Plasma II (PHYS-424)

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Based on lecture notes by
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Spring Semester 2025

Swiss
Plasma
Center

Introduction to Plasma II

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- Course material on https://moodle.epfl.ch/course/view.php?id=14996

Content

- **Introduction to Plasma Physics**
  - Plasma state of matter
  - Microscopic description (particle picture)
  - Fluid description (2 fluids, single fluid, waves, equilibrium)
- **Plasma I**
  - Collisional and relaxation phenomena
  - Transport in plasmas
  - Waves (cold magnetised, hot un-magnetised/magnetized plasmas)
  - Examples of nonlinear effects
- **Plasma II** – Applications
  - Fusion energy (magnetic confinement)
  - Industrial applications
  - Astrophysics
  - Plasma diagnostics

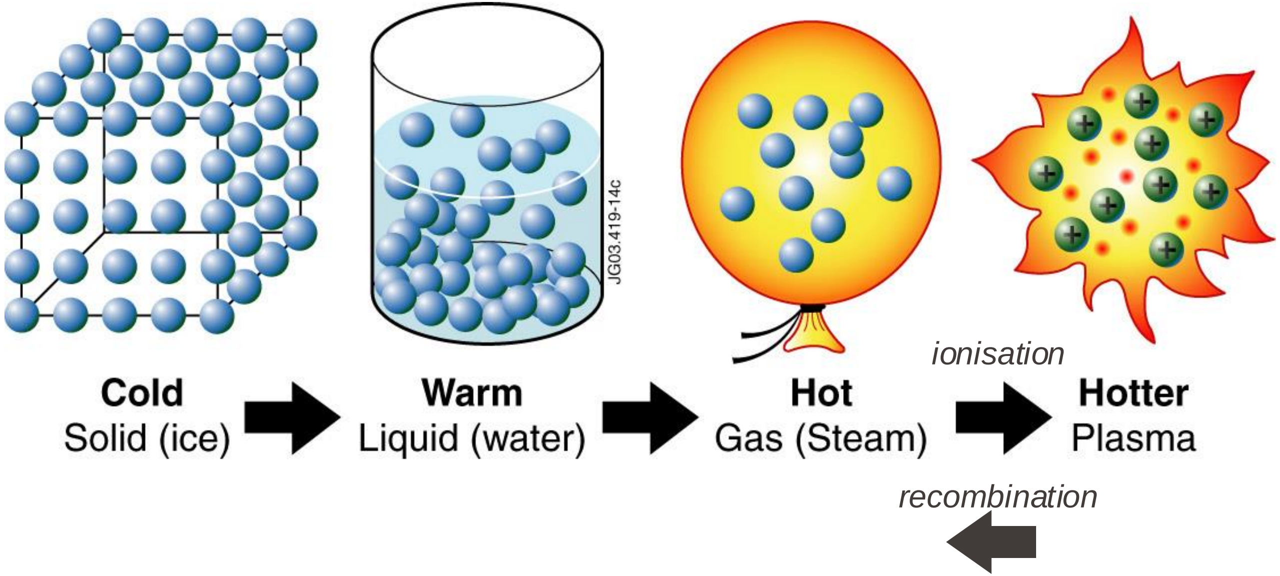
Plasma II – Applications

	Lecture	Date
L1	**Fusion energy 1** - The basics of fusion energy	21.02.2025
L2	**Fusion energy 2** - Magnetohydrodynamic (MHD) description of the plasma	28.02.2025
L3	**Fusion energy 3** - Tokamak configuration and other options	07.03.2025
L4	**Fusion energy 4** - MHD stability and performance limits	14.03.2025
L5	**Fusion energy 5** - Diffusion and transport in tokamak plasmas	21.03.2025
L6	**Fusion energy 6** – Heating, burning plasmas, ITER and route to fusion energy	28.03.2025
L7	**Industrial plasmas 1** - Breakdown	04.04.2025
L8	**Industrial plasmas 2** – Sheath and Etching	11.04.2025
	Good Friday & Easter holidays	
L9	**Astrophysics 1** – Solar physics	02.05.2025
L10	**Astrophysics 2** – From flows to magnetic fields	09.05.2025
L11	**Astrophysics 3** – Magnetic reconnection, the solar wind and the heliosphere	16.05.2025
L12	**Plasma diagnostics 1** – Passive measurements	23.05.2025
L13	**Plasma diagnostics 2** – Active measurements	30.05.2025#

#Pont d'ascension

Plasma – 4th state of matter

- Hot ionised gas
  - Name “plasma” coined by Irving Langmuir in the late 1920ies



- States typically change when particle energy exceeds binding energy

Plasma – Generation

Example: Water/hydrogen

- In thermal equilibrium: $\langle E_{\mathrm{kin}} \rangle = \frac{3}{2} k_{\mathrm{B}} T$ * with

$$k_{\mathrm{B}} = 1.381 \times 10^{-23} \frac{J}{K}$$

- Ionisation energy typically expressed in electron-volts

$$1eV = 1.602 \times 10^{-19} J$$

- Boltzmann constant k_{B} links energy and temperature

$$1eV \longleftrightarrow 11600K$$

*For mono-atomic gases

Ionisation energy [eV]	
Hydrogen	13.6
Oxygen	13.6
O^{+}	35.1
…	
O^{7+}	872
Ar	15.8

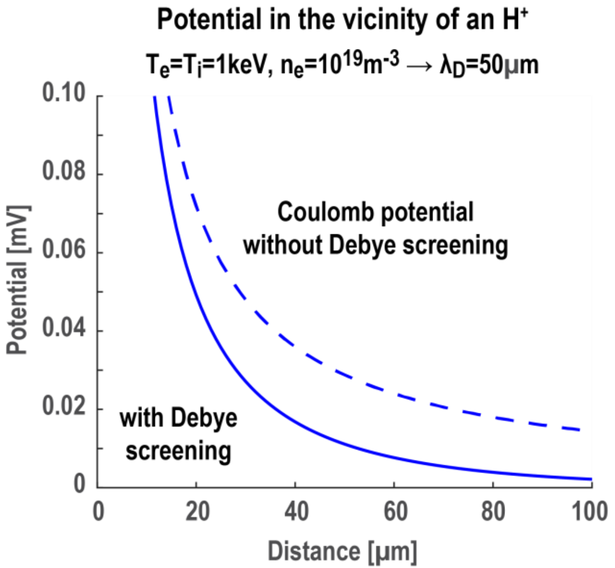
Plasma – Characteristics

- Macroscopically neutral – *Debye screening*

- Potential in the vicinity of charge q

$$U(r) = \frac{q}{4\pi\varepsilon_0 r} e^{-\frac{r}{\lambda_\mathrm{D}}}$$

with *Debye length* $\lambda_\mathrm{D} = \sqrt{\frac{\varepsilon_0 k_\mathrm{B} T}{2 n_\mathrm{e} e^2}}$



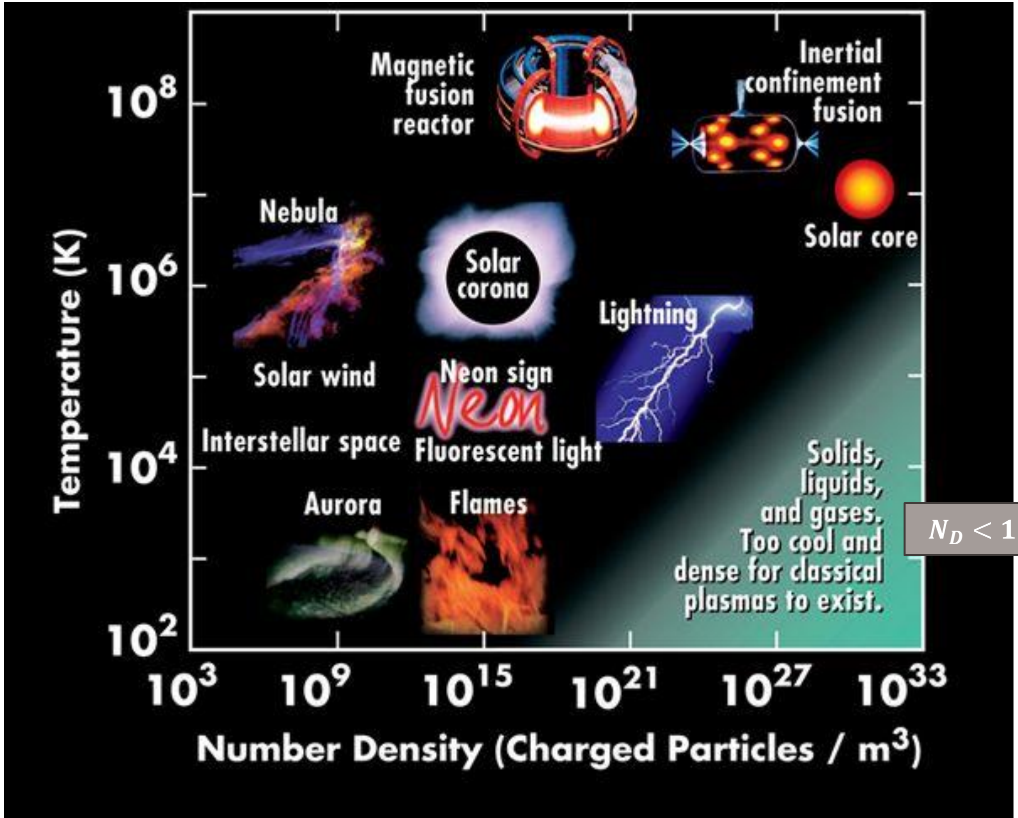
Plasma – Characteristics

- Macroscopically neutral – *Debye screening*
- Collective behaviour dominates (response to macroscopic fields)
- Requirements for a system to behave as a plasma
  - Dimensions sufficiently large for shielding $L \gg \lambda_{\mathrm{D}}$
  - Enough particles (free electrons) within *Debye-sphere* to establish shielding

