Integrating markets with control on electricity networks

John Ledyard
Caltech
For NEGT 11/20/14

With help from many others at Caltech and Southern California Edison
Especially Desmond Cai

A Work in Progress

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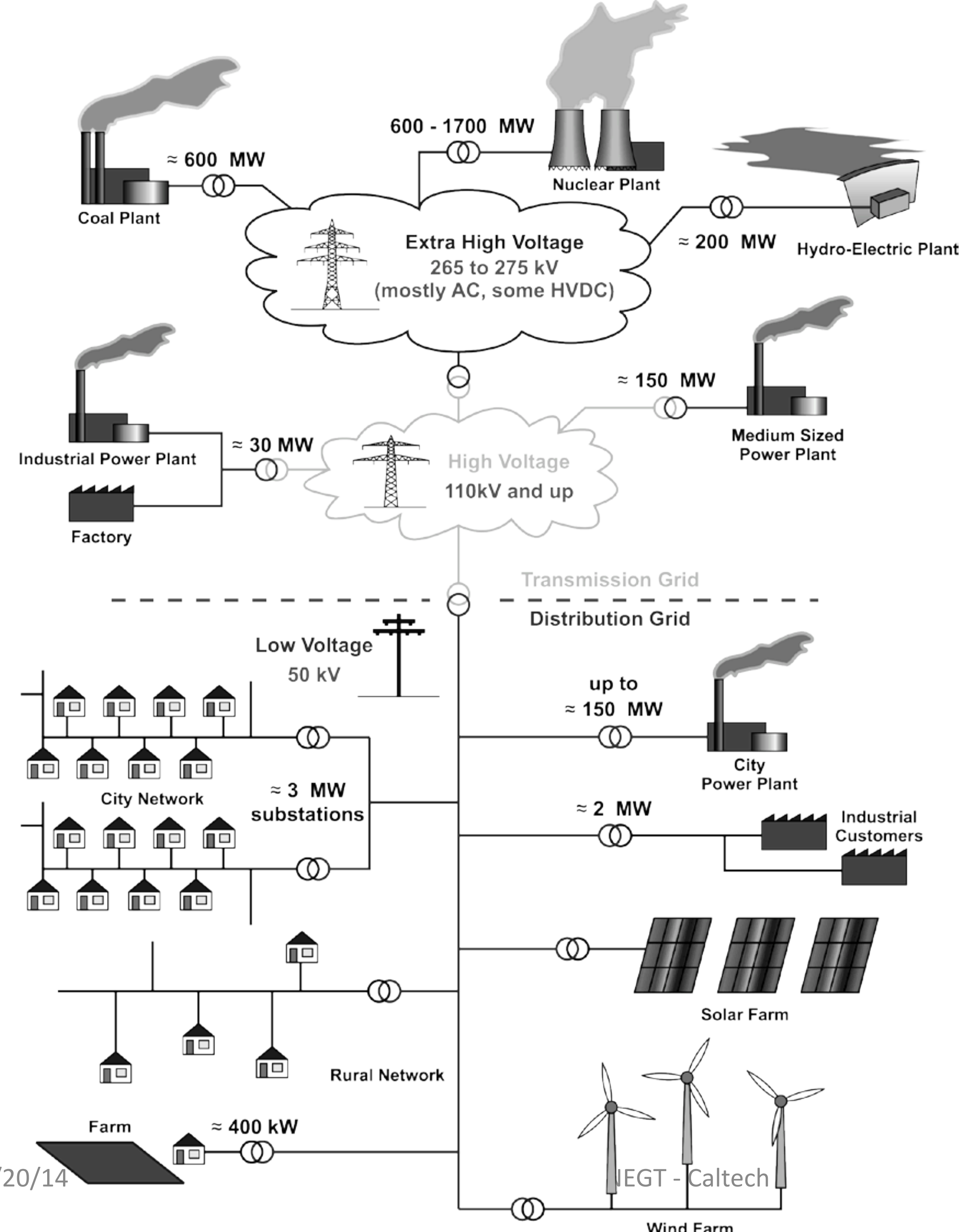
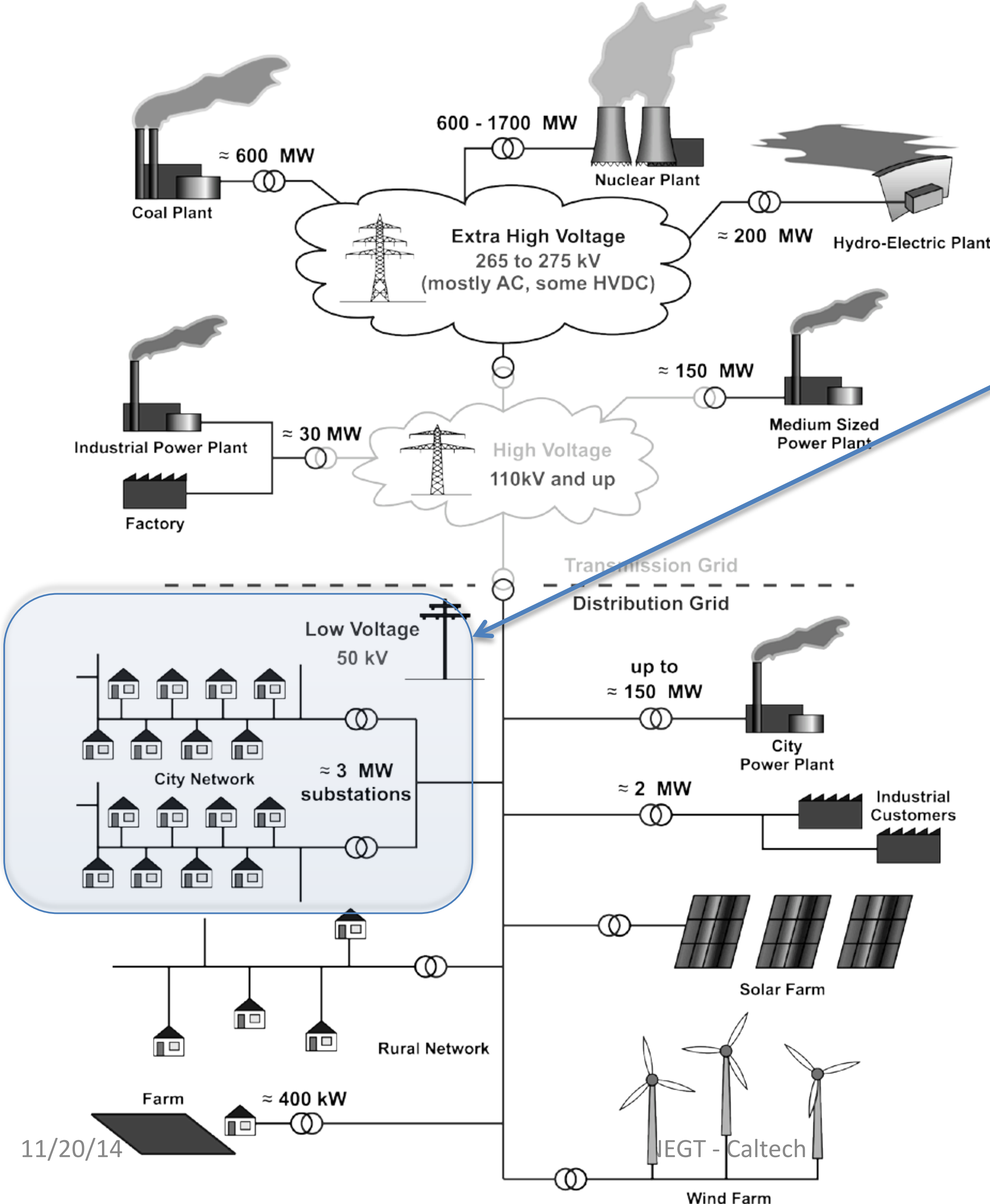
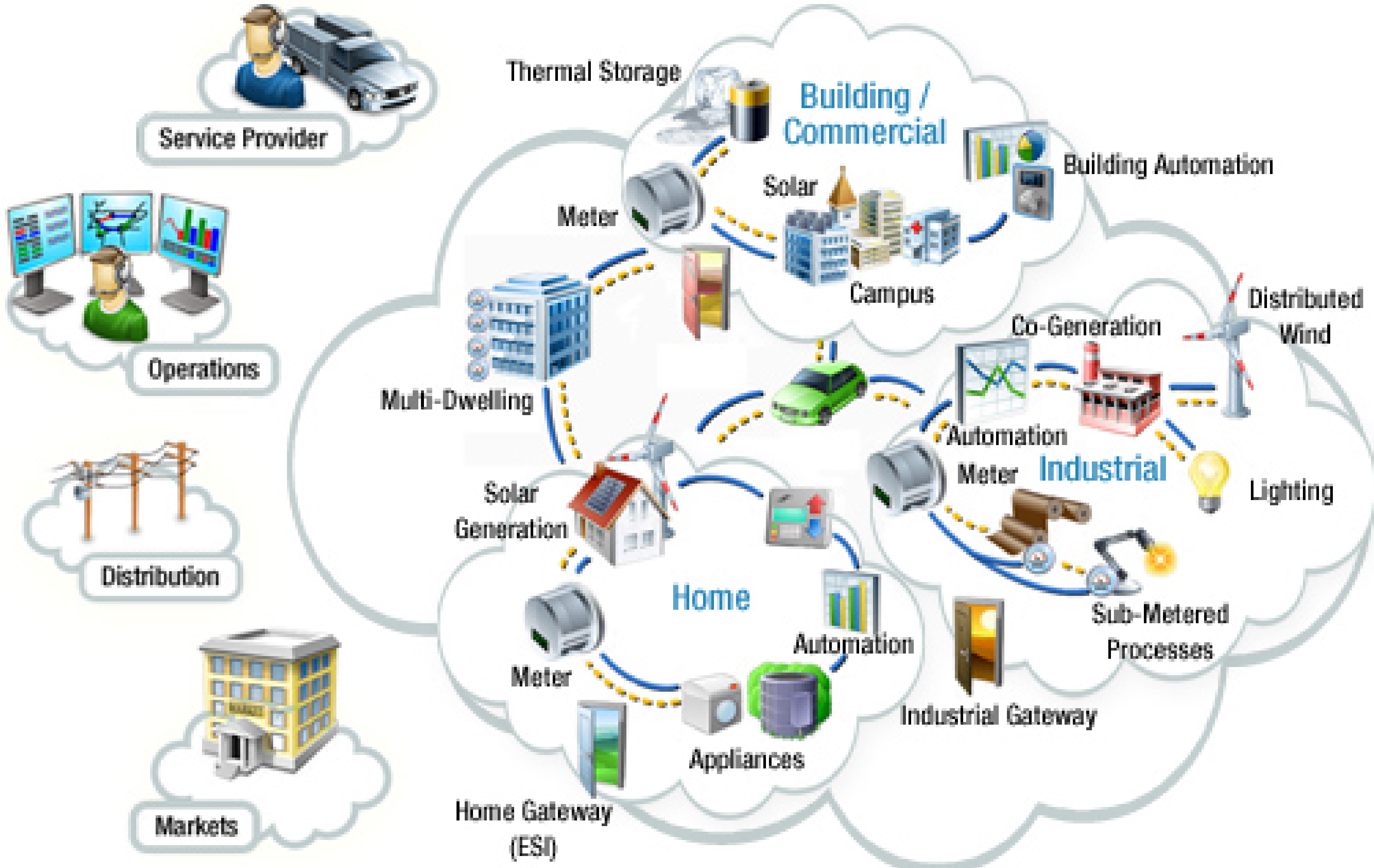

