ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

EuroTech PhD summer school

Integrated Approach to Energy Systems

Feb 2nd to 13th, 2015

Introduction to Demand Response

Prof. Jean-Yves Le Boudec

EPFL Laboratory LCA2

Feb 4 , 2015

Clickers

- We use clickers for more fun

- Clickers are anonymous, don't hesitate to respond

- Use your smartphone or computer and go to

http://www.rwpoll.com

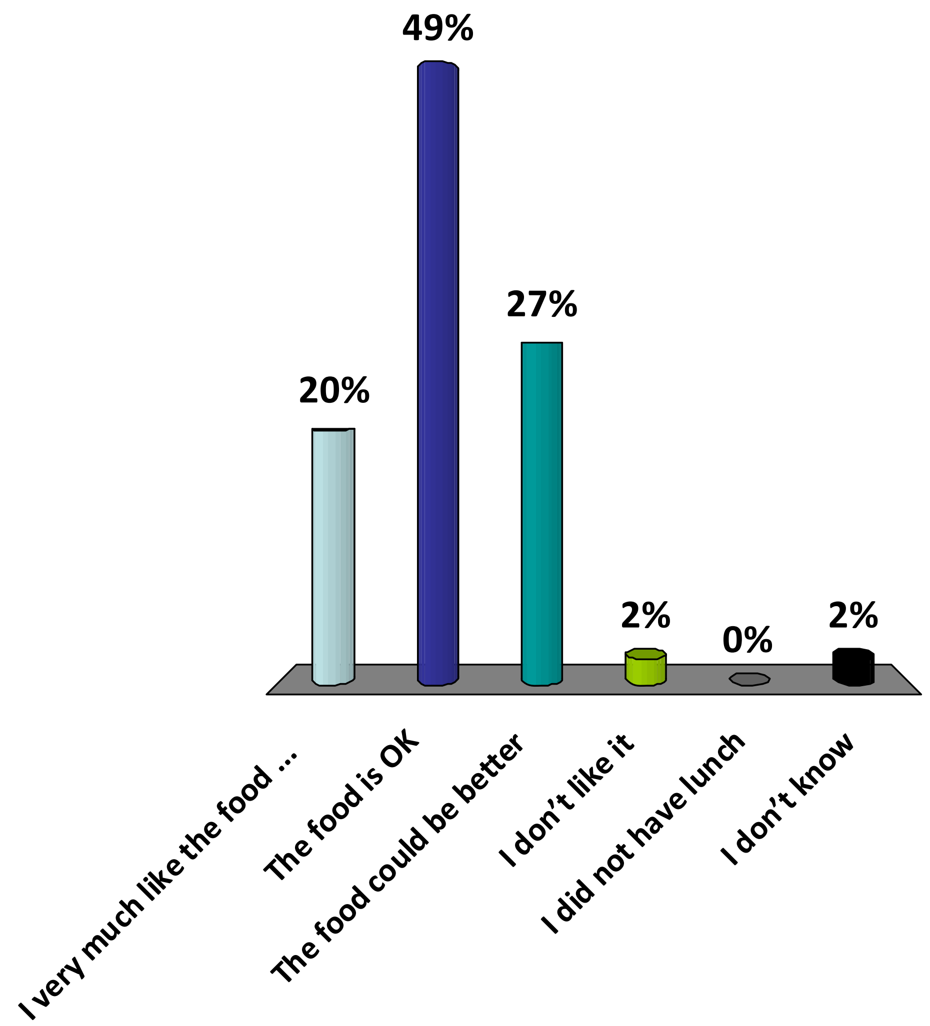
enter session id 786 666

– no login

- you may also use a clicker from the box

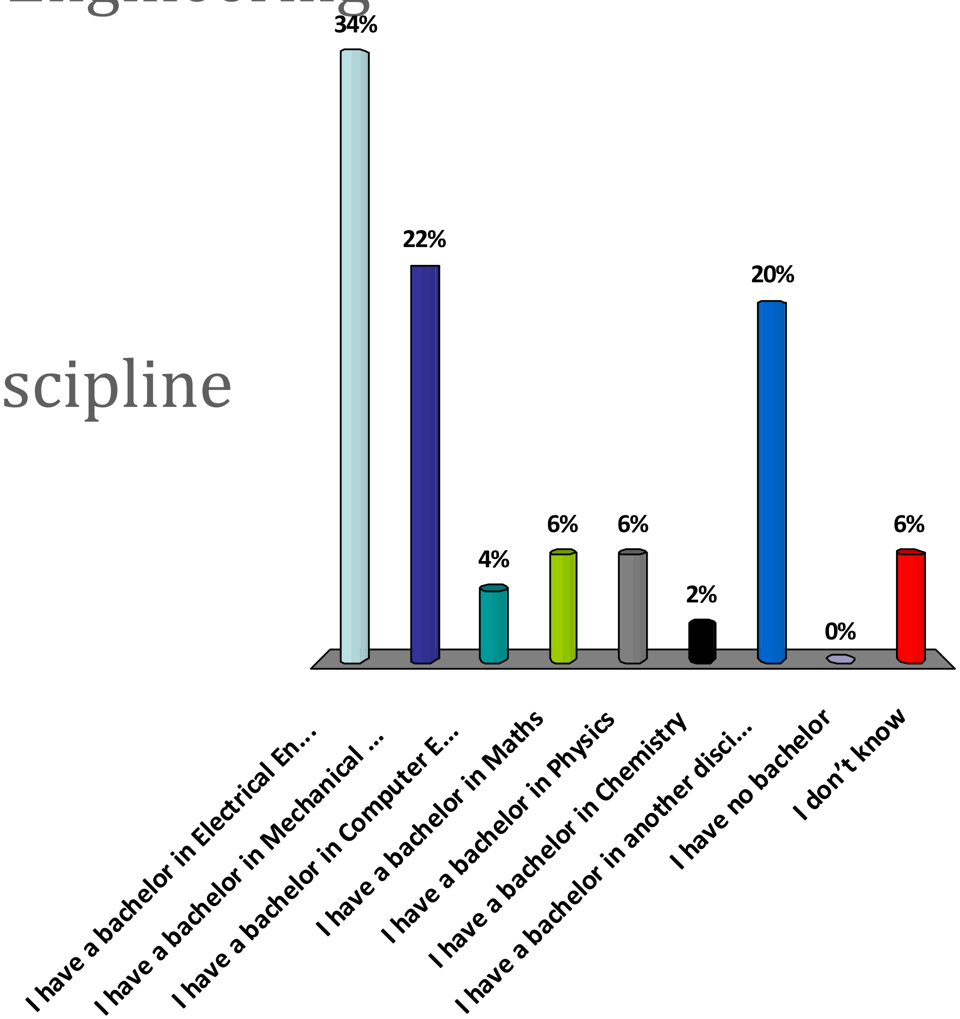
Test your clicker

A. I very much like the food served at BC cafeteria
B. The food is OK
C. The food could be better
D. I don’t like it
E. I did not have lunch
F. I don’t know



Test your clicker again

A. I have a bachelor in Electrical Engineering
B. I have a bachelor in Mechanical Engineering
C. I have a bachelor in Computer Engineering
D. I have a bachelor in Maths
E. I have a bachelor in Physics
F. I have a bachelor in Chemistry
G. I have a bachelor in another discipline
H. I have no bachelor
I. I don't know



Contents

1.
What is demand response ?
An illustration with eight examples
A taxonomy

2.
Elements of theory

WHAT IS DEMAND RESPONSE ?

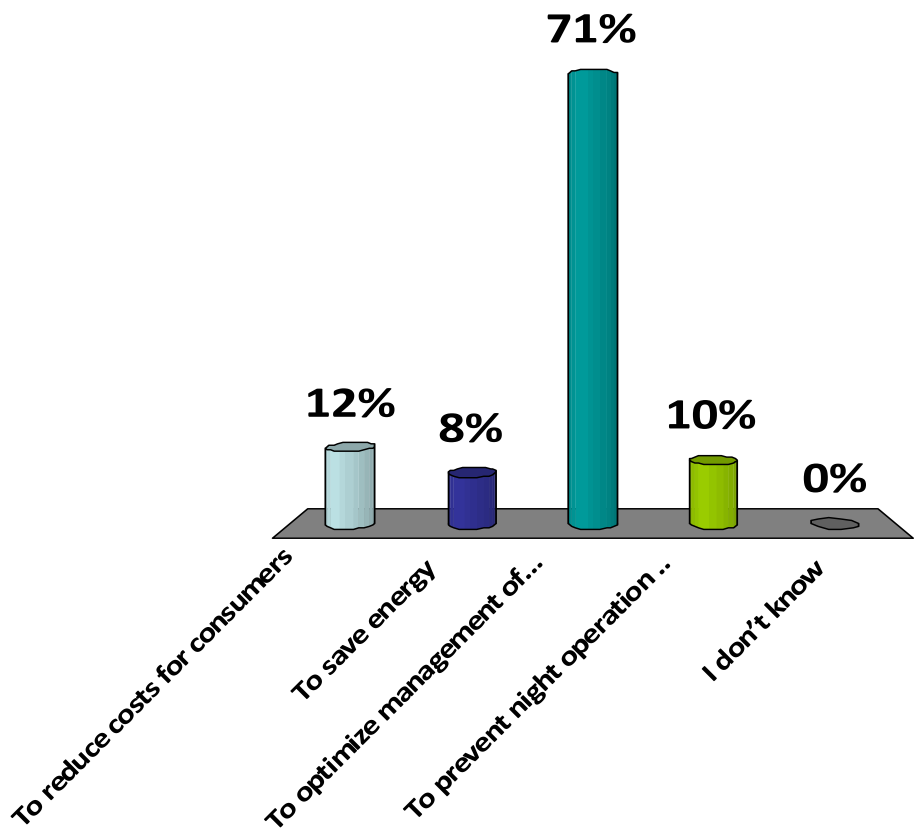
Terminology
Demand Response (DR)
≈ Demand Side Management (DSM)

A clothes dryer connected to a load control "smart" switch (Wikimedia Commons)

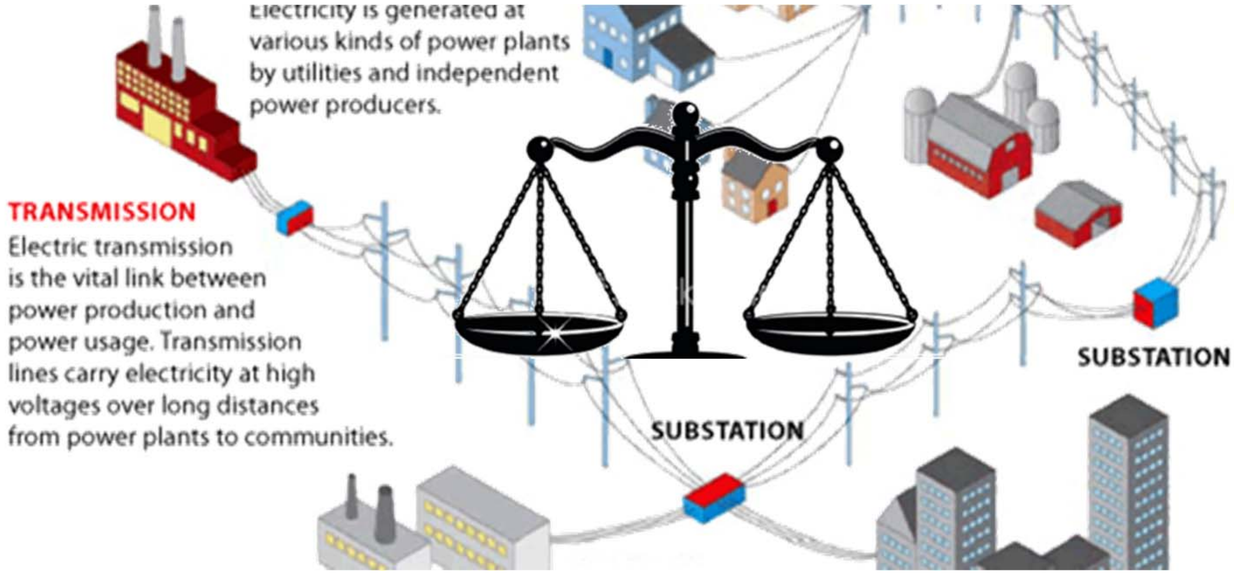
- *Demand Side Management* = electric utility manipulates user appliance
- *Demand Response* = Demand Side Management as a response to price
- in practice both phrases often used interchangeably
- ≥ 100 years old (“Load Management”, inband tones “ripple control”, AM signal)

Demand Response (DR) = Demand Side Management (DSM)
Why invented ?

1. To reduce costs for consumers
2. To save energy
3. To optimize management of the electrical grid
4. To prevent night operation of noisy equipment
5. I don't know



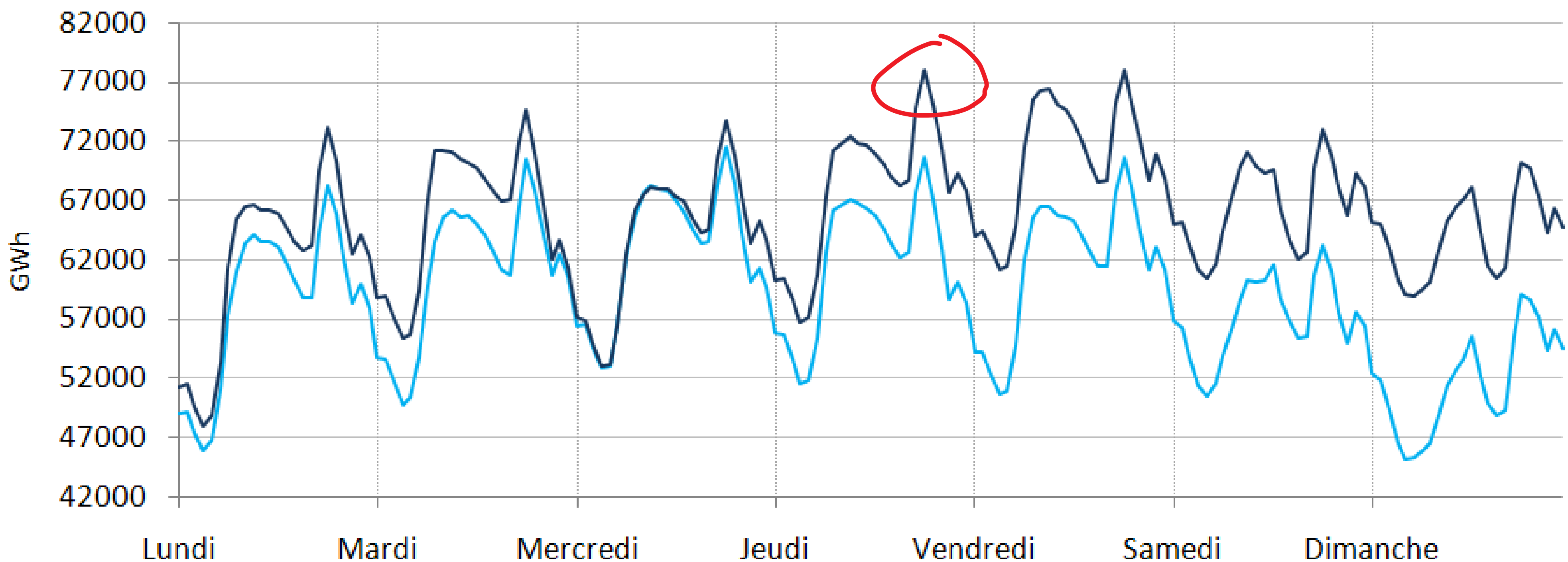
Solution



- electrical systems must balance energy instantly
- energy balance in electrical grid is mainly done by adjusting supply to demand :
  - scheduling and forecasting + large scale interconnection ; frequency response; reserves
- demand response = adjust *demand* to supply
  is one of the tools used to manage the power grid
- energy *efficiency* is obtained by managing demand efficiently
  but is outside the scope of this tutorial

Examples of Use of Demand Response

- peak shaving



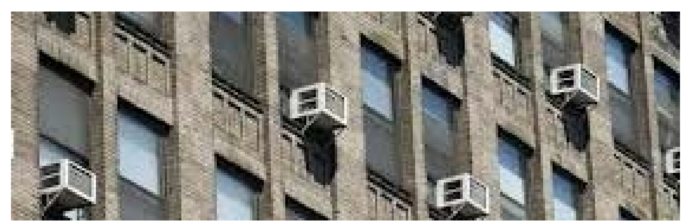
France’s comsumption on cold and average november week; Xavier Brossat (EDF), Energy Systems Week, 2013

- response to failures (avoid blackout)
- mitigate volatility of wind and solar energy
- mitigate network problems (congestion, voltage)

What can be subject to Demand Response ?

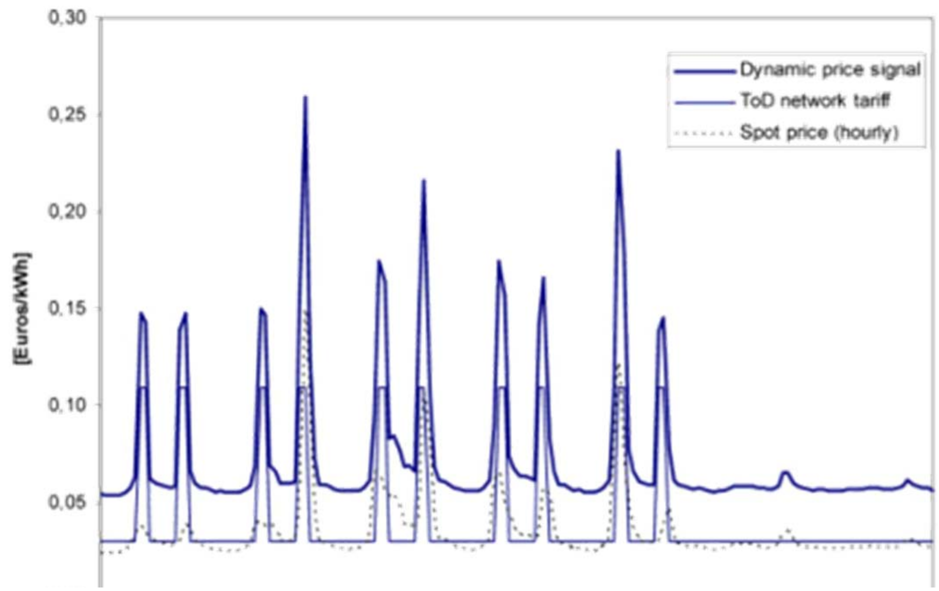
- Demand response applies to *elastic* loads (load = consumer of electricity)
- Non elastic loads
  - lighting, watching TV, hair drying

- Elastic loads
  - boiler, car or bicycle battery, data center, fridges and freezers, air conditioner, washing machine



Demand Response Example 1
Norway's pilot study [Saele and Grande 2011]

- tariff is increased at pre-defined times (8-10, 17-19)
- users made aware of high tariffs and times
- In some homes heating is also directly controlled
- study concludes that it works



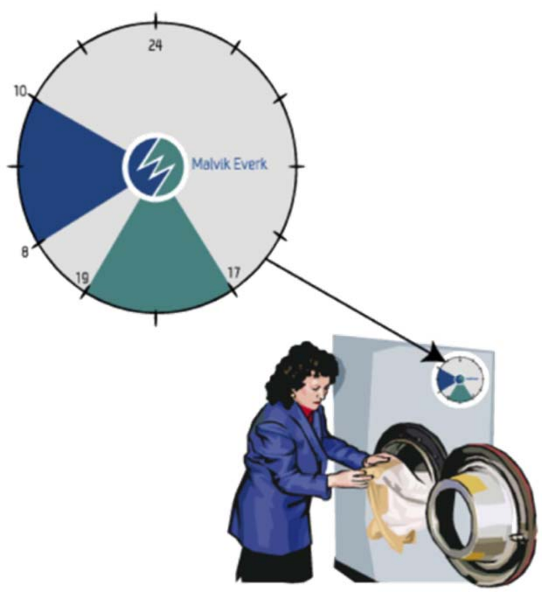


Fig. 7. Customer information token, the "El-button" [13].

