Towards Usable Flexibility in Power Systems

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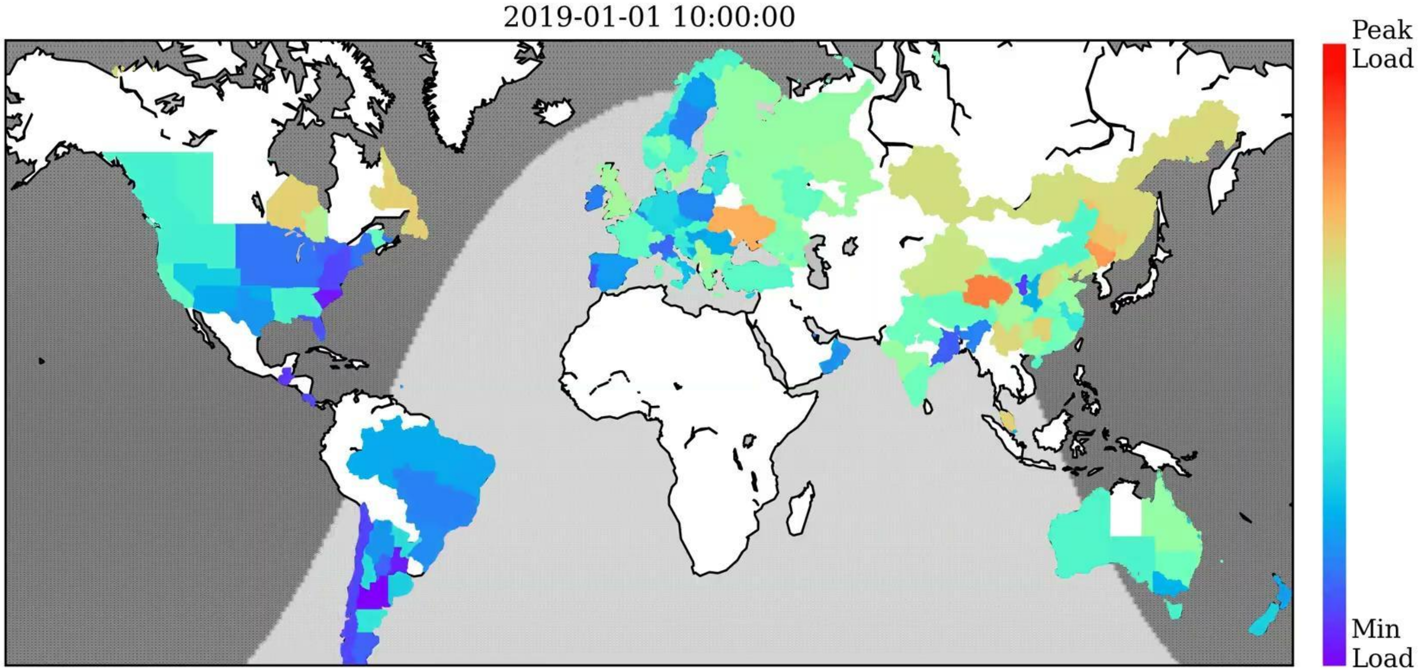
Spatio-temporal variation in electricity demand



Data available at constancecrozier.github.io/code/

Traditional operation: Supply follows demand

Future operation: Coordination from both sides

Real examples of demand response

ERCOT on Twitter


ERCOT
@ERCOT_ISO

ERCOT is requesting energy conservation at this time. Consumers and businesses are urged to reduce their electricity use this afternoon and into the evening.

3:42 PM · Apr 13, 2021 · Twitter Web App

679 Retweets 3,111 Quote Tweets 832 Likes

Octopus "Agile" Tariff

Outline

How much flexibility do we have?
Building aggregate models of flexible loads

How useful is this flexibility?
Quantifying the value of flexibility

Linear Programming Basics

Decision Variables

The “free variables” in our problem

(Linear) Constraints

Rules which our solution must satisfy

Convex problem → Single minima

Can be solved in seconds, even with thousands of variables

Linear Objective Function

Our expression for success – which we want to maximize or minimize

Definitions of flexible load

(1) Battery charging

(2) Thermostatically controlled loads

(3) Scheduling of processes

Definitions of flexible load

(1) Battery charging

Decision variables

$$\sum_{t \in \mathbb{T}} \eta p_t^+ - \frac{1}{\eta} p_t^- \geq \frac{E}{\Delta_t}$$