$$N_D = n_e \frac{4}{3}\pi\lambda_D^3 \gg 1$$

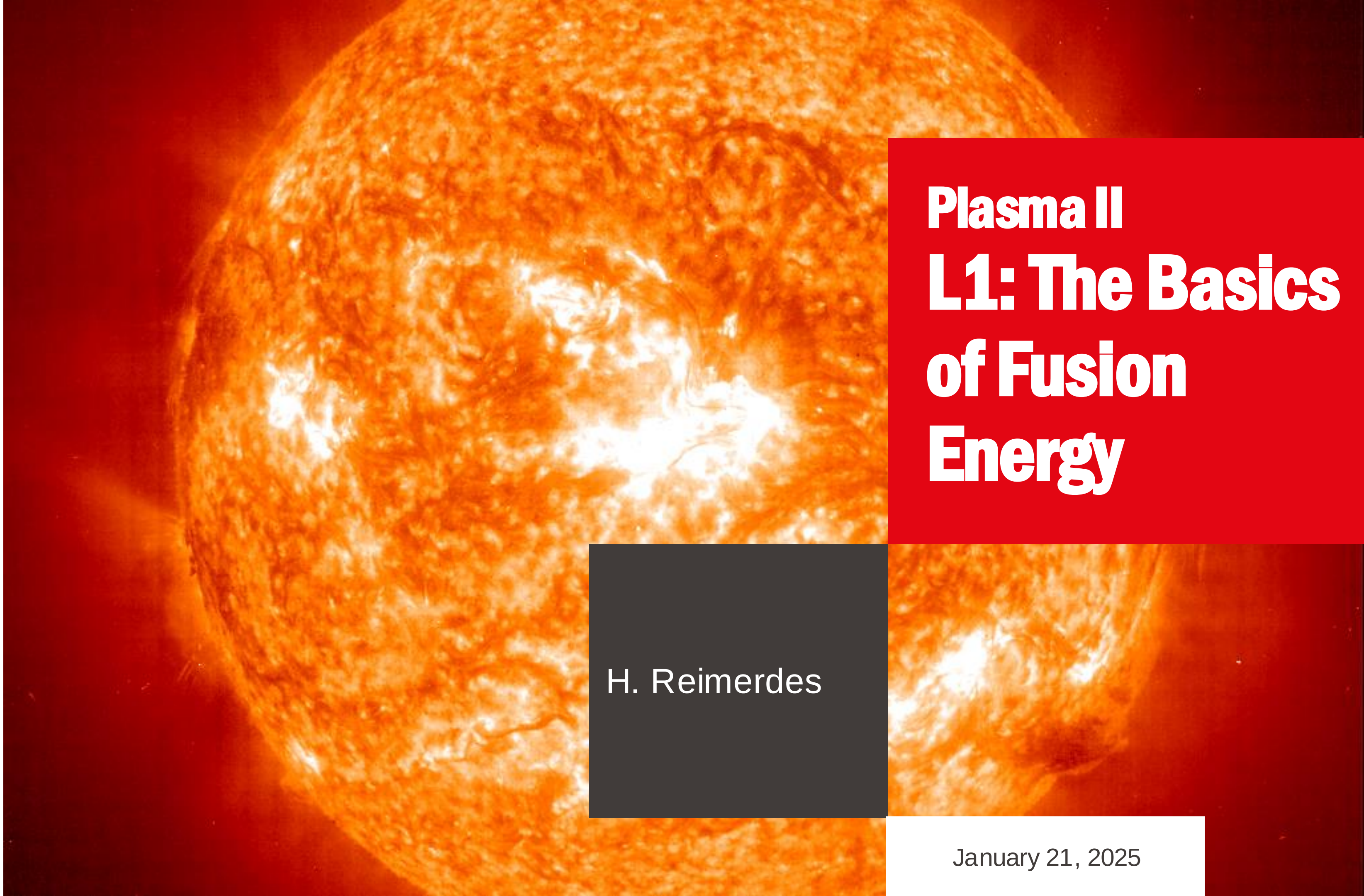
Examples of plasmas

- Most common state of matter in the universe



$N_D < 1$

EPFL



Plasma II
L1: The Basics of Fusion Energy

H. Reimerdes

January 21, 2025

Swiss Plasma Center

Literature for module on Fusion Energy

General reading

- J. Freidberg, *Plasma Physics and Fusion Energy*, Cambridge University Press, 2007.

Detailed subjects

- *Fusion Physics* (edited by M. Kikuchi, K. Lackner and M.Q. Tran), IAEA, 2012.
- J. Wesson, *Tokamaks* - Third Edition, Clarendon Press - Oxford, 2004.
- J. Freidberg, *Ideal Magnetohydrodynamics*, Plenum Press,1987.

Outline

1. **The energy landscape**
   - Energy needs
   - Options
2. **Develop nuclear fusion energy as an alternative**
3. **Power balance of a fusion reactor**

See also

- EPFL MOOC *Plasma physics: Applications* #6a,b
  - https://courses.edx.org/courses/course-v1:EPFLx+PlasmaApplicationX+1T_2018
- *Fusion Physics*, Chapter 1
- Freidberg, *Plasma Physics and Fusion Energy*, Chapters 1-4

Energy consumption

- *Primary energy consumption* includes commercially traded fuels and renewables used to generate electricity
  - Uses ‘input-equivalent’ basis: non-fossil power generation (e.g. renewables) contribute based on the equivalent amount of fossil fuels required in thermal power station (~40% conversion efficiency)

- Primary energy consumption (2023)

  14,800 Mtoe ~ 6.2×10^{20} J   +2%

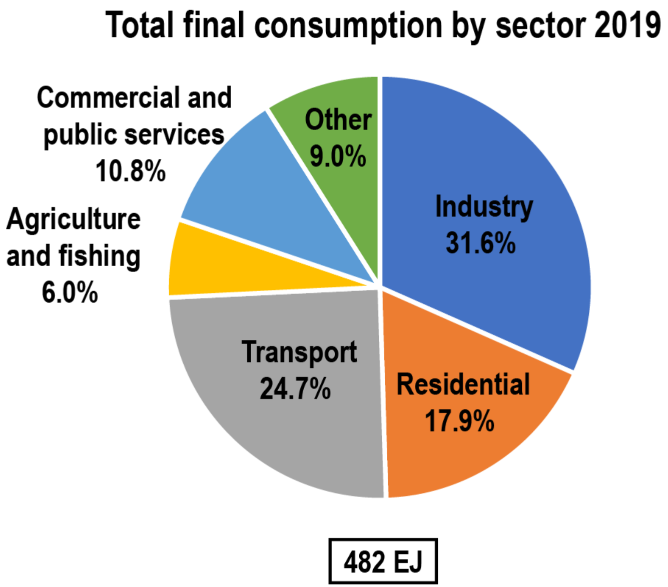
- Electricity consumption (2023)

  29,925 TWh ~ 1.08×10^{20} J   +2.5%

[73rd Statistical Review of the World Energy 2024]

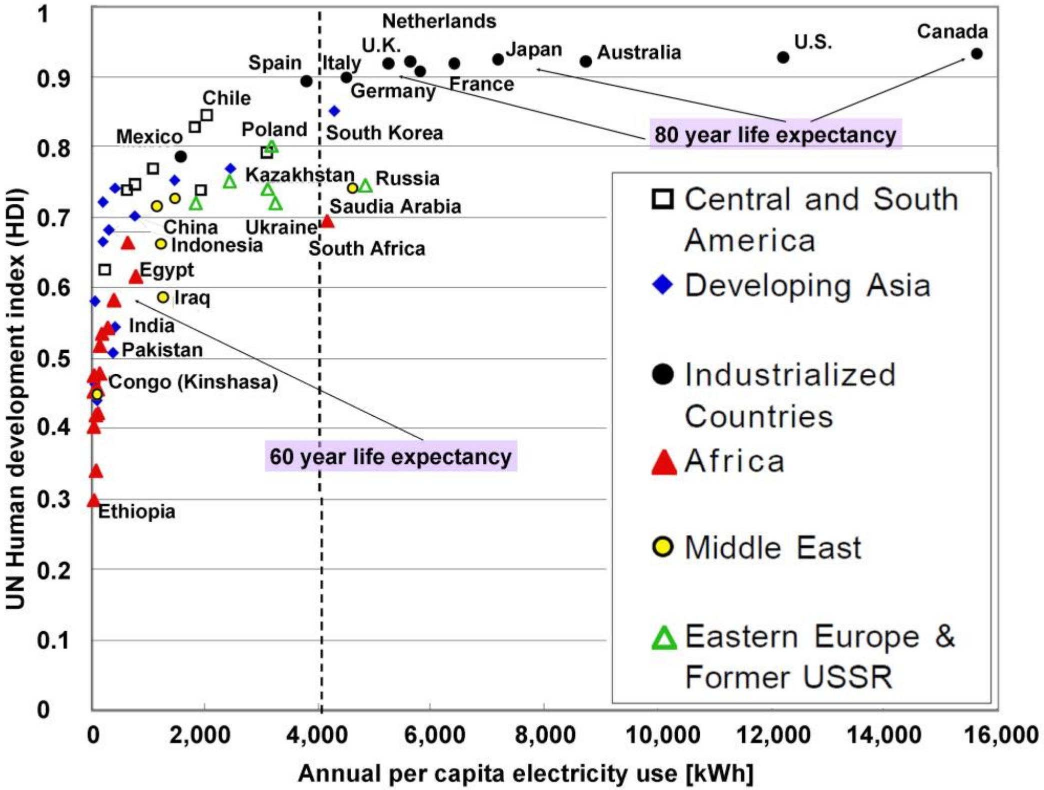
Energy usage

- *Final consumption* excludes energy used by the energy sector (e.g. deliveries, transformation)



