Electrical energy systems

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About the class

Main objectives:

- Get a broad understanding of the field electrical energy systems.
- Develop your ability to reason formally (using numbers and possibly small computer programs) in the world of (electrical) energy.
- Improve your ability to answer in an autonomous way scientific/technical questions as well as your presentation skills.

Organisational aspects of the class

Seven plenary lectures given by Prof. Damien Ernst on Thursday afternoon.

Plenary lectures interlaced by presentations of the students based on technical reports that they have to produce (and sent the day before the presentation). Quality of the presentations/technical reports count for 40% of the final note. There is a written exam at the end of the year that counts for 60%.

Participation to the class is mandatory.

Teaching material (slides plus links to reference books) available on my website : http://www.blogs.ulg.ac.be/damien-ernst/ . You can also follow Damien Ernst on facebook, twitter, google plus and linkedin where he regularly posts/discusses material related to this class.

Program of the class

Lesson 1-3: Units for energy - Computing the price of electrical energy - Why green energy? - Forms of production and of consumption of energy in a future green energy system that has electricity as structuring element.

Lesson 4: Solving the problem of fluctuations of consumption and production in a green energy system.

Lesson 5: Description of the electrical grid - direct and three phase current - transmission lines and electro-magnetic fields.

Lesson 6: Markets for electricity.

Lesson 7: The global grid for harvesting renewable energy - Microgrids - The future of electricity production in Belgium.

Units for energy and power

Joule (J): Unit of energy. It is equal to the energy transferred (or work done) when applying a force of one newton through a distance of one metre (1 newton metre or N·m), or in passing an electric current of one ampere through a resistance of one ohm for one second.
Watt (W): Unit of power (or rate of energy). The unit is defined as joule per second.
watt-hour (symbol Wh): Unit of energy. It is equal to the amount of energy produced during one hour by a constant power source of 1 W. 1 Wh = 3600 J.
kWh, MWh, GWh and TWh: 10^3, 10^6, 10^9 and 10^{12} Wh.
calorie: 4.182 J. Amount of energy required to warm one gram of air-free water from 19.5 to 20.5 °C at standard atmospheric pressure.

nutritional calorie or Calorie (with a capital C): 1000 calories.
British thermal unit (Btu): 2.93×10^{-7} MWh. Used in the gas business.
MMBtu: 10^6 Btu = 0.2930 MWh.
tonne of oil equivalent (toe): unit of energy defined as the amount of energy released by burning one tonne of crude oil. Equivalent to 11.63 megawatt-hours (MWh). Multiples of the *toe* are used, in particular, the megatoe (Mtoe, one million toe).
barrel of oil equivalent (BOE): Energy released by burning one barrel of crude oil($\simeq$ 159 litres). Equivalent to 1.6282 MWh of energy.

Exercise 1: The world energy consumption was equal to 155,055 TWh in 2012. How many 1000 MW nuclear power plants would be required to generate over one year this amount of energy?

Exercise 2: They are 7 billion humans on Earth. A human needs in average 2500 Calories of food per day. Compare the total amount of energy eaten every day by human with the daily amount of oil energy consumed everyday by the planet. *Data:* The world is consuming 90 million barrels of oil per day; there are 158.98 liters of oil in one barrel; amount of energy contained in 1 barrel of oil: 1.6282 MWh.

Answer 1:

Yearly energy produced by a 1000 MW power plant:
$\frac{1000\times10^6\times8760}{10^{12}} = 8.76$ TWh

Number of nuclear power plants required: $\frac{155{,}055}{8.76} = 17700$.

Answer 2:

Total energy intake of humans (in TWh): $\frac{7\times10^9\times2000\times4.18\times1000}{3600\times10^{12}} =$ 16.2 TWh.

Daily oil energy consumption (in TWh): $\frac{90\times10^6\times1.6282\times10^6}{10^{12}} = 146.5$ TWh.

Energy intake of humans is 9.05 times less than oil energy consumption.

