Tecnología eléctrica

Tema 4: Electricity markets

Contents

History of electricity markets

Around 30-40 years ago all power systems were operated as monopolies:

- The same company was in charge of the production, transportation, distribution and commercialization of electricity (vertical integration)
- Customers had no choice
- The demand was centrally forecast
- Power producers their "true" generation cost
- Dispatch quantities were determined using economic dispatch, optimal power flow, etc. to minimize the cost of satisfying demand

History of electricity markets

In 1990s the electricity sector is liberalized in some countries (Chile, UK, Australia)

- The same company cannot be in charge of the production, transportation, distribution and commercialization of electricity (horizontal integration)
- Competition is introduced in the production and commercialization of electricity through a wholesale electricity market and a retail electricity market, respectively
- Transportation and distribution of electricity is still operated as a monopoly (there is only one network)
- Consumers can choose among "several" options
- There is an independent system operator (ISO) and a market operator (MO). Sometimes both entities are the same.

Features of electricity markets

- Common features of the electricity market
  - Some people need a certain product
  - Some people can produce a certain product
  - Both group of people meet to exchange a product for money
- Particular features of the electricity market
  - Electricity cannot be stored
  - Electricity transportation according to Kirchhoff laws
  - Electricity consumption is not very elastic

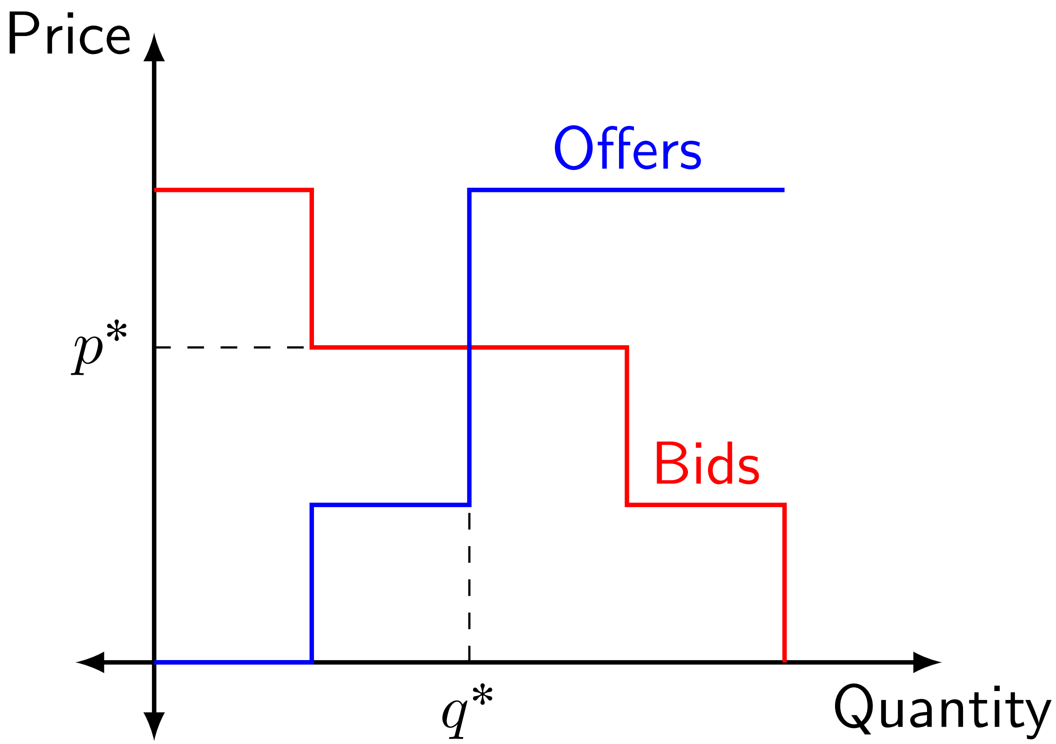
Wholesale electricity market

Wholesale electricity market

- Retailers and large consumers submit their bids to buy electricity
- Producers submit their offers to sell electricity
- Accepted bids and offers are determined according to a market clearing algorithm
- The market price is the one that makes demand and supply equal (also called equilibrium price)

Wholesale electricity market

A market-clearing condition is an equation (or other representation) stating that supply equals demand.



$p^* \rightarrow$ Clearing price

$q^* \rightarrow$ Clearing quantity

Exercise 1

The table below includes offers/bids to sell/buy electricity. Determine the market clearing price and the accepted offers and bids.

Offers			Bids		
Quantity (MWh)	Price (€/MWh)	Accepted (MWh)	Quantity (MWh)	Price (€/MWh)	Accepted (MWh)
50	17		80	12	
100	11		220	25	
180	5		40	3	
30	23		50	10	

- What would happen if the price increases above the market clearing price?
- What would happen if the price decreases below the market clearing price?

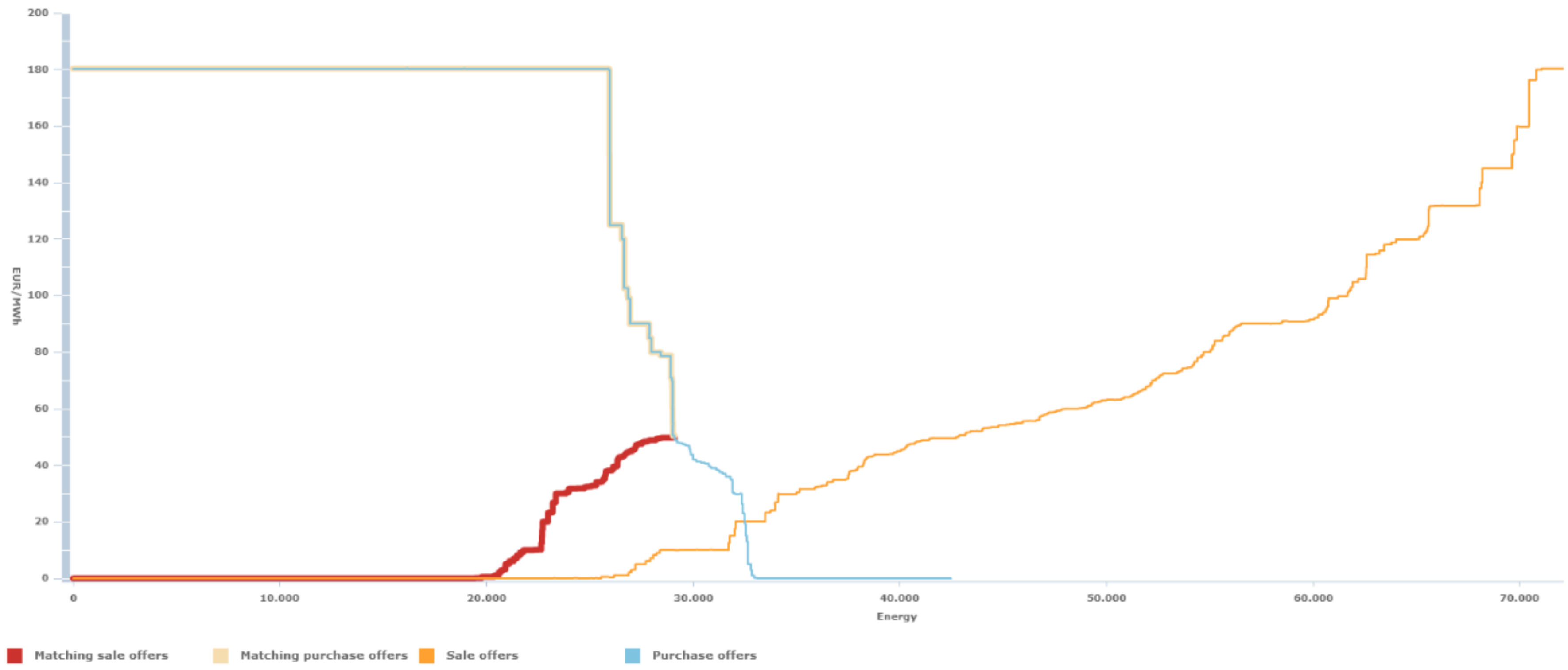
Exercise 1 (cont)

Fill in the table below with the accepted offers and bids for each price

Offers		Prices				Bids		Prices			
q	p	5	11	12	13	q	p	5	11	12	13
50	17					80	12				
100	11					220	25				
180	5					40	3				
30	23					50	10				

Wholesale electricity market

Not so different from reality!!