[Data: Key world statistics 2021, IEA September 2021, https://www.iea.org]

Energy and human development



A. Pasternak, US Department of Energy Report UCRL-ID- 140773, LLNL , Livermore, CA (2000) 38.

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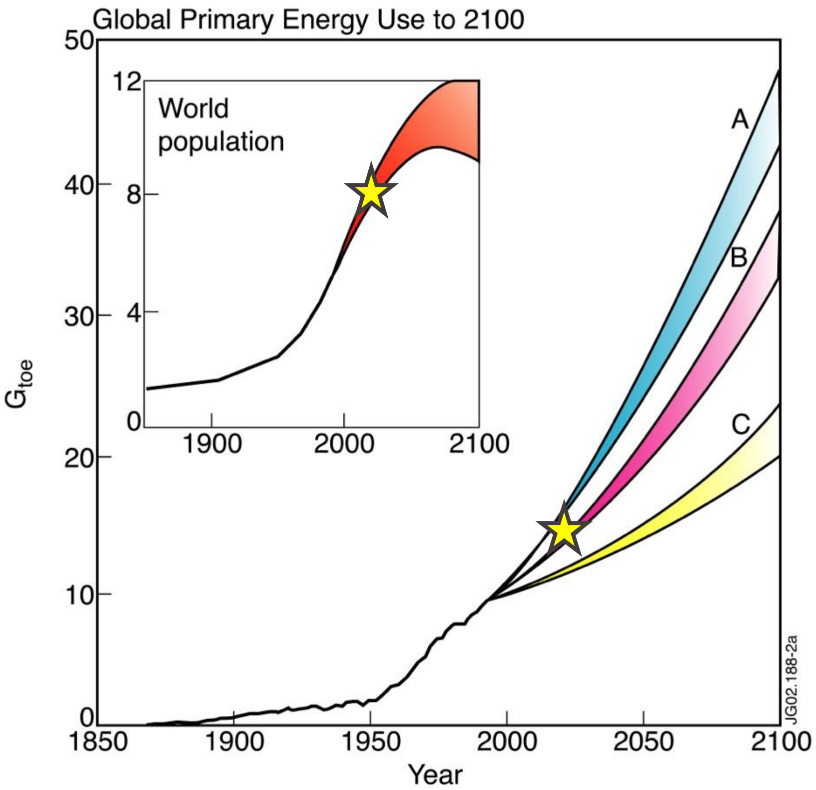
Growth of world population and energy demand



- Energy demand grows even faster than world population

Discussion of today's energy options

- **Coal (26%*)**
- **Natural gas (23%*)**
- **Oil (32%*)**
- …

Fossil fuels
(>80% of the primary energy supply!)

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Reliance on fossil fuels

Fossil fuels have been produced from decayed plant and animal matter over millions of years and cannot be re-formed in time

Limited proven reserves and uneven geographical distribution of fossil fuels

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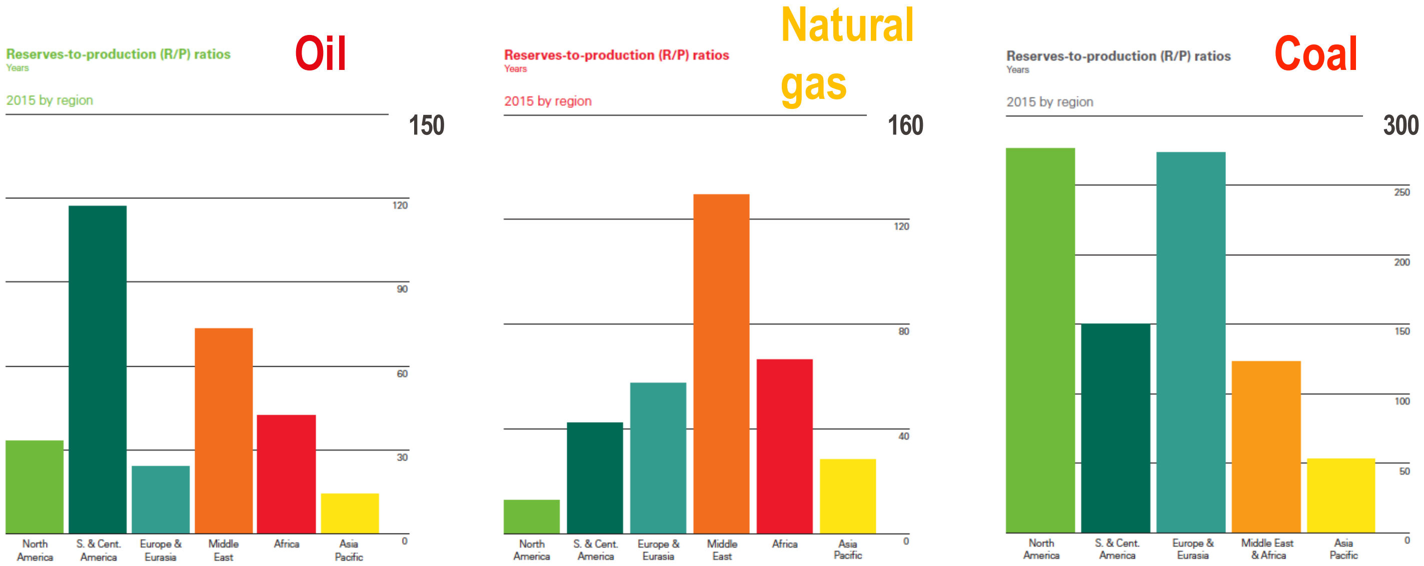
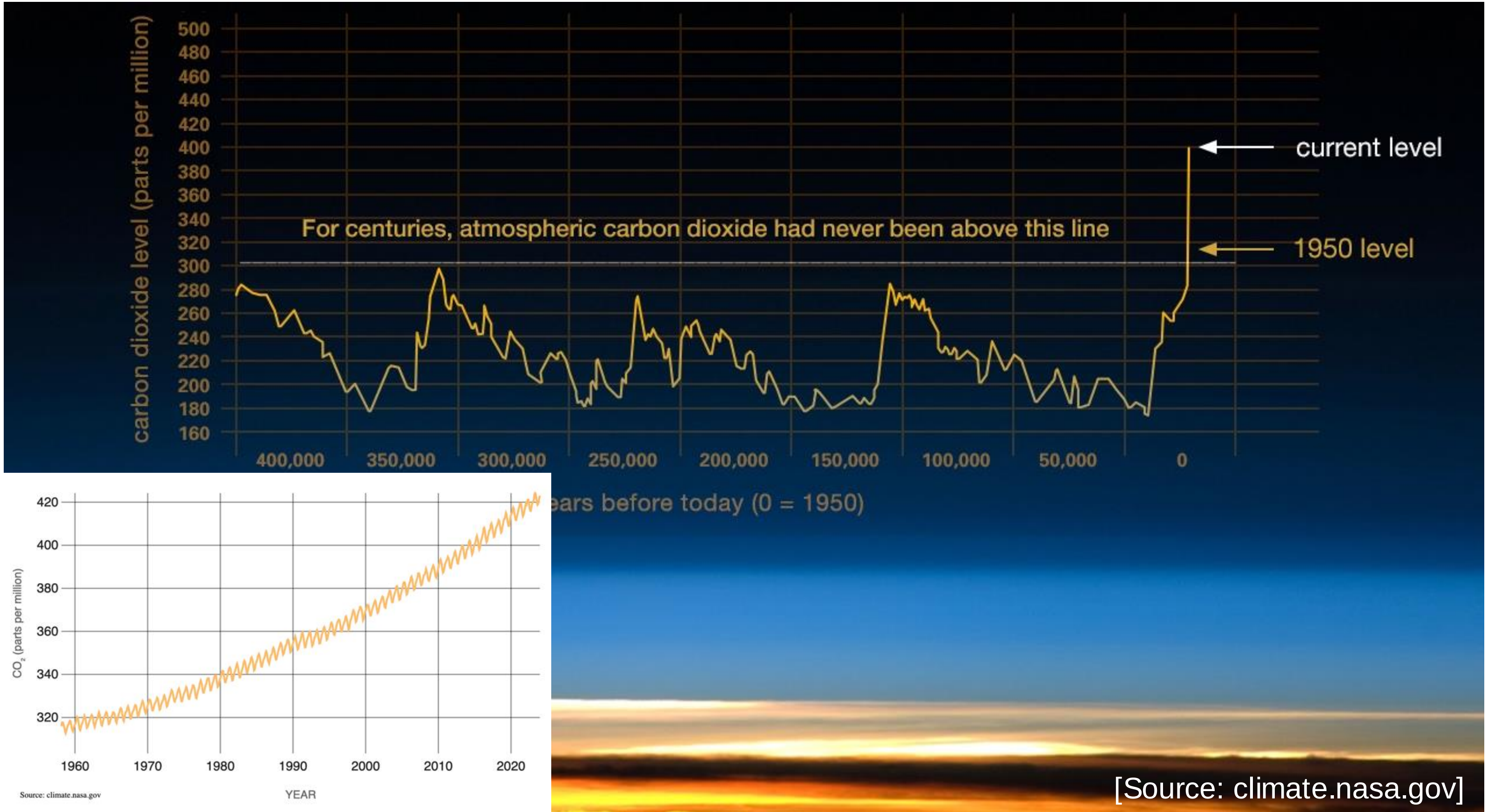


