# Renewable Energy in Europe – What is Needed, What is Possible?

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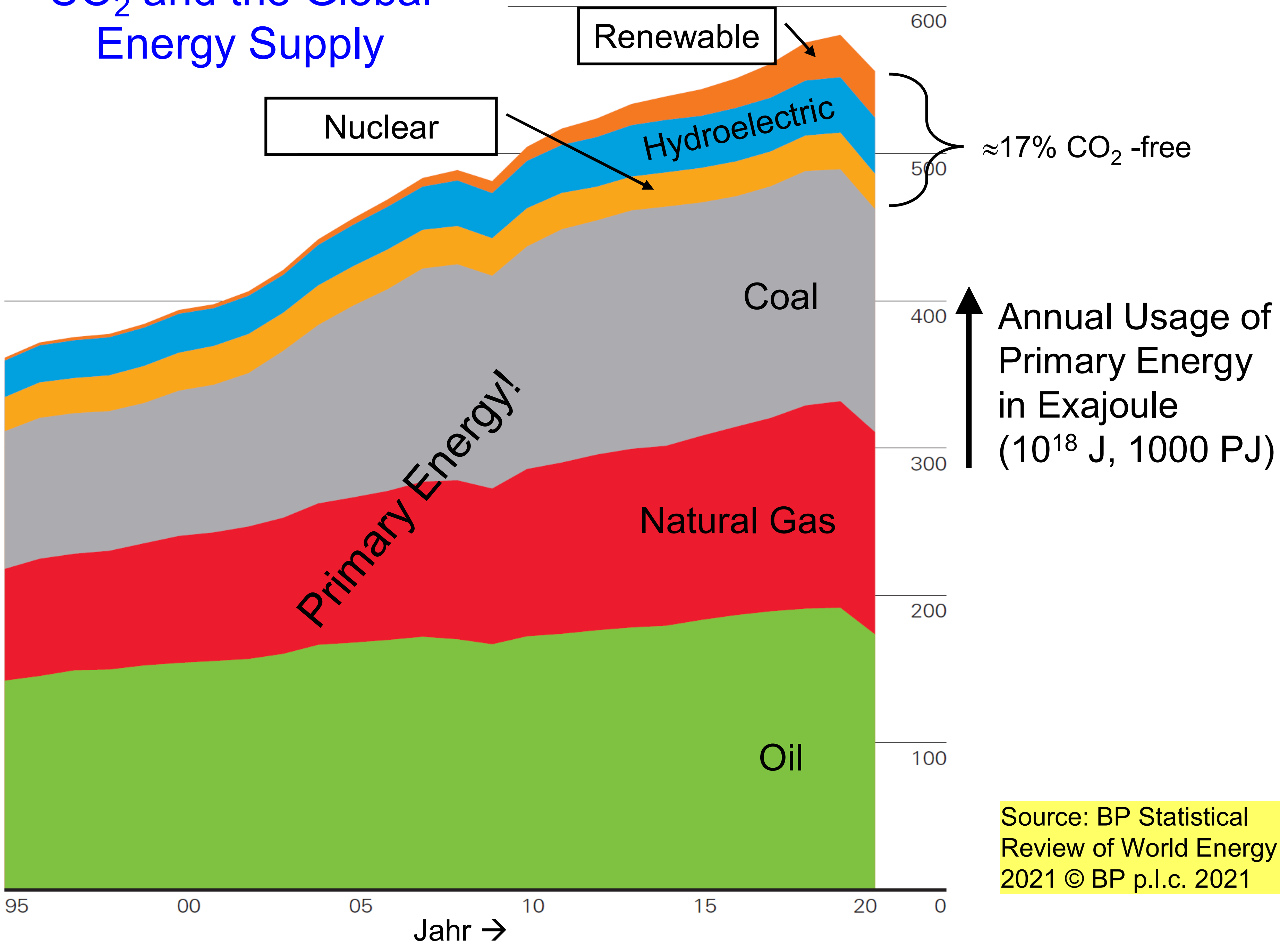
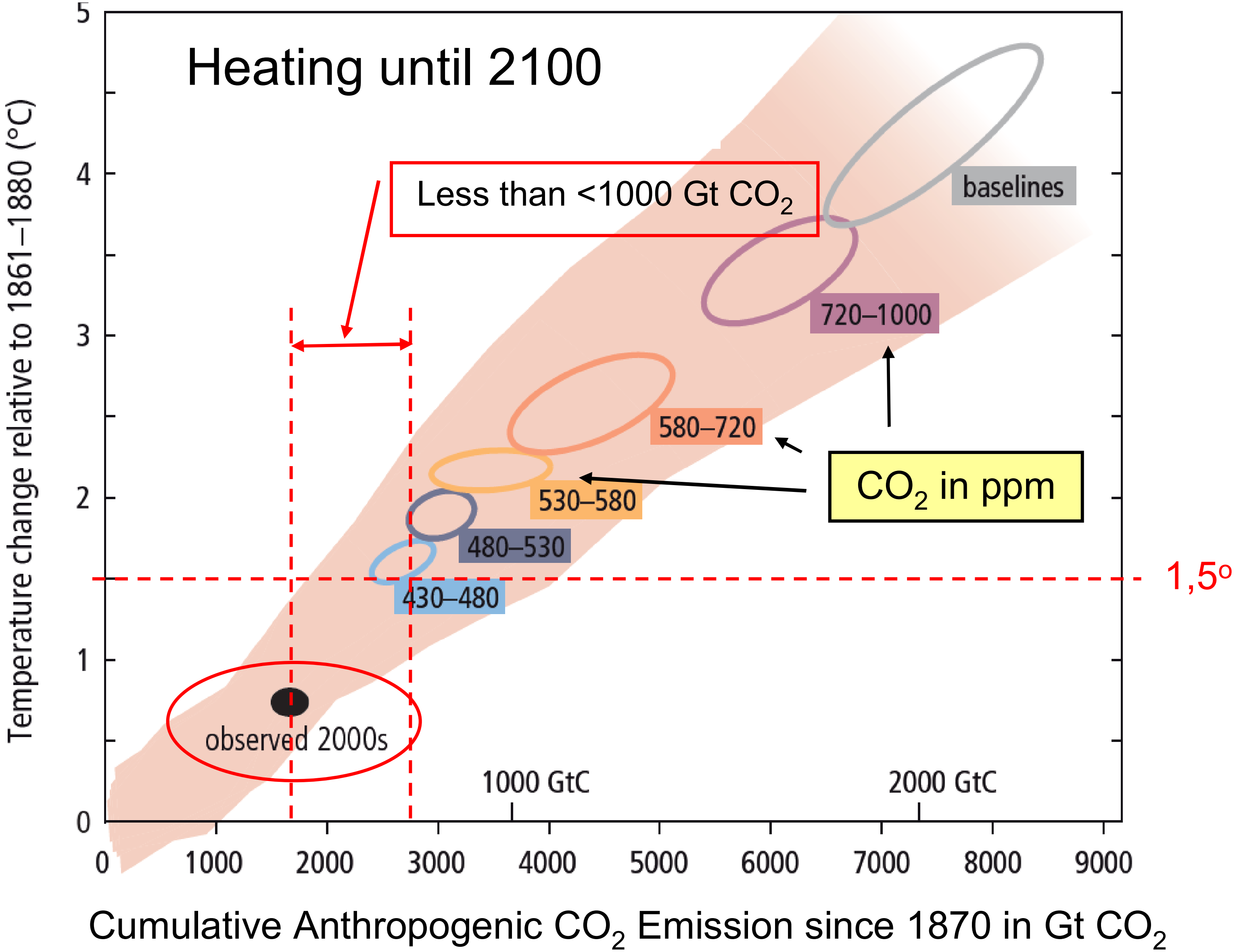
- Energy and Climate – The $CO_2$-Problem
- Where is the Energy used? – „Sectors“
- Greenhous-gas free Energy Supply
  „100% Renewable Energy“
- Storage Requirements
- Storage Technologies & cost
- Soutions to the Storage problem

# $CO_2$ and the Global Energy Supply



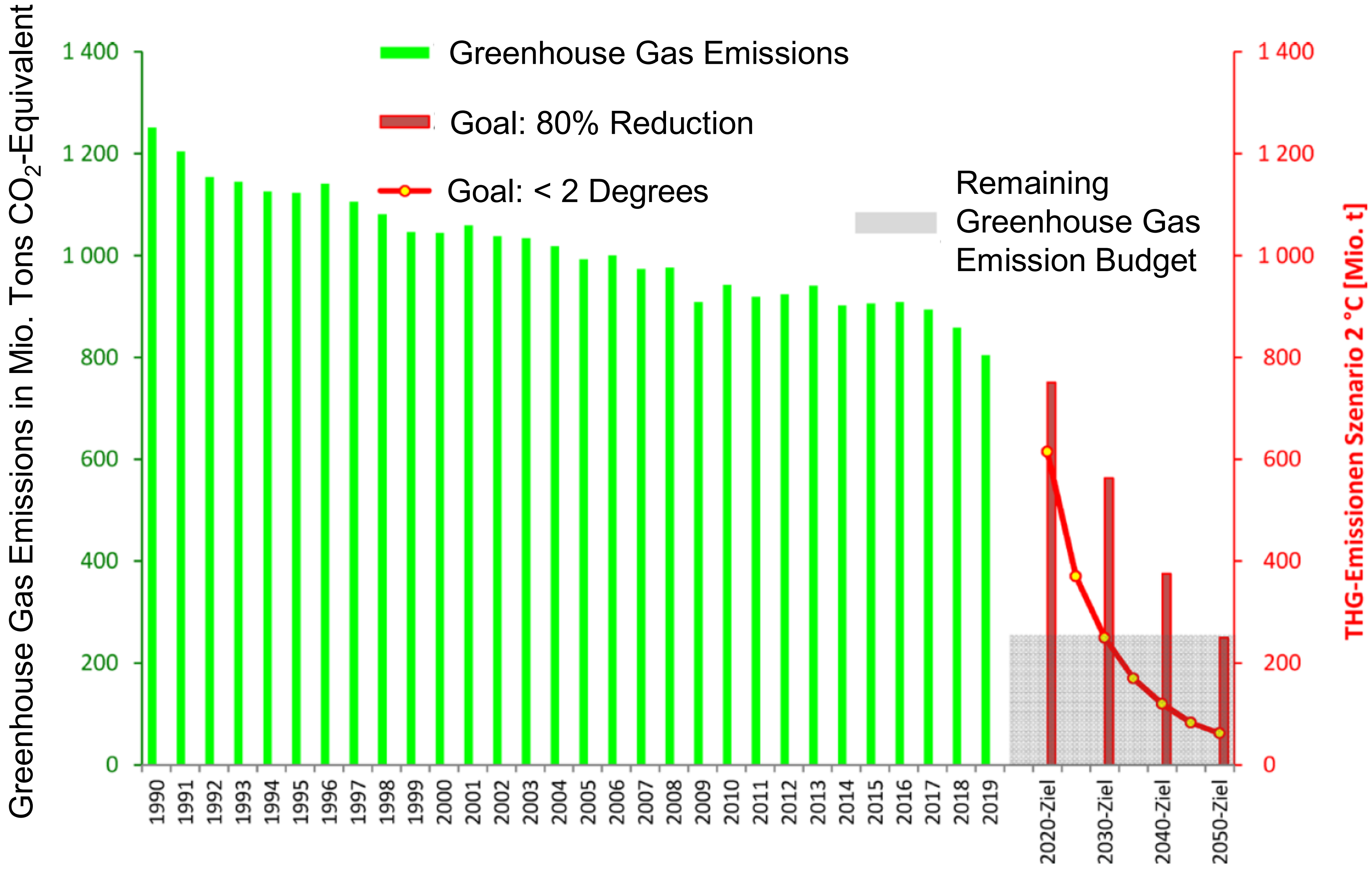
Source: BP Statistical Review of World Energy 2021 © BP p.l.c. 2021

# Global Heating as a Consequence of the Cumulated $CO_2$-Emission



Quelle: IPCC-AR5 Climate Change 2014 Synthesis Report

# Consequences for Germany?



VDI-Sonderdruck 2021 , Regenerative Energien‘

# Primary Energy – Final Energy – Net Energy

## Units: Joule, J, kJ, 1 kWh = 3600 kJ

**Primary Energy**: Energy stored in the originally ocurring form (“Energy source”),
- Chemical energy of coal, oil, Biomass or natural gas
- Transformed from other energy carriesr like Solar, Wind, ....

**Secondary Energy:** Supplied by transformation of primary energy, for instance:
- Coal, Gas, Nuclear Energy to Electricity
- Crude oil to fuel (petrol, diesel fuel, …).

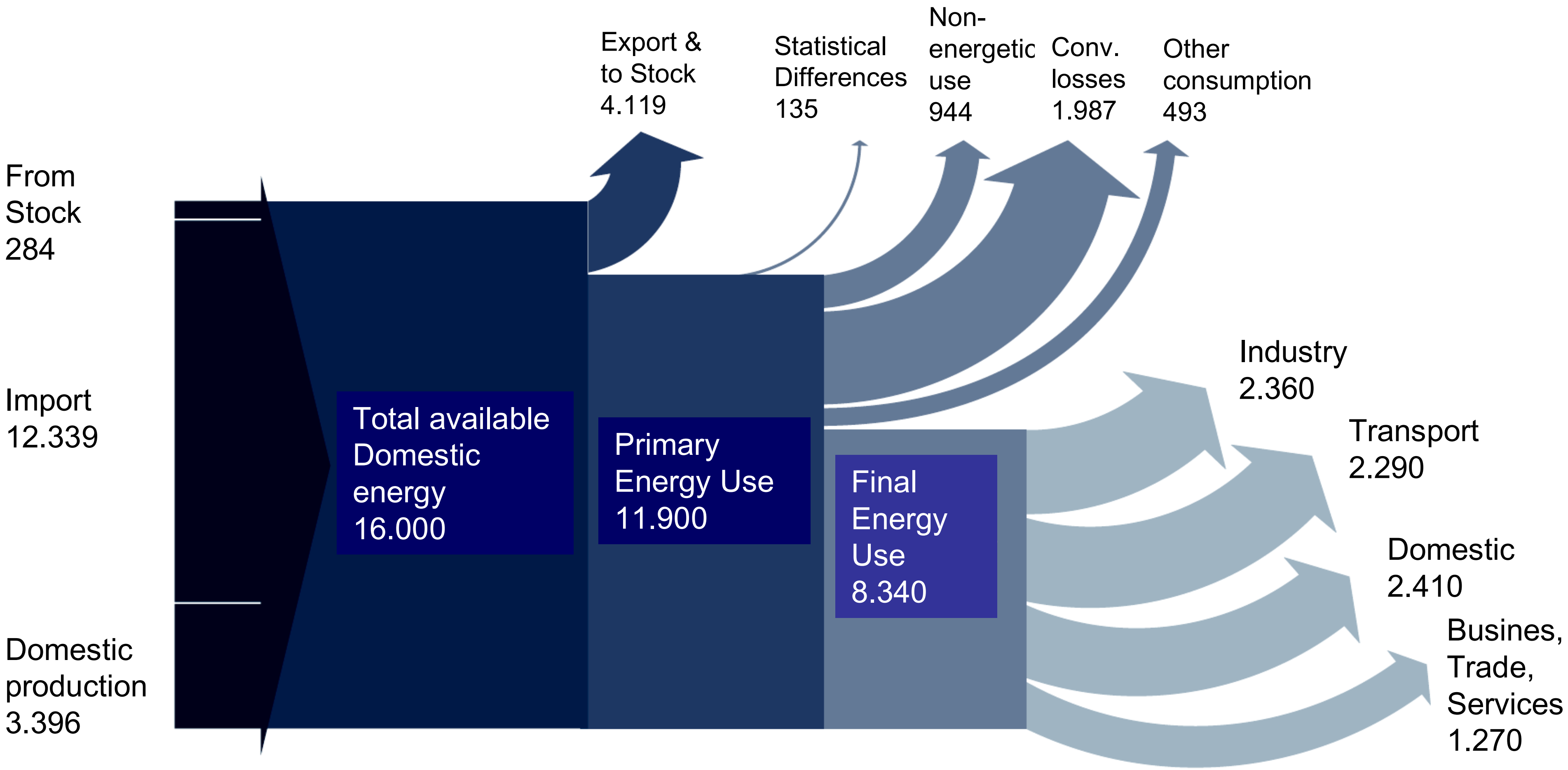
Considerable losses usually occur in this process.

**Final Energy:** Energy useable by consumer, (electricity, petrol, diesel) after “transfer”, (there my be transfer losses).

**Net Energy (Useful Energy):** Actually used Energy (e.g. light, mechanical power, …), i.e. final energy minus transformation losses (e.g. fuel to heat or fuel to motion) occuring by consumer.

# Energy Fluxes, Germany 2020

## Figures in Petajoule, 1 PJ = $10^{15}$ Joule (278 GWh)



From Stock
284

Import
12.339

Domestic production
3.396

Total available Domestic energy
16.000

Export & to Stock
4.119

Primary Energy Use
11.900

Statistical Differences
135

Non-energetic use
944

Conv. losses
1.987

Other consumption
493

Final Energy Use
8.340

Industry
2.360

Transport
2.290

Domestic
2.410

Busines, Trade, Services
1.270

Der Anteil der erneuerbaren Energieträger am Primärenergieverbrauch liegt bei 16,5 %.
Abweichungen in den Summen sind rundungsbedingt.
* Alle Zahlen vorläufig/geschätzt.
29,3 Petajoule (PJ) ≙1 Mio. t SKE
Quelle: Arbeitsgemeinschaft Energiebilanzen 09/2021

Source: Arbeitsgemeinschaft Energiebilanzen 09/2021

# What is a Peta Joule (PJ) ?

4 ½ Chocolade bars

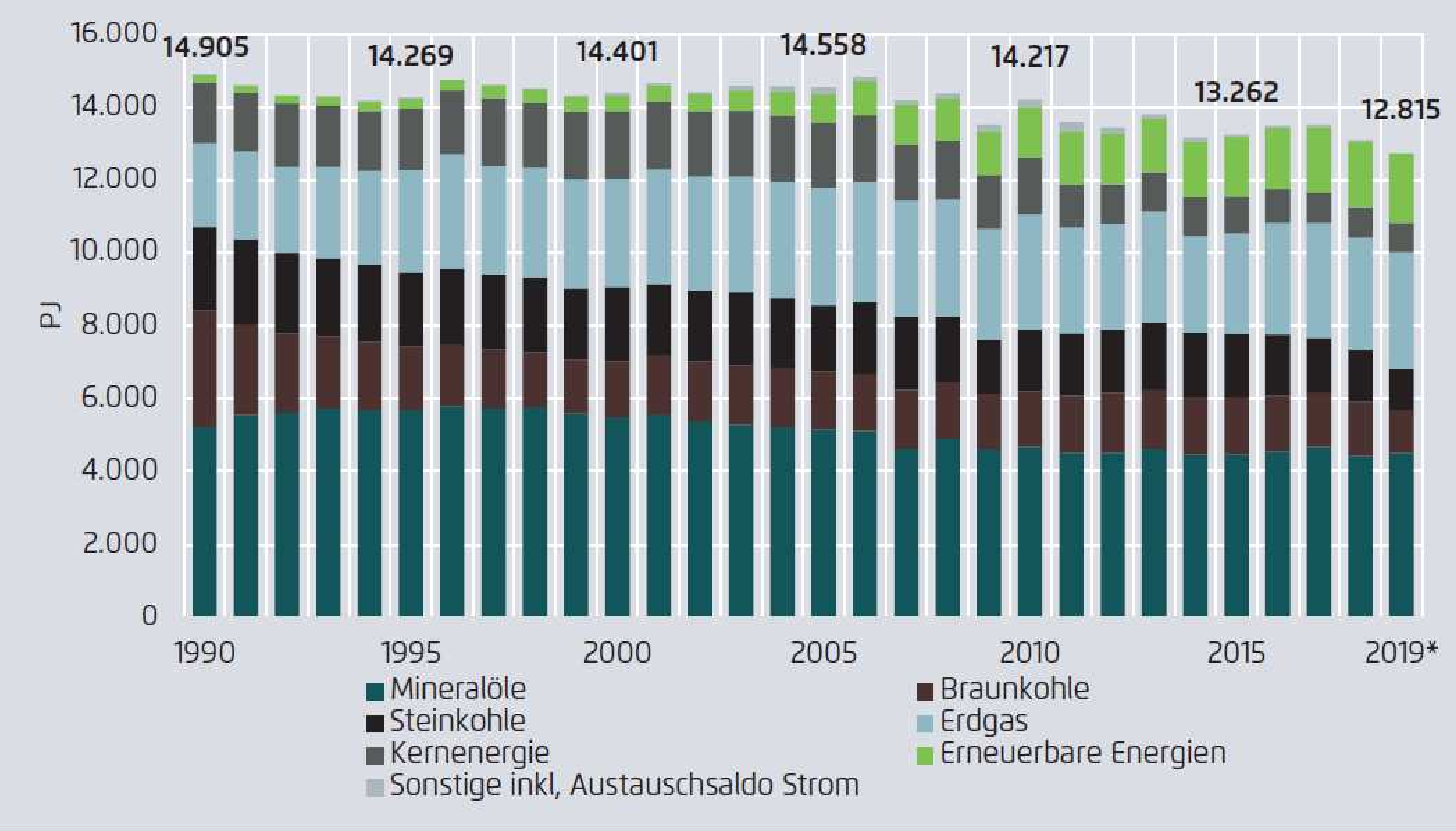
Answer 1: 1 PJ = $10^{15}$ Joule or 278 GWh
or 278 Mio. kWh

Answer 2:
Daily Energy consumption of a human:
≈2400 Kilocalories or ≈10.000.000 Joule (10.000 kJ, $10^7$J)

All Germans (83 Mio.) per year (365 Tage):
„Consume“ $3{\cdot}10^{17}$ J or **300 PJ** as food.

