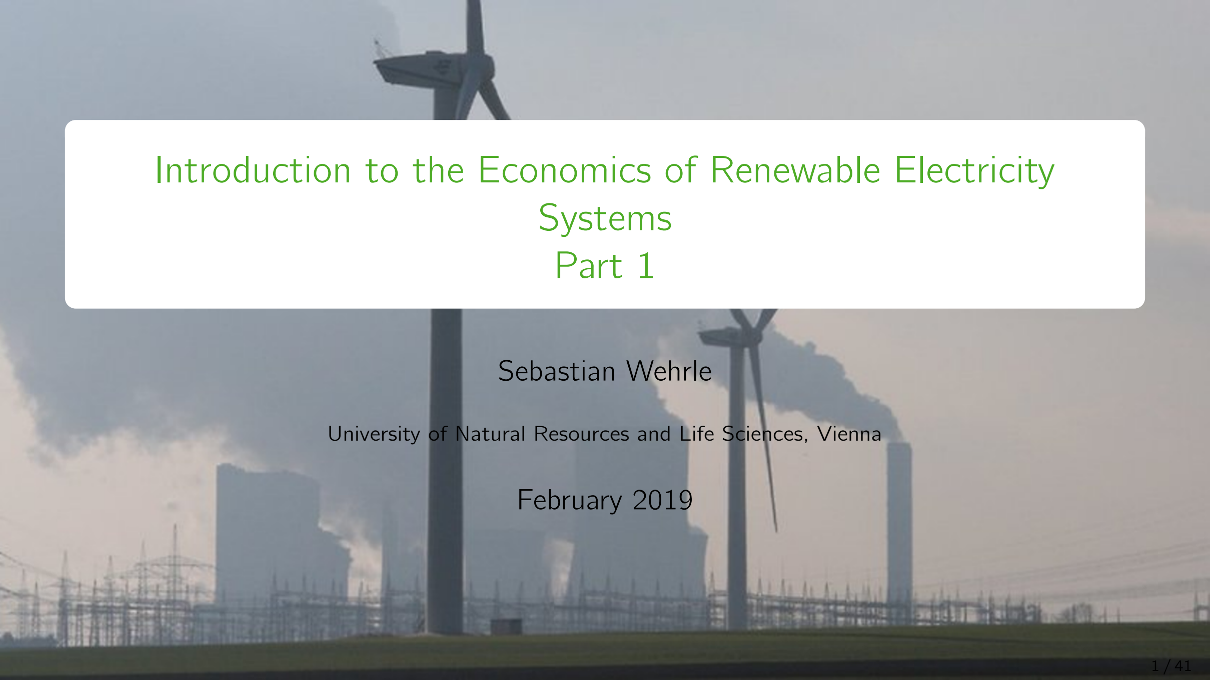

Introduction to the Economics of Renewable Electricity Systems
Part 1

Sebastian Wehrle

University of Natural Resources and Life Sciences, Vienna

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Economics of Renewable Electricity Systems

Economics is . . .

- *"an inquiry into the nature and causes of the wealth of nations."* A. Smith, 1776
- *"the science of production, distribution, and consumption of wealth."* J. B. Say, 1803
- *"a calculus of pleasure and pain."* W. S. Jevons, 1871
- *"a science which studies human behaviour as a relationship between ends and scarce means which have alternative uses."* L. Robbins, 1932
- *"what economists do."* R. Backhouse & S. Medema, 2008