Fig. 8. Load profile for a household customer with hot water space heating system and RLC [13].

Norway's pilot study [Saele and Grande 2011] Demand Response may reduce prices

- 120 EUR/MWh difference between 2 areas inside Norway
- [Saele and Grande 2011] claims that the price peak would be suppressed with demand response

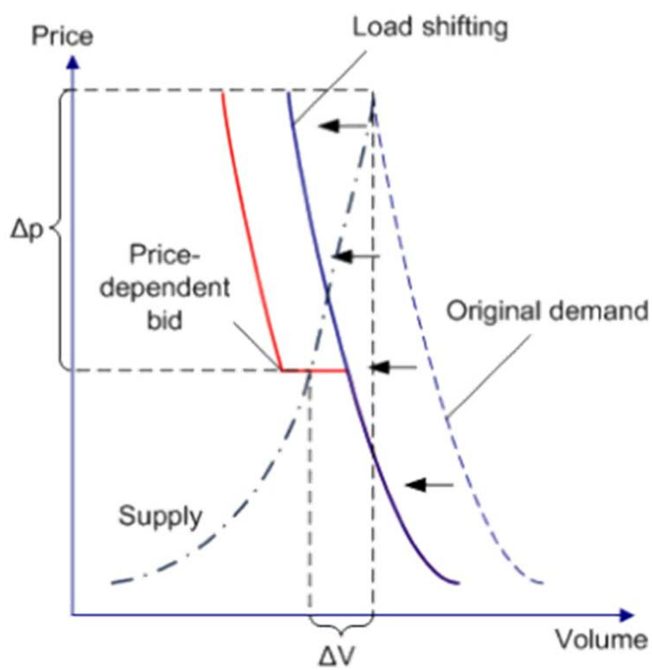


Fig. 2. Different bid curves for demand response.

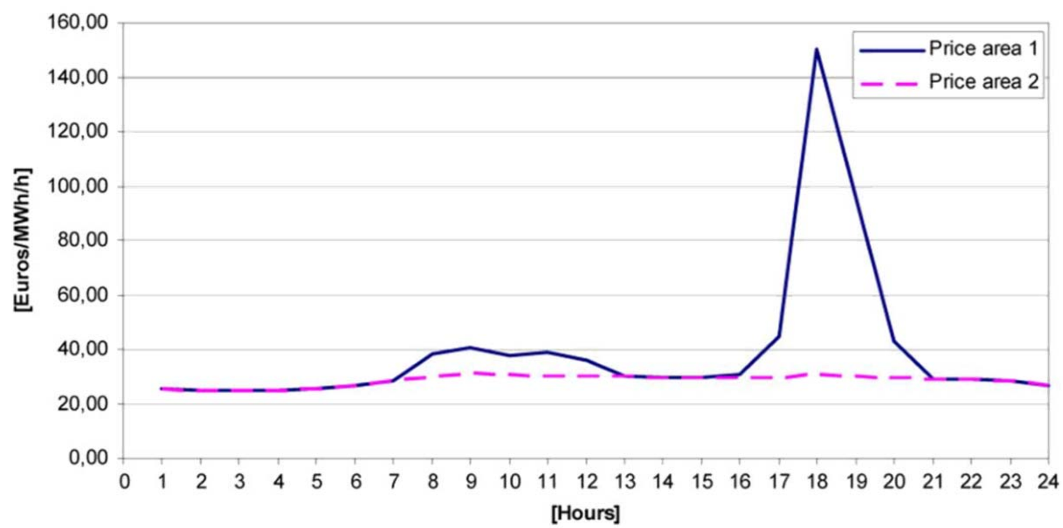


Fig. 3. Hourly spot prices in two price areas in Norway, 6 February 2007 (data source: NordPool).

A similar example (GulfPower, USA)

[Borenstein et al 2002]

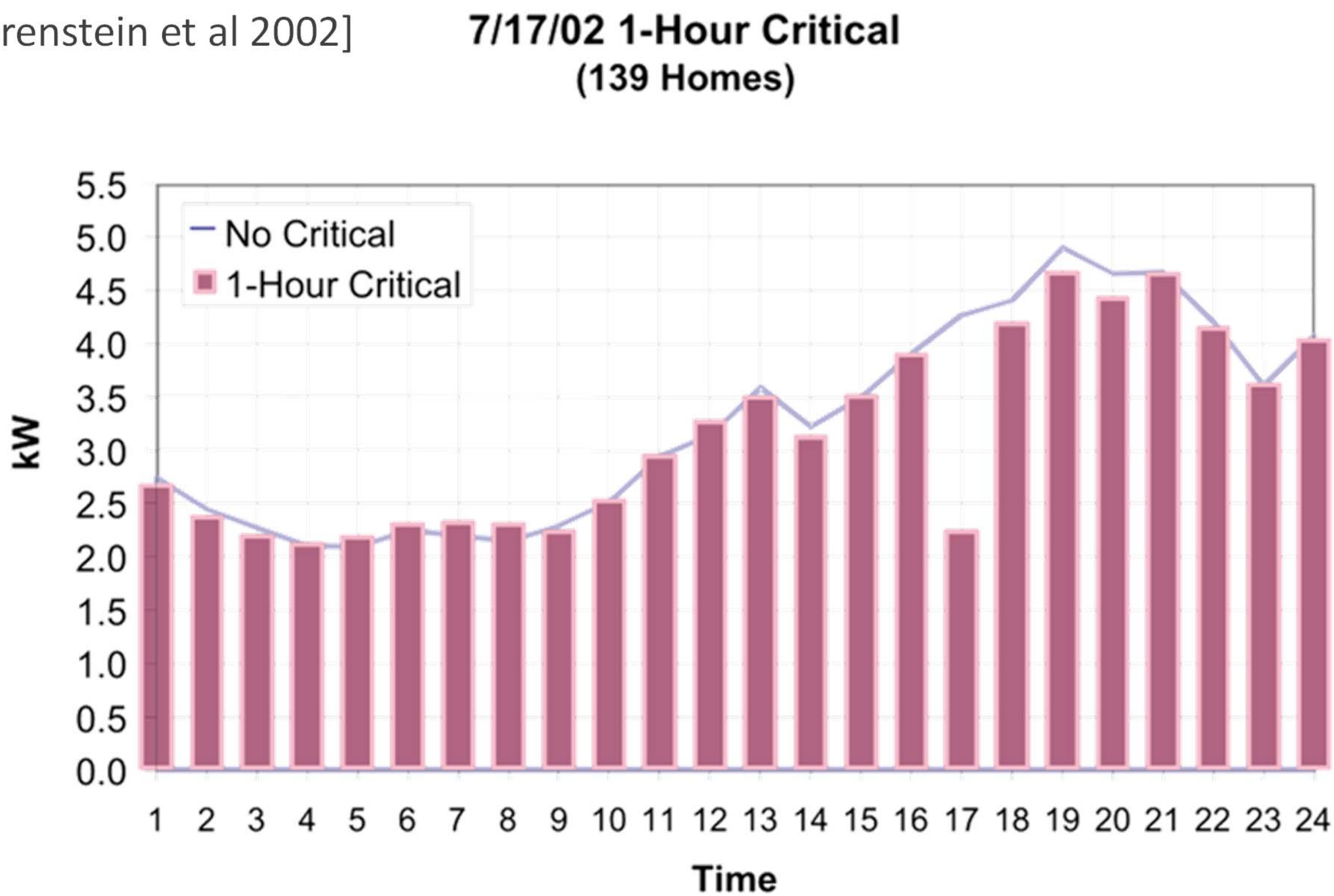


Figure 3-h. Average Load and Load Reduction in Gulf Power CPP program. The TOU rate (11 a.m. to 8 p.m.) was 9.3 ¢/kWh. The 1- and 2-hour CPP was 29 ¢/kWh, an extra 20 ¢/kWh. The 1-hour CPP dispatch was at hour 17.

Source: Brian White, Gulf Power

Example 2 : Romande Energie

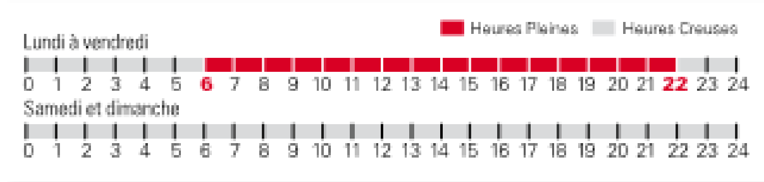
- *Time of Use* tariff
  Night tariff is lower

voltadouble, Double	Famille vivant dans un logement de 5 pièces avec cuisinière électrique et sèche-linge (sans chauffe-eau).	4500 kWh/an	**HP** 22.54-23.94 cts/kWh* **HC** 13.99-15.39 cts/kWh*

*Le montant dépend des taxes perçues par votre commune.
Sous réserve de modification des taxes et émoluments par les Autorités.

HP : heures plei…

Horaire hebdomadaire, heures pleines/heures creuses



Les personnes qui souhaitent opter po… (heures pleines/heures creuses) doive… comptage double, dont les frais d'insta… charge. Pour les locataires, l'accord du… logement est nécessaire.

- *Interruptible Supply*:

interruptible supply (service is available e.g. 20 hours per day)

[Le Boudec and Tomozei 2011]

Interruptible Court, Interruptible Court

Ce tarif est destiné particulièrement au chauffe-eau électrique (boiler). Il dispose d'une fourniture journalière de 8 heures sur 24.
Cette application nécessite un compteur additionnel qui engendre des frais supplémentaires de branchement, mais pas de frais de location de compteur.

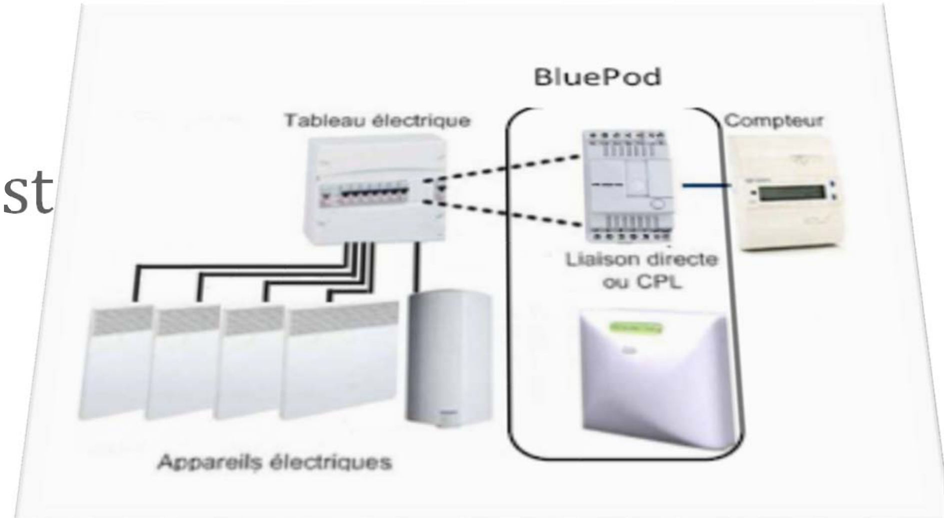
Interruptible Long, Interruptible Long

Ce tarif peut être utilisé pour des applications pompe à chaleur et chauffe-eau électrique. Il dispose d'une fourniture journalière de 20 heures sur 24 (4 x 1 heure de délestage réparties sur la journée).
Cette application nécessite un compteur additionnel qui engendre des frais supplémentaires de branchement, mais pas de frais de location de compteur. Nous déconseillons ce tarif pour les pompes à chaleur situées en altitude.

http://www.romande-energie.ch/images/File/Tarifs/2013_tarifs_RE.pdf

Example 3 :Voltalis

- Widely deployed in France
- *Interruptible Load*
  Voltalis device stops electrical resistive heating / boiler for at most 60 mn per day
- Device («Bluepod») receives GSM signal and stops thermal loads
- No charge / no payment
- Acceptance based on
  - Voltalis claims energy usage reduction
  - Good citizens
- Similar schemes with incentive payment to users: PeakSaver (Canada), www.pge.com (USA), New Zealand, NGT frequency service (UK)



VOLTALIS
The e-power company

www.voltalis.com

Example 4: Dynamic Demand

- also called frequency service
- smart fridges, smart boilers, smart heaters / HVACs
- recall that frequency is the first signal of power imbalance

- primary frequency control traditionally done with *dynamic generators* -- fossil fuel generators, using droop control

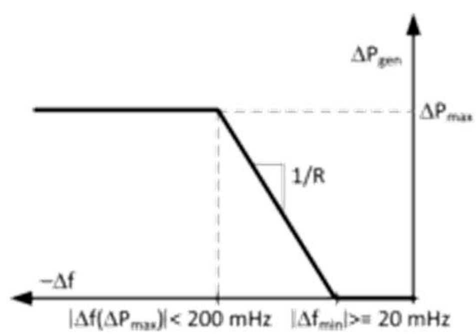
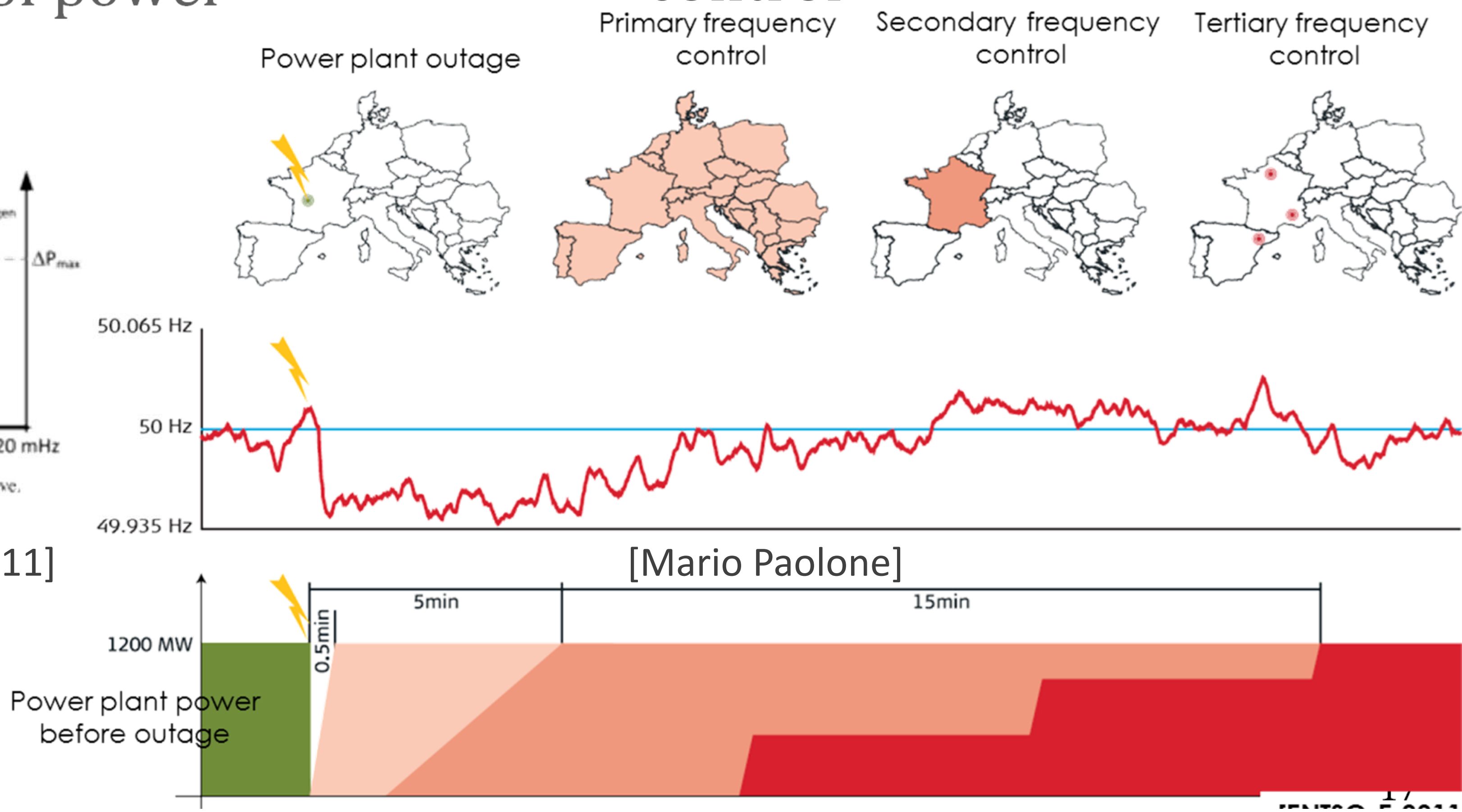


Fig. 1. UCTE specification for primary frequency reserve.

[Molina-Garcia et al 2011]



[Mario Paolone]

Example 4: Dynamic Demand

- *dynamic demand* is an alternative to dynamic generators
- How it works:("*grid friendly controller*") (underfrequency): fridge delays compressor when frequency drops and anticipates when freq. increases [Molina-Garcia et al 2011]

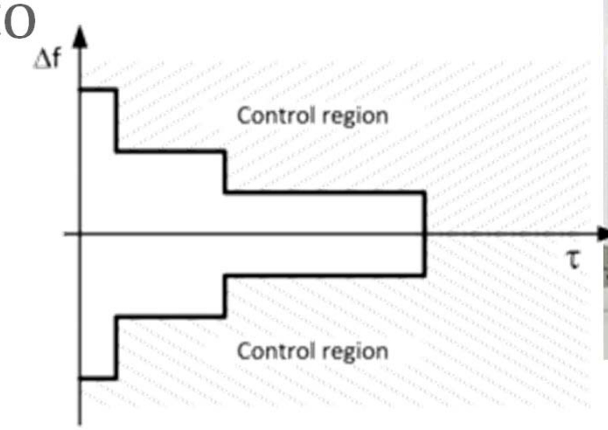
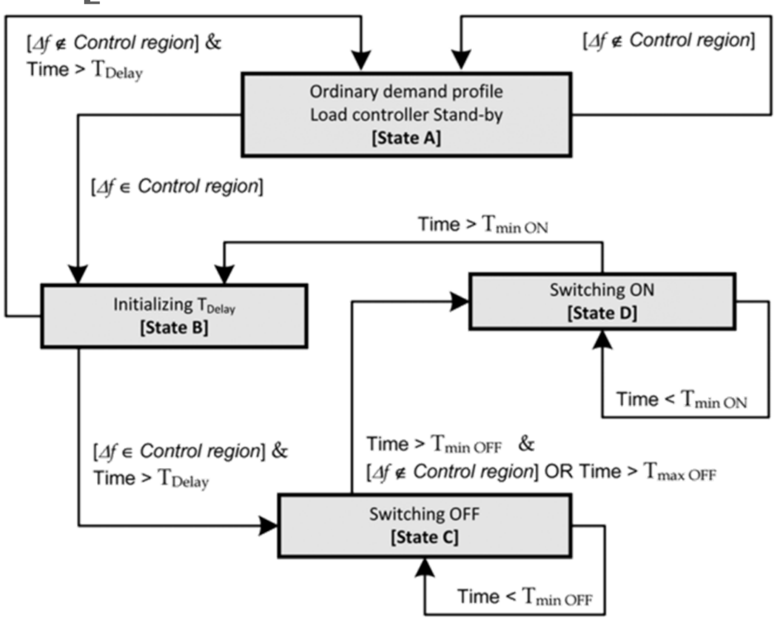


Fig. 2. Individual load controller Δf-time characteristic.