Exercise 1: Compute the money you would spend on gas for producing one MWh of electricity in a combined cycle gas turbine (CCGT) power plant having an efficiency of 60%. *Data:* Price of gas: 3 \$/MMBtu.

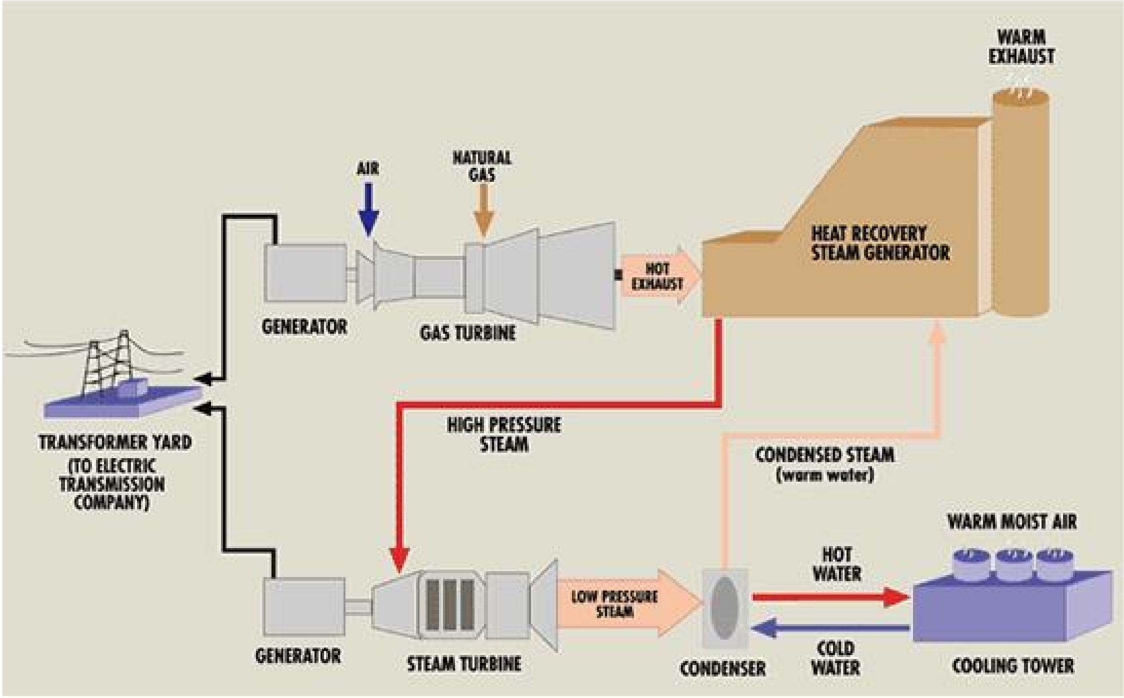
Exercise 2: Compute the money you would spend on coal for producing one MWh of electricity in a last generation coal-fired power station having an efficiency of 43%. *Data:* Price of one ton of coal \$40. There are 8.14 MWh of energy in one ton of coal.

Answer 1:
Cost of gas in \$/MWh: $\frac{3}{0.2930} = 10.23$ \$/MWh
Cost of gas for producing one MWh of electricity: $\frac{10.23}{0.60} = 17.05$ \$/MWh.

Answer 2:
Cost of coal in \$/MWh: $\frac{40}{8.14} = 4.91$ \$/MWh
Cost of coal for producing one MWh of electricity: $\frac{4.91}{0.43} = 11.42$ \$/MWh.

Combined cycle gas turbine (CCGT)

Basic principle of CCGTs: Use two complementary thermodynamic cycles to efficiently generate electricity. Heat generated by the combustion of natural gas in a primary gas turbine is then used to create high pressure steam that powers secondary steam turbines. These systems can have a thermal efficiency of 60%, rather than around 40% for open cycle gas turbines.



Measures of cost for (electrical) energy

The Levelized Cost of Electricity (LCOE) - or Levelized Energy Cost (LEC) is often taken as a measure for defining the cost of electrical energy. It is the net present value of the unit-cost of electricity.

