Demand Response Management (DRM)

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Learning Objectives

Throughout this lecture, it is aimed for the students to be able to

- **Learn the basic concepts in Demand Response Management (DRM)**
- **Learn different pricing schemes in smart grid**
- **Understand the energy scheduling problem formulation for a home energy management system, solution, tool and applications related to demand response**

Industry Invited Talk Today

- **Speaker**: **Kari Dalen, *Seniorrådgiver, System- og balansetjeneste, Statnett***

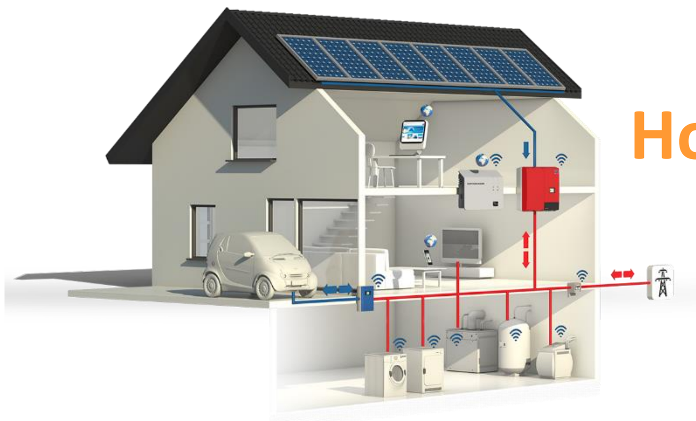
- **Title**: **Demand Response: industrial perspective**

- **Statnett**: **Statnett is Norway's national main grid owner and operator**

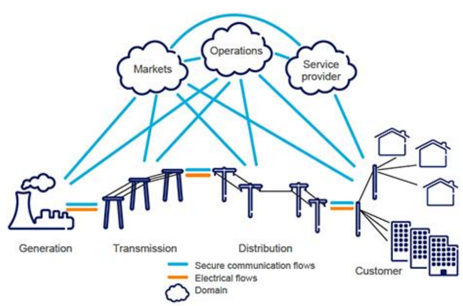
Statnett

Outline

Definition and Key Concepts

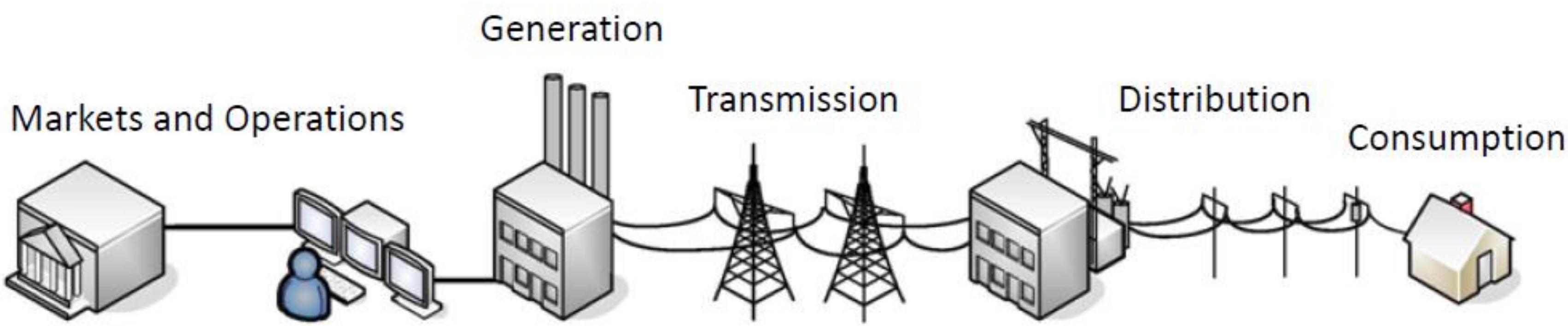


Home Energy Management



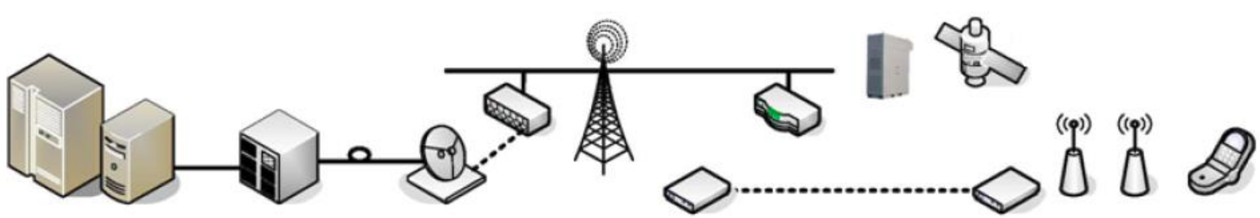
Communication perspective and examples

Smart Grid = Power Grid + ICT (Information & Communications Technology)



Power infrastructure

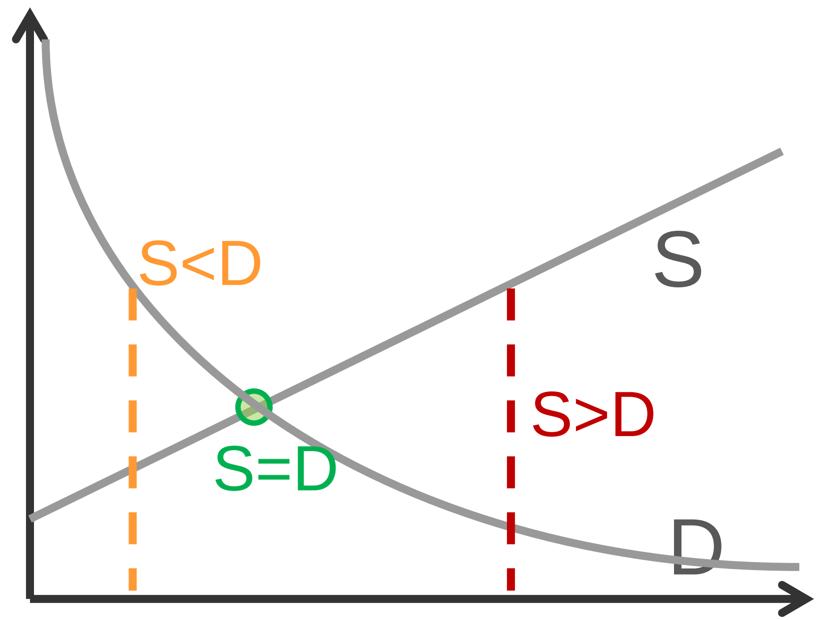
Two way flow of electricity and data



Communications infrastructure

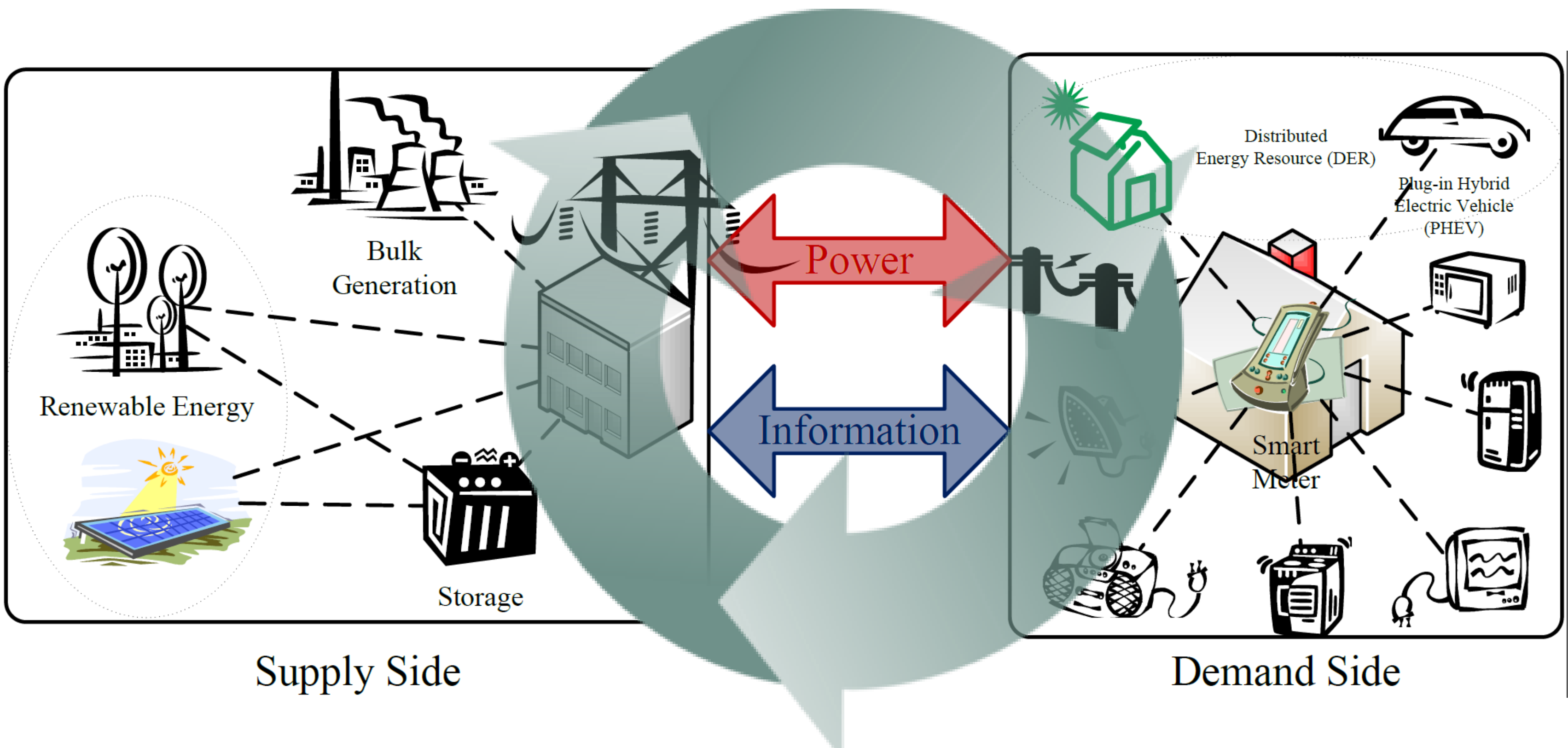
Energy balance: power generation is equal to power demand

- **S: power supply from generators**
- **D: power demand from customers**
- **Energy balance point: S=D**
- **Energy balance is very important for energy systems stability and economy -Q: why?**



- **If S>D, power generation is too much, generators have financial loss**
- **If S<D, power generation is not sufficient, power blackout may happen**

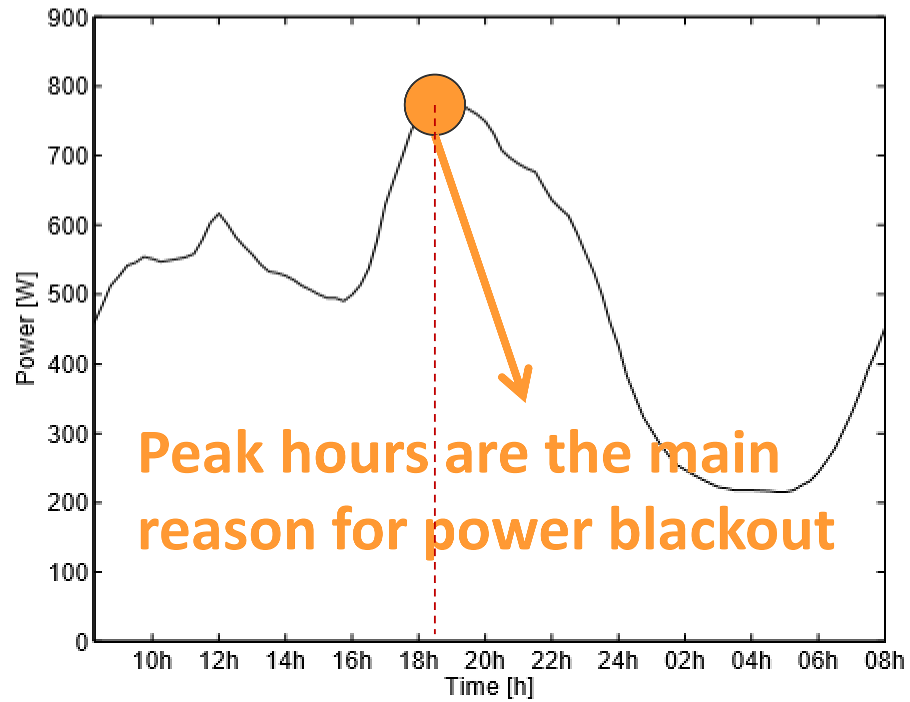
Demand Response Management (DRM) is the main approach to achieve energy balance



DRM studies the interaction between the supply and the demand sides by two-way flows of power and information.

