Energy Systems, Summer Semester 2023
Lecture 2: Measuring & Converting Energy

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Table of Contents

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1. Measuring energy

2. Energy conversion

Measuring energy

Units of Energy: Joule and tonne of oil equivalent

Joule (J) is the SI unit of energy.

Conventional primary energy sources are often measured in units corresponding to their natural form: volume, mass etc.

We can convert from measurements of mass [kg] and volume [m^3] to energy units using the **calorific value** [J/kg, J/m^3], which measures the heat from combustion.

Example: the unit **tonne of oil equivalent** (toe) is the energy generated by burning one metric ton of oil. Since the calorific value of oil is 41.88 MJ/kg, we have

$$1 \text{ toe} = 41.88 \text{ GJ}$$

[Reminder: k = kilo = 1e3, M = Mega = 1e6, G = Giga = 1e9, T = Tera = 1e12, P = Peta = 1e15, E = Exa = 1e18.]

Lower Heating Values of Energy Fuels

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	Density	Energy [10^9 J]	Remarks
1 t Crude oil	0.86 g/cm^3	39–43	Mean: 41.9·10^9 J
1 Barrel (bbl) crude oil		5.7	=159 l (ca. 50/365 t.o.e.)
1 t Heating oil el.	0.84 g/cm^3	42.5	at 15–20 °C
1 t Gasoline	0.75 g/cm^3	43.1	at 15–20 °C
1 t Methanol (CH_3OH)	0.80 g/cm^3	19.7	
1 t Ethanol (C_2H_5OH)	0.80 g/cm^3	26.9	
1 t Liquefied Petroleum Gas LPG	0.53 g/cm^3	45.9	at 2–18 bar
1 t Liquefied Natural Gas LNG	0.47 g/cm^3	47.2	at –164 °C
1 t Hydrogen (LH_2)	0.071 g/cm^3	120.4	at –252 °C
1000 m^3 Natural gas L	0.82 kg/m^3	33.4	Mean: 35.6·10^9 J
1000 m^3 Natural gas H	0.79 kg/m^3	36.6	
1000 m^3 Compressed gas CNG	156 kg/m^3	7000	at 200 bar
1000 m^3 Petroleum gas		40.7	
1000 m^3 Methane (CH_4)	0.65 kg/m^3	35.8	
1000 m^3 Propane (C_3H_8)	1.87 kg/m^3	86.7	
1000 m^3 hydrogen (H_2)	0.09 kg/m^3	10.8	
1000 m^3 Liquefied hydrogen (H_2)	15.6 kg/m^3	1950	at 200 bar
1 t Hard coal		29–35	Mean 29.3· 10^9 J
1 t Lignite		7.5–13	
1 t Wood	0.6 g/cm^3	14.6	3.5 · 10^6 kcal
1 t Uranium oxide (U_3O_8)		414'000	Light Water Reactor LWR

Higher and Lower Heating Values

- **Lower Heating Value (LHV)** is the maximum amount of usable heat from combustion without counting the condensation enthalpy of water vapor contained in the exhaust gas.
- **Higher Heating Value (HHV)** includes the condensation enthalpy of water vapor contained in the exhaust gas. It is always higher than the LHV (e.g. 11% higher for methane).

Fuel	State at ambient temperature and pressure	HHV (MJ/kg)	LHV (MJ/kg)
Hydrogen	Gas	141.9	119.9
Methane	Gas	55.5	50
Ethane	Gas	51.9	47.8
Gasoline	Liquid	47.5	44.5
Diesel	Liquid	44.8	42.5
Methanol	Liquid	20	18.1

LHV is most commonly used in European statistics. HHV becomes relevant in e.g. condensing combined heat and power plants (CHP) where vapor is condensed.

Power: Flow of energy

Power is the rate of consumption of energy.