- **Reserve-to-production ratios of the order of 100 years**
  - Less for oil and natural gas, more for coal
- **Geographical distribution does not match demand**

[BP Statistical Review of the World Energy June 2016]

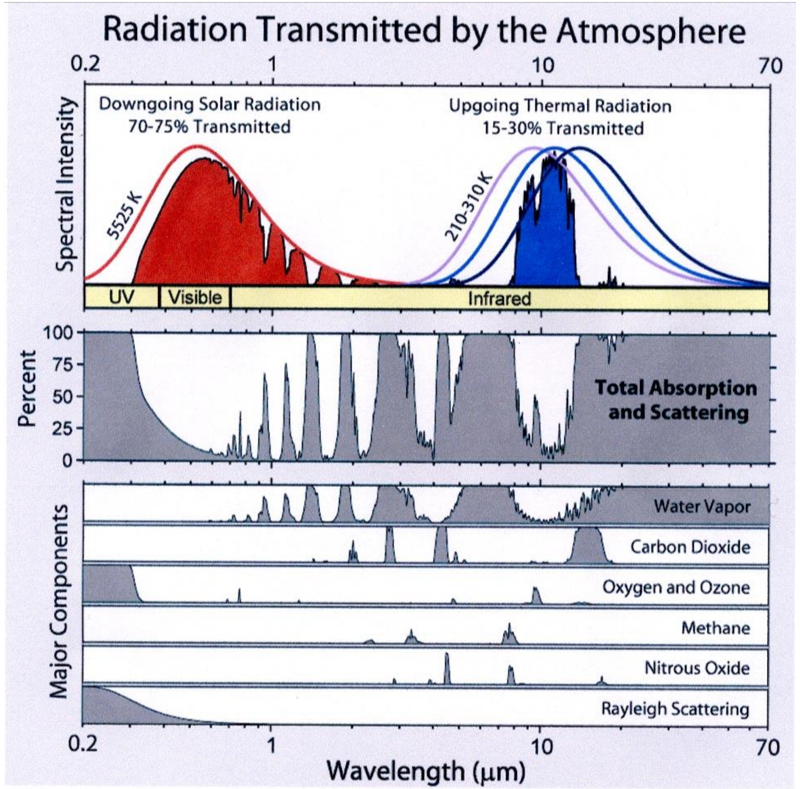
Greenhouse gas emission (CO_2) contributing to global warming



[Source: climate.nasa.gov]

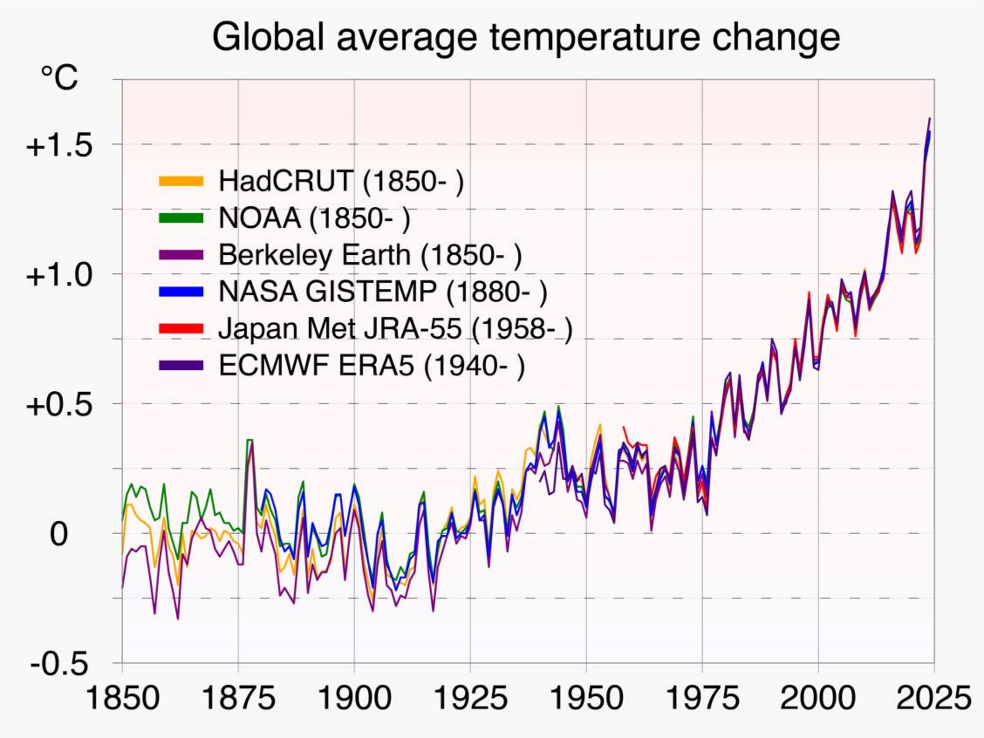
Greenhouse gas emission (CO_2) contributing to global warming

- Greenhouse effect
  - Sunlight passes atmosphere with little absorption
  - **Transport** of longer-wavelength IR radiation slowed by resonances with excited states of molecules
    - H_2O
    - CO_2
    - CH_4
    - N_2O

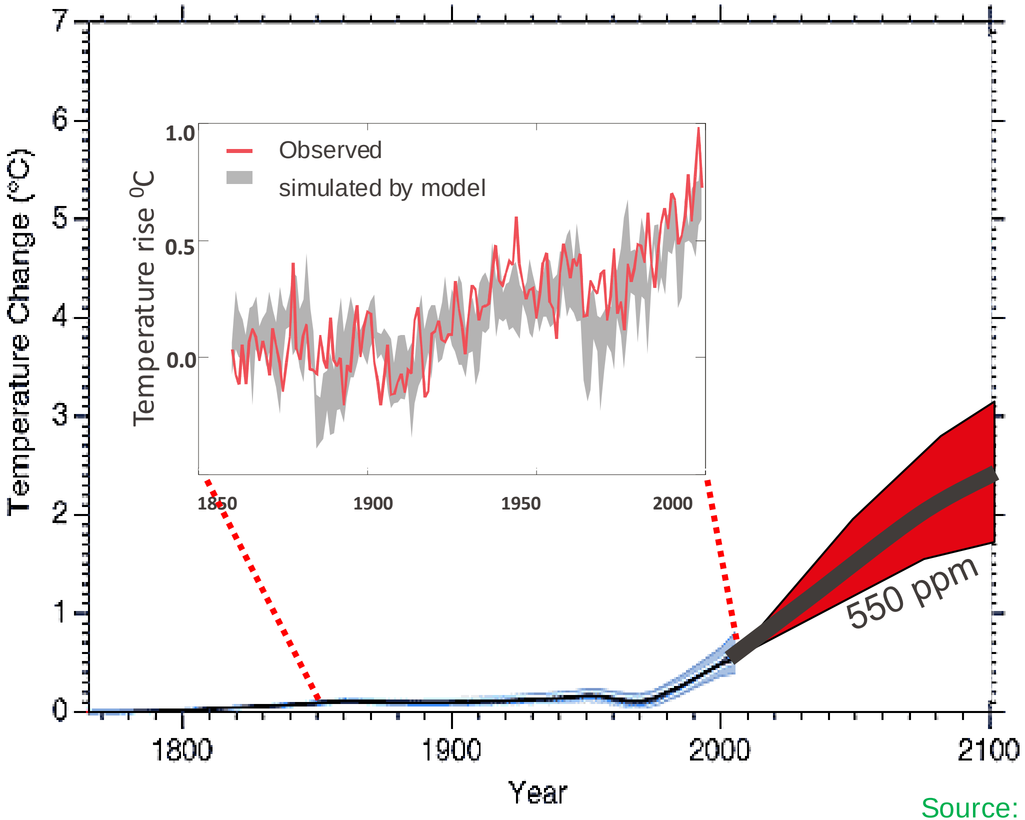


Source: "Global warming; The human contribution" – Jack Barrett

Global surface temperature measurements confirm global warming



Modelling global warming



Source: Hadley Centre

The effects of climate change

- **Sea level rise**
  - Increase in costal flooding
- **Increase occurrence of extreme weather events (heat waves, droughts, storms, etc.)**
  - Increase of intensity
- **Geographic shift of climate zones**
  - Mass migration

- COP21 (Paris agreement, 2016): limit emissions to limit global warming to (well below) +2°C
  - Reach global peaking of greenhouse gas emission as soon as possible!