A typical residential household load during winter

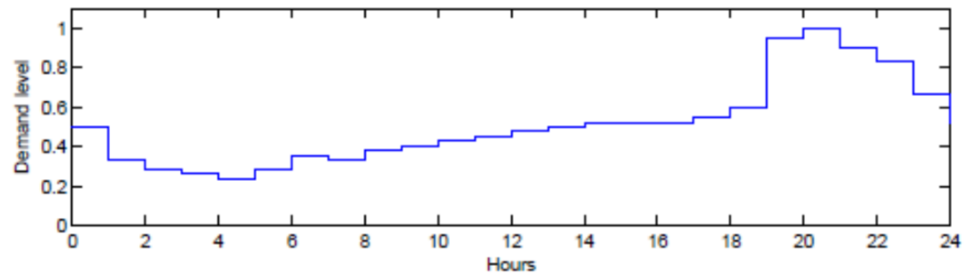
- **The power load may significantly vary over time and location**
- **The practical load profile is very unbalanced**
  - **Residential peak load (late afternoon)**
  - **Industrial peak load (morning)**



Household load in winter (source: www.vreg.be)

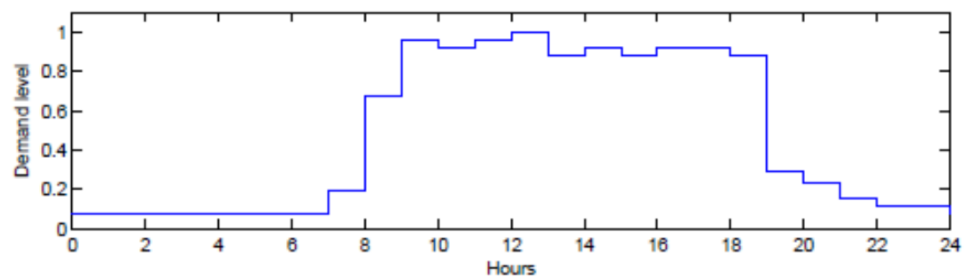
Different users have different power demand load

- **Residential users**



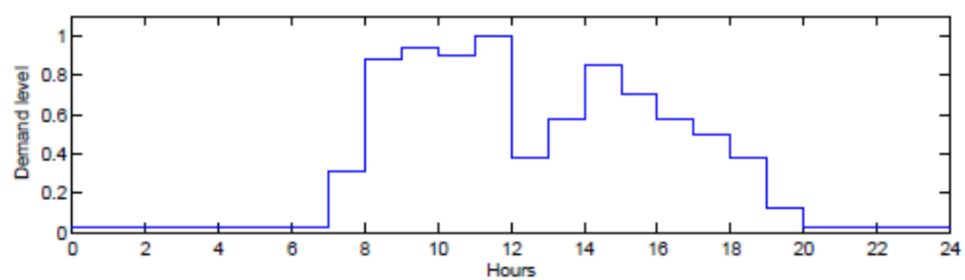
(a) Residential load.

- **Commercial users (e.g., shopping mall)**



(b) Commercial load.

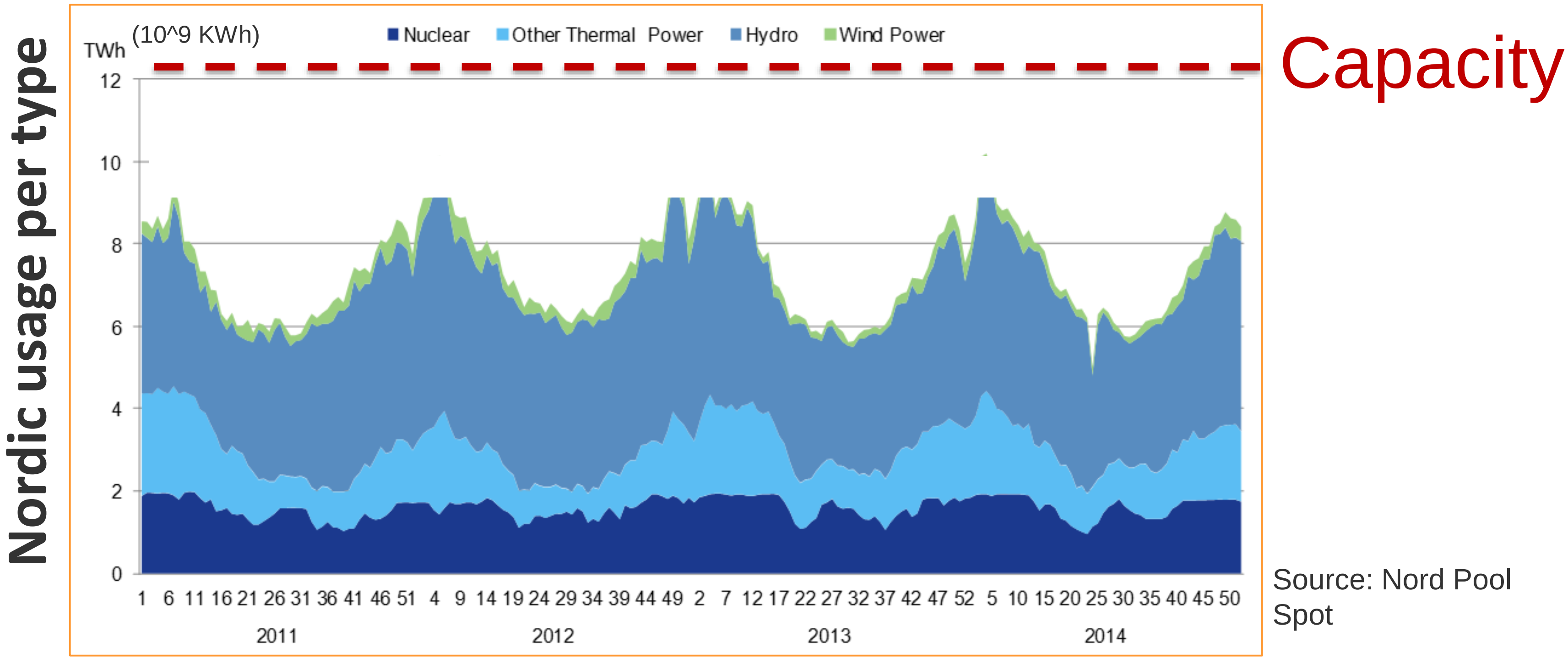
- **Industrial users (e.g., factory)**



(c) Industrial load.

- **Q: still remember the main difference between these curves?**

The peak load issue



Source: Nord Pool Spot

- **Power infrastructure is designed for peak loads.**
- **Peaks have less than 1% of the time. Reducing peaks can then reduce power generation and save a lot of money**

Demand Response Management (DRM) definition

- **According to the US. Department of Energy**

  Demand Response Management (DRM) is defined as changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

- **In plain language**
  - **Users will change energy usage behaviors according to different electricity prices, or incentive payments, or system reliability**

- **Q: can DRM help reduce peak load?**

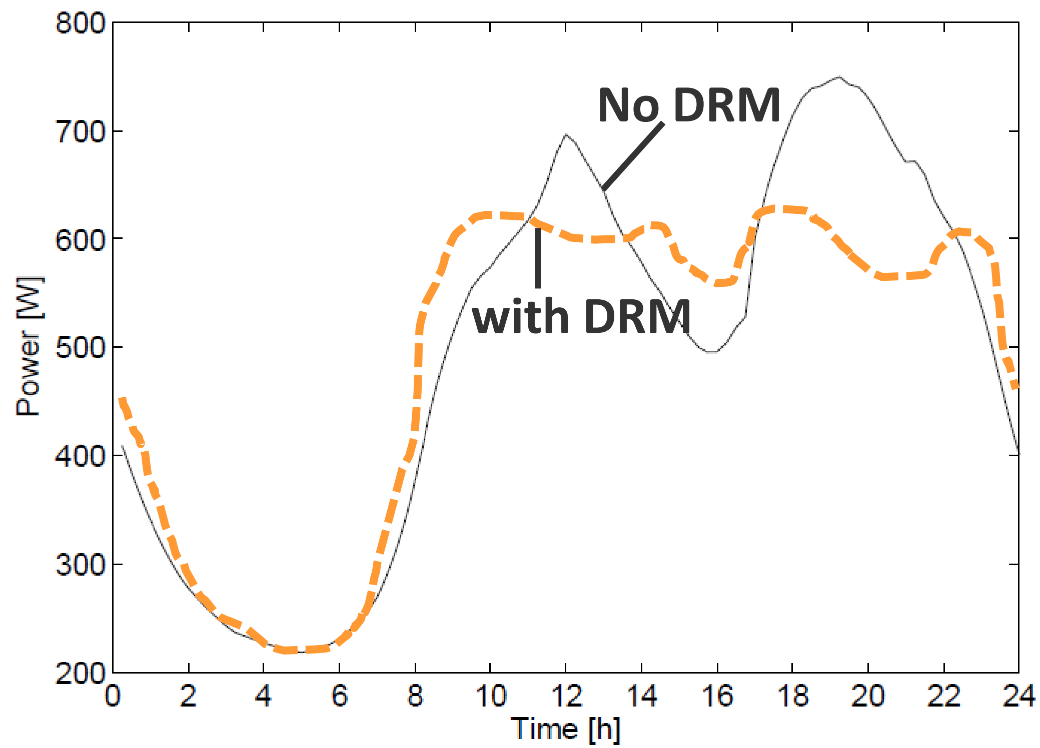
DRM two objectives

Reduce energy consumption

- **encourage energy-aware consumption patterns**
- **Reduce power generation**

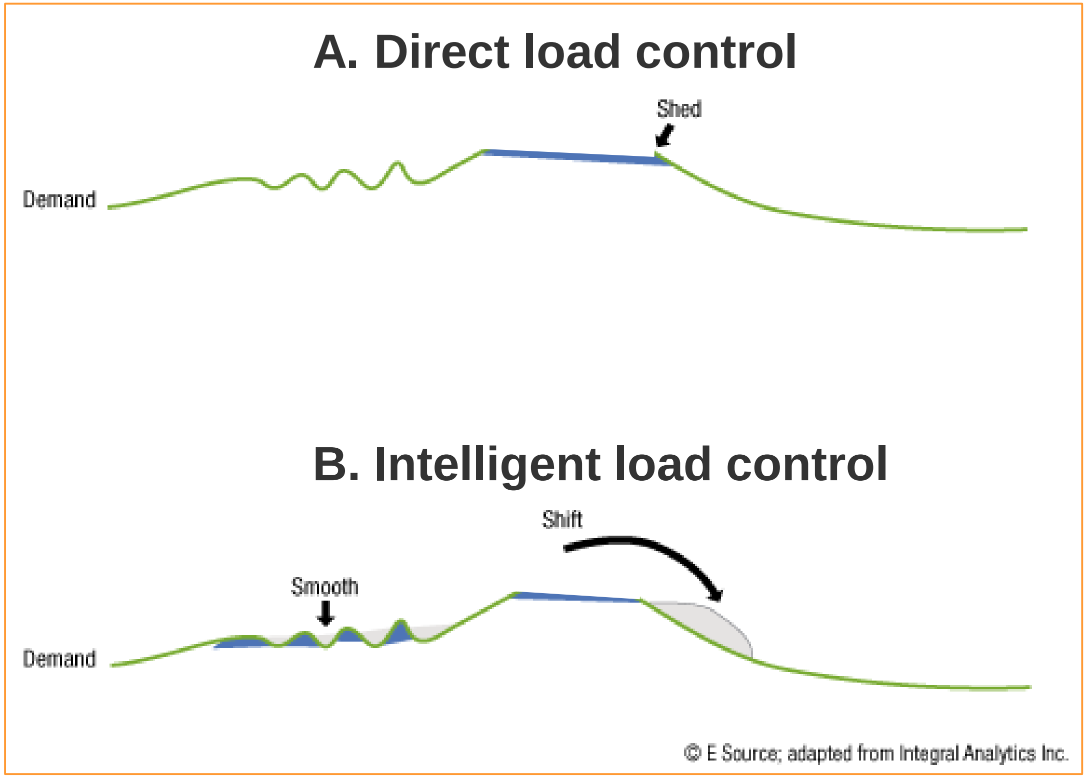
Shift the energy consumption

- **Mitigate power load during the peak hours**
- **Improve grid reliability**



Two approaches to DRM

- **Direct Load Control (DLC)**
- **Intelligent Load Control / Pricing**



Q: What is the difference between these two approaches?