Economics of Renewable *Electricity Systems*

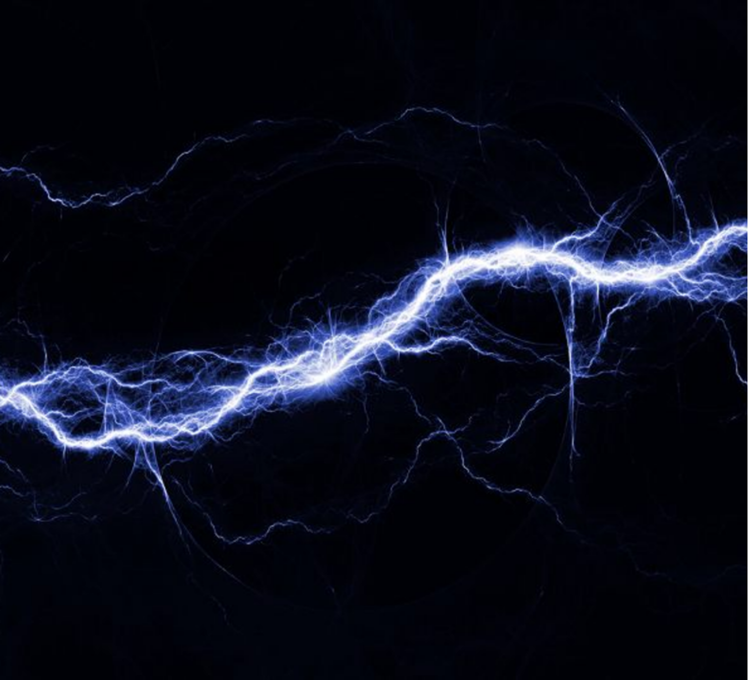
Classical Electricity Economics is concerned with:

- energy supply, mostly from a firm's perspective
  - in which plant should we invest?
  - at which price should we sell electricity?
- determinants of electricity consumption
  - what happens to consumption when the price of electricity increases by 10%?
  - how could we incentivise consuming less electricity?
- market structure & market performance
  - how are prices formed on the market?
  - is there collusion between firms?
- market regulation
  - how can we prevent collusion of firms?
  - how do we incentivise policy goal xyz?

Economics of Renewable Electricity Economics

This course will cover some economic aspects of the transition to electricity systems with high shares of electricity generation from renewable sources.

- which direct and external costs and benefits does renewable electricity generation have?
- how much of which renewable generation technology should we deploy?
- how to reduce CO_2 emissions from power generation at the lowest cost?
- do we need support schemes for renewable energy? If so, how should these be designed?



Electricity

Electricity

According to Wikipedia,

> *Electricity is the set of physical phenomena associated with the presence and motion of matter that has a property of electric charge.*

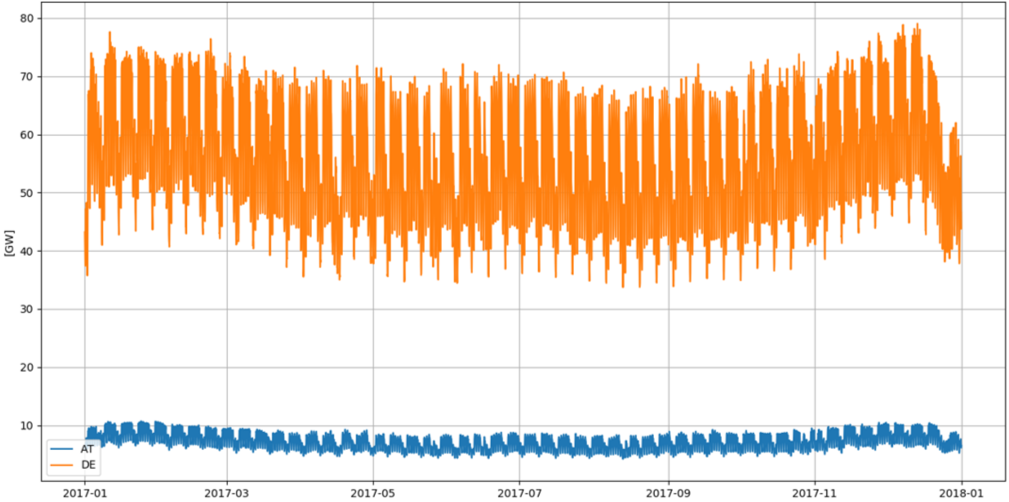
Electricity from an Economist's perspective