τ = time during which Δf is observed



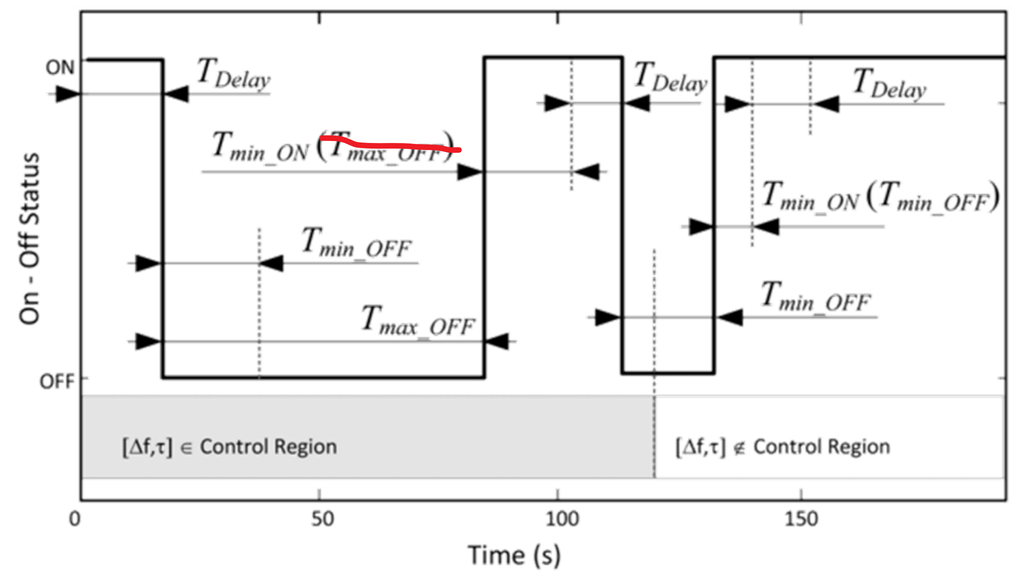


Fig. 5. Example of energy recovery time periods. Underfrequency.

Is something missing with this algorithm ?

1. Nothing
2. Timers need to be randomized
3. Internal temperature needs to be taken into account
4. Outside temperature needs to be taken into account
5. I don't know

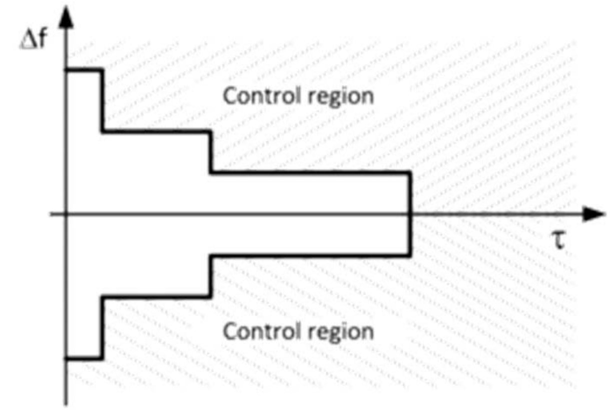


Fig. 2. Individual load controller Δf-time characteristic.

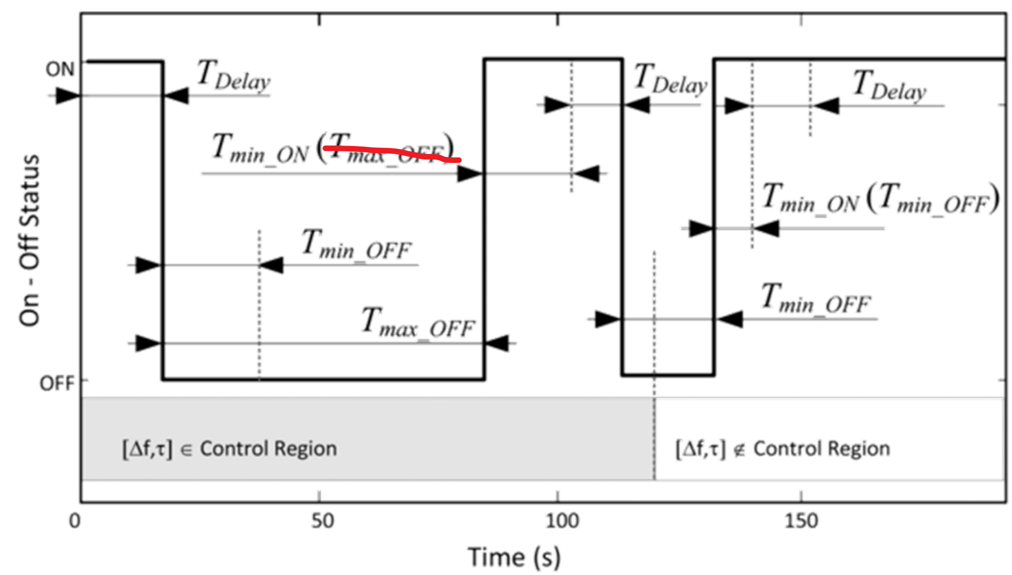
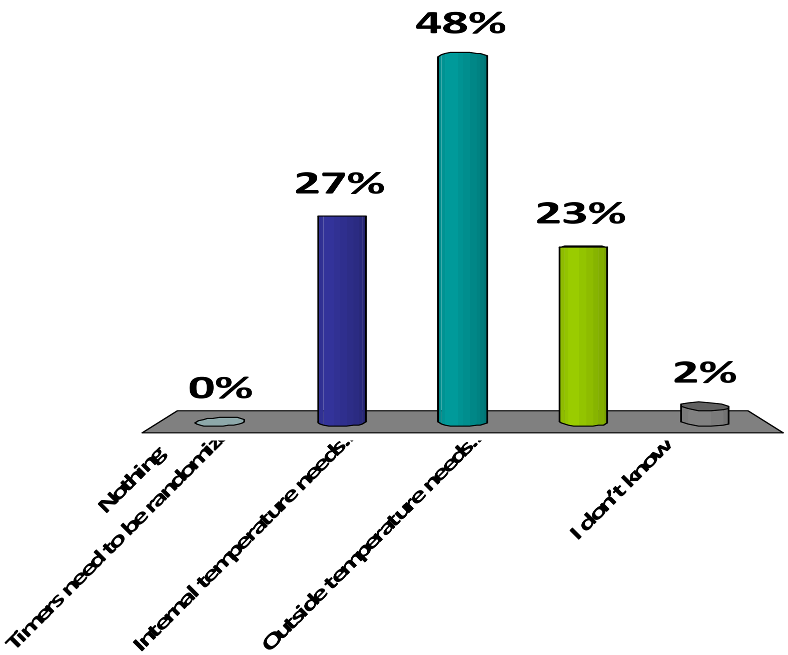


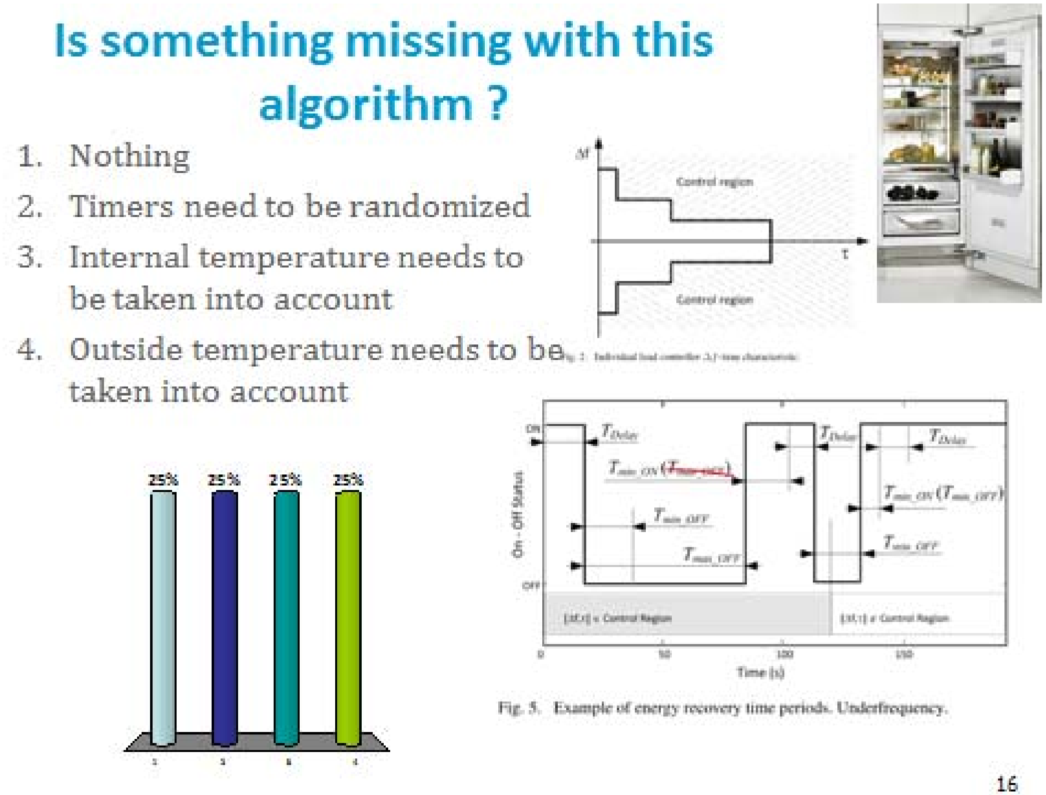
Fig. 5. Example of energy recovery time periods. Underfrequency.



Solution

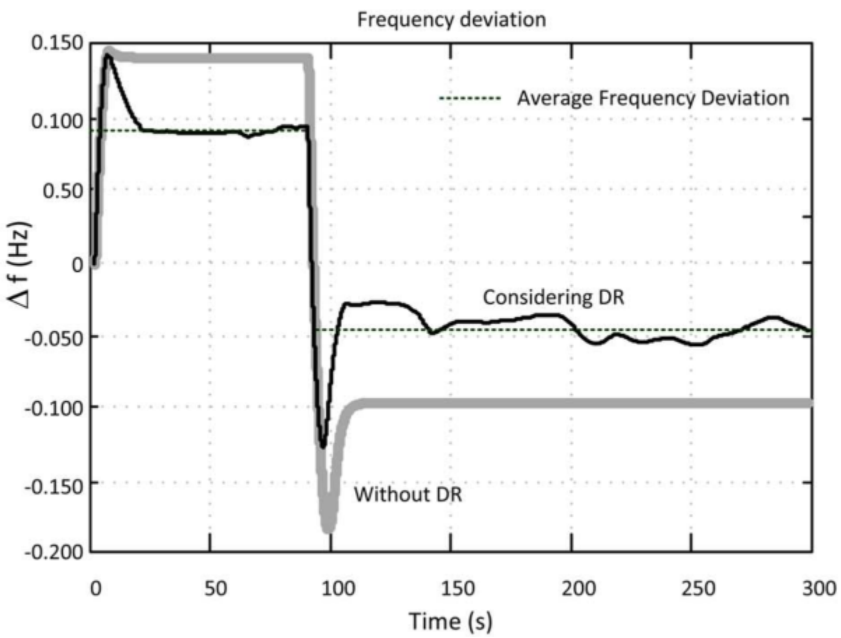
- Avoid synchronized response ⇒ [Molina, Garcia et al 2011] use randomized T_delay

- Internal temperature should be accounted for



Dynamic Demand

- Simulation results for [Molina-Garcia et al 2011] with 10% of loads implementing dynamic demand in a hypothetical country grid



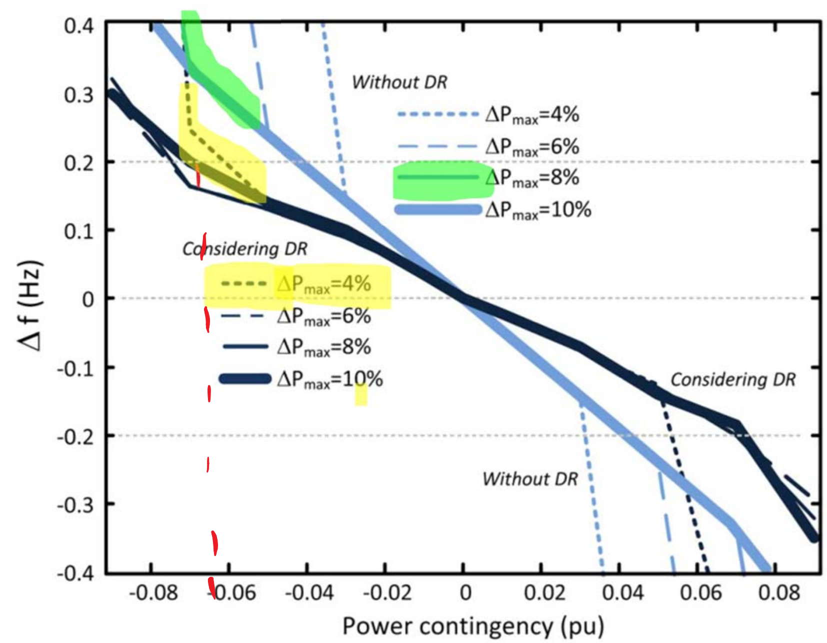


Fig. 10. Δf average simulated values with different amounts of primary frequency response available from the generation.

dynamic demand ≈ doubles the reserve

Dynamic Demand

- Simulation results for [Molina-Garcia et al 2011] with 10% of loads implementing dynamic demand in a hypothetical country grid – dynamic demand ≈ doubles the reserve

- Fridges as primary/secondary response could provide ca 1 GW of reserve to UK grid [Milborrow 2009]

- 70% of secondary regulation power (8 sec to 3 mn) in the US can be provided by building air conditioning and heating *fans* alone [Hao et al 2012]

Example 5: Boilers as Tertiary Reserve [Sundstrom et al 2012]

- Primary reserve = real time
  Secondary reserve = within minutes
  Tertiary reserve = starts after 15 mn
- Thermal loads can be anticipated or delayed
- Upper and lower energy curves for one boiler give bounds on feasible energy provision *schedules*

upper bound: deliver 3kW for 1.71h then 200 W

lower bound: deliver 0W for 6h then 200 W

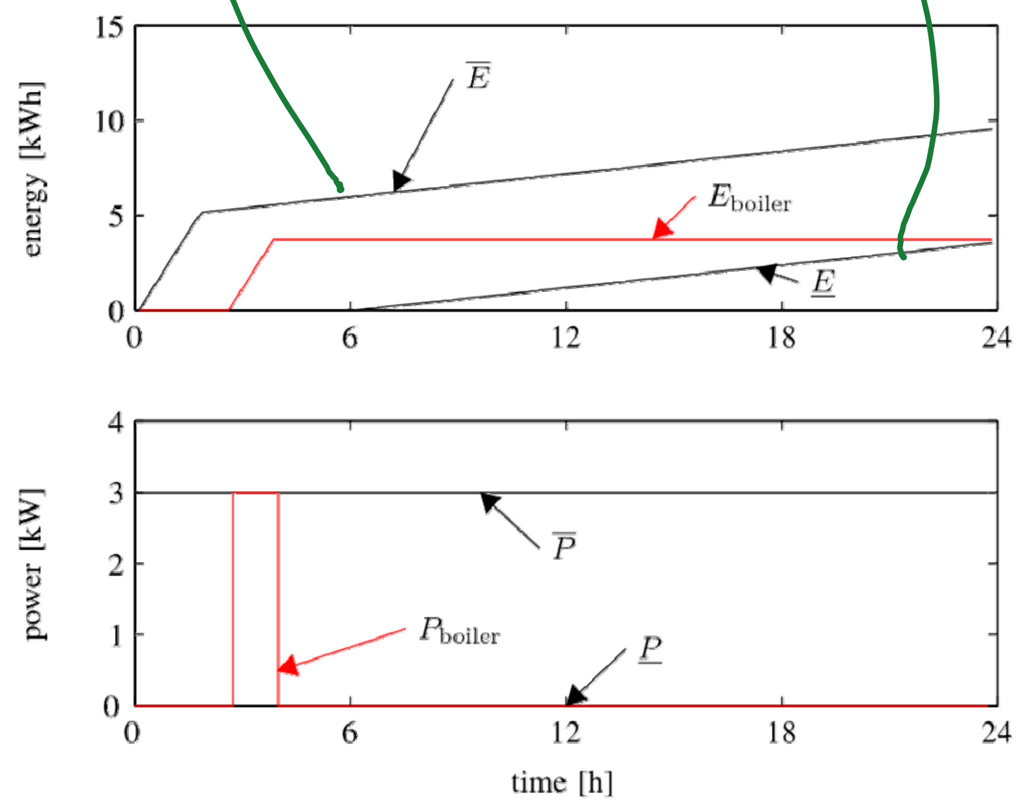


Figure 8. Flexibility of a sample boiler with 6 kWh equivalent energy storage, an initial energy level of 1.2 kWh, and an average consumption of 200W.

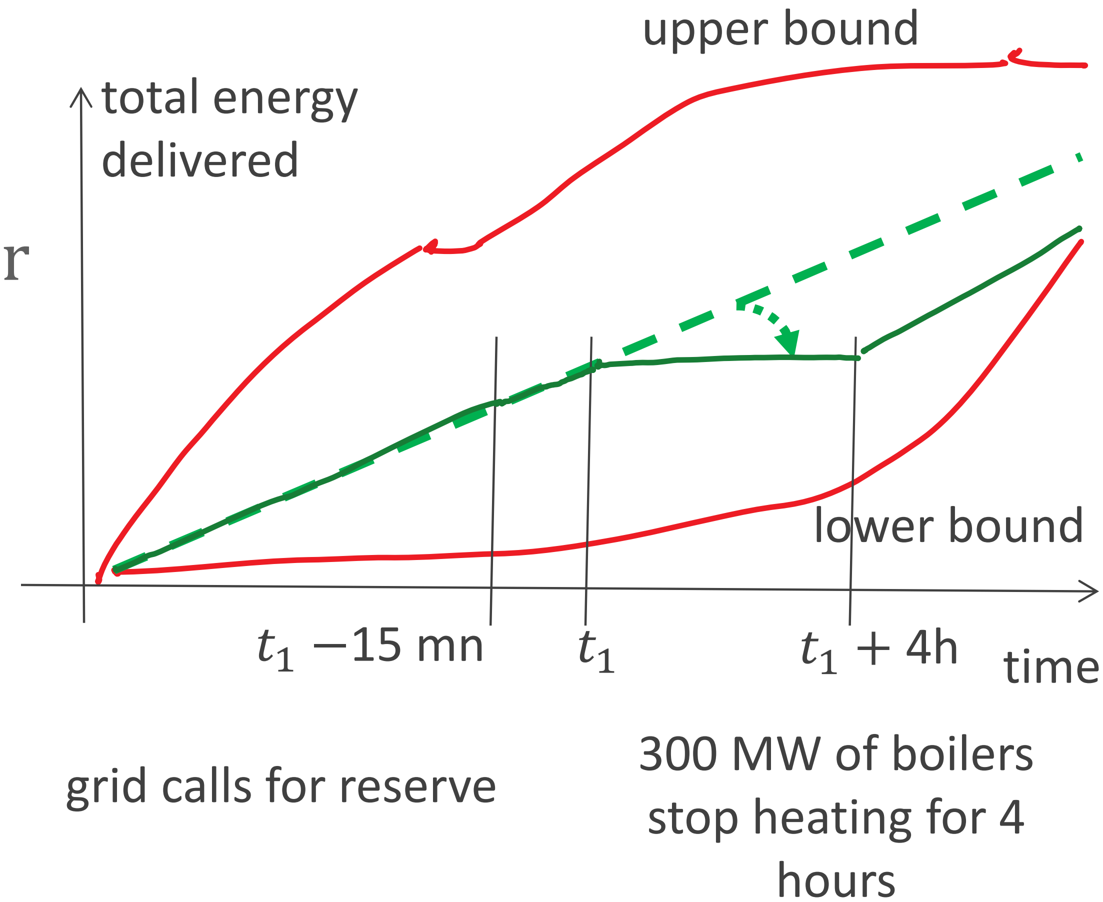
[Sundstrom et al 2012]

Boilers as Tertiary Reserve

- Assume operator ("Service aggregator") controls a large set of boilers and can predict the upper and lower bounds for the aggregate energy curves.