Direct Load Control (DLC)

- **The utility has remote access to certain load of users**
  - **Air conditioner**
  - **Water heater**
- **The utility can remotely turn on or off the load when needed**
- **DLC should be transparent to users. (Q: Why?)**

Direct Load Control example – Energex in Queensland, Australia

- **New device**: a signal receiver is installed in a air-conditioner. The utility can remotely turn on or off the load; or cap energy consumption when needed
- **Reward**: participants are rewarded by up to $400
- **Result**: (1) be transparent to users (**Q**: Why?); (2) reduce peak

You may watch 2-minute video at: https://youtu.be/fQQYNMofG5w

Intelligent Load Control / Smart Pricing

- **Price-based program provides users with different prices at different times**
- **When users know about the price changes**
  - **They will naturally use less electricity when electricity prices are high**
  - **This will reduce the demand at peak hours**
- **This program indirectly induces users to dynamically change their energy usage patterns according to the variance of electricity prices, instead of directly controlling their loads.**
- **Three pricing models: Time-of-Using (ToU) pricing; Real-time Pricing (RTP); and Inclining Block Rates (IBR)**

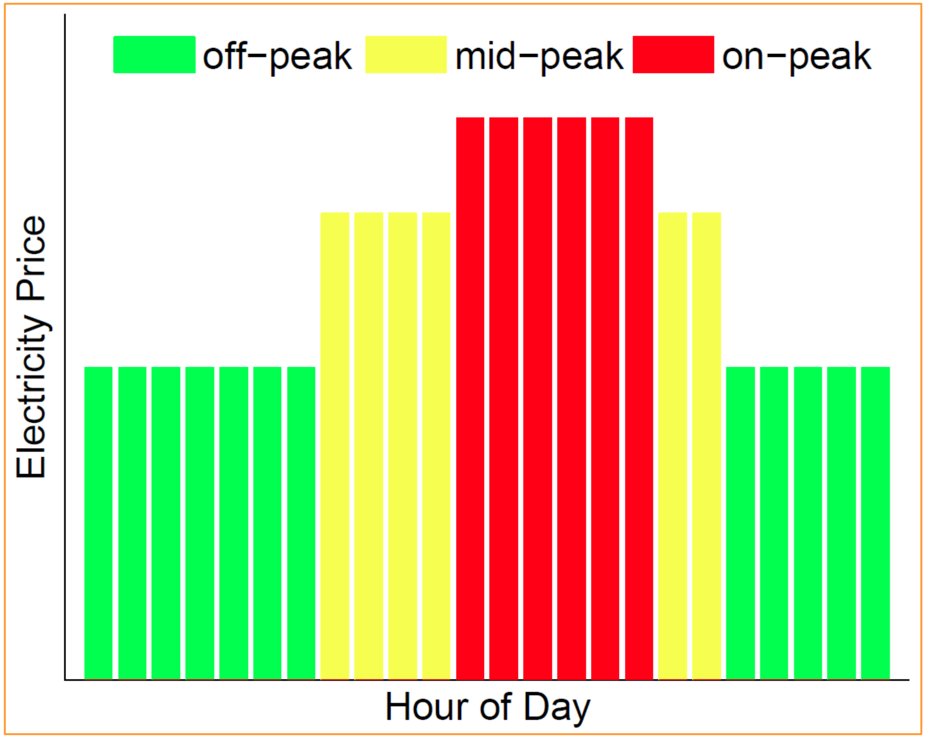
Time-of-Use (ToU) Pricing

- When users consume energy at different time intervals of a day, they are charged at different electricity prices

- ToU pricing is usually released far in advance, and keeps unchanged for a long time period.

Examples

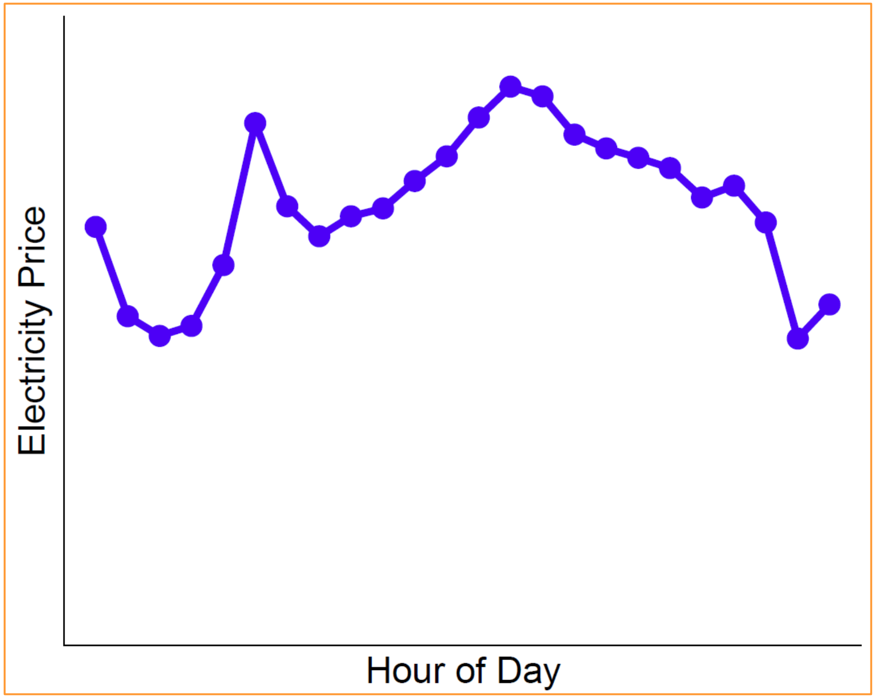
- Ontario, Canada
- Ausgrid (Australia)



Three-level (on-peak, mid-peak, off-peak) ToU pricing

Real-Time Pricing (RTP)

- **The electricity price usually varies at different time intervals of a day (e.g., in each hours)**
- **RTP is usually released on an hour-ahead pricing or day-ahead pricing basis**

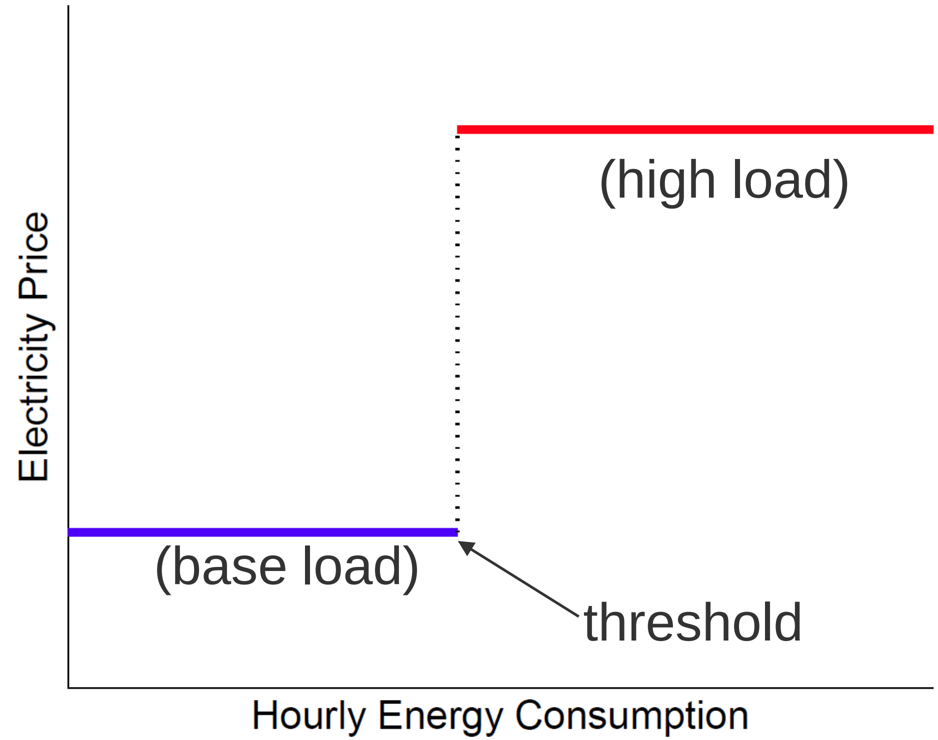


Examples

- **Chicago uses hourly-based RTP**
- **In Oslo, you may have RTP from Sognekraft AS in the name of "Innkjøpspris" plan (source: http://www.strompris.no)**

Inclining Block Rates (IBR)

- Two-level rate structures
  - base load and high load
  - Price increases sharply if energy usage exceeds threshold
- Motivations
  - A user pays more when consuming more energy
  - Users evenly distribute loads among different times of a day to avoid higher rates



Adopted by Pacific Gas and Electric, USA; British Columbia Hydro, Canada

A few decades ago in Norway…

- **IBR looks like the tariff in Norway a few decades ago**
- **The high load price was referred to as «Overforbruk». Every home had a meter showing the current load and a «overforbruk» marker.**

- **This ensured that Norwegian families did not use too much power. Light started flashing when it was used too much electricity. The power to the house was cut if they spent too much power.**
- **<<Overforbruk>> acted as a switch that turned off the power, and then you have to turn off the ceiling lights or stove to reduce power consumption so that the power came back.**

Now, Electricity Pricing in Oslo (source: http://www.strompris.no)

Fixed Price (e.g., Helgeland Kraft AS)

A fixed price for an agreed period of time, normally one year. In exchange you cannot change supplier within the period

Variable Price (e.g., FjordKraft AS)

Price will be as offered for the next 2-3 weeks. Maybe changed, normally with 2 weeks notice.