Electricity

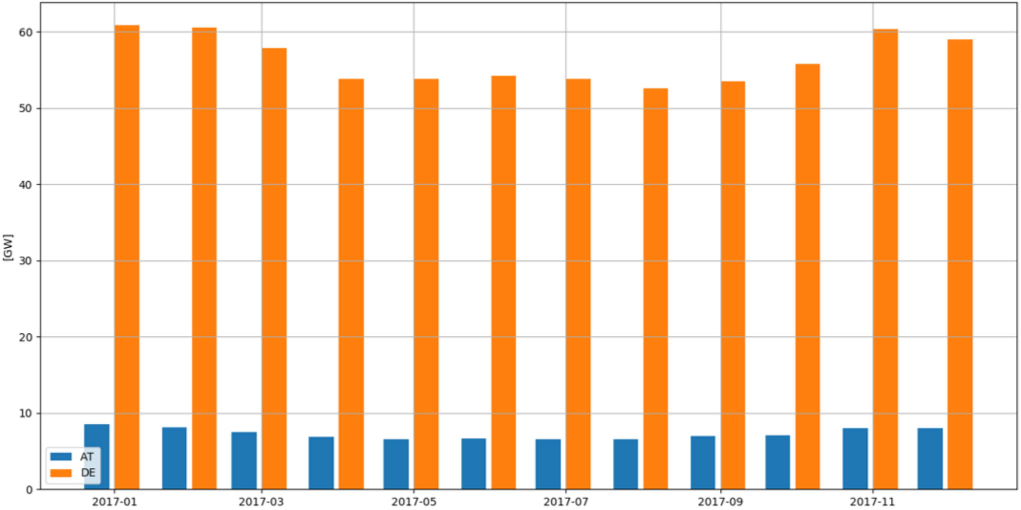
- is a homogeneous product ⇒ how to differentiate products?
- is hard to store ⇒ economic value depends on time and location
- has few alternatives ⇒ price elasticity of demand is very low
- is best when transmitted /distributed via grid, but natural monopoly in transmission / distribution

