 m^2

Installed PV Generation				kW/person
	2010	Now	Population	
Australia	~1GW	~15GW	25 million	0.60
Germany	~18GW	~55GW	84 million	0.65
USA	~1GW	~108GW	333 million	0.32
China	~0.8GW	~268GW	1,447 million	0.18

Demand profile



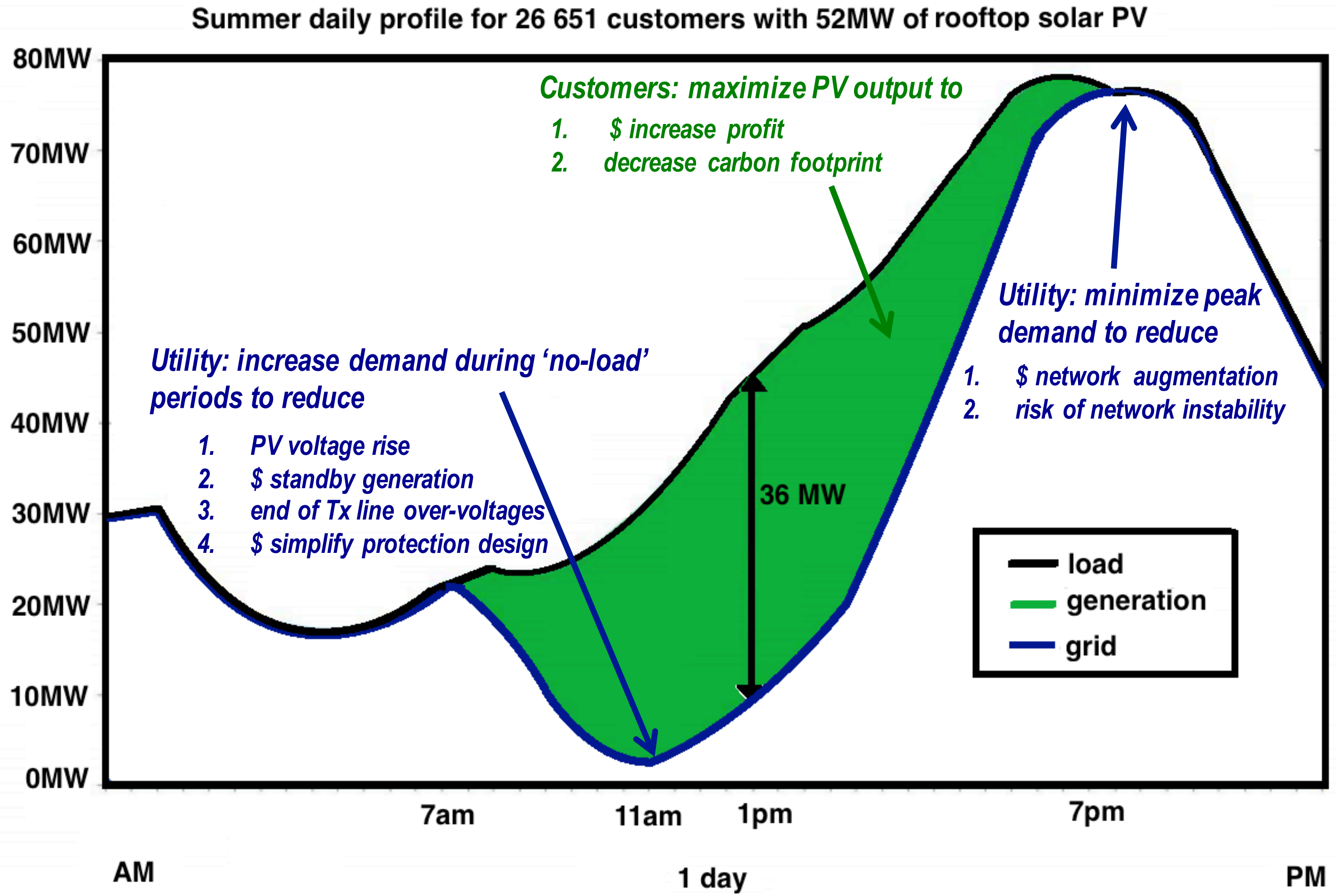
Load



Load + PV

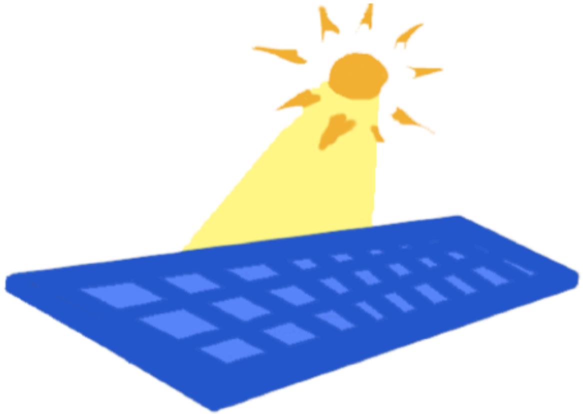
https://www.ausgrid.com.au/~/media/Files/About%20Us/Newsroom/Discussions/Solar%20Effect%20on%20the%20Grid.pdf

Problem: Customer vs. Utility



An Australian PV customer

+



Residential Load ≈ 20 kWh/day

$\approx \$5$/day

1.5 kW PV unit produces ≈ 5 kWh/day

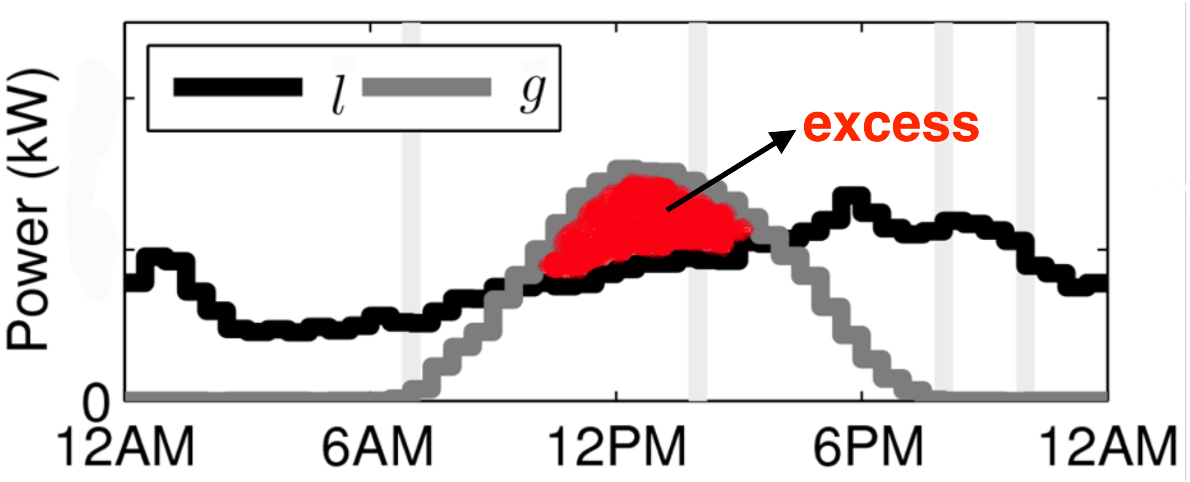
$\approx \$2$/day

1.5 kW PV unit exports ≈ 2 kWh/day

What about excess generation?

https://www.energymadeeasy.gov.au/

What about the excess generation?



What happens if we store it in a battery?

Is this cost effective?

What is the optimal use of this battery?

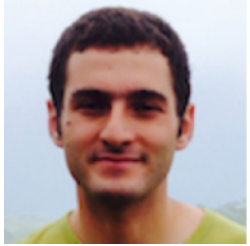
1. “An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit,” Renewable Energy, 2015
2. “Scheduling residential battery storage with solar PV: Assessing the benefits of net metering,” Applied Energy, 2015
3. “Central versus localized optimization-based approaches to power management in distribution networks with residential battery storage,” International Journal of Electric Power and Energy Systems, 2016

1. A single residential system

2. Coordinated residential systems

3. New Control Paradigms

4. "Distributed energy storage system scheduling considering tariff structure, energy arbitrage and solar PV penetration," Applied Energy, 2017

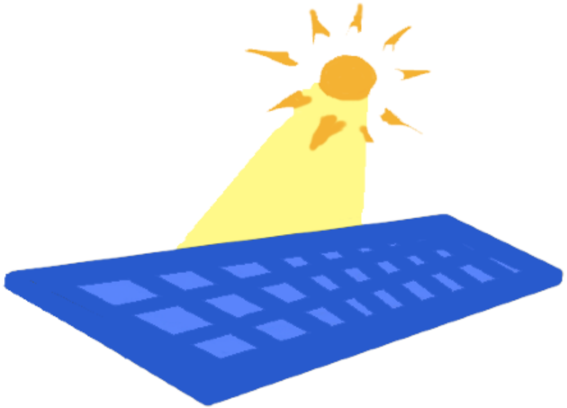
An Australian PV + Battery Customer

Residential Load

≈ 20kWh/day

≈ $5/day

+

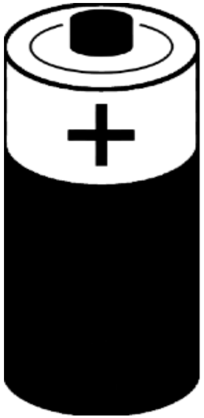


1.5kW PV unit produces

≈ 5kWh/day

≈ $3/day ($2)

+



10kWh battery

?

Notation: A single residential system

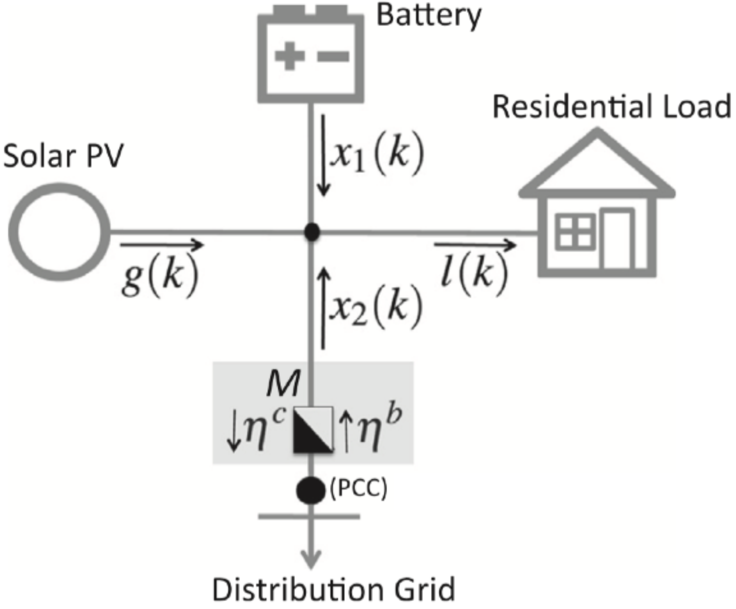
$x_2(k)$ measured power flow (in kW) over the k^{th} interval of length Δ

$x_1(k)$ average power (kW) delivered from (or to) the battery

$\chi(k)$ is the state of charge of the battery (in kWh) at time $k\Delta$

$$\chi(k) = \chi(0) - \sum_{j=1}^{k} x_1(j)\Delta \quad \text{for all } k \in \{1, \ldots, s\}$$

$$0 \leq \chi(k) \leq C$$



$g(k)$ average PV generation (kW) over the period $((k-1)\Delta, k\Delta)$

$l(k)$ average power delivered to the residential load (in kW)

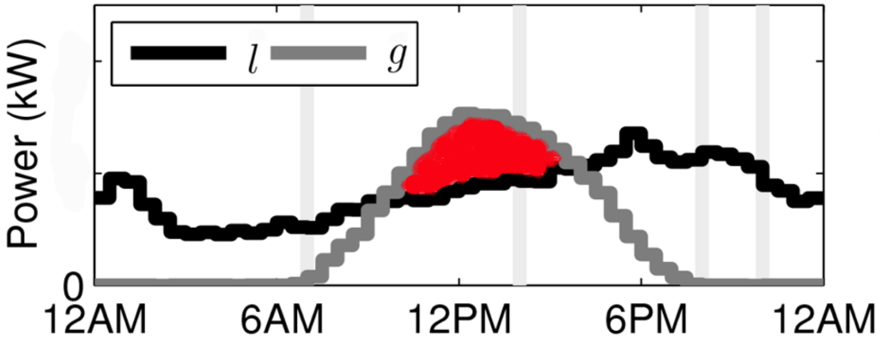
$\eta^b(k)$ electricity billing (in \$/kWH) at meter M

$\eta^c(k)$ electricity compensation (in \$/kWH) at meter M

EL Ratnam, SR Weller, CM Kellett, "An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit," Renewable Energy, 2015

Notation: Day-ahead profiles and energy savings

s is the number of time intervals of length Δ
$T = s\Delta$ (in hours) is the time window of interest
$\mathbb{R}^s$ denote s-dimensional vectors of real numbers



$g := [g(1), \ldots, g(s)]^T \in \mathbb{R}^s_{\geq 0}$ *generation profile* over $[0, T]$
$l := [l(1), \ldots, l(s)]^T \in \mathbb{R}^s_{\geq 0}$ *load profile* over $[0, T]$
$x_1 := [x_1(1), \ldots, x_1(s)]^T \in \mathbb{R}^s$ *battery profile* over $[0, T]$
$x_2 := [x_2(1), \ldots, x_2(s)]^T \in \mathbb{R}^s$ *grid profile* over $[0, T]$

state of charge profile $\chi := [\chi(0), \ldots, \chi(s)]^T \in \mathbb{R}^{s+1}$

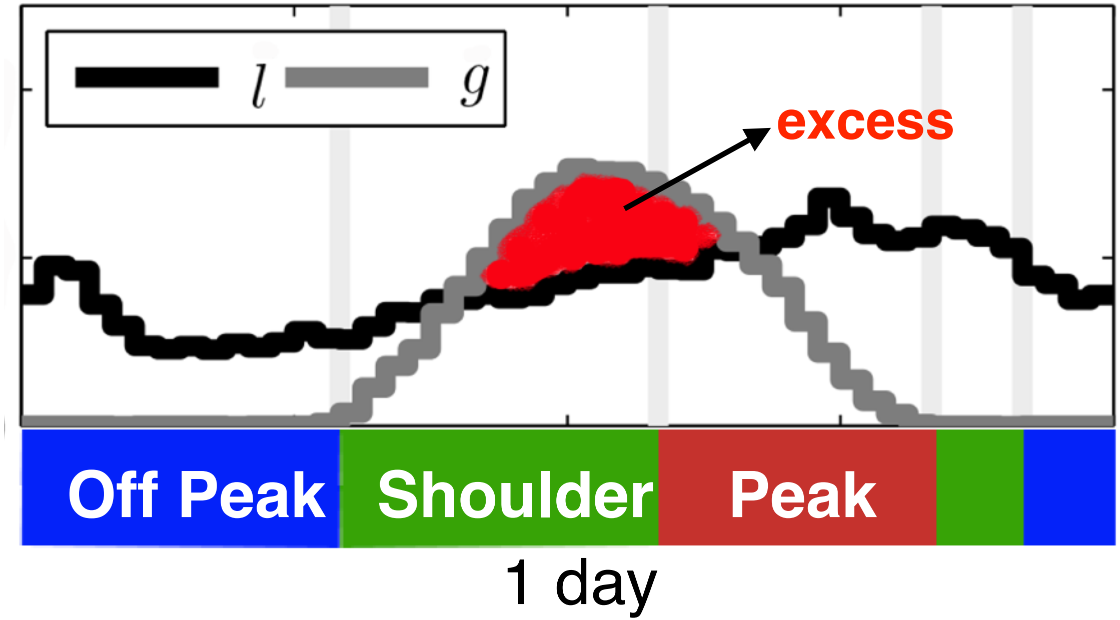
$\eta^b := [\eta^b(1), \ldots, \eta^b(s)]^T \in \mathbb{R}^s_{\geq 0}$ *electricity billing profile* over $[0, T]$
$\eta^c := [\eta^c(1), \ldots, \eta^c(s)]^T \in \mathbb{R}^s_{\geq 0}$ *electricity compensation profile* over $[0, T]$