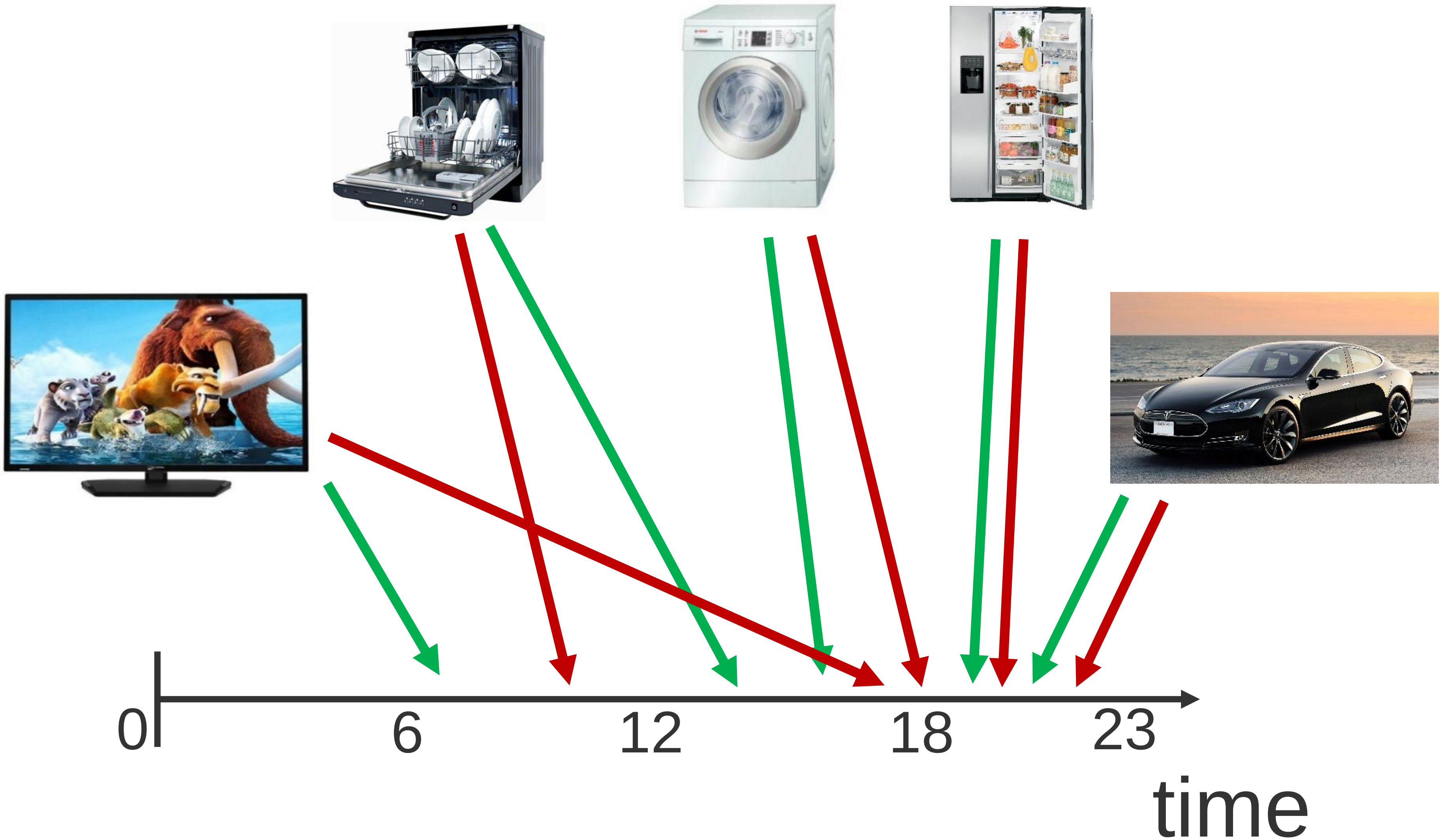
Purchase Price (e.g., Sognekraft AS)

Price follows **the hourly prices** at the electricity exchange Nord Pool Spot

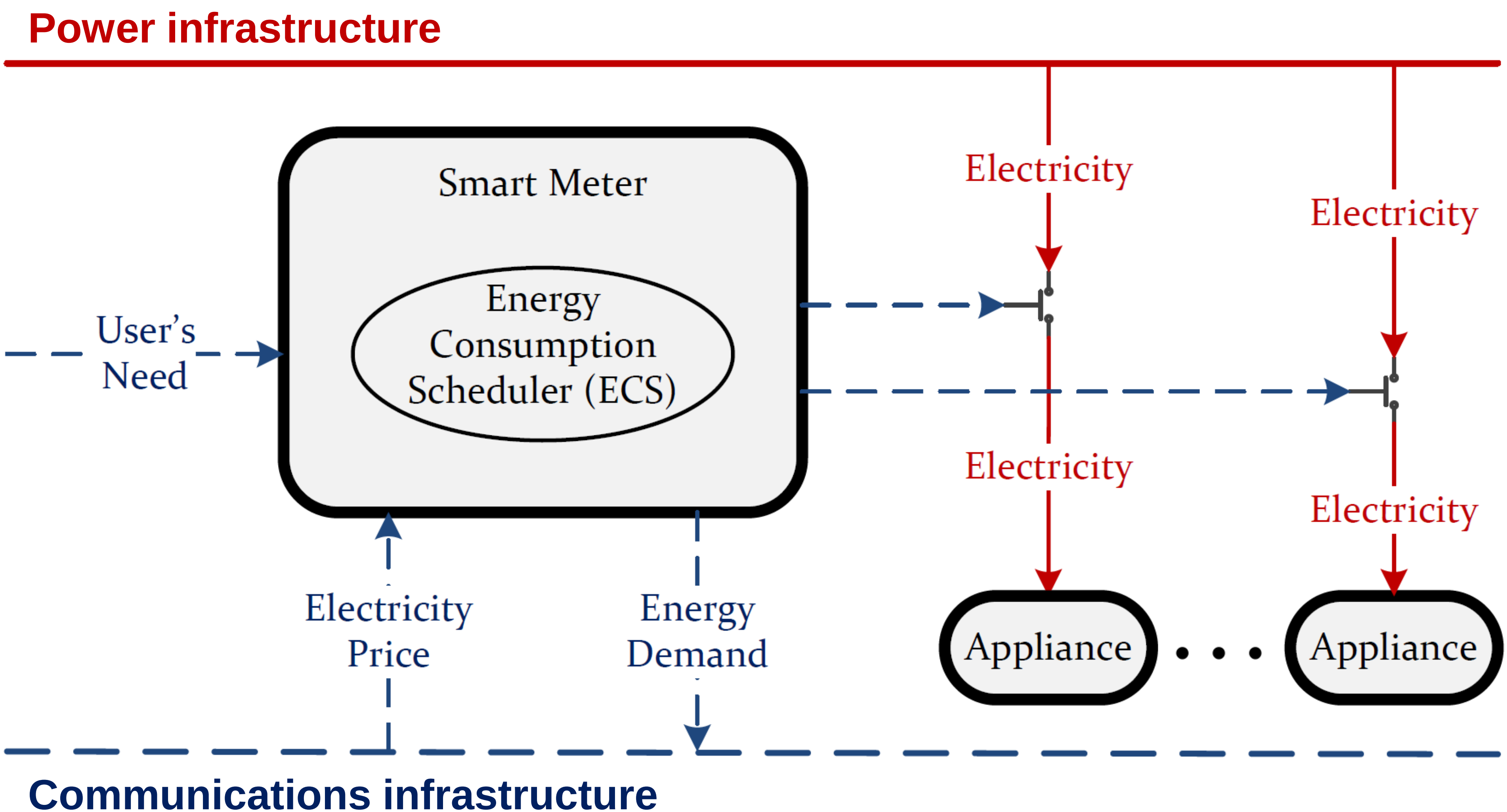
➔ Similar as **real-time pricing**

HOME ENERGY MANAGEMENT SYSTEM

When shall we use appliances/devices at home?

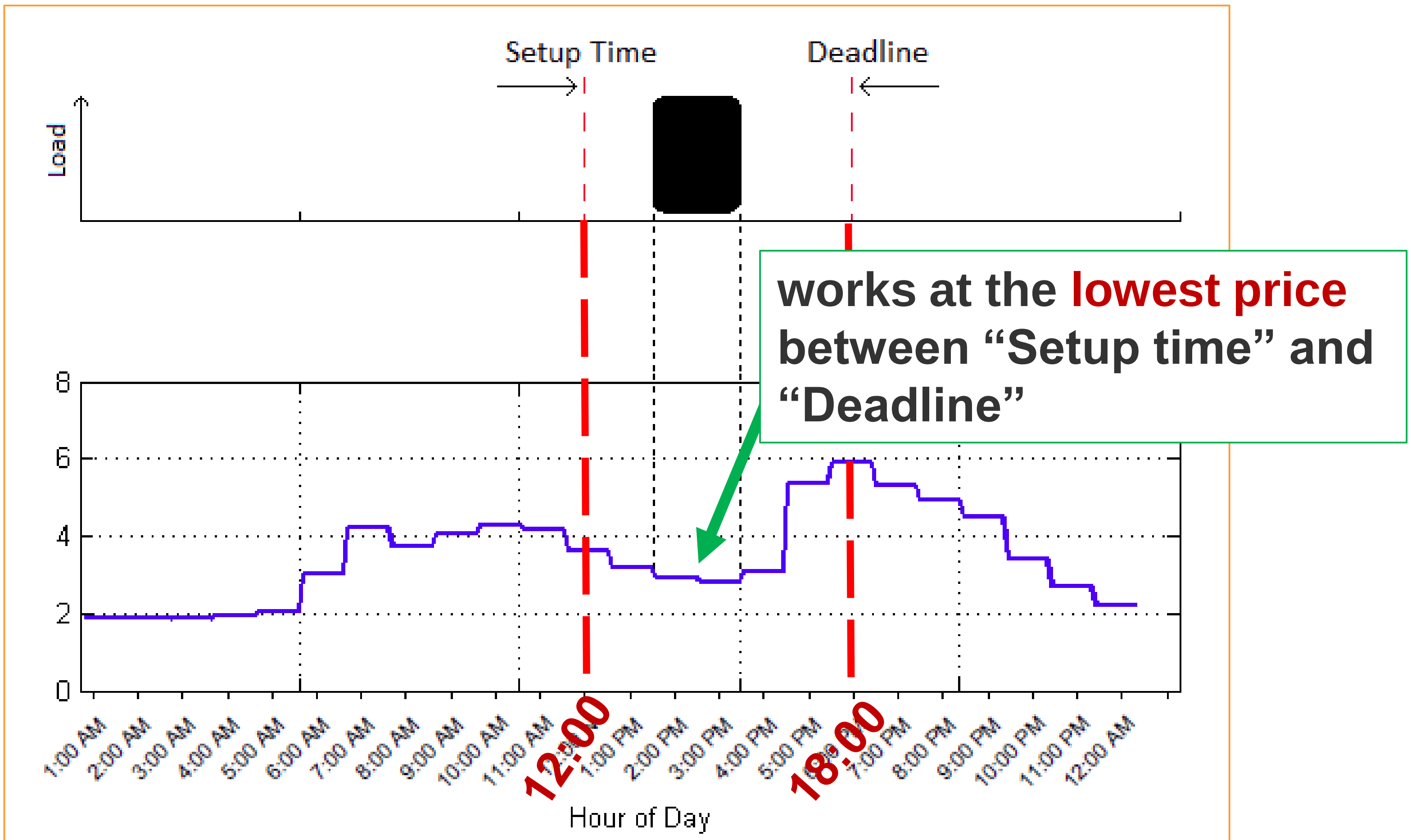


In a house, a smart meter can automatically coordinate appliances to satisfy the user's need via ON/OFF control



Energy Consumption Scheduling

- **A simple example: dishwasher after lunch (Q: why choose time period between 1:30-3:30pm?)**



Energy Consumption Scheduling is actually not simple since we have many different appliances

- **Non-shiftable appliances** (e.g., TV, lights, cooking): must be kept ON for a certain period of time.