LCOE is often taken as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime. It is a first-order economic assessment of the cost competitiveness of an electricity-generating system that incorporates all costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital.

$$LCOE = \frac{cost}{electricity} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where:

I_t = Investment expenditures in the year t

M_t = Operations and maintenance expenditures in the year t

F_t = Fuel expenditures in the year t

E_t = Electricity generation in the year t

r = Discount rate

n = Life of the system

The net present value (NPV) of a project for electricity generation is defined as:

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t}$$

where C_n is the cash flow during year n. C_n is equal to $R_t - M_t - F_t - I_t$ where R_t are the revenues generated by the power plant during year t.

The internal rate of return (IRR) of a project is the value of r that leads to a NPV equal to 0:
$NPV(r) = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} = 0$

The payback period is the period of time required to recoup the funds expended in an investment.

Exercice: Mister X has installed at home 4 kWp of PV panels at a price of 6000 €. His panels have a lifetime of 20 years. This installation generates 3500 kWh of electricity per year.
[A] Compute the LCOE given a discount rate of 0% and 5%.
[B] Assume a retail price for electriciy of 23 c/kWh, compute the payback period of the installation.
[C] Given the same retail price for electricity, compute the internal rate of return of the project.
Reminder: $\sum_{k=a}^{b} q^k = \frac{q^a - q^{b+1}}{1-q}$ where $a, b \in \mathbb{N}$ and $q \neq 1$.

[A] We have: (i) $I_1 = 4000$ € and $I_t = 0$ if $t \neq 1$ (ii) $M_t = 0$, $F_t = 0$, $E_t = 3500\ \forall t$ (iii) $n = 20$.
If $r = 0$, we have LCOE$=\frac{6000}{3500\times 20}=$ 8.5 c/kWh.
If $r \neq 0$, the LCOE can be rewritten as:

$$
\begin{aligned}
LCOE &= \frac{\frac{6000}{(1+r)}}{\sum_{t=1}^{20} \frac{3500}{(1+r)^t}} = \frac{6000 \times q}{3500 \times \sum_{t=1}^{20} q^t} \\
&= \frac{6000 \times q}{3500 \frac{q-q^{21}}{1-q}}
\end{aligned}
$$

where $q = \frac{1}{1+r}$. If $r = 0.05$, we have $q = 0.952$ and LCEO $= \frac{5712}{3500\times 12.42} =$ 13.1 c/kWh. If $r = 0.10$, we have $q = 0.909$ and LCEO $= \frac{5454}{3500\times 8.50}$ 18.3 c/kWh.

[B] Every year, the installation is generating $0.23 \times 3500 = 805$ € worth of electricity. The installation costs 6000 €. The payback time is therefore equal to $\frac{6000}{805}$ =7.45 years.

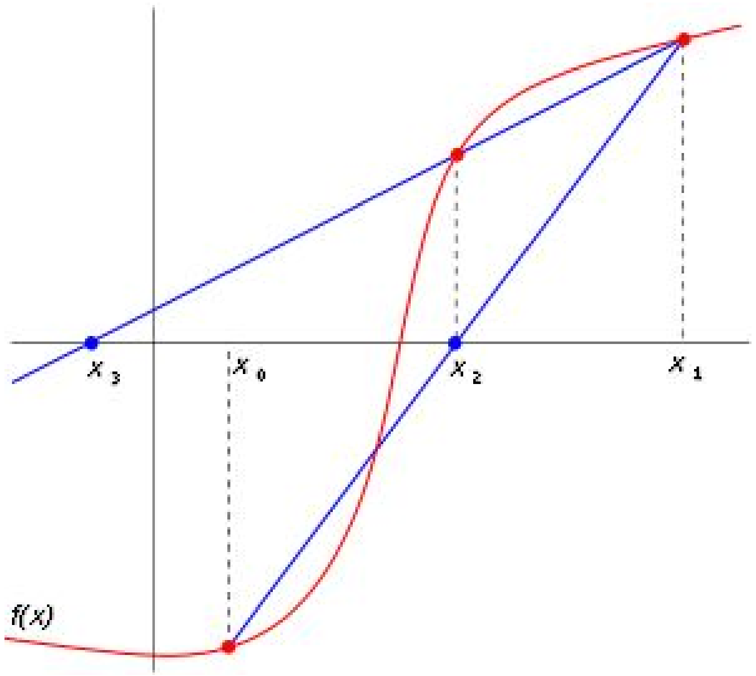
[C] No closed-loop solution. How to proceed?