  Service aggregator can select a middle trajectory and therefore obtain some reserve that can be sold to grid.

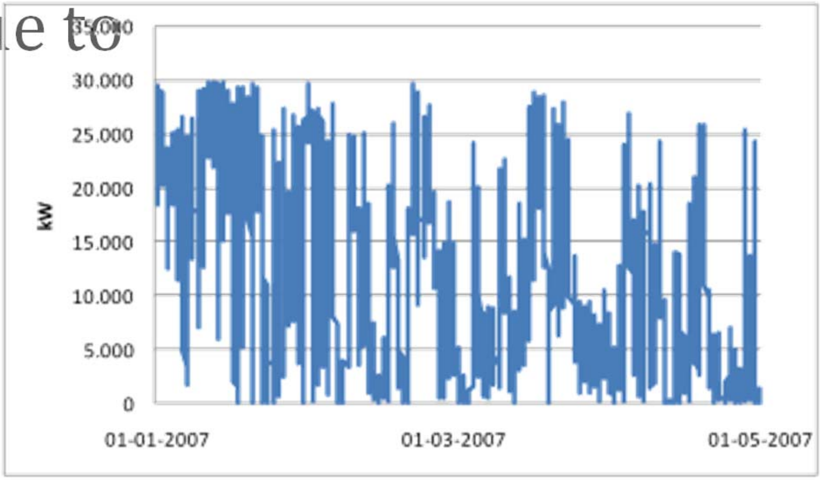
  Can be implemented with pricing and /or smart meters



Example 6: Island with Large Penetration of Renewables

- [James-Smith and Togeby 2007]
- Bornholm (DK) object of EcoGrid EU project
- Electricity : Peak demand 55 MW, Supply 30MW wind turbines, 60MW AC cable to mainland, one Combined Heat and Power plant (coal, 35 MW total)

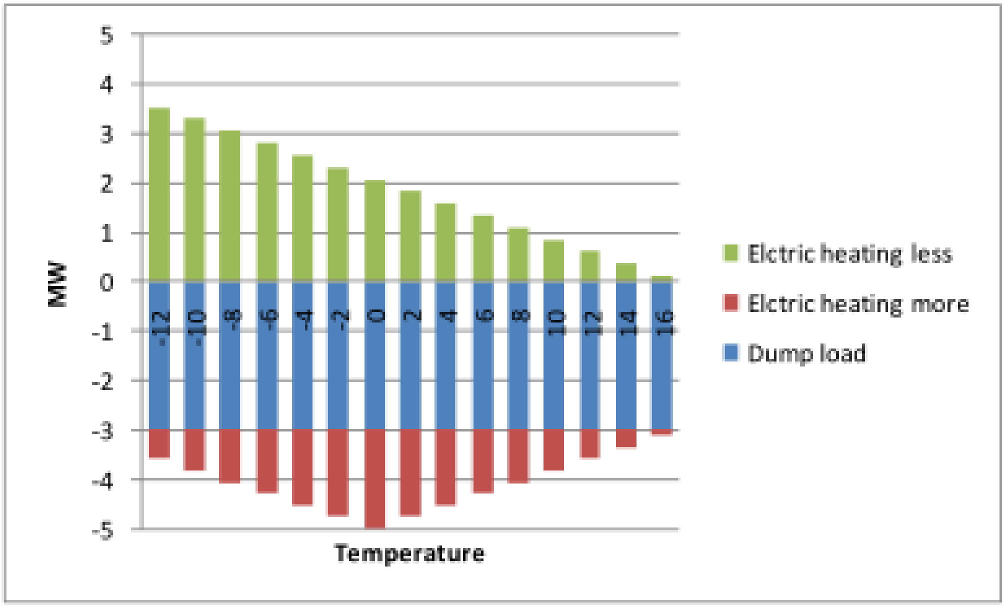
- Issue: operation in islanded mode due to frequent cable cuts
  - *Wind volatility*
  - Generation may become large
  - Coal plant is not fast enough
  - $\pm$3 MW of additional fast response (within 15 mn) is required

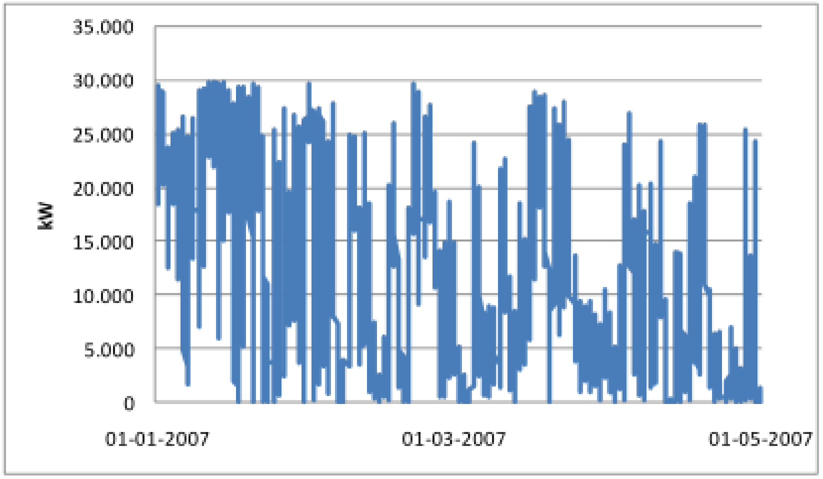


[James-Smith and Togeby 2007]

Example 6: Findings in [James-Smith and Togeby 2007]

- Demand response in homes (heating, hot water, refrigerators can provide 3MW of capacity in winter
- Positive demand response (homes, district heating system) can avoid spilling wind energy





[James-Smith and Togeby 2007]

Example 7: Impact of e-car charging on distribution network [Clement-Nyns et al 2010]

- E-car charges are high power (4kW), stress electrical distribution network – peak demand at nights

TABLE I
RATIO OF POWER LOSSES TO TOTAL POWER [%] FOR THE 4 kW CHARGER IN CASE OF UNCOORDINATED CHARGING

Charging period	Penetration level	0%	10%	20%	30%
21h00-06h00	Summer	1.1	1.4	1.9	2.2
	Winter	1.4	1.6	2.1	2.4
18h00-21h00	Summer	1.5	2.4	3.8	5.0
	Winter	2.4	3.4	4.8	6.0
10h00-16h00	Summer	1.3	1.8	2.6	3.2
	Winter	1.7	2.2	3.0	3.6

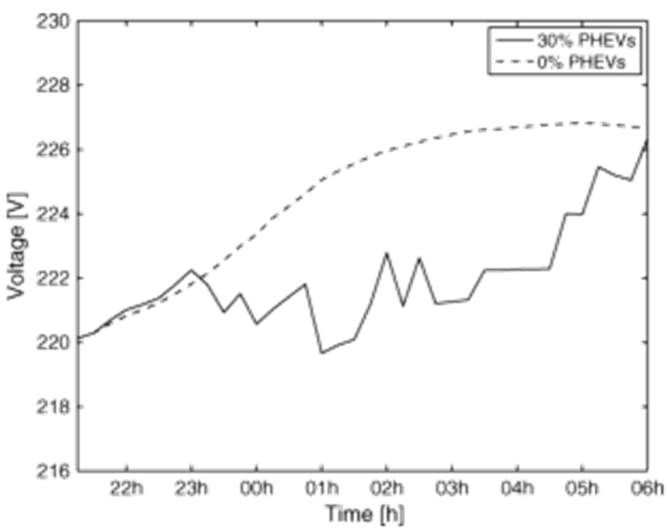


Fig. 4. Voltage profile in a node with 30% PHEVs compared to the voltage profile with 0% PHEV.

TABLE II
MAXIMUM VOLTAGE DEVIATIONS [%] FOR THE 4 kW CHARGER IN CASE OF UNCOORDINATED CHARGING

Charging period	Penetration level	0%	10%	20%	30%
21h00-06h00	Summer	3.1	3.5	4.4	5.0
	Winter	4.2	4.4	4.9	5.5
18h00-21h00	Summer	3.0	4.4	6.5	8.1
	Winter	4.8	6.3	8.5	10.3
10h00-16h00	Summer	3.0	4.1	5.6	6.9
	Winter	3.7	4.9	6.4	7.7

Simulation of 34-bus residential grid [Clement-Nyns et al 2010]

Scheduled Charging

- problem can be solved by *scheduling* the loads (e-cars), i.e. coordinate them
- e-cars communicate with a scheduler, through smart meter or other communication means
- coordinator solves optimization problem and sends schedule to e-car chargers

$$\min \sum_{t=1}^{t_{max}} \sum_{l=1}^{lines} R_l \cdot I_{l,t}^2$$

≈ power loss

$$s.t. \begin{cases} \forall t, \forall n \epsilon \{nodes\} : 0 \leq P_{n,t} \leq P_{\max} \\ \forall n \epsilon \{nodes\} : \sum_{t=1}^{t_{max}} P_{n,t} \cdot \Delta t \cdot x_n = C_{max} \\ x_n \epsilon \{0, 1\}. \end{cases}$$

power scheduled to car n at time t

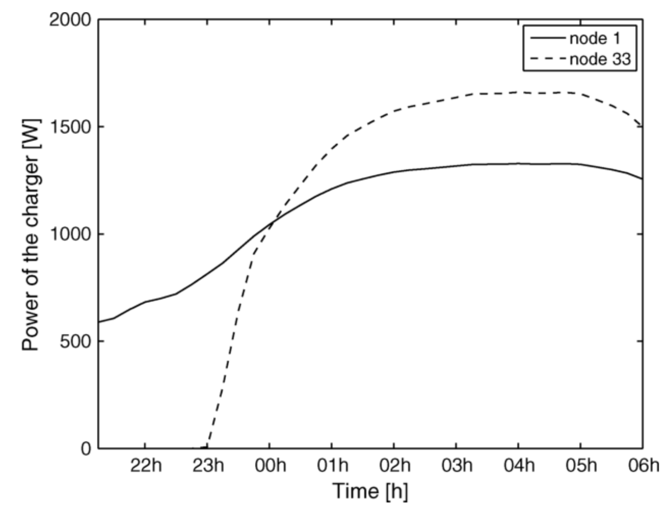


Fig. 7. Load profile of the 4 kW charger for the charging period from 21h00 until 06h00 during winter.

- requires : model of grid; of state and availability of e-cars; is frequently recomputed to address stochastic changes

Scheduled charging can eliminate need to upgrade distribution network

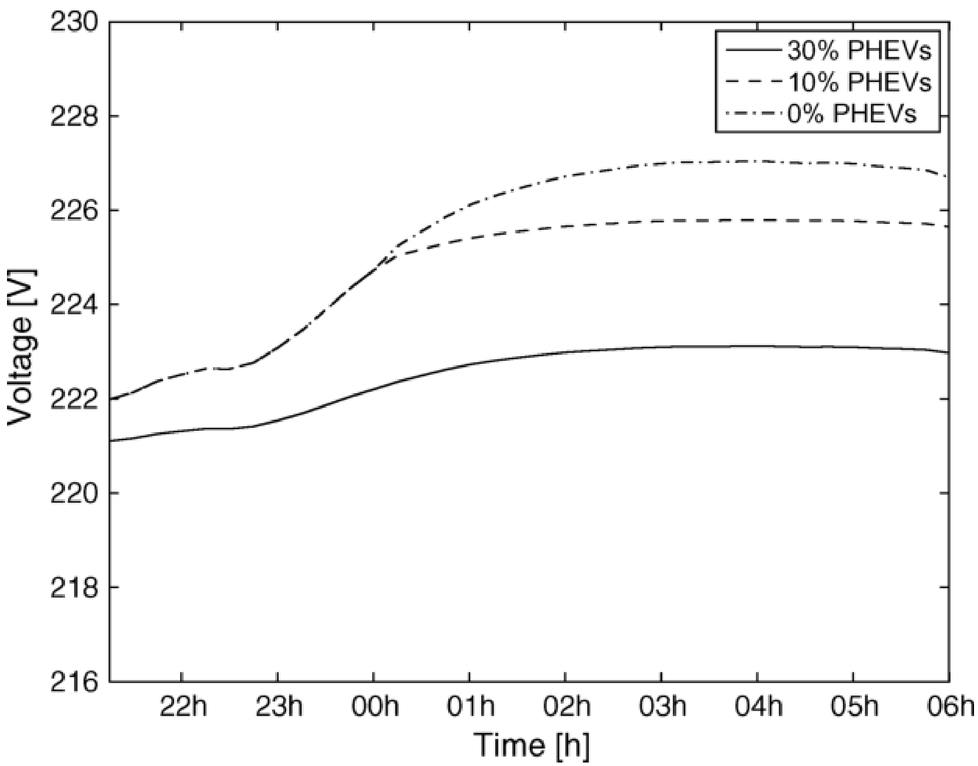


Fig. 6. Voltage profile in a node with 30% and 10% PHEVs compared to the voltage profile with 0% PHEV for coordinated charging.

TABLE III
RATIO OF POWER LOSSES TO TOTAL POWER [%] FOR THE 4 kW CHARGER IN CASE OF COORDINATED CHARGING

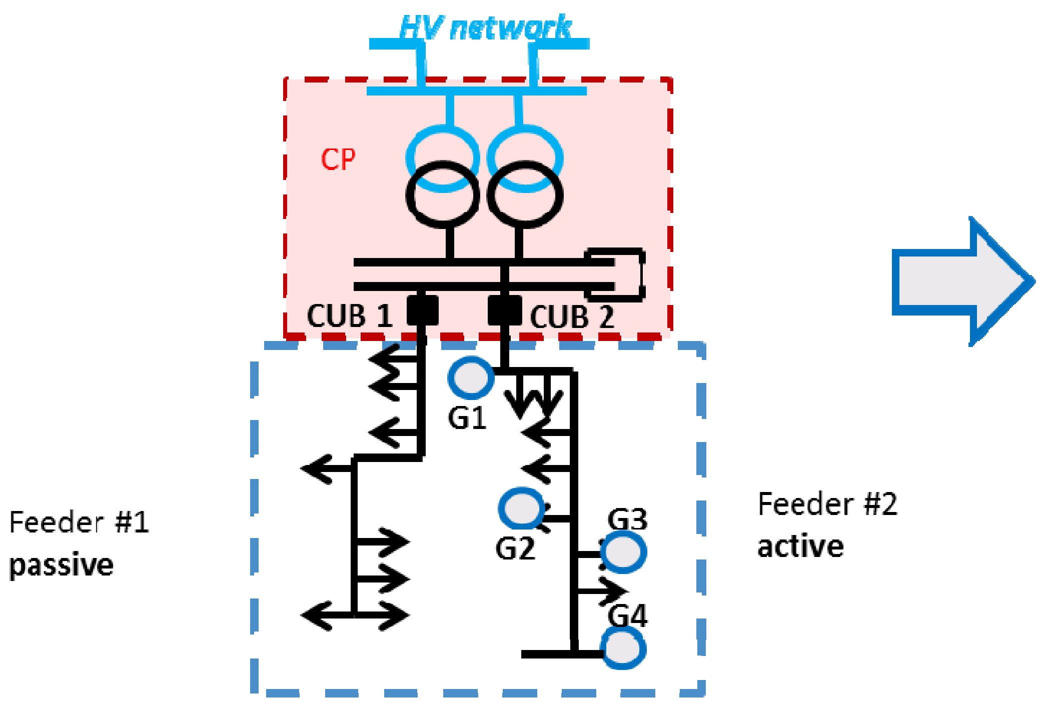
Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**
21h00-06h00	**Summer**	1.1	1.3	1.7	1.9
	Winter	1.4	1.5	1.8	2.1
18h00-21h00	**Summer**	1.5	2.3	3.7	4.7
	Winter	2.4	3.3	4.7	5.8
10h00-16h00	**Summer**	1.3	1.7	2.3	2.8
	Winter	1.7	2.1	2.7	3.2

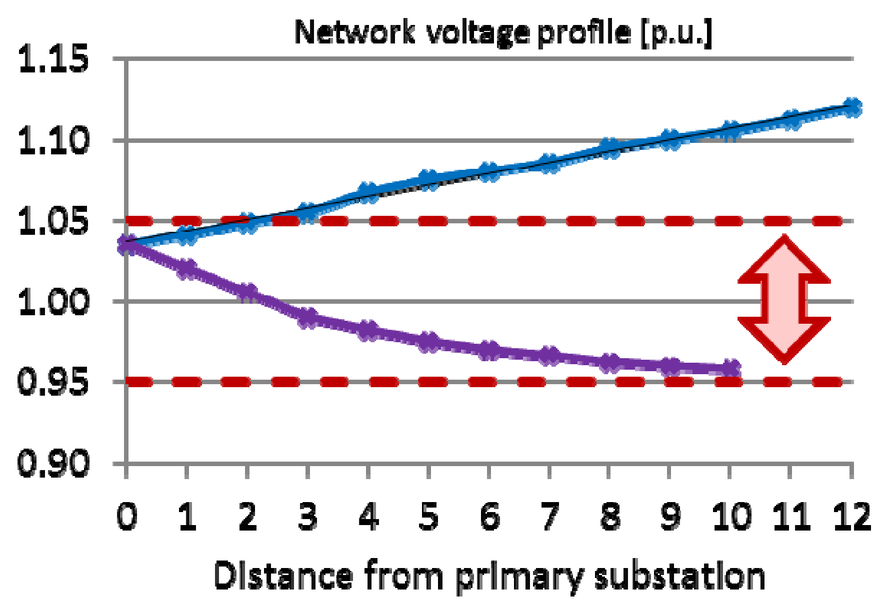
TABLE IV
MAXIMUM VOLTAGE DEVIATIONS [%] FOR THE 4 kW CHARGER IN CASE OF COORDINATED CHARGING

Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**
21h00-06h00	**Summer**	3.1	3.1	3.3	3.7
	Winter	4.2	4.2	4.2	4.3
18h00-21h00	**Summer**	3.0	4.1	5.8	7.2
	Winter	4.8	6.0	7.8	9.1
10h00-16h00	**Summer**	3.0	3.3	4.1	4.7
	Winter	3.7	4.0	4.9	5.5

Example 8: Grid Explicit Congestion Notification (GECN) [Christakou et al, 2014]

- Goal: solve voltage and ampacity problems *locally* in *distribution networks* posed by distributed generation (solar PVs, Combined heat and power)





GECN uses a broadcast explicit congestion control signal

- GECN controller broadcasts every few seconds $g(t) \in [-1,1]$:
  - $g(t)$ is unique per MV network bus
  - rate of a few bits per second
  - $|g(t)|$: intensity of required response
  - $g > 0$ means: reduce consumption
    $g < 0$ means: increase consumption
- Appliance reacts by reducing or increasing consumption
  - Mini-cycle avoidance
  - Temperature constraints

Response of a Refrigerator to GECN

- Without GECN: the thermostat implements the duty cycle $X_{t+1} = h(X_t, \theta_t)$

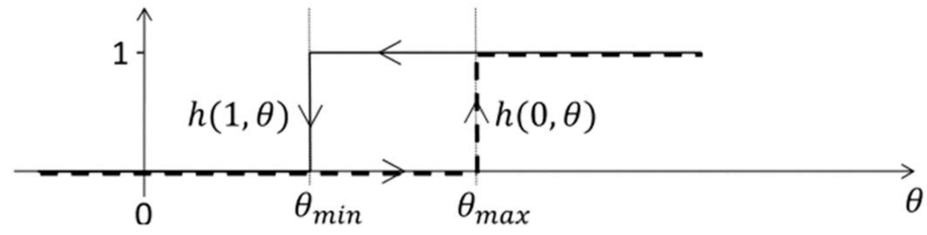
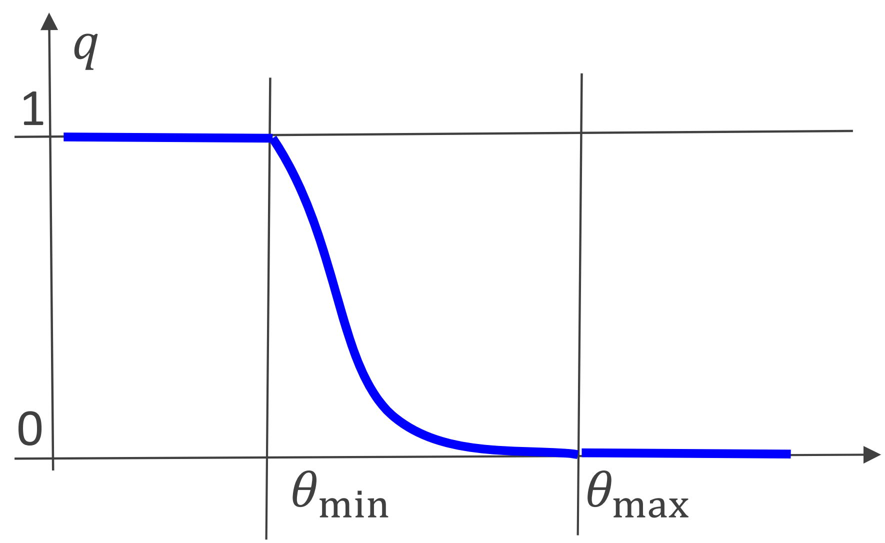


Fig. 1. Duty-cycle for appliances with deadband-constrained state.