- **Shiftable appliances** (e.g., washing machines, Electric Vehicles, and clothes dryers): the operation task can be shifted to a different time period

- **Q:** which type of appliances?

refrigerator

dishwashers

fire alarm

Energy Consumption Scheduling problem

- **Q: Given the price values, how should we schedule the power load?**
- **Scheduler should analyze**
  - **User's energy consumption needs**
  - **Price values**
- **The schedule is normally an optimal solution with different preferences**
  - **Minimize the cost of electricity**
  - **Maximize user's comfort**

tradeoff

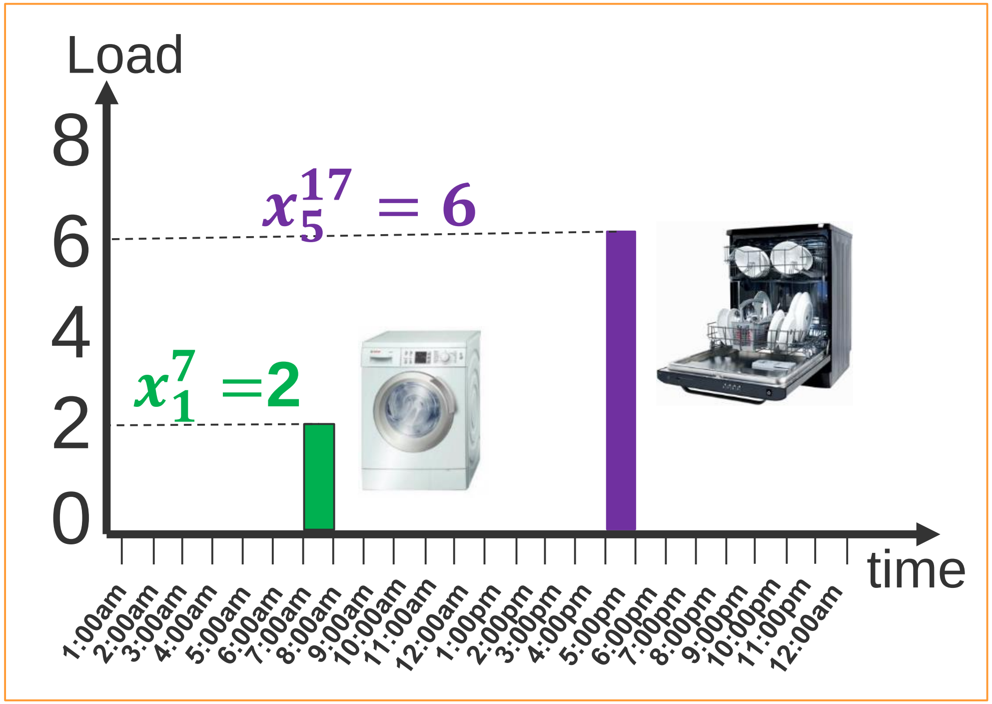
Energy Consumption Scheduling – parameters

- **Let A denote the set of appliances**
  - **Washing machines, TV, lights, Dryer, Dishwasher, EVs (Electric Vehicle)…**

- **For each appliance $a \in A$, we define a daily energy consumption scheduling vector x_a as follows:**

$$x_a = [x_a^1, \cdots, x_a^H]$$

  - **where $H = 24$ hours**

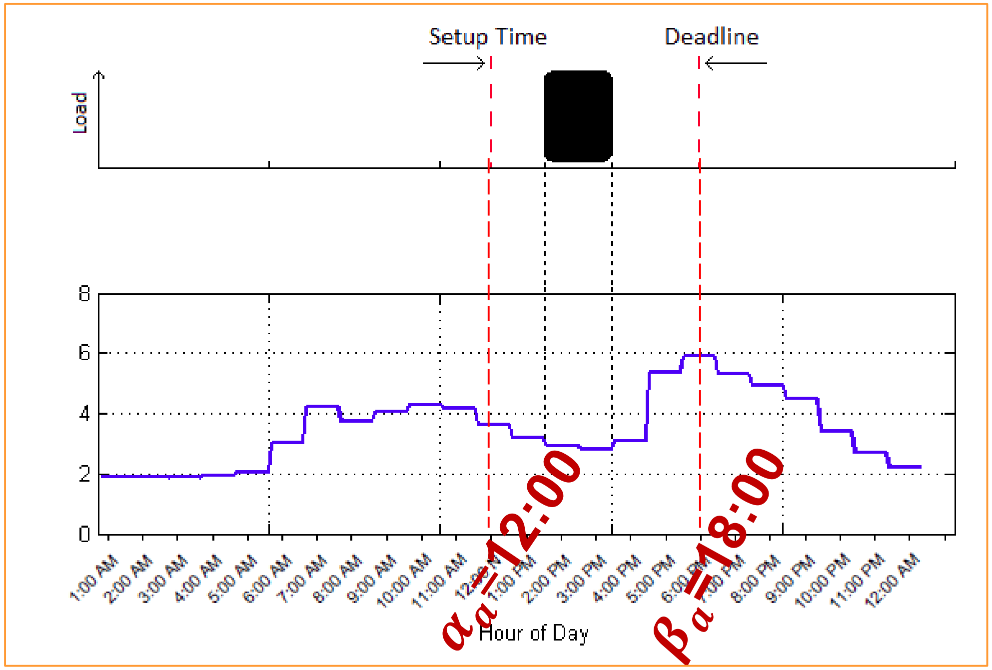


Energy Consumption Scheduling – operation time constraint

- **For each appliance $a \in A$, the user should indicate:**
  - **α_a: beginning of the operation time (setup time)**
  - **β_a: end of the operation time (deadline)**
- **Operation should be scheduled within $[\alpha_a, \beta_a]$**

Example

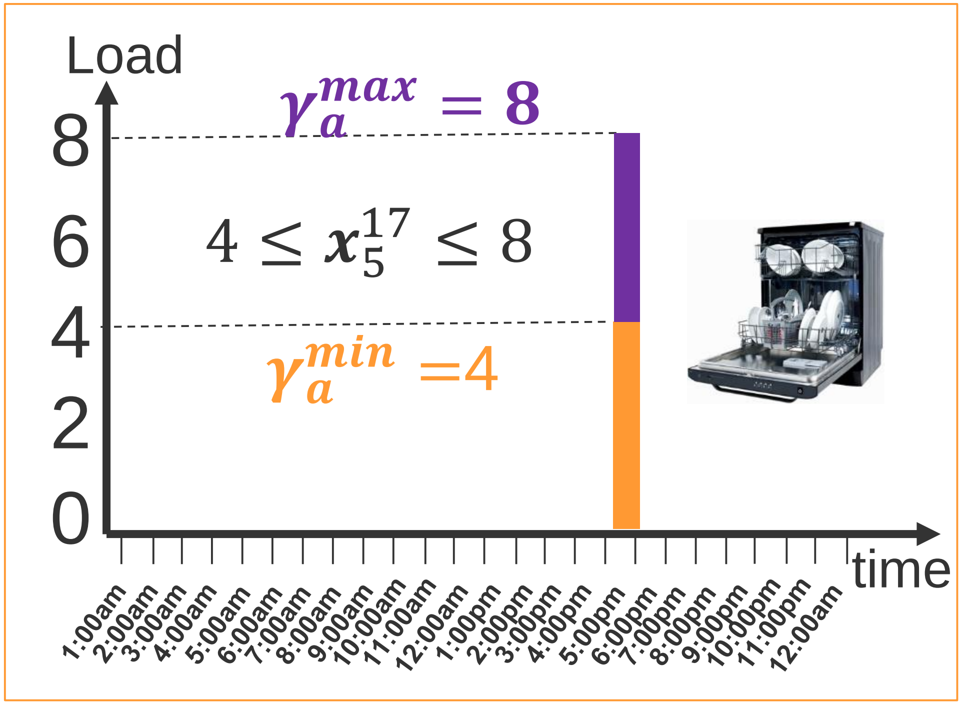
- **Dish washer after lunch: setup time α_a= 12 Noon and deadline β_a= 6 PM (make dishes ready for dinner)**



Energy Consumption Scheduling – power level constraint

- **Each appliance $a \in A$ usually has a maximum power level γ_a^{max}**
  - **NISSAN Leaf: charged up to 3.6 kW per hour**
- **Each appliance $a \in A$ may also have a minimum power level γ_a^{min}**
- **For each appliance $a \in A$, it is required that**

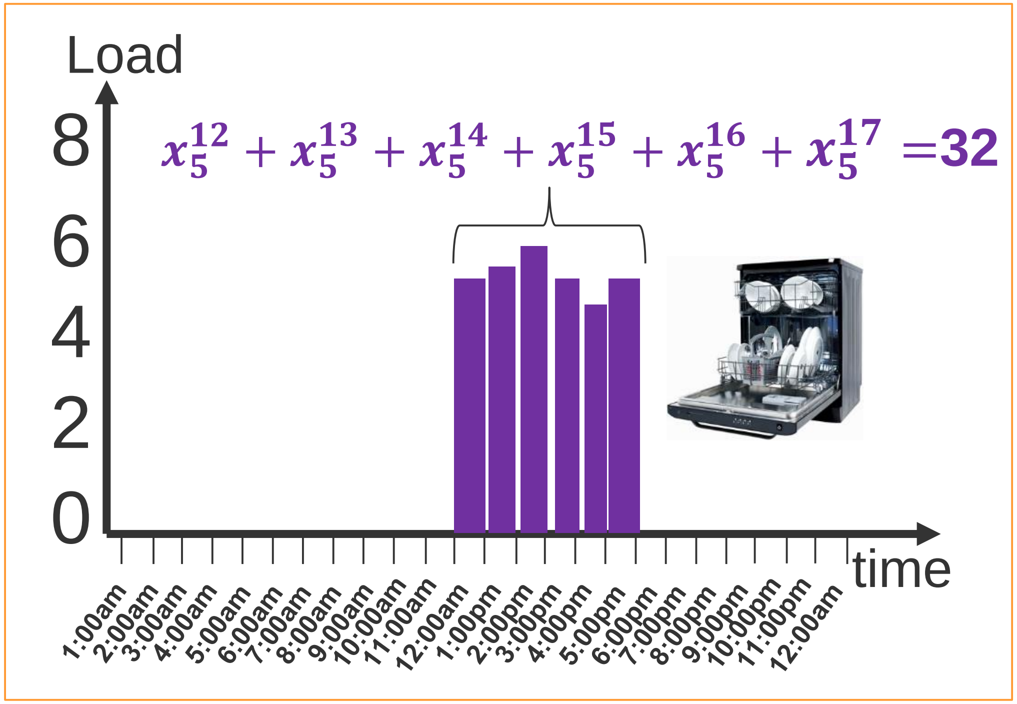
$$\gamma_a^{min} \leq x_a^h \leq \gamma_a^{max}$$
$$\forall a \in A, h \in [\alpha_a, \beta_a]$$



Energy Consumption Scheduling – total energy constraint

- **Let E_a denote the total energy needed for the operation of appliance $a \in A$**
  - **Bosch WAS20160UC washing machine: E_a = 0.36 kWh per load**
- **Given parameters E_a, α_a, and β_a, it is required that**

$$\sum_{h=\alpha_a}^{\beta_a} x_a^h = E_a, \quad a \in A.$$



Cost Minimization

- **Energy Consumption Scheduling problem to minimize cost:**

$$\min_{\boldsymbol{x}} \sum_{h=1}^{H} p^{h} \times \left(\sum_{a \in A} x_a^h \right)$$

Load from all appliances in hour *h*

Subject to

$$\sum_{h=\alpha_a}^{\beta_a} x_a^h = E_a, \qquad \forall a \in A,$$

$$\gamma_n^{\min} \le x_a^h \le \gamma_n^{\max}, \qquad \forall a \in A, h \in [\alpha_a, \beta_a]$$

$$x_a^h = 0, \qquad \forall a \in A, h \notin [\alpha_a, \beta_a]$$

  – **where p^h denote the price of electricity at hour *h*. Could be ToU or RTP model**

- **Q: Is this a linear programming optimization problem?**

Optimization Basics

- **Optimization in standard form**

$$\begin{array}{lll} \text{minimize} & f_0(x) & \\ \text{subject to} & f_i(x) \le b_i, & i = 1, \ldots, m \end{array}$$

objective function

constraints functions

- $x = (x_1, x_2, \cdots x_n)$**: optimization variables**
- **Optimal solution:** x^* **has smallest value of** f_0 **among all vectors that satisfy the constraints**