Wholesale electricity market

- Marginal pricing
  - All producers with accepted offers sell electricity at the market clearing price
  - All consumers with accepted bids buy electricity at the market clearing price
  - There is no missing money problem
  - Generators are encouraged to submit their real marginal costs
- Pay-as bid
  - Producers with accepted offers sell electricity at the submitted price
  - Consumers with accepted bids buy electricity at the submitted price
  - There is missing money problem
  - Generators are encouraged to increase the offer prices

Electricity market clearing

Indexes and sets

i index for selling electricity offers

j index for buying electricity offers

Parameters

$\overline{p}_i$ quantity for selling offer i

c_i price for selling offer i

$\overline{d}_j$ quantity for buying bid j

u_j price for buying bid j

Variables

p_i accepted quantity for selling offer i

d_j accepted quantity for buying bid

Electricity market clearing

- Electricity market clearing algorithms are formulated as optimization problem in most cases
- The market clearing price and accepted offers and bids can be obtained by solving the following optimization problem

$$\max_{p_i, d_j} \quad \sum_j u_j d_j - \sum_i c_i p_i$$

subject to

$$0 \leqslant p_i \leqslant \overline{p}_i \quad \forall i$$

$$0 \leqslant d_j \leqslant \overline{d}_j \quad \forall j$$

$$\sum_i p_i = \sum_j d_j$$

- The optimization model above is a linear programming problem (objective function and constraints are linear) that can be solved using commercial optimization software such as GAMS

Exercise 2

Use the code marketclearing.gms to check that the results provided by GAMS are the same than those obtained “manually” in exercise 1. Take into account that the market clearing price is equal to the marginal of the power balance constraint.

Exercise 3

Let us assume that offers and bids of exercise 1 are not located in the same geographical location but in two different buses. The capacity of the line connecting both buses is 150 MW. Determine the accepted offers and bids and the marginal price.

Offers				Bids			
Bus	Quantity	Price	Accepted	Bus	Quantity	Price	Accepted
2	50	17		2	80	12	
1	100	11		2	220	25	
1	180	5		2	40	3	
2	30	23		2	50	10	

Exercise 3

Offers				Market price		
Bus	Quantity	Price	Accepted			
2	50	17				
1	100	11				
1	180	5				
2	30	23				

Bids				Market price		
Bus	Quantity	Price	Accepted			
2	80	12				
2	220	25				
2	40	3				
2	50	10				

Locational pricing

- Electricity prices are different at each bus
- Locational marginal prices or nodal prices are calculated as follows:

$$\lambda_n = \frac{\Delta C_n}{\Delta d_n}$$

$\lambda_n \rightarrow$ Nodal price at bus n

$\Delta d_n \rightarrow$ Hypothetical demand increase at bus n

$\Delta C_n \rightarrow$ Total cost increase due to the demand increase at bus n

- Electricity prices are lower at buses with an excess of generation and higher at buses with an excess of demand
- Different electricity prices are caused by network congestion
- There is a congestion surplus. This surplus cannot be kept by the market operation or return to market participants. It can be used to upgrade the network, for example.

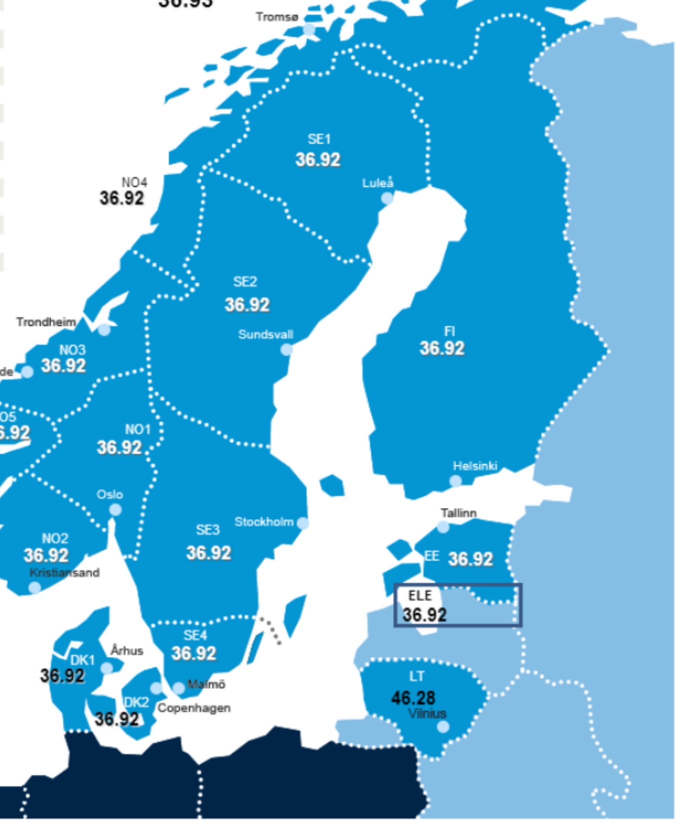
Locational pricing

01-11-2012 Resolution 10 - 11 Currency EUR Capacities ITVC Flow ITVC Area Prices

Elspot volumes

	Buy	Sell
NO1	5 241,4	3 491,2
NO2	4 405,9	5 829,5
NO3	2 430,0	1 451,6
NO4	2 218,5	2 742,7
NO5	1 715,8	1 621,4
DK1	3 083,2	2 617,0
DK2	1 720,9	1 216,7
SE1	1 270,6	3 581,3
SE2	1 675,2	5 613,7
SE3	10 732,2	10 186,9
SE4	3 100,5	947,4
FI	6 112,6	4 539,6
EE	333,4	642,9
ELE	476,4	34,7
LT	923,0	923,0