It is measured in **Watts**:

$$1 \text{ Watt} = 1 \text{ Joule per second}$$

The symbol for Watt is W, 1 W = 1 J/s.

$$1 \text{ kilo-Watt} = 1 \text{ kW} = 1{,}000 \text{ W}$$

$$1 \text{ mega-Watt} = 1 \text{ MW} = 1{,}000{,}000 \text{ W}$$

$$1 \text{ giga-Watt} = 1 \text{ GW} = 1{,}000{,}000{,}000 \text{ W}$$

$$1 \text{ tera-Watt} = 1 \text{ TW} = 1{,}000{,}000{,}000{,}000 \text{ W}$$

Power: Examples of consumption

At full power, the following items consume:

Item	Power
New efficient lightbulb	10 W
Old-fashioned lightbulb	70 W
Single room air-conditioning	1.5 kW
Kettle	2 kW
Factory	∼1-500 MW
CERN	200 MW
Germany total demand	35-80 GW

Power: Supplying world's energy with wind and solar

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If all energy is electrified in 2050 and energy consumption equalises between nations, the average electricity consumption of the world would be around 12 TW.

Suppose half is met with wind (capacity factor 33.3%) and half is met with solar PV (capacity factor 16.6%). [Capacity factor = average generation / capacity.] How much wind and solar capacity does the world need (assuming perfect lossless storage)?

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Wind: 6 TW / 0.333 = 18 TW (around 743 GW was installed by 2020)

Solar: 6 TW / 0.166 = 36 TW (around 626 GW was installed by 2019)

Power: Supplying world's energy with wind and solar

If installed wind density on average is 10 MW/km^2 and solar is 72 MW/km^2, what percentage of world land (510 million km^2) is taken with each?

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If installed wind density on average is 10 MW/km^2 and solar is 72 MW/km^2, what percentage of world land (510 million km^2) is taken with each?

Wind: 18 TW/(10 MW/km^2) = 1.8 million km^2 (around 0.35% of total land = area of Indonesia)

Solar: 36 TW/(72 MW/km^2) = 0.5 million km^2 (around 0.1% of total land = area of Spain)

Nota Bene:

- Wind doesn't interfere with other land uses like agriculture
- 10 MW/km^2 is a **local** maximum installation density for wind, but to allow wind replenishment over large areas 2 MW/km^2 is suitable as a **wide-area** limit
- Solar can be rooftop or combined with agriculture = agrivoltaics

Units of energy: Watt-hour

In the electricity sector, energy is usually measured in 'Watt-hours', Wh.

1 kWh = power consumption of 1 kW for one hour

E.g. a 10 W lightbulb left on for two hours will consume

10 W * 2 h = 20 Wh

It is easy to convert this back to the SI unit for energy, Joules:

1 kWh = (1000 W) * (1 h) = (1000 J/s)*(3600 s) = 3.6 MJ

Yearly energy to power

Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the *average* power consumption in GW?

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$$\begin{aligned} 600\ \mathrm{TWh/a} &= \frac{(600\ \mathrm{TW}) * (1\ \mathrm{h})}{(365 * 24\ \mathrm{h})} \\ &= \frac{600}{8760}\ \mathrm{TW} \\ &= 68.5\ \mathrm{GW} \end{aligned}$$

Tables for converting units

multiply by:	GJ	Toe	MBtu	MWh
GJ	1	0.024	0.948	0.278
Toe	41.868	1	39.683	11.630
MBtu	1.055	0.025	1	0.293
MWh	3.600	0.086	3.412	1

Units used in the United States:

- British thermal unit (Btu), 1 million Btu = MBtu (often written MMBtu) = 0.293 MWh
- Quad = 1e15 Btu

Energy conversion

Energy conversion/transformation processes

Output Input	Mechanical energy	Thermal energy	Chemical energy	Electricity	Radiation
Mechanical energy	–	Frictional heat	–	Hydropower turbine	–
Thermal energy	Heat engine	–	Thermo-chemistry	Electrical generator	–
Chemical energy	Combustion engine	Boiler	–	Fuel cell	Gas lamp
Electricity	Electric engine	Induction heater	Electrolysis	–	Electric bulb
Radiation	Laser	Microwave oven	Solar chemistry	Photovoltaic	–
Nuclear energy	–	Nuclear reactor	–	–	Radioactivity

Source: Zweifel, Praktiknjo & Erdmann (2017)

Energy conversion efficiency

Efficiency of an energy conversion device (e.g. power plant, vehicle engine):

$$\text{Efficiency, } \eta = \frac{\text{Useful energy output}}{\text{Energy input}}$$

Example: How much much natural gas is required for generating 100 MWh of electricity in a gas power plant with an efficiency of 50%?