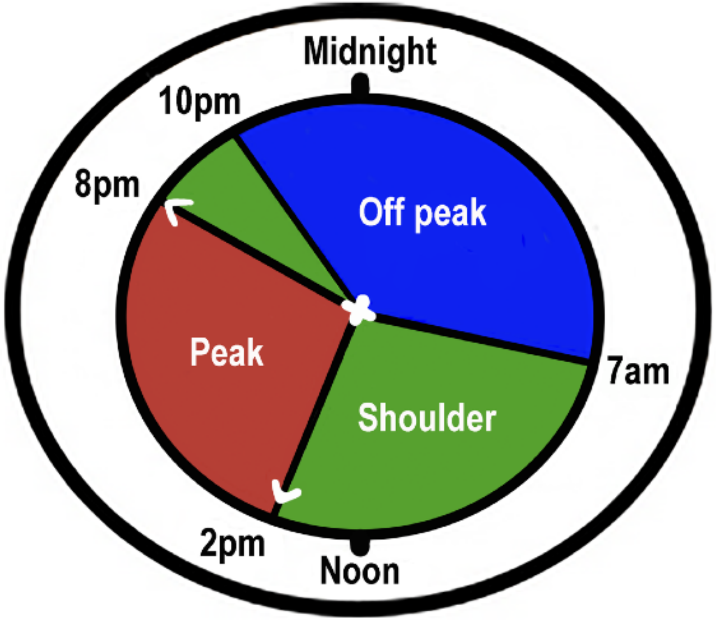
$\widetilde{\Sigma}$ *energy bill without a battery* over the time window $[0, T]$
Σ *energy bill with a battery* over time window $[0, T]$

$\Psi := \widetilde{\Sigma} - \Sigma$
energy savings (in \$/day)

Approach:

1. Consider the **benefits** of residential **battery** storage
2. In the context of financial policies (e.g., net metering and feed-in tariffs)
3. When customers are billed according to the time that they use electricity.





Customer: Is this cost effective?

$\Psi = \$0$

$\mathbb{1} \in \mathbb{R}^s_{\geq 0}$ denotes the all-1s column vector of length s

Fix $\eta > 0$ and let the electricity billing and compensation profiles in the financial policy satisfy the following

$$\eta^b(j) = \eta^c(k) = \eta \text{ for all } j, k \in \{1, \ldots, s\},$$
$$\eta^b = \eta^c = \eta \mathbb{1}.$$

Then for all choices of battery capacity C the energy savings are $\Psi(C) = 0$.

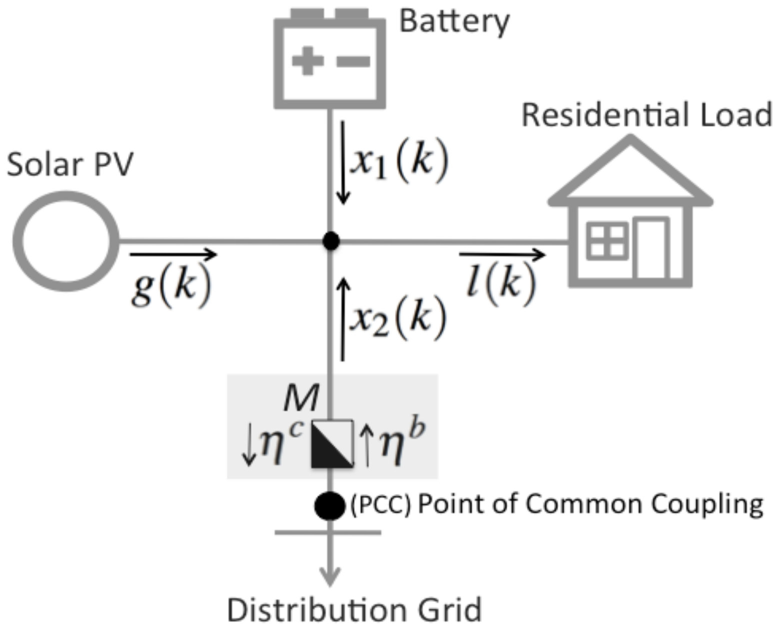
EL Ratnam, SR Weller, CM Kellett, "Scheduling residential battery storage with solar PV: Assessing the benefits of net metering," Applied Energy, 2015

Net metering

Financial policy of *net metering* defined by a resident being billed at the same rate as they are compensated for excess generation.

$$\eta^b(k) = \eta^c(k) \text{ for all } k \in \{1, \ldots, s\},$$

irrespective of the direction of $x_2(k)$



Financial policy of net metering

$\eta := \eta^b = \eta^c$, where $\eta \in \mathbb{R}^s_{\geq 0}$

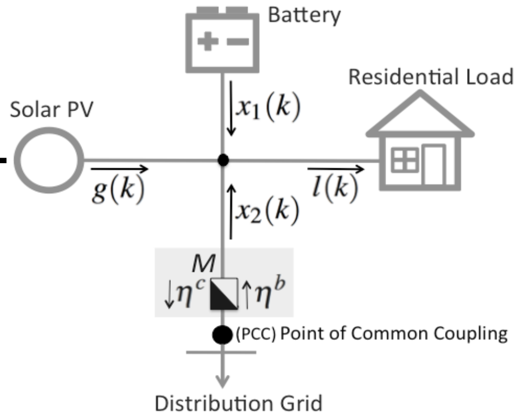
Energy Bill with a battery $\Sigma := \Delta\eta^T x_2$

Customer: How to calculate the operational savings?

Consider a residential energy network employing a financial policy of net metering, where $\eta \in \mathbb{R}^s_{\geq 0}$ is assumed fixed and known.

Let $x_1 \in \mathbb{R}^s$ represent the battery profile over $[0, T]$ where $T = s\Delta$.

Then the operational savings are given by $\Psi = \Delta \eta^T x_1$



EL Ratnam, SR Weller, CM Kellett, "Scheduling residential battery storage with solar PV: Assessing the benefits of net metering," Applied Energy, 2015

Customer: Linear Program (LP) to maximise savings

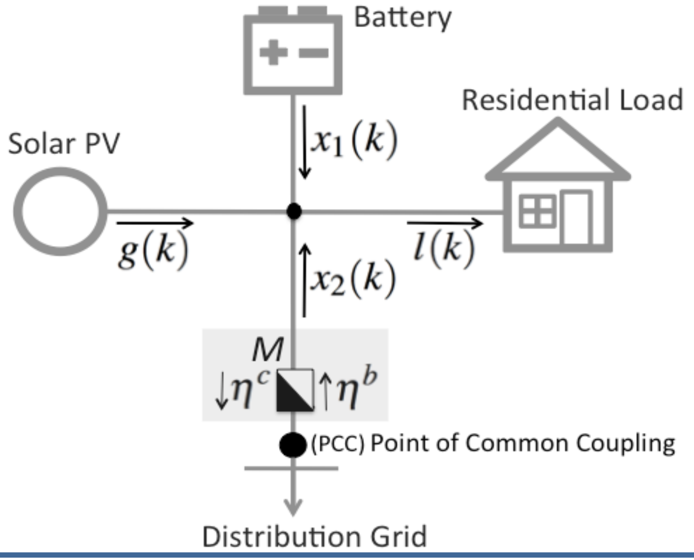
Maximise operation savings

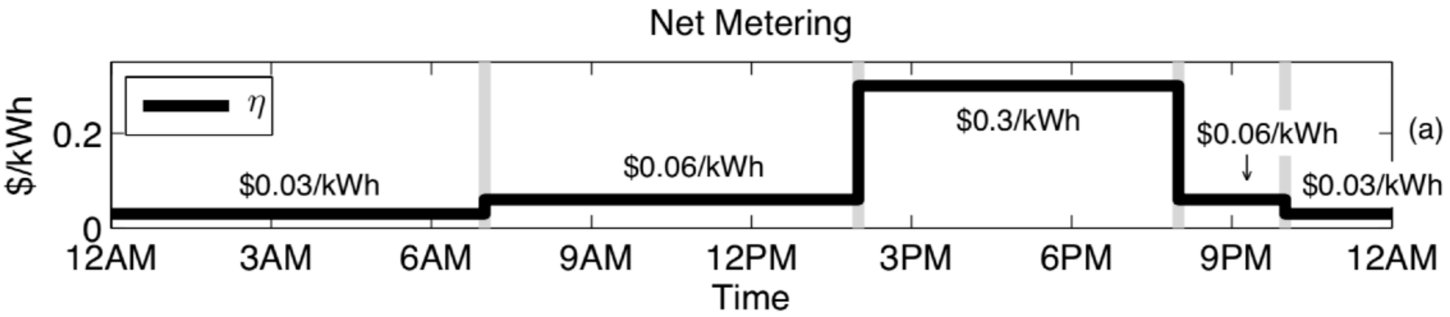
$$\max_{x_1 \in \mathbb{R}^s} \quad \Delta\eta^T x_1$$

such that

$$A_1 x_1 \leq b_1,$$
$$\mathbb{1}^T x_1 = 0.$$

Battery Constraints





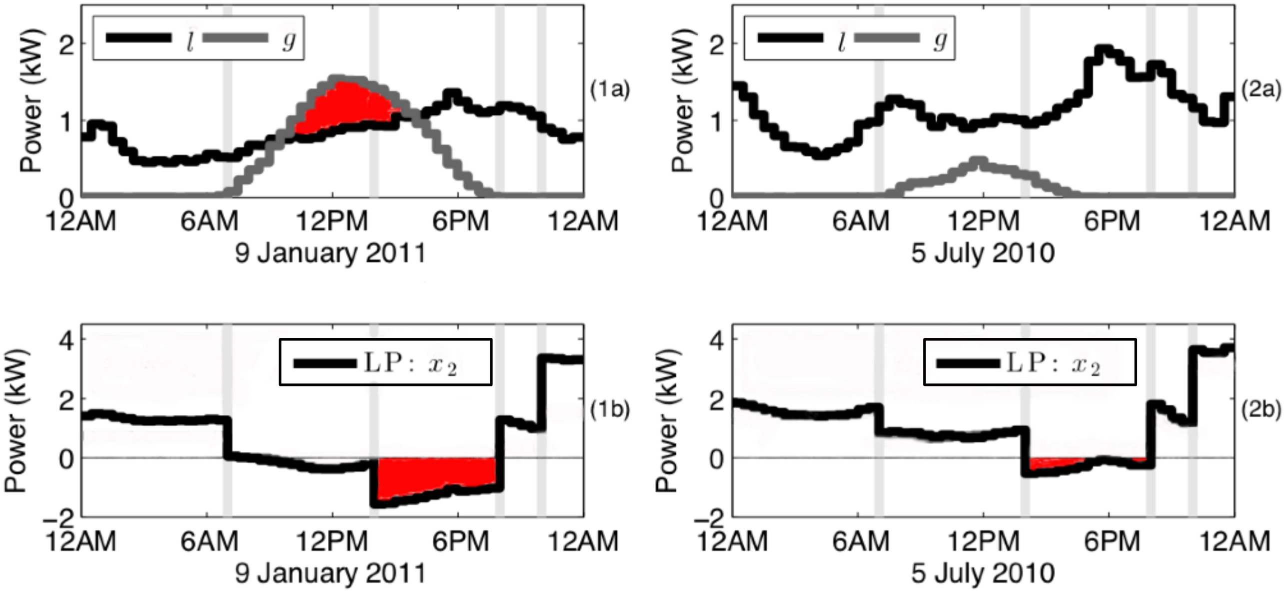
C=10kWh

$988/yr

Customer (maximise savings) vs Utility (Reverse power flow)

Average load and generation profiles

Average grid profiles



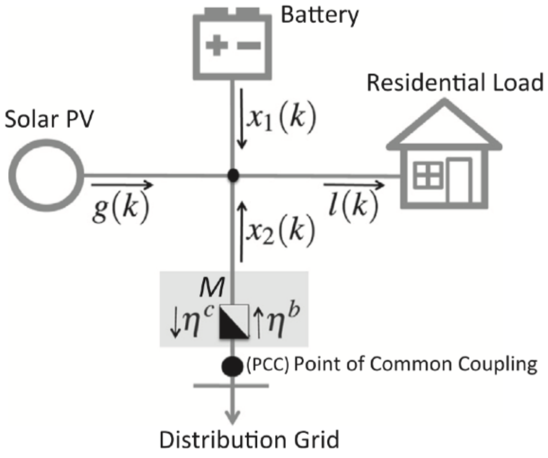
Summer **Winter**

EL Ratnam, SR Weller, CM Kellett, "Scheduling residential battery storage with solar PV: Assessing the benefits of net metering," Applied Energy, 2015

Utility (flatten the load curve)

To penalise large voltage swings stemming from reverse power flow and peak load and to increase daily operational savings, we minimise the following expression,

$$\sum_{k=1}^{s} h(k)(x_2(k))^2$$



where $h(k) \geq 1 \; \forall \; k \in \{1, \ldots, s\}$
and k is a time index

s is the number of time intervals of length Δ

Subject to Constraints

$x_2(k) = l(k) - g(k) - x_1(k) \quad \forall \quad k \in \{1, \ldots, s\}$ → Power Balance Equation

Battery → $\underline{B}\mathbb{1} \leq x_1 \leq \overline{B}\mathbb{1} \qquad \mathbf{0} \leq \chi \leq C \begin{bmatrix} \mathbb{1} \\ \mathbb{1} \end{bmatrix} \qquad \chi(s) = \chi(0) \qquad \chi(k) := \chi(0) - \sum_{j=1}^{k} x_1(j)\Delta$ for all $k \in \{1, \ldots, s\}$

EL Ratnam, SR Weller, CM Kellett, "An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit," Renewable Energy, 2015