System price:
36.93

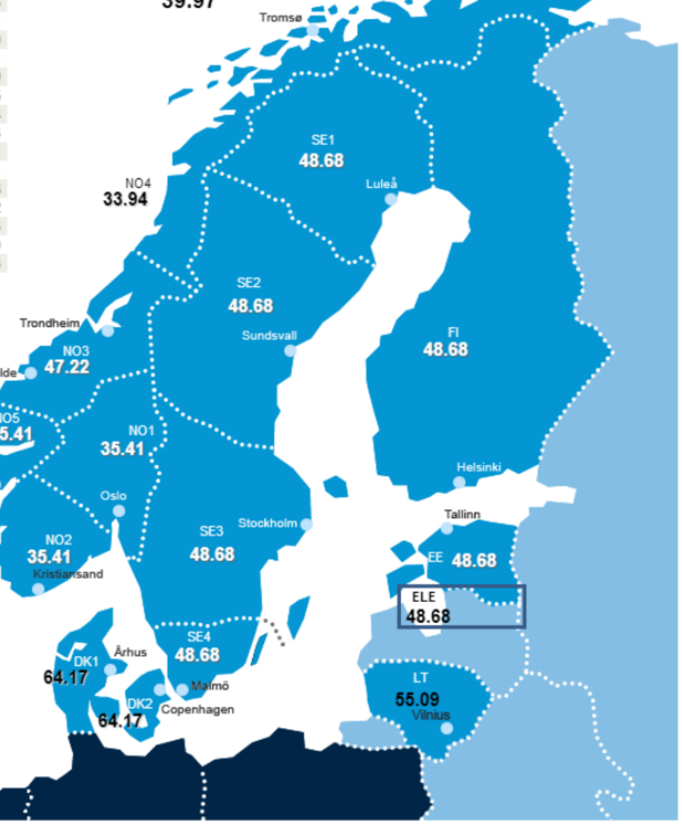


10-10-2012 Resolution 18 - 19 Currency EUR Capacities ITVC Flow ITVC Area Prices

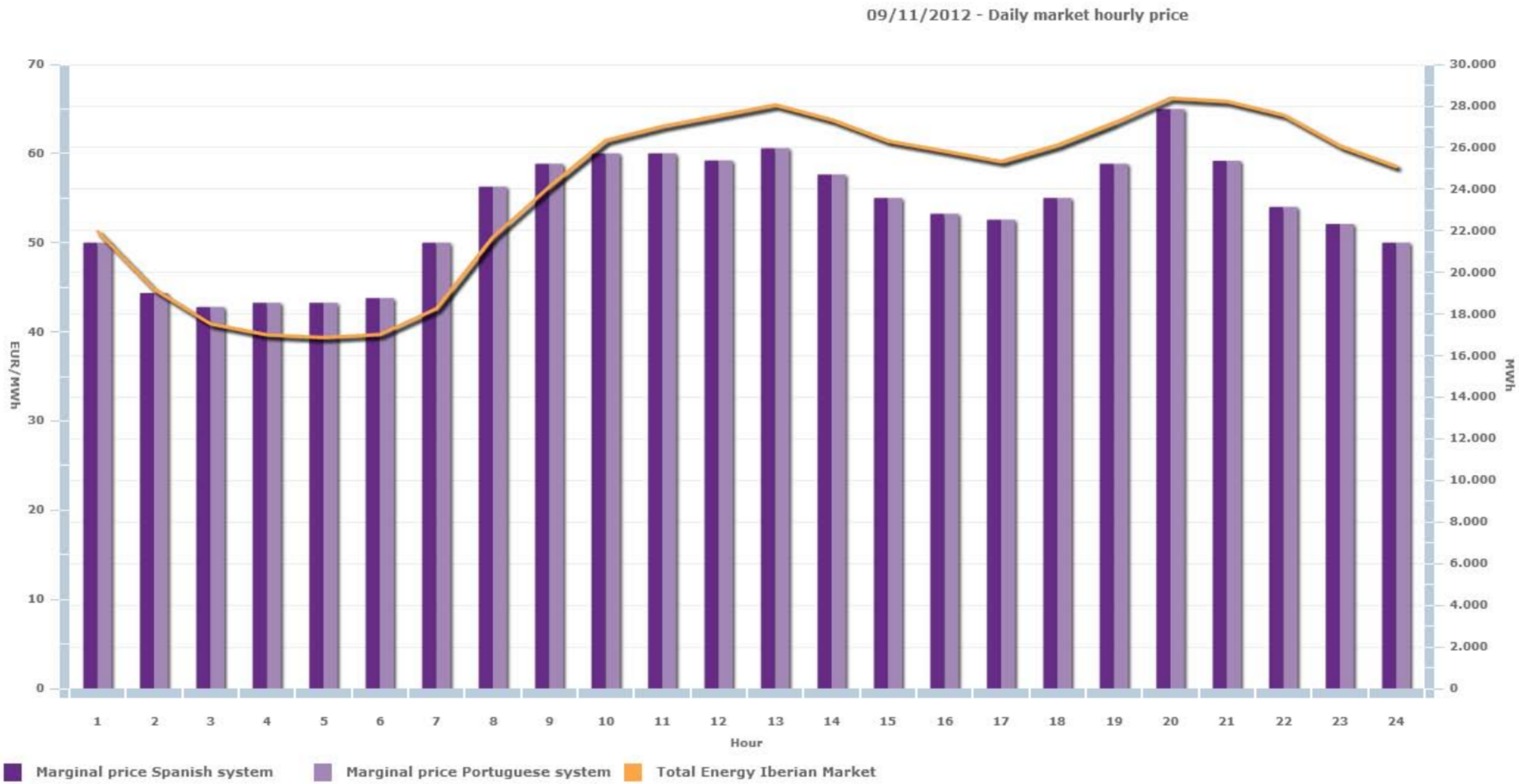
Elspot volumes

	Buy	Sell
NO1	4 141,1	3 195,6
NO2	3 876,6	6 074,1
NO3	2 134,0	1 934,0
NO4	1 824,1	2 874,1
NO5	1 419,9	1 697,9
DK1	3 439,5	2 079,5
DK2	2 280,4	980,4
SE1	1 206,4	3 866,6
SE2	1 709,4	5 787,1
SE3	10 524,0	9 213,1
SE4	3 968,4	485,3
FI	6 436,9	4 722,2
EE	315,7	637,6
ELE	334,1	63,0
LT	818,6	818,6

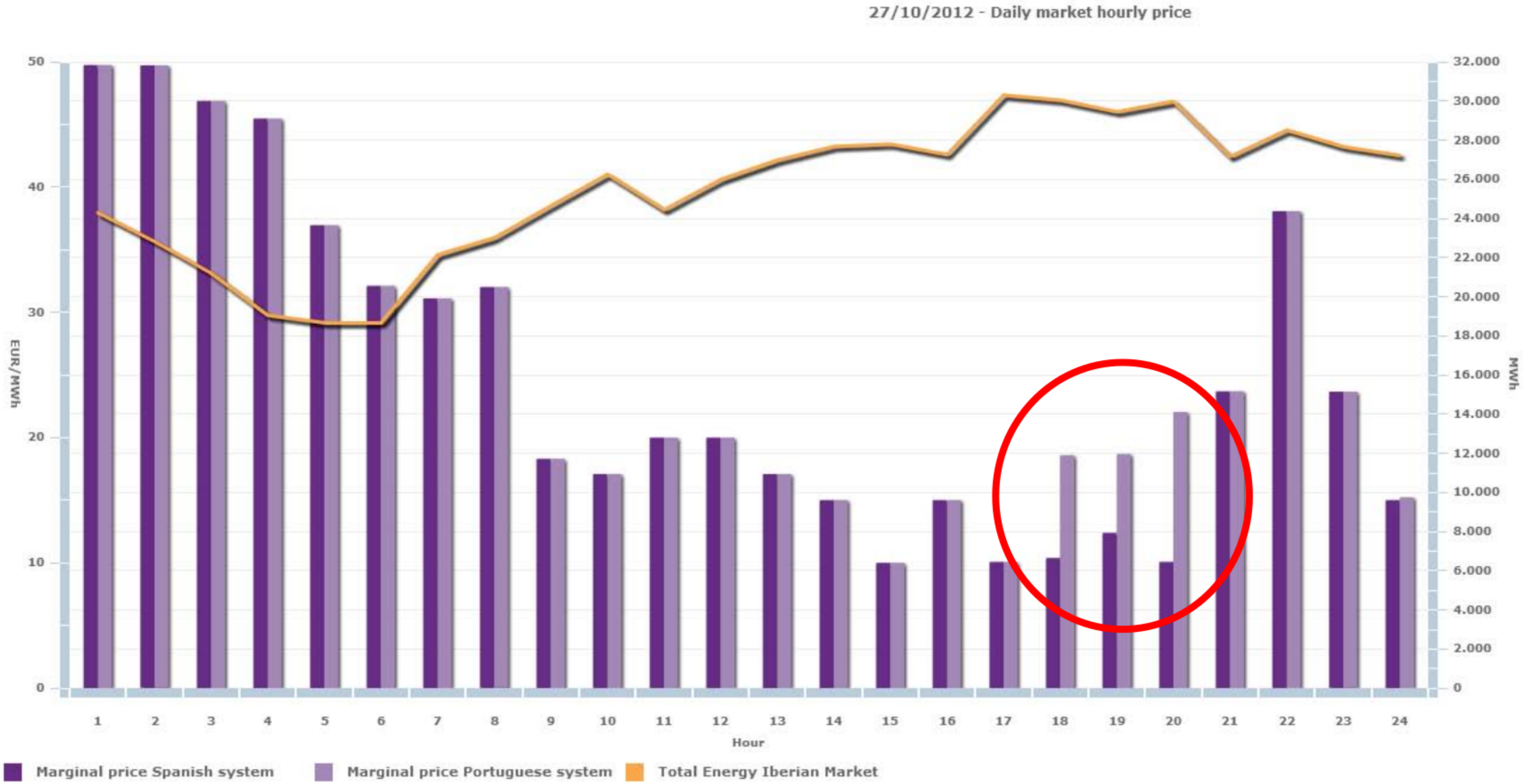
System price:
39.97



Locational pricing



Locational pricing



Exercise 4

Determine the congestion surplus of exercise 3. To do so, compute the money received by the market operator from the customers and the money paid by the market operator to the producers and compute the difference.

Locational pricing

Indexes and sets

i	index for selling electricity offers
j	index for buying electricity offers
n	index for network buses
Φ_n	set of selling offers at bus n
Ψ_n	set of buying bids at bus n

Parameters

$\overline{p}_i$	quantity for selling offer i
c_i	price for selling offer i
$\overline{d}_j$	quantity for buying bid j
u_j	price for buying bid j
$\overline{f}_{nm}$	capacity of transmission line nm

Variables

p_i	accepted quantity for selling offer i
d_j	accepted quantity for buying bid
f_{nm}	power flow from bus n to bus m

Locational pricing

A generic market clearing with network can be formulated as follows

$$\max_{p_i, d_j, f_{nm}} \quad \sum_j u_j d_j - \sum_i c_i p_i$$

subject to

$$0 \leqslant p_i \leqslant \overline{p}_i \quad \forall i$$

$$0 \leqslant d_j \leqslant \overline{d}_j \quad \forall j$$

$$\sum_{i \in \Phi_n} p_i = \sum_{j \in \Psi_n} d_j + \sum_m f_{nm} \quad \forall n$$

$$-\overline{f}_{nm} \leqslant f_{nm} \leqslant \overline{f}_{nm} \quad \forall n, m$$

$$f_{nm} = -f_{mn} \quad \forall n, m$$

- The optimization problem is still linear
- The nodal price is the marginal of the balancing equation
- In this generic formulation the flows of electricity do not follow Kirchhoff's laws (electricity transported as apples!!).
- To properly model electricity features, power flow equations must be considered (usually DC power flow equations)