Corresponds to ca. **1/40** of the annual German Total Primary Energy usage of ≈12.000 PJ.

# Primary Energie Use in Germany



Ren. Energy

Nuclear

Nat. Gas

Coal

Lignite

Oil

nergiebilanzen (2019a), *vorläufige Angaben

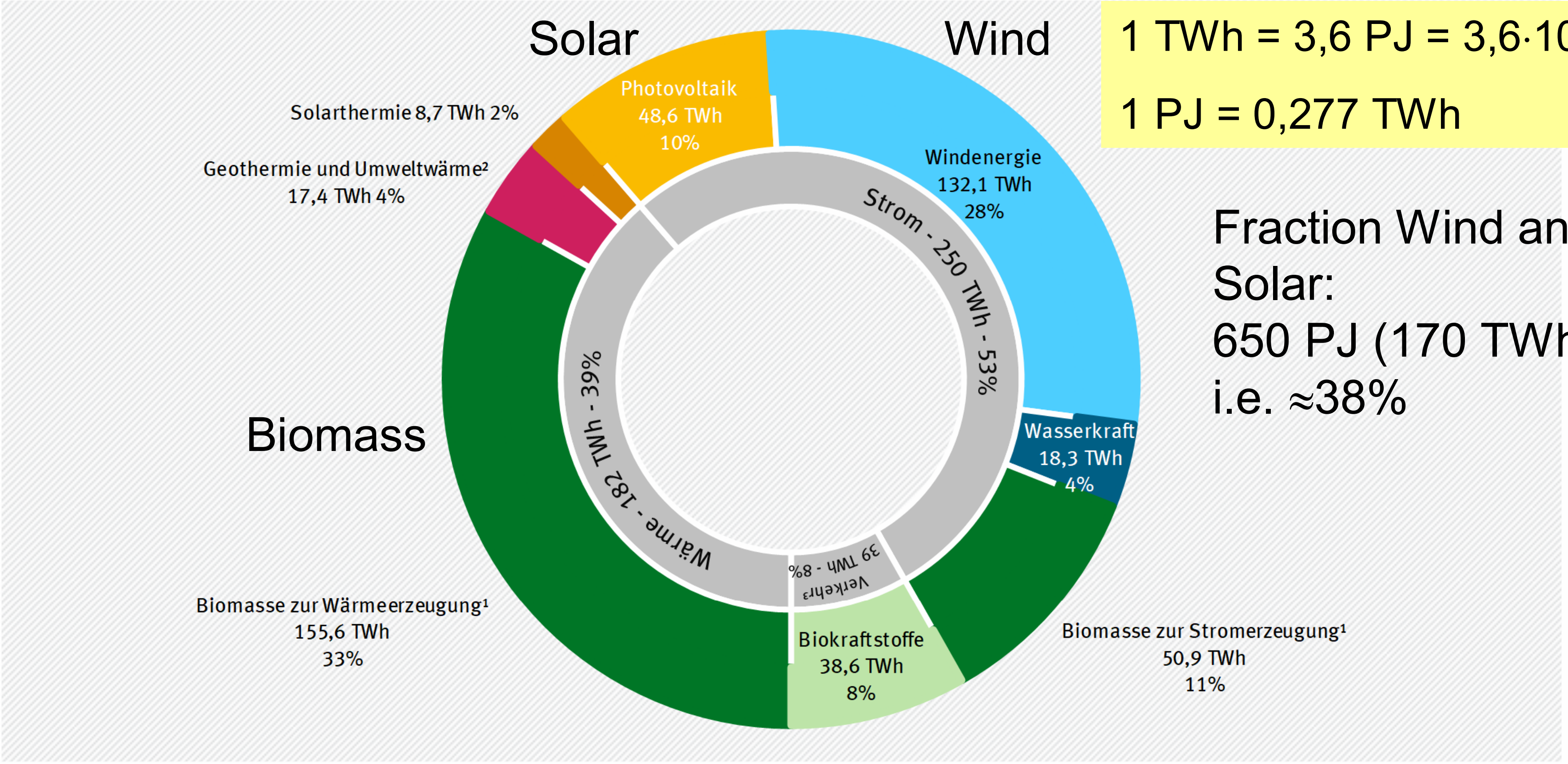
Renewable Energy 2020: 1700 PJ (≈17%)

Source: Agora Jahresauswertung: Die Energiewende im Stromsektor: Stand der Dinge 2019

# Energy Supply from Renewable Sources, Germany, 2020, total: 470 TWh or 1700 PJ

1 TWh = 3,6 PJ = $3{,}6\cdot10^{15}$ J

1 PJ = 0,277 TWh



Fraction Wind and Solar:
650 PJ (170 TWh)
i.e. ≈38%

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[1] mit biogenem Anteil des Abfalls

[2] Stromerzeugung aus Geothermie etwa 0,2 TWh (nicht separat dargestellt)

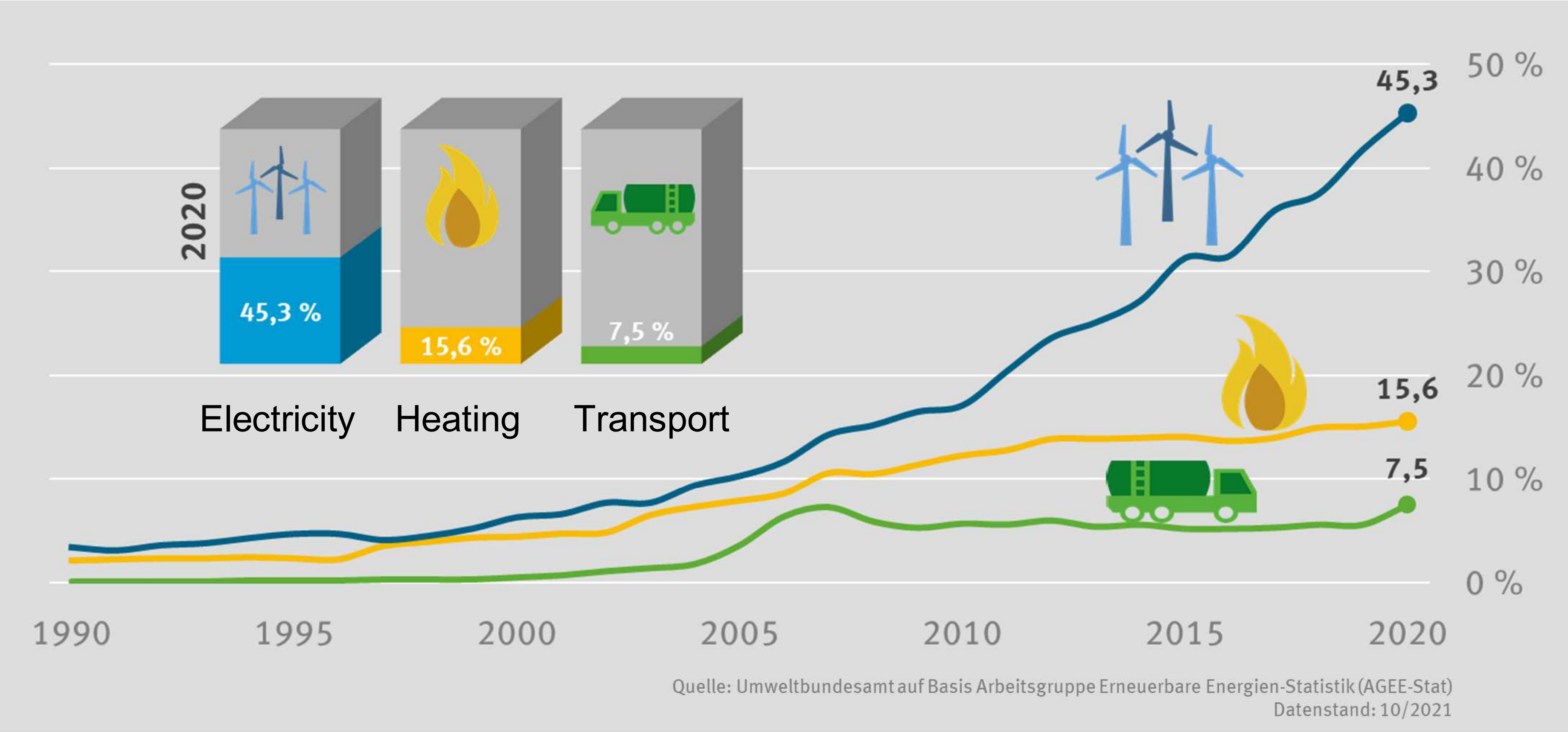
[3] Verbrauch von EE-Strom im Verkehr etwa 4,9 TWh

Abweichungen bedingt durch Rundungen

Quelle: Umweltbundesamt (UBA) auf Basis AGEE-Stat
Stand 10/2021

Source: Umweltbundesamt auf Basis AGEE-Stat:
https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#uberblick

# Fraction of RE in the Sectors Electricity, Heating and Transport, Germany 1990 - 2020



Quelle: Umweltbundesamt auf Basis Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat)
Datenstand: 10/2021

Source: Umweltbundesamt: https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#uberblick

# 100% Renewable Energy (RE)
## in Germany, Europe, the World

See also: Lecture by
Hans-Martin Henning

0. Approximation: Today (2022/2023 in D) we have ≈17% fraction of RE from the total use of primary energy
   → does it mean that an incease by a **Faktor 1/0.17 ≈ 6** is necessary for 100% RE??

**The matter is more complicated!**

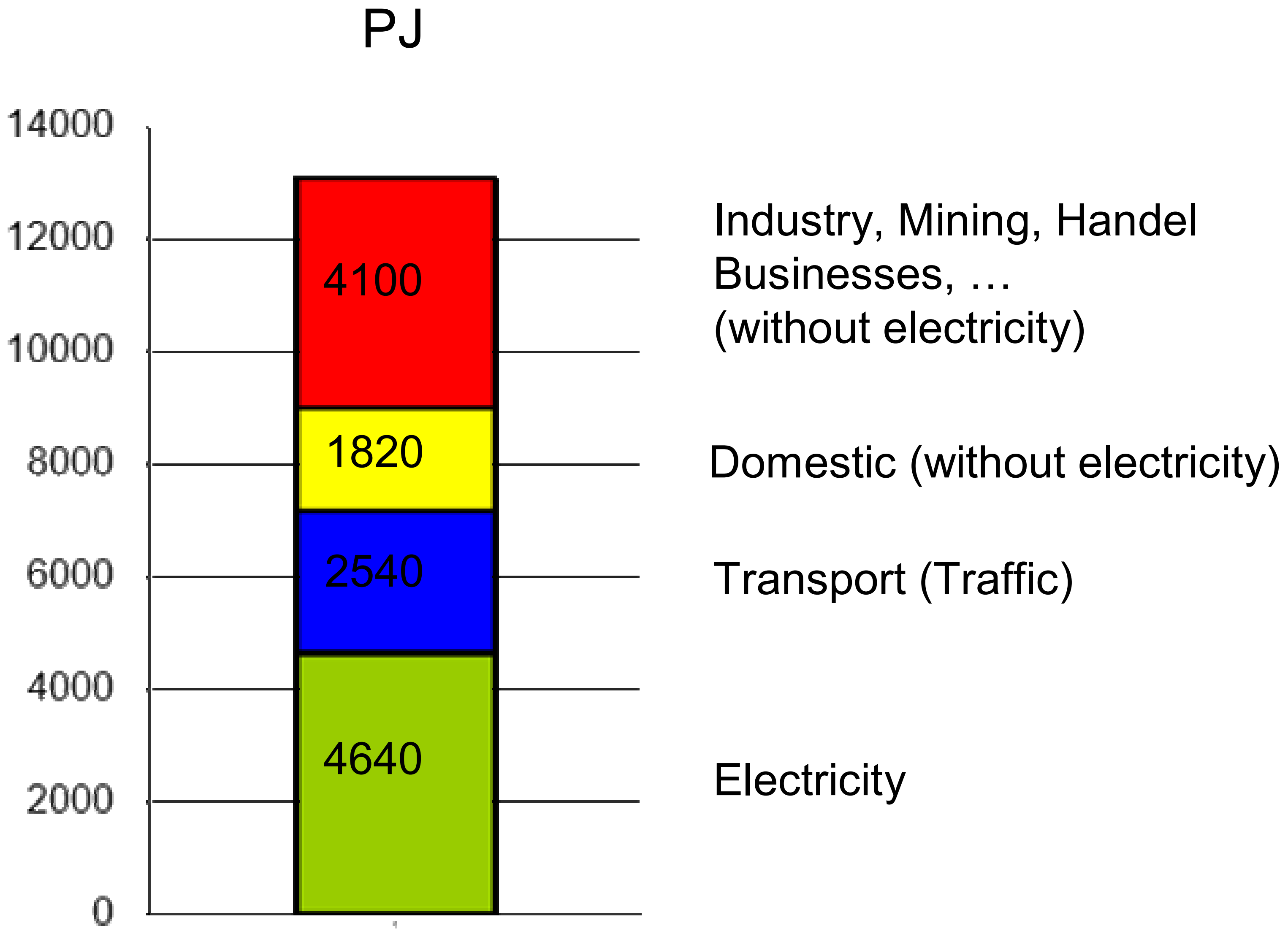
Problems:

Renewable Energy is „much better“ than fossil Energy

1) **Primary Energie** is not a good measure, actually we are interested in **Net Energy**. Therefore we need to look at the sectors individually.

2) The RE supply is very variabel, we need to look at **Energy-mix**, **Storage** and **Excess-capacity**.

# Primary Energy use in Germany in the Sectors



For 2018, Source: Arbeitsgemeinschaft Energiebilanzen

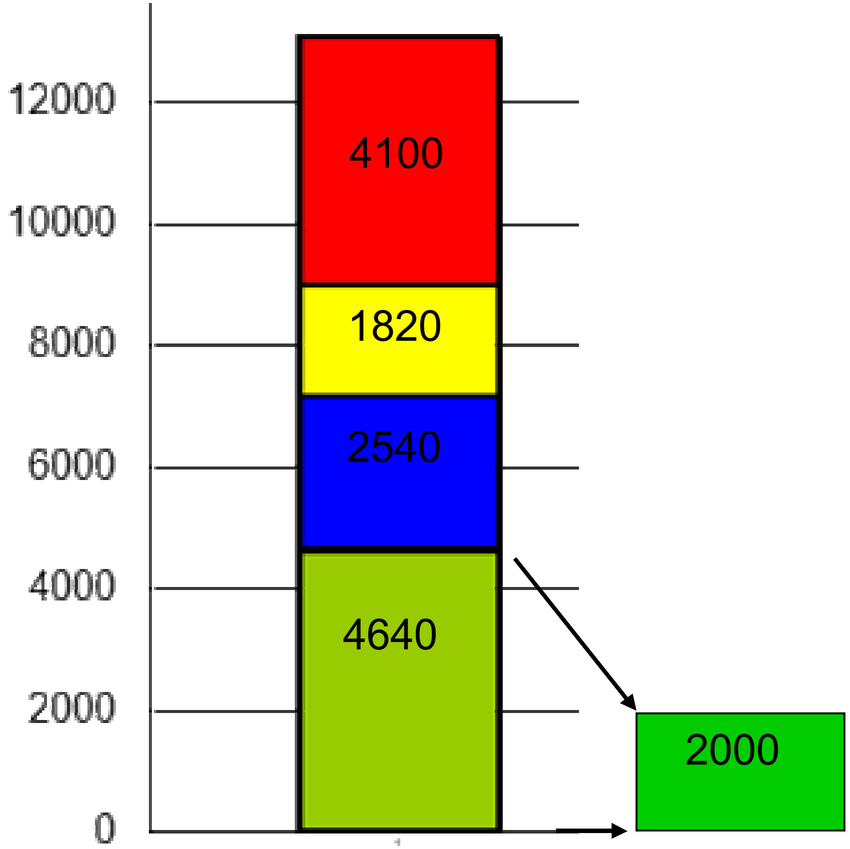
# Looking into the Sectors 1: Electricity

Primary Energy Use 2018: 4640 PJ (35,4% of PEU)
Net inland 2000 PJ Electricity (≈64 GW x 1 yr)
≈ 45% RE: Final Energy ≈ Primary Energy
≈ 55% Fossil+Nuclear: Final Energie ≈ 0.35*Primary Energy

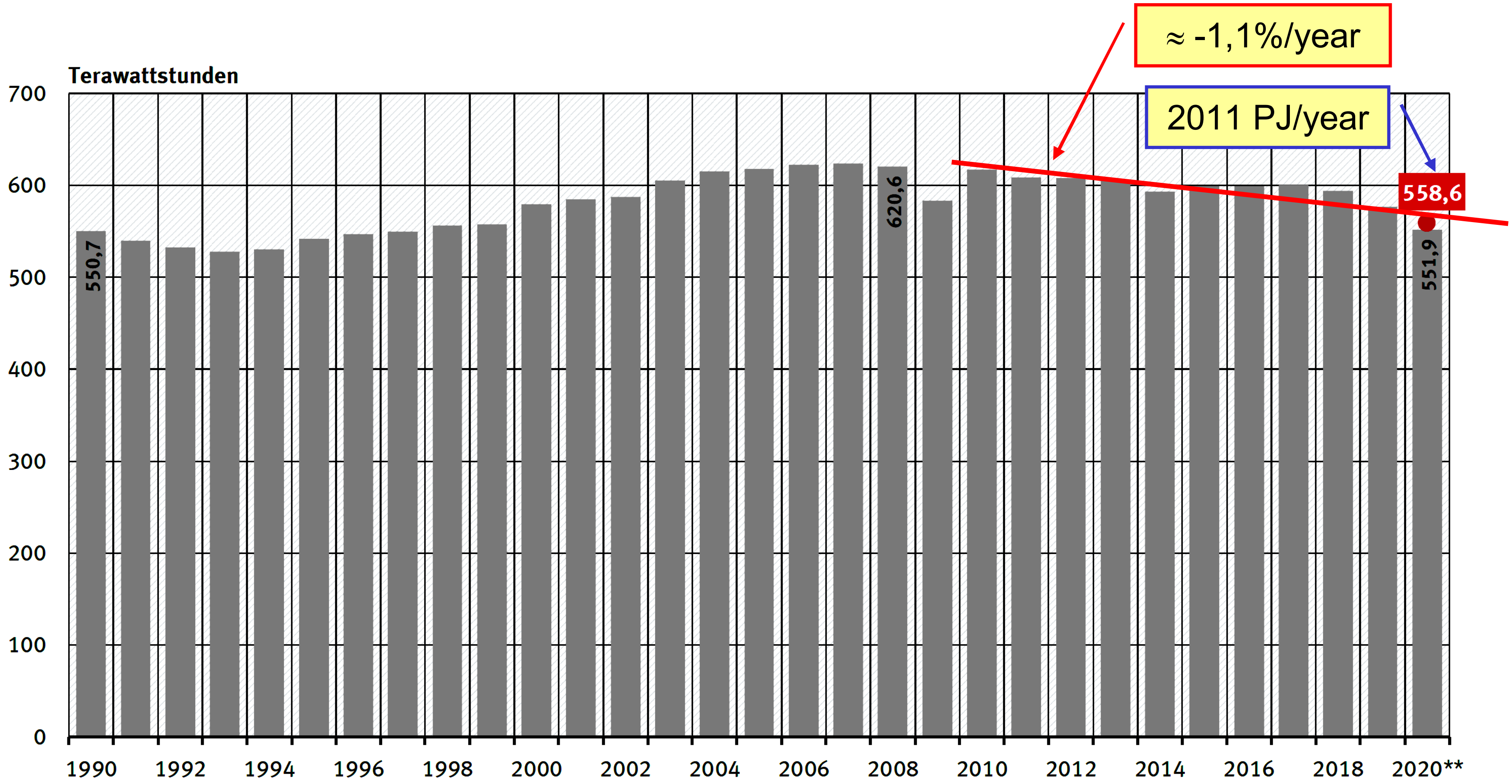
→ ≈23% of Primary Energie from Renewable E.