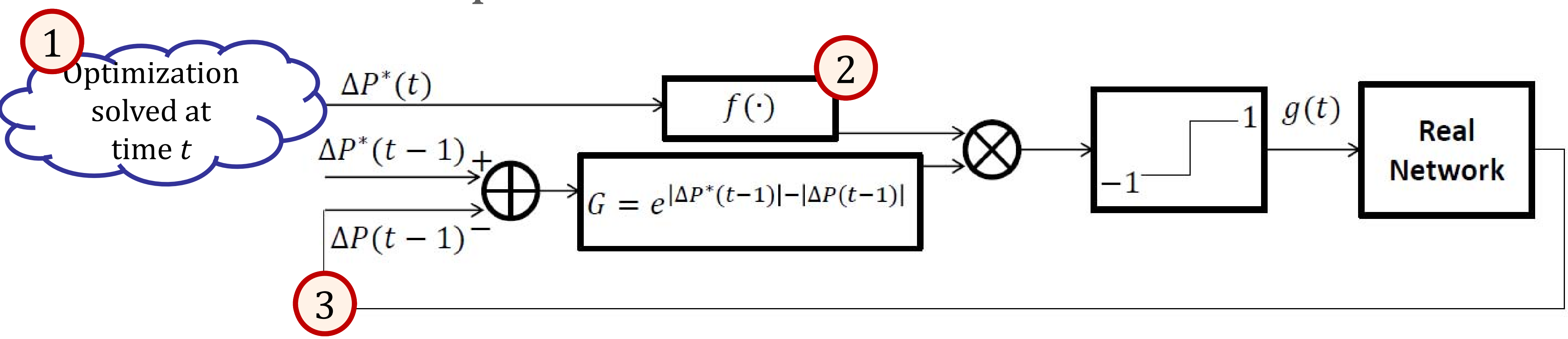
- With GECN, for example when signal $g = 0.75$ is received by a fridge that is ON
  - Flip a first coin: with proba 0.25 do nothing (i.e. continue the duty cycle),
  - with proba 0.75 consider doing something
    flip a second coin and with proba $q(\theta)$ go to OFF state



Feedback is implicit, no return channel

Implementation:

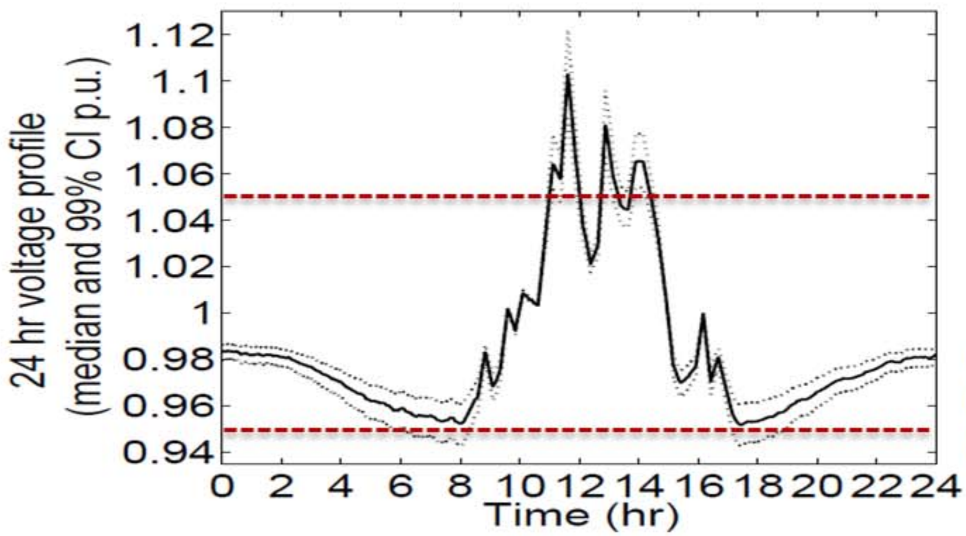
- Closed loop control



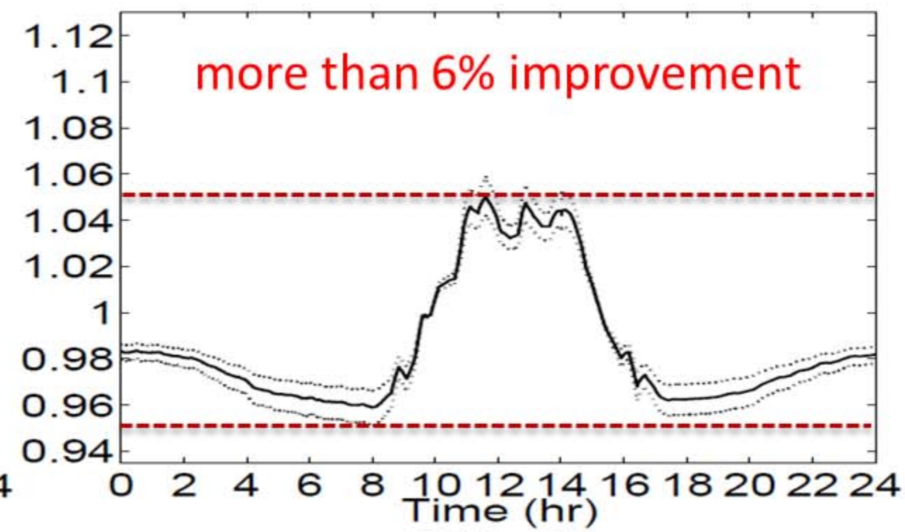
1. Optimal power set-points are solution to an optimization problem
2. The set-points are mapped to GECN signals $g(t)$ and sent to the network
3. DNO observes variation of power in the MV buses via a state estimation process and adjusts $g(t)$

Voltage (p.u.)

Without any control



With GECN



Taxonomy of Demand Response

Type of user contract

1. Time of use (e.g day versus night)
2. Control by tariff (dynamic prices)
3. Control by quantity (interruptible supply, schedules)

Mode of communication

1. inband tones (Ripples)
2. powerline communication and smart meters
3. radio communication

Time scale of operation

1. Static
2. Dynamic

   5mn-24 hours (smart meters)
3. Real time

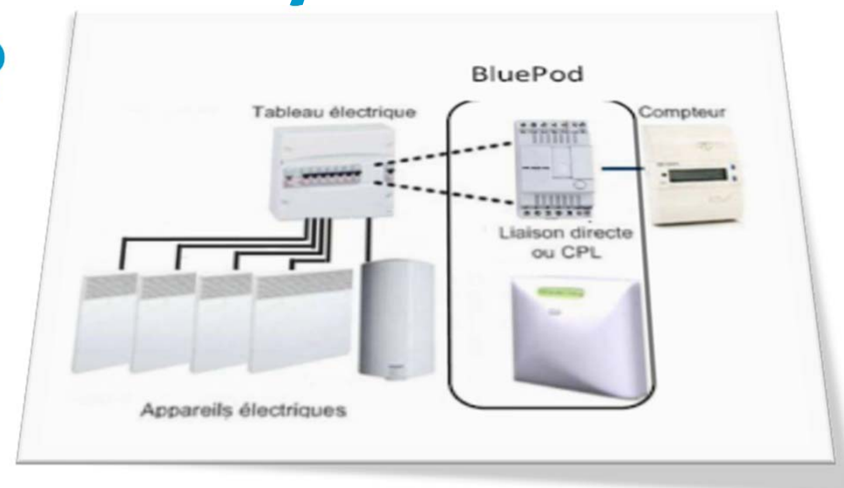
   (frequency response, GECN)

Global Effect

1. Shift the load (delay or anticipate)
2. Reduce demand (emergency, shave the peak on exceptional days)

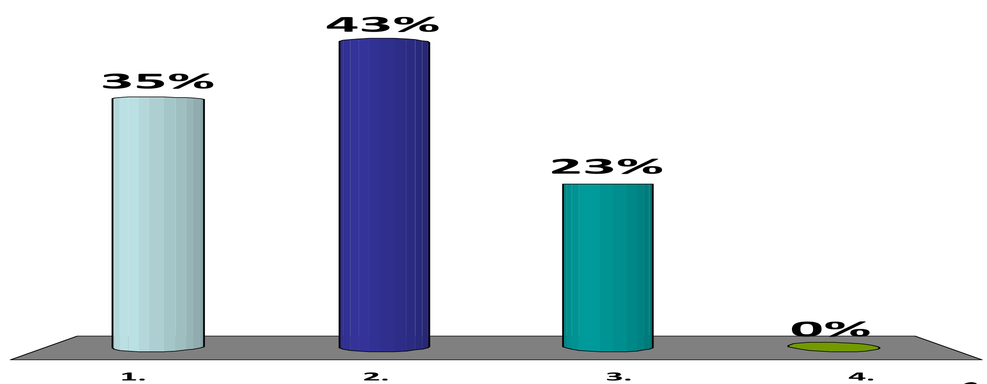
Voltalis does not pay nor charge anything to consumers but claims that consumers benefit by seeing a reduced electricity bill. Do you think this is true ?

1. Yes, there must be a reduction in total energy consumed
2. No, there cannot be any reduction in total energy consumed
3. Total energy consumed is increased
4. I don’t know



VOLTALIS
The e-power company

www.voltalis.com

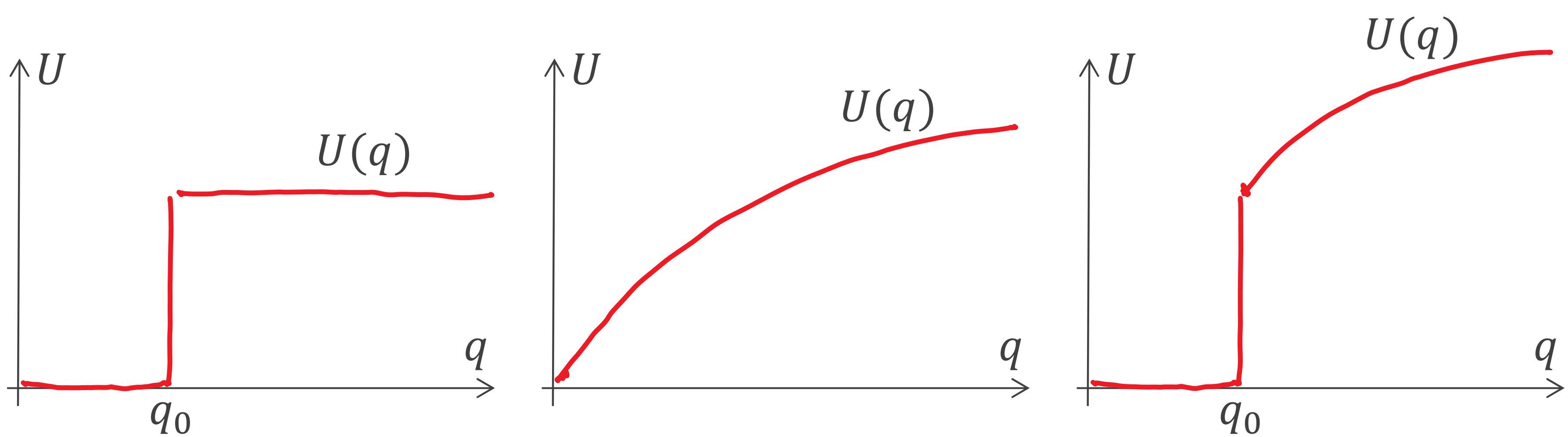


ELEMENTS OF THEORY

1. Demand and Supply Curves
2. Elasticity
3. Evaporation

1. The Economic Theory of Demand Response
Consumer Side

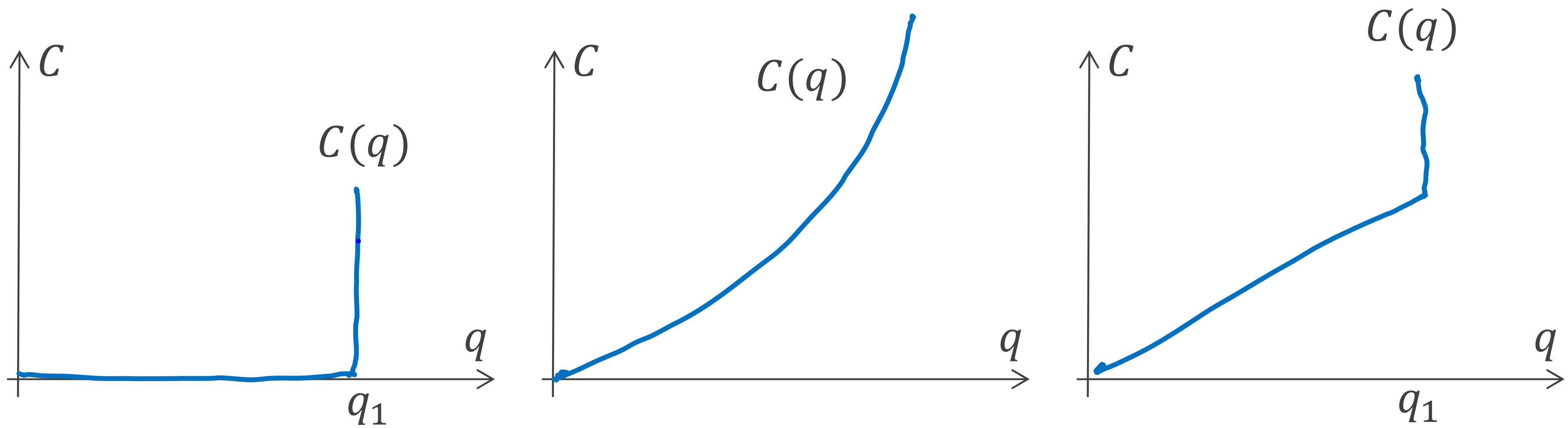
- The economic theory of Demand Response is based on the following model.
- Assume consumers are willing to consume some amount of energy q at a price p ; in a given time slot, the *utility* of q is assumed to be measurable and equal to $U(q)$; the consumer chooses the value of q that maximizes $U(q) - pq$



non elastic load　　elastic load　　elastic load with minimum requir't

The Economic Theory of Demand Response
Supplier Side

- Assume suppliers users are willing to sell some amount of energy q at a price p ; in a given time slot, the *running cost* of generating q is assumed to be measurable and equal to $C(q)$; the supplier chooses the value of q that maximizes $pq - C(q)$



wind supplier

flexible supplier

flexible supplier with maximum capacity

Demand and Supply Curves

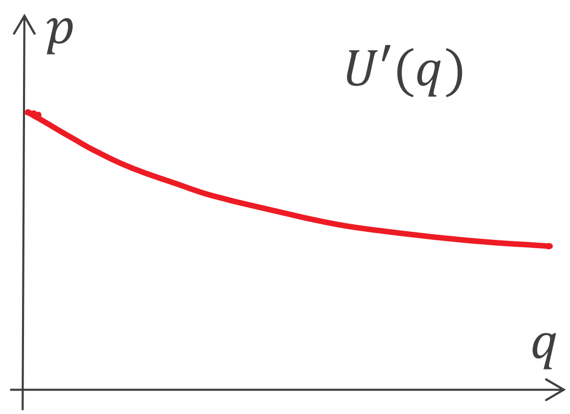
- *Demand Curve* = how much consumer is willing to buy at a given price
  Supply curve = how much supplier is willing to sell at a given price

- Consumer maximizes $U(q) - pq$ therefore $U'(q) = p$
  Supplier maximizes $pq - C(q)$ therefore $C'(q) = p$

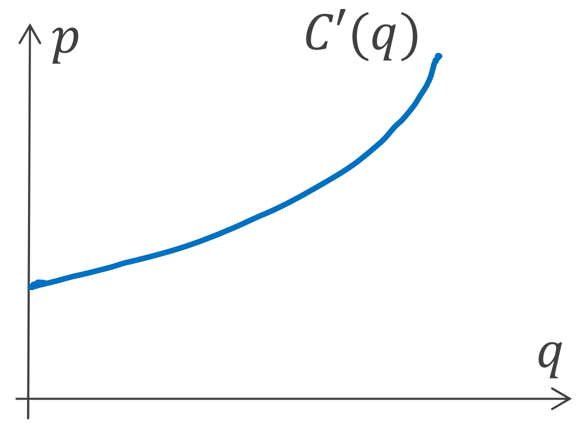
  demand curve is $q \mapsto U'(q)$
  supply curve is $q \mapsto C'(q)$

- U concave $\Rightarrow$
  $U'$is decreasing

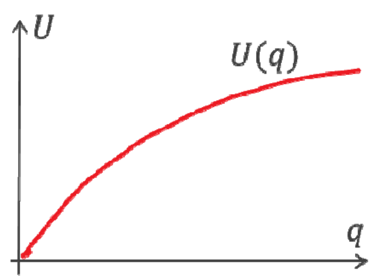
- C convex $\Rightarrow$
  $C'$is increasing