Locational pricing

Indexes and sets

i	index for selling electricity offers
j	index for buying electricity offers
n	index for network buses
Φ_n	set of selling offers at bus n
Ψ_n	set of buying bids at bus n

Parameters

$\overline{p}_i$	quantity for selling offer i
c_i	price for selling offer i
$\overline{d}_j$	quantity for buying bid j
u_j	price for buying bid j
$\overline{f}_{nm}$	capacity of transmission line nm
x_{nm}	reactance of transmission line nm

Variables

p_i	accepted quantity for selling offer i
d_j	accepted quantity for buying bid
f_{nm}	power flow from bus n to bus m
θ_n	voltage angel at bus n

Locational pricing

A generic market clearing with a DC representation of the network is formulated as follows

$$\max_{p_i, d_j, f_{nm}, \theta_n} \quad \sum_j u_j d_j - \sum_i c_i p_i$$

subject to

$$0 \leqslant p_i \leqslant \overline{p}_i \quad \forall i$$

$$0 \leqslant d_j \leqslant \overline{d}_j \quad \forall j$$

$$\sum_{i \in \Phi_n} p_i = \sum_{j \in \Psi_n} d_j + \sum_m f_{nm} \quad \forall n$$

$$-\overline{f}_{nm} \leqslant f_{nm} \leqslant \overline{f}_{nm} \quad \forall n, m$$

$$f_{nm} = \frac{1}{x_{nm}}(\theta_n - \theta_m) \quad \forall n, m$$

- The optimization problem is still linear
- Power losses in transmission lines are neglected
- Physical laws for electricity transportation are considered

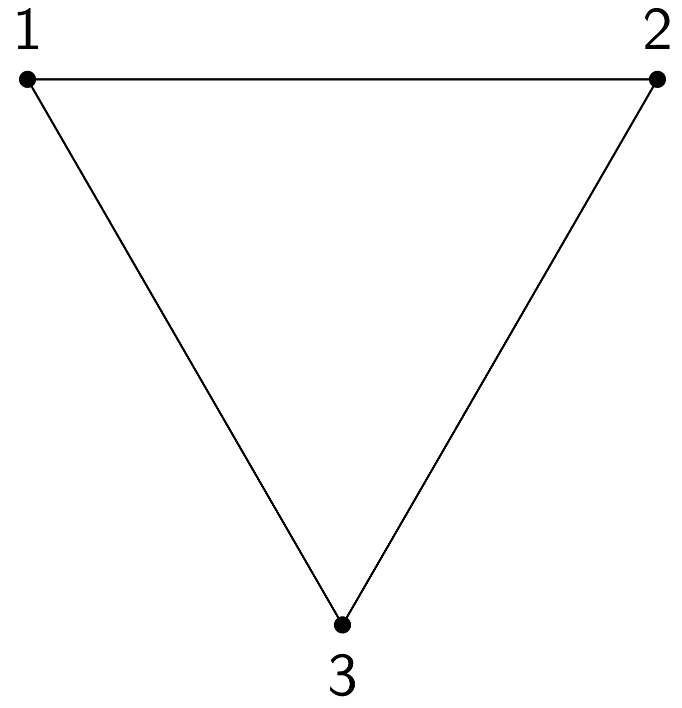
Exercise 5

Modify the code marketclearing.gms to include the equations of a DC representation of the network. Run the code with the data of exercise 3 (the susceptance of line 1-2 is 0.5 p.u. and the base power 100 MVA). Check that the solutions provided by GAMS are the same than those in exercise 3.

Exercise 6 (to be handed in)

Design a system with 3 buses as the one shown in the figure below. Pick the data (offers, bids and network) to illustrate:

- the effect of network congestion on prices and total cost
- the differences between a market clearing considering a pipeline representation of the network and a market clearing considering the DC power flow equations.



Power producers

- Main assumptions:
  - All parameters are known (no uncertainty)
  - Power producers' decisions do not affect prices (no market power)
  - Power producers sell their production in the day-ahead market (no other trading floors or derivatives)
- Classification:
  - Conventional power producers (nuclear, gas, coal,)
  - Hydro power producers (conventional, pumped-storage,)
  - Renewable power producers (wind, solar,)

Conventional power producer

- The generation can be changed between 0 and the maximum capacity (dispatchable)
- The generation must comply with certain physical limits (ramping, minimum times, etc)
- The production cost depends on the fuel price and is usually modeled as a linear or quadratic function
- Depending on the price, a conventional power producer must decide how much electricity must be generated for each hour of the day

Exercise 7

Let us assume that we own a coal power plant of 100 MW. The generating cost function is $c(p) = 15 \cdot p$, where p is the amount of electricity produced in a given hour in MWh and $c(p)$ is the total cost in €. If λ_t denotes the electricity price in hour t in €/MWh, determine the electricity produced in each hour p_t in MWh.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
p_t (MWh)					

Exercise 8

Let us assume that we own a coal power plant of 100 MW. The generating cost function is $c(p) = 5 \cdot p + 0{,}1 \cdot p^2$, where p is the amount of electricity produced in a given hour in MWh and $c(p)$ is the total cost in €. If λ_t denotes the electricity price in hour t in €/MWh, determine the electricity produced in each hour p_t in MWh.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
p_t (MWh)					

Exercise 9

Let us assume that we own a coal power plant of 100 MW. The generating cost function is $c(p) = 15 \cdot p$, where p is the amount of electricity produced in a given hour in MWh and $c(p)$ is the total cost in €. If λ_t denotes the electricity price in hour t in €/MWh, determine the electricity produced in each hour p_t in MWh. The generating unit has now ramping limits imposing that the production between two consecutive hours cannot change more than 50 MWh.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
p_t (MWh)					

Conventional power producer

Indexes and sets

t index for hours

Parameters

a, b cost function parameters

$\overline{p}$ maximum generation capacity

λ_t electricity price in time t

Variables

p_t generation quantity in time t

Conventional power producer

- Determining how much electricity must be produced to maximize the profit can also be formulated as an optimization problem

$$\max_{p_t} \quad \sum_t \lambda_t p_t - (a p_t^2 + b p_t)$$

subject to

$$0 \leqslant p_t \leqslant \overline{p} \quad \forall t$$

- If $a = 0$, the optimization model above is a linear programming problem that can be solved using GAMS (LP)
- If $a > 0$, the optimization model above is a quadratic programming problem that can be solved using GAMS (QP)

Exercise 10

Use the code conventional.gms to check that the solution of exercise 7 is the optimal one.

Exercise 11

Modify the code conventional.gms to check that the solution of exercise 8 is the optimal one.

Conventional power producer

Indexes and sets

t	index for hours

Parameters

a, b	cost function parameters
$\overline{p}$	maximum generation capacity
λ_t	electricity price in time t
r^U	up ramping limit
r^D	down ramping limit

Variables

p_t	generation quantity in time t

Conventional power producer

- Ramping limits have been included in the formulation as follows

$$\max_{p_t} \quad \sum_t \lambda_t p_t - (a p_t^2 + b p_t)$$

subject to

$$0 \leqslant p_t \leqslant \overline{p} \quad \forall t$$

$$-r^D \leqslant p_t - p_{t-1} \leqslant r^U \quad \forall t > 1$$

- Other technical constraints such as minimum up and down time can be also considered using binary variables

Exercise 12

Modify the code conventional.gms to compute the optimal solution of exercise 9 if you had problems solving it by hand.

	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$
λ_t (€/MWh)	10	20	22	16	5
p_t (MWh)					

Hydropower producer

- The generation can be changed between 0 and the maximum capacity (dispatchable)
- The generation depends on the available water and on the physical features of the reservoir
- There is no fuel and the production costs are usually assumed equal to 0
- Depending on the price, a hydropower producer must decide how much electricity must be generated for each hour of the day
- It is usually imposed that the water level at the beginning and the end of the planning horizon are the same

Hydropower producer

Indexes and sets

t	index for hours

Parameters

η	conversion parameter (MWh/m^3)
$\overline{p}$	maximum generation capacity
$\overline{v}$	maximum stored water
λ_t	electricity price in time t
v_t^i	water inflow in time t
v_0	initial stored water

Variables

p_t	generation quantity in time t
v_t	stored water in time t
v_t^-	water used to produce electricity in time t
v_t^s	water spill in time t

Hydropower producer

- Determining how much electricity must be produced to maximize the profit can also be formulated as an optimization problem

$$\max_{p_t, v_t} \quad \sum_t \lambda_t p_t$$

subject to

$$p_t = \eta v_t^- \quad \forall t$$

$$0 \leqslant p_t \leqslant \overline{p} \quad \forall t$$

$$v_t = v_{t-1} + v_t^i - v_t^- - v_t^s \quad \forall t$$

$$0 \leqslant v_t \leqslant \overline{v} \quad \forall t$$

$$v_0 = v_T$$

- The optimization model above is a linear programming problem that can be solved using GAMS (LP)