≈77% of Primary Energy from Fossil + Nuclear

→ 100% EE require ≈**2000 PJ** Energy from Wind, Solar, …
Only ≈45% of present day Primary Energy use for Electricity!



# Looking into the Sectors 1: Total Electricity Usage in Germany 1990-2020 in TWh (=Billion KWh)



≈ -1,1%/year

2011 PJ/year

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* Berücksichtigung des Stromhandelssaldos
** 2020 vorläufig; Ziel 2020: Energiekonzept der Bundesregierung 2010: Senkung des Bruttostromverbrauchs um 10 % gegenüber 2008

Quelle: Umweltbundesamt auf Basis AG Energiebilanzen, Sondertabelle Bruttostromerzeugung in Deutschland von 1990 bis 2020 nach Energieträgern, Stand 02/2021

Source: Umweltbundesamt: Sondertabelle Bruttostromerzeugung in Deutschland 1990-2020

# Looking into the Sectors 2: Traffic

Primary Energy usage 2018: 2540 PJ (19,4%)

≈ 10% Trains, Tram Final Energy ≈ Primary Energy

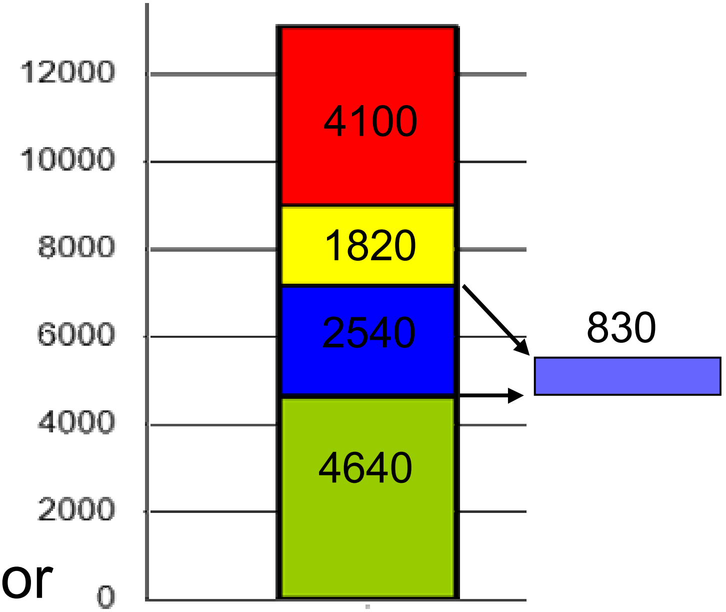
≈ 90% Combustion engines: Final Energy ≈ 0,2*Primary Energy

Replacement by:
Electric cars Final Energy = 0,8*Primary Energy

→ ≈10% (260 PJ) alread electrified (Trains, Tram)

≈90% (2280 PJ) Combustion engines
→ Battery electrical power
→ 570 PJ

→ 100% RE requires only ≈**830 PJ**
Just ≈ 30% of today‘s
Primary Energy usage in the traffic sector
→ **570 PJ (ca. 20%)** additional Electricity



Remarks: $H_2$-cars: +80% additional electricity
Synthetic fuels: +200% additional Electricity

See also Lecture by:
Maximilian Fichtner
„The transformation
of propulsion“

# Looking into the Sectors 3: Domestic use (w.o. Electricity)

Another ≈700 PJ

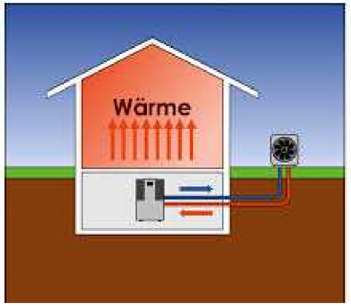
Primary Energie usage 2018: **1820 PJ** (13,9%)

Essentially only Heating: 1820 PJ (90% Efficiency)

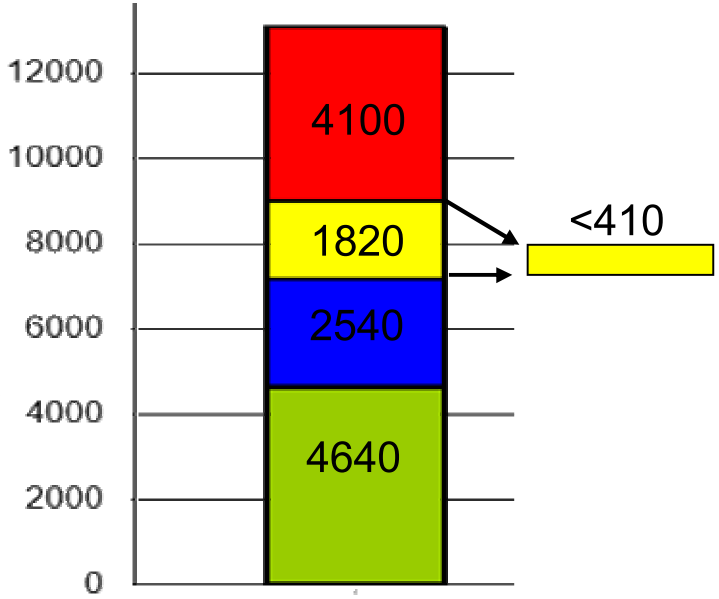
→ Replacement by Heat Pumps with avg. COP = 4:

1820 PJ (Net Energy 1640 PJ) → 410 PJ

Coefficien Of Performance



Already > 50% of new houses with Heat Pumps, more in the future …



→ Total Energy requirement ≈**410 PJ**
Only ≈ 22% of today‘s Primary Energy Usage in the Domestic Sector (without electricity)

→ **max. 20%** additional Electricity usage (better insulation, additional Geothermal Energy, Biomass, …)

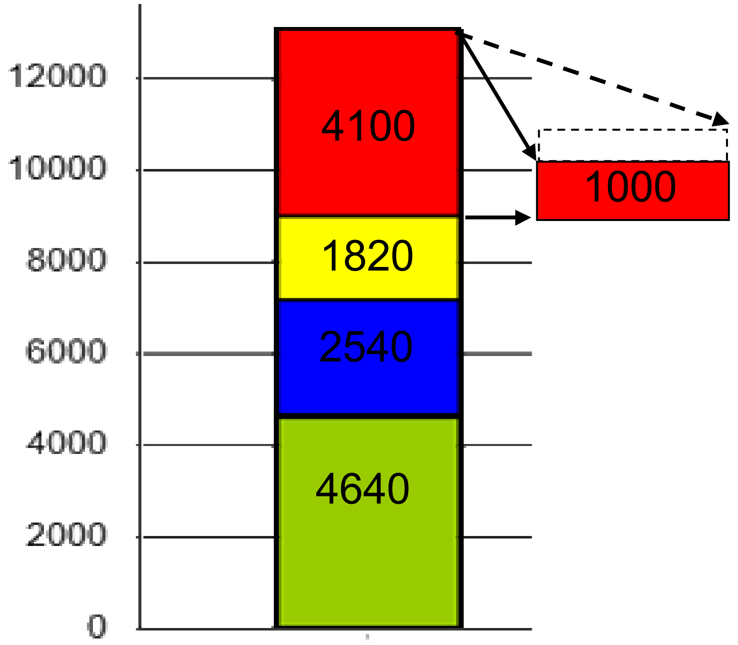
# Looking into the Sectors 4: Industry, Mining, Bussines & Trade (without electricity)

Primary Energy use 2018: 4100 PJ (31,3%)

Many different Processes

→ Energy requirement of (additional) electricity difficult to estimate, assume: 1000 PJ
(similar Faktor: Used Energy/Primary Energy as in Transport, Domestic)

Rest via Recycling (non energetic consumption), Biomass, Fossil Energy + CCS

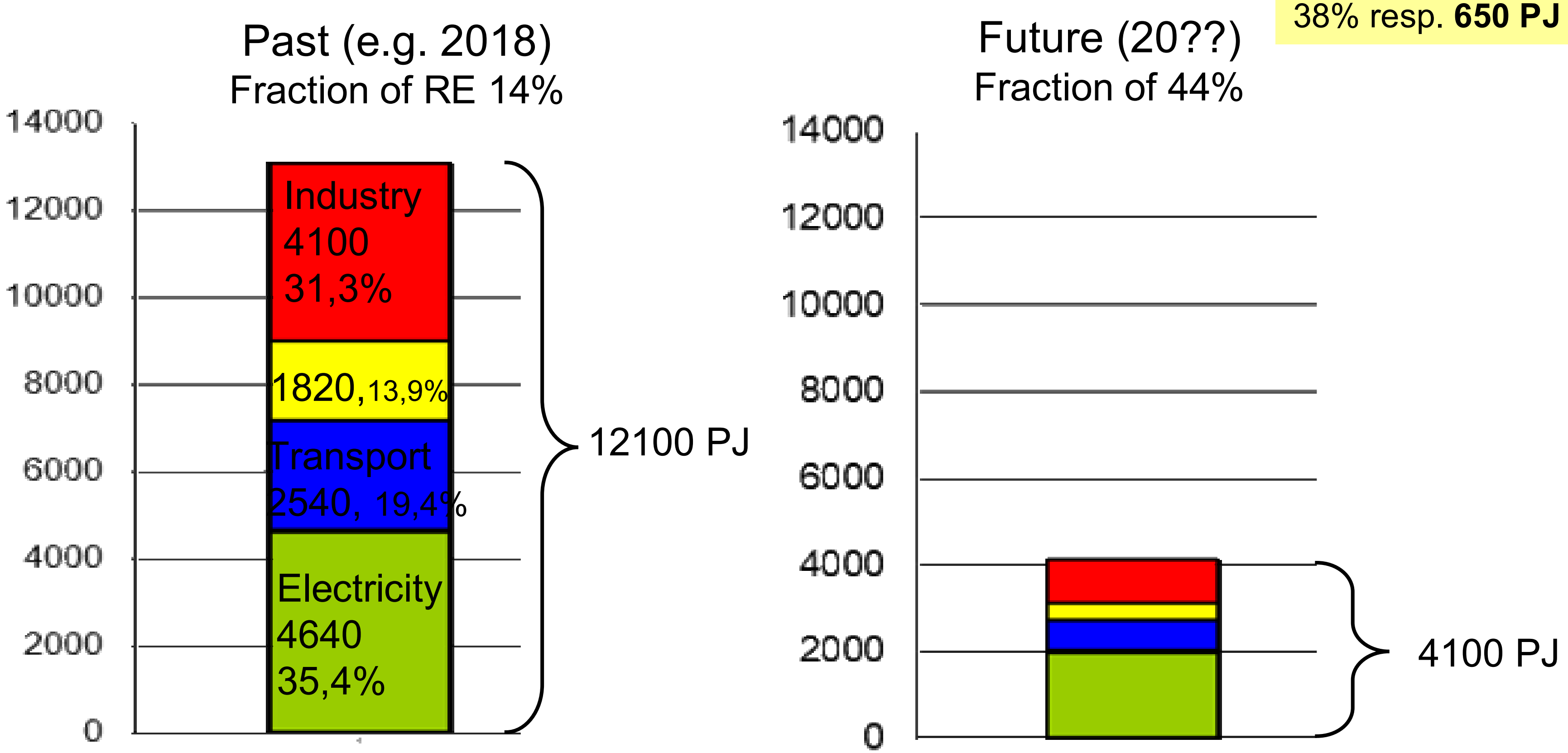


→ Required ≈ **1000 PJ** additional Electricity (e.g. for $H_2$)

**ca. 50%** additional Electricity required

# Primary Energy usage and Renewable Energy required for Replacement (Germany 2018)

Renewable Energy:
2018: 1700 PJ*
Wind+Solar thereof:
38% resp. **650 PJ**



Preliminary Conclusion:

**„For 100% RE we would have to increase RE-by a Factor of ≈2.4“**
More Energy required as Electricity (**2000 → 3800 PJ, +90%)**

**Problem: Variability of RE → Storage**

*Source: Agora Jahresauswertung: Die Energiewende im Stromsektor: Stand der Dinge 2019

# Question: How much Storage Capacity is Required for 100% Electricity Supply from Renewable Sources?

Measure of Storage Size:

$$\text{SupplyTime} = \frac{\text{Stored Energy}}{\text{Mean Consumption}}$$

Some Answers: 3 Months (!)

Better Answers:

- Depends on Energy Mix (i.e. Wind – Solar)
- Depends on Excess capacity*
- Depends on desired Reliability of Supply

*Term
„Excess Capacity“ will be explained later

Let us have a look on these topics …

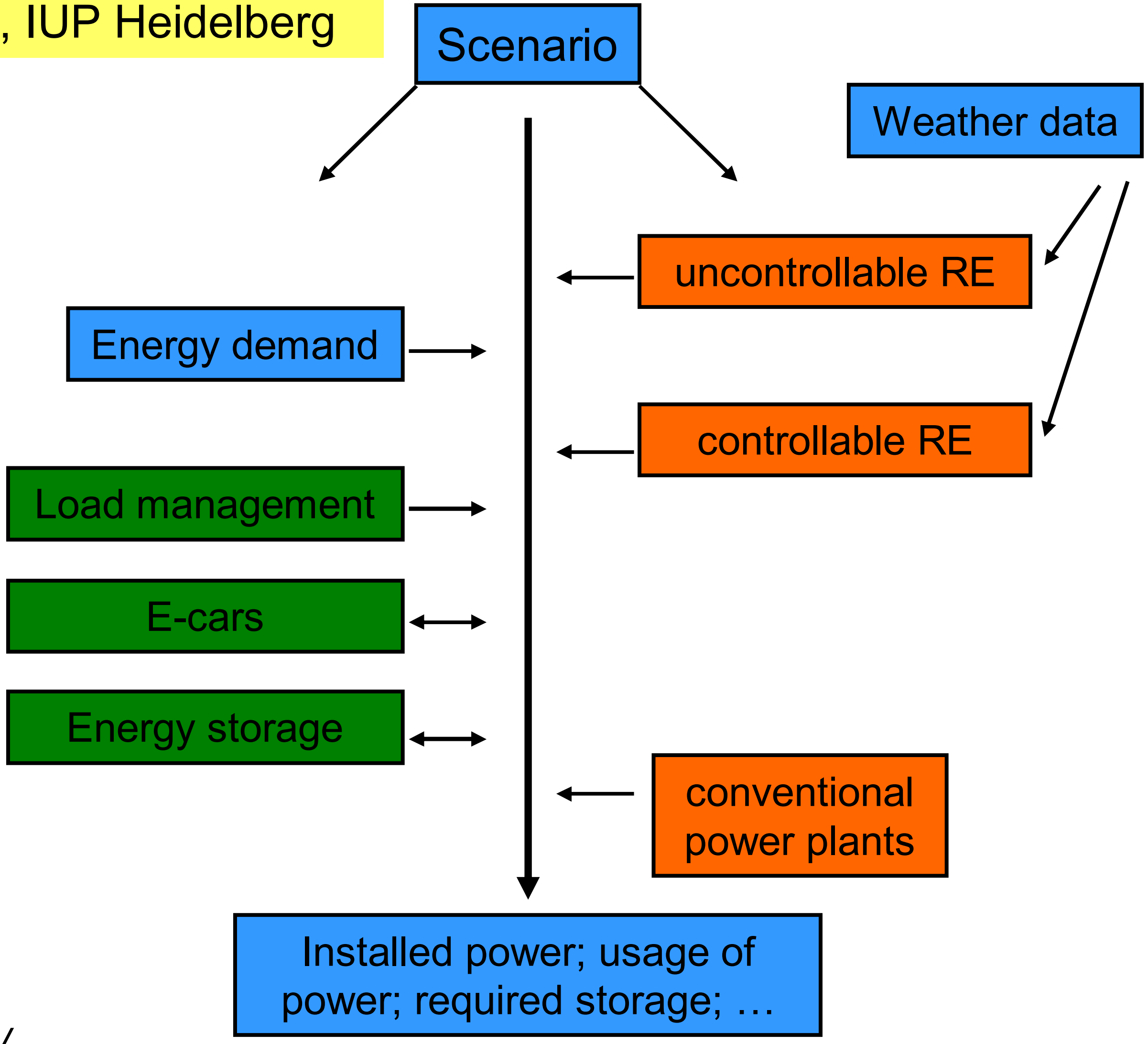
See also: Lecture by
Franz W. Iven

# The “Meteorological based Energy Eqilibrium Testing – Model” (MEET)

**Tobias Tröndle Doctoral Thesis, IUP Heidelberg**

Developed at IUP Heidelberg

- Electricity only
- Time period: 1 year, MERRA*- and ERA-interim - weather data for 2000-2010
- All of Europe
- 10 different types of power sources
  (Gas, Coal, Nuclear, Biomass, Hydro, Solar-thermal, photovoltaic, wave, Wind)
- Unlimited grid capacity („copper plate“)
- Spatial resolution: 2,5°
- Time resolution: 1 hour
- Energy storage efficiency: 81%