Electricity Consumption

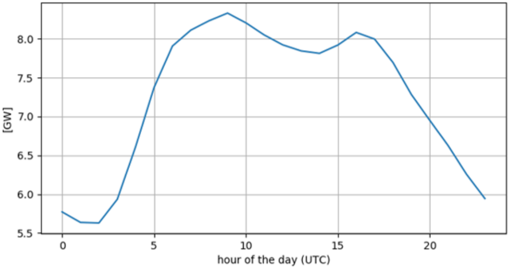
hourly system load 2017

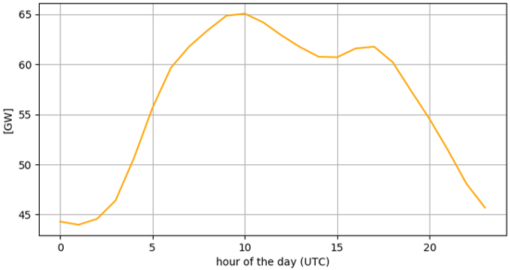


average monthly system load 2017

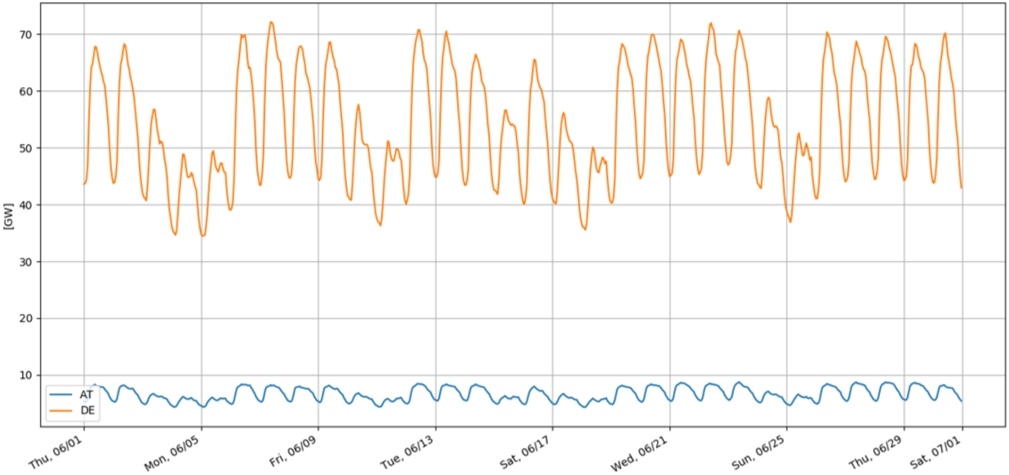


hourly average system load 2017

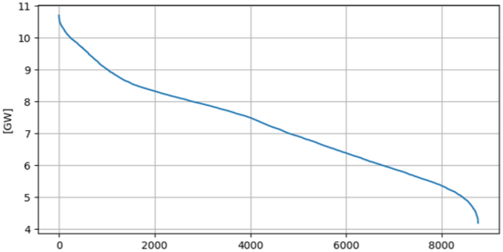


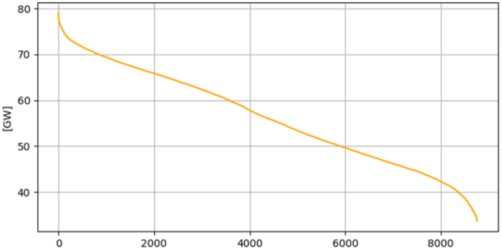


hourly system load June 2017



load duration 2017





Electricity Generation

Electricity Generation

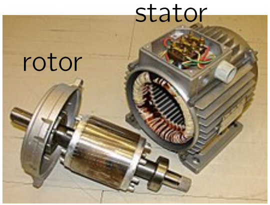
Most of the electricity consumed from the grid is generated by generators

- remainder generated by photovoltaic effect (plus a tiny bit electrochemically)
- electric current is induced, when a magnetic rotor rotates in the stator, which consists of copper coils

The mechanical energy for rotating the rotor comes from turbines

- steam turbine
- combustion turbine
- water turbine
- wind turbine

For further technical details on turbines and generators, please consult an engineer or encyclopaedia of your choice.



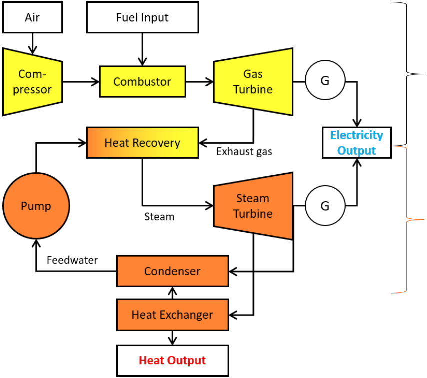
generator

combustion turbine

Thermal Electricity Generation

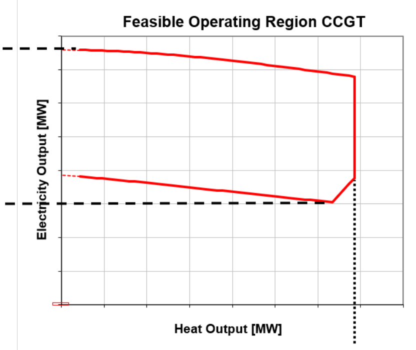
thermal electricity generation

example of a combined-cycle gas turbine (CCGT)



combustion turbine process

steam turbine process



Rated electrical capacity

Minimal feasible electricity output

Rated thermal capacity

thermal electricity generation

technical operating constraints

start-up of a unit

- requires (additional) fuel
- causes wear and tear
- takes some time (till a stationary operation state is reached)
- how much time depends on the state of the unit (hot/warm/cold)

ramping (i.e. a change in the level of output)