≈ 600 MW
Coal Plant
600 - 1700 MW
Nuclear Plant
Extra High Voltage
265 to 275 kV
(mostly AC, some HVDC)
≈ 200 MW
Hydro-Electric Plant
≈ 150 MW
Medium Sized
Power Plant
Industrial Power Plant
≈ 30 MW
High Voltage
110kV and up
Factory
Transmission Grid
Distribution Grid
Low Voltage
50 kV
up to
≈ 150 MW
City
Power Plant
City Network
≈ 3 MW
substations
≈ 2 MW
Industrial
Customers
Solar Farm
Rural Network
Farm
≈ 400 kW
Wind Farm

The Problem

- Increasing adoption of distributed energy resources (DER) implies difficulties for frequency and voltage control of electricity networks
  - Especially if economical storage is slow to come online
- Control of the wholesale side is not enough.
- Need to integrate distribution networks (retail) into the management of the grid.

Distribution Network




Service Provider
Operations
Distribution
Markets
Thermal Storage
Building / Commercial
Building Automation
Solar
Meter
Campus
Multi-Dwelling
Co-Generation
Distributed Wind
Automation
Meter
Industrial
Lighting
Solar Generation
Home
Meter
Automation
Sub-Metered Processes
Appliances
Industrial Gateway
Home Gateway (ESI)

How should we do this?

- Engineers – Give us control
  - Implementable but not optimal

- Economists – Let there be markets
  - Optimal but not implementable

- There is a way that is both implementable and optimal – <u>**Economic Control**</u>

Outline

- Optimal Distribution Network Operation
- Direct control
- Markets
- Economic Control

We focus on Vol/Var control in 5 min increments

– Principles would apply to frequency regulation, etc.

A Model of the DN: the network

There are $N+1$ buses. We identify $i=0$ with the substation bus connecting the DN to the grid managed by the ISO.

$$\text{Kirchoff's laws: } \tilde{P}_i - P_i - \sum_j |V_i||V_j||Y_{ij}|cos(\theta_{ij}+\delta_j-\delta_i) = 0, \forall i$$

$$\tilde{Q}_i - Q_i - \sum_j |V_i||V_j||Y_{ij}|sin(\theta_{ij}+\delta_j-\delta_i) = 0, \forall i$$

$$\text{Voltage limits: } V_i^{min} \le V_i \le V_i^{max}$$

where

$\tilde{P}_i$ = real power generation at i.
$\tilde{Q}_i$ = reactive power generation at i.
P_i = real power demand of customer at bus i.
Q_i = reactive power demand of customer at bus i.
Y_{ij} = the ij^{th} term of the bus admittance matrix.
V_i = the voltage at bus i.
θ_{ij} = the phase angle of the admittance Y_{ij}.
δ_i = the voltage angle at bus i.