Scenario

Weather data

uncontrollable RE

Energy demand

controllable RE

Load management

E-cars

Energy storage

conventional power plants

Installed power; usage of power; required storage; …

*Modern Era Retrospective-Analysis for Research and Applications, NASA

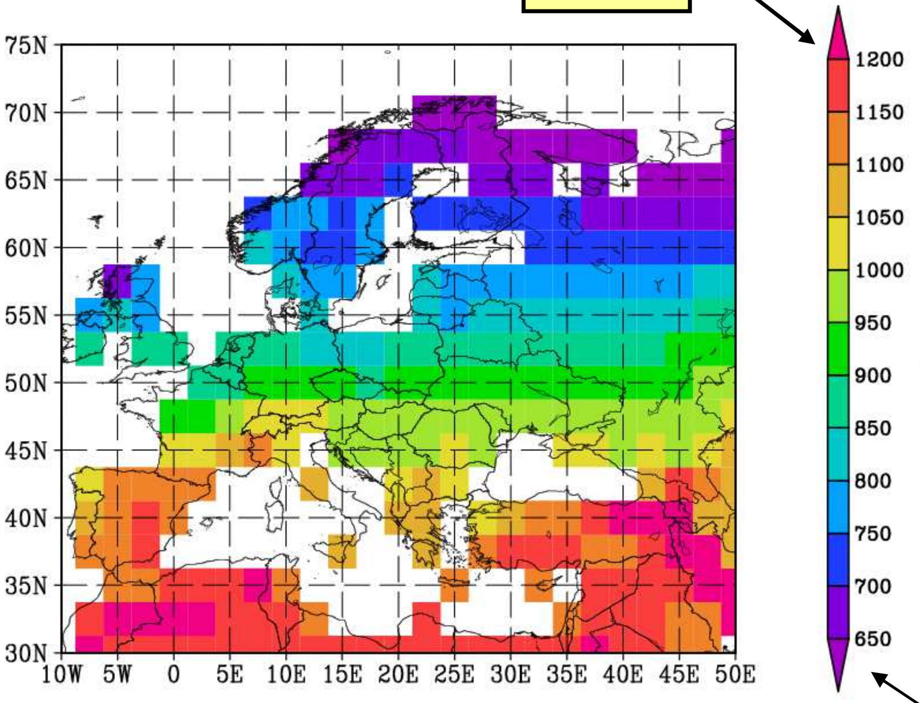
# Potential of Wind and Solar Power in Europe (Mean 2000 to 2010)

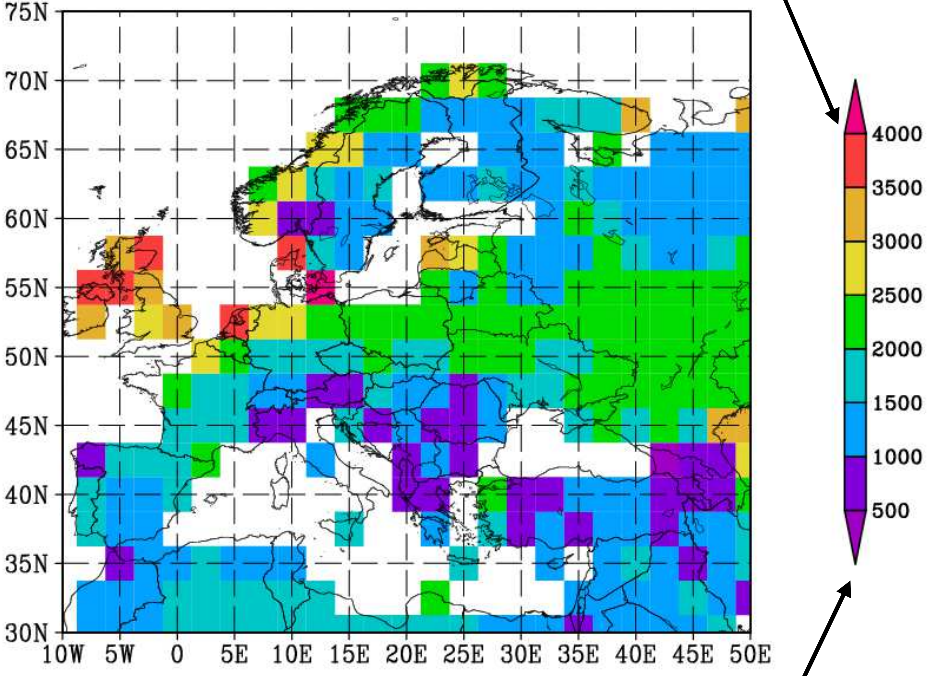
Annual PV electricity generation potential

Annual wind-electricity generation potential

13.7%

45.7%

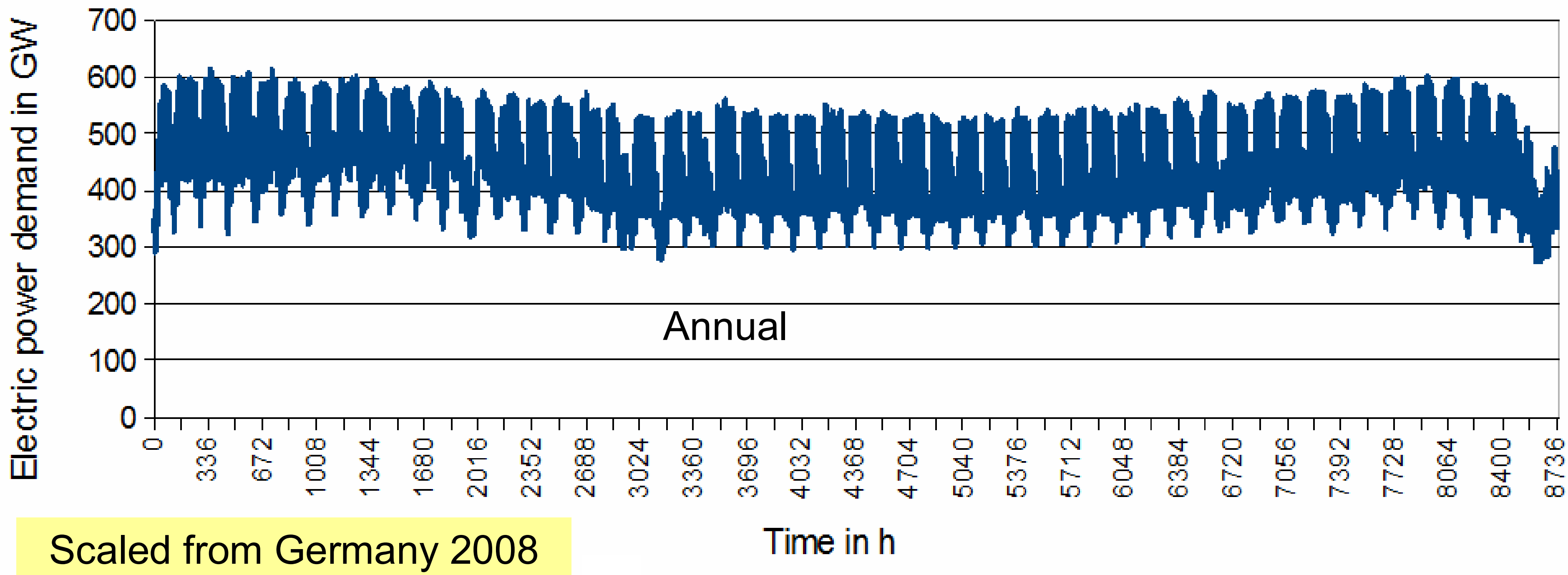




Percentage:
Fraction of generated
kWh‘s of 8760 kWh

kWh per year and $kW_{peak}$

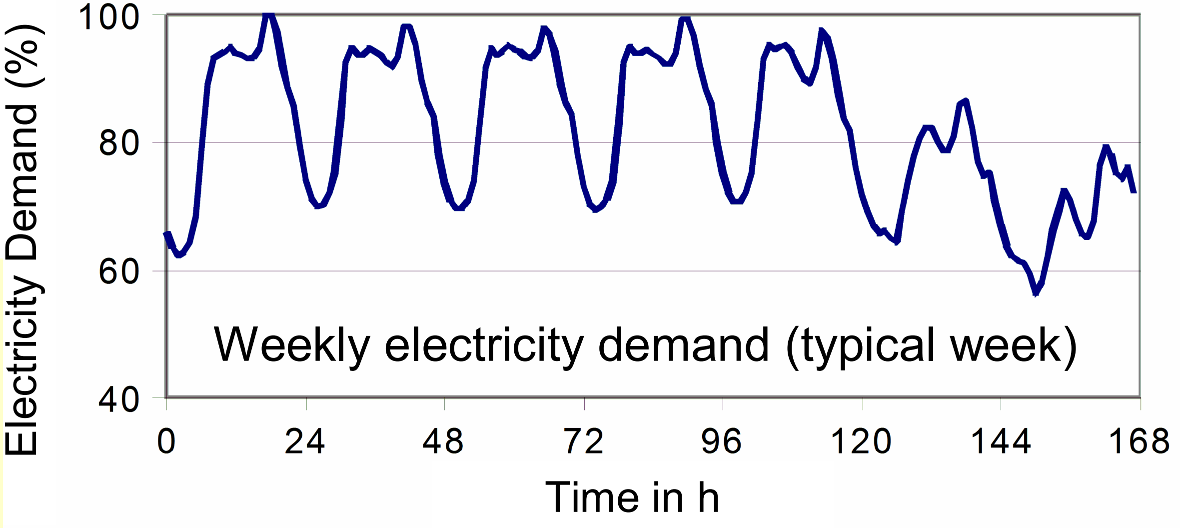
# Annual/Weekly Electricity Demand in Europe (MEET)



Scaled from Germany 2008

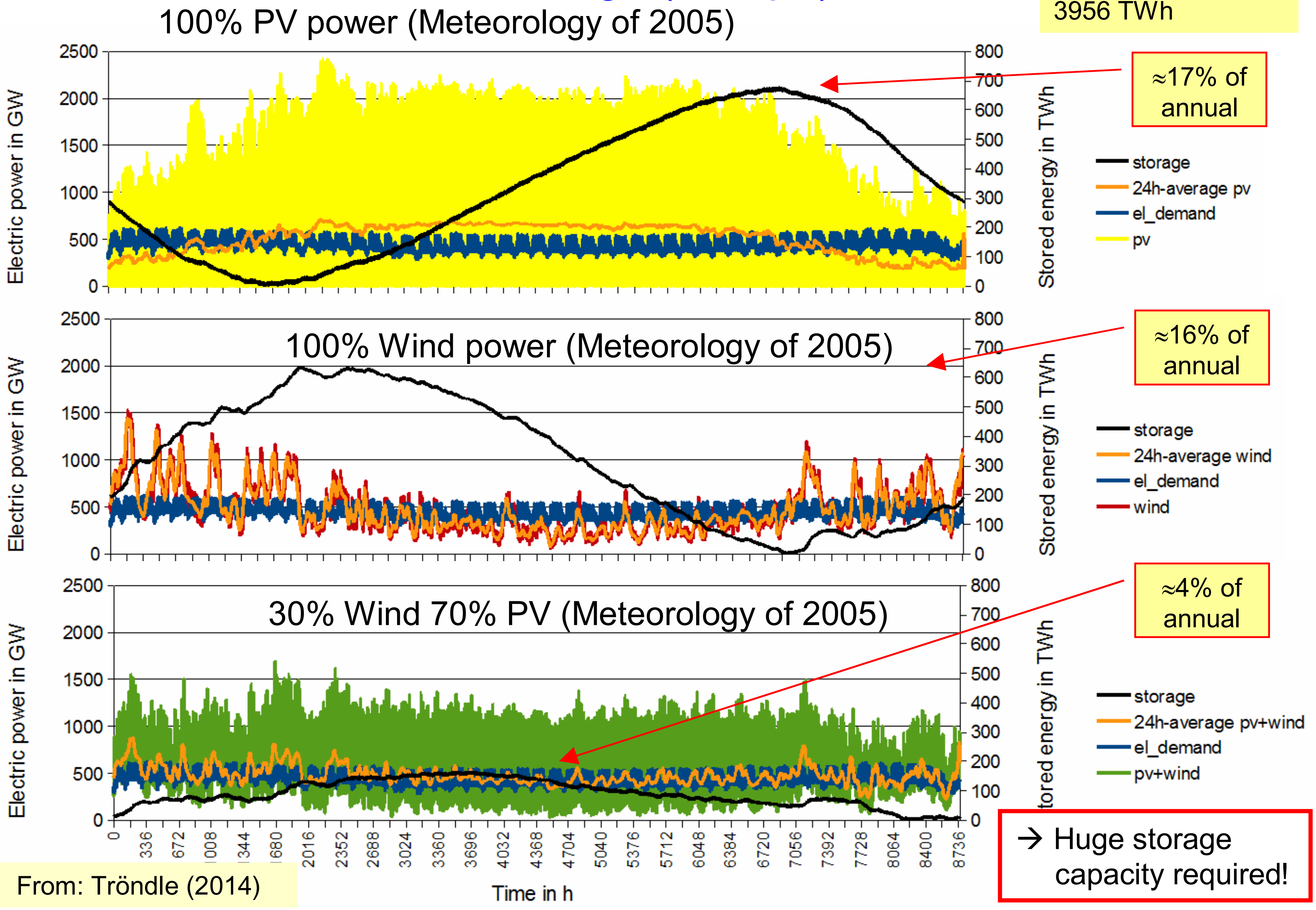
→ Most of the variation in demand is diurnal variation

Tröndle (2014), Development of a global electricity supply model and investigation of eletricity supply by renewable energies with a fous on energy storage requirements for Europe, Doctoral Thesis, Ruprecht-Karls-Universität, Heidelberg.



# Time Series of Wind, Solar, and Storage (Europe)

Anual electricity demand of Europe: 3956 TWh



100% PV power (Meteorology of 2005)

100% Wind power (Meteorology of 2005)

30% Wind 70% PV (Meteorology of 2005)

≈17% of annual

≈16% of annual

≈4% of annual

→ Huge storage capacity required!

From: Tröndle (2014)

# Required Storage Capacity (100% renewable), Wind + Solar (2000 – 2010)

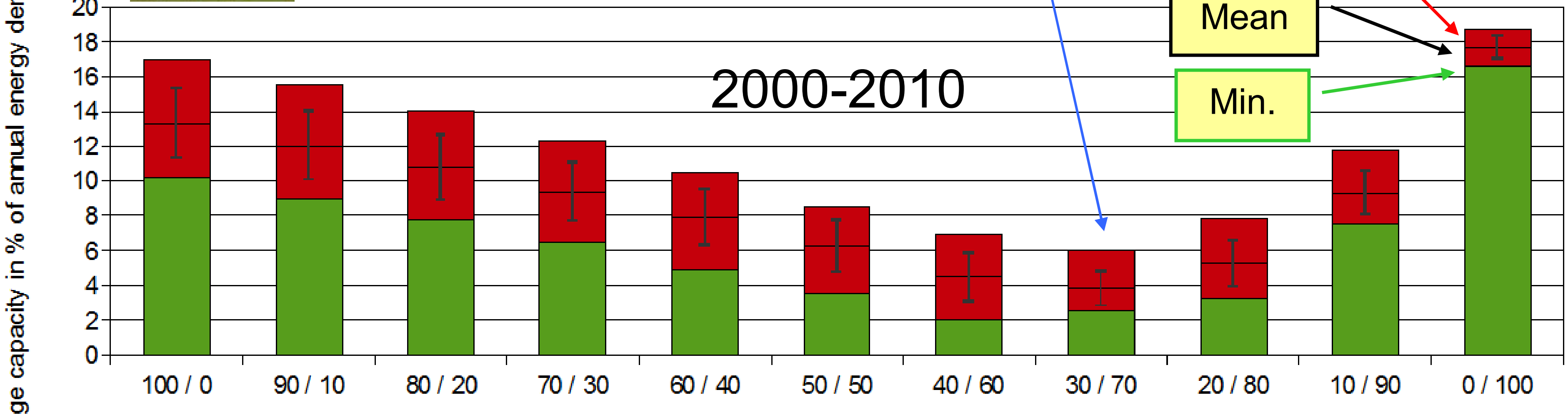
See also: Lecture by Gerhard Luther

Fraction of Electricity produced Wind/Solar ≈55/45

Max.

Mean

Min.



Ratio of installed Power Wind/Solar

Only Wind

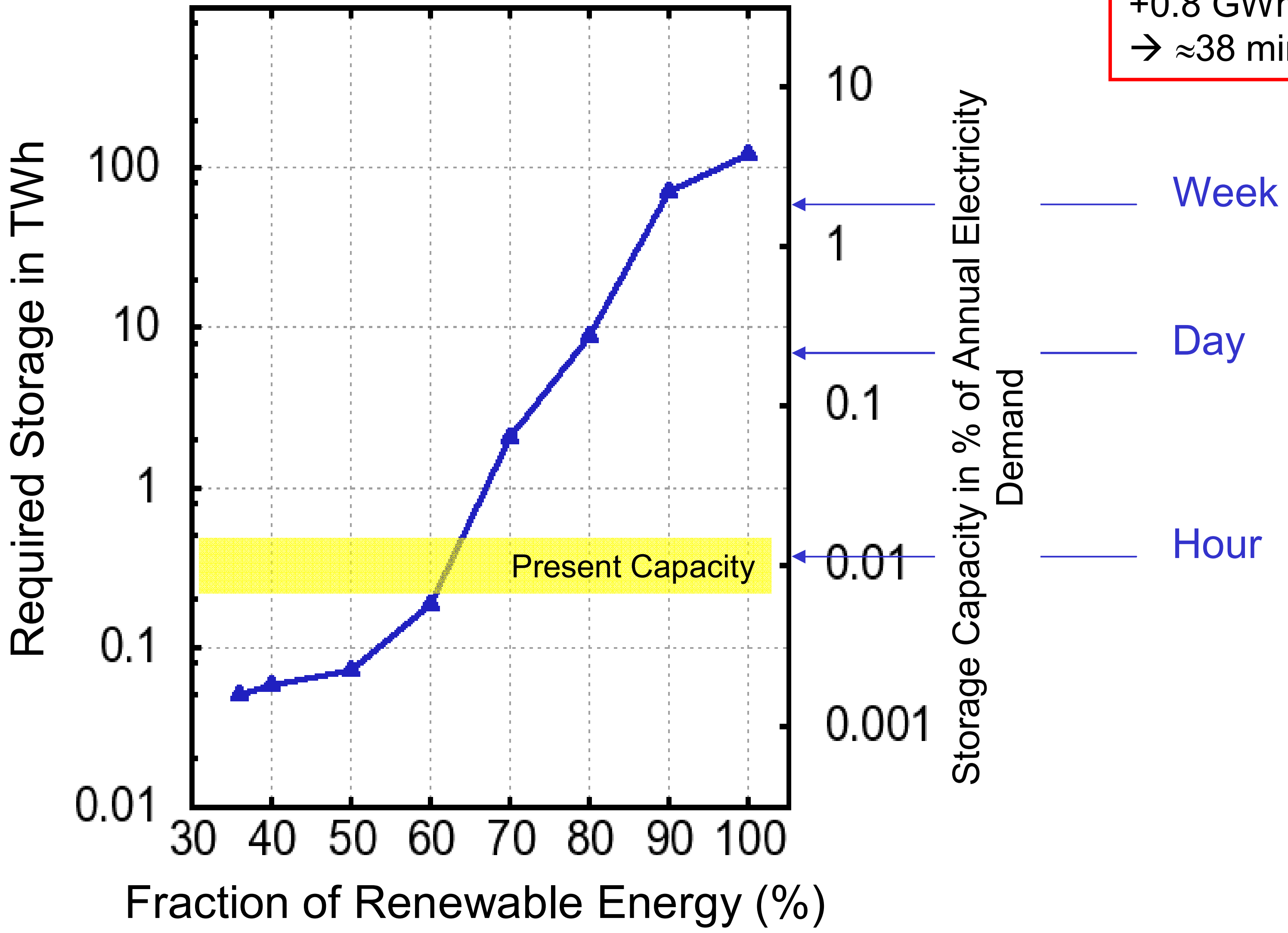
Only Solar

→ Combination of Wind + Solar reduces required storage capacity by a factor of >4
Still large storage requirement (ca. 2 weeks)!