Efficiency

When fuel is consumed, much/most of the energy of the fuel is lost as waste heat rather than being converted to electricity.

The thermal energy, or calorific value, of the fuel is given in terms of $\mathrm{MWh_{th}}$, to distinguish it from the electrical energy $\mathrm{MWh_{el}}$.

The ratio of input thermal energy to output electrical energy is the **efficiency**.

Fuel	Calorific energy $\mathrm{MWh_{th}}$/tonne	Per unit efficiency $\mathrm{MWh_{el}/MWh_{th}}$	Electrical energy $\mathrm{MWh_{el}}$/tonne
Lignite	2.5	0.4	1.0
Hard Coal	6.7	0.45	2.7
Gas (CCGT)	15.4	0.58	8.9
Uranium (unenriched)	150000	0.33	50000

Fuel costs to marginal costs

The cost of a fuel is often given in €/kg or €/MWh_{th}.

Using the efficiency, we can convert this to €/MWh_{el}.

For the full marginal cost, we have to also add the CO_2 price and the variable operation and maintenance (VOM) costs.

Fuel	Per unit efficiency $\text{MWh}_{\text{el}}/\text{MWh}_{\text{th}}$	Cost per thermal €/MWh_{th}	Cost per elec. €/MWh_{el}
Lignite	0.4	4.5	11
Hard Coal	0.45	11	24
Gas (CCGT)	0.58	19	33
Uranium	0.33	3.3	10

CO2 emissions per MWh

The CO_2 emissions of the fuel.

Fuel	t_{CO2}/t	t_{C02}/MWh_{th}	t_{CO2}/MWh_{el}
Lignite	0.9	0.36	0.9
Hard Coal	2.4	0.36	0.8
Gas (CCGT)	3.1	0.2	0.35
Uranium	0	0	0

Current CO_2 price in EU Emissions Trading Scheme (ETS) is around €50-100/t_{CO2}

You calculate: What CO_2 price to switch gas and lignite?

What CO_2 price, i.e. x $€/t_{CO2}$, is required so that the marginal cost of gas (CCGT) is lower than lignite?

NB: It helps to track units.

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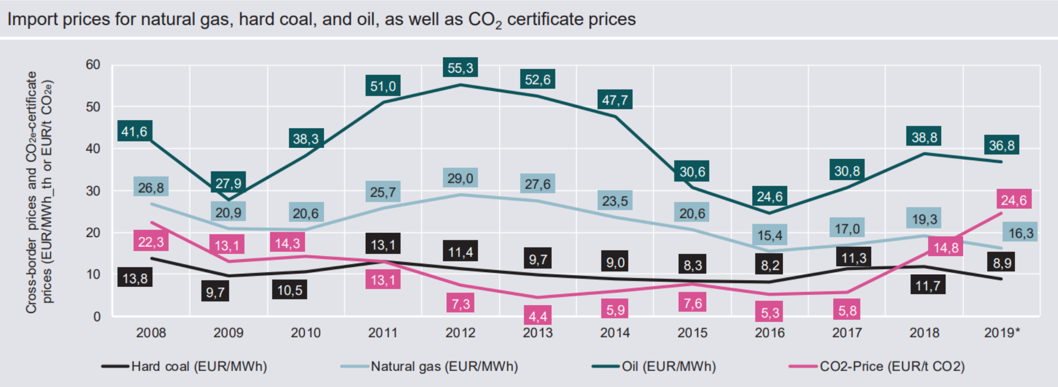
We need to solve for the switch point by adding the CO_2 price to the fuel cost. Left is lignite, right is gas:

$$11\ €/\mathrm{MWh_{el}} + (0.9\ \mathrm{tCO_2/MWh_{el}}) \cdot (x\ €/\mathrm{tCO_2}) = 33\ €/\mathrm{MWh_{el}} + (0.35\ \mathrm{tCO_2/MWh_{el}}) \cdot (x\ €/\mathrm{tCO_2})$$

Solve:

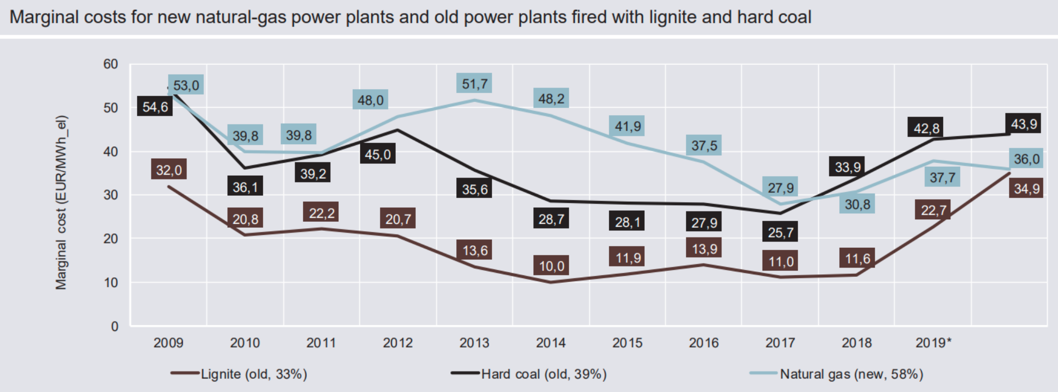
$$x = \frac{33 - 11}{0.9 - 0.35} = 40$$

CO2 and import costs change over time...



Source: Agora Energiewende, 2019

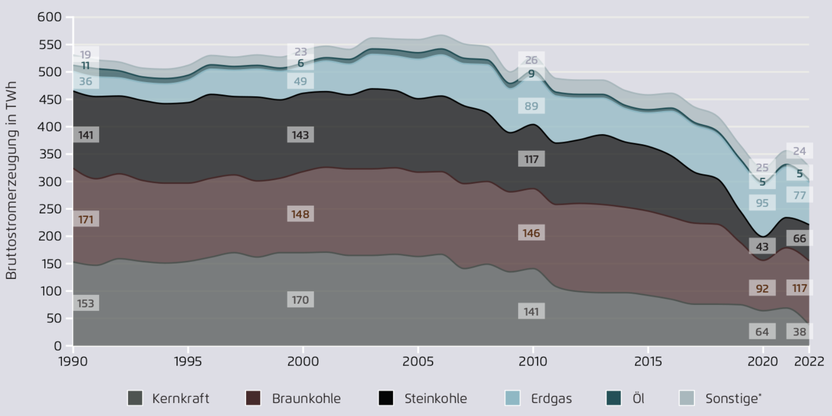
...which affects the marginal costs of generation



Source: Agora Energiewende, 2019

CO2 emissions from electricity sector

CO_2 emissions in electricity generation stagnated for years because of coal, which is slowly being pushed out by the CO_2 price and in the longer term by the Kohleausstieg.



Source: Agora Energiewende Jahresauswertung 2022

Hydrogen in REPowerEU by 2030

The European Commission's REPowerEU plan, published in March 2022, aims for 10 Mt/a of clean hydrogen to be produced domestically in the European Union by 2030, with another 10 Mt imported.

If electrolysis of water to hydrogen is 70% efficient (LHV) and there is 33 MWh/tH_2 (LHV), what will be the electricity consumption from electrolysis for hydrogen in the EU in 2030?

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Consumption will be

$$\frac{10 \text{ MtH}_2/\text{a} * 33 \text{ MWh}_{\text{H}_2}/\text{tH}_2}{0.7 \text{ MWh}_{\text{H}_2}/\text{MWh}_{\text{el}}} = 471 \text{ TWh}_{\text{el}}/\text{a}$$

Compare to the current electricity consumption in Europe of around 3200 TWh_{el}/a.

Capacity Factors and Full Load Hours

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A generator's **capacity factor** is the average power generation divided by the power capacity.

For variable renewable generators it depends on weather, generator model and curtailment; for dispatchable generators it depends on market conditions and maintenance schedules.

A generator's **full load hours** are the equivalent number of hours at full capacity the generator required to produce its yearly energy yield. The two quantities are related:

$$\text{full load hours} = \text{per unit capacity factor} \cdot 365 \cdot 24 = \text{per unit capacity factor} \cdot 8760$$

Typical values for Germany:

Fuel	capacity factor [%]	full load hours
wind	20-35	1600-3000
solar	10-12	800-1000
nuclear	70-90	6000-8000
open-cycle gas	20	1500