Utility: Quadratic Program

$$\mathbf{H} := \mathrm{diag}(h(1), \ldots, h(s))$$

$$\mathbf{H} := \mathrm{diag}(1, \ldots, 1)$$

$$\min_{x} \quad x^T H x$$

$$x := \begin{bmatrix} x_1^T & x_2^T \end{bmatrix}^T \quad \in \quad \mathbb{R}^{2s}$$

$$H := \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{H} \end{bmatrix} \quad \in \mathbb{R}^{2s \times 2s}$$

such that

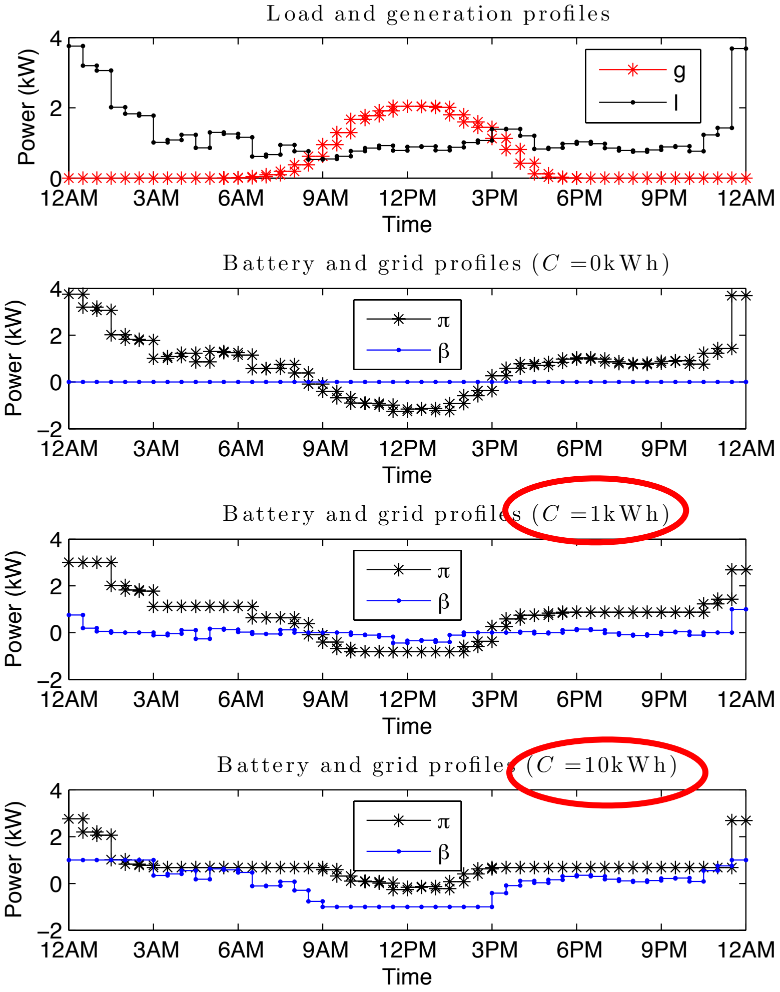
$$A_1 x \leq b_1$$

$$A_2 x = b_2$$

battery constraints

power balance equation + battery constraints

$\mathbf{0}$ denotes an all-zero matrix



QP: Balancing Customer and Distributor Benefits

Maximize

$$\sum_{k=1}^{s} w\Delta\eta(k)x_1(k) - \eta(k)(x_2(k))^2$$

maximise savings (LP) — **flatten the load curve (QP)**

where w is a distributor weighting.

Constraints

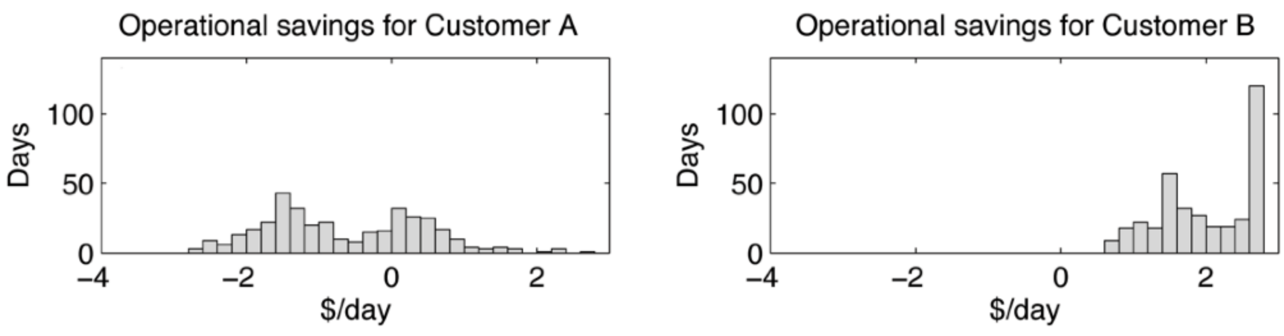
$x_2(k) = l(k) - g(k) - x_1(k) \quad \forall \quad k \in \{1,\ldots,s\}$ → Power Balance Equation

Battery → $\underline{B}\mathbb{1} \leq x_1 \leq \overline{B}\mathbb{1} \qquad \mathbf{0} \leq \chi \leq C\begin{bmatrix}1\\ \mathbb{1}\end{bmatrix} \qquad \chi(s) = \chi(0) \qquad \chi(k) := \chi(0) - \sum_{j=1}^{k} x_1(j)\Delta$ for all $k \in \{1,\ldots,s\}$

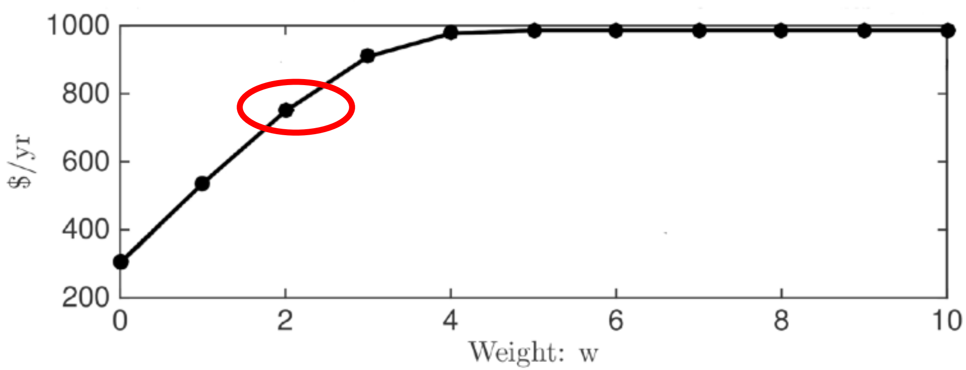
EL Ratnam, SR Weller, CM Kellett, "Central versus localized optimization-based approaches to power management in distribution networks with residential battery storage," International Journal of Electric Power and Energy Systems, 2016

Operational Savings: 145 customers

Not all customers benefit



Average operational savings

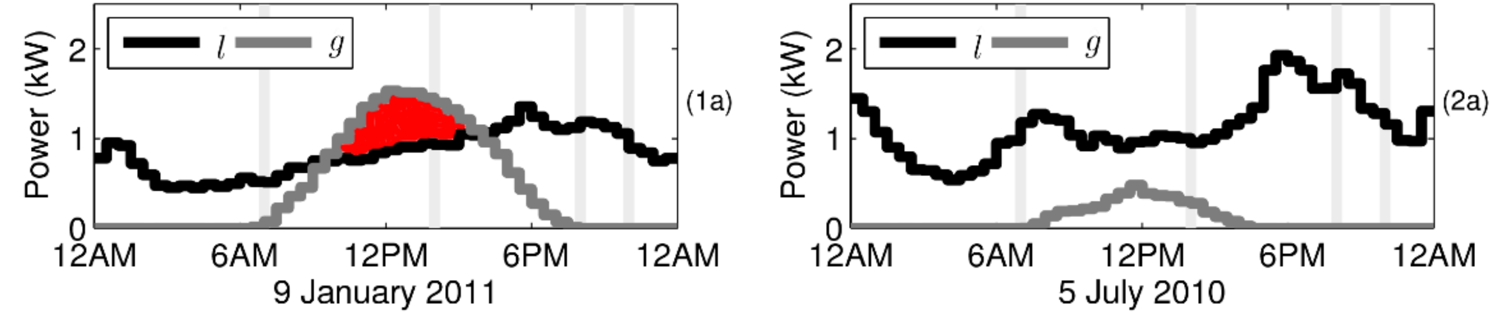


EL Ratnam, SR Weller, CM Kellett, "Central versus localized optimization-based approaches to power management in distribution networks with residential battery storage," International Journal of Electric Power and Energy Systems, 2016

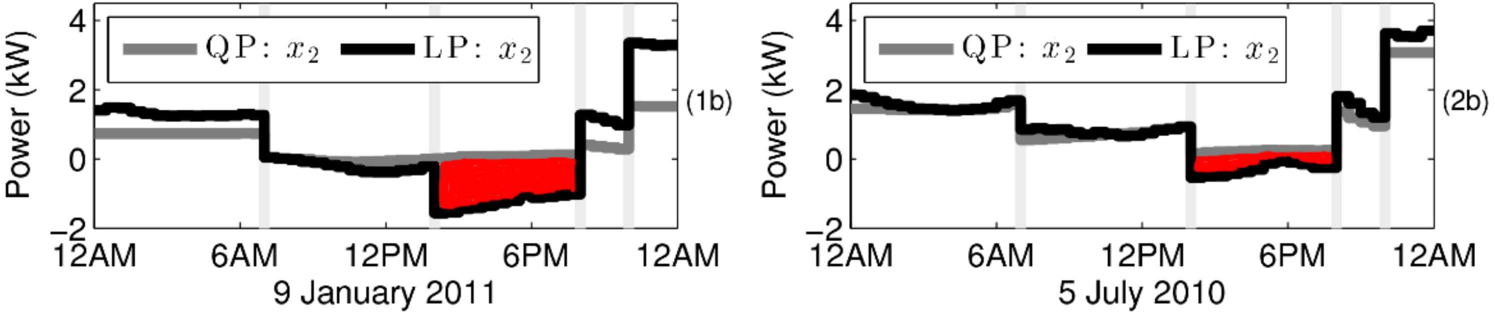
Assessing the utility benefit: 145 Customers

$w \approx 2$

Average load and generation profiles



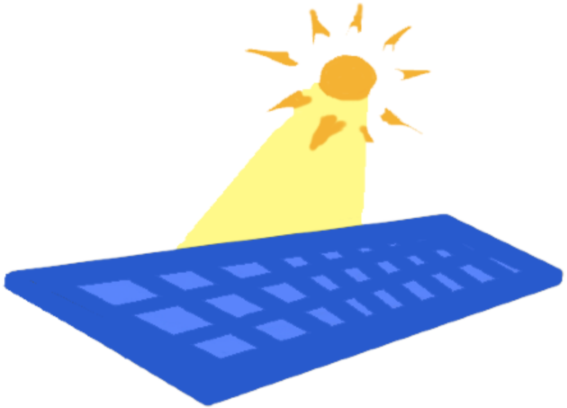
Average grid profiles



EL Ratnam, SR Weller, CM Kellett, “Scheduling residential battery storage with solar PV: Assessing the benefits of net metering,” Applied Energy, 2015

An Australian PV + Battery Customer

+



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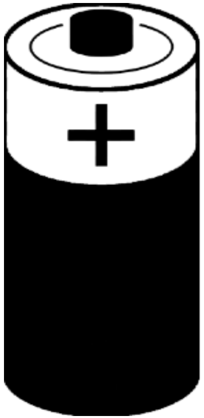


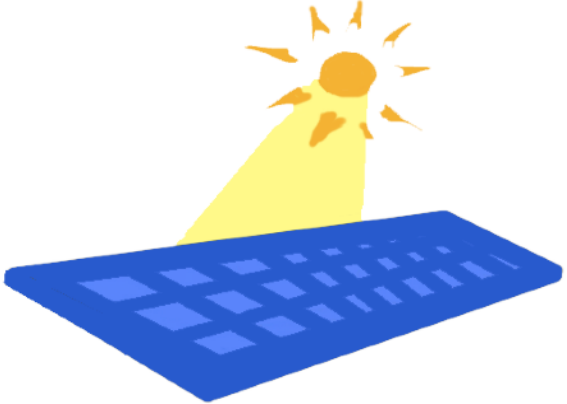
Residential Load
≈ 20kWh/day
≈ $5/day

1.5kW PV unit produces
≈ 5kWh/day
≈ $3/day ($2)

10kWh battery
LP ≈ -$1/day ($4)
QP ≈ $1/day ($2)

What about Electric Vehicle customers?

+



+

Residential Load

≈ 20 kWh/day

$\approx \$5$/day

1.5 kW PV unit produces ≈ 5 kWh/day

$\approx \$2$/day

1.5 kW PV unit exports ≈ 2 kWh/day

≈ 5 kWh/day

≈ 40 km

?

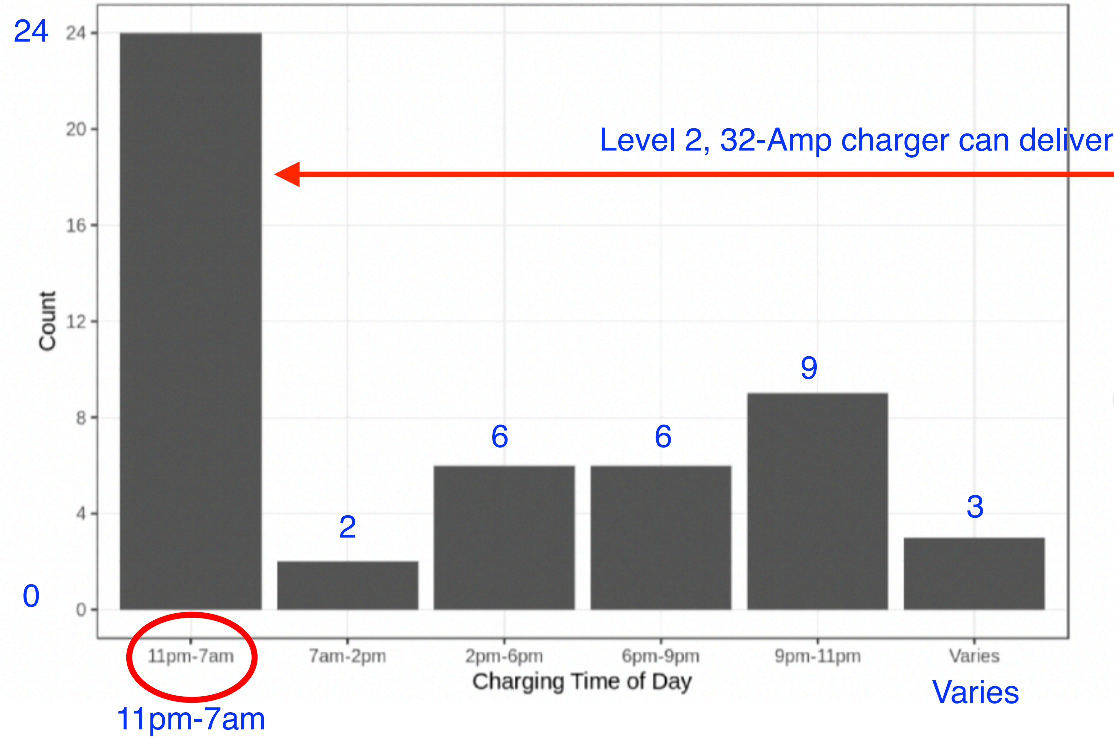
What about excess generation?

https://www.energymadeeasy.gov.au/

https://www.tesla.com/en_AU/support/range-calculator

EV Charging - How do we grid-integrate EVs?