A side note on the computation of the IRR

Computing the IRR is equivalent to finding the value of r that satisfies the equation $NPV(r) = 0$. In the general case, no closed form solution exists. A finite difference approximation of the Newton-Raphson method can however be used for finding a solution to this equation:

$$r_{n+1} = r_n - \frac{NPV(r_n)}{\frac{NPV(r_n)-NPV(r_{n-1})}{r_n - r_{n-1}}}$$

where r_n is considered the n^{th} approximation of the IRR.



The first two iterations of the Newton's method for finding the root of the function $f(x)$

The convergence behaviour of the sequence is the following:

- If the function $NPV(r)$ has a single real root IRR, then the sequence converges reproducibly towards IRR.

- If the function $NPV(r)$ has n real roots IRR_1, IRR_2, ... , IRR_n, then the sequence converges to one of the roots, and changing the values of the initial pairs may change the root to which it converges.

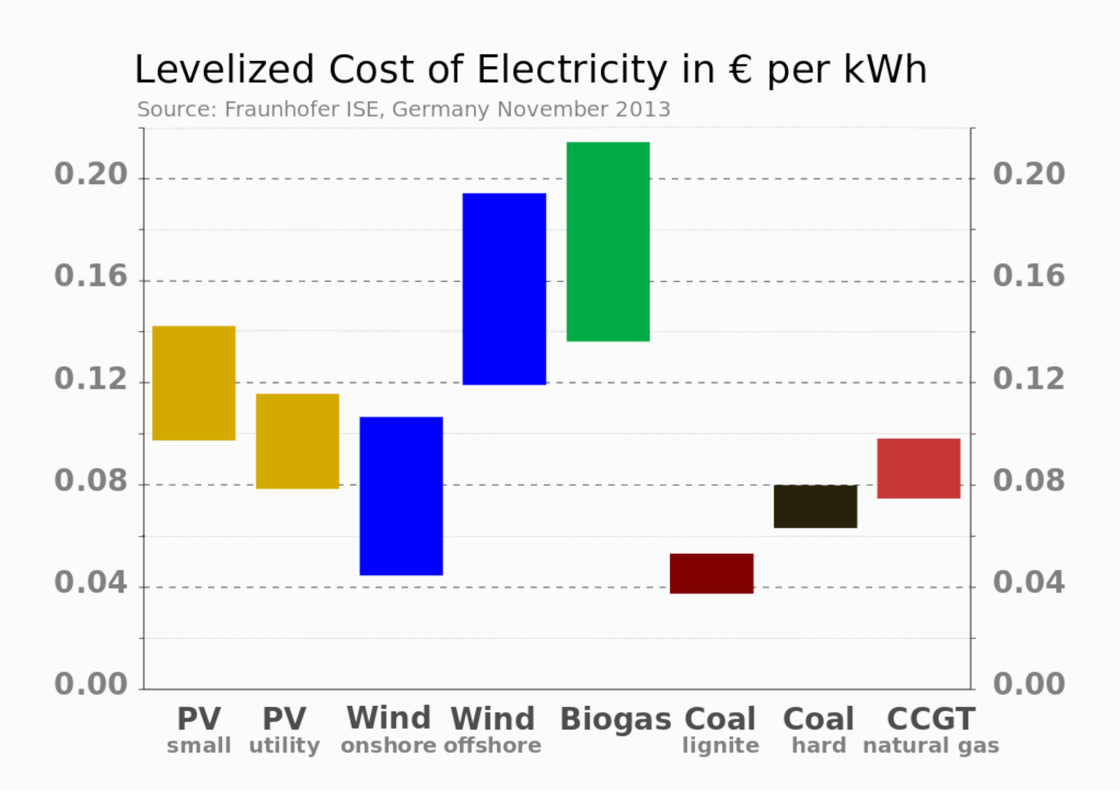
- If function NPV(r) has no real roots, then the sequence tends towards $+\infty$.