# Required Storage Capacity vs. Renewable Energy Fraction

Wind/Solar = 30/70

Germany:
37.4 GWh Pump storage
+0.8 GWh Battery storage
→ ≈38 min

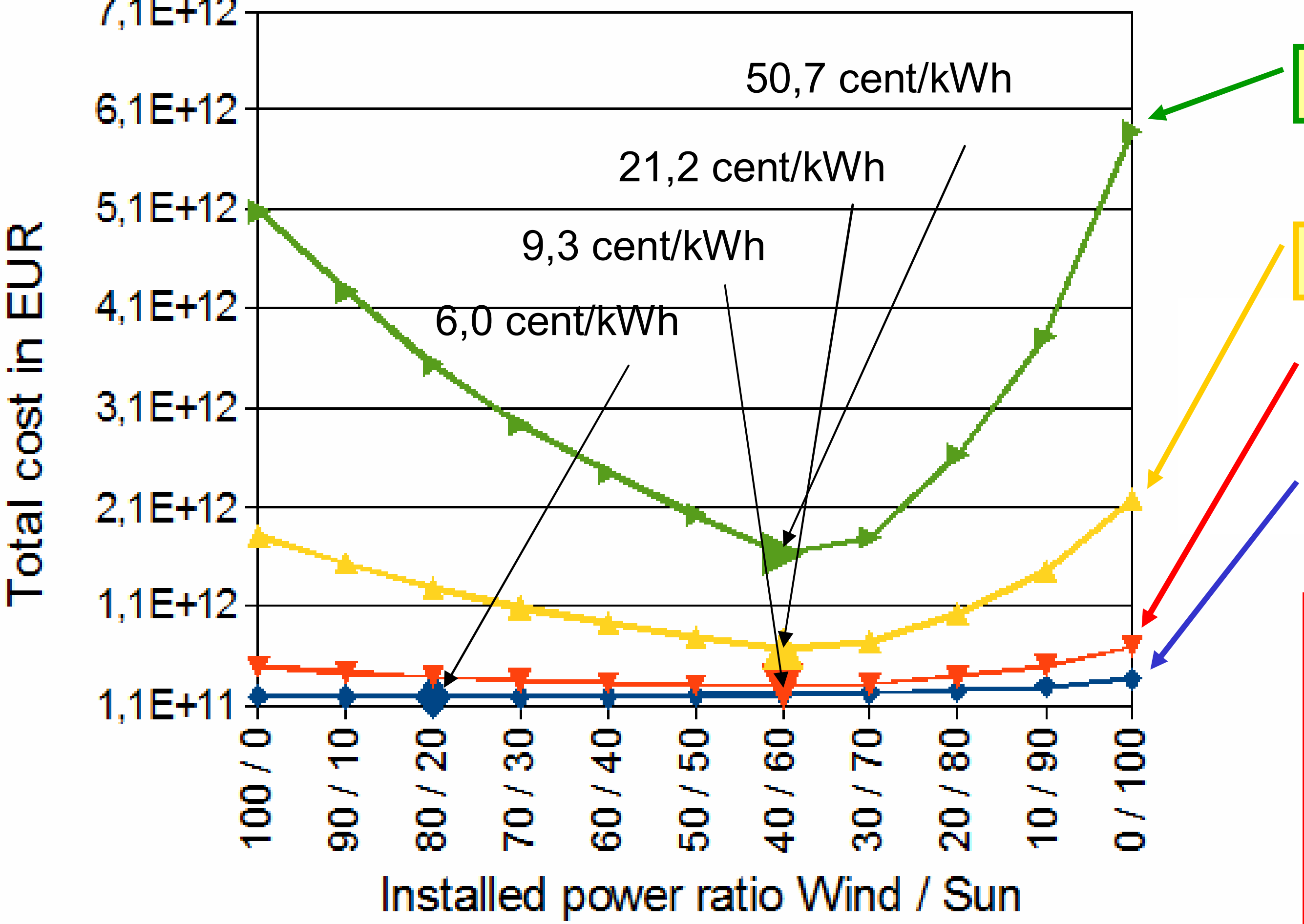


Long-term storage:

Turnover about twice/year!

Tröndle 2014

# Cost of Power including Storage (no excess production capacity)



150 €/kWh

50 €/kWh

10 €/kWh

1 €/kWh

Without excess capacity:

Acceptable electricity cost only if storage is rather cheap

| | Cost | Lifetime (years) |
|---|---|---|
| PV: | 1700€/kW | 20 |
| Wind: | 1000€/kW | 15 |

Storage: 1, 10, 50, 150 €/kWh, Lifetime 40 years, Interest: 5%

# What is **Excess Capacity**?

All Electricity supply systems encompass a (annual mean) production capacity exceeding größer the (annual mean) consumption.
thus:

$$\text{Excess capacity} = \frac{\text{Installed Capacity} - \text{Mean Consumption}}{\text{Mean Consumption}} \cdot 100\%$$

Example: Germany has had 100-120% Excess Capacity since decades (Without Renewable Energy!).

Do not confuse with **Capacity Factor**

Renewable Energy is usually available only during a fraction of time, thus:

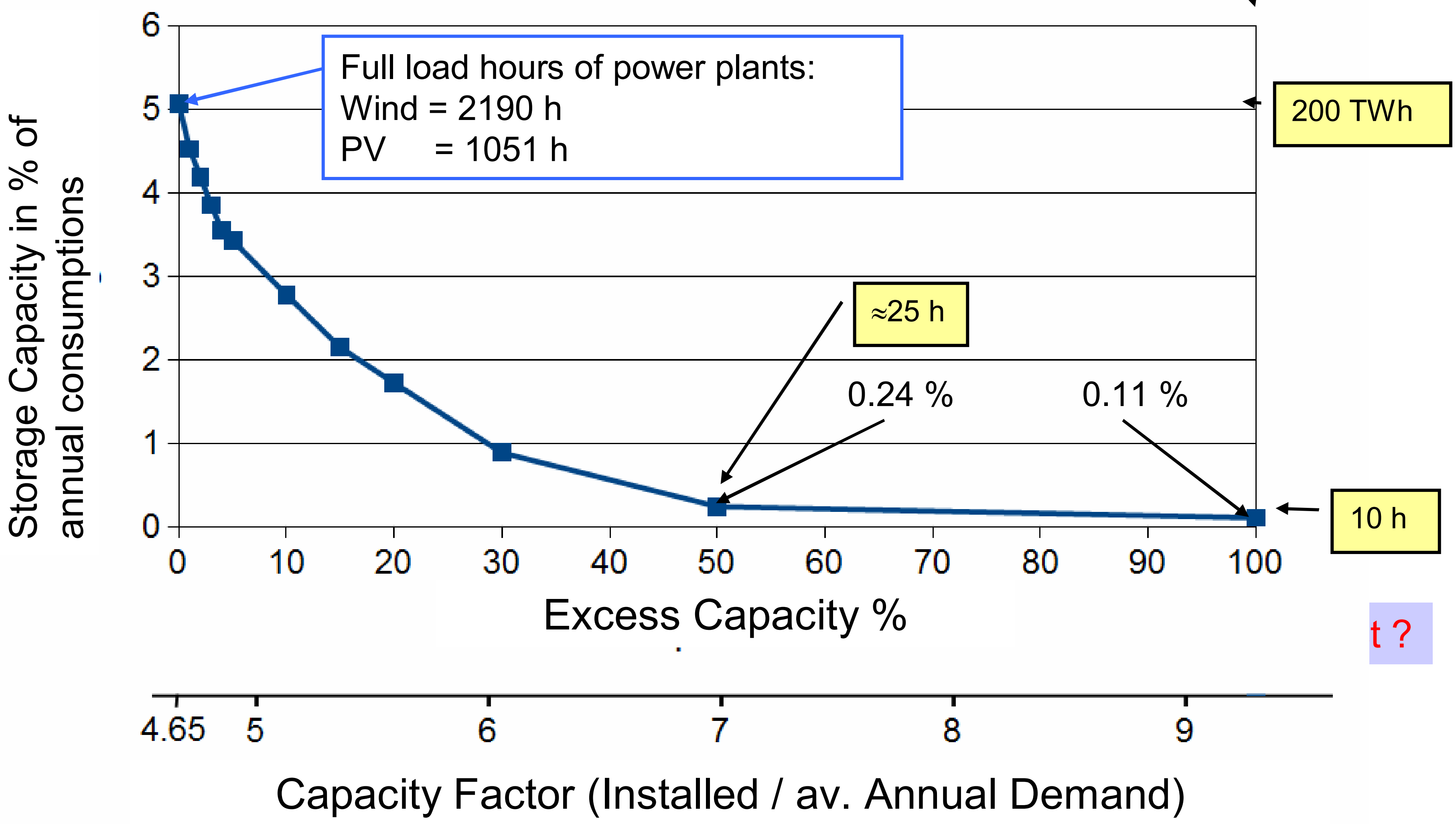
$$\text{Capacity Factor} = \frac{\text{Installed Power} \cdot 8760\,\text{hours}}{\text{Annual Harvest}} \cdot 100\%$$

| Typ. Capacity Factors: | | |
|---|---|---|
| | Solar Germany | 10% |
| | Solar S. Europe: | 20% |
| | On shore Wind: | 20% |
| | Off shore Wind: | 40% |

# Required Storage vs. Excess Capacity

Considerably lower storage requirements by installing „excess capacity“, i.e. capacity which is not always used.

twice the cost for electricity generation, 2.2% of storage cost



Full load hours of power plants:
Wind = 2190 h
PV = 1051 h

200 TWh

≈25 h

0.24 %

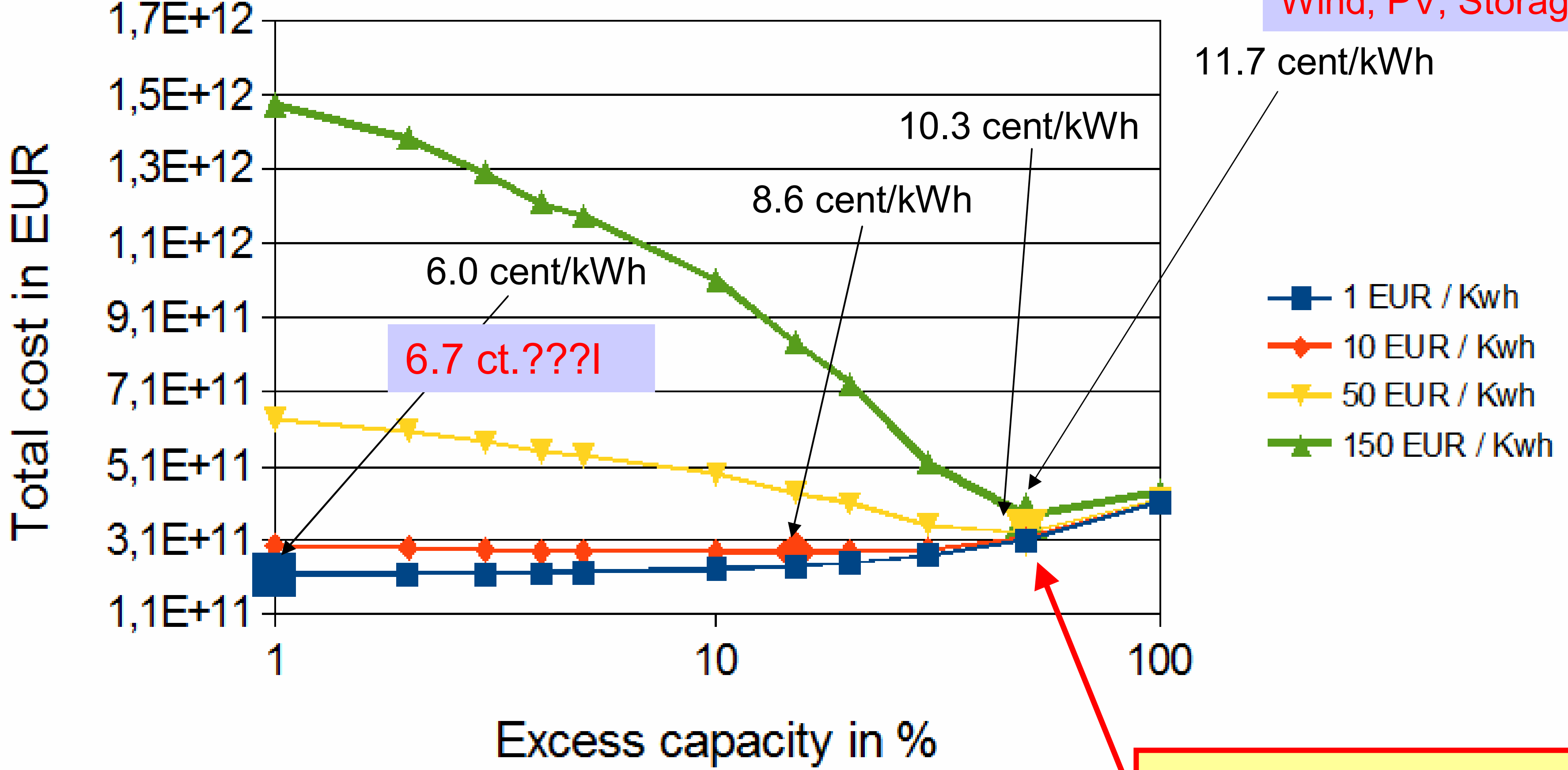
0.11 %

10 h

t ?

# Cost of Power + Storage
# including excess cap

Breakdown of cost: Wind, PV, Storage?



11.7 cent/kWh

10.3 cent/kWh

8.6 cent/kWh

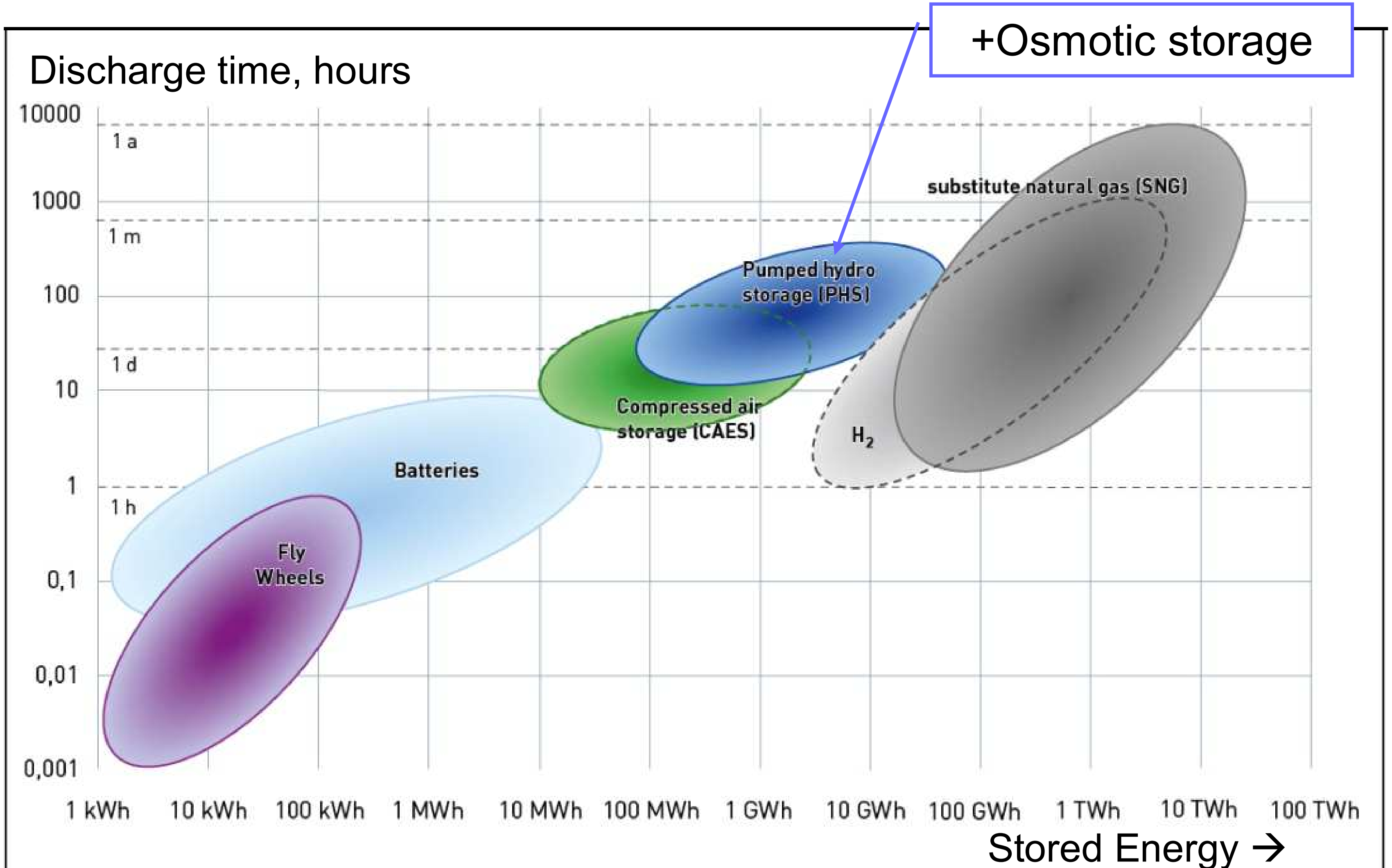
6.0 cent/kWh

6.7 ct.???l

| | Cost | Lifetime (years) |
|---|---|---|
| PV: | 1700€/kW | 20 |
| Wind: | 1000€/kW | 15 |

With excess capacity:
- Much lower cost.
- Economic optimum much less dependent on storage cost

# Storage Technologies for Electric Energy



Source: Zentrum für Sonnenenergie- und Wasserstoffforschung Baden-Württemberg, as of 04/2012

www.unendlich-viel-energie.de

# Diffusion: The Pfeffer Cell Apparatus

Wilhelm Pfeffer 1877

**van't Hoff's law**:

Particles (ions) in a solution behave similar to molecules in a gas.