A Model of the DN: the consumer

Utility function: $u^i = u^i(c^i(t))$

Consumption requires power:

$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t, e^i(t)).$$

$e^i(t)$ are temperature, work schedules,etc.

F captures thermal properties such as insulation, ...
- Ignores dynamics. We will get to that later.

Faced with prices $\pi(t)$, the consumer will choose $[c^i(1), \ldots, c^i(T)]$ to

$$\max_{(c,P)} \sum_t u^i(c^i(t)) - \pi(t)[F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t, e^i(t))].$$

We assume that Q^i and $\tilde{Q}^i$ are fixed or proportional to P and $\tilde{P}$.

The Goal is
Socially Optimal Management

Maximize Consumers' welfare + Producer's welfare

subject to

Laws of Physics and Laws of Economics

For now we assume there is only one producer on the network – the Distribution Network Operator.

- Assumed to be regulated and willing to follow rules.
- Allows us to focus on consumer responses.

Socially Optimal Vol/Var control

Choose $c(t), P^0(t), P(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), \theta(t)$ to solve

$$\max \sum_t \{\sum_i u^i(c^i(t)\} - \lambda(t)P^0(t) \qquad \text{subject to}$$

$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t)$$

$$\tilde{P}^i - P^i - \sum_j |V^i||V^j||Y_{ij}|cos(\theta_{ij} + \delta_j - \delta_i) = 0$$

$$\tilde{Q}^i - Q^i - \sum_j |V^i||V^j||Y_{ij}|sin(\theta_{ij} + \delta_j - \delta_i) = 0$$

$$V^i_{min} \leq V^i \leq V^i_{max}$$

Socially Optimal Vol/Var control

Choose $[c(t), P^0(t), P(t), Q(t), \tilde{Q}(t), V(t), \theta(t)]$ to solve

$\max \sum_t \{\sum_i u^i(c(t))\} - \lambda(t) P^0(t)$ subject to

Physics:

$$K(P^0(t), P(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), \theta(t)) \geq 0$$
$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t).$$

- What about economics and computer science?

3 difficulties in solving the optimal VVC

- Computation
  - NP hard (non-convexities)
  - Time scale – We do 5 minute intervals
  - Time correlation (EV, pool pumps,…)
- Information
  - The DNO does not know the consumers' utility functions.
- Incentive compatibility
  - Getting the consumer to "do the right thing"

Socially Optimal Vol/Var control

Choose $[c(t), P^0(t), P(t), Q(t), \tilde{Q}(t), V(t), \theta(t)]$ to solve

$\max \sum_t \{\sum_i u^i(c(t))\} - \lambda(t) P^0(t)$ subject to

<u>Physics</u>:

$$K(P^0(t), P(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), \theta(t)) \geq 0$$
$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t).$$

<u>Economics</u>:

Information and Incentive constraints

<u>Computer Science</u>:

Computational constraints

The engineers' solution: Let me control everything

- Give the DNO access to the consumers' devices.
  - Both controls and information.

- Minimize the cost of power (from ISO) subject to the laws of physics with bounds on what can be done to the consumers.

- Maintain standard regulatory average cost pricing policy with payments for access.

The engineers' solution

Given $\bar{c}(t)$, choose $[P^0(t), P(t), Q(t), \tilde{Q}(t), V(t), \theta(t)]$ to solve

$$\max -\lambda(t)P^0(t) \text{ subject to}$$

$$K(P^0(t), P(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), \theta(t)) \geq 0$$
$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t)$$
$$\bar{c}^i(t) - \epsilon \leq c^i(t) \leq \bar{c}^i(t) + \epsilon.$$

The consumer chooses $\bar{c}^i(t)$ to solve

$$\max u^i(c) - \bar{\pi}^i(t)[F^i(c, V^i(t), e^i(t)) - \tilde{P}^i(t)].$$

The Problem with the engineers’ solution

- Not optimal
  - Completely ignores consumer preferences
  - Doesn’t use the full range of potential consumer responses.
- Computation is not easy
  - Will assume it is computable so we can concentrate on the economics.
  - Open question: Can economics help the computation?

The economists' solution: Let there be markets

- A 5 minute market for power at each node.
  - Centralized, bi-lateral, brokered, … ?
- Given prices, consumers maximize utility.
- Given prices, the DNO maximizes net receipts from power.
- Prices are set (by whom) so that:

  Aggregate consumer demand = DNO supply.

The economists' solution: Let there be markets

Suppose there is a (locational) market for each $P^i(t)$ with price $\pi^i(t)$.

Given $\pi^i(t)$ and $V^i(t)$ <u>the rational consumer will solve</u>

$$\max_{c,P^d} u^i(c(t)) - \pi^i(t)P^{di}(t)$$

subject to

$$P^{di}(t) = [F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t, e^i(t))]$$

where P^{di} is i's demand for power.

<u>The DNO (distribution network operator) will solve</u>

$$\max_{P^s,\tilde{P},Q,\tilde{Q},V,\theta} \sum_i \pi^i(t)P^{si}(t) - \lambda(t)P^0(t)$$

subject to

$$K(P^0, P^s(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), Y(t), \theta(t)) \geq 0.$$

<u>The market will choose</u> $\pi^i(t)$ so that $P^{di}(t) = P^{si}(t)$.

The Problem with the economists' solution

- Optimal only if voltage is not a choice variable.
  - The equilibrium solves the optimal VVC only if dF/dV = 0.
- Markets do not equilibrate instantaneously.
  - Requires simultaneous solution by consumers and DNO and price setter, but no one has the information needed to equlibrate in one shot.
  - If information and calculation are iterated, computational constraints require time to overcome. Not enough time.
- Temporary solution is not feasible during iteration.
  - Need to consider the dynamics

Prices to Devices

- The power demanded by the DN generates a substation LMCP from the ISO.
- Given c, the DNO minimizes the cost of power acquired from ISO. (This is just a CVR program.)
- The LMCP and the CVR problem determine a DMCP for each consumer.
- Given their DMCP, each consumer chooses c to maximize their utility minus their cost of power.

Prices to Devices

Given $c_{t-1}, e_t, \tilde{P}_t$, the DNO solves the CVR problem (conservation voltage reduction):

$$\begin{aligned} &\min_{P^0, P, Q, \tilde{Q}, V, \theta} \quad P^0 \\ &\text{subject to} \\ &K(P^0, P, Q, \tilde{P}, \tilde{Q}, V, \theta) \geq 0 \\ &P_t^i = F^i(c_{t-1}^i, V_t^i, e_t^i) - \tilde{P}_t^i \qquad (1) \end{aligned}$$

This generates a DMCP price β_t^i, the multiplier on (1).