Figure 10: Focus Group Participant Response to PEV Charging Time of Day

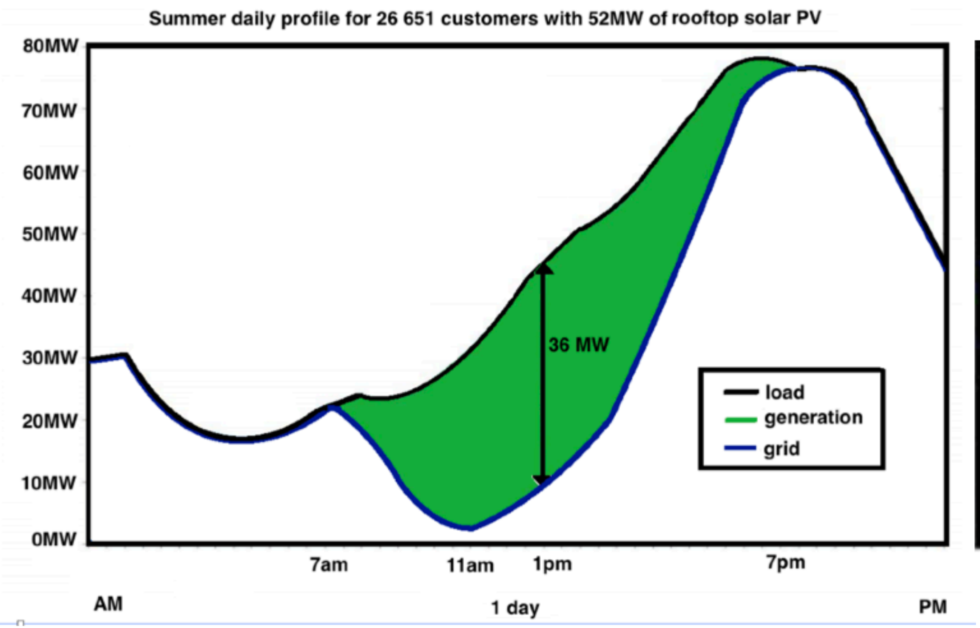


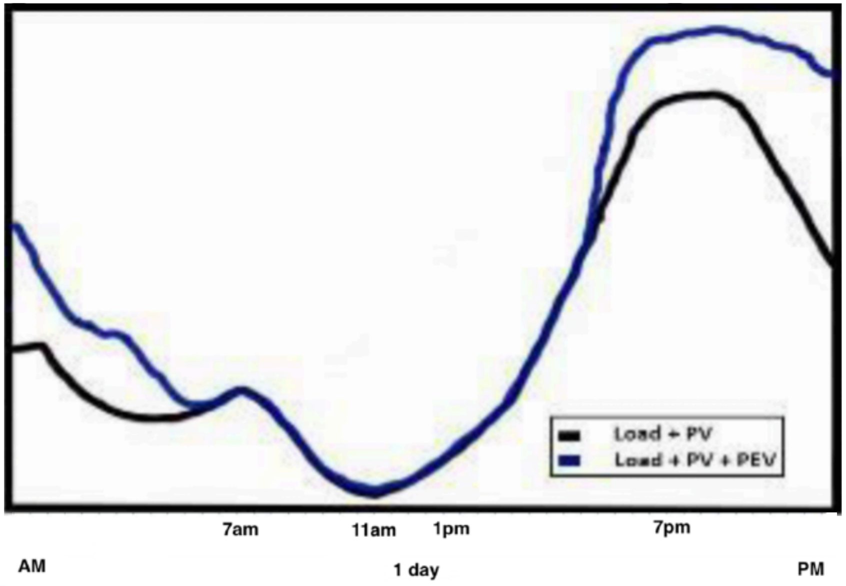
Level 2: 20 to 100 km Per Hour

Charging: from 11pm-7pm

https://ww2.energy.ca.gov/2020publications/CEC-500-2020-005/CEC-500-2020-005.pdf

Demand profile





Load + PV **Load + PV + EV ?**

https://www.ausgrid.com.au/~/media/Files/About%20Us/Newsroom/Discussions/Solar%20Effect%20on%20the%20Grid.pdf


1. "Central versus localized optimization-based approaches to power management in distribution networks with residential battery storage," International Journal of Electric Power and Energy Systems, 2016
2. "Receding horizon optimization-based approaches to manage supply voltages and power flows in a distribution grid with battery storage," EL Ratnam, SR Weller, Applied Energy, 2018

1. A single residential system

2. Coordinated residential systems

3. New Control Paradigms

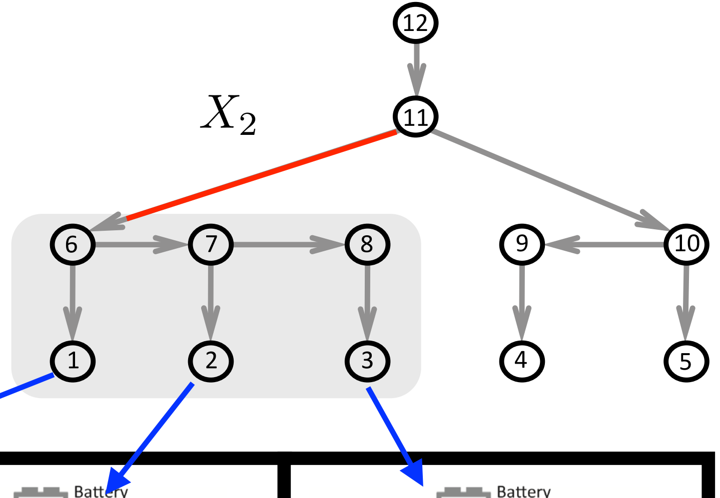


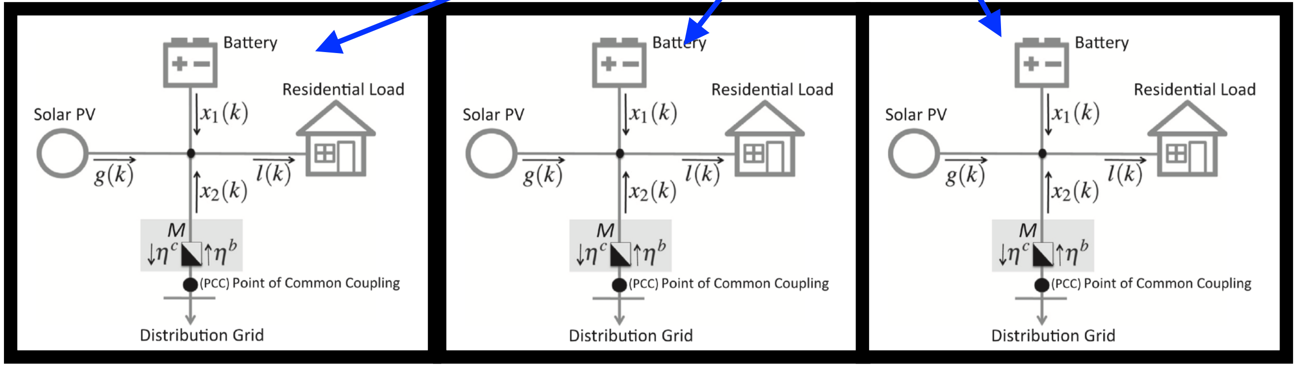

1. N. I. Nimalsiri, E. L. Ratnam, D. B. Smith, C. P. Mediwaththe and S. K. Halgamuge, "Coordinated Charge and Discharge Scheduling of Electric Vehicles for Load Curve Shaping," in *IEEE Transactions on Intelligent Transportation Systems*, doi: 10.1109/TITS.2021.3071686.
2. Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

Can we reduce the risk of critical failures?

Coordinate residential systems

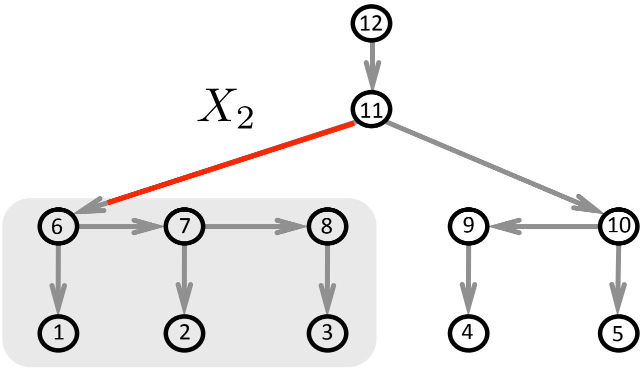
1. **Reduce peak load and reverse power flow along a critical line or through a transformer**





2. **What about the supply voltages?**

Central QP energy-shifting



Maximize

$$\sum_{k=1}^{s} w\Delta\eta(k)X_1(k) - \eta(k)(X_2(k))^2$$

w is a scalar weighting

$\eta(k)$ is the net metering electricity price in \$/kWh over the k^{th} interval of length Δ

$X_1(k)$ is combined power to or from microgrid batteries

$X_2(k)$ is the power (in kW) to or from the microgrid

Subject to Constraints

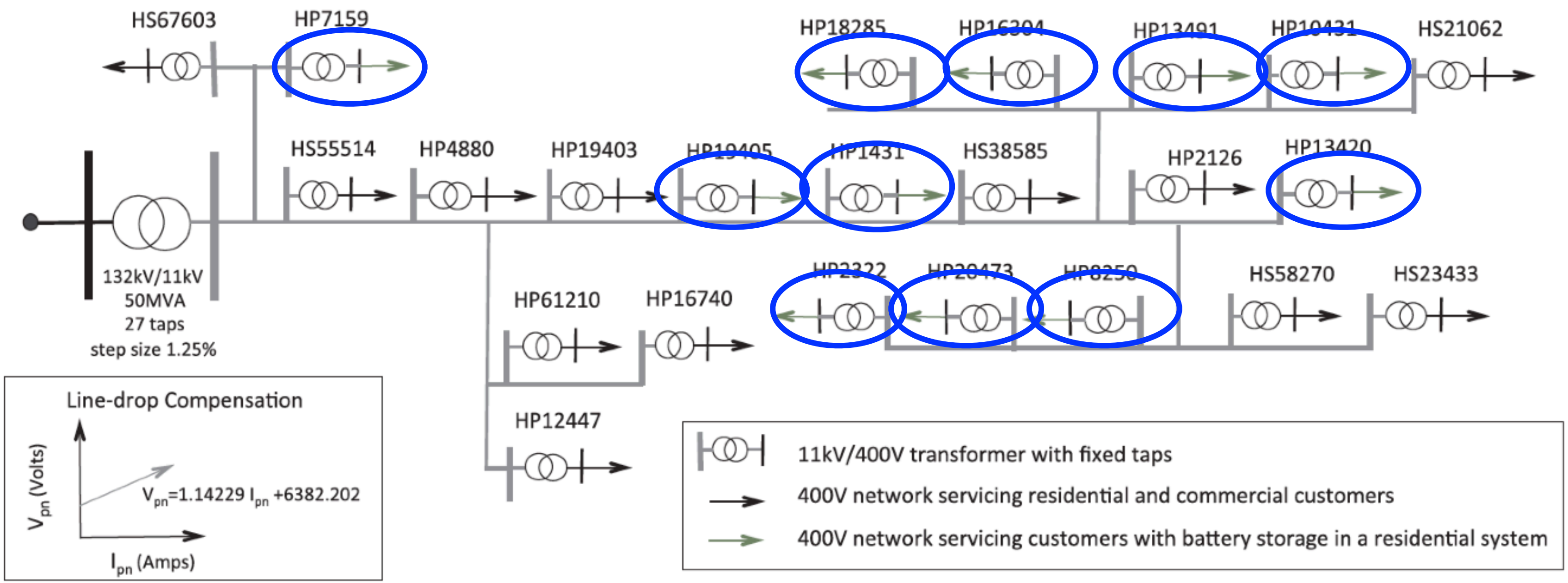
$$\underline{\mathbf{P}}\mathbb{1} \leq X_2 \leq \overline{\mathbf{P}}\mathbb{1}$$

$$A_1X_1 \leq Nb_1, \ \mathbb{1}^T X_1 = 0 \quad \text{and} \quad X_2 = X_1 + L - G$$

EL Ratnam, SR Weller, “Receding horizon optimization-based approaches to manage supply voltages and power flows in a distribution grid with battery storage,” Applied Energy, 2018