- happens gradually
- causes wear and tear

shut-down of a unit

- takes some time
- requires fuel

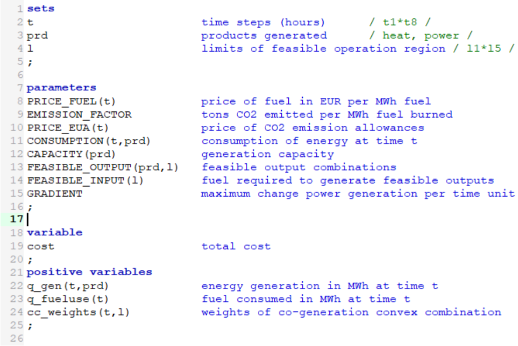
thermal electricity generation

some properties

fuel	technology	typical efficiency	CO_2 intensity fuel	CO_2 intensity power	invest cost	fuel cost	o&m cost	lifetime
nuclear	steam turbine	35	0	0	6000+	1.50	4	45
lignite	steam turbine	35	450	1285	1200+	2.50	3.50	40
lignite	steam turbine (BoA)	42	450	1070	1500	2.50	3.50	40
hard coal	steam turbine (subcritical)	39	330	940	1200	10	3	40
hard coal	steam turbine (supercritical)	44	330	750	1300	10	3	40
hard coal	steam turbine (ultrasupercrit.)	46	330	720	1400	10	3	40
natural gas	steam turbine	41	200	490	450	20	1.50	35
natural gas	combustion turbine	39	200	510	450	20	1.50	35
natural gas	combined cycle	60	200	330	800	20	2	35

modelling thermal power generation

a simple example in GAMS



```
sets
t                         time steps (hours)      / t1*t8 /
prd                       products generated      / heat, power /
l                         limits of feasible operation region / l1*l5 /
;

parameters
PRICE_FUEL(t)             price of fuel in EUR per MWh fuel
EMISSION_FACTOR           tons CO2 emitted per MWh fuel burned
PRICE_EUA(t)              price of CO2 emission allowances
CONSUMPTION(t,prd)        consumption of energy at time t
CAPACITY(prd)             generation capacity
FEASIBLE_OUTPUT(prd,l)    feasible output combinations
FEASIBLE_INPUT(l)         fuel required to generate feasible outputs
GRADIENT                  maximum change power generation per time unit
;

variable
cost                      total cost
;
positive variables
q_gen(t,prd)              energy generation in MWh at time t
q_fueluse(t)              fuel consumed in MWh at time t
cc_weights(t,l)           weights of co-generation convex combination
;

```

```
objective..               cost
                          =E=
                          sum(t, q_fueluse(t) * (PRICE_FUEL(t)
                                                   + EMISSION_FACTOR * PRICE_EUA(t)) )
                          ;
supply_demand_balance(t,prd)..
                          q_gen(t,prd)
                          =G=
                          CONSUMPTION(t,prd)
                          ;
caplim_generation(t, prd)..
                          q_gen(t,prd)
                          =L=
                          CAPACITY(prd)
                          ;
cc_a(t)..                 Sum(l, cc_weights(t,l))
                          =E=
                          1
                          ;
cc_b(t,prd)..             q_gen(t,prd)
                          =E=
                          Sum(l, cc_weights(t,l) * FEASIBLE_OUTPUT(prd,l) * CAPACITY(prd) )
                          ;
cc_c(t)..                 q_fueluse(t)
                          =G=
                          Sum(l, cc_weights(t,l) * FEASIBLE_INPUT(l) * CAPACITY('power') )
                          ;
ramp_up(t)..              q_gen(t,'power') - q_gen(t-1,'power')
                          =L=
                          GRADIENT * CAPACITY('power')
                          ;
ramp_down(t)..            q_gen(t,'power') - q_gen(t-1,'power')
                          =G=
                          - GRADIENT * CAPACITY('power')
                          ;
```

modelling thermal power generation

further reading

G. Morales-Espana, J.M. Latorre and A. Ramos (2013):
Tight and compact MILP Formulation for the Thermal Unit Commitment Problem
in: IEEE Transactions on Power Systems, 28(4), 4897-4908

implements

- on/off - decision
- minimum generation level
- minimum up and down times
- start-up and shut-down cost
- depending on unit state