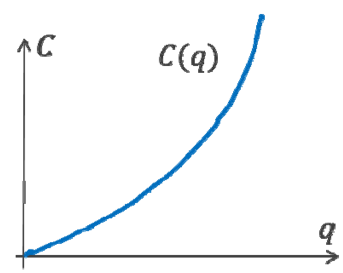
elastic load



supply curve, flexible supplier



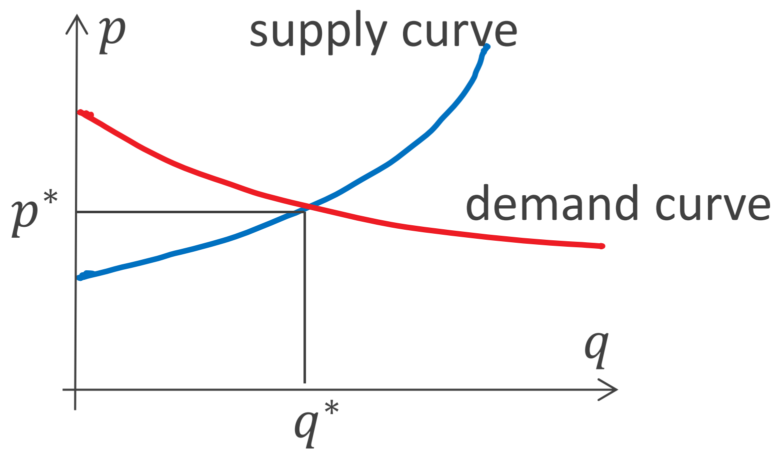
elastic load



flexible supplier

Market Equilibrium

- Assume there is a perfect market to fix prices; the supplier and consumer prices are equal
  Price and quantity are given by intersection of supply and demand curves



market values q^*, p^*

Supply and Demand Curves Without Demand Response [Kirschen 2003]

- No demand response means loads are inelastic ;generation or grid outages cause prices to surge

- Elastic loads may avoid price peaks

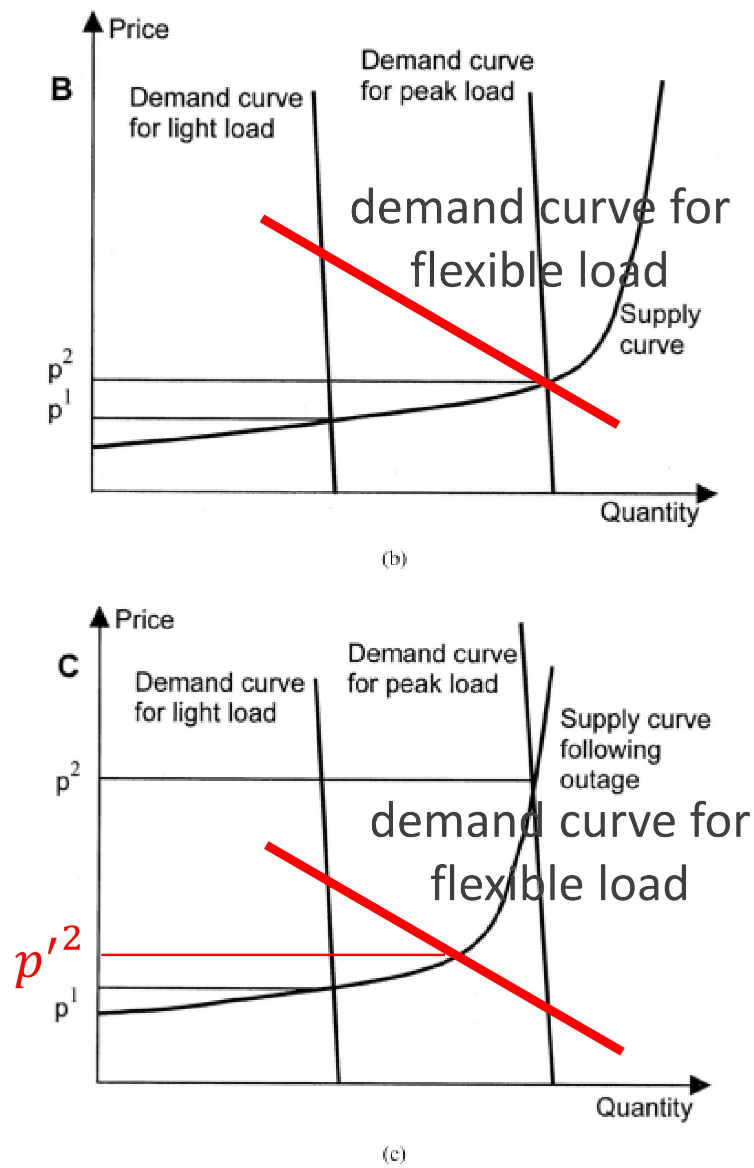
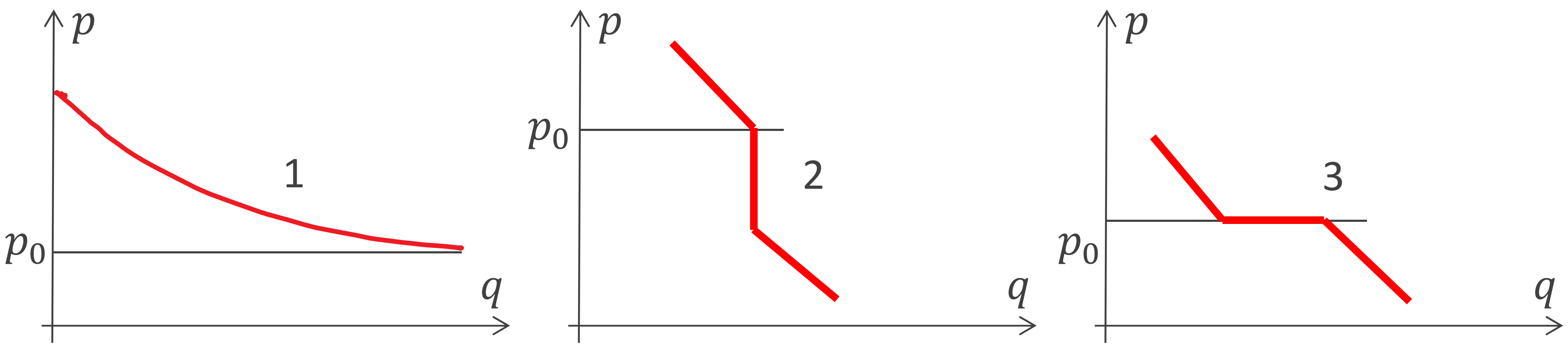
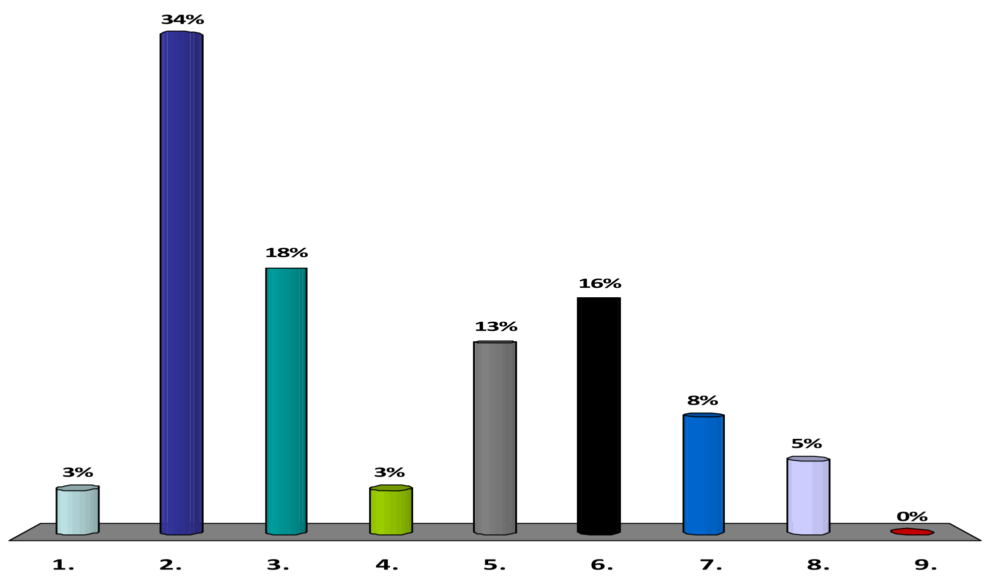


Fig. 1. (a) Market equilibria for a "normal" commodity. (b) Typical supply and demand curves for electrical energy. (c) Supply and demand curve following a major generation outage.

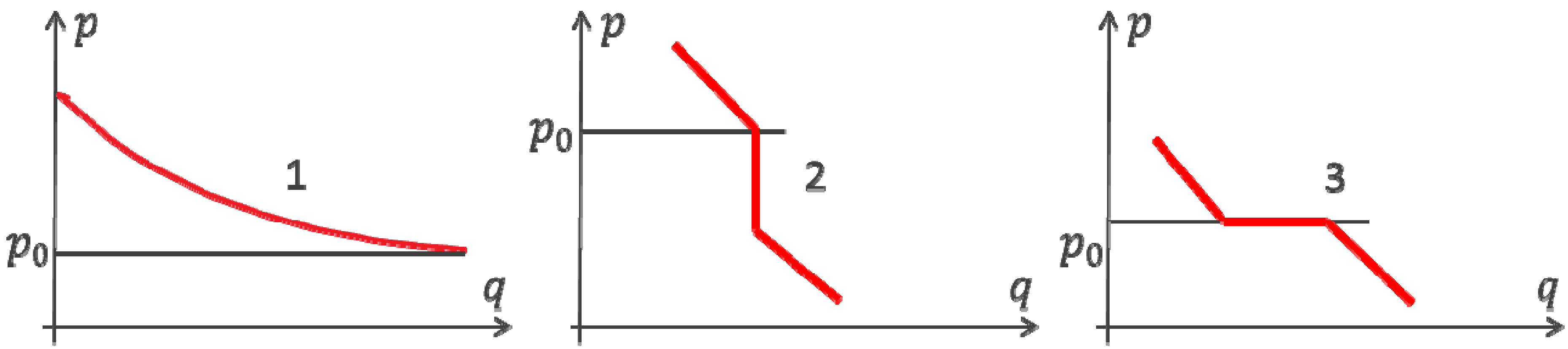
Assume some loads disconnect when price becomes $> p_0$ Which curve could be a demand curve for the aggregate demand ?



1. Curve 1
2. Curve 2
3. Curve 3
4. Either 1 or 2
5. Either 1 or 3
6. Either 2 or 3
7. All
8. None
9. I don't know



Solution



- With 1 the price is always > 0 so it does not express the disconnection
- With 2, the demand is insensitive to price when price is betweeb p_1 and p_0
- With 3, the demand has a negative jump when the price increases to p_0

Correct answer is 3

Norway's pilot study [Saele and Grande 2011] Demand Response may reduce prices

- 120 EUR/MWh difference between 2 areas inside Norway
- [Saele and Grande 2011] claims that the price peak would be suppressed with demand response

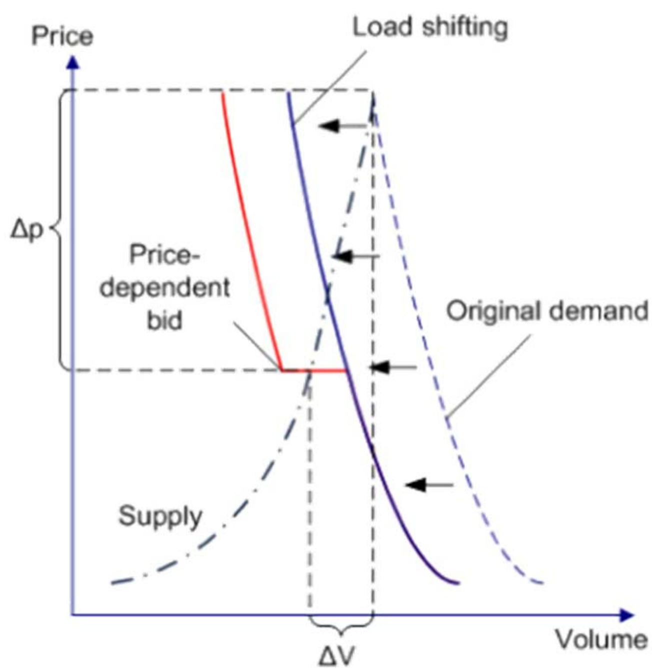


Fig. 2. Different bid curves for demand response.

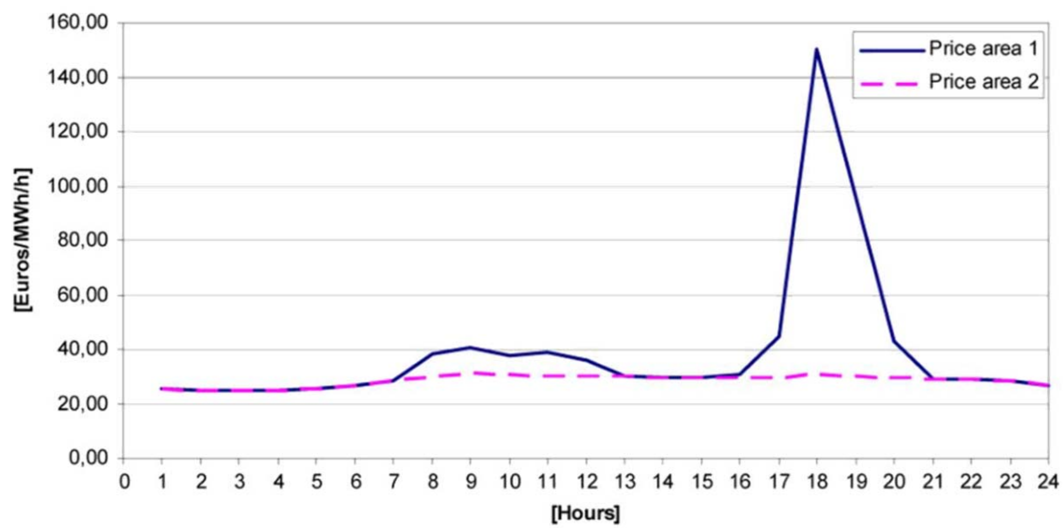


Fig. 3. Hourly spot prices in two price areas in Norway, 6 February 2007 (data source: NordPool).

Supply Curve for Industrial Customers

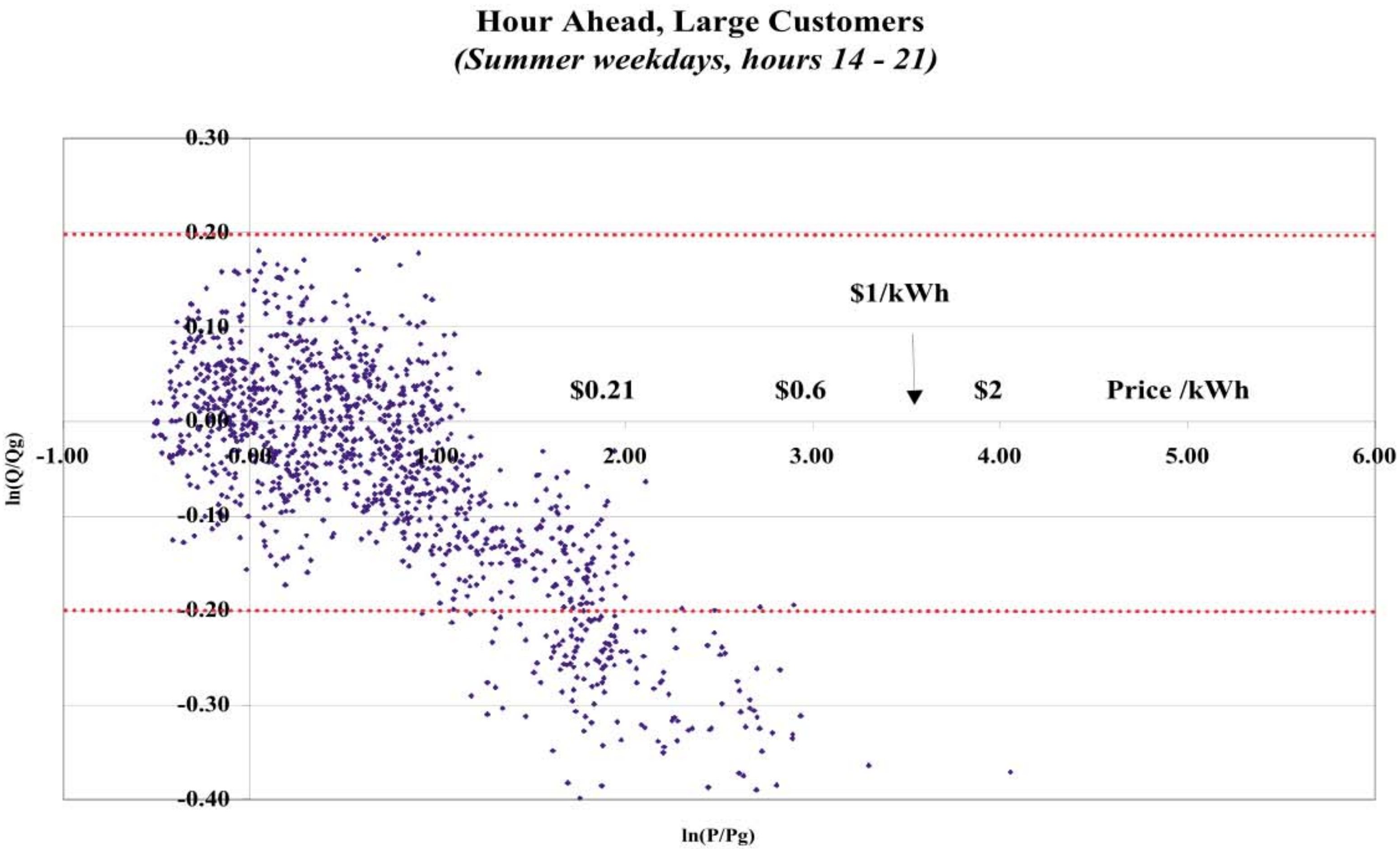
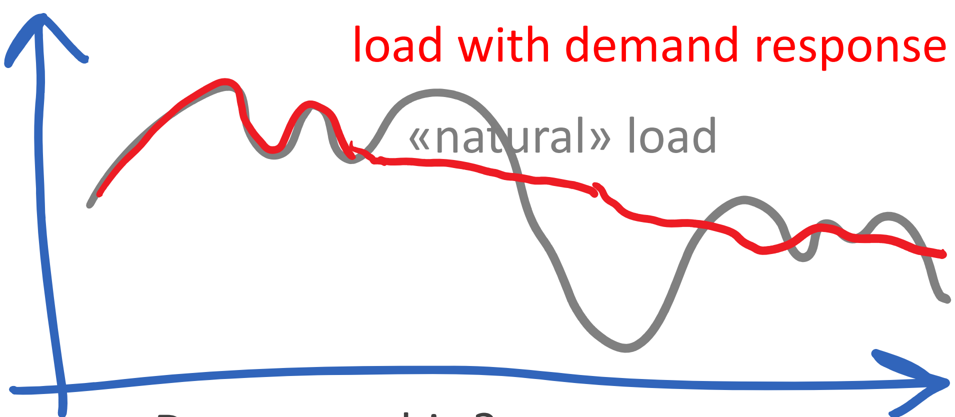


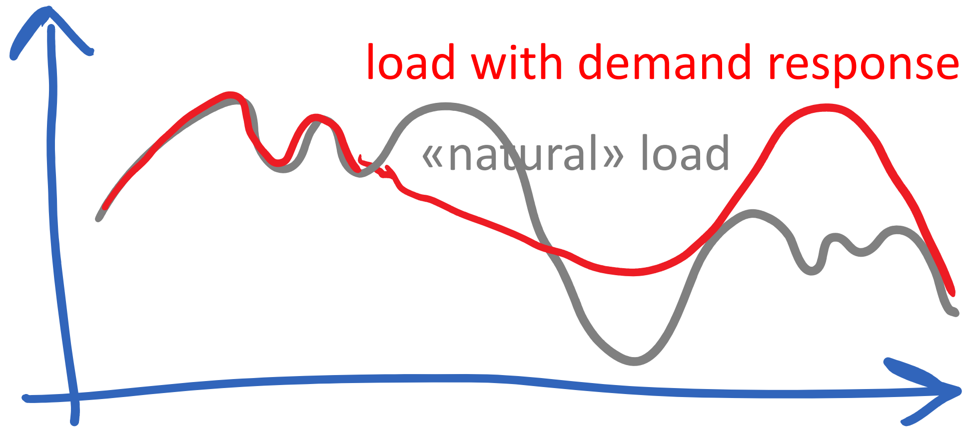
Figure 3-k. Demand response of large industrial Hour-Ahead customers in Georgia Power's RTP program. Scales are logarithmic. We have added on the x-axis a few price levels in $ per kWh.