Linear Programming Basics

$$\textbf{minimize} \quad f^T x$$
$$\textbf{subject to} \quad Ax \le b$$

where $f = (f_1, f_2, \cdots, f_n)$; $b = (b_1, b_2, \cdots, b_n)$; **A=** $\begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & & a_{1,n} \\ \vdots & & \ddots & \vdots \\ a_{m,1} & a_{m,1} & \cdots & a_{m,n} \end{pmatrix}$

- **Matlab linprog function solves linear programming optimization problem**

$$\min_x f^T x \text{ such that } \begin{cases} A \cdot x \le b, \\ Aeq \cdot x = beq, \\ lb \le x \le ub. \end{cases}$$

$A \cdot x \le b$ → inequality constraint

$Aeq \cdot x = beq$ → equality constraint

$lb \le x \le ub$ → bound constraint

→ x = linprog(f,A,b,Aeq,beq,lb,ub)

For more information: http://se.mathworks.com/discovery/linear-programming.html

Other Programming Languages

- Free software environment for statistical computing. https://www.r-project.org/
- Several solvers available for solving linear programming models. A list can be found in http://bit.ly/1zkJpVw.
- Of particular interest: lp_solve is implemented through the lpSolve and lpSolveAPI packages.
- More information: Google "linear programming with R"

- You can use package scipy.optimize.linprog
- An easy and good example: http://www.vision.ime.usp.br/~igor/articles/optimization-linprog.html
- More information: Google "linear programming with Python"

Demand Response Example: two appliances at a home

Assumption:

- **two appliances: EV and washing machine**
- **we assume that we have 4 hours per day**

Now, we need to decide:

- **for EV, how much energy should be used in each timeslot**
- **for washing machine, how much energy should be used in each timeslot**

Demand Response Example: two appliances at a home

We define

- **x_i ($i=1,2,3,4$): amount of energy be used for EV in hour i**
- **y_i ($i=1,2,3,4$): amount of energy be used for washing machine in hour i**
- **p_i ($i=1,2,3,4$): price in each hour. Price is an input parameter**

We need to decide x_i and y_i to minimize the energy cost

- **x_i ($i=1,2,3,4$): amount of energy be used for EV in hour i**
- **y_i ($i=1,2,3,4$): amount of energy be used for washing machine in hour i**

Problem formulation

Cost minimization: p1 * x1 + p2 * x2 + p3 * x3 + p4 * x4 + p1 * y1 + p2 * y2 + p3 * y3 + p4 * y4

subject to

10 constraints

- x1 + x2 + x3 + x4 = 9.9 → **total energy consumption per day for EV**
- y1 + y2 + y3 + y4 = 5.0 → **total energy consumption per day for washing machine**
- x1 <= 3.0
- x2 < = 3.0
- x3 < = 3.0
- x4 < = 3.0

→ **max power usage per hour for EV**

- y1 <= 1.5
- y2 < = 1.5
- y3 < = 1.5
- y4 < = 1.5

→ **max power usage per hour for washing machine**

Programming in R (I)

```
p <- runif(4) #random function to generate price in each hour

f.obj <- c(p[1], p[2], p[3], p[4], p[1], p[2], p[3], p[4])

c1 <- c(1, 1, 1, 1, 0, 0, 0, 0)

c2 <- c(0, 0, 0, 0, 1, 1, 1, 1)

c3 <- c(1, 0, 0, 0, 0, 0, 0, 0)

c4 <- c(0, 1, 0, 0, 0, 0, 0, 0)

c5 <- c(0, 0, 1, 0, 0, 0, 0, 0)

c6 <- c(0, 0, 0, 1, 0, 0, 0, 0)

c7 <- c(0, 0, 0, 0, 1, 0, 0, 0)

c8 <- c(0, 0, 0, 0, 0, 1, 0, 0)

c9 <- c(0, 0, 0, 0, 0, 0, 1, 0)

c10 <- c(0, 0, 0, 0, 0, 0, 0, 1)

f.con <- matrix (c(c1, c2, c3, c4, c5, c6, c7, c8, c9, c10), nrow =
10, byrow=TRUE)
```

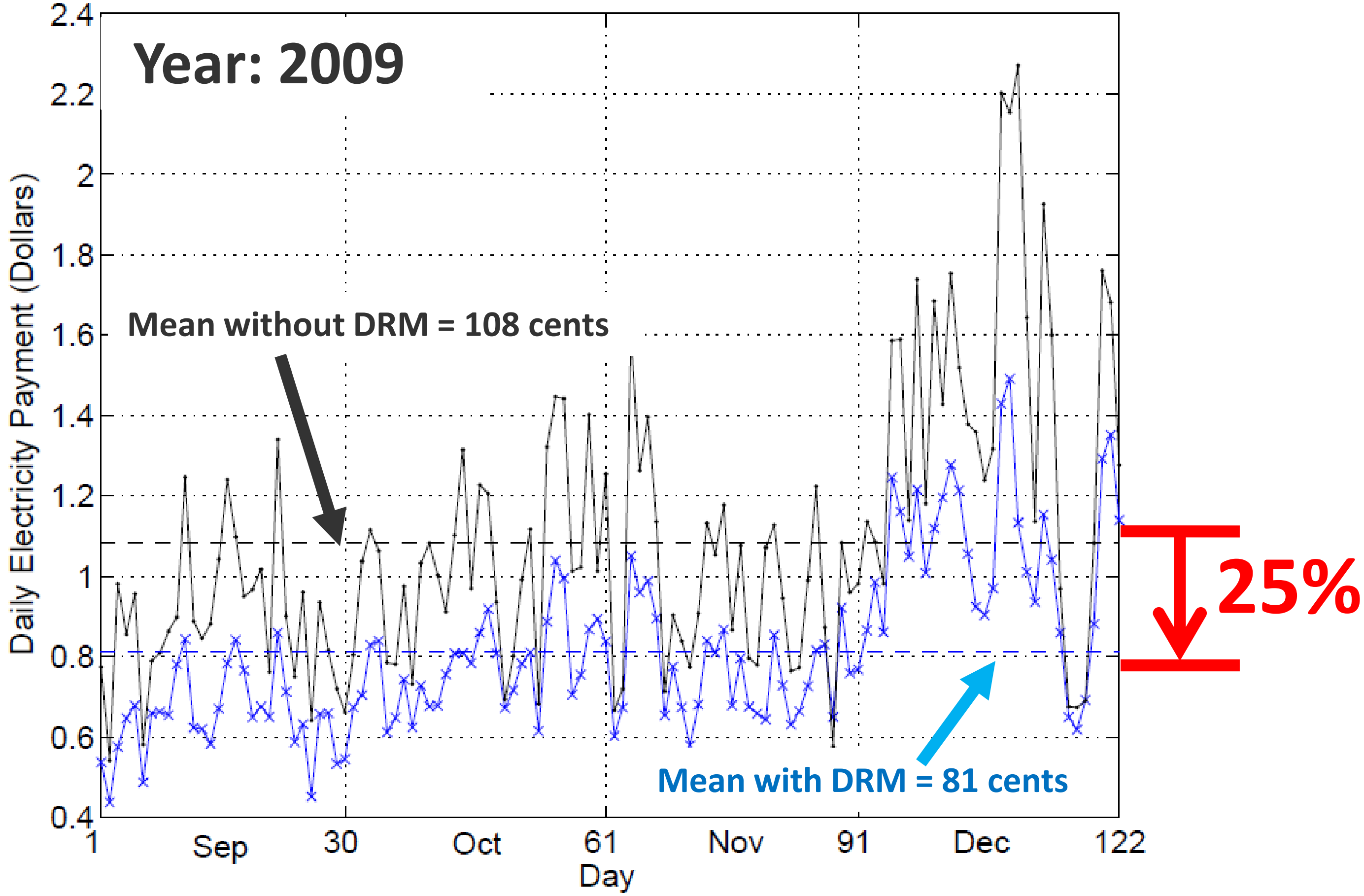
Programming in R (II)

```
f.dir <- c("=", "=", "<=", "<=", "<=", "<=", "<=",
"<=", "<=", "<=")

f.rhs <- c(9.9, 5.0, 3.0, 3.0, 3.0, 3.0, 1.5, 1.5, 1.5,
1.5)

# Now run.

lp ("min", f.obj, f.con, f.dir, f.rhs)

lp ("min", f.obj, f.con, f.dir, f.rhs)$solution
```

Output:

```
> lp ("min", f.obj, f.con, f.dir, f.rhs)
Success: the objective function is 8.079396
> lp ("min", f.obj, f.con, f.dir, f.rhs)$solution
[1] 3.0 3.0 3.0 0.9 1.5 1.5 1.5 0.5
> |
```

DRM reduces cost of electricity



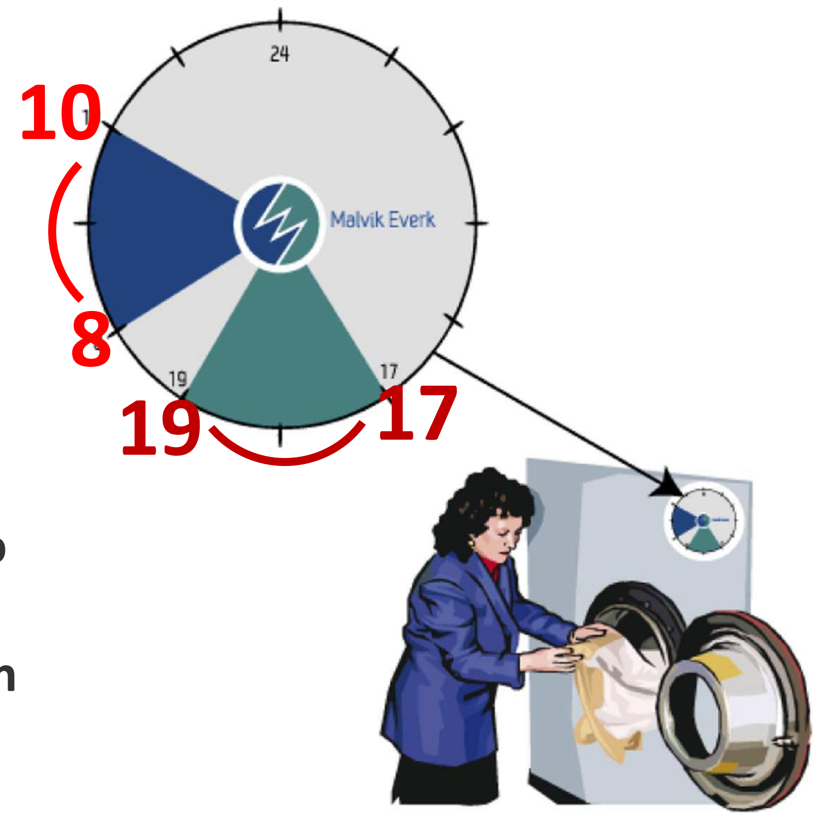
- **A household with varying number of appliances (10-25) at each day and it subscribes Real-Time Pricing (RTP)**

Demand Response Pilot Study – Norway (I)