(2) Thermostatically controlled loads

(3) Scheduling of processes

Definitions of flexible load

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$$\sum_{t \in \mathbb{T}} \eta p_t^+ - \frac{1}{\eta} p_t^- \geq \frac{E}{\Delta_t}$$

(2) Thermostatically controlled loads

$$T_{t+1} = T_t + \frac{(T_{out} - T_t)}{RC} - \eta_c p_t^c + \eta_h p_t^h \qquad T^{min} \leq T_t \leq T^{max} \quad \forall t$$

(3) Scheduling of processes

$$\sum_{t \in \mathbb{T}} x_t \geq N_T \quad x_t \in \mathbb{Z}$$

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$$\sum_{t \in \mathbb{T}} x_t \geq N_T \quad x_t \in \mathbb{Z}$$

Considering optimal control of a single device (EVs)

$$\min \quad \sum_{t} c_t(p_t^+ - p_t^-)$$

$$\text{s.t.} \quad \sum_{t \in \mathbb{T}} \eta p_t^+ - \frac{1}{\eta} p_t^- \geq \frac{E}{\Delta_t}$$

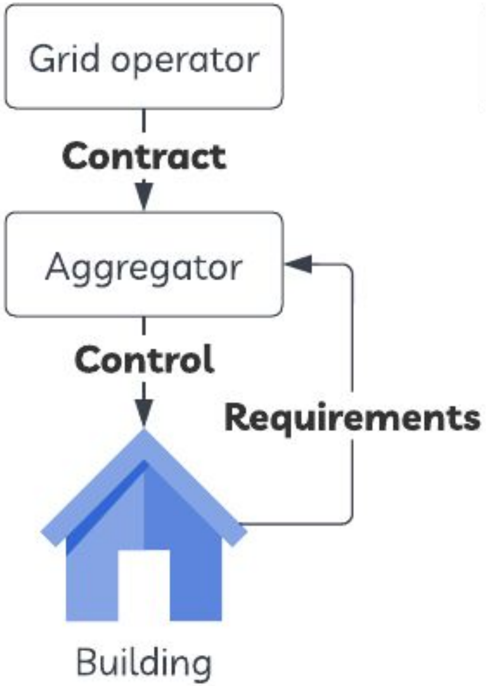
$$0 \leq p_t^+, p_t^- \leq p^{max} \quad \forall t$$

Linear programming problem
Solves in under a second
Scales well

Requires knowledge of: EV miles driven, parking schedule, battery size.

Although we could solve this problem with 1000s of EVs, it is not realistic to get this sensitive data from them

Control via a third party aggregator



This solves at least one problem, but creates another:

The aggregator needs to build a temporal model for the total flexibility they have

Challenge 1: Many governing factors

Time of day

Temperature

Big events

All also influential factors in **non flexible load** and (in some cases **renewable generation**!