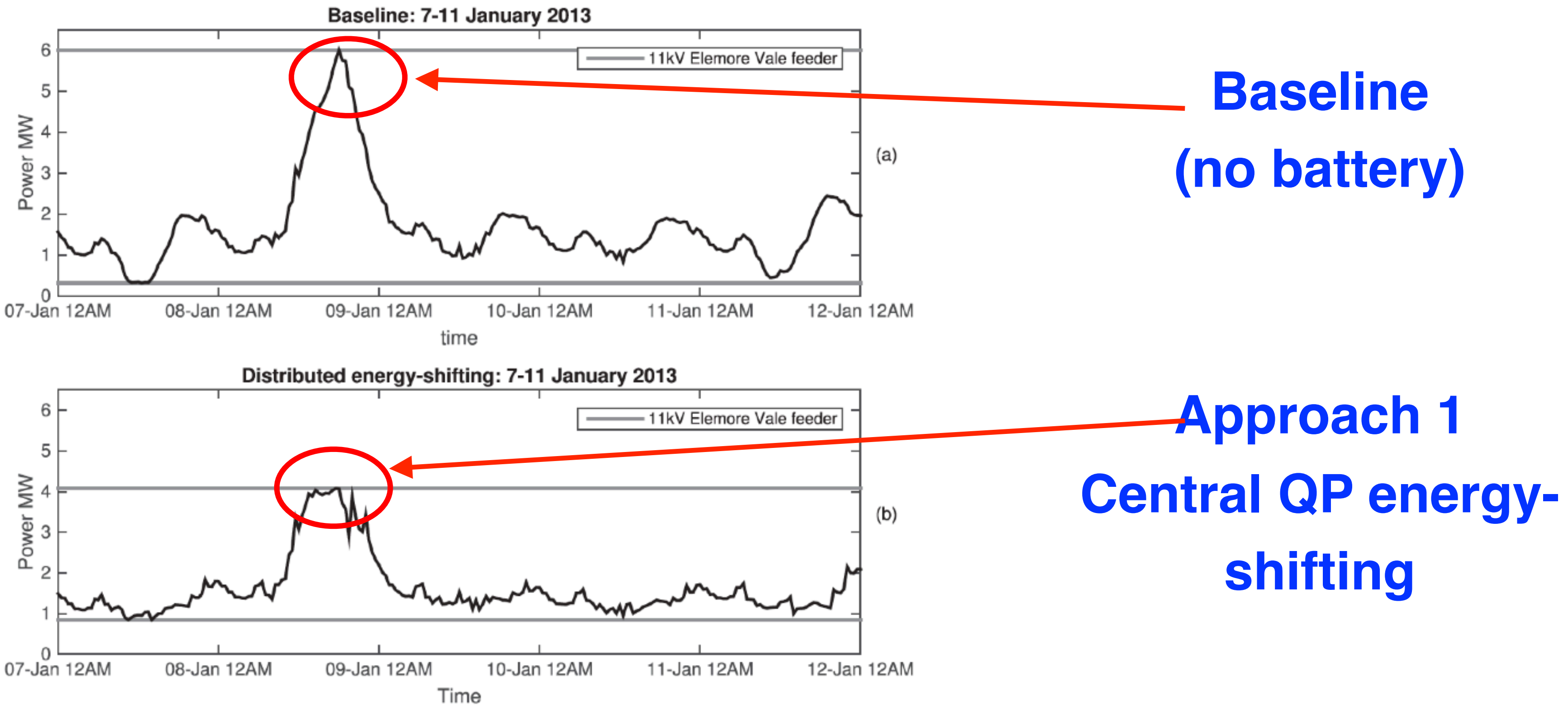
Newcastle: Elermore Vale Feeder Model

~ 50% PV Penetration



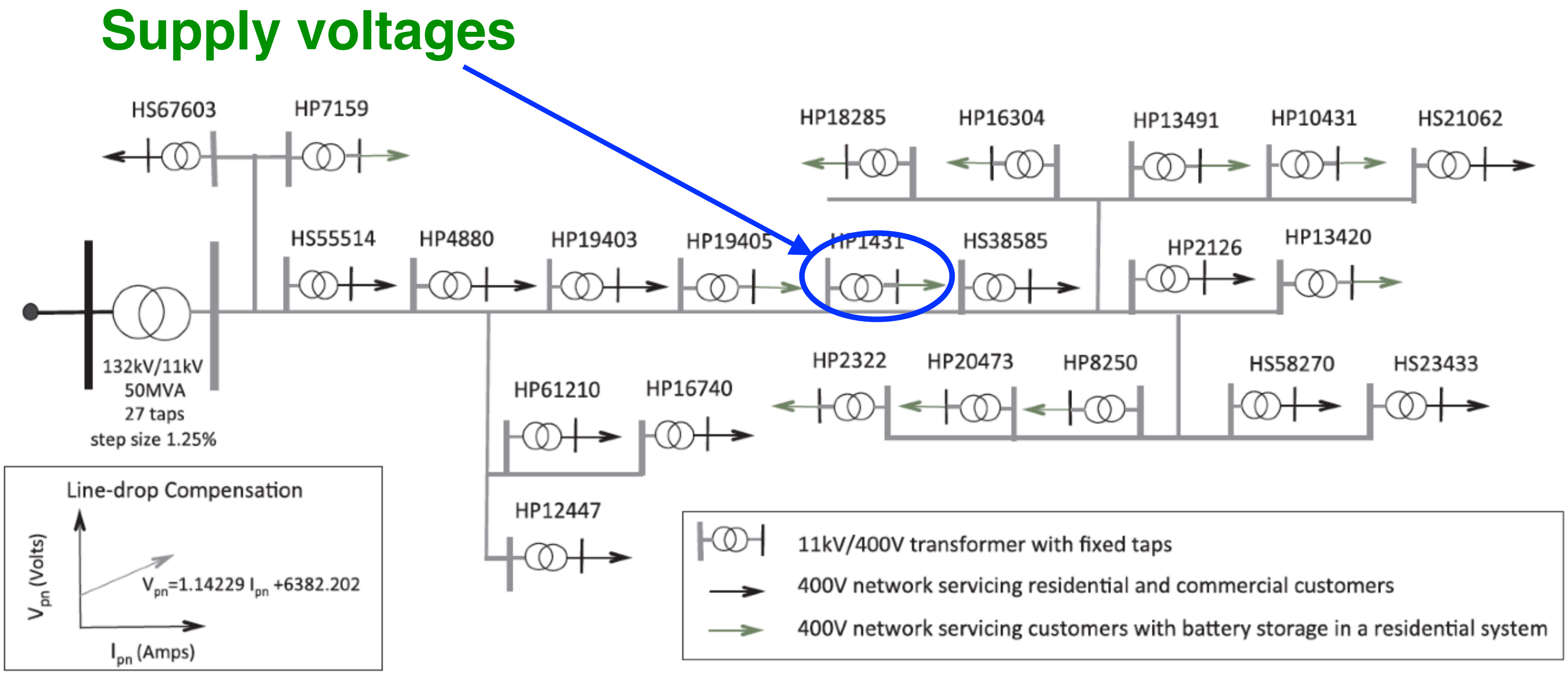
EL Ratnam, SR Weller, "Receding horizon optimization-based approaches to manage supply voltages and power flows in a distribution grid with battery storage," Applied Energy, 2018

Peak load reduction of $\sim$ 2MW



EL Ratnam, SR Weller, "Receding horizon optimization-based approaches to manage supply voltages and power flows in a distribution grid with battery storage," Applied Energy, 2018

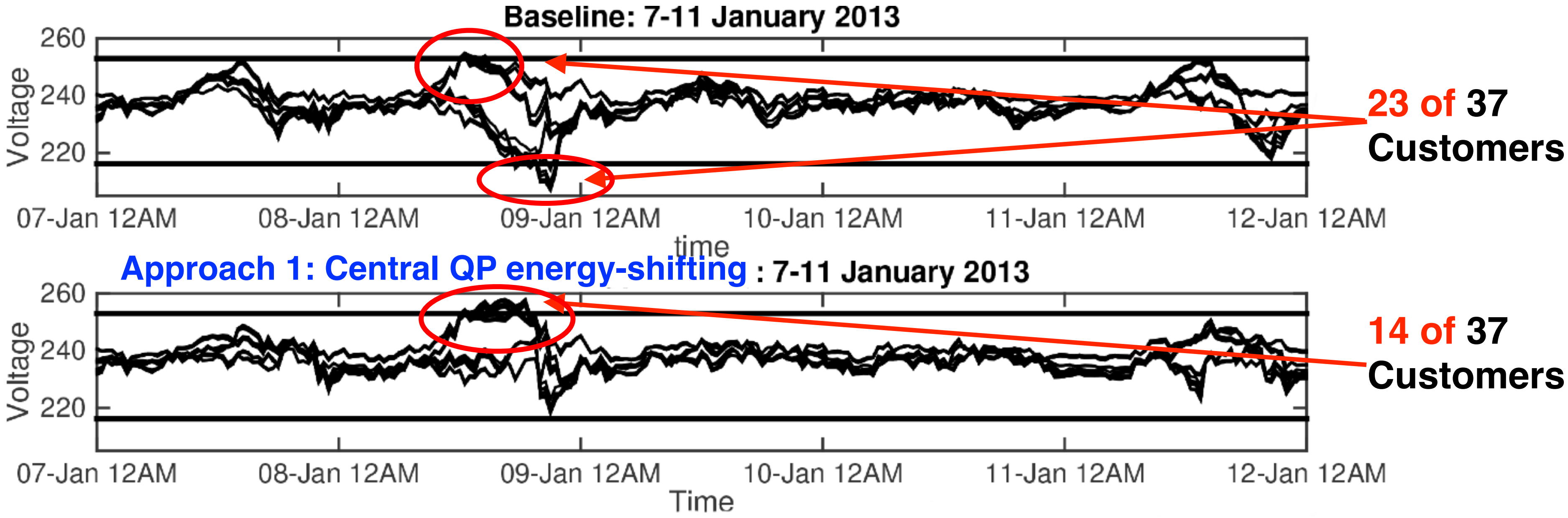
What about the supply voltages?



+10%/-6% of 230V, AS 60038-1012 Standard Voltages

Voltage Violations - Inverters switch off

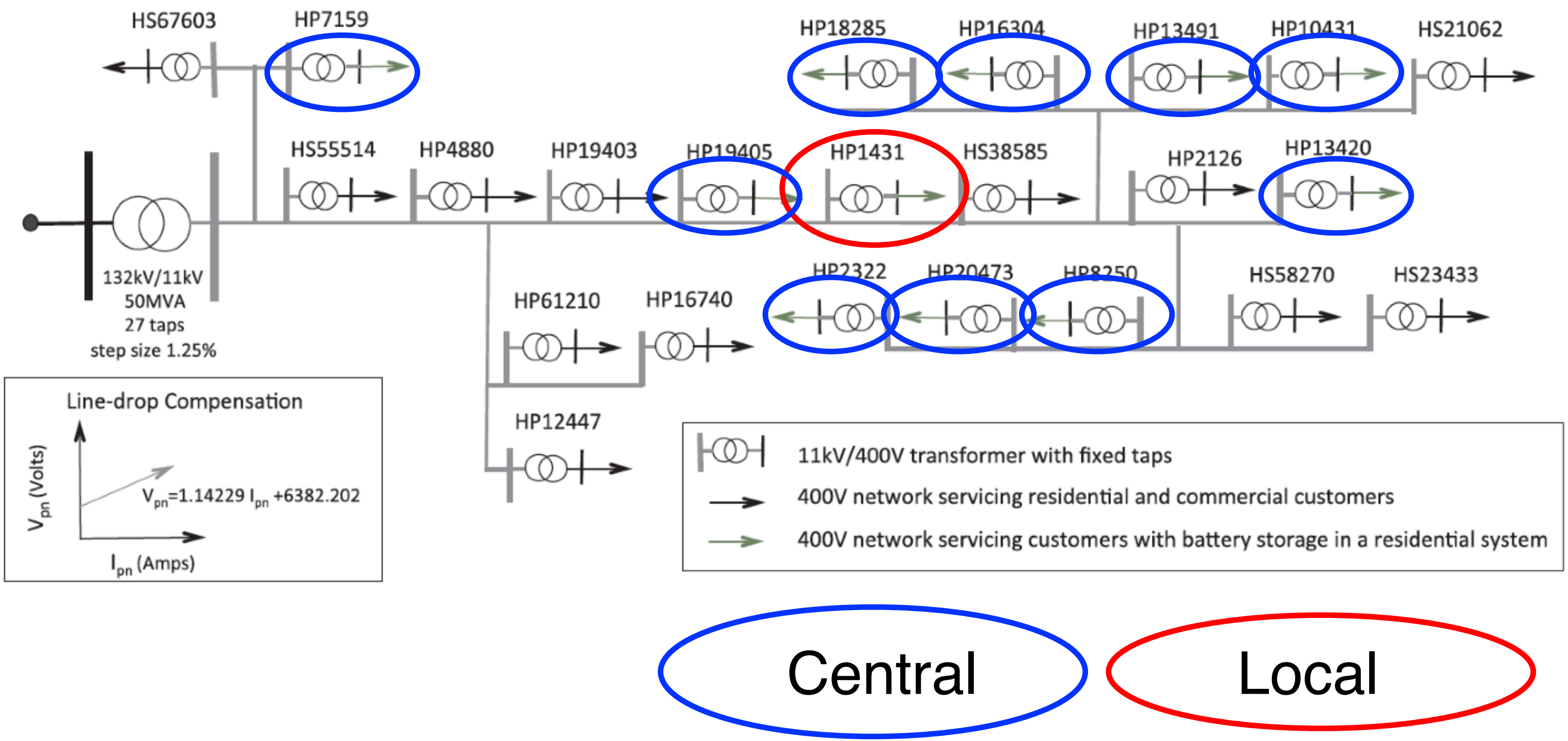
+10%/-6% of 230V



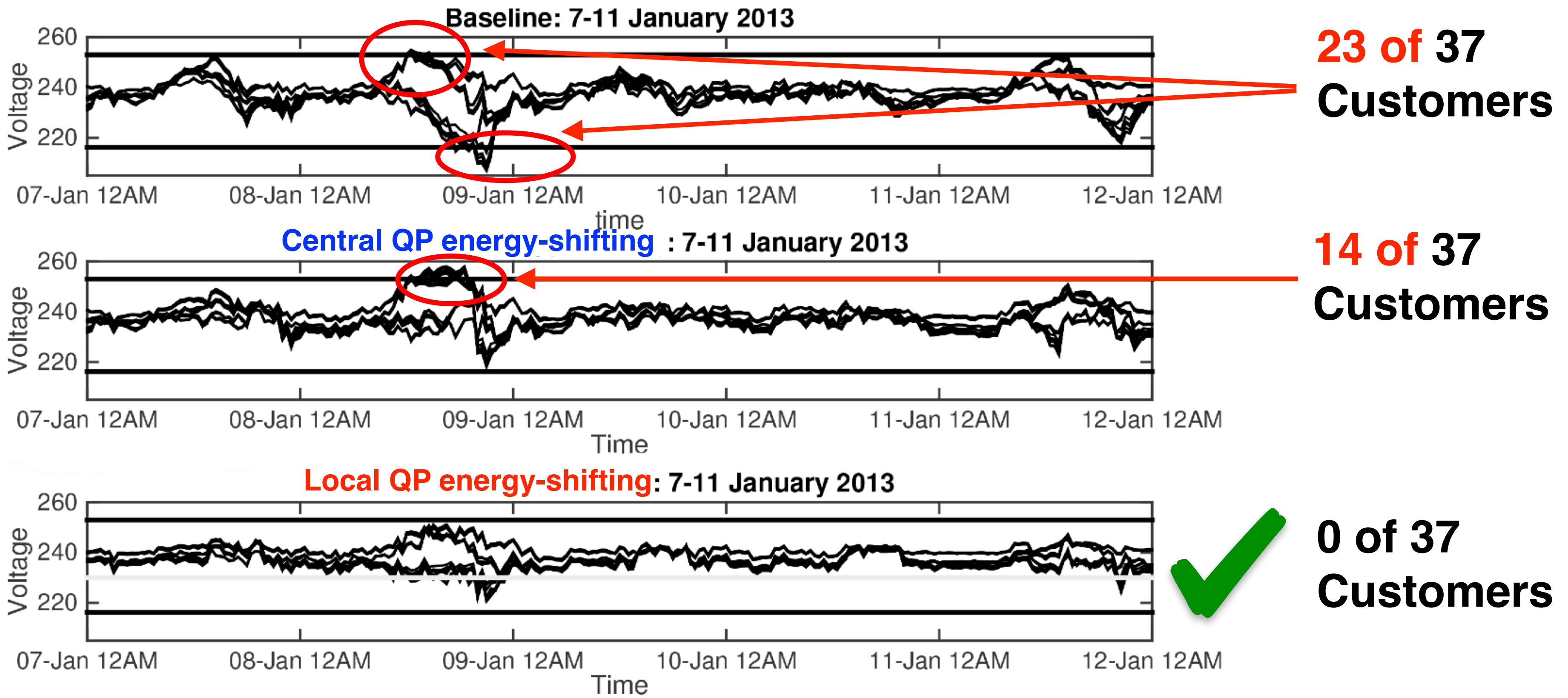
EL Ratnam, SR Weller, "Receding horizon optimization-based approaches to manage supply voltages and power flows in a distribution grid with battery storage," Applied Energy, 2018