- **Malvik Everk: Distribution Systems Operator (DSO) in Central-Norway**

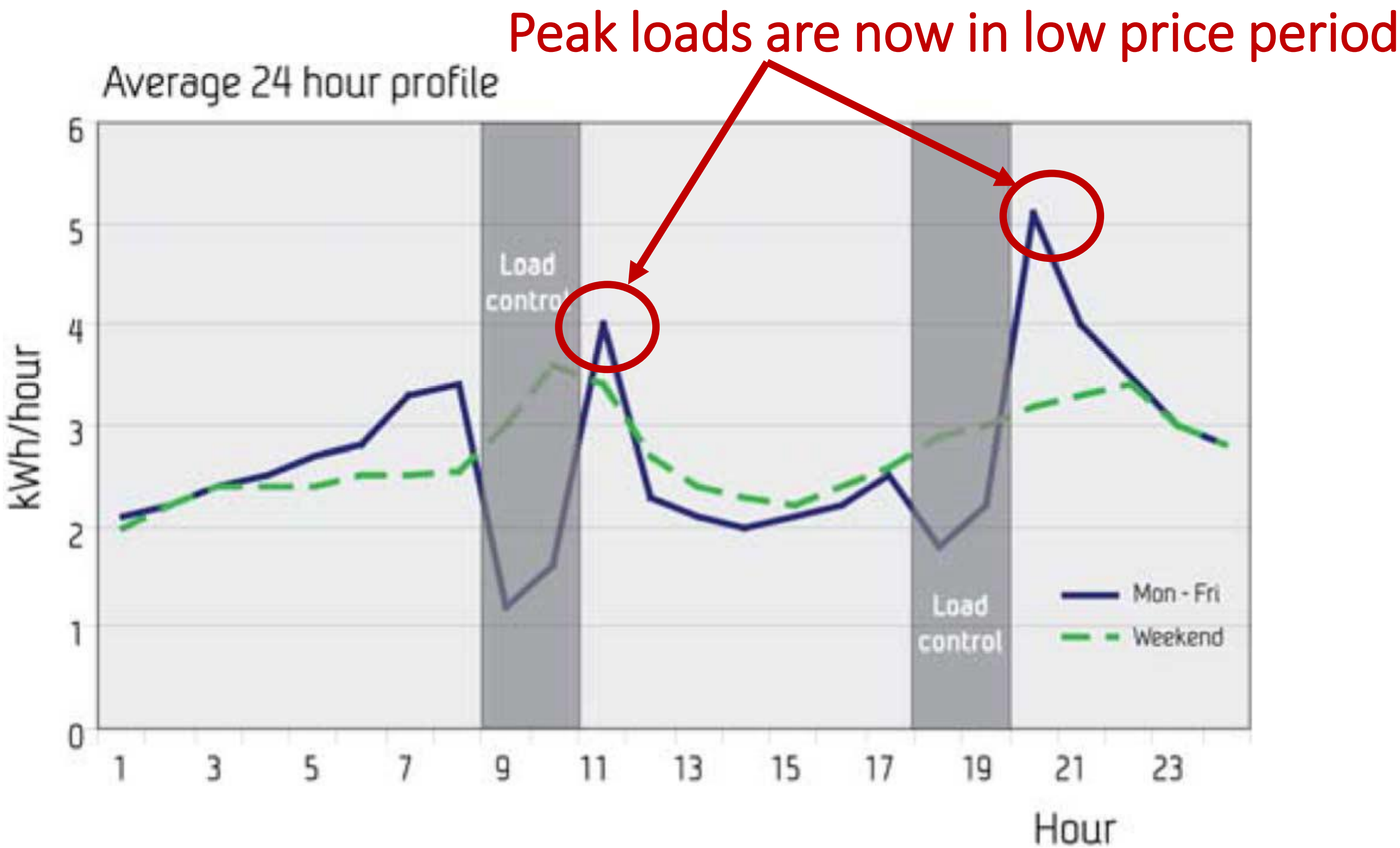
Pilot study:

- **One year study**
- **40 household customers are giving hourly metering of energy consumption**
- **Each household was equipped with the "El-buttons," to be placed on dishwashers, washing machines, etc., to remind the households to avoid usage of these energy consuming appliances in the predefined peak load periods.**



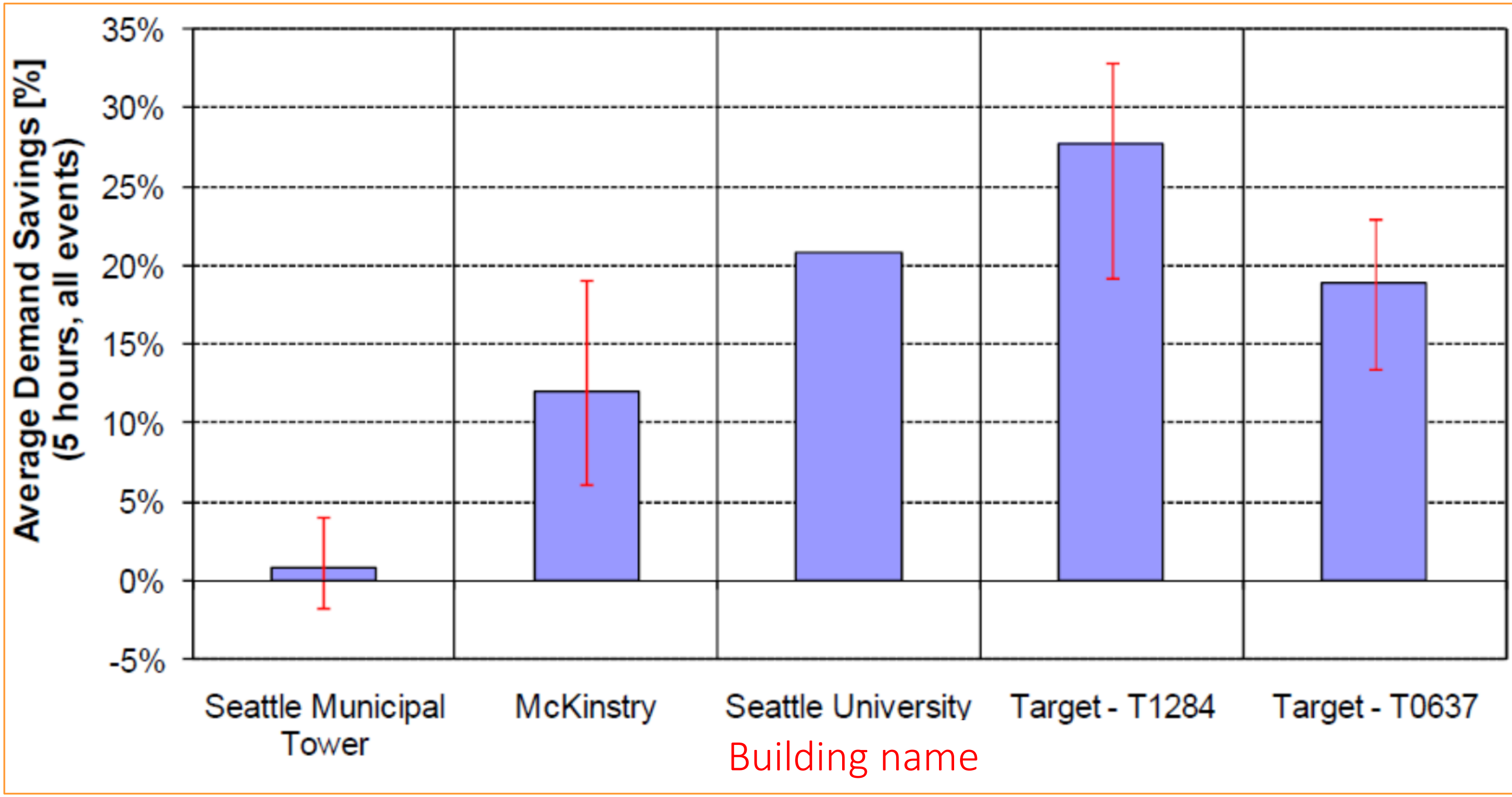
H. Sæle and O.S. Grande, *Demand response from household customers: experiences from a pilot study in Norway*, IEEE T. Smart Grids 2(1):90–97 (March 2011)

Demand Response Pilot Study – Norway (II)



- **Main observation**: **load shifting from peak periods to off-peak periods. This resulted in an economic benefit for the customers due to moving loads from hours with high prices to hours with lower prices.**

Demand Response Pilot Study - Seattle

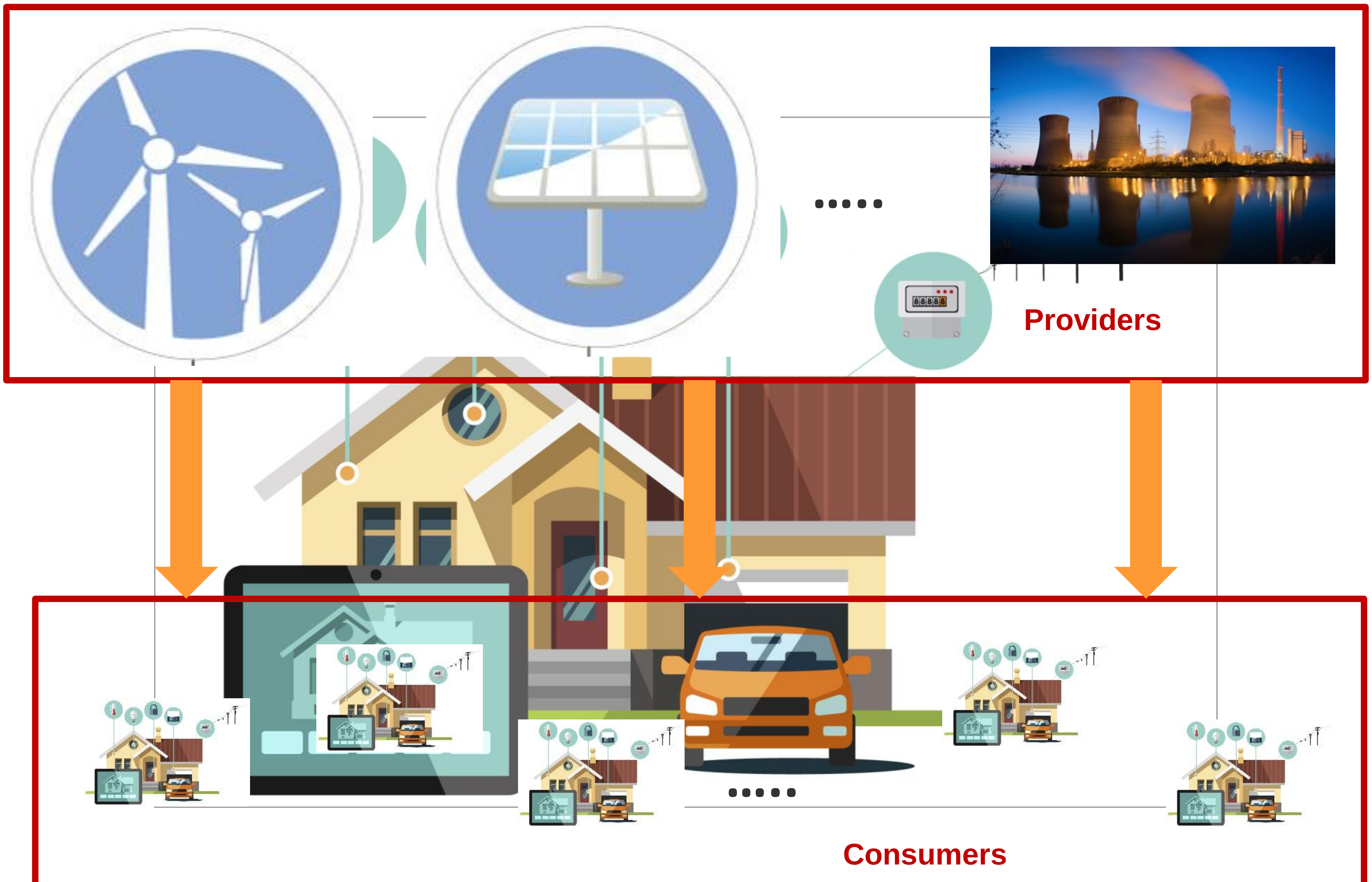


- **Power demand reduction at each building during summer after using demand response**