Challenge 2: Aggregation of many devices

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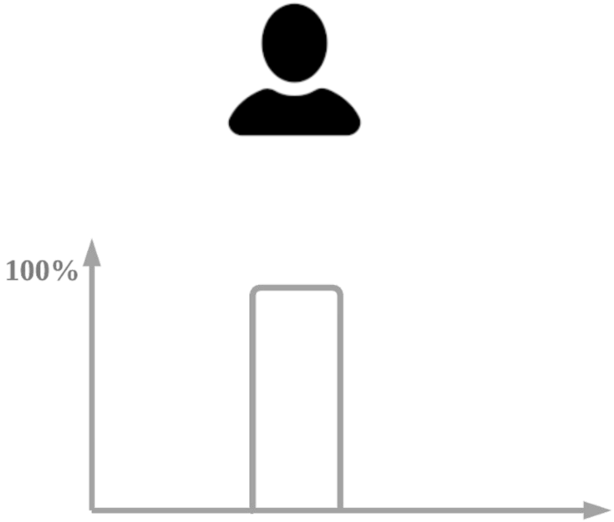
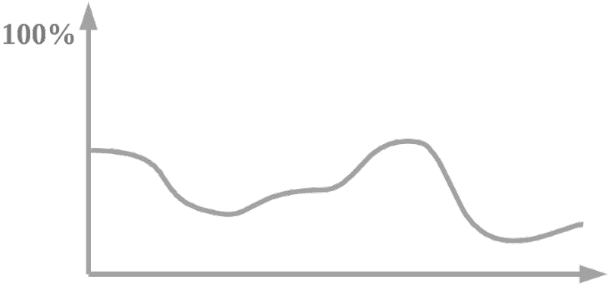
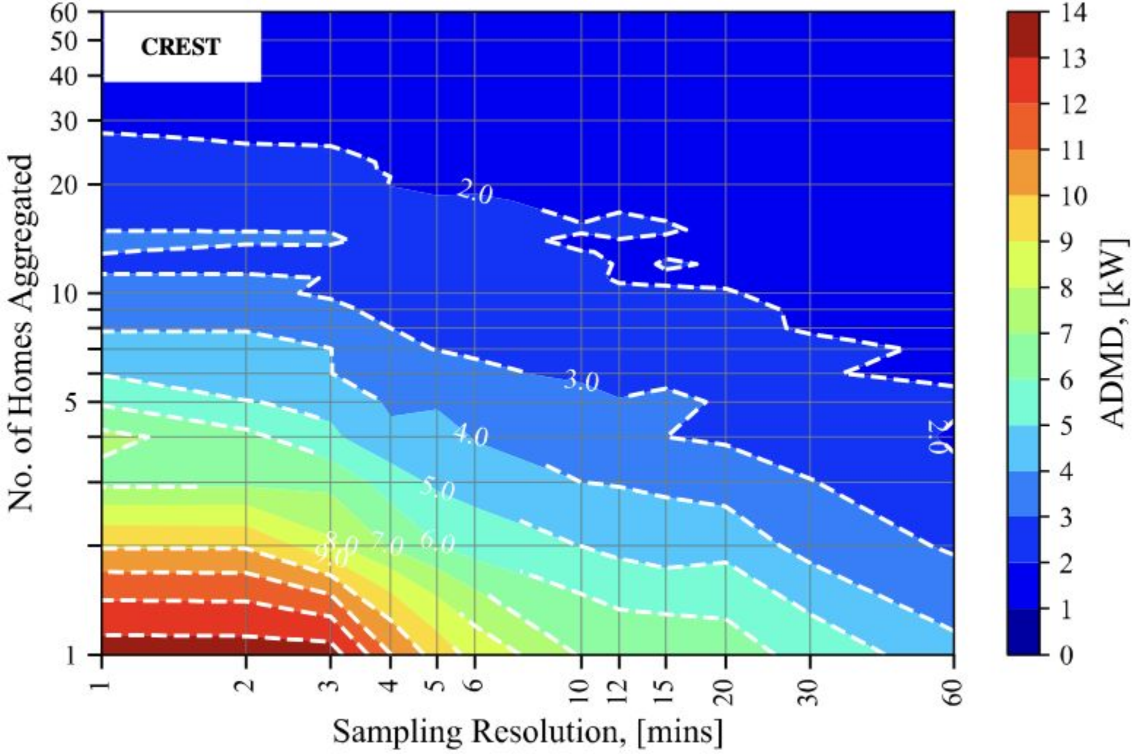


Challenge 2: Aggregation of many devices



Effects of aggregation on uncertainty



ADMD

After **D**iversity **M**aximum **D**emand

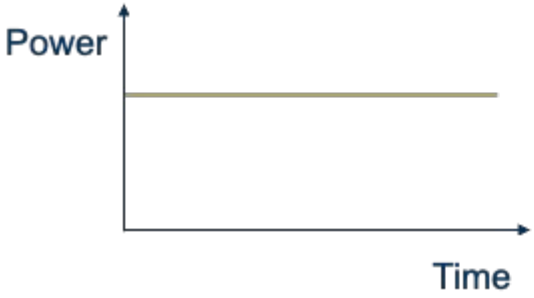
Elombo et al, Africon, 2017

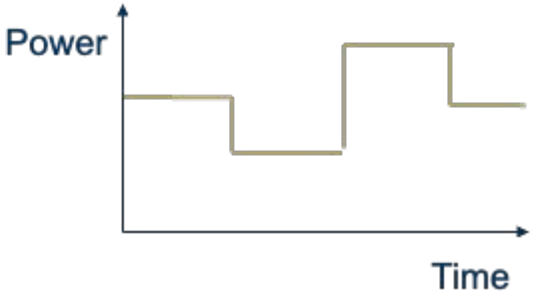
Can we model aggregate demand as a battery?