Given $\pi_t^i = \lambda_t \beta_t^i, V_t^i, e_t^i, \tilde{P}_t^i$ the consumer solves:

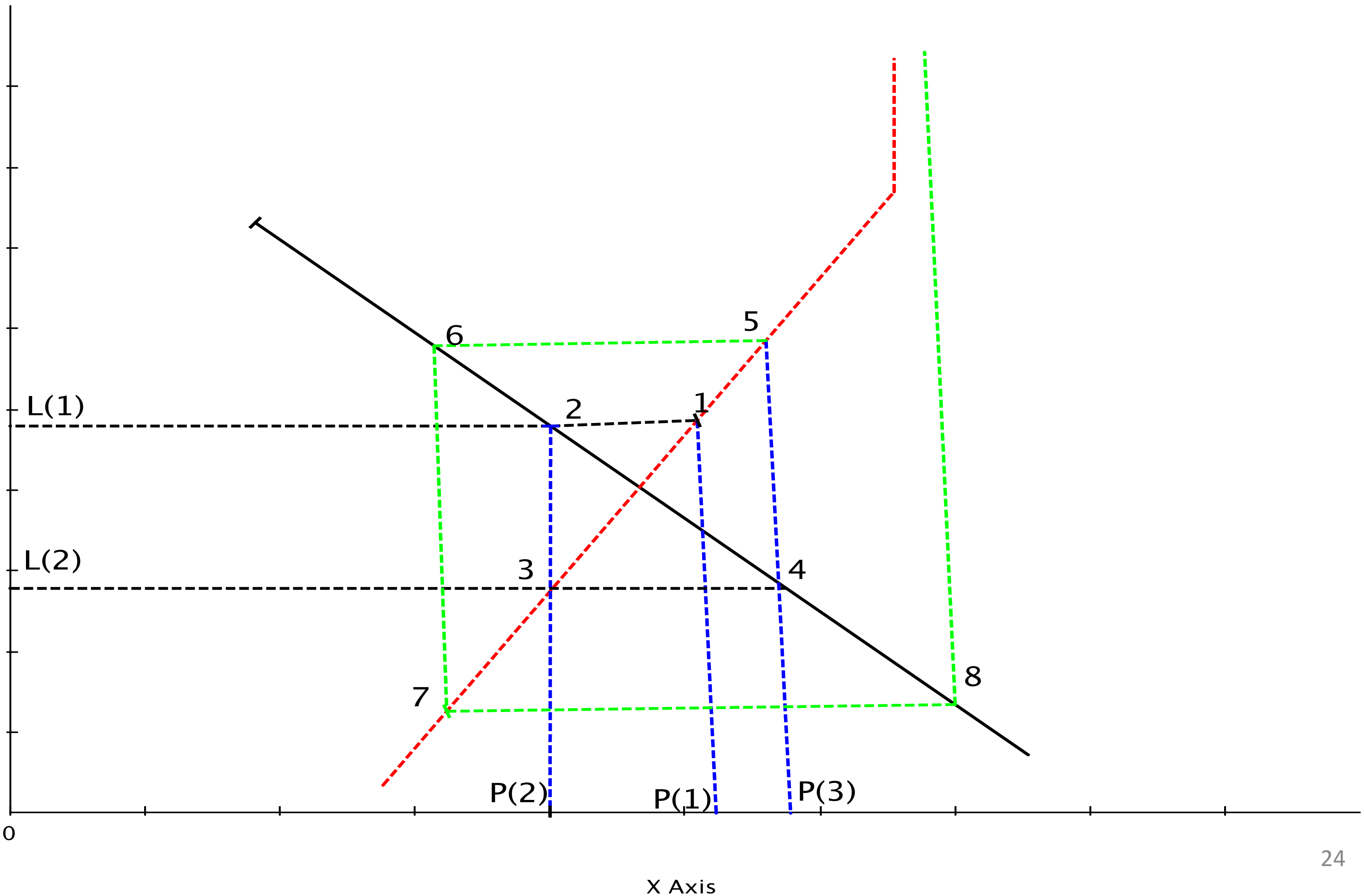
$$\max_{c_t^i} u^i(c_t^i) - \pi_t^i [F^i(c_t^i, V_t^i, e_t^i) - \tilde{P}_t^i].$$

Prices to Devices

- In equilibrium, P2D is optimal.
- But there are lags in the dynamics which creates a potential for instability.
- The reason is found in the corn-hog cycle.

Prices to Devices is potentially unstable.

- The reason is the standard cobweb cycle.



Prices to Devices

- In equilibrium, P2D is optimal.

- But there are lags in the dynamics which creates a potential for instability.

- The network and DNO exacerbate the problem.

Prices to Devices dynamics simplified

Given $\lambda_t, c_{t-1}, \tilde{P}_t$, the DNO solves the CVR which implies $V_t^i = V^i(c_{t-1}), \beta_t^i = \beta^i(c_{t-1})$. Then

$$\begin{aligned}
\pi_t^i &= \lambda_t \beta^i(c_{t-1}) \\
c_t^i &= d^i(\pi_t^i, V^i(c_{t-1}) \\
P_t^0 &= P^0(c_t, V(c_{t-1})) \\
\lambda_{t+1} &= H(P_t^0).
\end{aligned}$$

Therefore

$$c_t^i = d^i[H(P^0(c_{t-1}, V(c_{t-1}))\beta^i(c_{t-1}), V^i(c_{t-1})]$$

Locally this is unstable if

$$|d_\pi H_P P^0_{c^i} \beta^i + d_\pi H_P P^0_V V_{c^i} \beta + d_\pi H \beta^i_{c^i} + d_{V^i} V^i_{c^i}| > 1$$

Stability of Prices to Devices

Locally P2D is unstable if

$$|d_\pi H_P P^0_{c^i} \beta^i + d_\pi H_P P^0_V V_{c^i} \beta + d_\pi H \beta^i_{c^i} + d_{V^i} V^i_{c^i}| > 1$$

H_P is the slope of the inverse supply function of the ISO.
It is positive and grows towards ∞ as P^0 approaches capacity.

$P_{c^i} d^i_\pi$ is how responsive P^0 is to i's DMCP.

P2D is likely to be unstable
(1) the more responsive consumers's are, and
(2) the closer to capacity the system is.

Stability of Prices to Devices

- P2D is more likely to be unstable
  - The more responsive consumers are to prices
  - The closer the ISO is to capacity.

- Paradox: We need consumers to be responsive when we are near capacity, but if they are too responsive this policy won't work.

- We can improve on P2D by reducing the lag.
  - Higher payoff
  - More stable

Economic Control

- The power demanded by the DN generates a substation LMCP from the ISO.

- Each consumer reports a utility function, $\hat{u}$, to the DNO.

- The DNO maximizes the sum of utilities less the cost of power acquired from ISO.
  - This is the optimal VVC program.
  - It determines the consumption of the consumer and the price they will pay.

Economic Control

- The consumer "reports" $\hat{u}$ to the DNO.

- The DNO solves the Optimal VVC with that $\hat{u}$.