Solution: local plus central QP energy-shifting

~ 50% PV Penetration

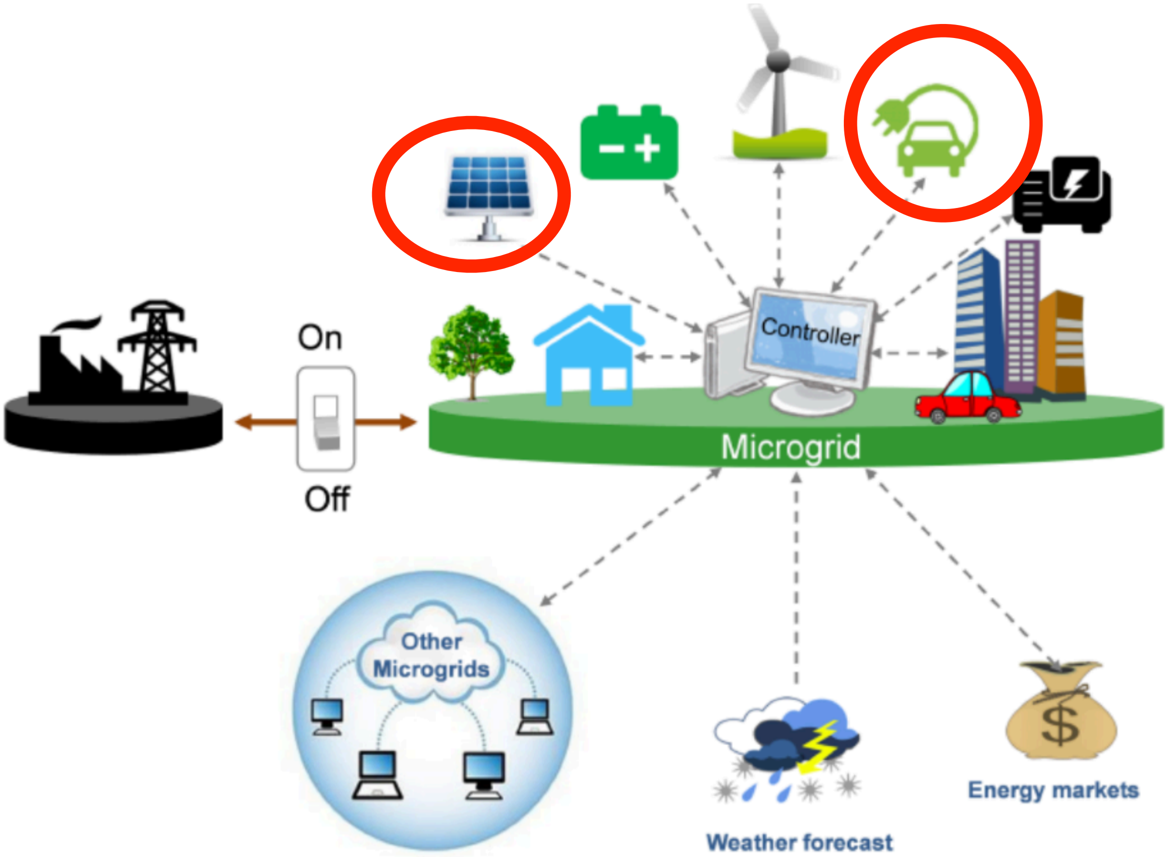


Supply voltages Ok

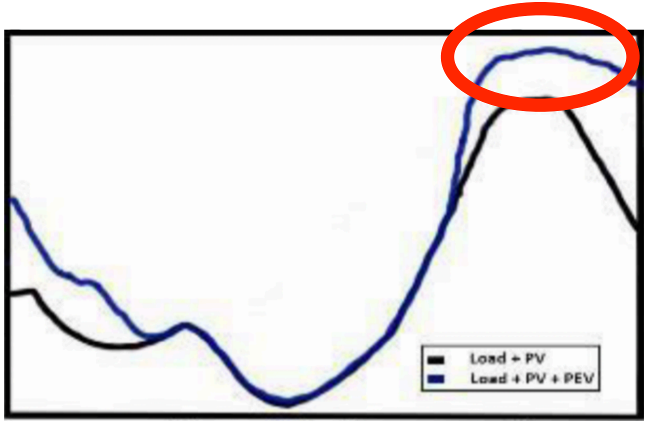


EL Ratnam, SR Weller, "Receding horizon optimization-based approaches to manage supply voltages and power flows in a distribution grid with battery storage," Applied Energy, 2018

Coordinating EV Charging and Discharging

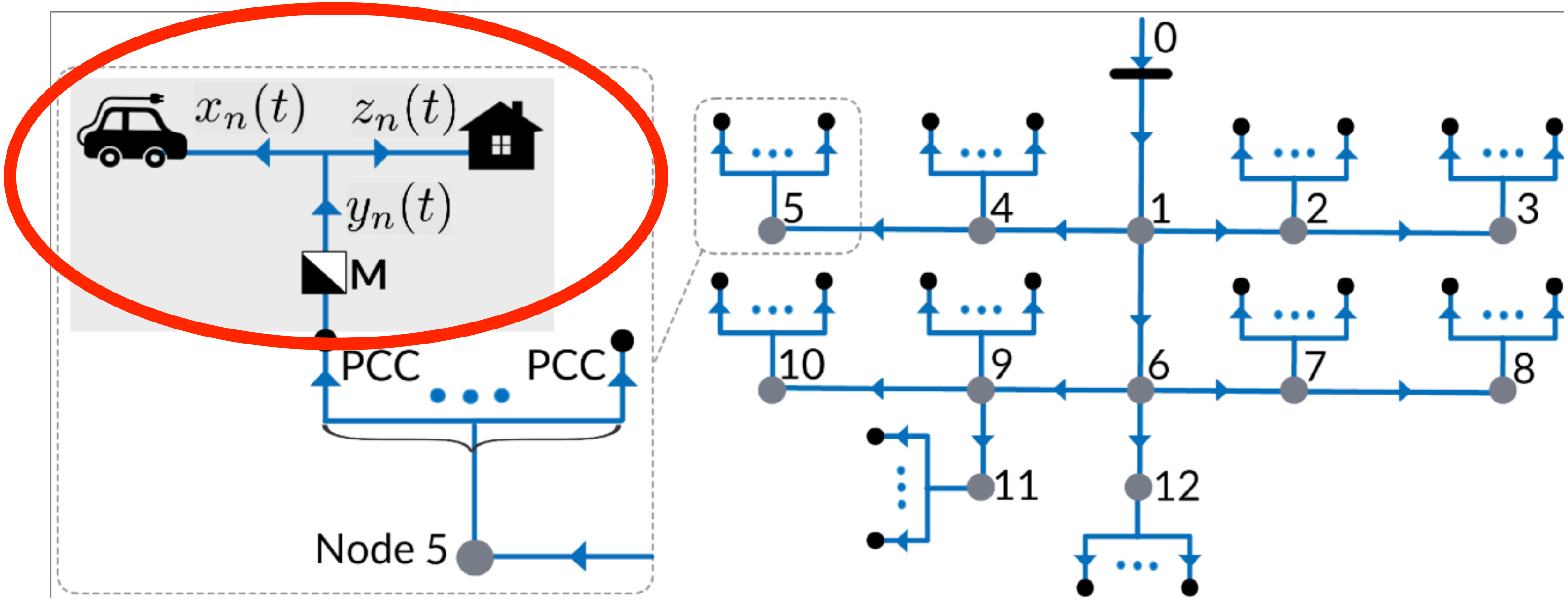


Load + PV + EV



Coordinating EV Charging and Discharging

Vehicle 2 Grid operation?



1. **Reduce peak load through a transformer**
2. **What about the supply voltages?**

N. I. Nimalsiri, E. L. Ratnam, D. B. Smith, C. P. Mediwaththe and S. K. Halgamuge, "Coordinated Charge and Discharge Scheduling of Electric Vehicles for Load Curve Shaping," in *IEEE Transactions on Intelligent Transportation Systems*, doi: 10.1109/TITS.2021.3071686.

LP: Balancing Customer and Distributor Benefits

$$\max_{x_1 \in \mathbb{R}^s} \quad \Delta\eta^T x_1$$

such that

$$A_1 x_1 \leq b_1,$$
$$\mathbb{1}^T x_1 = 0.$$

→ **maximise savings (LP)**

→ **EV Battery constraints**

Plus → **Linearised Power Flow Equations (LinDistFlow) with Voltage Constraints**

$$\underline{v}^2 \mathbf{1} \leq \boldsymbol{\mathcal{V}} + \sum_{n=1}^{h} \overline{D}_n \mathbf{x}_n \leq \overline{v}^2 \mathbf{1}$$

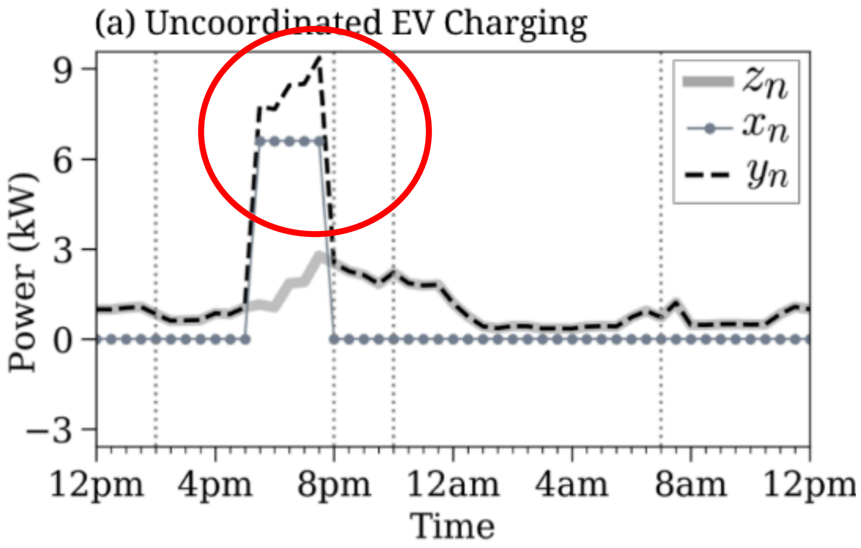
Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

Coordinate EV Charging with V2G

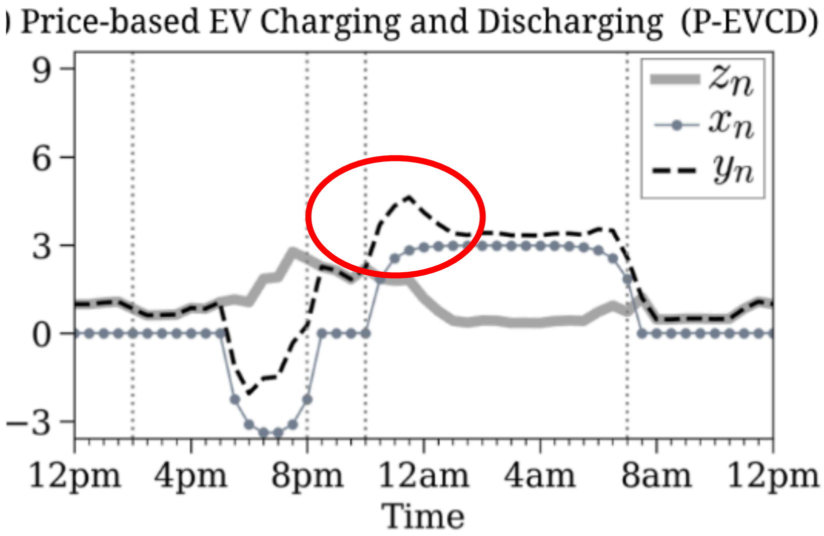
≈ 14 kWh/day
≈ 110 km

?

What about the supply voltages?



Cost: $9.02



Cost $0.72

Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

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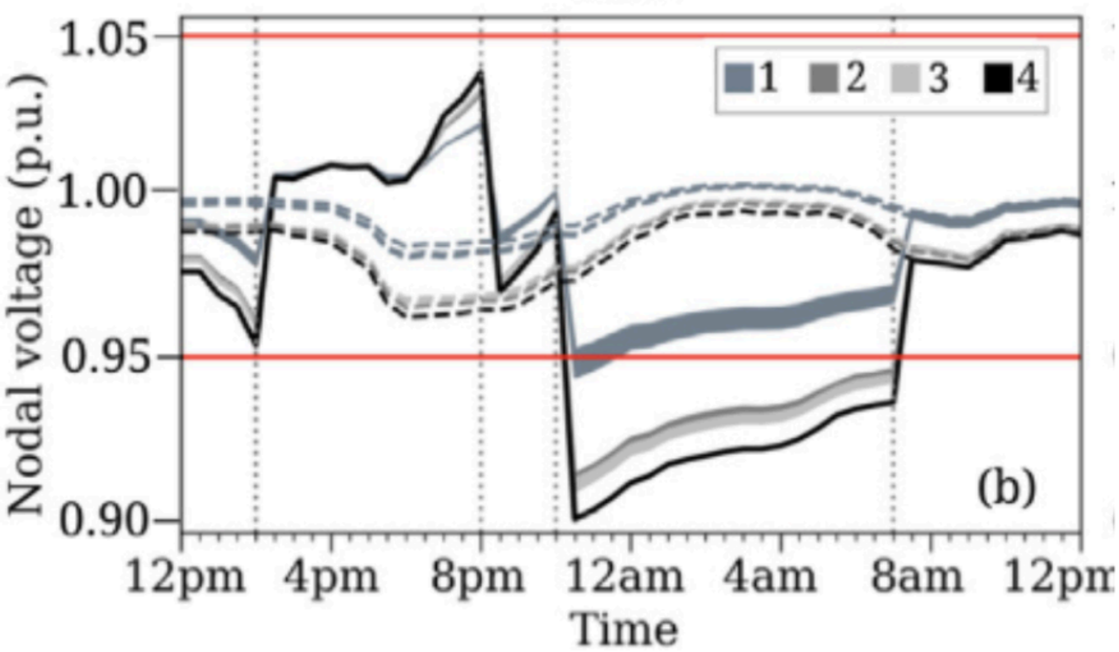

Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

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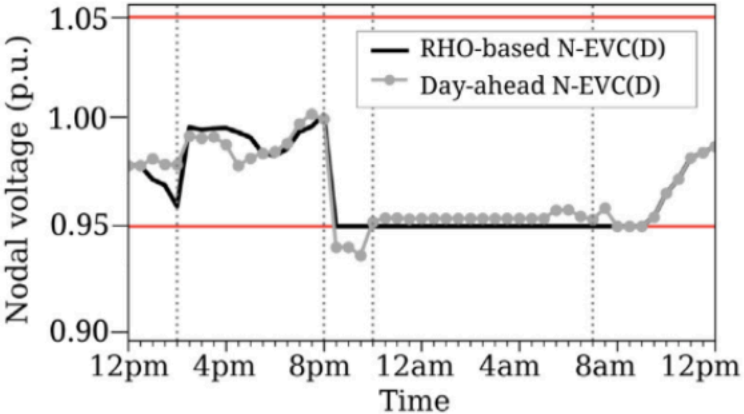
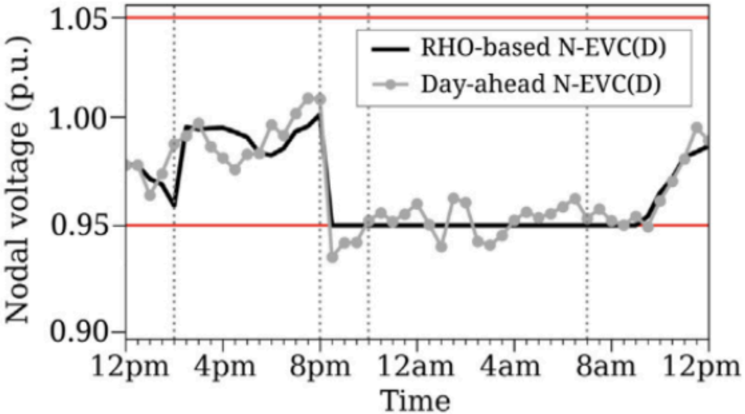


(a)

Day-ahead EV arrival times are different from actual EV arrival times



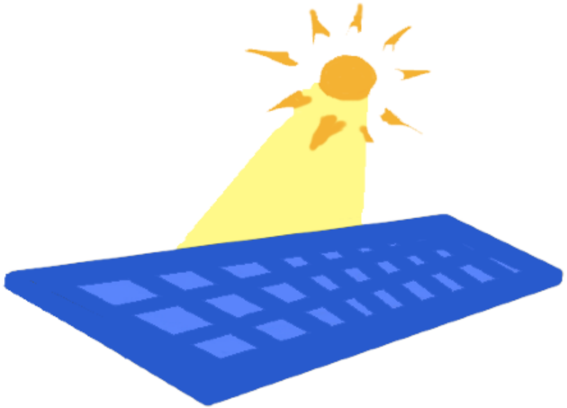
(b)

Day-ahead non-EV load is different from actual non-EV load

Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

What about Electric Vehicle customers?