“**Capacity**”: the power demand that can be reduced

“**Duration**”: how long the load can be reduced

“**Efficiency**”: the % of the energy which is kept





Batteries have nice linear dynamics

$$\min \quad \sum_t c_t(p_t^c - p_t^d)$$

$$\text{s.t.} \quad E_{t+1} = E_t + p_t^c \eta - \frac{p_t^d}{\eta}$$

$$0 \leq E_t \leq E^{max} \quad \forall t$$

$$0 \leq p_t^c, p_t^d \leq p^{max}$$

Linear programming problem

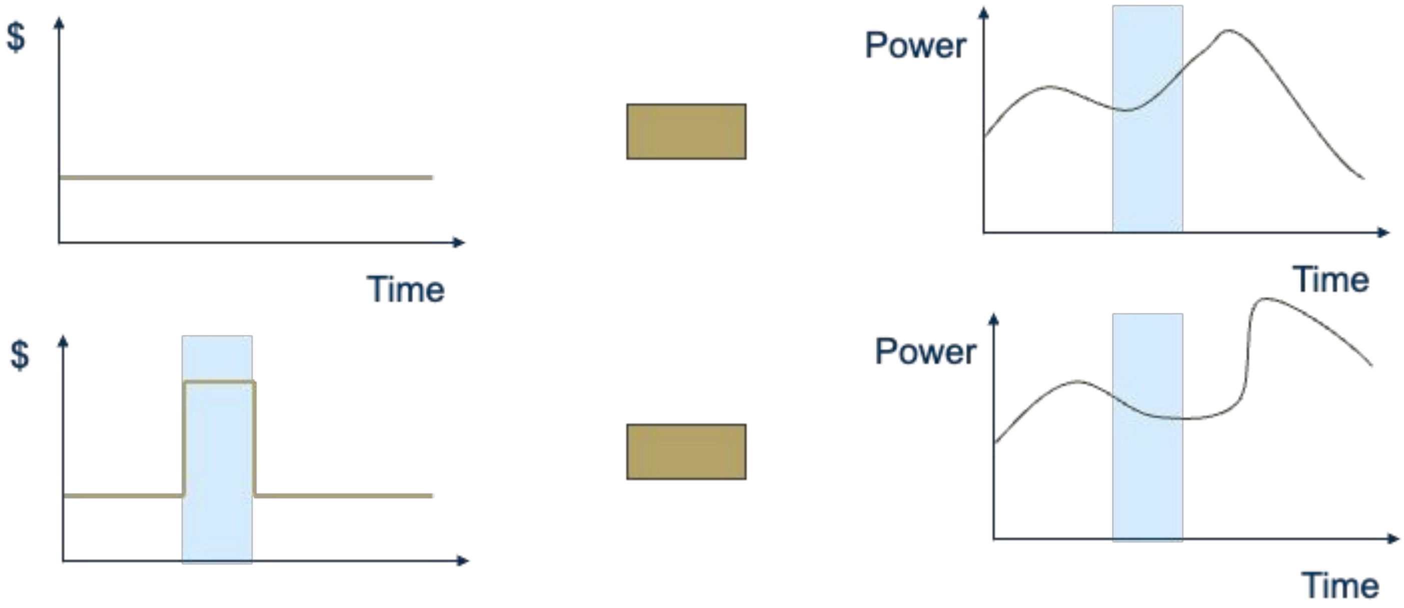
Convex

Solves is seconds

Can be directly included in traditional unit commitment problems (more on this to come)