Source: Braithwait, Christensen and Associates

2. Elasticity



Do we get this ?



… or that ?

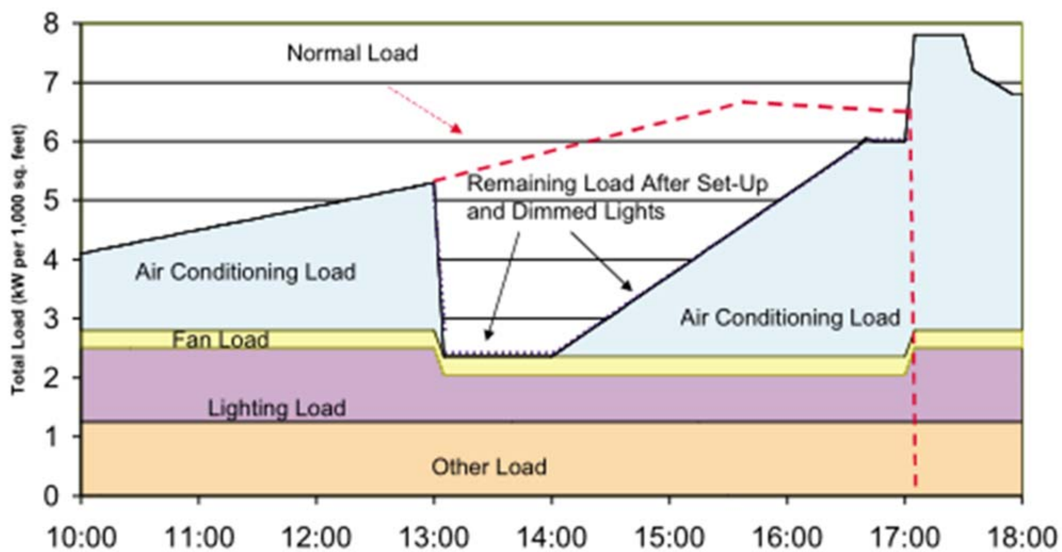


Figure 3-d is a conceptual illustration of the response of a building to CPP on a hot afternoon. The example assumes CPP is invoked from 13:00 to 17:00. The figure shows two different usage patterns in a single sketch. Pattern 1 (Normal Load) is a typical office, where loads drop at about 5 p.m. For Pattern 2, the air conditioning demand actually increases after 5 p.m. because the thermostat has been set back down to 72° F.

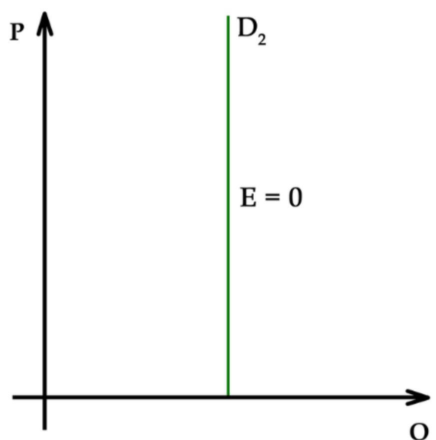
Source: Pat McAuliffe, CEC

CPP = critical peak pricing

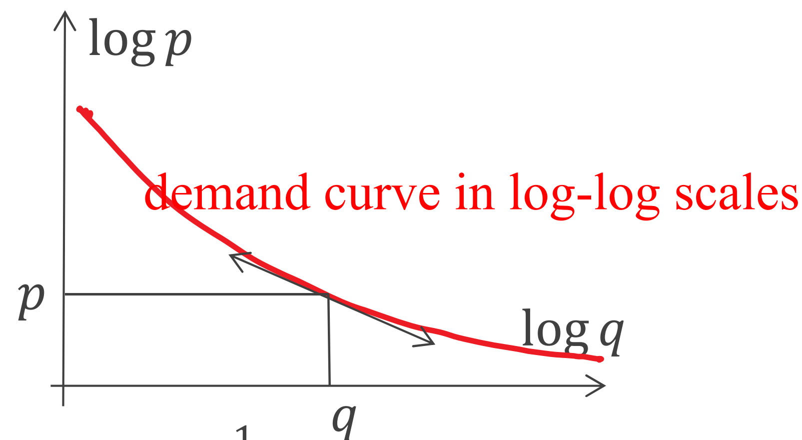
Elasticity and Cross-Elasticity

- Demand response causes demand reduction and time shifting
- The quantitative effect is captured by

$$\text{(self)-elasticity} \coloneqq \frac{dq}{dp}\frac{p}{q} = \frac{d(\log p)}{d(\log q)}$$



Wikimedia Commons /File:Elasticity-inelastic.png



$\frac{1}{\text{slope}}$ is the elasticity at p

and

$$\text{cross-elasticity } E_{t+h,t} \coloneqq \frac{\partial q_{t+h}}{\partial p_t}\frac{p_t}{q_{t+h}}$$

defined for example for $h \in [-24\text{hours}, +24\text{ hours}]$

Example of Cross-Elasticity [Kirschen et al 2000]

- Users expect some prices p_t based on historical data
  Resulting demand is q_t
  assumes two demand response models with cross-elasticity
- Market decides for different prices, Δp_t = difference between expected price and actual price. Demand response cause users to change their loads. [Kirschen et al 2000] assumes that

$$\Delta q_t = \sum_{h=-24}^{+24} \frac{\Delta p_{t+h}}{p_{t+h}} \varepsilon_{t,t+h} \, q_{t+h}$$

where $\varepsilon_{t,t+h}$ is called the *Cross-Elasticity Coefficient*

(it slightly differs from $E_{t,t+h}$)

$\varepsilon_{t,t+h} \times \frac{\Delta p_{t+h}}{p_{t+h}}$ is the fraction of the load at time $t+h$ that is moved to time t due to a change in price at time $t+h$

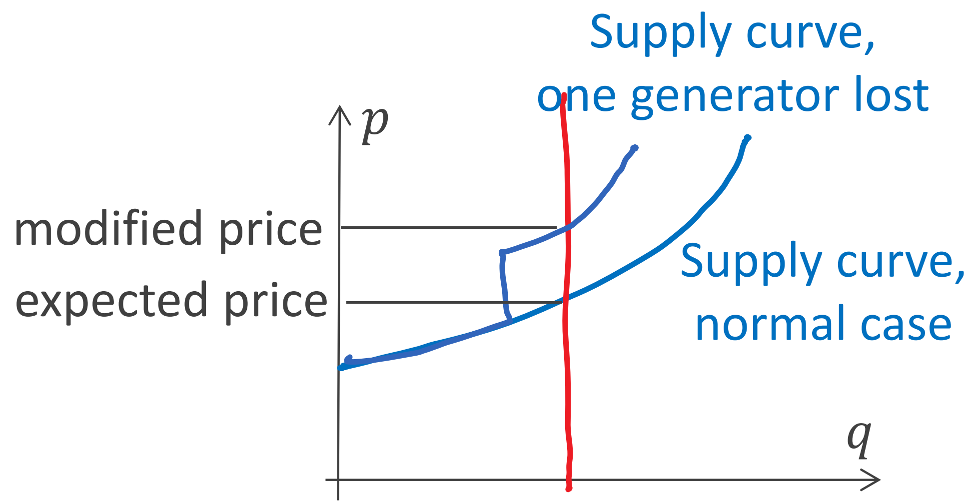
Example of Cross-Elasticity Coefficients

- $\Delta q_t = \sum_{h=-24}^{+24} \frac{\Delta p_{t+h}}{p_{t+h}} \varepsilon_{t,t+h}\, q_{t+h}$
- [Kirschen et al 2000] considers two possible scenarios
  Scenario 1: (Time Shifting, "Inflexible"):
  $$\varepsilon_{t-3,t} = \varepsilon_{t-2,t} = \varepsilon_{t-1,t} = +0.0033$$
  $$\varepsilon_{t+3,t} = \varepsilon_{t+2,t} = \varepsilon_{t+1,t} = +0.0033$$
  $$\varepsilon_{t,t} = -0.20$$
  i.e. change in price at t changes load by $-0.2 \times \%$ price increase
  load is transferred to 3 hours before and 3 hours after t
- **Scenario 2:** ("Optimizer"):
  $$\varepsilon_{0,t} = \cdots = \varepsilon_{2,t} = \varepsilon_{16,t} = \cdots = \varepsilon_{23,t} = +0.01$$
  $$\varepsilon_{4,t} = \cdots = \varepsilon_{7,t} = +0.025$$
  $$\varepsilon_{t,t} = -0.20$$
  i.e. change in price at t changes load by $-0.2 \times \%$ price increase
  most load is transferred to early and late hours of the day

Impact on Price

- Assuming no elasticity, prices are formed by matching demand
  let $\vec{q} \mapsto \vec{p} = \vec{F}(\vec{q})$ the process of price formation
  where $\vec{p} = (p_0, p_1, \dots, p_{23})$

- [Kirschen et al 2000] studies a case with normal operation and with planned loss of generator



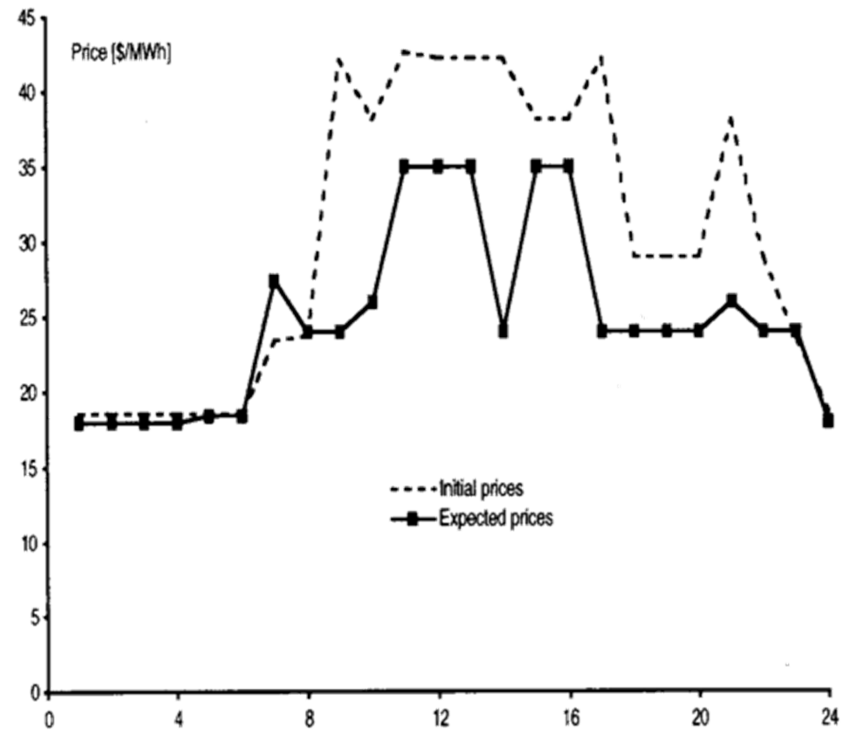


Fig. 5. Expected prices and initial prices.

Impact on Price (continued)

- Assume now elastic loads with known cross-elasticity. The actual load depends on the market price: let $\vec{p} \mapsto \vec{q} = \vec{G}(\vec{p})$ be the process of load adaptation
- Assume market aggregator knows elasticity; she can compute market prices by solving a fixed point problem

$$\begin{cases} \vec{p} = \vec{F}(\vec{q}) \\ \vec{q} = \vec{G}(\vec{p}) \end{cases}$$

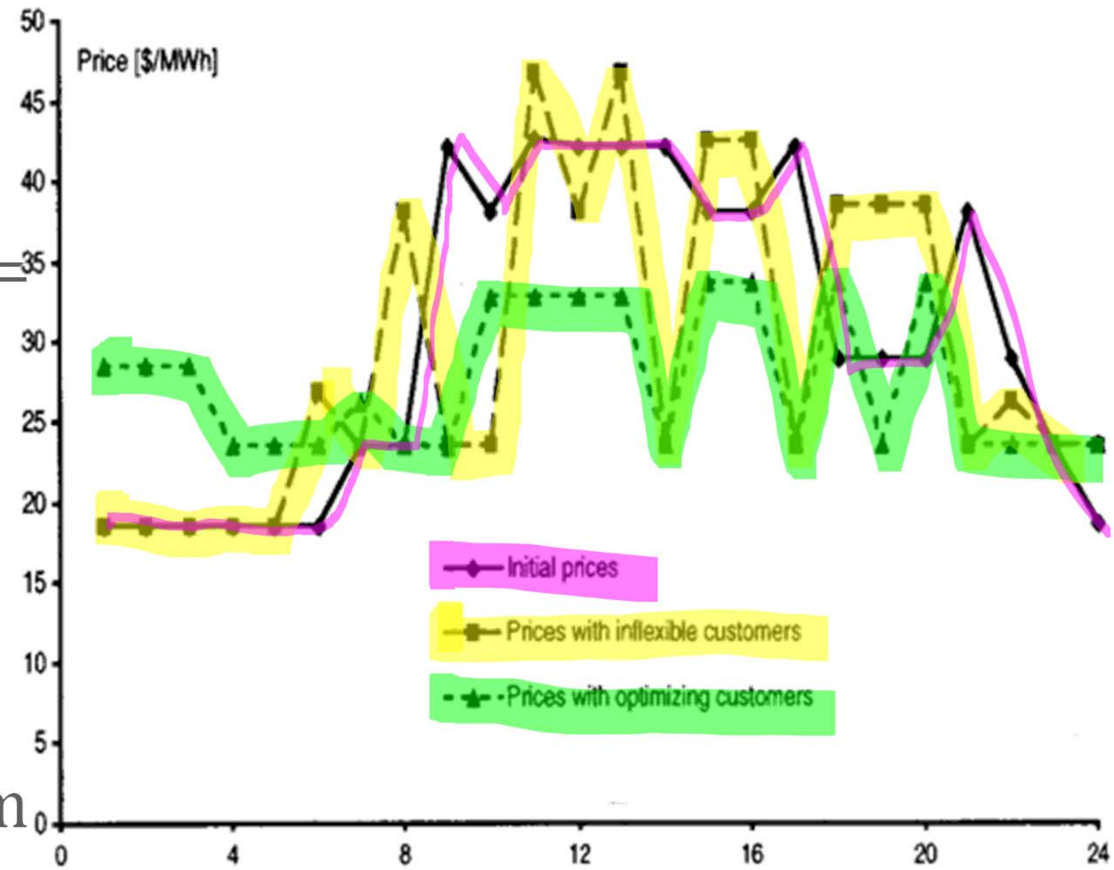
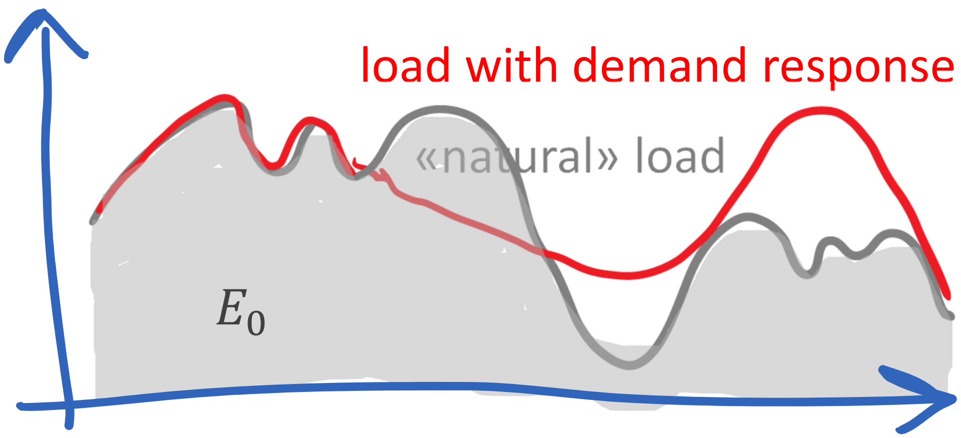


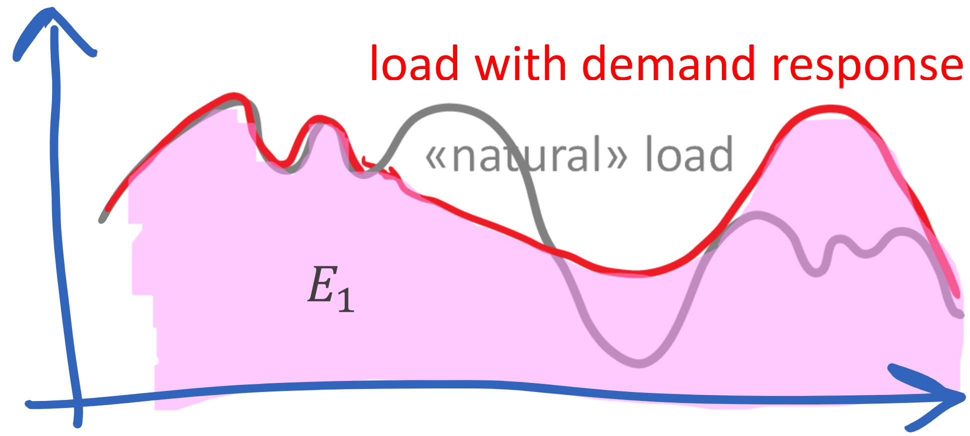
Fig. 7. Initial prices and prices as modified by elasticities.

[Kirschen et al 2000]

3. Evaporation

- Evaporation $=$ fraction of energy that is saved due to demand response [Le Boudec and Tomozei 2013]



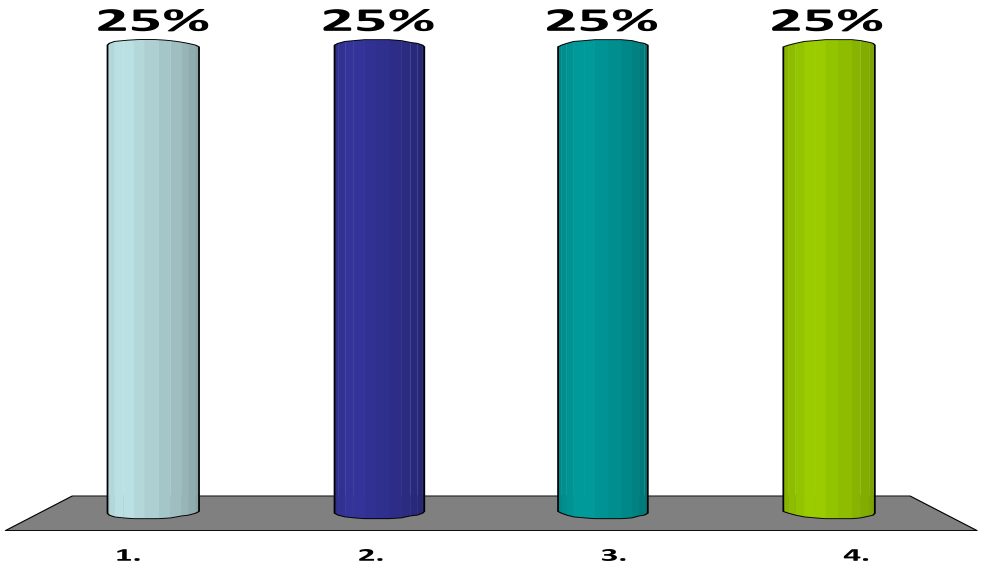


$$\text{evaporation} = \frac{E_0 - E_1}{E_0}$$

- with pure demand shifting, evaporation = 0
- If it is true that demand response saves energy, we should see evaporation > 0
- What do we expect in general ?