Choose $[c(t), P^0(t), P(t), Q(t), \tilde{Q}(t), V(t), \theta(t)]$ to solve

$\max\{\sum_i \hat{u}^i(c^i)\} - \lambda(t)P^0(t)$ subject to

$$K(P^0(t), P(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), \theta(t)) \geq 0$$
$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t)$$

Economic Control

- The consumer "reports" $\hat{u}$ to the DNO.

- The DNO solves the Optimal VVC with that $\hat{u}$.

Choose $[c(t), P^0(t), P(t), Q(t), \tilde{Q}(t), V(t), \theta(t)]$ to solve

$\max\{\sum_i \hat{u}^i(c^i)\} - \lambda(t)P^0(t)$ subject to

$$K(P^0(t), P(t), \tilde{P}(t), Q(t), \tilde{Q}(t), V(t), \theta(t)) \geq 0$$
$$P^i(t) = F^i(c^i(t), V^i(t), e^i(t)) - \tilde{P}^i(t)$$

The consumer pays $\pi^i(t)[F^i(c, V^i(t), e^i(t)) - \tilde{P}^i(t)]$.

Economic Control

- Three issues
  - Communication: Will the consumer be able to describe their utility function?
  - Incentives: Will the consumer be willing to report their true utility function?
  - Computation: Will the DNO be able to solve the Optimal VVC with the utility functions in it?

- If the answer is yes to all three, then in equilibrium economic control will be optimal.

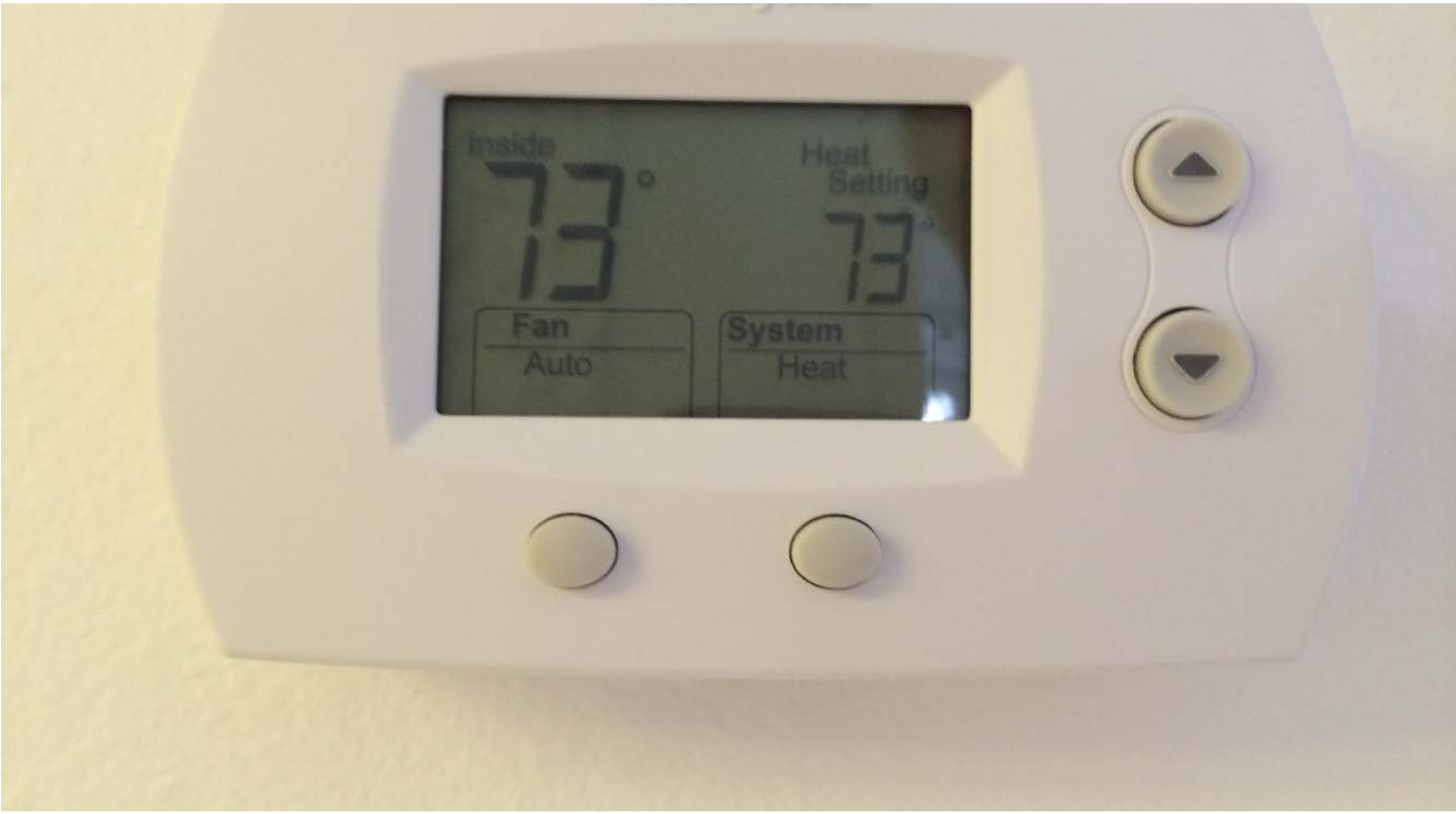
Will the consumer be able to describe their utility function?

- Consider an approximation around the consumer's ideal setting c*.
  - The ideal setting is what the consumer would choose if power were free. $u_c(c^*) = 0$.