Exercise 13

A 100-MW hydropower unit has a conversion parameter of 400 MWh/10^6m^3. The capacity of the reservoir is $1 \cdot 10^6$ m^3 and its initial volume $0{,}5 \cdot 10^6$ m^3. The water inflows and electricity prices for five consecutive hours are provided in the table below. Determine the optimal production schedule.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
v_1^i (10^6m^3)	0,0	0,0	0,0	0,2	0,55
p_t (MWh)					
v_t^- (10^6m^3)					
v_t^s (10^6m^3)					
v_t (10^6m^3)					

Exercise 14

Use the code hydro.gms to check that the solution to exercise 13 is the optimal one

Pump hydropower producer

- The generation can be changed between 0 and the maximum capacity (dispatchable)
- The generation depends on the available water and on the physical features of the reservoir
- There is no fuel and the production costs are usually assumed equal to 0
- Depending on the price, a hydropower producer must decide how much electricity must be generated for each hour of the day
- It is usually imposed that the water level at the beginning and the end of the planning horizon are the same
- If price is particularly low, water can be pumped up to increase the amount of stored water

Pump hydropower producer

Indexes and sets

t	index for hours

Parameters

η	conversion parameter (MWh/m^3)
$\overline{p}$	maximum generation capacity
$\overline{v}$	maximum stored water
λ_t	electricity price in time t
v_0	initial stored water

Variables

p_t	generation quantity in time t
v_t	stored water in time t
v_t^-	water used to produce electricity in time t
v_t^+	water pumped to the reservoir in time t
v_t^s	water spill in time t

Pump hydropower producer

- Determining how much electricity must be produced to maximize the profit can be formulated as an optimization problem

$$\max_{p_t, v_t} \quad \sum_t \lambda_t p_t$$

subject to

$$p_t = \eta(v_t^- - v_t^+) \quad \forall t$$

$$-\overline{p} \leqslant p_t \leqslant \overline{p} \quad \forall t$$

$$v_t = v_{t-1} - v_t^- + v_t^+ - v_t^s \quad \forall t$$

$$0 \leqslant v_t \leqslant \overline{v} \quad \forall t$$

$$v_0 = v_T$$

- The water inflow is disregarded
- It is assumed that the efficiency of the turbine is the same functioning as generator or motor
- The optimization model above is a linear programming problem

Exercise 15

Modify the code hydro.gms to determine the generation schedule of a pump hydropower plant with the same characteristics. Fill in the table below with the results.

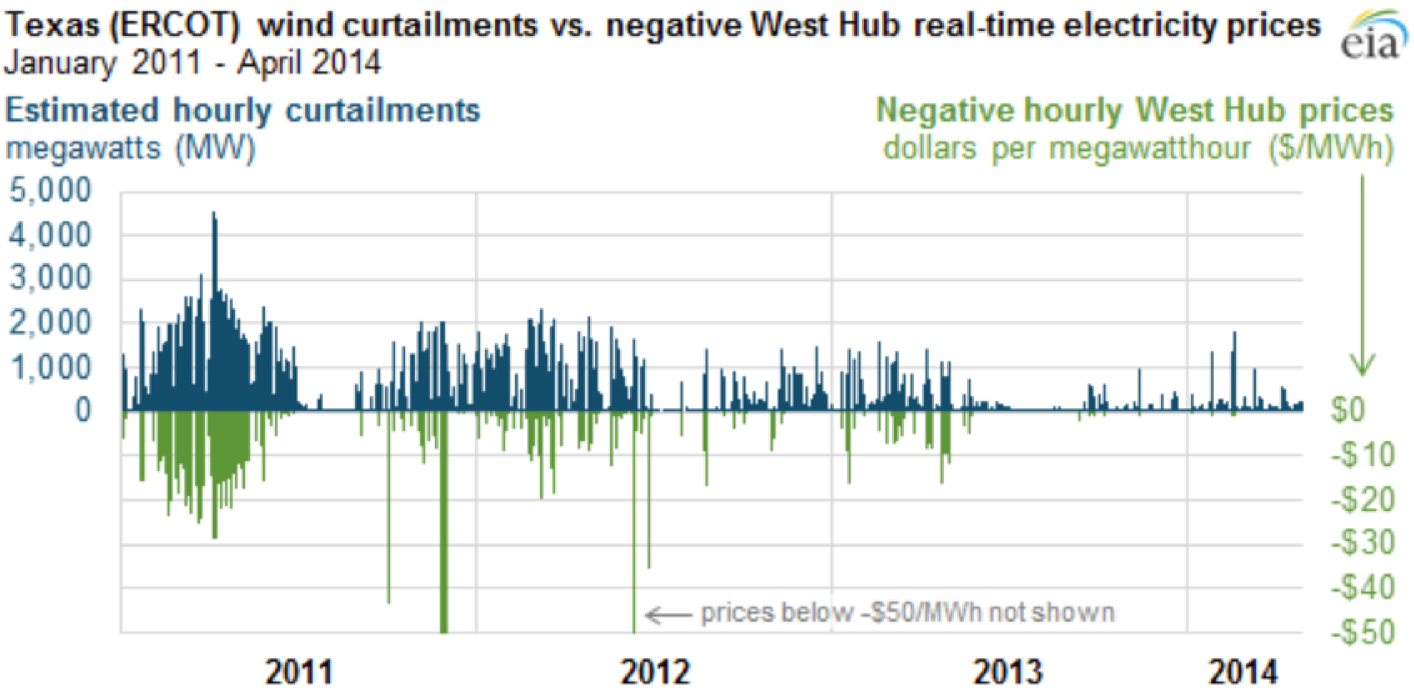
	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$
λ_t (€/MWh)	10	20	22	16	5
p_t (MWh)					
v_t^- (10^6m^3)					
v_t^+ (10^6m^3)					
v_t^s (10^6m^3)					
v_t (10^6m^3)					

Renewable power producer

- The maximum generation depends on weather conditions and therefore, such maximum capacity changes throughout time and is uncertain
- There is no fuel and the production costs are usually assumed equal to 0
- Depending on the price, a renewable producer must decide how much electricity must be generated for each hour of the day (there are negative prices!!)
- Some of these producers are subsidized

Renewable power producer

Fewer wind curtailments and negative power prices seen in Texas after major grid expansion



Source: U.S. Energy Information Administration, based on the Electric Reliability Council of Texas (ERCOT) for curtailments and SNL Energy for electricity prices

Full new at https://goo.gl/XxbKpT

Renewable power producer

Indexes and sets

t index for hours

Parameters

ρ_t capacity factor in time t (p.u.)

$\overline{p}$ maximum generation capacity

λ_t electricity price in time t

Variables

p_t generation quantity in time t

Renewable power producer

- Determining how much electricity must be produced to maximize the profit can also be formulated as an optimization problem

$$\text{máx}_{p_t} \quad \sum_t \lambda_t p_t$$

subject to

$$0 \leqslant p_t \leqslant \rho_t \overline{p} \quad \forall t$$

- The optimization model above is a linear programming problem

Exercise 16

Determine the optimal generation schedule of a 100-MW renewable power producer considering the electricity prices and the capacity factors of the table below.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
ρ_t (p.u.)	0,2	0,4	0,7	1	0,5
p_t (MWh)					

Exercise 17

Formulate the GAMS code to solve exercise 16. Check that the solution is the optimal one.

Exercise 18 (to be handed in)

Choose a portfolio of three power plants including:

- A conventional power plant (nuclear, coal, gas, etc)
- A hydropower plant (regular or pumped)
- A renewable power plant (wind or solar)

Try to find realistic parameters for the chosen power plants and find realistic prices of an electricity market. Write the optimization problem to determine the optimal generation schedule of each power plant and the aggregated output, code it in GAMS and provide the results. Try to be original so that the results show something interesting.