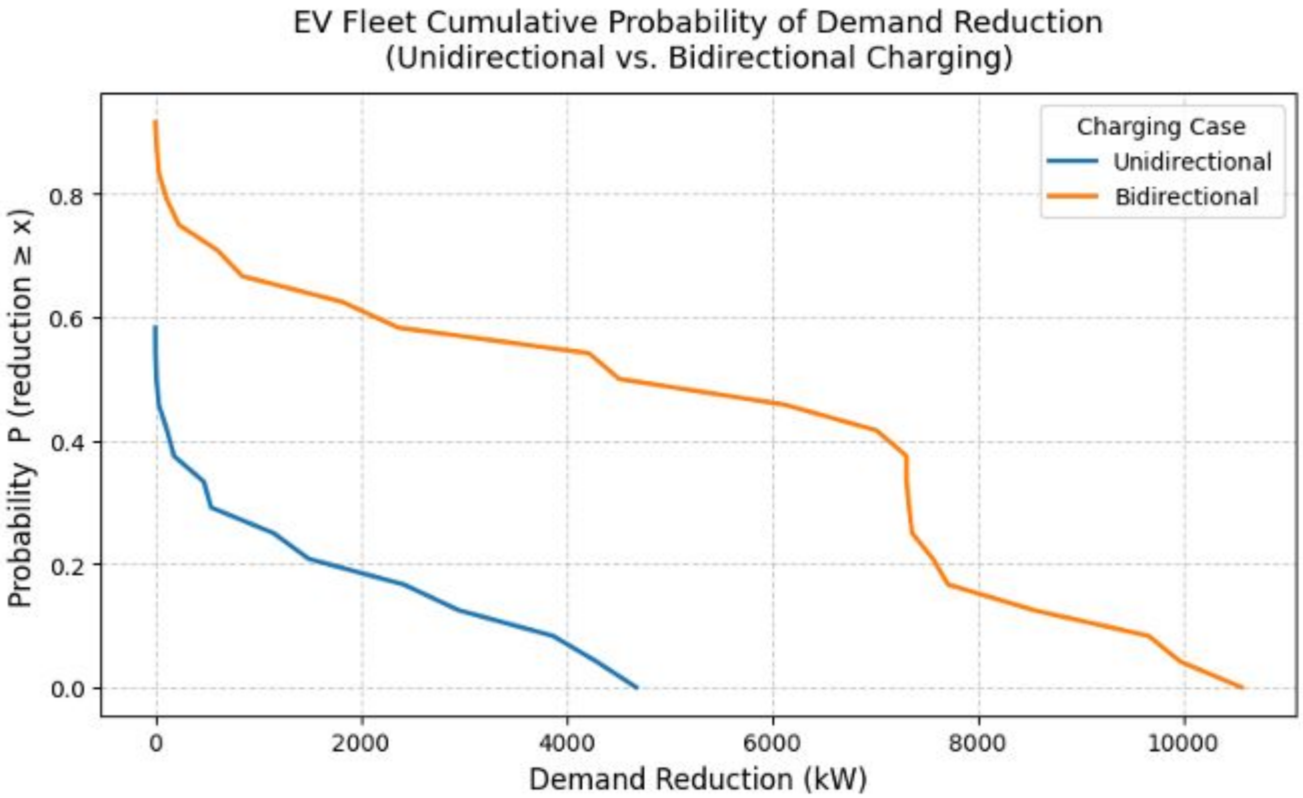
"All models are wrong, but some are useful" – George Box

For flexible load capacity is time-variant



The only thing we can meaningfully quantify is the amount load can be reduced for a specific price at a specific time

Example using 1000 electric vehicles



Catherine Wang

Outline

How much flexibility do we have?
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DC OPF: Finding the minimum cost generators

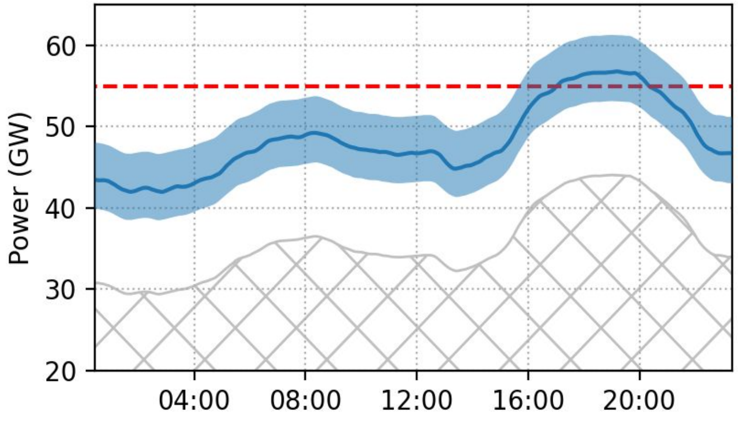
$$
\begin{aligned}
\min \quad & f(p_g) \\
\text{s.t.} \quad & 0 = \sum_{g \in G_i} p_g - \sum_{l \in L_i} p_l - \sum_{e \in E_i} b_e(\theta_i - \theta_{e_j}) \quad \forall i \\
& -p_e^{max} \leq b_e(\theta_{e_i} - \theta_{e_j}) \leq p_e^{max} \\
& p_g \leq p_g^{max} \quad \forall g \\
& -\pi \leq \theta_i \leq \pi \quad \forall i \\
& p_g \geq 0 \quad \forall g, i
\end{aligned}
$$