Differentiate among fossil fuels

- CO_2 emission depends on fuel and use

	kg CO_2 emitted per million Btu*	Power plan efficiency (US 2018)	Grams CO_2 emitted per kWh electricity
Coal (anthracite)	103.7	32.5	1089
Coal (lignite)	97.7	32.5	1026
Oil (diesel, heating)	73.2	30.8	810.6
Gasoline	71.3		
Propane	63.0		
Natural gas (primarily CH_4)	53.1	43.6	415.3

*Btu: British thermal unit; 1Btu~1055J

Source: www.eia.gov

Discussion of today's energy options

- Coal (26%*)
- Natural gas (23%*)
- Oil (32%*)
- **Hydro-electric (6%*)**
- …

Fossil fuels

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Discussion of today's energy options

- Coal (26%*)
- Natural gas (23%*)
- Oil (32%*)
- Hydro-electric (6%*)
- **Wind**
- ...

Fossil fuels

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Discussion of today's energy options

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- Natural gas (23%*)
- Oil (32%*)
- Hydro-electric (6%*)
- Wind
- **Solar**
- …

Fossil fuels

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Discussion of today's energy options

- Coal (26%*)
- Natural gas (23%*)
- Oil (32%*)

Fossil fuels

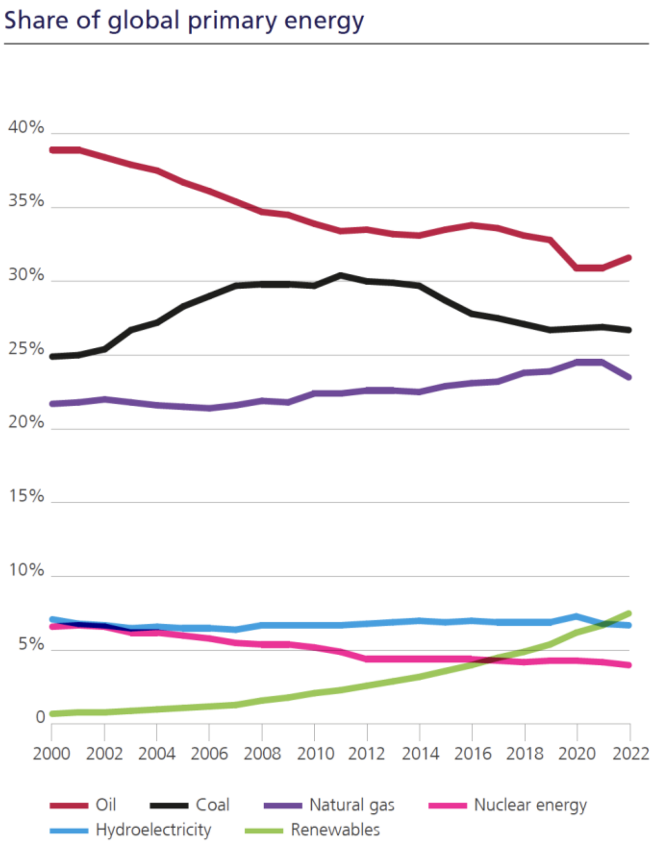
- Hydro-electric (6%*)
- Wind
- Solar
- **Biomass**

(8%*)

Renewables

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

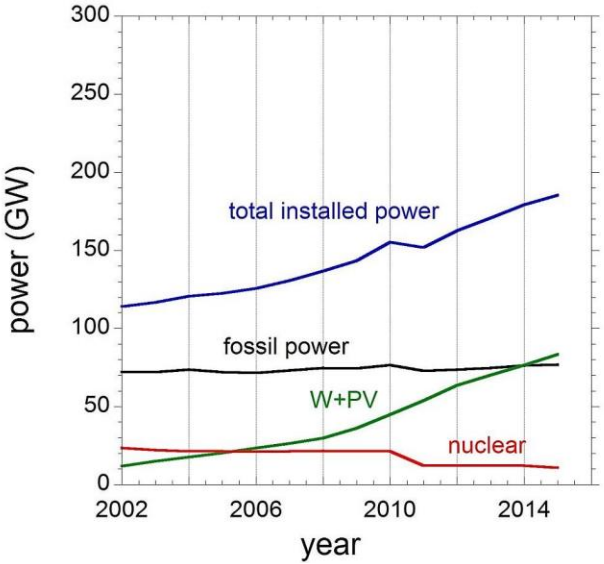
Renewable energy supply grows fast



[Statistical Review of World Energy, 2022]

Example: Germany

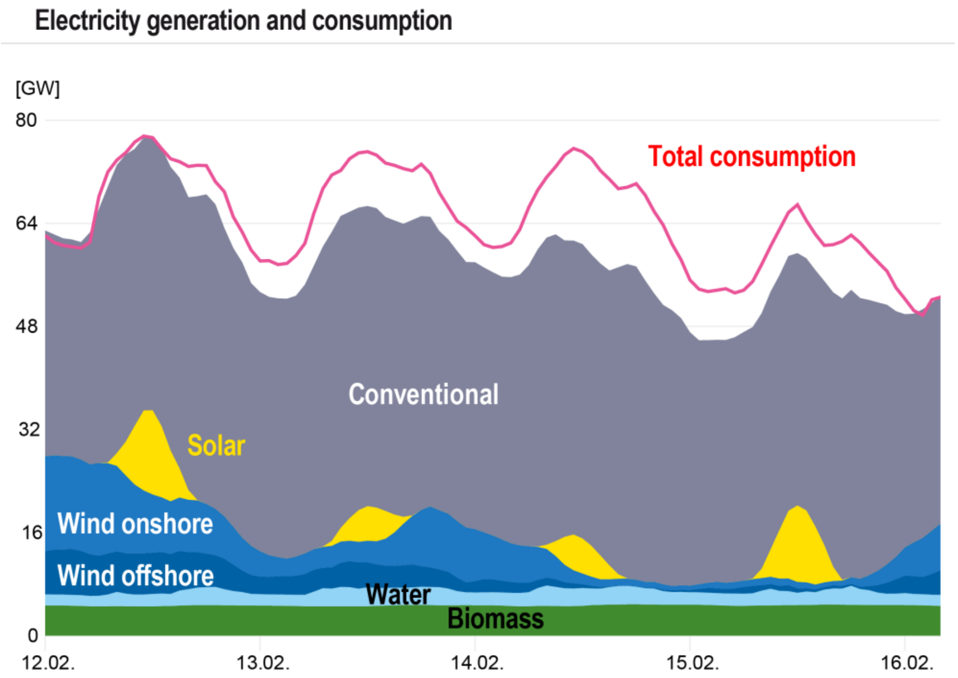
- Installed renewable electricity source in Germany now exceeds the peak load



[F. Wagner, EPFL colloquium, 22.5.2017]

Current situation (last week)

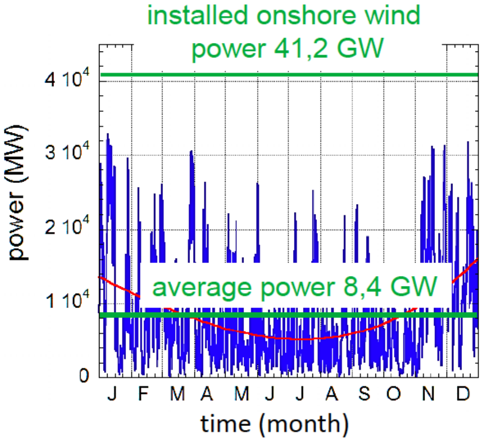
- Significant reliance on fossil fuels remains

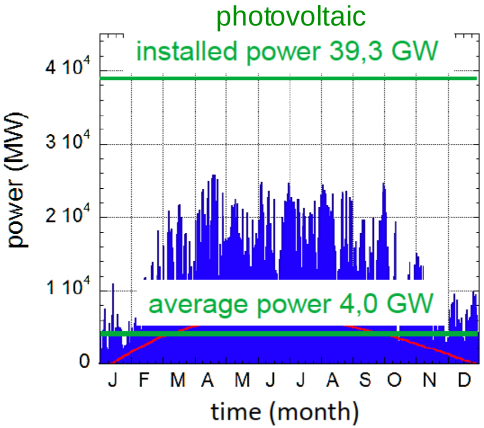


[https://www.agora-energiewende.de/service/agorameter/]

Issues: Problems of intermittent electricity production

- *Capacity factor* $= \dfrac{\text{Average power}}{\text{Installed power}} <<1$





Germany 2015
[F. Wagner, EPFL colloquium, 22.5. 2017]

  - ➢ Need to install significant overcapacity (5-10x average power)

- Production does not always coincide with demand
  - ➢ Need for high-capacity, long-term energy storage or back-up power

Issues: Energy returned on invested (EROI)