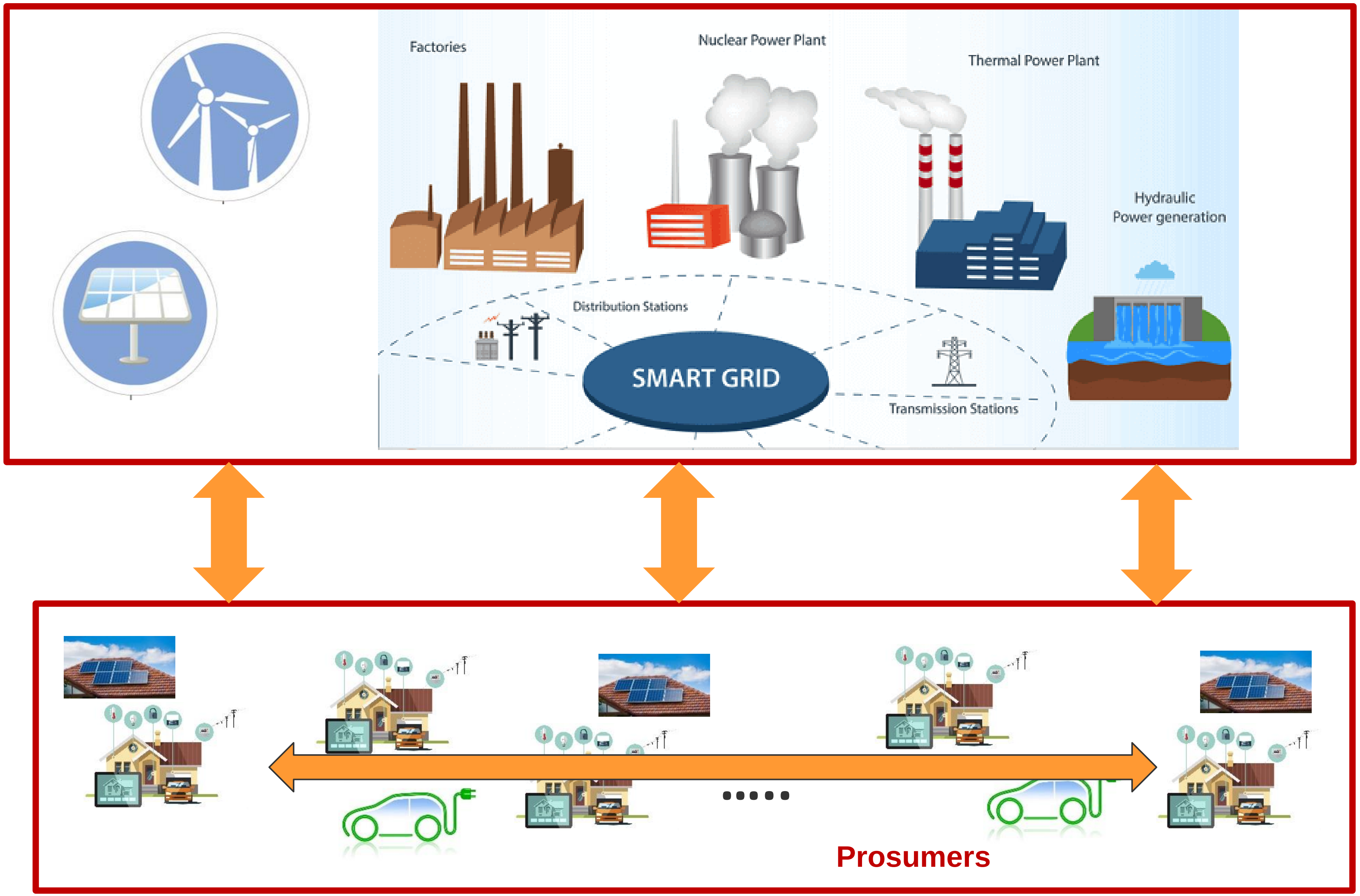
https://www.bpa.gov/EE/Technology/demand-response/Documents/2008-09_OpenADR_Pilot_Final_Report.pdf

MORE CONSIDERATIONS…

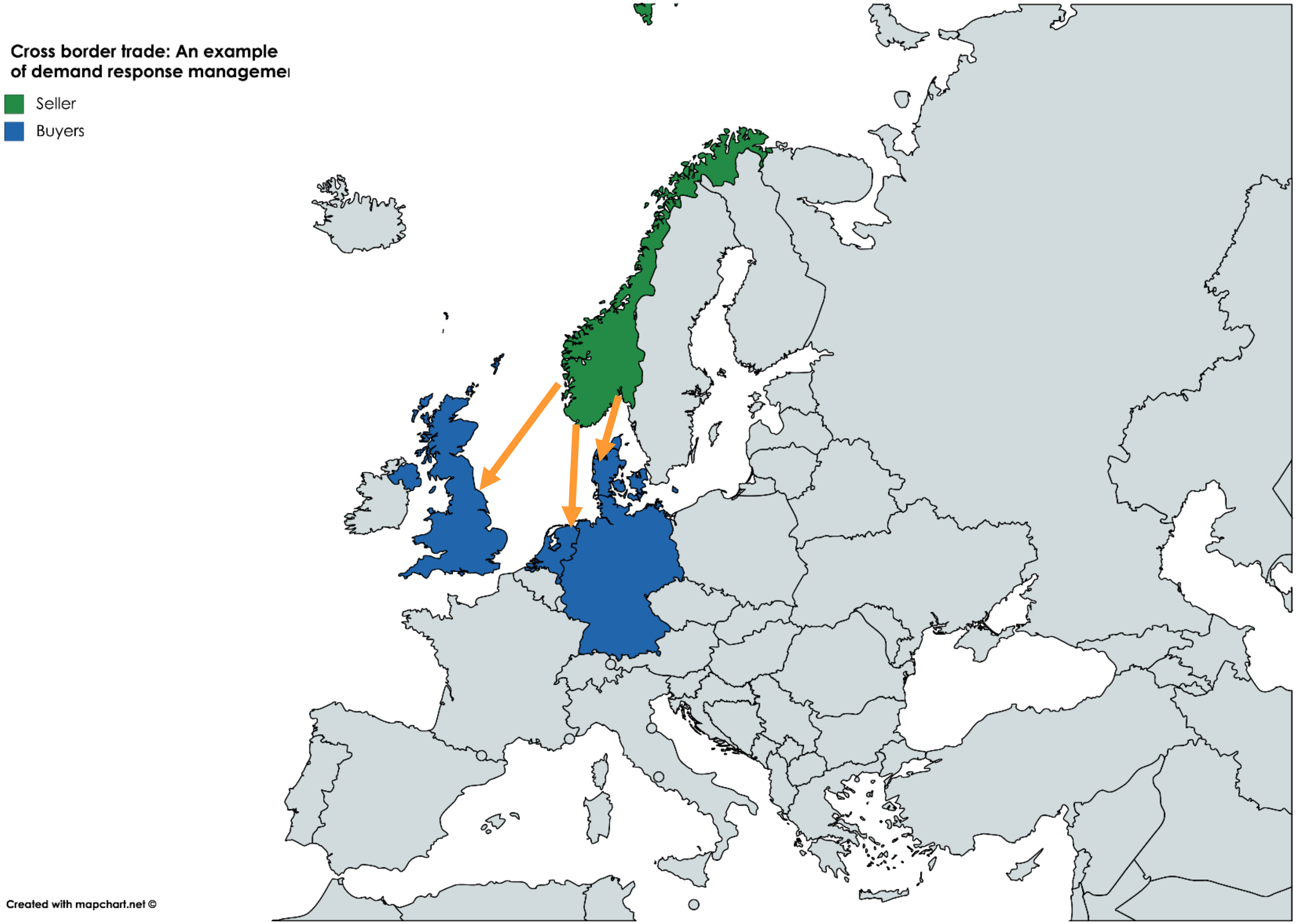
Demand Response Management involving multiple providers: Selection of providers or amount?



Demand Response Management involving multiple prosumers



Cross border electricity trade: An example of demand response management



Demand response applications: Data Centers

- **Daily services supported by data centers**
  - **Gmail**
  - **Facebook**
  - **Dropbox**
  - **DNB (**supported by Green Mountain data center in Stavanger**)**
  - **Q: more?**

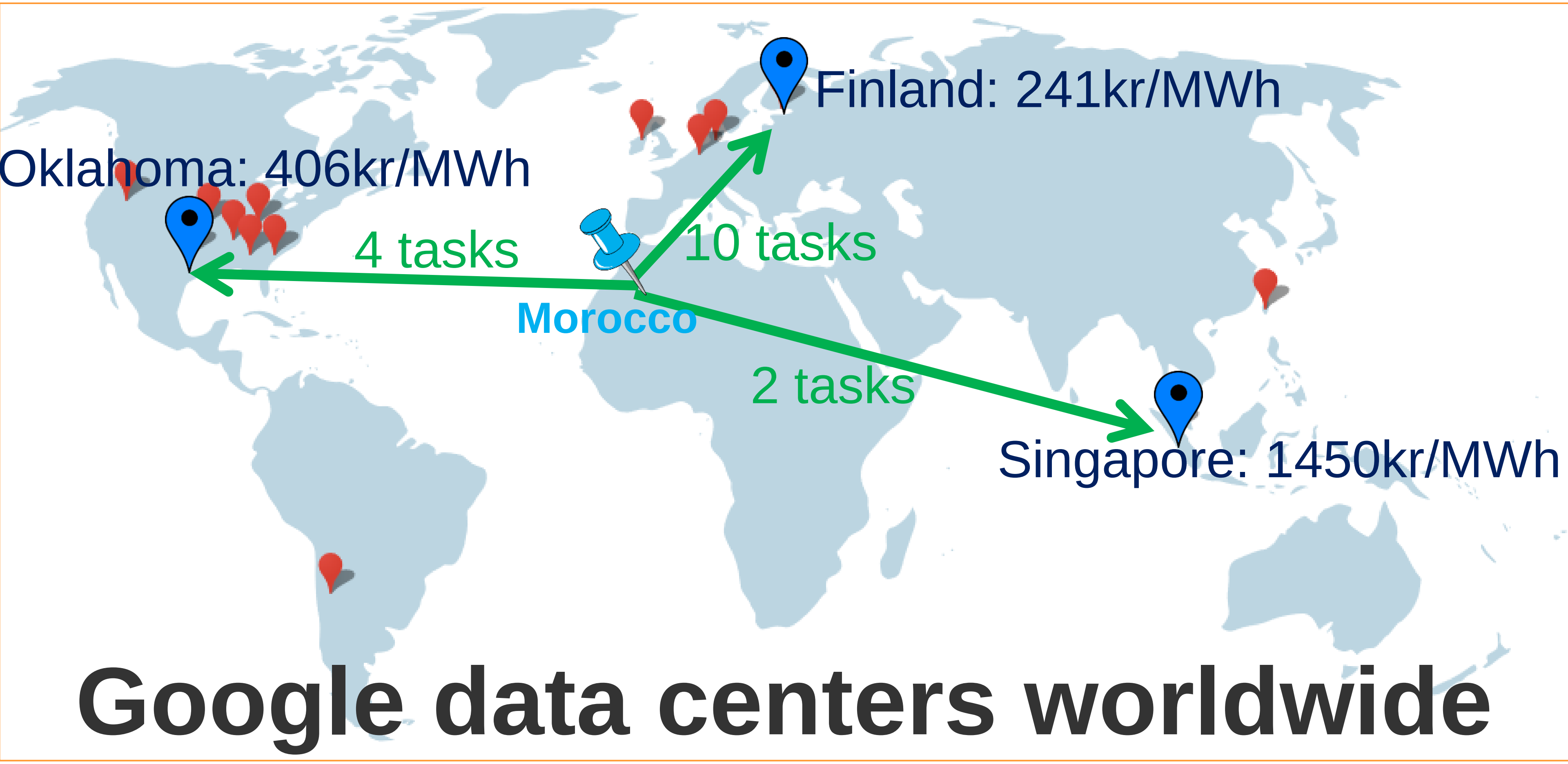
Google Data Centre at Mayes County, Oklahoma

Demand response applications: Data Centers

- **Q: Why place data centers in Finland or undersea?**
- **Data centers are huge energy consumers, in particular cooling systems, and**
  - **pay a lot for electricity bill**
  - **make power grid instable during peak hours**
- **Cooling system uses sea water from the Bay of Finland and reduces energy use**

Demand response applications: Data Centers

- **Q: can DRM help data centers to reduce energy cost?**
- **Allocate computation tasks to locations with cheaper prices**



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Thank you!