Exercice: Write a small program for computing the IRR of previous exercise and illustrate the results obtained.

```python
#Program for computing the IRR of the PV installation


def NPVExample(r):
    C = [None]*20
    C[0]=3500*0.23-6000
    for n in range(1,20):
        C[n]=3500*0.23
    NPV=0
    n=0
    while n < len(C):
        NPV=NPV+C[n]/(1+r)**(n+1)
        n=n+1
    return NPV


def NewtonRaphston(x0, x1, f, iterMax, accuracy):
    iter=0
    xnMinus1=x0
    xn=x1
    while (f(x0) != f(x1)) & (iter < iterMax) &  (f(x1) < accuracy):
        xnPlus1=xn-f(xnMinus1)/((f(xn)-f(xnMinus1)/(xn-xnMinus1)))
        iter=iter+1
    return xnPlus1



print 'The value of the IRR for the project is '
print  NewtonRaphston(x0=0, x1=10, f=NPVExample,iterMax=1000, accuracy=0.00001)
```

If you run this program in Python, you will get an IRR of 16.84%

The levelized cost of electricity for some newly built renewable and fossil-fuel based power stations in euro per kWh in Germany (estimation done in 2013 by the Fraunhofer Institute):



Why green energy?

The three classical arguments usually used for green energy:
1. Fossil fuels are a finite resource (we will run out of cheap gas and oil in our lifetime) that should be used for better uses than simply setting fire to them.
2. Even if fossil fuels are still available around the world, we perhaps do not want to depend on untrustworthy foreigners or finance regimes that do not embrace our Western values (e.g., Saudi Arabia).
3. The environmental motivations: (i) the burning of fossil-fuel is believed to be a major contributor to climate change through the release of carbon dioxide emissions (CO_2) (ii) burning of fossil fuel also releases other pollutants into the atmosphere (e.g., SO_2 or NO_x) (iii) Extracting fossil fuels may significantly pollute the environment.

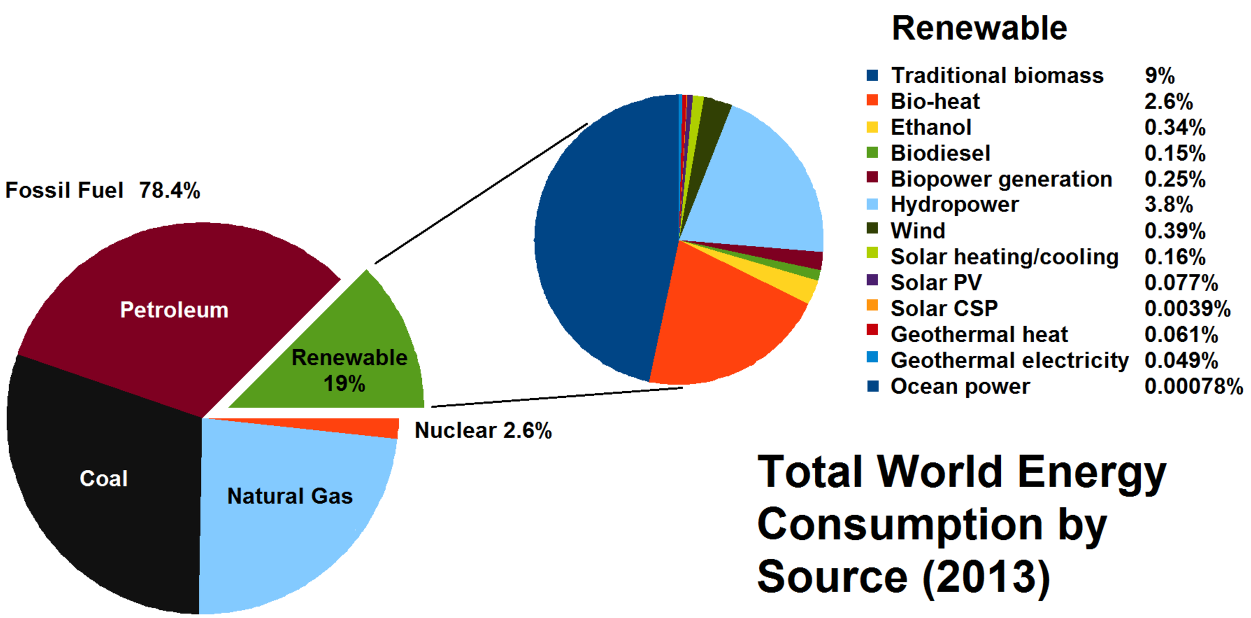
And a fourth one is appearing: **Renewable energy - especially wind and solar energy - is becoming a cheap.**