- Requires consistent application to evaluate efficiency of power plant technology [Weissbach, et al, EPJ Web of Conferences (2018)]
  - *Exergy*: Ordered energy (e.g. electricity, mechanical work)
  - *Anergy*: Disordered energy (e.g. heat, noise)
  - Need exergy to create goods and services

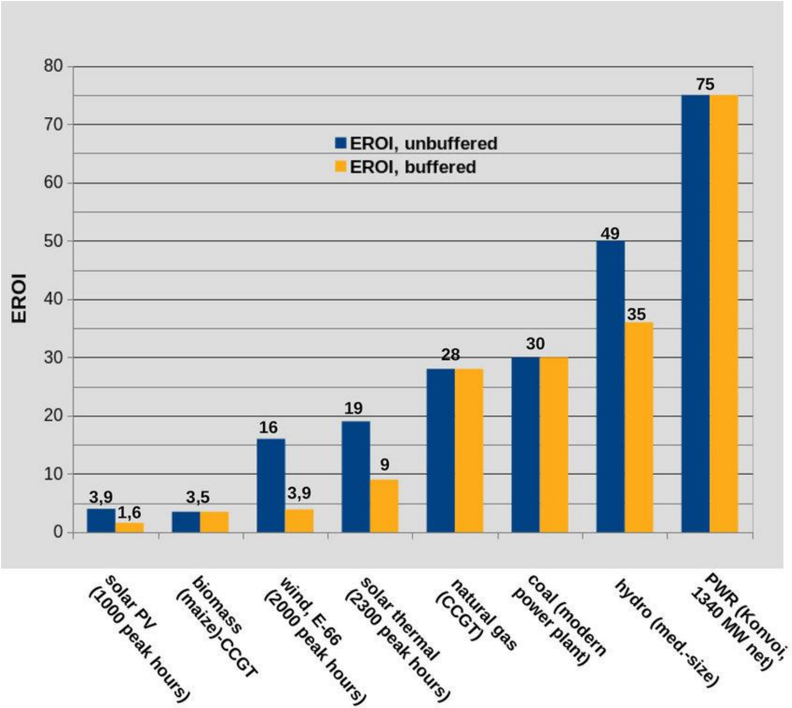
$$\mathrm{EROI} \equiv \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}$$

Typically electricity output

Incl. exergy for fuel extraction, construction, buffering, maintenance

Issues: Energy returned on invested (EROI)

- Need EROI>1 to create services and goods
- Low numbers increase the overall energy demand



Source: Weissbach, et al, EPJ Web of Conferences (2018)

Discussion of today's energy options

- Coal (26%*)
- Natural gas (23%*)
- Oil (32%*)

Fossil fuels

- Hydro-electric (6%*)
- Wind
- Solar
- Biomass

(8%*)

Renewables

- **Nuclear fission (4%)**

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Discussion of today's energy options

- Coal (26%*)
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- Oil (32%*)
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- Nuclear fission (4%)
- **'Conservation'**

Fossil fuels

(8%*)

Renewables

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Lecture 1 recap

- The global primary energy use will continue to rise
  - Increase driven by developing countries and population growth
- Dependence on carbon based fossil fuels must decrease (global warming, limited resources)
- A wide range of alternative energy sources exists
  - Deployment of renewables too slow to meet climate change goals
    - Main issues of renewables are intermittency, low EROI and land use (not discussed)
  - Advantages and disadvantages call for a mix of energy sources alongside with the development of new sources, energy storage and efficient energy transport

Discussion of today's energy options

- Coal (26%*)
- Natural gas (23%*)
- Oil (32%*)
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- Wind
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- Biomass
- Nuclear fission (4%)
- 'Conservation'
- **Nuclear fusion?**

Fossil fuels

(8%*)

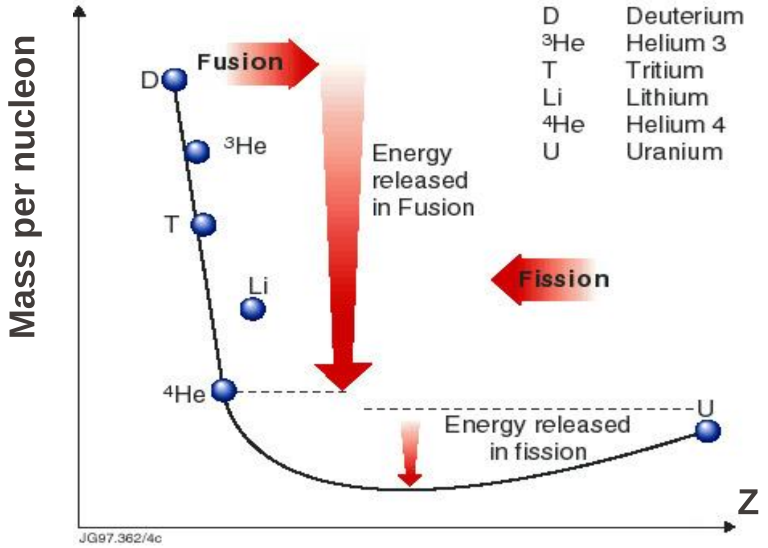
Renewables

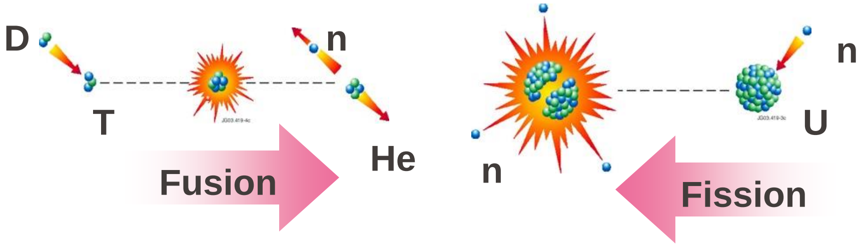
*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Outline

1. The energy landscape
    - Energy needs
    - Options
2. **Develop nuclear fusion energy as an alternative**
3. Power balance of a fusion reactor

Fusion works on same principle as fission: $E = mc^2$





Fusion reactions

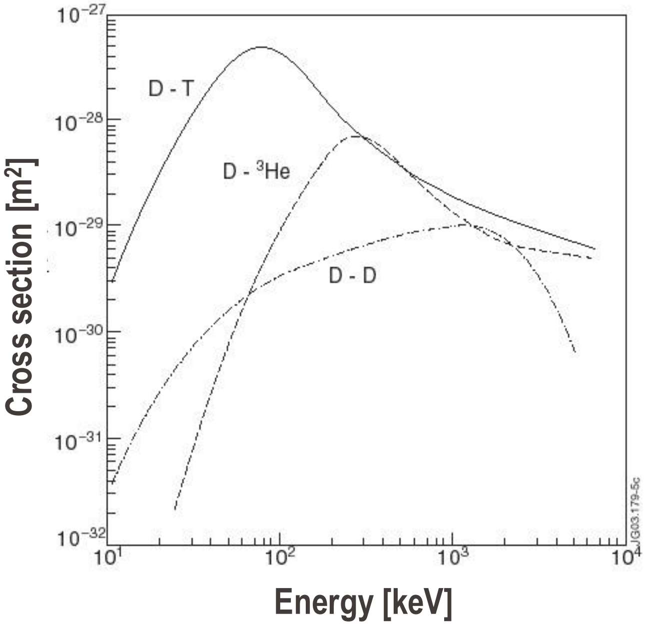
- Basic fusion reaction in the **sun**: $4p \rightarrow He^4 + 2e^+ + 2\nu_e$ + energy
- Reactions of interest for fusion energy
  1. $D^2 + T^3 \rightarrow (He^4 + 3.5\ \text{MeV}) + (n^1 + 14.1\ \text{MeV})$
  2. $D^2 + D^2 \rightarrow (He^3 + 0.8\ \text{MeV}) + (n^1 + 2.5\ \text{MeV})$

     $\rightarrow (T^3 + 1.0\ \text{MeV}) + (H^1 + 3.0\ \text{MeV})$
  3. $D^2 + He^3 \rightarrow (He^4 + 3.7\ \text{MeV}) + (H^1 + 14.7\ \text{MeV})$
  4. $H^1 + B^{11} \rightarrow \ldots \rightarrow 3He^4 + 8.7\ \text{MeV}$

Energy distribution among fusion products

Likelihood of reaction determined by its cross-section

‘Activation’ energy?