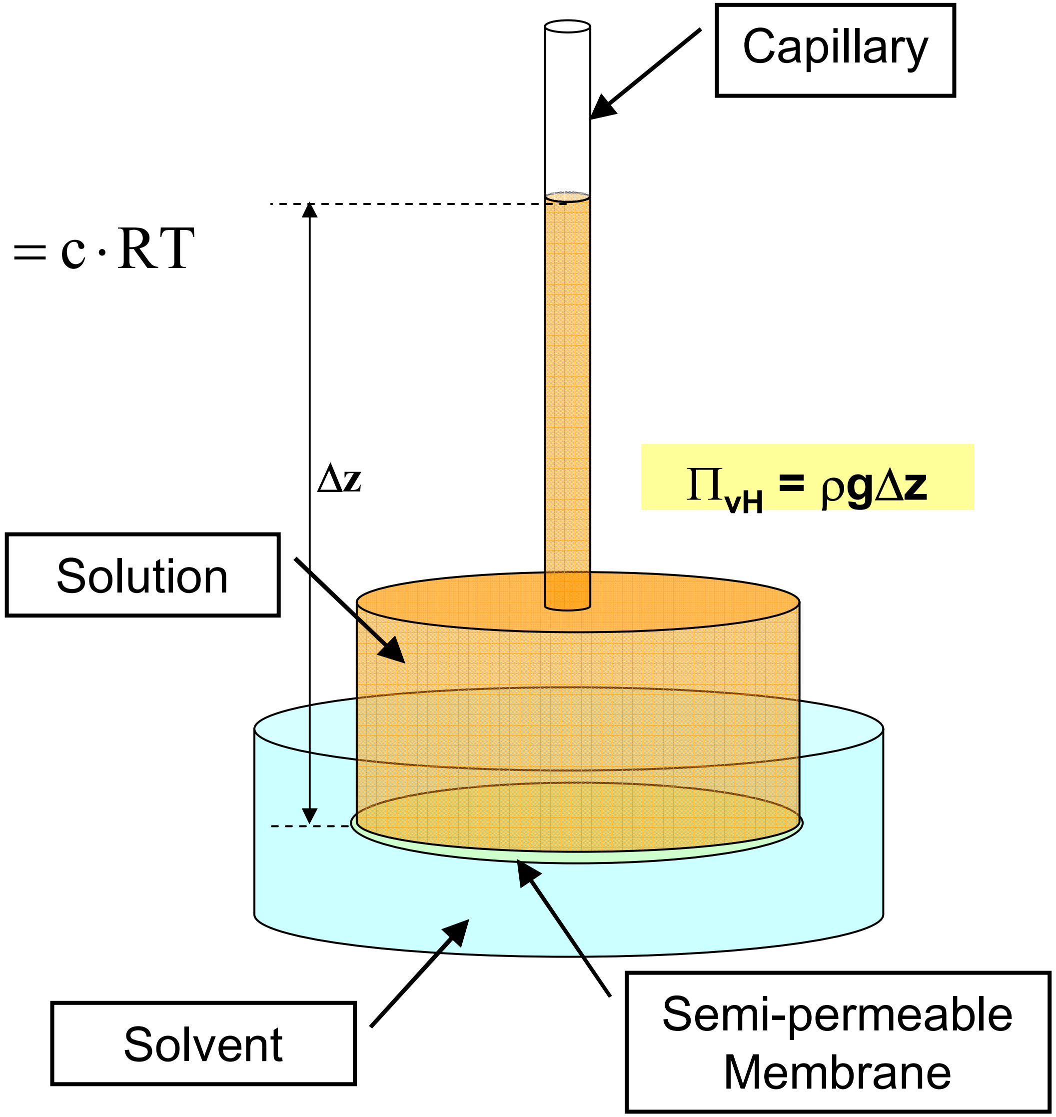
$$\Pi_{vH} V = \nu RT, \quad \Rightarrow \quad \Pi_{vH} = \frac{\nu}{V} RT = c \cdot RT$$

**Osmotic pressures:**

Seawater: 28.8 bar (2.88 MPa)

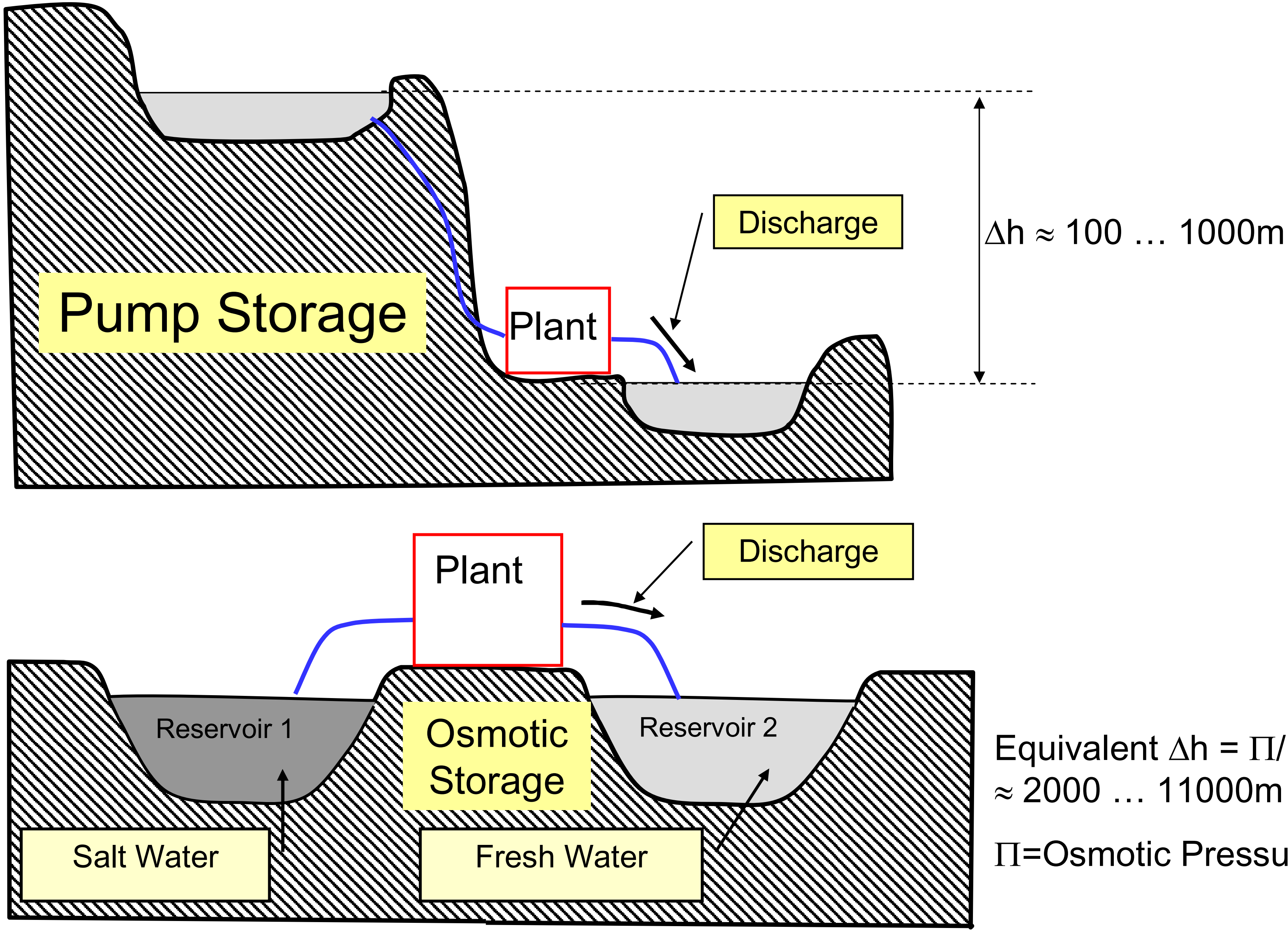
Lemonade: ≈ 5-10 bar

Blood: ≈ 9 bar



$$\Pi_{vH} = \rho g \Delta z$$

# Pump Storage- vs. Osmotic Storage Plant



Pump Storage

Plant

Discharge

$\Delta h \approx 100 \ldots 1000$m

Plant

Discharge

Reservoir 1

Osmotic Storage

Reservoir 2

Salt Water

Fresh Water

Equivalent $\Delta h = \Pi/(\rho \cdot g)$
$\approx 2000 \ldots 11000$m

$\Pi$=Osmotic Pressure

# The Osmotic Pressure of Salt Solutions

In first approximation, i.e. for diluted solutions, the osmotic pressure $\Pi$ of two salt solution with salt concentration (in moles/m$^3$) $c_1$, $c_2$ is given by Van’t Hoff’s law (Van’t Hoff 1887):

$$\Pi_{VH} = n_i \cdot R \cdot T \cdot (c_2 - c_1)$$

with:
$n_i$ = Van’t Hoff factor denoting the number of ions per dissolved molecule
($n_i$ = 2 for NaCl)
R = Universal gas constant: 8.31 J/(mole K)
T = Absolute temperature, e.g. 293.2 K

For concentrated solutions the ‚activity‘ of solute (salt) and solvent (water) has to be used. This can lead to large deviations from V.H. Law

van’t Hoff J.H. (1887), Die Rolle des osmotischen Druckes in der Analogie zwischen Lösungen und Gasen, Zeitschrift für Physikalische Chemie, Band 1U, Heft 1, 481–508, ISSN (Online) 2196-7156, ISSN (Print) 0942-9352, DOI: https://doi.org/10.1515/zpch-1887-0151

# The (theoretical) Energy Storage Density of Osmotic Plant (1)

Amount E of energy released from an initial brine volume $V_0$ containing an initial salt concentration $c_0$ giving rise to an initial osmotic pressure $\Pi_0$:
Energy dE released upon injection of a fresh water volume dV and keeping in mind that the salt concentration c = n/V reduces with the amount of fresh water admitted to the osmosis cell:

$$dE = \Pi(V)\,dV$$

$$E(V) = \int_0^V \Pi(V')\,dV'$$

Assuming a linear correspondence between osmotic pressure and salt conc.

$\Pi(c) \propto c$ and $c(V) = c_0 \cdot V_0 / (V_0 + V)$ we obtain:

$$\Pi(V) = \Pi_0 \cdot \frac{V_0}{V_0 + V}$$

and:

$$E(V) = \int_0^V \Pi(V')\,dV' = \Pi_0 V_0 \int_0^V \frac{dV'}{V_0 + V'}$$

$$= \Pi_0 V_0 \cdot \ln\left(\frac{V_0 + V'}{V_0}\right)\Bigg|_0^V = \Pi_0 V_0 \cdot \ln\left(\frac{V_0 + V}{V_0}\right) = \Pi_0 V_0 \cdot \ln\left(1 + \frac{V}{V_0}\right)$$

# The (theoretical) Energy Storage Density of Osmotic Plant (2)

For very small volumina V << $V_0$ of added fresh water this simplifies to

$$E(V) \approx \Pi_0 V_0 \cdot (1 + \frac{V}{V_0} - 1) = \Pi_0 V$$

While for very large volumina V >> $V_0$ we get approximately:

$$E(V) \approx \Pi_0 V_0 \cdot \ln\left(\frac{V}{V_0}\right) \propto \ln(V)$$

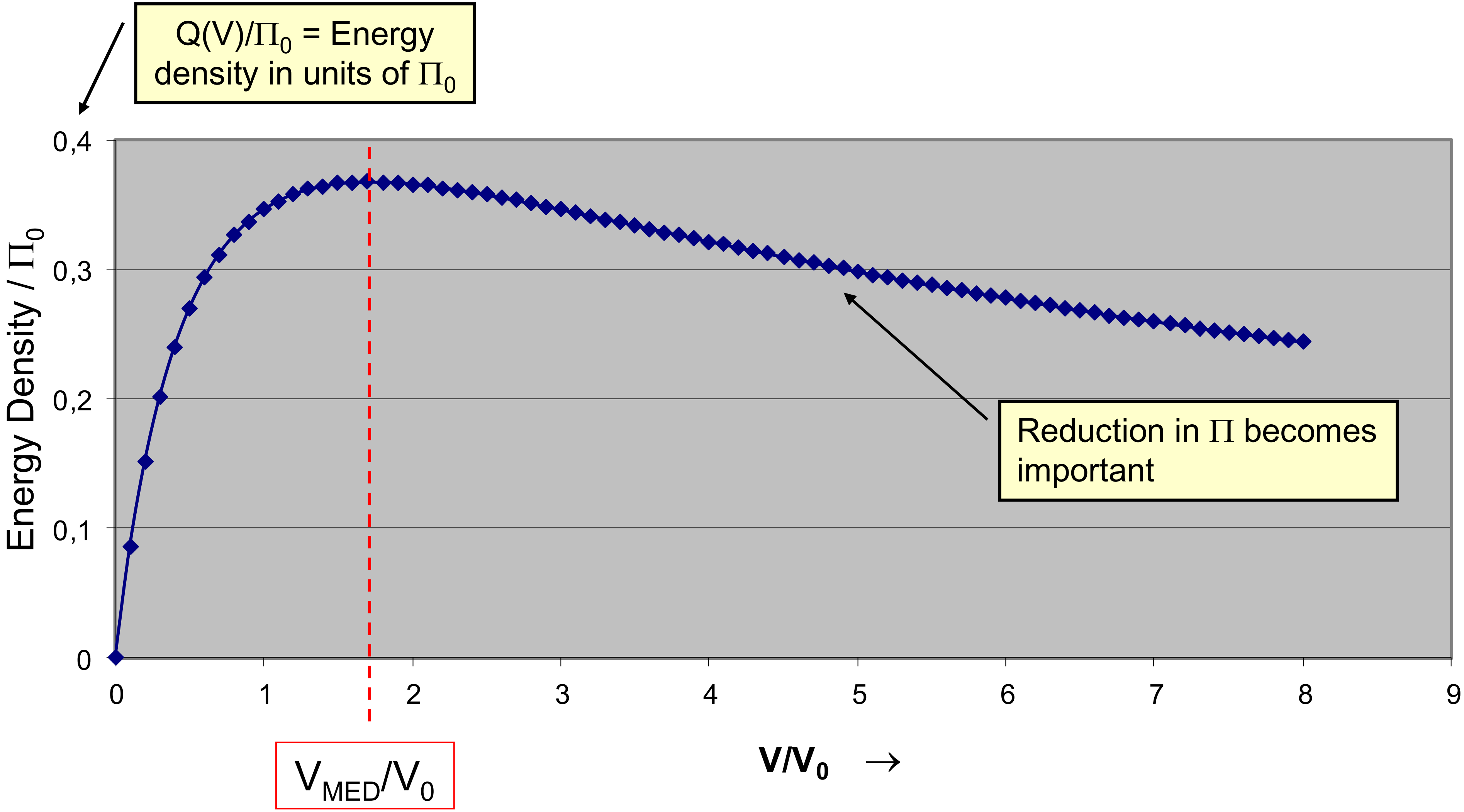
→ The amount of mixing energy for a given amount of salt solution can become infinite if infinite amounts of fresh water are available.

However the interesting quantity is the **energy density** E(V)/(V+$V_0$), which can be achieved in a particular configuration.

For a ‘one reservoir’ configuration the energy density Q is given by:

$$Q(V) = \frac{E(V)}{V + V_0} = \Pi_0 V_0 \cdot \frac{\ln\left(\frac{V + V_0}{V_0}\right)}{V + V_0}$$

# The (theoretical) Energy Storage Density of an Osmotic Plant (3)

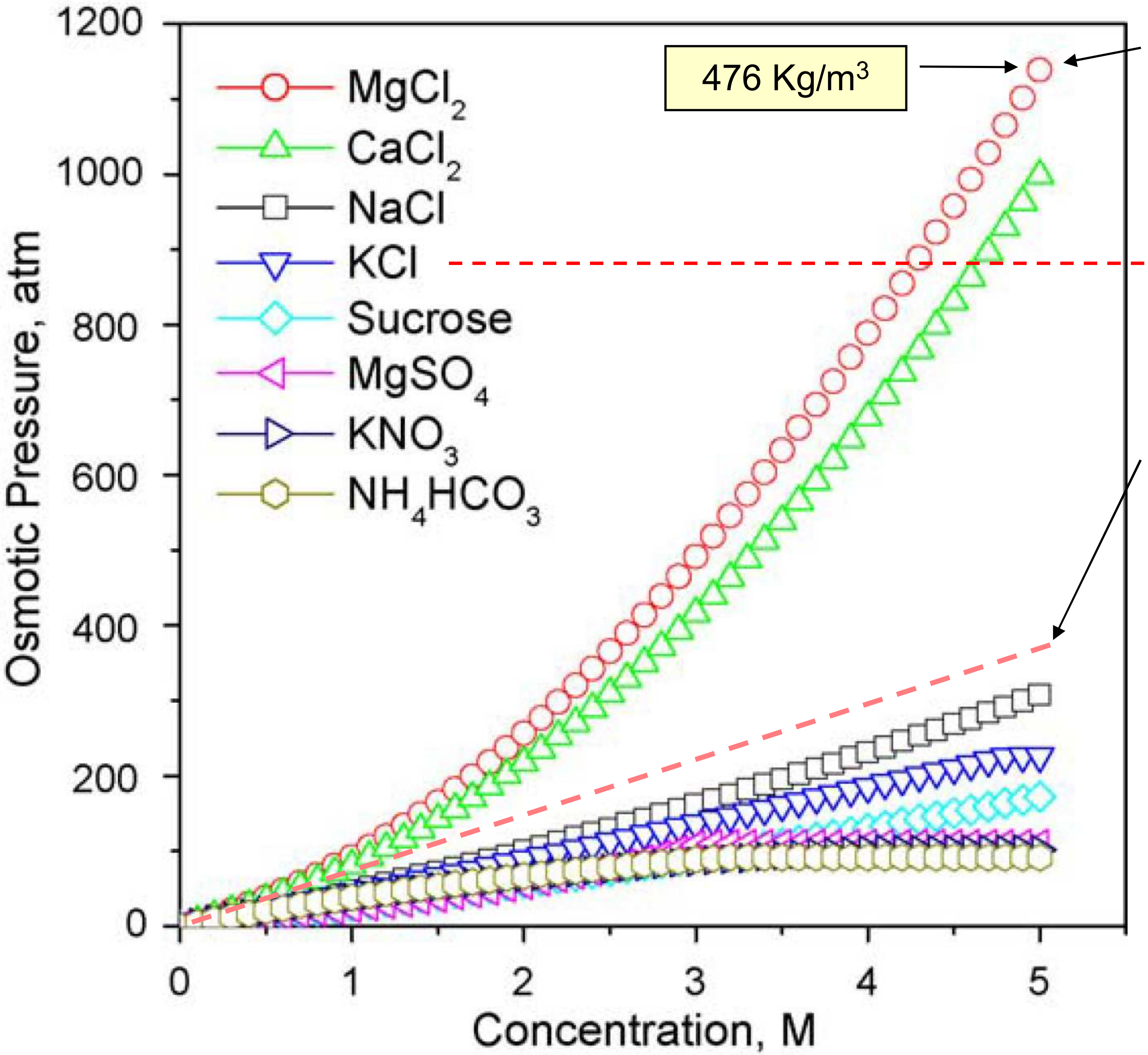


$Q(V)/\Pi_0$ = Energy density in units of $\Pi_0$

Reduction in $\Pi$ becomes important

Comment: Pressure [$N/m^2$] = Energy Density [$Nm/m^3 = J/m^3$]

# Measured Osmotic Pressures of Some Salts



476 Kg/m$^3$

1130 atm ⇒
$1.13 \cdot 10^8$ Pa ⇒
113 MJ/m$^3$ ⇒
31.4 kWh/m$^3$

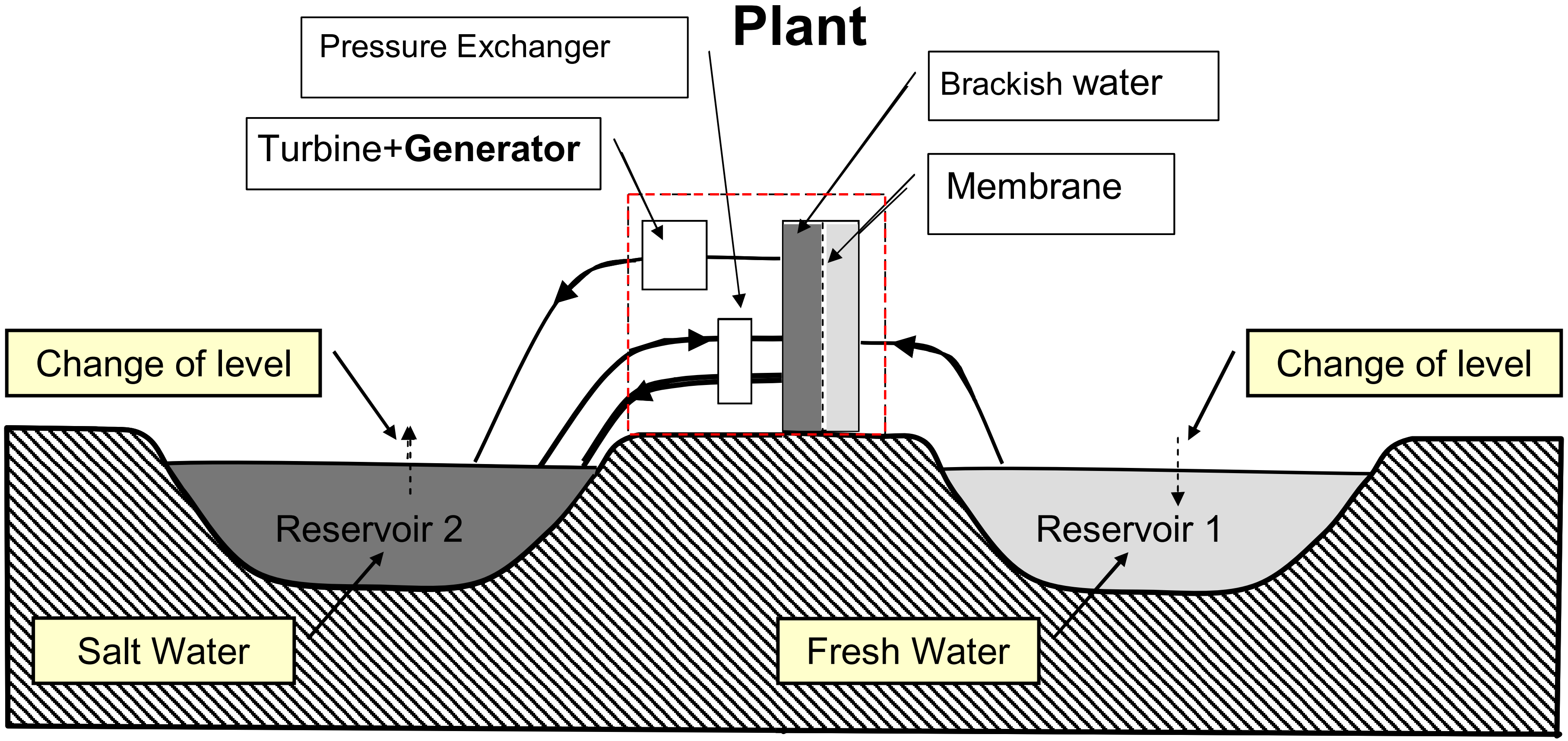
Mt. Everest
(8849m, 868 atm)

$MgCl_2$ – van t'Hoff

From:

Cath T.Y., Childress A.E., Elimelech M. (2006), Forward osmosis: Principles, applications, and recent developments, J. Membrane Sci. 281, 70–87.