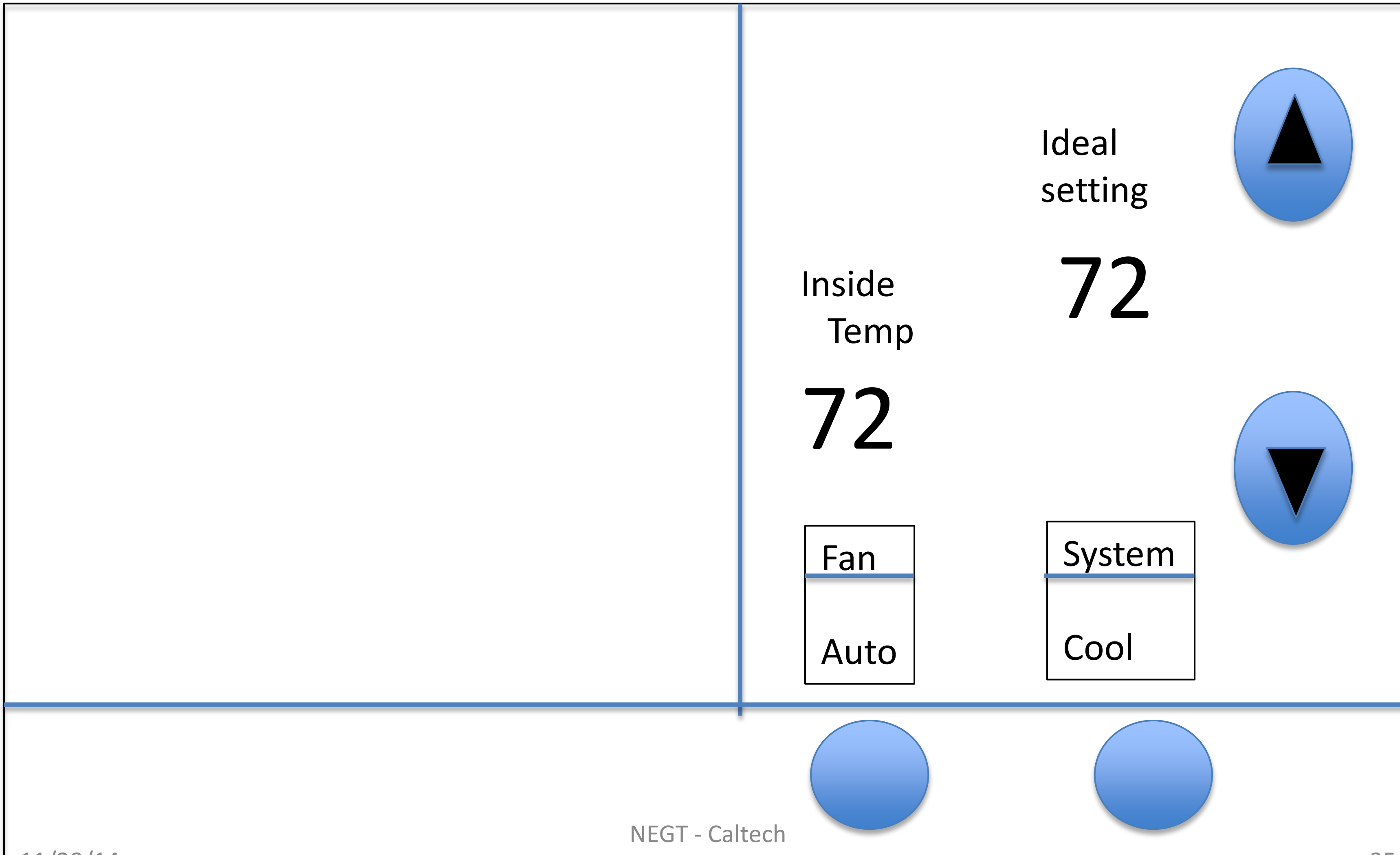
$$u(c_t) \sim u(c^*) + u_c(c^*)(c_t - c^*) + \frac{1}{2}u_{cc}(c^*)(c_t - c^*)^2$$
$$\sim u(c^*) + \frac{1}{2}u_{cc}(c^*)(c_t - c^*)^2$$

- The consumer "reports" only two numbers
  - A set-point, c*
  - A strength of preference, $u_{cc}(c^*)$