Hydro Electricity Generation

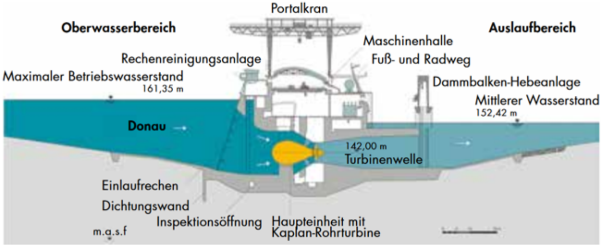
hydro electricity generation

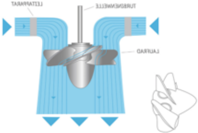
run-of-river plant

Freudenau power plant

power: $172 MW$
annual generation: $1030 GWh$
flow rate: $3000 \frac{m^3}{s}$

head: $8.6 m$

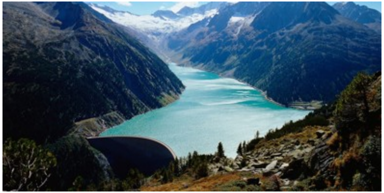


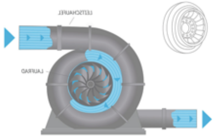


Kaplan turbine

hydro electricity generation

reservoir & pumped storage plant



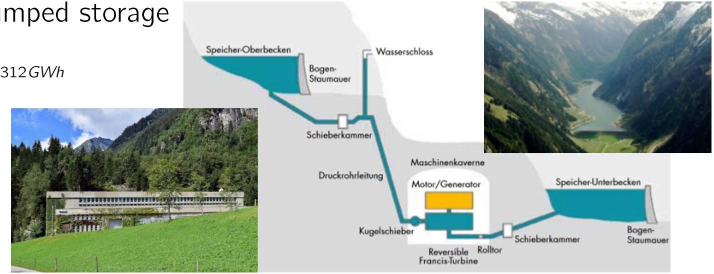


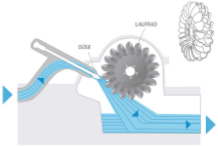
Francis turbine

Rosshag pumped storage

power: 231 MW
annual generation: 312 GWh
flow rate: 52 $\frac{m^3}{s}$

head: 630 m

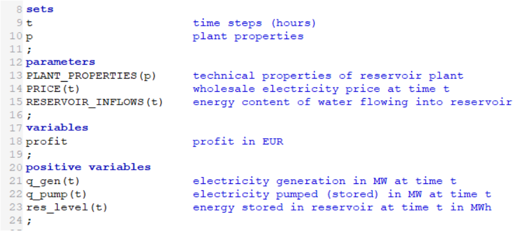




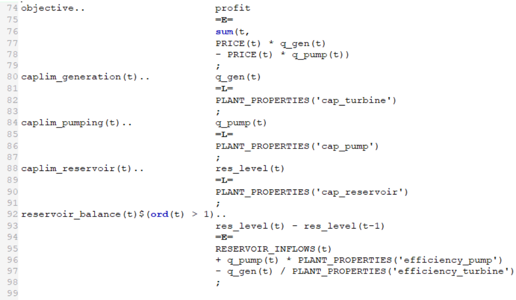
Pelton turbine

modelling hydro storage plant

a simple example in GAMS



```
sets
t                       time steps (hours)
p                       plant properties
;
parameters
PLANT_PROPERTIES(p)     technical properties of reservoir plant
PRICE(t)                wholesale electricity price at time t
RESERVOIR_INFLOWS(t)    energy content of water flowing into reservoir
;
variables
profit                  profit in EUR
;
positive variables
q_gen(t)                electricity generation in MW at time t
q_pump(t)               electricity pumped (stored) in MW at time t
res_level(t)            energy stored in reservoir at time t in MWh
;
```



```
objective..                      profit
                                 =E=
                                 sum(t,
                                 PRICE(t) * q_gen(t)
                                 - PRICE(t) * q_pump(t))
                                 ;
caplim_generation(t)..           q_gen(t)
                                 =L=
                                 PLANT_PROPERTIES('cap_turbine')
                                 ;
caplim_pumping(t)..              q_pump(t)
                                 =L=
                                 PLANT_PROPERTIES('cap_pump')
                                 ;
caplim_reservoir(t)..            res_level(t)