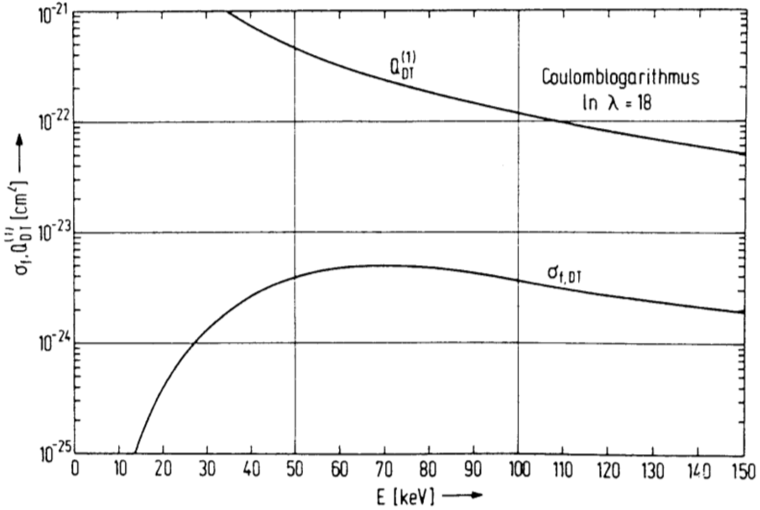


- At energies of interest matter is in the **plasma** state

Need of thermonuclear fusion for energy production

- Nuclei are also subject to Coulomb collisions
- Compare fusion cross-section with Coulomb cross-section Q_{DT} (e.g. for 90° scattering)

➢ Coulomb cross-section much larger than fusion cross-section for all energies E



➢ Particles undergo multiple Coulomb collisions before they may fuse
  – Impossible to make fusion energy with beams
  – Deal with a Maxwellian equilibrium generated by Coulomb collisions

➔ This is why we speak of **thermonuclear fusion**

Fusion rate for thermal distribution of D and T

- Fusion rate (per unit volume and time)

$$r_{\mathrm{D-T}} = n_{\mathrm{D}} n_{\mathrm{T}} \sigma_{\mathrm{DT}}(v') v'$$

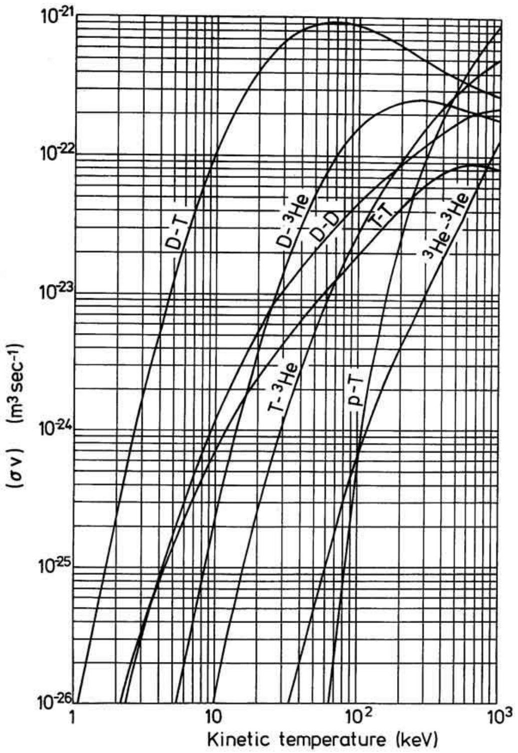
- Average over Maxwellian velocity distribution

$$f(\boldsymbol{v}) = n \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{m\boldsymbol{v}^2}{2kT}}$$

yields rate coefficient

$$\langle \sigma_{\mathrm{DT}}(v) v \rangle = \left(\frac{m_r}{2\pi kT}\right)^{3/2} \int_0^\infty 4\pi v^3 e^{-\frac{m_r v^2}{2kT}} \sigma_{\mathrm{DT}}(v) dv$$

- With reduced mass $m_r = \frac{m_{\mathrm{D}} m_{\mathrm{T}}}{m_{\mathrm{D}} + m_{\mathrm{T}}}$
- High energy tail of thermal distribution responsible for most fusion reactions



Sources of fuel for D-T reaction

- Deuterium (D): natural abundance of D is 0.015%
  - ➢ Extract from (ocean) water
- Tritium (T): does not occur naturally as it is radioactive and short lived (12.5 years), but can be bred from Lithium (Li)

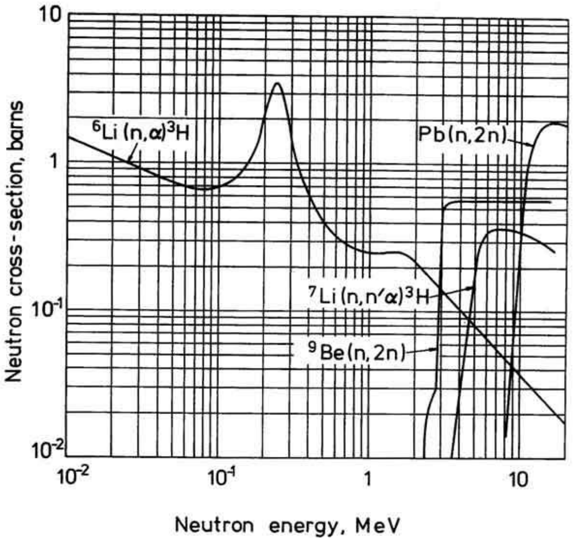
$n_0^1 + Li_3^6 \rightarrow T_1^3 + He_2^4 + 4.8\text{MeV}$

(Li_3^6 is ~7%)

$n_0^1 + Li_3^7 \rightarrow T_1^3 + He_2^4 + n_0^1 - 2.5\text{MeV}$

(Li_3^7 is ~93%)

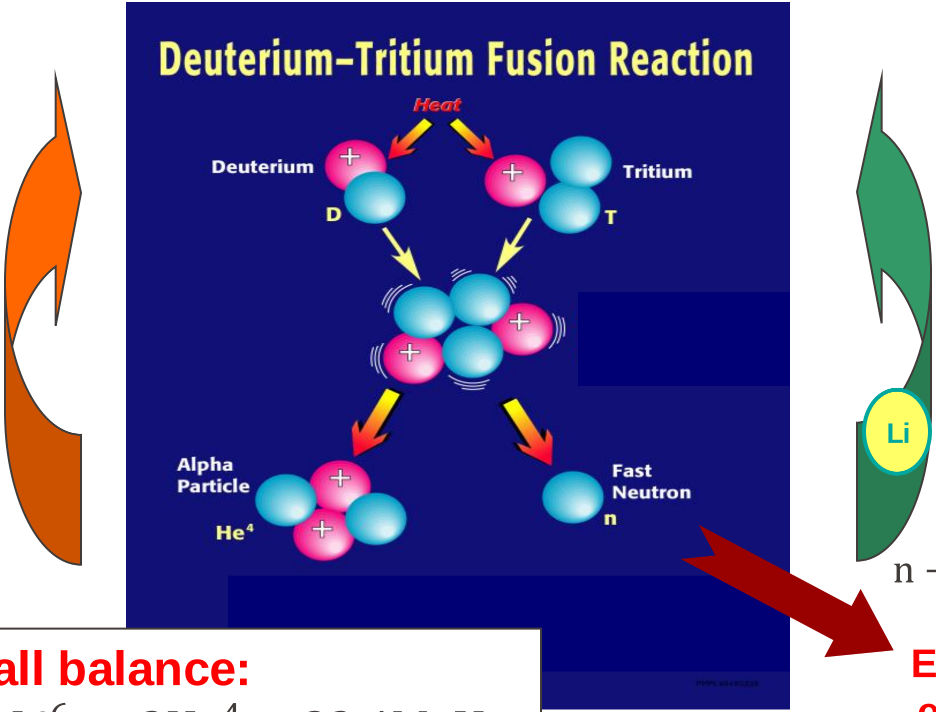
- Li^6 cross section larger for low energies
- Neutron multiplication is needed, and is possible above ~3MeV with Pb or Be



- Li: occurs in earth crust and in ocean water (0.15g/m^3)

The D-T fusion reaction

$$D + T \rightarrow He^4\ (3.5\mathrm{MeV}) + n(14\mathrm{MeV})$$



Plasma
self-heating

Tritium
replenishment

$$n + Li^6 \rightarrow He^4 + T$$

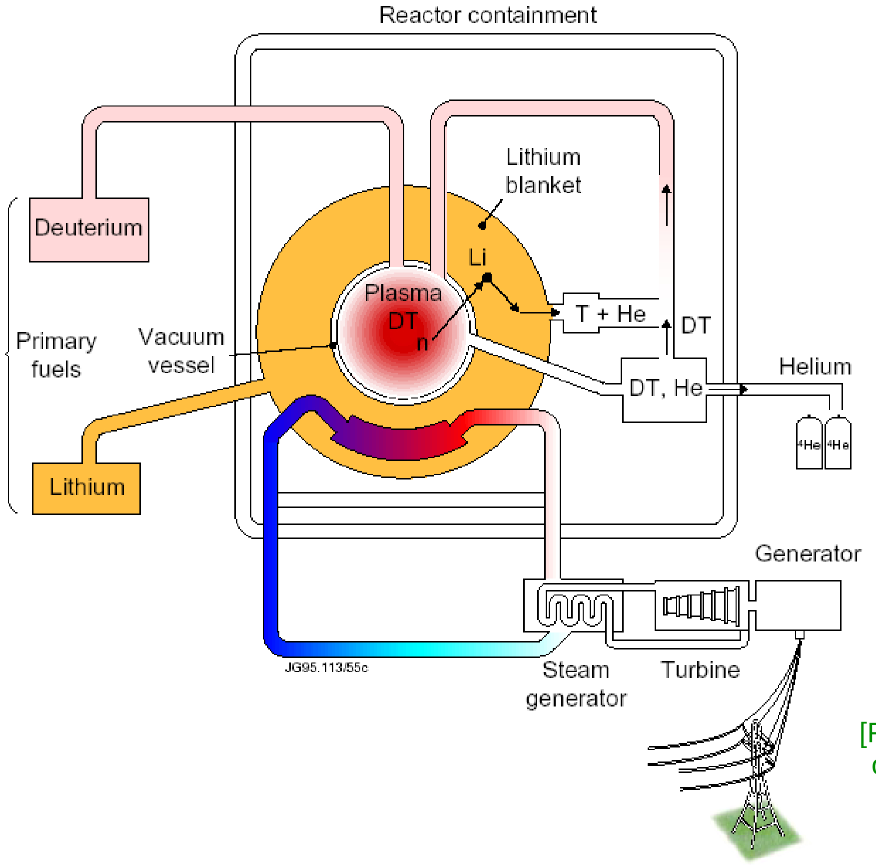
Energy for
electricity

Overall balance:

$$D + Li^6 \rightarrow 2He^4 + 22.4\mathrm{MeV}$$

Schematic of a fusion power plant

Fusion fuel



Fusion ash

[Figure: Status report on fusion research, Nucl. Fusion 2005]