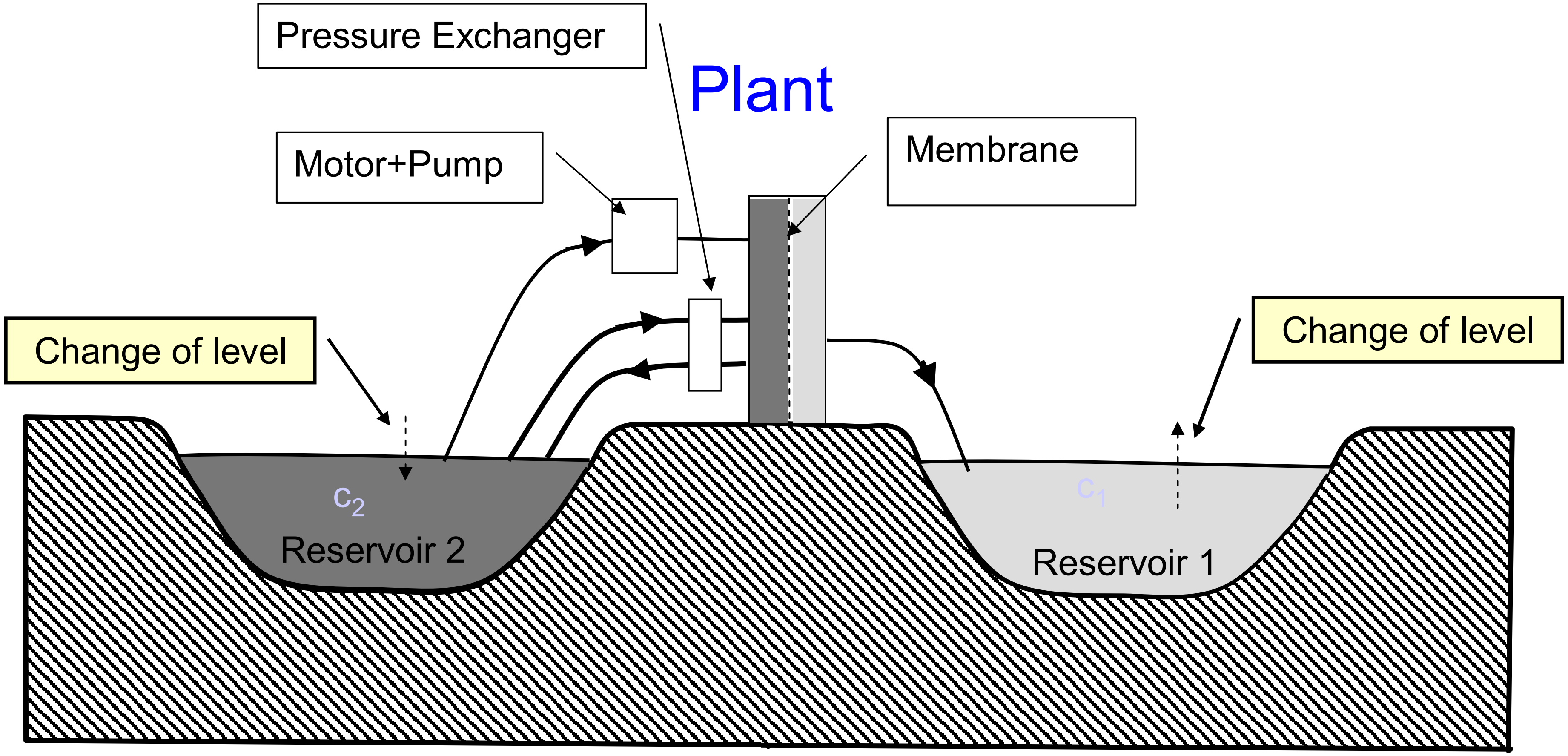
# Sketch of an Osmotic Storage Plant Discharge Operation



See e.g.: Dinger F., Tröndle T., Platt U. (2013), Osmotic power plants and their potential, J. Renewable Energy, (Hindawi Publishing Corp.) Vol. 2013, Article ID 496768, doi.org/10.1155/2013/496768.

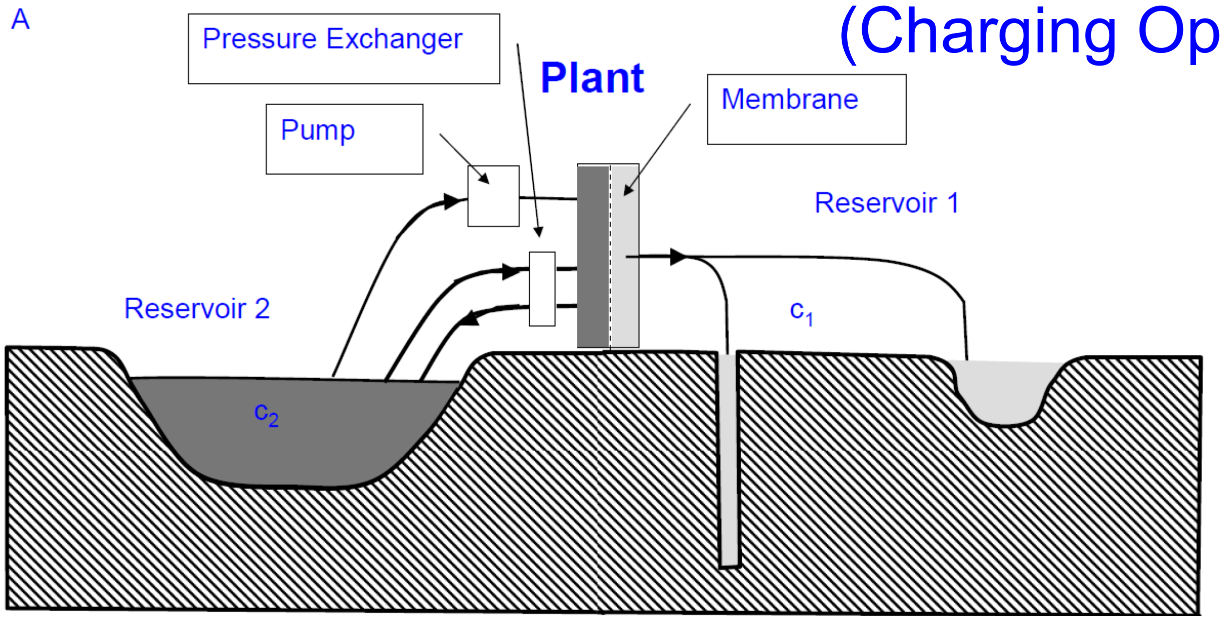
Helfer F., Lemckert C., Anissimov Y.G. (2014), Osmotic power with Pressure Retarded Osmosis: Theory, performance and trends – A review, J. Membrane Science 453, 337–358.

# Sketch of an Osmotic Storage Plant
# Charging Operation

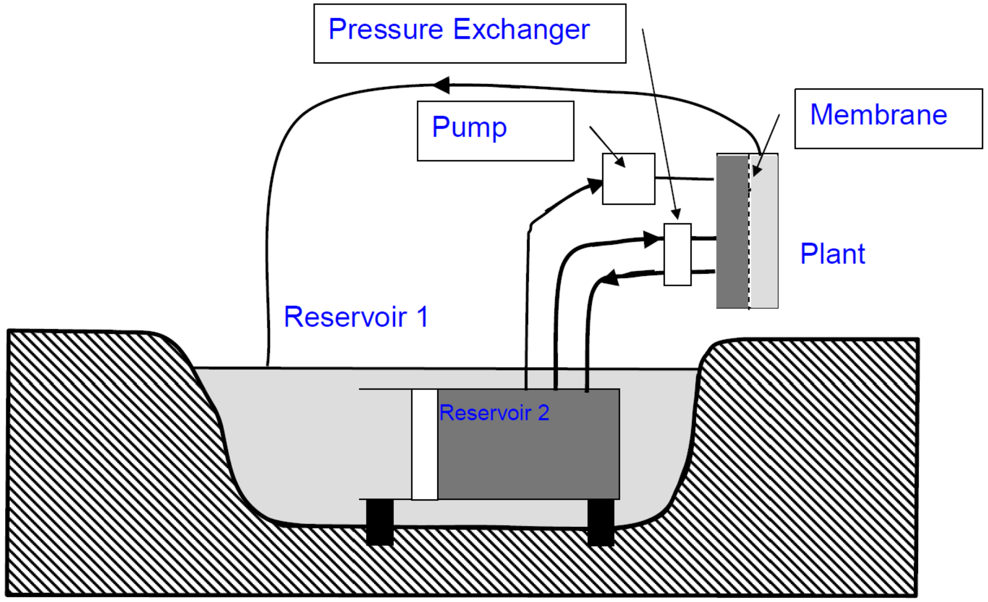


# Alternative Designs of Osmotic Storage Plant

## (Charging Operation)



1) Use ‚external‘ supply of fresh water (River, ground water)



2) Put salt water reservoir ‚inside‘ fresh water reservoir

→ Reservoir level stays constant

# Energy Density and Efficiency of Storage Technologies

| Technology | Efficiency | Energy density kWh/$m^3$ | Remark |
|---|---|---|---|
| Pump storage | 75-80% | ≈1* | at $\Delta h=350$m |
| Compressed air storage CAES | 54-70% | ≈3* | at p=13 MPa (130 bar) |
| Li Ion Battery | 70-95% | ≈200 | |
| Hydrogen | 34-44% | ≈2.6 (1.6*)<br>≈340 (200*) | Atm. pressure<br>at p=13 MPa (130 bar) |
| Methane (Power-to-Gas) | 30-38% | ≈400* | at p=13 MPa |
| Osmotic storage | 40-60% | ≈12* | $MgCl_2$ |

*including electricity re-conversion losses

Further possibilities: Use biomass as storage  
(<10% of annual consumption required)

# „Hambacher Loch“

## Hambach Surface Mine

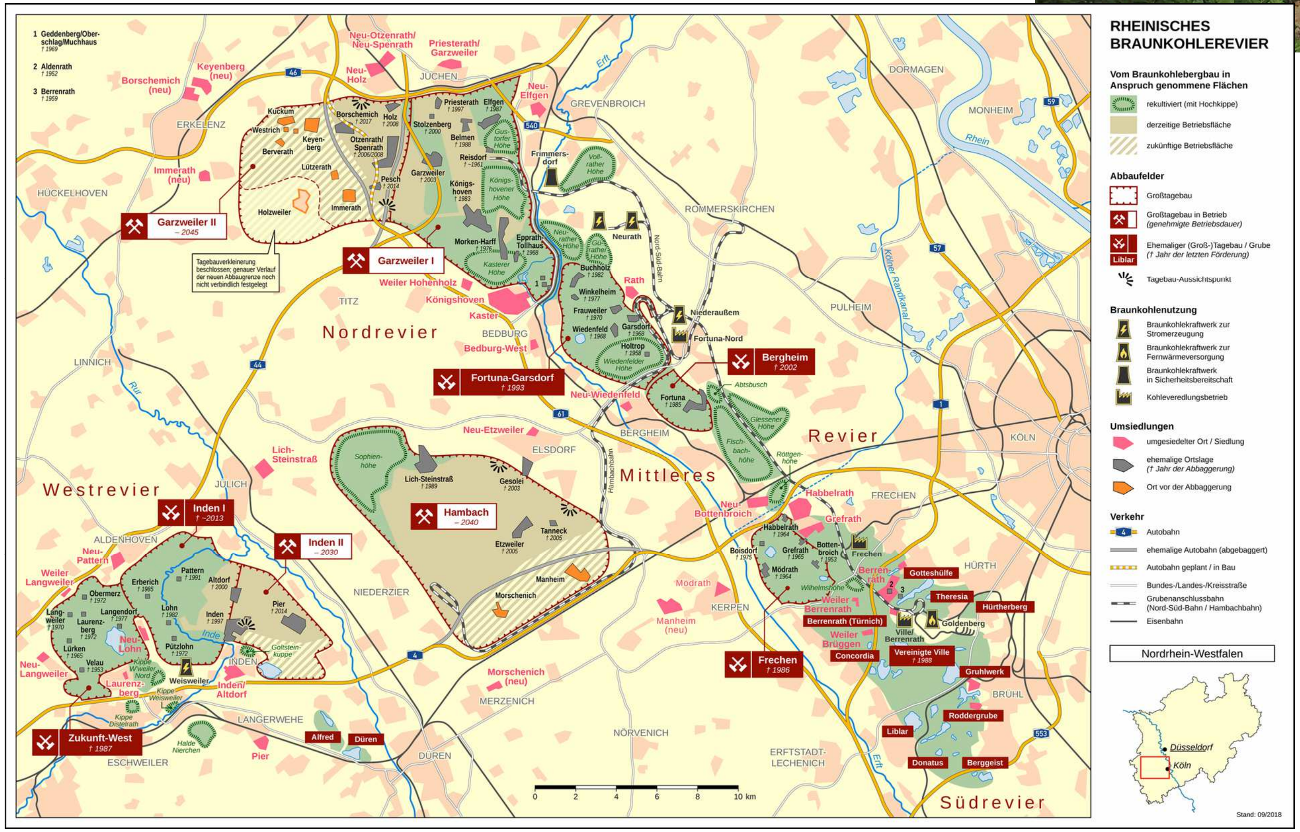
Volume: ca. 10 Mrd m³

(18.6 km³ in 2040)

→ At 11.6 kWh/m³

Stored Energy: >1·10¹⁴ Wh

or 100 TWh or Germany for ≈60 days



Total annual electricity consumption in Germany: 600 TWh

See:
https://en.wikipedia.org/wiki/Hambach_surface_mine

https://de.wikipedia.org/wiki/Tagebau_Hambach

Luther G. and Schmidt-Böcking H., The role of short-term storage like hydropower in abandoned opencast mines in the energy transition.

# Other (realistic) „Storage“ Technologies

Short-term storage (<24h): Small amount of energy, but turnover ca. 100 times/year
→ Pump storage, Osmotic storage, Batteries

Long-term storage (>24h) turnover few times/year
→ 1) Pump storage, Osmotic storage,
2) **Gas turbine with Bio-gas**:
ca. 6% of (present day) electricity generation from Bio-gas, but only about 0,25-1% of annual generation are required as long-term storage .

Equivalent cost of storage: 1-2 €/kWh

The available amount of bio- gas (Germany) would be sufficient to fill the storage about 5-times/year (at twice the present electricity demand).
Model result: only 2-3 times required (at 150% capacity)
→ **Only about 1% of the electricity demand pass the storage**

# 100% Renewable Energy Supply, Significance for Germany (1)

Assume: 150% Capacity (50% Excess Capacity)

30%/70% Wind/Solar (mean. power: 9/7, 56%/44%)

Wind:   Annual mean =30% of installed peak power
Solar:  Annual mean  =10% of installed peak power

Germany:       ≈ **60 GW**
→ 114 GW mean Electricity consumption 100% EE (+90%)
→ ≈**170 GW** incl. 50% Excess Capacity

→ ≈**750 GW Solar** (75 GW MW) + **320 GW Wind** (96 GW MW)

→ 2021 in G. installed: 56 GW Solar,  62 GW Wind
(incl. ≈8 GW offshore)

→ **Solar x13;  Wind x5** (rough calculation) Total: x9

Includes Elektromobility, Industry & Heating!

# 100% Renewable Energy Supply, Significance for Germany (2)

≈**750 GW Solar** (75 GW MW) + ≈**320 GW Wind** (95 GW MW)

**Required Area for Solar** at 200 $W/m^2$: **3.750 $km^2$**

Potential G.: 6.000 $km^2$ Roof Area, 12.000$km^2$ Fron

**Required Area for Wind** at 26 $MW/km^2$ (mean value)(2)
→ 12.500 $km^2$, ≈3.5% of the total area (357.600 $km^2$)

Compatible with 2%

Max useable on-shore Wind Power: 1800 GW[3]

Reduction due to off-shore Wind Energy,
Energy Imports ($H_2$, Electricity, Synthetic Fuels)

[1] see e.g. Behnisch et al. 2020, doi: DFNS/2020_12_DFNS/025_behnisch.pdf
[2] Bons et al.(2019), Flächenanalyse Windenergie an Land, Abschlussbericht, CLIMATE CHANGE 38/2019 EVUPLAN, Forschungskennzahl 37EV 16 117 0 FB000157.
[3] Miller et al. 2015, www.pnas.org/cgi/doi/10.1073/pnas.1408251112

# Conclusions

- 100% renewable energy is well possible with existing technologies (there is no time anyway to develop fundamentally new technologies)
- Our energy System must be converted to (>80%) carbon free within the coming two decades in order to avoid a climate catastrophy
- Renewable energy can be supplied at competitive cost
- Energy storage is probably less critical than frequently implied
- Osmotic storage can provide storage densities of up to ≈12 kWh/m$^3$, equivalent to a >4000 m altitude difference pump storage plant, about one order of magnitude more than conventional pump storage plants
  - No need for mountains
    → lower investment, (in particular if not too much power is required), much more freedom in siting the plant
  - However, (somewhat) lower efficiency (≤60% vs. ≤80%)

Thank You!