                                 =L=
                                 PLANT_PROPERTIES('cap_reservoir')
                                 ;
reservoir_balance(t)$(ord(t) > 1)..
                                 res_level(t) - res_level(t-1)
                                 =E=
                                 RESERVOIR_INFLOWS(t)
                                 + q_pump(t) * PLANT_PROPERTIES('efficiency_pump')
                                 - q_gen(t) / PLANT_PROPERTIES('efficiency_turbine')
                                 ;

```

Levelized Cost of Electricity (LCOE)

Levelised Cost of Electricity

Imagine you are a simple strategist at some ancient utility. Your company has a monopoly in energy generation, transmission and distribution.

Your boss asks you to propose some investment in energy generation.

- how do you decide which technologx to invest in?
- how do you decide what to charge for the generated energy?

In all his simplicity, the strategist thinks: "let's compare *average* cost of all technologies. Then, we know

- which technology to chose (the cheapest, of course!)
- the minimal price that has to be charged to break even

This, however, must be done for the whole lifetime of the technology, as the exact engineer (who is the simple strategist's boss) points out.

Levelized Cost of Electricity

The simple strategist comes up with a formula for the expected real total cost (capital and operating cost) per MWh produced over the generating unit's lifetime.

The exact engineer calls it »levelized cost of electricity«, but the simple strategist thinks it's just a weird way of saying "*net present value of total cost per output*".

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$

with

- I_t investment cost,
- M_t o&m cost,
- F_t fuel cost,
- E_t energy generated,
- r discount rate,
- T system lifetime.

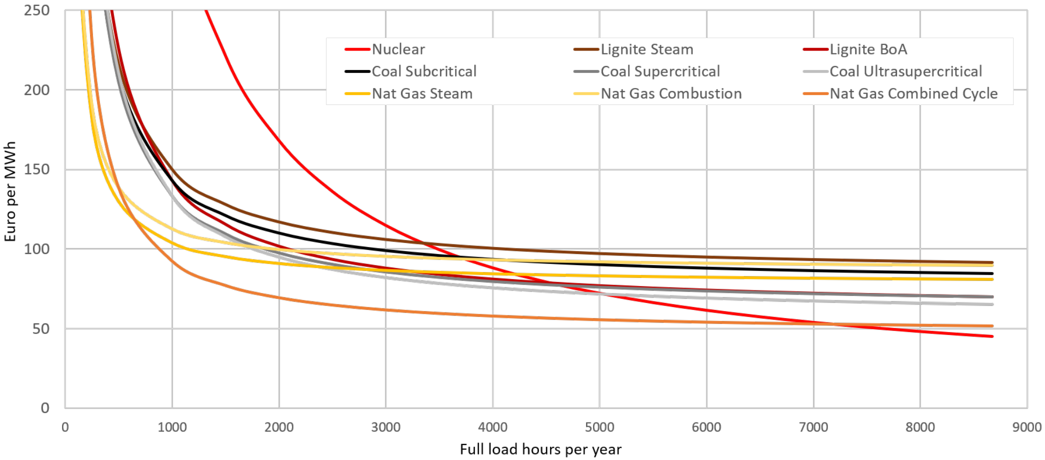
Levelized Cost of Electricity

Now having a formula, the exact engineer was happy.

The simple strategist was happy that the exact engineer was happy.