Advantages of fusion energy

- High energy density fuel

Fuel	Specific energy (MJ/kg)
Water, 100m dam height	0.001
Coal	30
Gasoline	50
Fission (U-235)	85’000’000
Fusion (D-T)	**350’000’000**

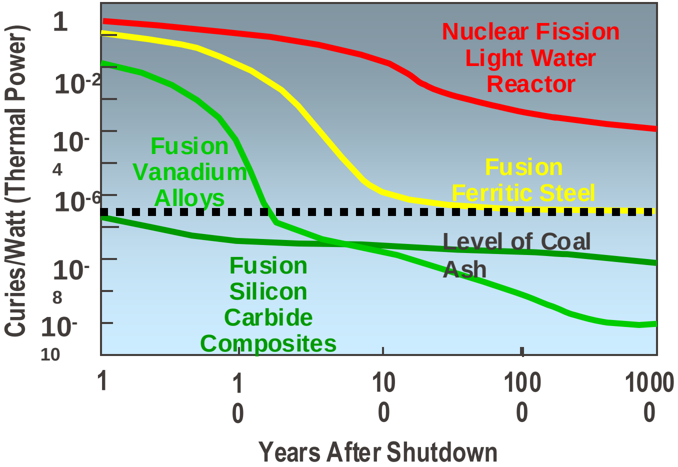
Advantages of fusion energy

- High energy density fuel

- Practically inexaustible fuel
  - **D** is 1/6400 of H
  - **Li** is in crustal rock and in oceans

Advantages of fusion energy

- High energy density fuel
- Practically inexaustible fuel
  - **D** is 1/6400 of H
  - **Li** is in crustal rock and in oceans
- Environmental
  - No CO_2 emission
  - No high-level, long-lived radioactive wastes
- No risk of nuclear accidents
  - Only ~1g of fuel in reactor
- No geographic concentration



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- Coal (26%*)
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Fossil fuels

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- Wind
- Solar
- Biomass

(8%*)

Renewables

- Nuclear fission (4%)
- 'Conservation'
- **Nuclear fusion**

*Contribution to total primary energy supply 2023
[Statistical Review of World Energy, 2024]

Outline

1. The energy landscape
   - Energy needs
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Power balance

- Break-even

Power balance (cont.)

- Power losses

Power balance (cont.)

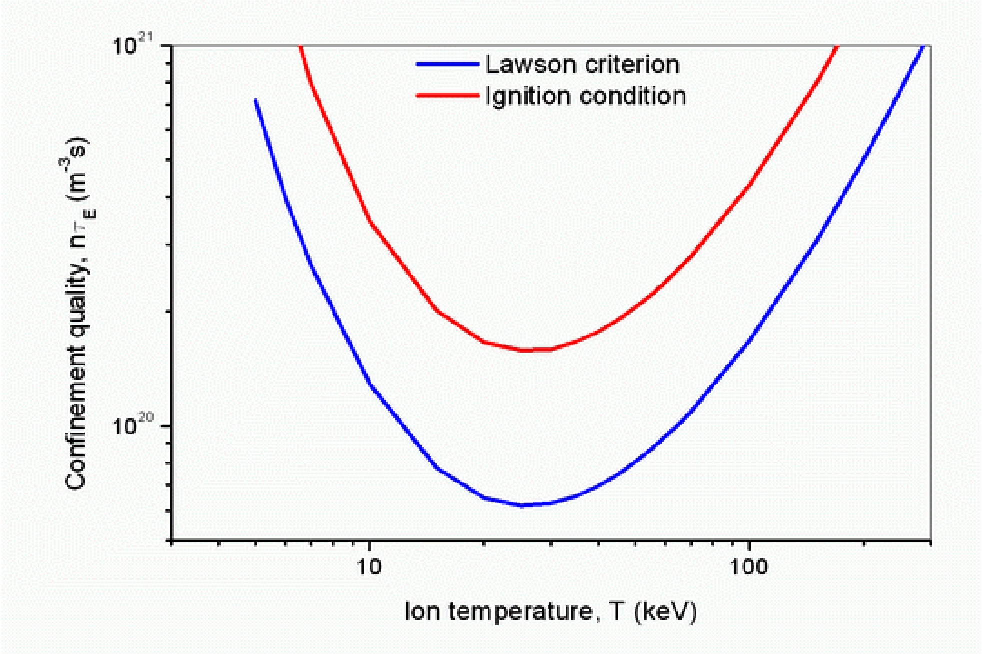
- Back to breakeven

Power balance (cont.)

- Breakeven neglecting bremsstrahlung

Lawson criterion for break-even

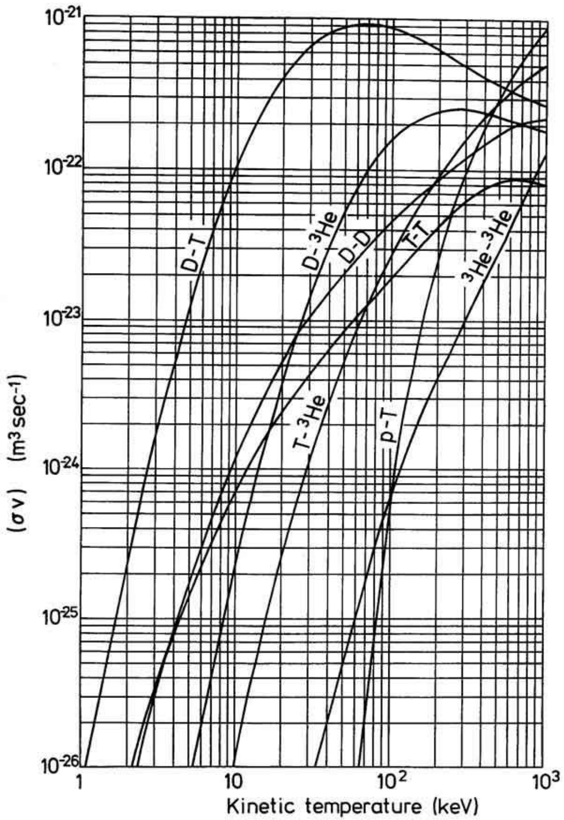
Break-even: $P_{fus}=P_{in}$



Fusion <σv> vs. plasma temperature

- For $10keV < T < 20keV$:

$$\langle\sigma v\rangle_{\mathrm{D-T}} \approx 1.1 \times 10^{-24} \left(\frac{T}{\mathrm{keV}}\right)^2 \frac{\mathrm{m}^3}{\mathrm{s}}$$



Power balance (cont.)

- Beyond break-even

Fusion gain

- *Fusion gain* describes condition needed for power/energy generation

$$Q = \frac{P_{\mathrm{fus}}}{P_{\mathrm{in}}}$$

  - Break-even: $Q = 1$
  - Ignition: $Q \to \infty$

- Need to amplify electric energy → *Engineering gain factor*

$$Q_{\mathrm{eng}} = \frac{\text{electric power out}}{\text{electric power in}}$$

  - Electric energy generation for $Q_{\mathrm{eng}} > 0$

Fusion gain needed for energy generation

- Schematic of a plant

Lecture 1 recap

- The global primary energy use will continue to rise
  - Increase driven by developing countries and population growth
- Dependence on carbon based fossil fuels must decrease (global warming, limited resources)
- A wide range of energy sources exists
  - Deployment of renewables too slow to meet climate change goals
  - Advantages and disadvantages call for mix of energy sources alongside with development of new sources, energy storage and efficient energy transport
- Nuclear fusion offers the potential for a clean, sustainable, practically inexhaustible, geographically independent energy source suitable for supplying the base load
- Fusion power plants will likely be based on the D-T fusion reaction with in situ breeding of T
- High probability of Coulomb scattering leads to a thermal velocity distribution of the fuel ➔ *thermo-nuclear* fusion
- Conditions for break-even is described by the *Lawson criterion* for $n\tau_E$ (further simplification yields a required *triple product* $n\tau_E T$)

Glossary

- Gtoe: 10^9 tons of oil equivalent
  - 1 toe=11.6 MWh
  - 1 toe=41.9 GJ
  - Note that conversion to/from electrical units may or may not take into account efficiency of conversion (η_t~40%)

- Energy unit: eV=$1.6\text{x}10^{-19}$ J
- Atomic mass unit u = $1.66\text{x}10^{-27}$kg
- Nuclear cross section unit b(barn)=10^{-28}m^2