Exercice: The world is consuming 90 million of barrels of oil per year. Assume that we can only recover the top seventeen reserves of oil of the world, as estimated in 2012.
[A] When will we run out of oil?
[B] How many years could we cover the world energy needs by using our remaining oil and by assuming that our energy consumption stays equal to 155,055 TWh. *Data:* (i) There is 1.6282 MWh of energy in one barrel of oil. (ii) See table on the right.

Summary of Proven Reserve Data as of 2012[2]

—	Country	Reserves[18] 10^9 bbl	Reserves 10^9 m^3	Production[19] 10^6 bbl/d	Production 10^3 m^3/d	Reserve/ Production Ratio[1] years
1	Venezuela	296.50	47.140	2.1	330	387
2	Saudi Arabia	265.40	42.195	8.9	1,410	81
3	Canada	175.00	27.823	2.7	430	178
4	Iran	151.20	24.039	4.1	650	101
5	Iraq	143.10	22.751	2.4	380	163
6	Kuwait	101.50	16.137	2.3	370	121
7	United Arab Emirates	97.80	15.549	2.4	380	156
8	Russia	80.00	12.719	10.0	1,590	22
9	Libya	47.00	7.472	1.7	270	76
10	Nigeria	37.00	5.883	2.5	400	41
11	Kazakhstan	30.00	4.770	1.5	240	55
12	Qatar	25.41	4.040	1.1	170	63
13	China	25.40	4.038	4.1	650	15
14	United States	25.00	3.975	7.0	1,110	10
15	Angola	13.50	2.146	1.9	300	19
16	Algeria	13.42	2.134	1.7	270	22
17	Brazil	13.20	2.099	2.1	330	17
	Total of top seventeen reserves	1,324.00	210.499	56.7	9,010	64

[A] We will run out of oil in: $\frac{1329\times10^9}{90\times10^6\times365} = 40.45$ years.
[B] Number of years we could cover the world energy consumption with our reserves of oil: $\frac{155055\times10^{12}}{1329\times10^9\times1.6282\times10^6} = 13.9$ years.
Relation between answer [A] and [B] in accordance with the following figure:



Beyond the notion of reserves: the EROI

The energy returned on energy invested (EROEI or ERoEI); or energy return on investment (EROI), is the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource.

$$EROI = \frac{\text{Usable Acquired Energy}}{\text{Energy expended}}$$

Comments: (i) the higher the EROI, the more likely the cheaper the energy will be (ii) a society that relies on energy that has a too low energy return on investment is very likely to go into recession (iii) the EROI for new oil discoveries keeps dropping, which is a sign of more and more expensive oil. A few numbers: at the beginning of the oil age, the ENROI for oil was 100. In 1970, US oil has EROI that had dropped to 30. For shale oil and gas - the US energy miracle - the EROI is around 5.

But the EROI for renewable energy may not be that flattering (see graphic below). There is a concern of energy cannibalism with renewable energy. Energy cannibalism refers to an effect where rapid growth of an entire energy producing or energy efficiency industry creates a need for energy that “cannibalizes” the energy of existing power plants or production plants.