Yet, doing all the math, the simple strategist wondered whether some aspect was overlooked.

Levelized Cost of Electricity



Screening Curves

Screening curves

Suppose, once again, you are a simple strategist working for an ancient utility.

Recently, you realized that most of the time you are not investing in a greenfield unit, but rather add or replace units in an existing system.

Thus, one should somehow take into account that not all units are generating energy all the time.

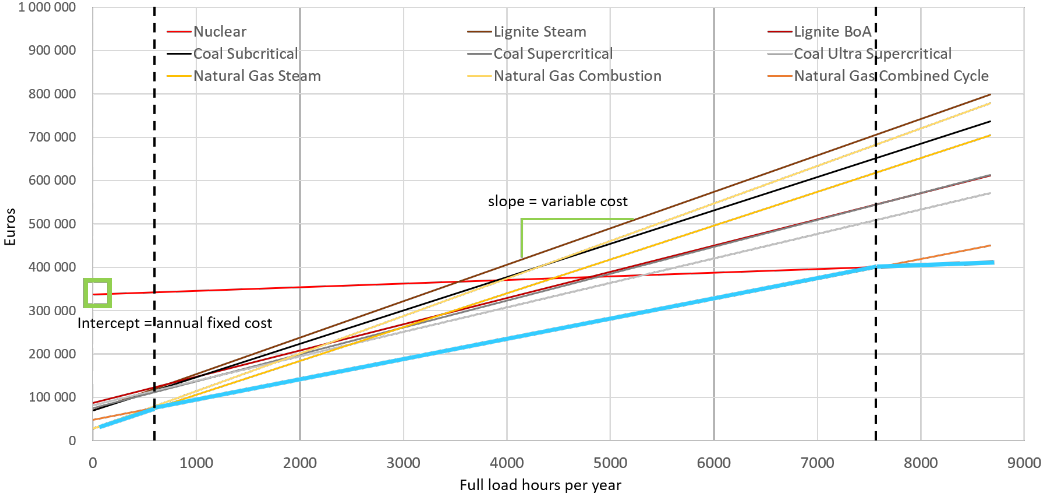
Is there a way to figure out which unit to invest in, given the new unit affects overall utilisation?

Screening curves

The simple strategist puts on his thinking cap:

> *If one looks at total annual cost instead of average cost, one should be able to identify minimal annual generation cost of all alternatives, conditional on the numer of full load hours.*

Screening curves



slope = variable cost

Intercept = annual fixed cost

Screening curves

Nice! Now we have an idea which plant is cheapest when operating for a given number of full load hours.

Hold on. Does this answer my questions?

- choice of capacity?
- expected utilisation?

Somehow we need to figure out how many hours each unit should operate at which capacity.

Screening curves

[Add screening curves method figure here]

GAMS

some basics

GAMS can easily read (properly formatted) text files.

- set identifiers need to be provided
- columns are separated by blanks

GAMS looks for inputs in your working directory (where the GAMS project file .gpr is located)

```
parameter INPUT(t) /
$include inputdata.txt
/;
```

GAMS

loops

1. define a set to loop over
2. define a PARAMETER to collect the results
3. set up the loop. First, modify the PARAMETER of interest, then solve your model. Finally, write results to the respective PARAMETER.

```
set iterations / i1*i10 /;
parameter RESULTS(iterations, *);
loop(iterations,
        co2_price = (ord(iterations) - 1) * 10;
        solve my_model using LP minimizing cost:
        results(iterations, "total cost") = cost.L;
```

GAMS

writing text files

GAMS can easily dump results in gdx-files. However, this can be inconvenient for rapid analysis. Using put, GAMS can also create text files.

```
file output / "filename.csv" /;
put output;
loop(set,
        put set.TL, ";", variable.L(t), ";" /
);
putclose
```

Universität für Bodenkultur Wien
Department für Wirtschafts- und
Sozialwissenschaften

thanks for your interest!

sebastian.wehrle@boku.ac.at