(Should I keep my chalet warm ?) When I am away I interrupt heating. Does this save energy ?

1. Yes, there must be a reduction in total energy consumed
2. No, there cannot be any reduction in total energy consumed
3. Total energy consumed is increased
4. I don't know



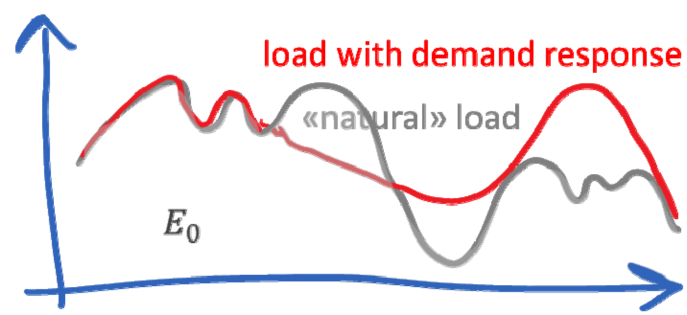
Evaporation is not the same as "Rebound Effect"

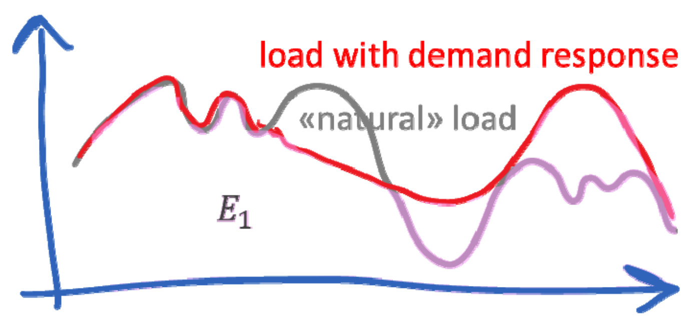
Q1. Does shutting down the heating today imply reducing total energy consumption compared to keeping temperature constant ? = is evaporation positive ?

A. we will see later.

Q2. Does shutting down the heating today (and swithing it off tomorrow) imply increasing tomorrow's energy consumption?

A. Yes (this is the rebound effect).



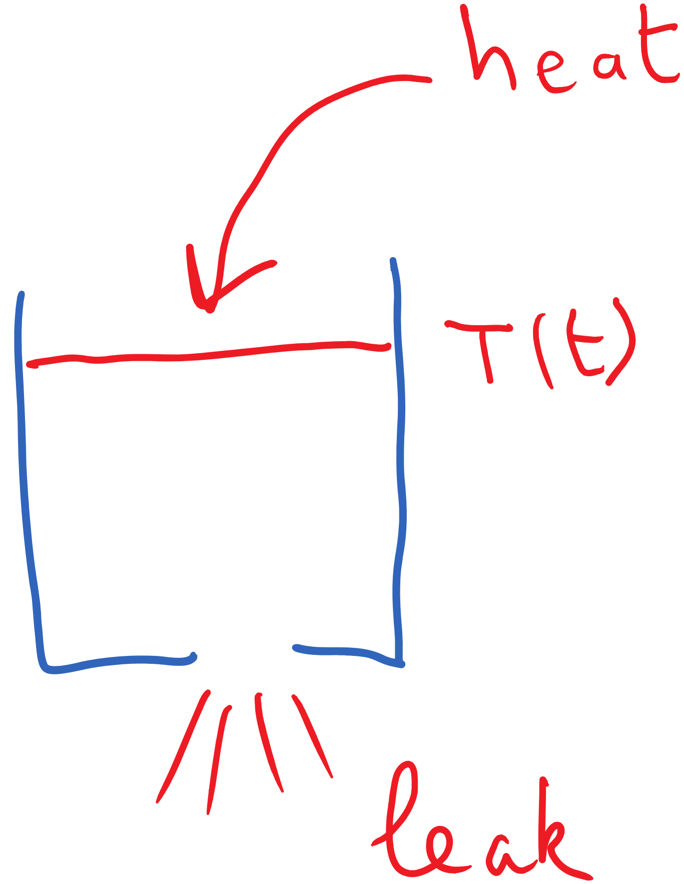


- Assume the house model of [McKay 2008]

heat provided to building

$$\boxed{d(t)\epsilon} = \boxed{K}(T(t) - \theta(t)) + \boxed{C}(T(t) - T(t-1))$$

leakiness outside inertia



heat provided to building $d(t)\epsilon = K(T(t) - \theta(t)) + C(T(t) - T(t-1))$

leakiness outside inertia

sum over t from 1 to τ :

efficiency $\epsilon \sum_{t=1}^{\tau} d(t) = K \sum_{t=1}^{\tau} \big(T(t) - \theta(t)\big) + C(T(\tau) - T(0)$

achieved t°

E, total energy provided

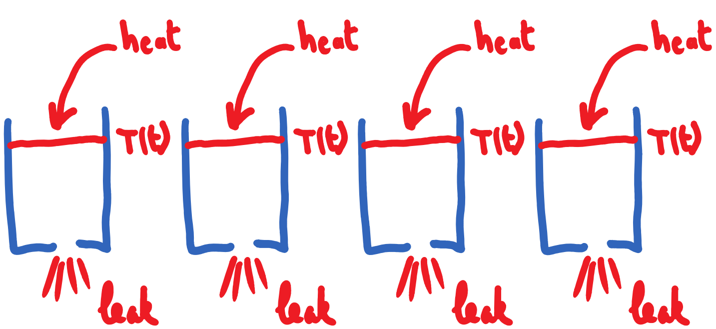
efficiency

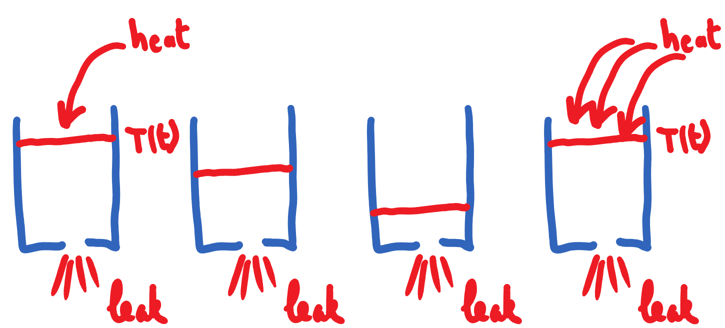
$$\boxed{\epsilon \sum_{t=1}^{\tau} d(t)} = K \sum_{t=1}^{\tau} \left(\boxed{T(t)} - \theta(t)\right) + C\left(T(\tau) - T(0)\right)$$

achieved t°

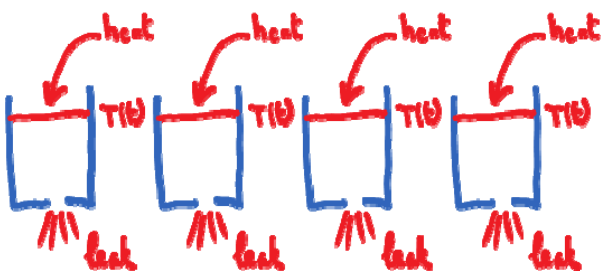
E, total energy provided

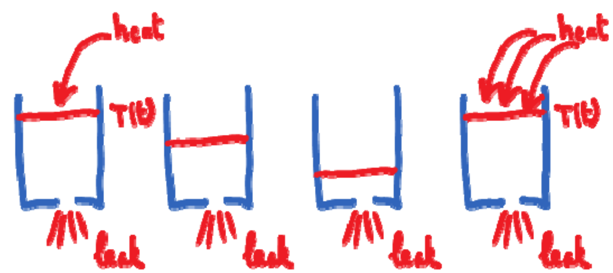
Scenario	***No interruption***	***With interruption***
Building temperature	$T^*(t), t = 0 \dots \tau$	$T(t), t = 0 \dots \tau,$ $T(t) \le T^*(t)$
Heat provided	$E^* = \frac{1}{\epsilon}\left(K \sum_{t=1}^{\tau} \left(T^*(t) - \theta(t)\right) + C\left(T^*(\tau) - T^*(0)\ \right)\right)$	$E < E^*$





Scenario	***No interruption***	***With interruption***
Building temperature	$T^*(t), t = 0 \ldots \tau$	$T(t), t = 0 \ldots \tau$, $T(t) \leq T^*(t)$
Heat provided	$E^* = \frac{1}{\epsilon}\left(K\sum_{t=1}^{\tau}(T^*(t) - \theta(t)) + C(T^*(\tau) - T^*(0))\right)$	$E < E^*$





Assume initial temperature = final temperature in both scenarios $T^*(\tau) = T^*(0) = T(\tau) = T(0)$. In this case integral of energy fed into building (E^* in scenario "No interruption", E in scenario "With Interruption") is equal to integral of leaked energy:

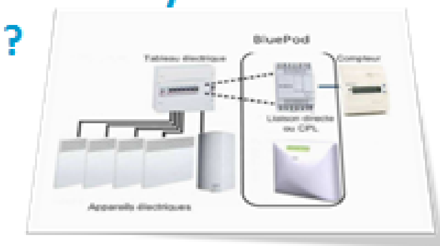
$$E^* = \frac{1}{\epsilon}K\sum_{t=1}^{\tau}(T^*(t) - \theta(t)) > E = \frac{1}{\epsilon}K\sum_{t=1}^{\tau}(T(t) - \theta(t))$$

It costs more heat to keep the chalet warm without interruption.

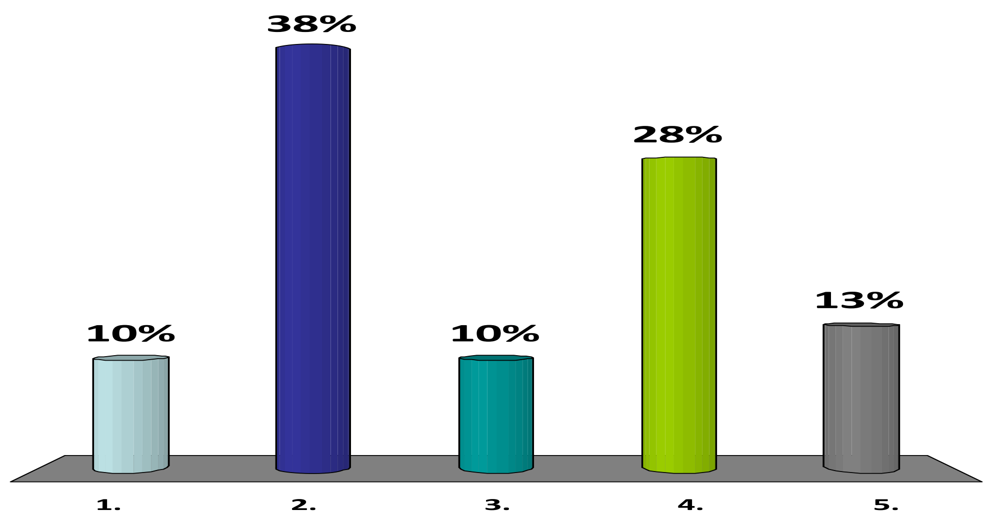
The French ADEME agency finds that consumers with Voltalis's load switching devices save ≈ 10% on heating but there is no significant saving on hot water boilers [ADEME 2012]. How do you interpret this ?

1. The model we saw is too simple and its findings do not apply.
2. Boiler leakage is small, house leakage is not.
3. House leakage is small, boiler leakage is not.
4. Hot water boiling is negligible consumption compared to house heating
5. I don't know.

Voltalis does not pay nor charge anything to consumers but claims that consumers benefit by seeing a reduced electricity bill. Do you think this is true ?



1. Yes, there must be a reduction in total energy consumed



Solution

- Does shutting down the heating today implies reducing total *heat* consumption compared to keeping temperature constant ?

- Answer: yes in all cases

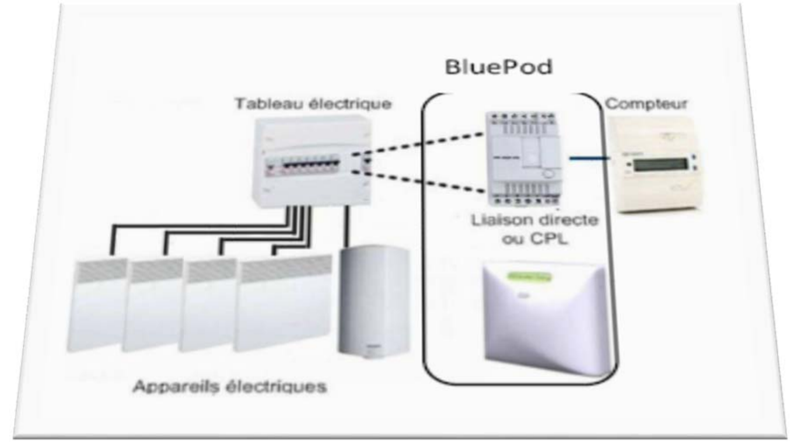
- Answer 3 is the only plausible

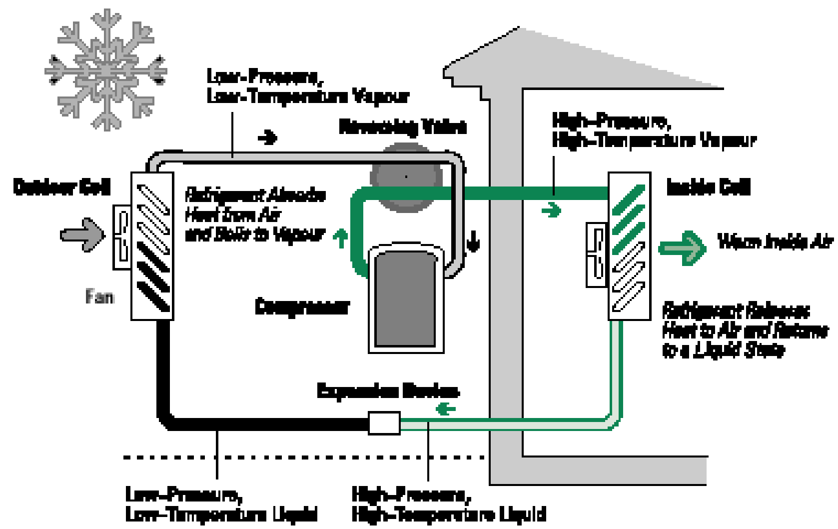
Evaporation

- Resistive heating system with poorly insulated building: heat provided is proportional to energy consumption evaporation is positive.

- If heat = heat pump, coefficient of performance ϵ may be variable. Evaporation may be positive or negative; negative evaporation is possible (heat pump operating at night in cold air).

- Electric vehicle: we expect evaporation = 0 (pure time shifting). However charge intensity impacts losses; fast charging may consume more energy, negative evaporation is possible.





Further Reading

- OpenADR: practical implementation of Demand Response by price http://www.openadr.org

- Demand response by price, toolkit for Grid Operators: http://www.pjm.com/markets-and-operations/demand-response.aspx

- http://www.voltalis.com/bluepod.php

- Impact of demand response on real time market prices [Gast et al, 2014]

Conclusion

- Demand response aims at controlling demand to better follow generation

- Demand response can be seen as a form of virtual electricity storage

  alternatives are: batteries, pump-hydro, compressed air, etc

- Demand response can act on
  - Energy time scale (15 mn or more) by price or direct control
    Such systems are deployed today
  - Power time scale (instantly) to counterbalance intermittency of solar and wind generation
    In the labs

References

- [Transpower New Zealand 2012] http://www.systemoperator.co.nz/presentations/demand-response-animation/ sampled on May 17, 2013
- [ADEME 2012] "Avis de l'ADEME", 8 October 2012, http://www2.ademe.fr/servlet/getBin?name=133DA6A2F68CD16926D050F0081C36D4_tomcatlocal1349692493746.pdf
- [Borenstein et al 2002] S Borenstein, M Jaske, A Rosenfeld, "Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets" , Report to The Energy Foundation, October 2002
- [Christakou et al, 2014] Christakou, K. et al. "GECN: Primary Voltage Control for Active Distribution Networks via Real-Time Demand-Response", IEEE Transactions on Smart Grid, 2014
- [Clement-Nyns et al 2010] Clement-Nyns, K.; Haesen, E.; Driesen, J., "The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid", IEEE TPS, 2010
- [Gast et al, 2014] N. Gast, J.-Y. Le Boudec and D.-C. Tomozei. Impact of demand-response on the efficiency and prices in real-time electricity markets. e-Energy '14, Cambridge, United Kingdom, 2014.
- [Hao et al, 2012] He Hao, Tim Middelkoop, Prabir Barooah and Sean Meyn, "How demand response from commercial buildings can provide the regulation needs of the grid", 50th Allerton Conference on Communication, Control, and Computing, 2012
- [Kirschen 2003] Kirschen D. S. "Demand-Side View of Electricity Markets", IEEE TPS 2003

- [James-Smith and Togeby 2007] E. James-Smith and M. Togeby "Security of Supply for Bornholm", Ea Energy Analyses report, www.eaea.dk, 2007
- [Kirschen et al 2000] Daniel S. Kirschen, Goran Strbac, Pariya Cumperayot, and Dilemar de Paiva Mendes "Factoring the Elasticity of Demand in ElectricityPrices"
- [le Boudec and Thiran 2001] Le Boudec J.Y. and Thiran P.,*Network Calculus*, Springer Verlag, 2001
- [Le Boudec and Tomozei 2011] Le Boudec, J.-Y.; Tomozei, D.-C., "Demand response using service curves" ISGT Europe 2011
- [Le Boudec and Tomozei 2013] Le Boudec, J.-Y.; Tomozei, D.-C., "Stability of a Stochastic Model for Demand-Response", Stochastic Systems, vol. 3, 2013
- [Molina-Garcia 2011] Molina-García, Angel, François Bouffard, and Daniel S. Kirschen. "Decentralized demand-side contribution to primary frequency control." *Power Systems, IEEE Transactions on* 26.1 (2011): 411-419.
- [McKay 2008] McKay, D. *Sustainable Energy-without the hot air*, UIT Cambridge,2008
- [Milborrow 2009] David Milborrow, "Managing Variability", 24 June 2009, A report to WWF-UK, RSPB, Greenpeace UK and Friends of the Earth EWNI)
- [Saele and Grande 2011] H. Saele and Ove S. Grande "Demand Response From Household Customers: Experiences From a Pilot Study in Norway", IEEE TSG 2011
- [Sundstrom et al 2012] Sundstrom, O.; Binding, C.; Gantenbein, D.; Berner, D.; Rumsch, W.-C., "Aggregating the flexibility provided by domestic hot-water boilers to offer tertiary regulation power in Switzerland", ISGT Europe 2012
- [Sundstrom and Binding 2012] Sundstrom, O. and Binding, C. "Flexible Charging Optimization for Electric Vehicles Considering Distribution Grid Constraints", IEEE TSG, 2012