Price-maker power producer

- So far power producers are assumed to be price-takers, that is, the price is independent of the produced quantities
- The offers to produce electricity will be the quantities p_t and the price 0, to be sure such offers are accepted
- In reality, the electricity price can be affected by the offers and bids of large enough producers and consumers
- In most cases, the aggregated bids of all consumers and retailers is modeled as a linear function called *inverse demand function*
- The inverse demand function related the electricity market price and the total generated quantity

$$\lambda = \alpha - \beta p, \qquad a, b > 0$$

Price-maker power producer (monopoly)

Indexes and sets

t	index for hours

Parameters

a, b	cost function parameters
α_t, β_t	inverse demand function parameters
$\overline{p}$	maximum generation capacity

Variables

p_t	generation quantity in time t
λ_t	electricity price in time t

Price-maker power producer (monopoly)

- Determining how much electricity must be produced to maximize the profit can also be formulated as an optimization problem

$$\max_{p_t} \quad \sum_t (\alpha_t - \beta_t p_t)p_t - (ap_t^2 + bp_t)$$

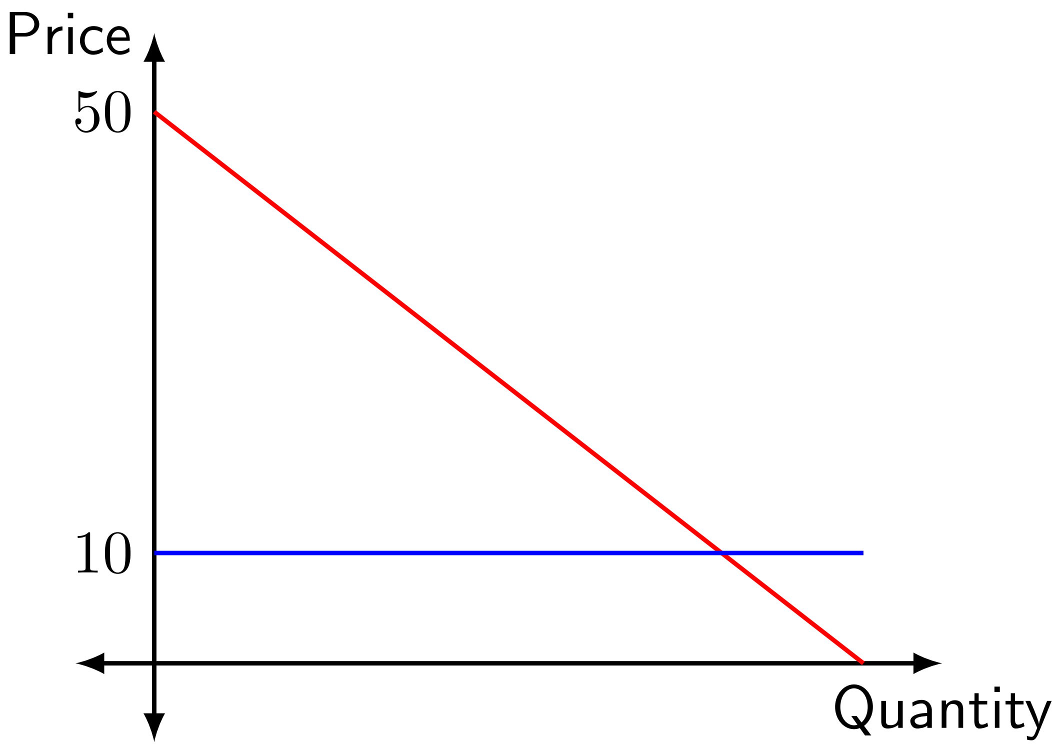
subject to

$$0 \leqslant p_t \leqslant \overline{p} \quad \forall t$$

- For $a, b > 0$, the optimization model above is a quadratic programming problem that can be solved using GAMS (QP)

Exercise 19

Let us assume that we own a price-maker coal power plant of 100 MW, that is the only power plant in a given system (monopoly). The generating cost function is $c(p) = 10 \cdot p$, where p is the amount of electricity produced in a given hour in MWh and $c(p)$ is the total cost in €. If $\lambda_t = 50 - 0{,}5 p_t$ denotes the electricity price in hour t in €/MWh, determine the optimal electricity to be produced. Plot the optimal quantity and price in the figure and compare it with the price if the power producer were price-taker.



p_t	λ_t	profit
20		
40		
60		
80		
100		

Exercise 20

Create a code name maker.gms and solve the exercise 19 using GAMS. Check that the solution is the optimal one.

Exercise 21

Let us assume that we have now two price-maker power producers of 50 MW of capacity (duopoly). The marginal costs of the two producers are 10 and 15, respectively. The inverse demand function is $\lambda = 50 - 0{,}5(p_1 + p_2)$, where p_1 and p_2 are the generating quantities of both producers. Fill in the table on the left with the optimal quantities of the first producer p_1^* for each amount produced by the second producer p_2. Fill in the table on the left with the optimal quantities of the second producer p_2^* for each amount produced by the first producer p_1. Is there any equilibrium? What is the price at equilibrium? Compare it with the price if both producers were price-takers.

p_2	p_1^*
10	
20	
30	
40	
50	

p_1	p_2^*
10	
20	
30	
40	
50	

Exercise 22

Modify the code maker.gms to create two new codes, maker1.gms and maker2.gms corresponding to the two power producers of exercise 21. Follow the steps below

1) Solve maker1.gms assuming that the amount generated by producer 2 is 50
2) Solve maker2.gms assuming that the amount generated by producer 1 is the one obtained in step 1)
3) Solve maker1.gms assuming that the amount generated by producer 2 is the one obtaned in step 2)
4) Continue the iterative process until neither of the solution change
5) Compare such solution with the one obtained in exercise 21

Uncertainty

- In most cases we have to make decisions facing some uncertain information

- In the problems analyzed in this chapter the uncertain parameters are:
  - Electricity prices
  - Fuel prices
  - Water inflow
  - Renewable capacity factor
- One can think that the best strategy is to calculate the average of the uncertain parameter and solve the optimization problem. Is that ok?

Renewable power producer under uncertainty

- The renewable capacity factor ρ_t is now uncertain depending on the weather conditions
- The renewable power producer must determine how much electricity to produce in each hour
- If the producer generates more than its commitment, it can sell the overproduction at a price lower than the electricity price
- If the producer generates less than its commitment, it must buy the missing generation at a price higher than the electricity price

Exercise 23

We have to determine the generation of a 100-MW renewable power producer for just one hour with in which the electricity price is 20€/MWh. The capacity factor is not known but can take the five equiprobable values: 0, 0.25, 0.5, 0.75, 1. If the producer generates more than expected, this overproduction can be sold at 15€/MWh. If the producer generates less than expected, it has to buy the missing production at 30 €/MWh. Determine the optimal generation (commitment) as done in Exercise 16 using the expected capacity factor. Afterwards, fill in the table below and compute the profit for each scenario and the expected profit.

Commitment	

	Overprod	Underprod	Profit
Scenario 1 ($\rho = 0$)			
Scenario 2 ($\rho = 0{,}25$)			
Scenario 3 ($\rho = 0{,}5$)			
Scenario 4 ($\rho = 0{,}75$)			
Scenario 5 ($\rho = 1$)			

Exercise 24

Fill in the same table assuming now that the commitment is equal to 25 MWh

Commitment	

	Overprod	Underprod	Profit
Scenario 1 ($\rho = 0$)			
Scenario 2 ($\rho = 0{,}25$)			
Scenario 3 ($\rho = 0{,}5$)			
Scenario 4 ($\rho = 0{,}75$)			
Scenario 5 ($\rho = 1$)			

Now compare the expected profit of Exercise 23 and the one corresponding to the table below. Which one is higher?

Commitment	Expected profit

Renewable power producer under uncertainty

- How many sets do we need?
  -
  -
  -
- How many parameters do we need? Which ones depend on the sets?
  -
  -
  -
- How many variables do we need? Which ones depend on the sets?
  -
  -
  -

Exercise 25

1) Write down the notation required for the problem of a renewable power producer under uncertainty

2) Write down the optimization problem to determine the optimal generation of a renewable power producer under uncertainty

3) Write the GAMS code to determine the optimal generation of a renewable power producer and verify whether 25 MWh is the optimal commitment.

Exercise 26 (to be handed in)

Use the formulation of a conventional hydropower producer and modify it to consider that the water inflow is uncertain. Use as many scenarios as you want. Prove that solving the optimization problem using the average water inflow provides a lower profit than the one obtained by solving the stochastic version of such problem.

- You can consider that the production of the first time periods of the planning horizon must be the same for all scenarios. The production for the last time periods of the planning horizon can depend on each scenario realization.
- In this problem only one electricity price is considered, there is no need to consider price for over- and underproduction. Note that if it rains more than expected, the extra water can be stored in the reservoir.
- For the same reason, there is no need to consider variables for under- and over production, since water can be stored.

Consumer

- Until now, all problems have been focused on determining the optimal generation schedule of different types of power producers to maximize profit. Now we have to decide the optimal consumption schedule of a power consumer to minimize the electricity bill.

- Electricity consumption can be flexible or inflexible. Flexible electricity consumption can be shifted in time. Inflexible electricity consumption has to be satisfied in specific time periods.