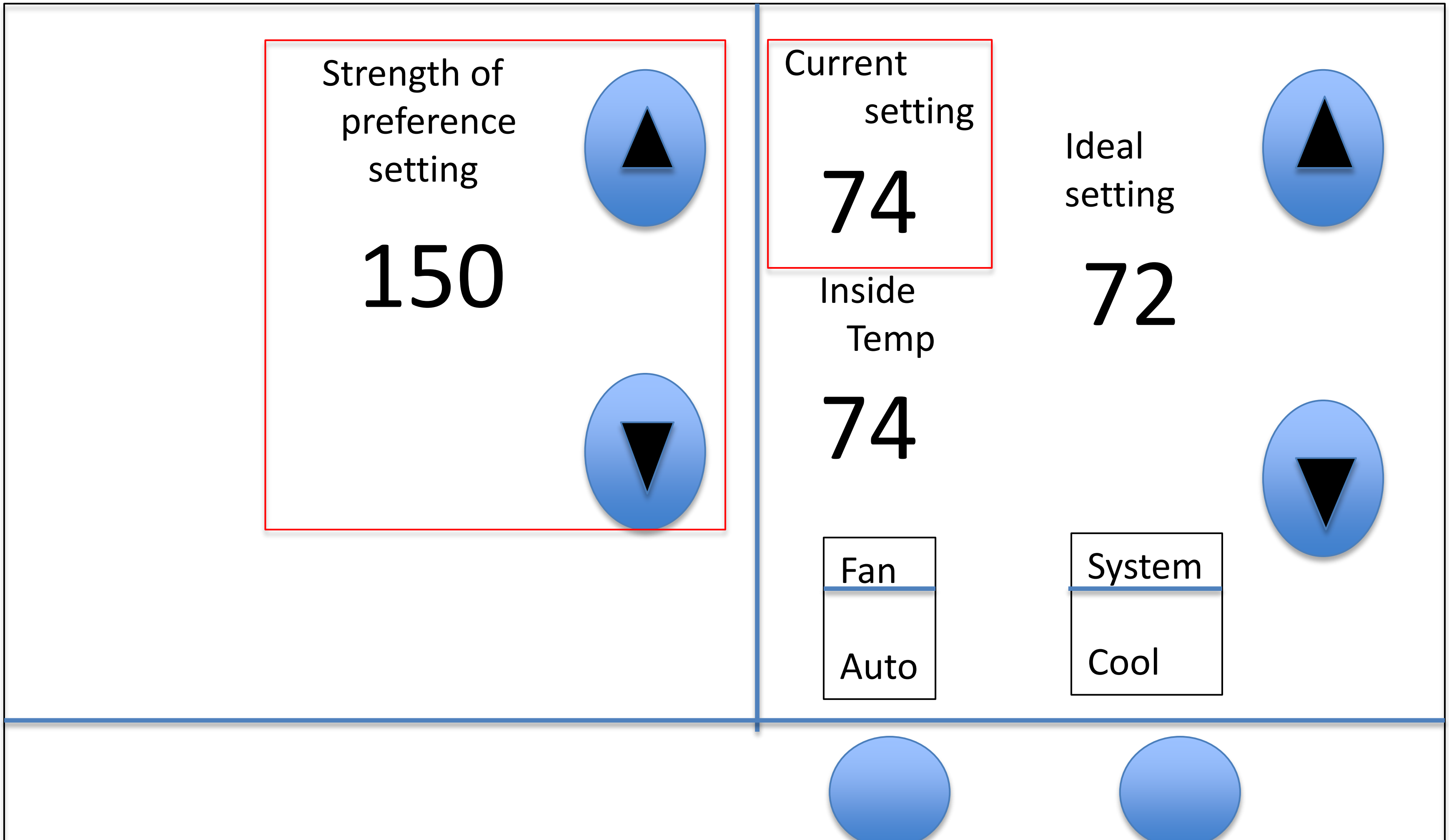
Today's simple thermostat



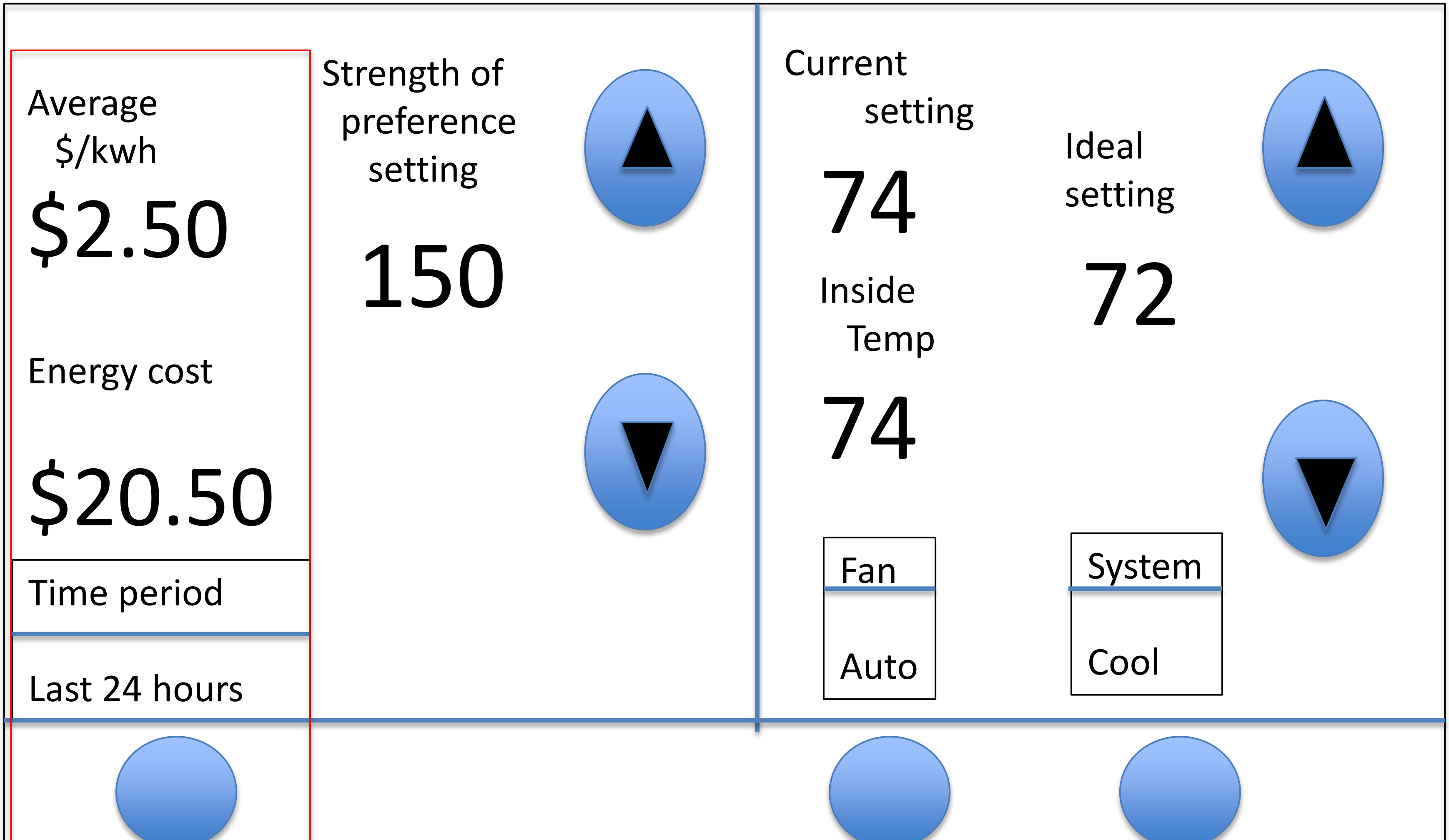
Today's thermostat



Tomorrow’s thermostat: Control



Tomorrow's thermostat: Economics



Will the consumer be able to describe their utility function? YES

- The technology is easy.

- Could also sign a contract with (c^*, σ) specified for the period of the contract.

- Could offer a menu of contracts with different values of (c^*, σ) and simulations of the possible payments required.

Will the consumer be willing to report their true utility function?

The DNO will solve the FOC:

$$\hat{u}_c^i - \delta^i F_c^i = 0$$
$$\delta^i + \beta K_{P^i} = 0$$
$$-\delta^i F_{V^i}^i + \beta K_{V^i} = 0$$
$$\lambda + \beta K_{P^0} = 0.$$

The consumer wants the DNO to solve:

$$u_c^i - \delta^i F_c^i = 0$$

If the consumer believes she can not affect δ^i, she will want to report the function $\hat{u}_c^i(c) = u_c^i(\mathrm{c})$.

If there are no network effects then $\delta^i = \lambda$, the ISO price.

Behaviorally, the answer is yes.

Will the consumer be willing to report their true utility function?

The DNO will solve the FOC:

$\hat{u}_c^i - \delta^i F_c^i = 0$
$\delta^i + \beta K_{P^i} = 0$
$-\delta^i F_{V^i}^i + \beta K_{V^i} = 0$
$\lambda + \beta K_{P^0} = 0.$

The consumer wants the DNO to solve:

$u_c^i - \delta^i F_c^i = 0$

If the consumer believes she can not affect δ^i,
she will want to report the function $\hat{u}_c^i(c) = u_c^i(\text{c})$.

If there are no network effects then $\delta^i = \lambda$, the ISO price.

Behaviorally, the answer is yes. Conjecture: use VCG or GL

Can the DNO solve the Optimal VVC with the utility functions?

- Use the quadratic approximation with information from the consumer.

$$u(c_t) \approx u(c^*) + \frac{1}{2}\sigma(c_t - c^*)^2,$$

- Can ignore constant term in the optimization.
- We are only adding quadratic terms to something that is already quadratic.

- This problem is no harder than the CVR problem.

Economic Control

- Without a network, EC = P2D.
- With a network, <u>in equilibrium</u>, EC is optimal.
- With a network, <u>out of equilibrium</u>, EC eliminates one of the lags in P2D so that
  - EC is more stable that P2D.
  - EC is more efficient than P2D
    - With respect to sum $u - \lambda P$

Stability of EC

Given $\lambda_t, \tilde{P}_t$, the DNO solves the CVR which implies $V_t^i = V^i(c_t), \beta_t^i = \beta^i(c_t)$ and

$$\begin{aligned} \pi_t^i &= \lambda_t \beta^i(c_t) \\ c_t^i &= d^i(\pi_t^i, V^i(c_t) \\ P_t^0 &= P^0(c_t, V(c_t)) \\ \lambda_{t+1} &= H(P_t^0). \end{aligned}$$

Therefore

$$c_t^i = d^i[H(P^0(c_{t-1}, V(c_{t-1}))\beta^i(c_t), V^i(c_t)]$$

Locally this is unstable if

$$\left|\frac{d_\pi H_P P_{c^i} \beta^i + d_\pi H_P P_V V_{c^i} \beta}{1 - d_\pi H \beta^i_{c^i} - d_{V^i} V^i_{c^i}}\right| > 1$$

Stability of EC vs P2D

Locally EC is unstable if $\left|\frac{d_\pi H_P P_{c^i} \beta^i + d_\pi H_P P_V V_{c^i} \beta}{1 - d_\pi H \beta^i_{c^i} - d_{V^i} V^i_{c^i}}\right| > 1$