+



+

Residential Load

≈ 20 kWh/day

$\approx \$5$/day

1.5 kW PV unit produces ≈ 5 kWh/day

$\approx \$2$/day

1.5 kW PV unit exports ≈ 2 kWh/day

≈ 14 kWh/day

≈ 110 km

≈ $9.0/day

LP ≈ $0.7/day ($8.3)

What about **excess** generation?

https://www.energymadeeasy.gov.au/

https://www.tesla.com/en_AU/support/range-calculator

1. A single residential system

2. Coordinated residential systems

3. New Control Paradigms

DOE EERE ENERGISE:
Phasor-Based Control for Scalable Solar Photovoltaic Integration,
$2.573 million
2017-2020

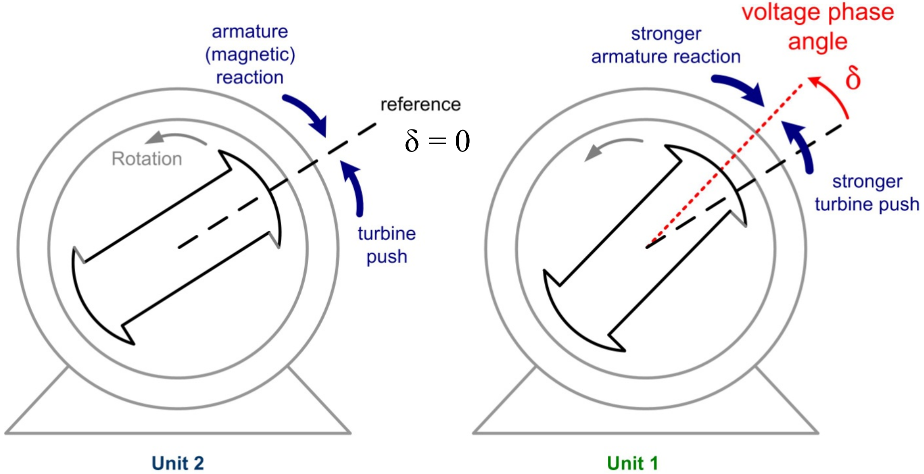
New Control Paradigm

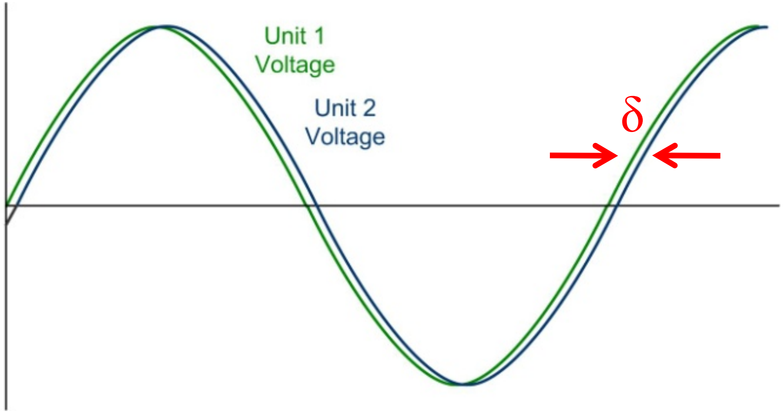
Synchrophasors compare the voltage phase angle at different locations

$$P \approx \frac{V_1 V_2}{Reactance} sin(\delta_{12})$$

$$|V_i|\angle\delta_i = \vec{V}_i(k)$$

The small phase angle δ between different locations on the grid drives a.c. power flow





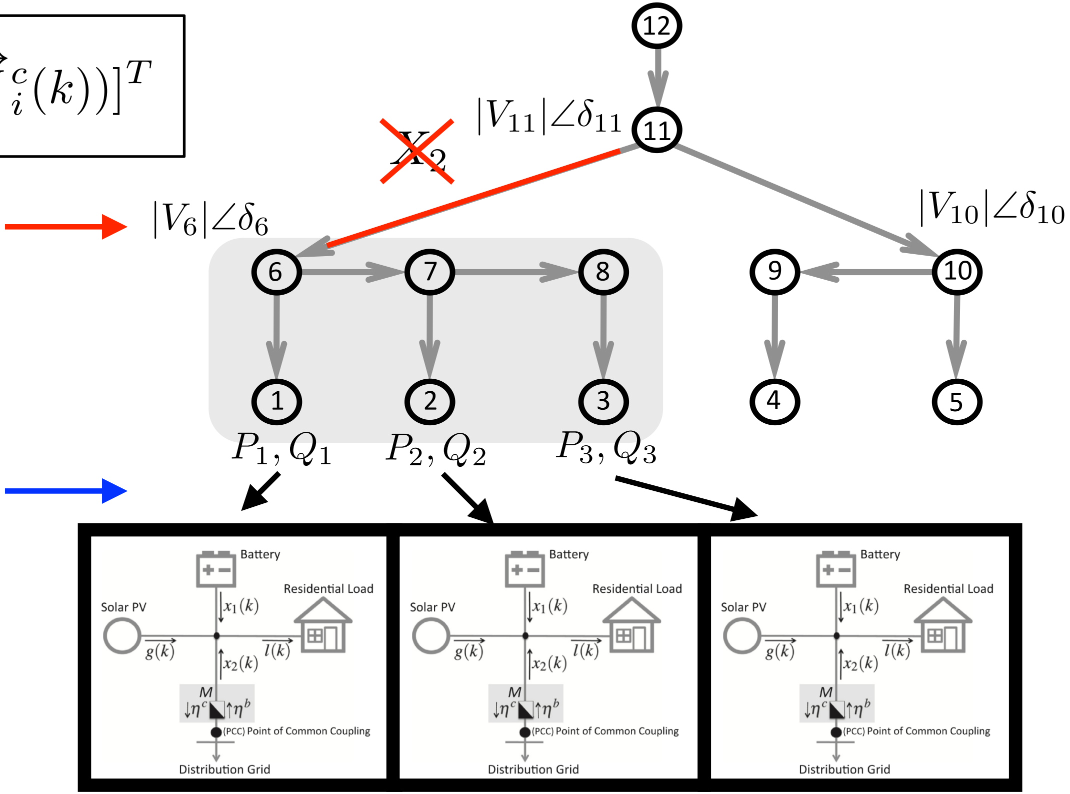
Power injection to the grid is greater where voltage phase angle is farther advanced. Power flows from Unit 1 toward Unit 2

Phasor-Based Control

$$|V_i|\angle\delta_i = \vec{V}_i(k) = [\vec{V}_i^a(k), \vec{V}_i^b(k), \vec{V}_i^c(k))]^T$$

Supervisory Layer

Local Layer



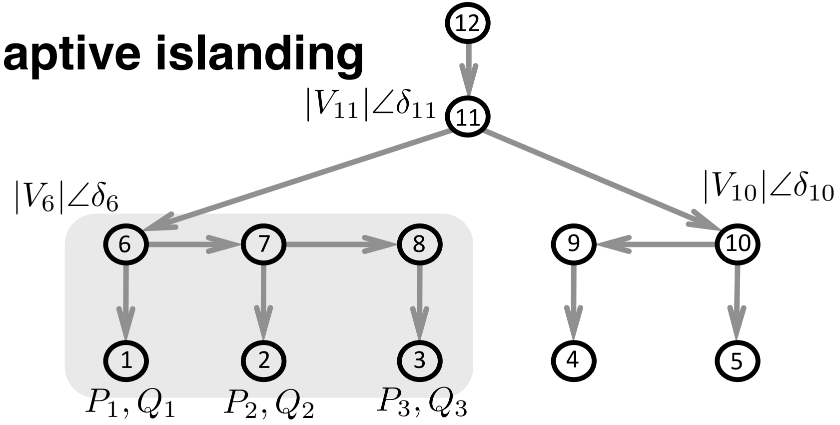
DOE EERE ENERGISE: Phasor-Based Control for Scalable Solar Photovoltaic Integration, $2.573 million

Phasor-Based Control for Scalable Integration of Variable Energy Resources, A von Meier, EL Ratnam, K Brady, K Moffat, J Swartz, Energies 13 (1), 190

Supervisory Layer: Quadratic Program

1. Phasor Alignment to operate a switch / adaptive islanding

$$\min \sum_{k=1}^{s} \|\vec{V}_{11}(k) - \vec{V}_{6}(k)\|$$



2. A-B-C phase balancing

$$\min \sum_{k=1}^{s} (V_6^a(k) - V_6^b(k))^2 + (V_6^a(k) - V_6^c(k))^2 + (V_6^b(k) - V_6^c(k))^2$$

Subject to constraints

Power flow constraints + voltage constraints

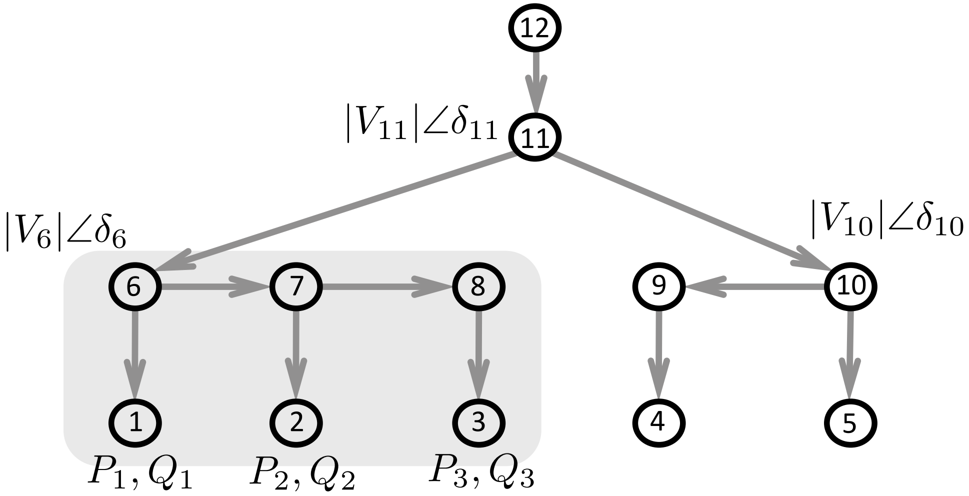
$A_1 X_1 \leq N b_1, \;\; \mathbb{1}^T X_1 = 0$ → battery constraints

Michael Sankur, K. Brady, E.L. Ratnam, A. von Meier - ENERGISE, and ANU PhD Wilhiam de Carvalho extending the work

Local Layer: Phasor Tracking

S-PBC Reference = $\begin{bmatrix} |\widetilde{V_6}| \\ \angle\widetilde{\delta_6} \end{bmatrix}$

1. Follow S-PBC reference
2. Disturbance rejection
3. Model free



Approach

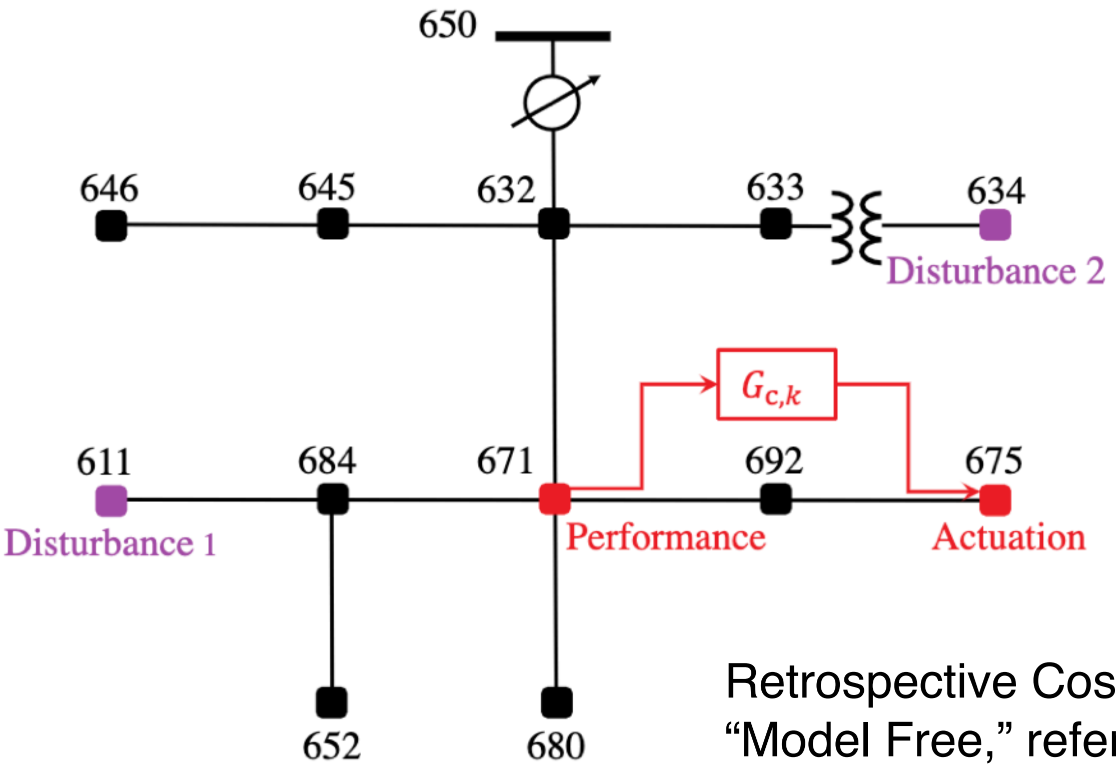
- PI control - with offline tuning
- Retrospective Cost Adaptive Control (RCAC)

1. Local Phasor-Based Control of DER Inverters for Voltage Regulation on Distribution Feeders, J Swartz, E Ratnam, TG Roberts, A von Meier, IEEE Green Technologies Conference (GreenTech)

2. Visual Tool for Assessing Stability of DER Configurations on Three-Phase Radial Networks, J. Swartz, B. Wais, E. Ratnam and A. von Meier, 2021 IEEE Madrid PowerTech, 2021, pp. 1-6

3. Phasor-Based Adaptive Control of a Test-Feeder Distribution Network: Application of Retrospective Cost Adaptive Control to the IEEE 13-Node Test Feeder, SAU Islam, EL Ratman, A Goel, DS Bernstein, IEEE Control Systems Magazine 39 (4), 56 - 74

RCAC controller



Retrospective Cost Adaptive Controller $G_{c,k}$
"Model Free," reference following, disturbance rejection

Phasor-Based Adaptive Control of a Test-Feeder Distribution Network: Application of Retrospective Cost Adaptive Control to the IEEE 13-Node Test Feeder, SAU Islam, EL Ratman, A Goel, DS Bernstein, IEEE Control Systems Magazine 39 (4), 56 - 74

SOCIAL SHAPING OF LINEAR QUADRATIC MULTI-AGENT SYSTEMS

Australian and New Zealand Control Conference - ANZCC 2021

Authors: Zeinab Salehi[1], Yijun Chen[2], Elizabeth Ratnam[1], Ian R. Petersen[1], and Guodong Shi[2]

Australian National University

[1]Research School of Engineering, The Australian National University, Canberra, Australia.