Exercise 27

The inflexible and flexible electricity consumption a factory throughout a planning horizon of five hours are denoted by d_t^I and d_t^F, respectively. Flexible consumption can be shifted in time but the total electricity consumption can never be higher than $\overline{d} = 100$ MWh. If electricity price is assumed to be known and equal to λ_t, determine the optimal electricity consumption schedule d_t.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
d_t^I (MWh)	30	10	20	15	25
d_t^F (MWh)	40	40	40	40	40
d_t (MWh)					

Exercise 28

Write down the notation and the optimization problem to determine the optimal consumption schedule of the factory described in exercise 27. Write also the GAMS code, solve it, and check whether the solution you proposed is the optimal one.

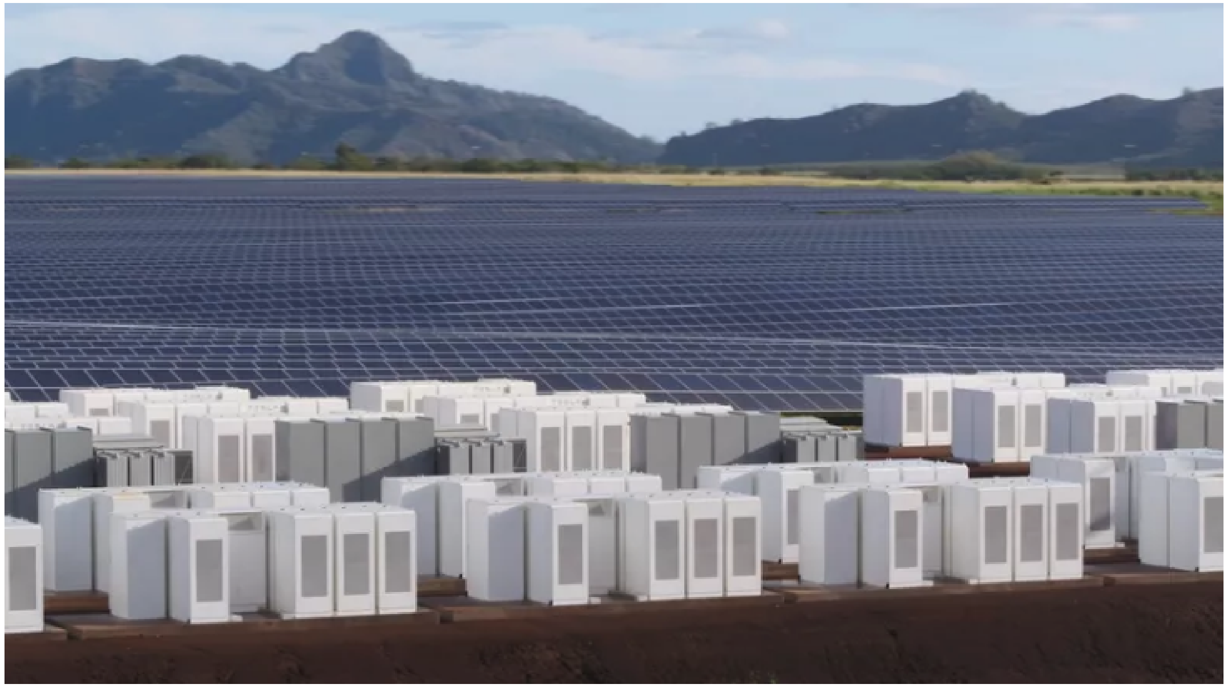
Electricity storage

- Storage electricity devices have not been economically efficient. Electricity could be only stored by hydropower units.

- Some argue that things are changing...

Electricity storage

Tesla built a huge solar energy plant on the island of Kauai (08/03/17)



The Kauai project consists of a 52 megawatt-hour battery installation plus a 13 megawatt SolarCity solar farm. Tesla and the Kauai Island Utility Cooperative, the power company that ordered the project, believe the project will reduce fossil fuel usage by 1.6 million gallons per year.

Electricity storage

Tesla's enormous battery in Australia, just weeks old, is already responding to outages in record time (26/12/17)

Fed by wind turbines at the nearby Hornsdale wind farm, the battery stores excess energy that is produced when the demand for electricity isn't peaking. It can power up to 30,000 homes, though only for short periods — meaning that the battery must still be supported by traditional power plants in the event of a long outage.

Electricity storage

A new Tesla Powerpack system brings business almost completely off-grid in France (10/01/18)

Neyrial says that by combining this new energy storage system with his rooftop solar array, his company will be able to run 100 % independently from the grid 8 months out of the year and the system will cover up to 80 % of the company's electricity needs for the other 4 months.

Electricity storage

Electricity energy storage (ESS) are characterized by:

- Power capacity ($\overline{p}$, MW): the maximum power to be charged or discharge
- Energy capacity (η, h): the number of hours required to fully charge the storage
- Round-trip efficiency (ξ, p.u.): the percentage of power losses in one cycle. For simplicity, you can assume that all losses occur during the charging.

Owners of EES can buy electricity to charge their devices when the price is low, and discharge them to sell electricity when the price is high.

Exercise 29

A 100-MW electricity energy storage device has an energy capacity of 2 hours and the round-trip efficiency is assumed to be 100 % (no losses). The charge and discharge variables are denoted by p_t^+ and p_t^-, respectively. Determine the optimal schedule if the storage level at $t = 0$ is 0 MWh. The energy level of the ESS is denoted by s_t

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
λ_t (€/MWh)	10	20	22	16	5
p_t^+ (MWh)					
p_t^- (MWh)					
s_t (MWh)					

Exercise 30

A 100-MW electricity energy storage device has an energy capacity of 1 hours and the round-trip efficiency is assumed to be 100 % (no losses). The charge and discharge variables are denoted by p_t^+ and p_t^-, respectively. Determine the optimal schedule if the storage level at $t = 0$ is 0 MWh. The energy level of the ESS is denoted by s_t

	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$
λ_t (€/MWh)	10	20	22	16	5
p_t^+ (MWh)					
p_t^- (MWh)					
s_t (MWh)					

Exercise 31

Write the notation and the formulation needed to determine the optimal charge and discharge schedule of a electricity energy storage device. Code it in GAMS and check that the solution to exercises 29 and 30 is correct.

Exercise 32 (to be handed in)

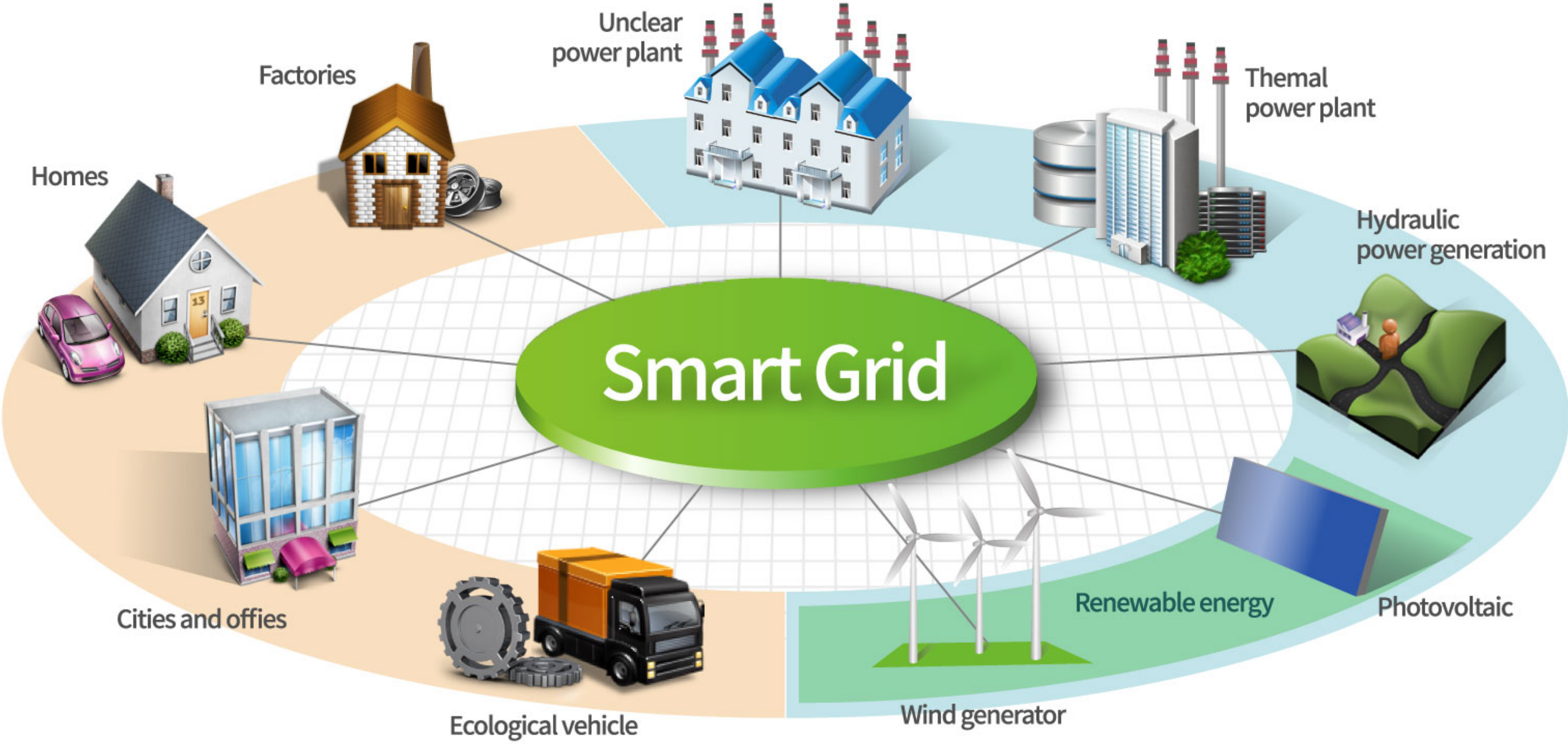
Consider a large factory with an inflexible electricity consumption over 24 hours. In order to reduce the electricity bill the factory's owner is thinking on installing solar panels and batteries. Write an optimization problem to determine the optimal amount of solar panels and batteries and solve it with GAMS. You need to figure out the following data:

- Electricity price throughout the planning horizon
- Electricity inflexible consumption throughout the planning horizon
- Solar capacity factor throughout the planning horizon
- Characteristics of each solar panel: maximum power and cost
- Characteristics of each battery: maximum power, round-trip efficiency, energy capacity and cost

  The objective function must include the purchase of electricity and the costs of solar panels and batteries. Note that the costs of solar panels and batteries should be adapted to the length of the planning horizon.

Smartgrids

A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers and those that do both) in order to efficiently deliver sustainable, economic and secure electricity supplies.



Smartgrids

A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies to:

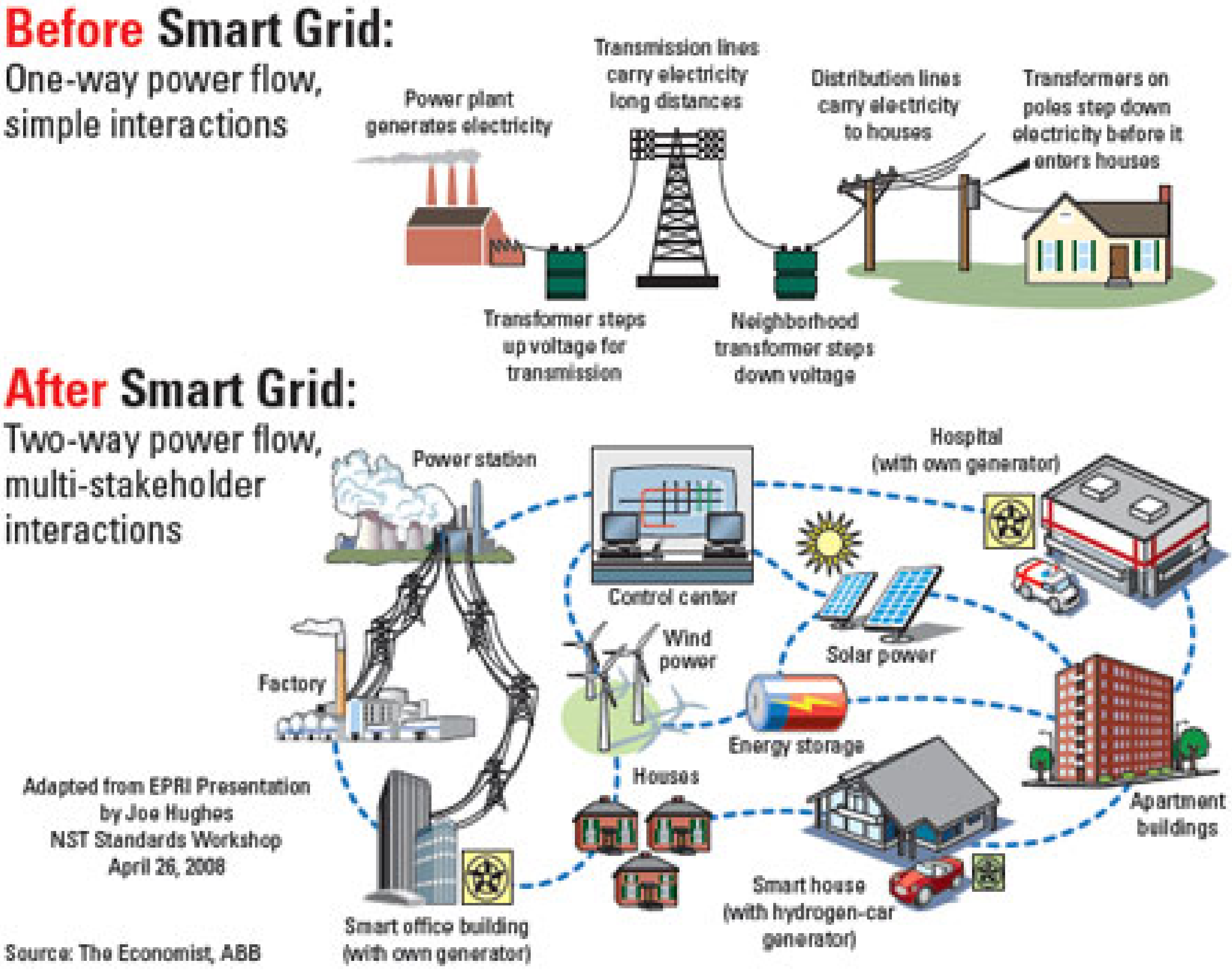
- enable the network to integrate users with new requirements
- better facilitate the connection and operation of generators of all sizes and technologies
- enhance the efficiency in grid operations
- allow electricity consumers to play a part in optimizing the operation of the system
- provide consumers with more information and choice in the way they secure their electricity supplies
- improve the market functioning and consumer services
- significantly reduce the environmental impact of the total electricity supply system
- deliver enhanced levels of reliability, quality and security of supply

Smartgrids

- The majority of changes will take place on the distribution level since:
  - A growing share of electricity will be generated in the distribution level.
  - Distribution networks will become active and will have to accommodate bi-directional power flows.
- One of the most important new devices in the smartgrids are the smart meters, which are electronic devices that record consumption of electric energy in intervals of an hour or less and communicates that information at least daily back to the utility for monitoring and billing.

Smartgrids

	Current Grid	**Smart Grid**
Communications	None or one-way Not real-time	Two-way Real-time
Customer interaction	Limited	Extensive
Metering	Electromechanical	Digital
Operation and maintenance	Manual time-based maintenance	Remote monitoring Predictive maintenance
Generation	Centralized	Centralized Distributed
Reliability	Prone to failures Cascading outages	Pro-active Real-time protection
Restoration	Manual	Self-healing
Topology	Radial	Network


Before Smart Grid:
One-way power flow, simple interactions
Power plant generates electricity
Transmission lines carry electricity long distances
Distribution lines carry electricity to houses
Transformers on poles step down electricity before it enters houses
Transformer steps up voltage for transmission
Neighborhood transformer steps down voltage
After Smart Grid:
Two-way power flow, multi-stakeholder interactions
Power station
Control center
Hospital (with own generator)
Solar power
Wind power
Factory
Energy storage
Houses
Apartment buildings
Adapted from EPRI Presentation by Joe Hughes NST Standards Workshop April 26, 2008
Smart house (with hydrogen-car generator)
Smart office building (with own generator)
Source: The Economist, ABB

OASYS group: Optimization and Analytics for Sustainable energY Systems

- Group starts in 2018
- Current members:
  - 2 senior researchers (Dr. Morales and Dr. Pineda)
  - 2 postdoctoral researchers (March 2018, March 2019)
  - 3 PhD students (February 2018, summer 2018, March 2019)
  - 1 young researcher starting in February 2018
- Research lines:
  - Decision-making under uncertainty
  - Data-driven optimization
  - Modeling of the energy sector based on game theory
  - Time series analysis and forecasting

OASYS group: Optimization and Analytics for Sustainable energY Systems

Options to join OASYS

- Before you finish your master:
  - Ayudas de iniciación a la investigación: se solicitan en Octubre, nota media superior a 7, 15 h/semana, 5 meses, 350€/mes.
- After you finish your master:
  - Empleo juvenil: se solicitan en Octubre, contrato en prácticas, 18 meses, 700-800€/mes.
  - Becas doctorado: distintas convocatorias (ministerio, junta, etc.), 36 meses, 1000-1200€/mes.