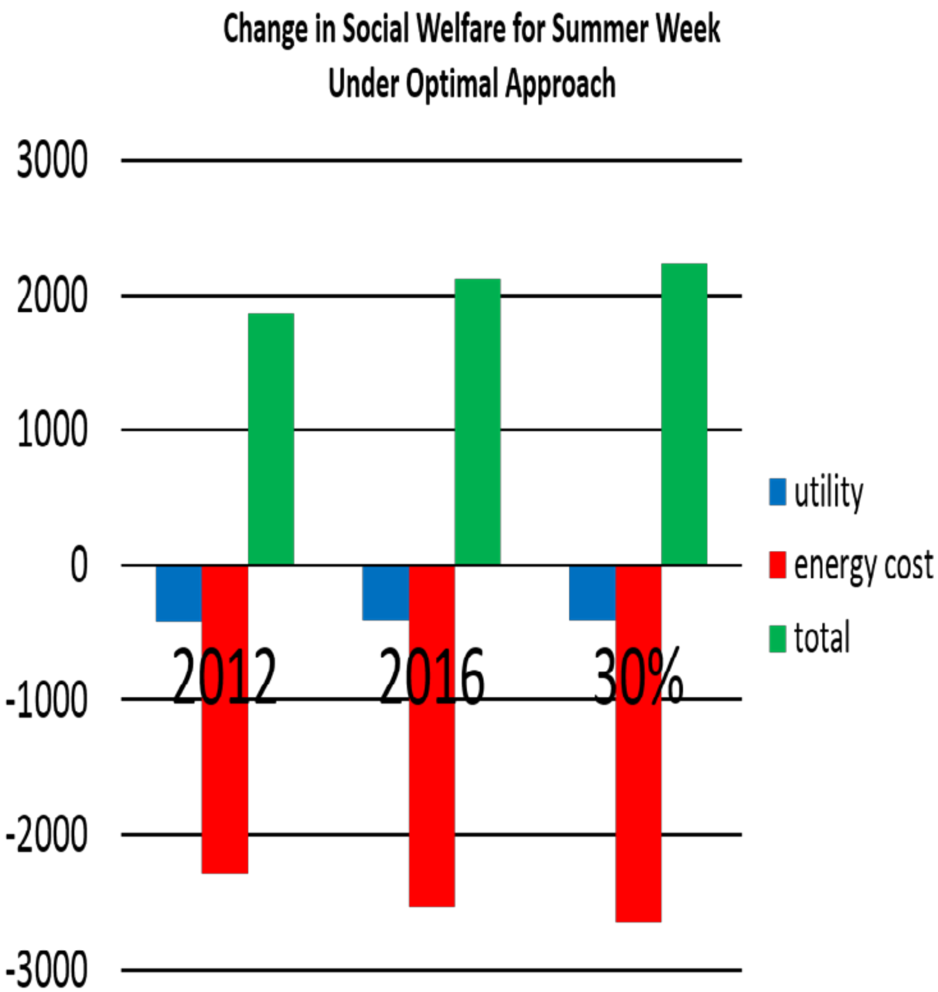
Locally P2D is unstable if
$|d_\pi H_P P_{c^i} \beta^i + d_\pi H_P P_V V_{c^i} \beta + d_\pi H \beta^i_{c^i} + d_{V^i} V^i_{c^i}| > 1$

Since everything is negative these reduce to:
EC: $\quad -1 < (a+b) - (c+d)$
P2D: $\quad -1 < (a+b) + (c+d)$

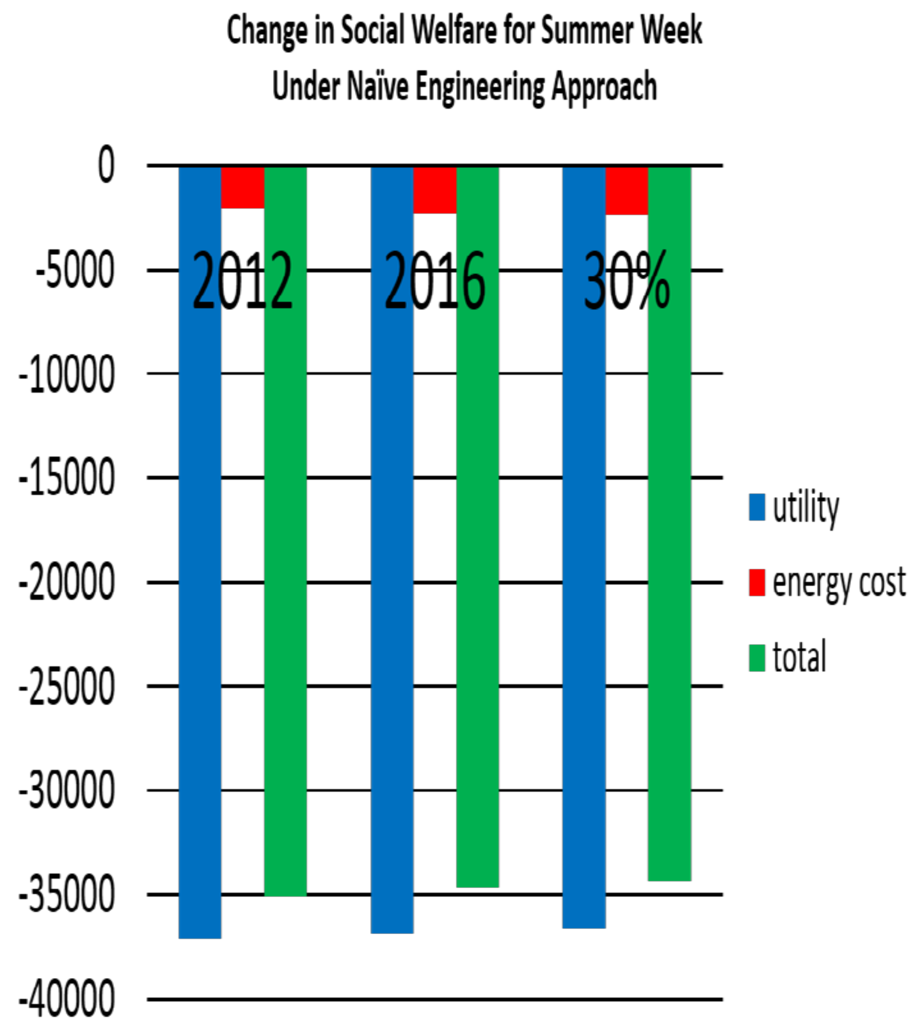
EC is more stable than P2D.

Recap

- Increasing DER adoption requires integration of distribution networks grid management.
- The Engineers' solution is implementable but not efficient.
- The Economists' solution is efficient but not implementable.
- Efficient Control is nearly optimal and implementable.
- Preliminary simulations provide some support for this.



Change in Social Welfare for Summer Week
Under Optimal Approach
3000
2000
1000
0
-1000
-2000
-3000
2012
2016
30%
utility
energy cost
total



Change in Social Welfare for Summer Week
Under Naïve Engineering Approach
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
2012
2016
30%
utility
energy cost
total

Open questions: or what I would like to know

- Optimal simple mechanism subject to feasible and stable implementation
- Understand the network effects for a DN
  - What is dP^0/dP^i?
- Does adding stochastics for solar or wind change the analysis at all?
  - Are expected values good enough?