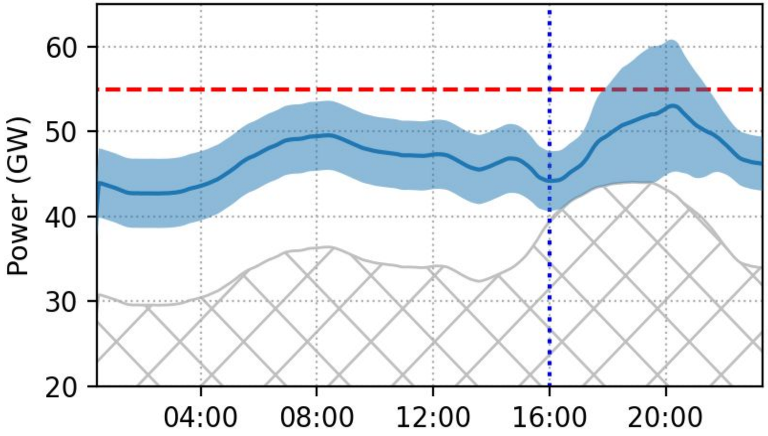
Locational marginal prices from the dual variables

i: network nodes (often referred to as buses)
g: generators
e: lines (often referred to as branches)
G_i: the set of generators connected to i

Flexibility has a time-dependency

With and without deploying flexible load at 4pm





We need to include load specific constraints

Example profit from V2G charging using LMPs

Perfect forecast of RT prices

Using DA prices as a forecast

Month	Assumption	Monthly Revenue	Best Daily Profit	Worst Daily Profit
Jan	Perfect Information	$128.81	$31.78	$0.86
Jan	Stochastic	$6.79	$12.78	-$13.33
March	Perfect Information	$345.33	$78.27	$1.11
March	Stochastic	$6.45	$7.04	-$7.78
July	Perfect Information	$168.43	$40.38	$0.68
July	Stochastic	$16.52	$6.20	$3.23

Value depends strongly on a few “key” price spikes

C. Crozier, A. Pigott, K. Baker, “Spatial arbitrage through bidirectional electric vehicle charging”, PESGM 23

“Value” may be in terms of deferred investments

Capital costs represent a large share of the total cost per MWh of generation

New Vogtle reactors cost $35bn for 1.1 GW of capacity

Assuming 35 year lifetime and 95% capacity factor

320,616 GWh over 35 years

$109/MWh

Just CAPEX, without financing

DC UC: Finding the minimum cost generators

$$\min \quad \sum_{g,t} c_{g,t} p_{g,t}$$

$$\text{s.t.} \quad 0 = \sum_{g \in G_i} p_{g,t} - \sum_{l \in L_i} p_{l,t} - \sum_{e \in E_i} b_e(\theta_{i,t} - \theta_{e_j,t}) \quad \forall i, t$$

$$-p_e^{max} \leq b_e(\theta_{e_i,t} - \theta_{e_j,t}) \leq p_e^{max} \quad \forall e, t$$

$$p_g^{min} \boxed{x_g} \leq p_{g,t} \leq p_g^{max} \boxed{x_g} \quad \forall g, t$$

$$p_{g,t-1} - r_g \delta_t \leq p_{g,t} \leq p_{g,t-1} + r_g \delta_t$$

i: network nodes (often referred to as buses)
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Capacity planning: how will we meet future peak demand

$$\min \quad \sum_{g,t} c^{op}_{g,t} p_{g,t} + \sum_{g} c^{cap}_{g} p^{max}_{g} + \sum_{e} c_e p^{max}_{e}$$

$$\text{s.t.} \quad 0 = \sum_{g \in G_i} p_{g,t} - \sum_{l \in L_i} p_{l,t} - \sum_{e \in E_i} b_e(\theta_{i,t} - \theta_{e_j,t}) \quad \forall i, t$$

$$-p^{max}_{e} \leq b_e(\theta_{e_i,t} - \theta_{e_j,t}) \leq p^{max}_{e} \quad \forall e, t$$

$$p^{min}_{g} x_g \leq p_{g,t} \leq p^{max}_{g} x_g \quad \forall g, t$$

$$p_{g,t-1} - r_g \delta_t \leq p_{g,t} \leq p_{g,t-1} + r_g \delta_t$$

i: network nodes (often referred to as buses)
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The chicken and the egg problem

Without establishing value streams for flexibility there is no incentive for development

While large scale flexibility remains at low TRL it is hard to build accurate models

Thanks for listening!

Happy to take questions, now or later

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