[2]The Australian Center for Field Robotics, The University of Sydney, NSW, Australia.

Texas: February 2021

An extreme cold weather event resulted in power a power outage disaster throughout the state. Consequently,

- Some Texans received bills of $USD 5000, or more for 5 days of power

February 17, after

Motivated by Texas: February 2021

We propose a transactive energy system to guarantee that the price for electricity at a competitive equilibrium is always socially acceptable.

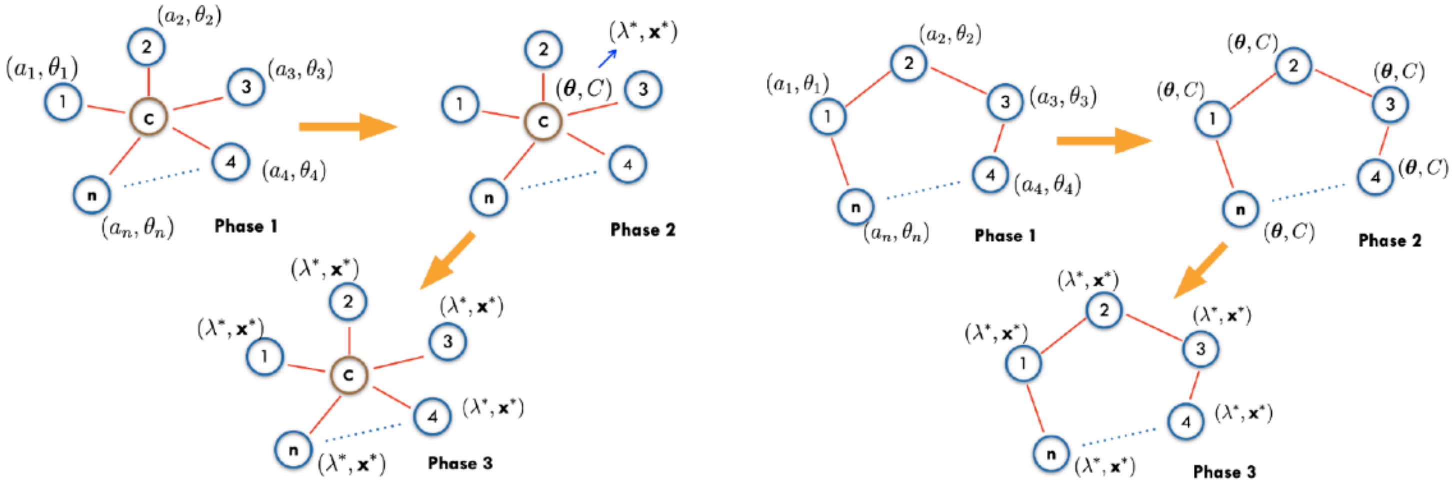
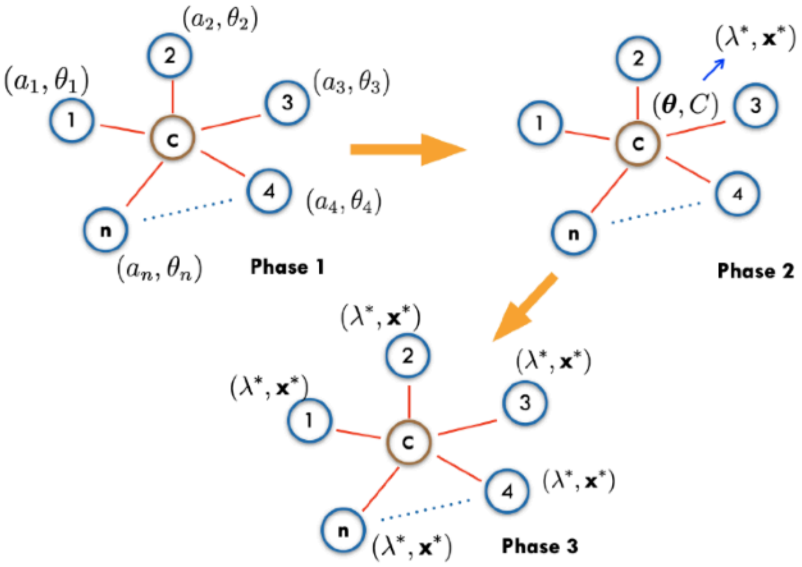


Fig. 1: Centralized (left) and distributed (right) implementations of competitive equilibriums for the proposed transactive energy systems. Each dark blue circle represents an agent in the system; the brown circle represents a central coordinator agent; each red line represent a communication link. The implementations take place in three sequential phases.

Motivated by Texas: February 2021

We propose a transactive energy system to guarantee that the price for electricity at a competitive equilibrium is always socially acceptable.

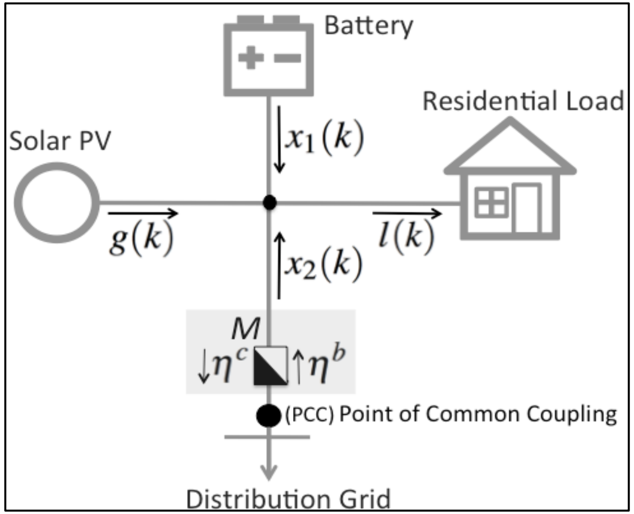
- Aim to reduce customer bills (when customers are prosumers)
- Satisfy thermal comfort of users
- Guarantee the price for electricity never exceeds an affordable price threshold, even during extreme weather events

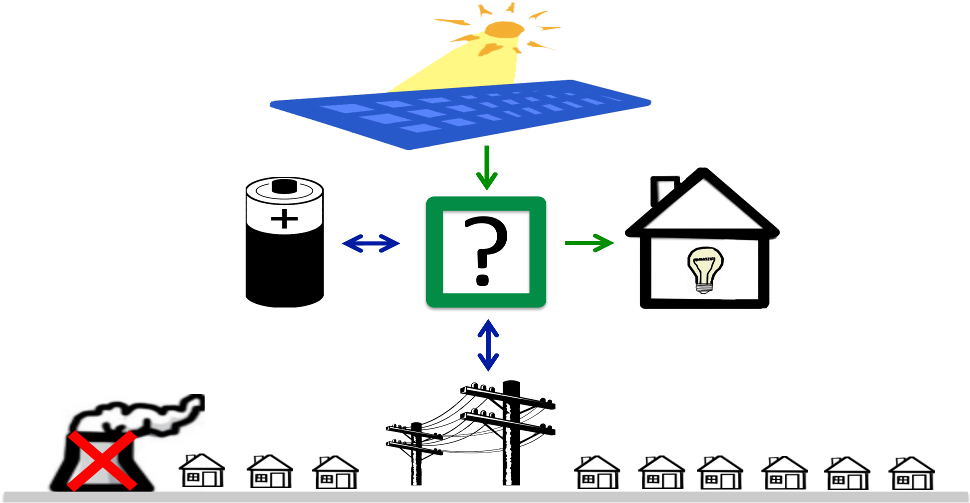


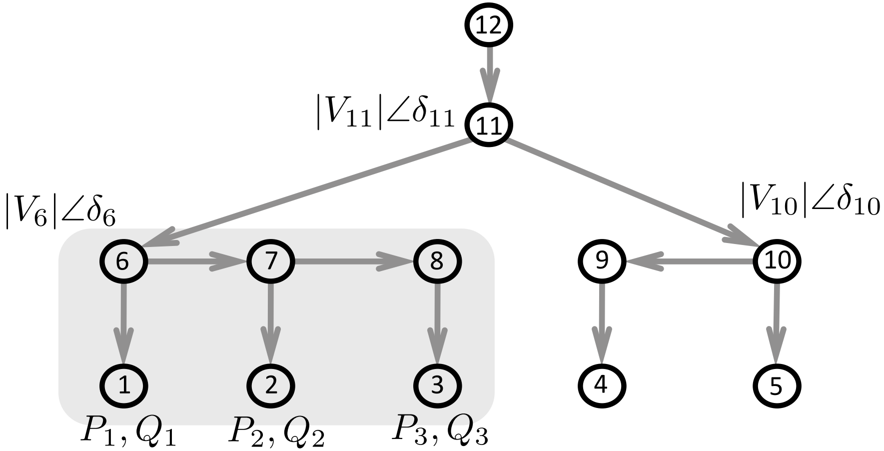
1. A single residential system

2. Coordinated residential systems

3. New Control Paradigms



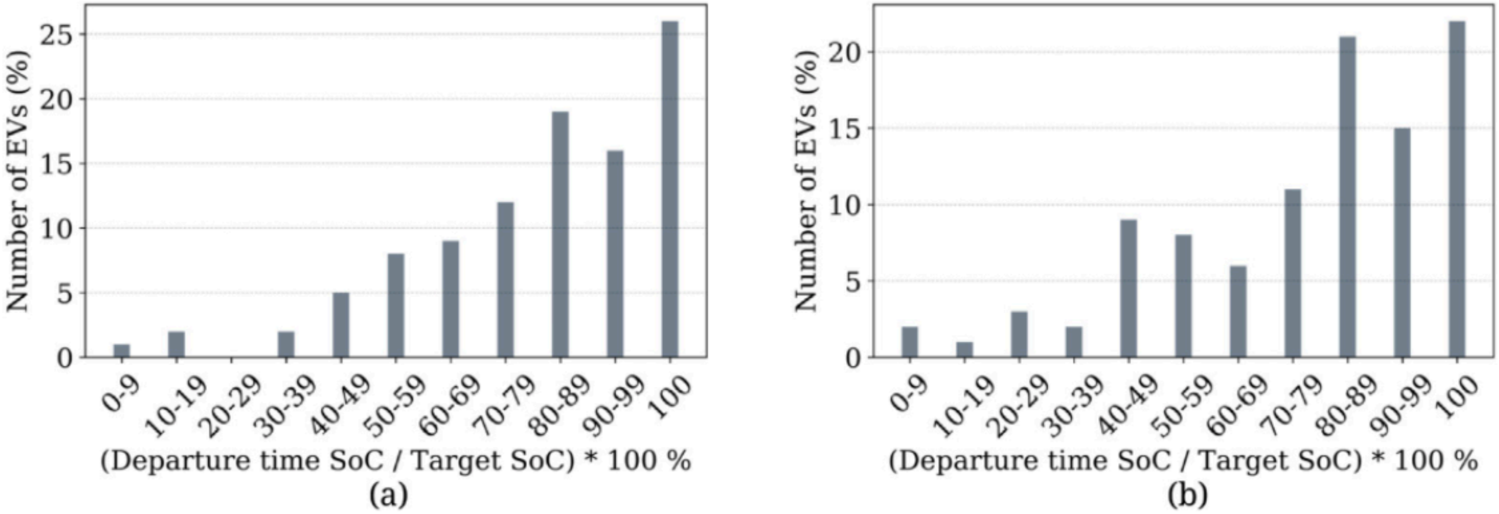




Thank you!

Coordinate EV Charging with V2G

2. What about the supply voltages?



Without RHO: Departure time SOC is not met in all cases,

With RHO: All EVs attain their target SoC ahead of the departure time

Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

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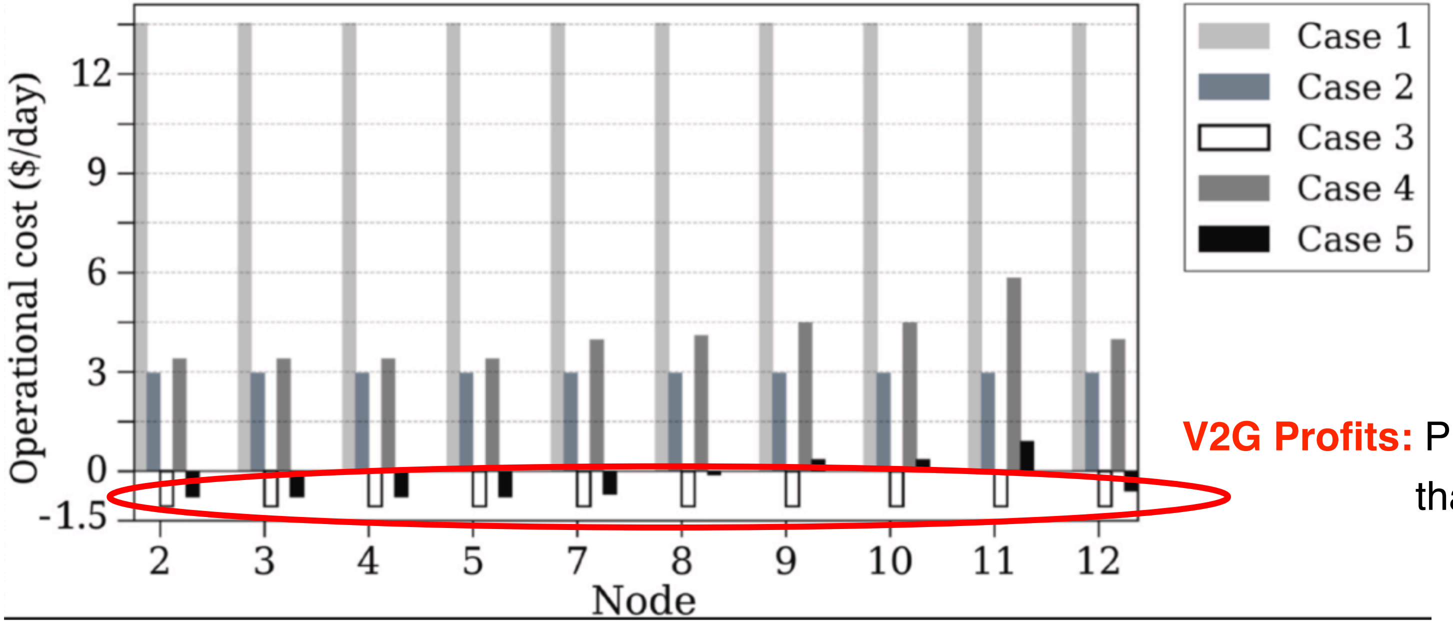

Uncoordinated
Price-based Charge
Price-based V2G
Network-based Charge
Network-based V2G

V2G Profits: Price-based higher than network-aware

Nanduni I. Nimalsiri, Elizabeth L. Ratnam, Chathurika P. Mediwaththe, David B. Smith, Saman K. Halgamuge, Coordinated charging and discharging control of electric vehicles to manage supply voltages in distribution networks: Assessing the customer benefit, Applied Energy, Vol 291, 2021

Fast AC Chargers (Level 2)

- A dedicated 32 amp AC charger up to 7kw on single phase power and 22kw on three phase power
- Dedicated circuit installed in homes, apartment complexes, workplaces, shopping centres and hotels
- Will add about 50-100km range per hour
- Will deliver a full charge from empty overnight for all EVs