# Some Further Literature

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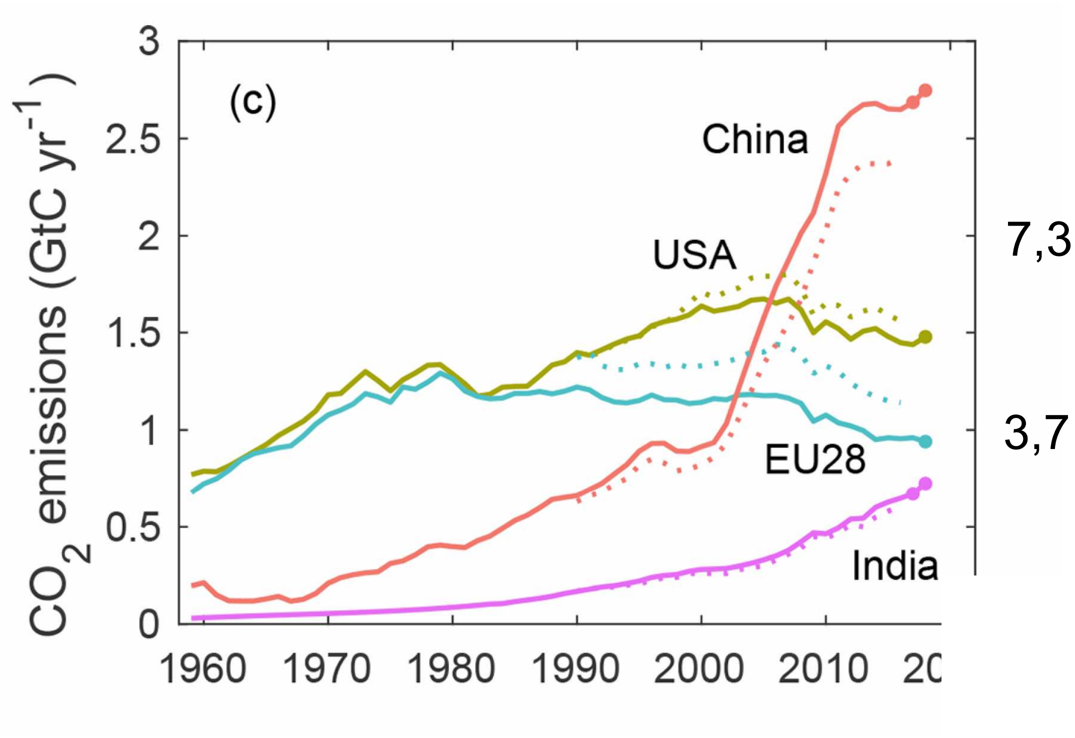
# Anthropogenic $CO_2$-Emission 1958-2018 in GtC

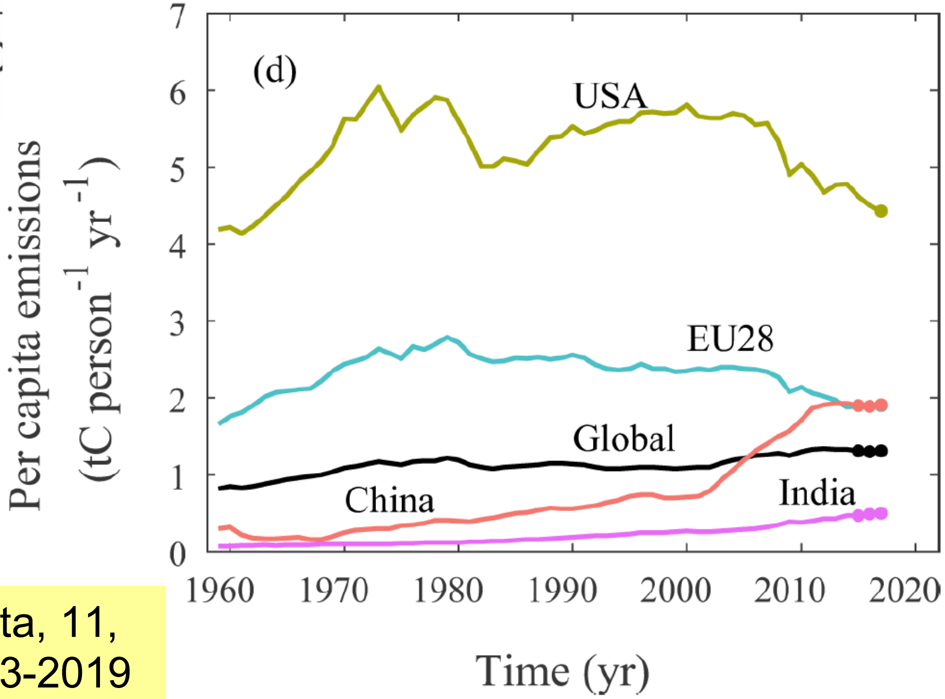


7,3 Gt $CO_2$

3,7 Gt $CO_2$

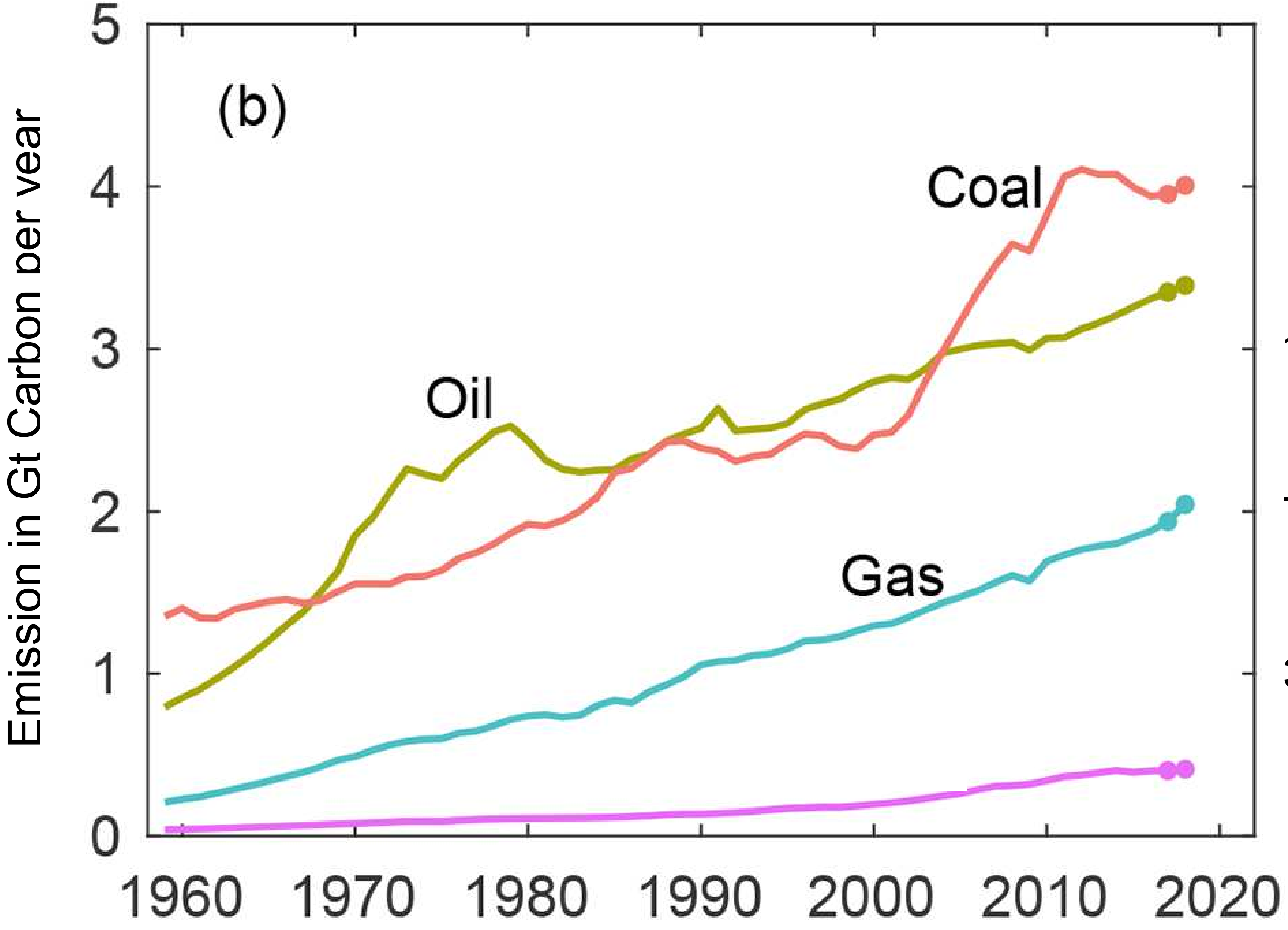
## Per capita - Emission

Tons of carbon per inhabitant and year



Friedlingstein P., et al. 2019, Earth Syst. Sci. Data, 11, 1783–1838, https://doi.org/10.5194/essd-11-1783-2019

# Sources of Anthropogenic $CO_2$-Emissions 1958-2018 in GtC



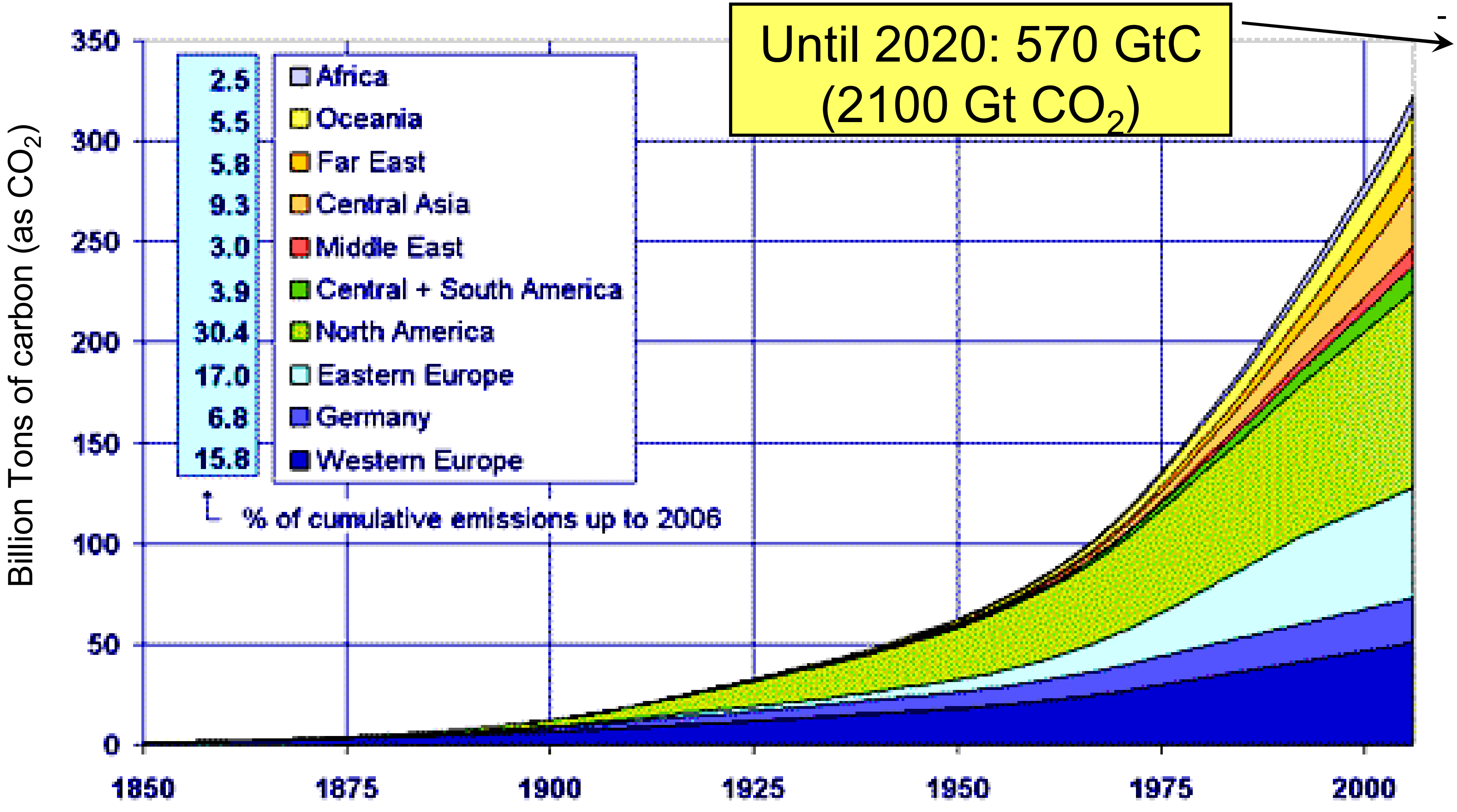
11,0 Gt $CO_2$

7,3 Gt $CO_2$

3,7 Gt $CO_2$

Friedlingstein P., et al. 2019, Earth Syst. Sci. Data, 11, 1783–1838, https://doi.org/10.5194/essd-11-1783-2019

# Cumulative Anthropogenic Emission of (fossile) $CO_2$ (in GtC) since 1850



Until 2020: 570 GtC
(2100 Gt $CO_2$)

Source: Carbon Dioxide Information Analysis Center (CDIAC.com) and values of atmospheric $CO_2$ concentrations from Mauna Loa, as well as other locations. Excluding carbon emissions from change of land use and deforestation.

# Which Salt(s) to Use?

Solubility data and osmotic pressures of a number of salts dissolved in water at 25°C (data from Cath et al. 2006)

| **Solute** | **Solubility (293.2 K) (g/l)** | **Molecular weight (g/mole)** | **Molar solubility (mole/l)** | **Van't Hoff Const. $n_i$** | **Osmotic pressure van't Hoff law (bar@5M)** | **Measured Osmotic pressure (bar@5M)** |
|---|---|---|---|---|---|---|
| $MgCl_2$ | 543 | 95.21 | 5.70 | 3 | 371.7 | 1130 |
| $CaCl_2$ | 745 | 110.98 | 6.71 | 3 | 371.7 | 1000 |
| NaCl | 358 | 58.44 | 6.13 | 2 | 247.8 | 310 |
| KCl | 347 | 74.55 | 4.65 | 2 | 247.8 | 220 |

Much higher than van't Hoff Formula would suggest!

Cath T.Y., Childress A.E., Elimelech M. (2006), Forward osmosis: Principles, applications, and recent developments, J. Membrane Science 281, 70–87.

Hamdan M., Sharif A.O., Derwish G., Al-Aibi S., Altaee A. (2015), Draw solutions for Forward Osmosis process: Osmotic pressure of binary and ternary aqueous solutions of magnesium chloride, sodium chloride, sucrose and maltose, J. Food Engineering 155, 10–15.

# Maximum Energy Storage Density of an Osmotic Plant (1)

The maximum energy density (MED) is reached at:

$$\frac{dQ(V)}{dV} = 0 = \frac{d}{dV}\left(\frac{E(V)}{V+V_0}\right) = \Pi_0 V_0 \cdot \frac{d}{dV}\left(\frac{\ln\left(\frac{V+V_0}{V_0}\right)}{V+V_0}\right)$$

Equivalent to:

$$0 = \frac{d}{dV}\left(\frac{\ln\left(\frac{V+V_0}{V_0}\right)}{V+V_0}\right) = -\frac{\ln\left(\frac{V+V_0}{V_0}\right)-1}{(V+V_0)^2}$$

→ (since V>0 and $V_0$>0) the volume for maximum energy density, $V_{MED}$ is:

$$\ln\left(\frac{V_0+V_{MED}}{V_0}\right) = 1 \Leftrightarrow \frac{V_{MED}}{V_0}+1 = e \Leftrightarrow \boxed{V_{MED} = V_0(e-1) \approx 1.718 \cdot V_0}$$

→ The MED is:

$$Q_1 = \frac{E(V_{MED})}{V_{MED}+V_0} = \Pi_0 V_0 \cdot \frac{\ln\left(\frac{V_0+V_{MED}}{V_0}\right)}{V_{MED}+V_0} = \Pi_0 V_0 \cdot \frac{\ln\left(\frac{eV_0}{V_0}\right)}{eV_0} = \frac{\Pi_0}{e}$$

# Maximum Energy Storage Density of an Osmotic Plant (2)

Depending on the assumptions there are 3 types of storage density:

0) Precipitation of salt is allowed, thus c=const. during charge/discharge

1) „fresh water“ is taken/discarded from/to well, river, or ocean

2) „fresh water“ is taken from another storage reservoir,
this needs to have at least a volume of $V_{MED}$

$$Q_0 = \Pi_0 \left[ Pa = \frac{N}{m^2} = \frac{Nm}{m^3} = \frac{J}{m^3} \right]$$

$$Q_1 = \frac{E(V_{MED})}{V_{MED} + V_0} = \frac{\Pi_0}{e} \approx 0.37 \cdot \Pi_0 \Rightarrow$$

$$Q_2 = \frac{E(V_{MED})}{2V_{MED} + V_0} = \frac{E(V_{MED})}{2V_0(e-1) + V_0} = \frac{E(V_{MED})}{2(e-1)V_0} = \frac{\Pi_0 V_0}{2(e-1)V_0} = \frac{\Pi_0}{2e-2}$$

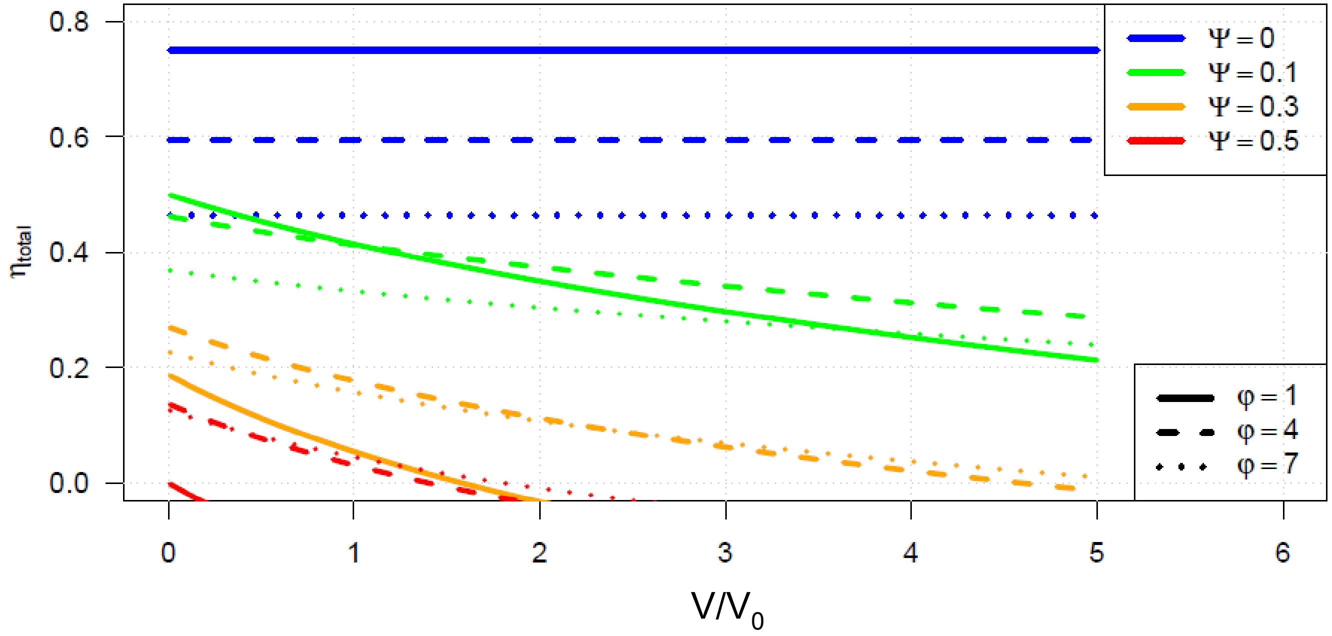
$$Q_2 = \frac{e}{2e-2} \cdot Q_1 \approx 0.79 \cdot Q_1 \approx 0.29 \cdot \Pi_0$$

# The (realistic) Energy Storage Density of an Osmotic Plant

Turbine- + generator effciencies:
$\eta_T = \eta_G = 0.9$

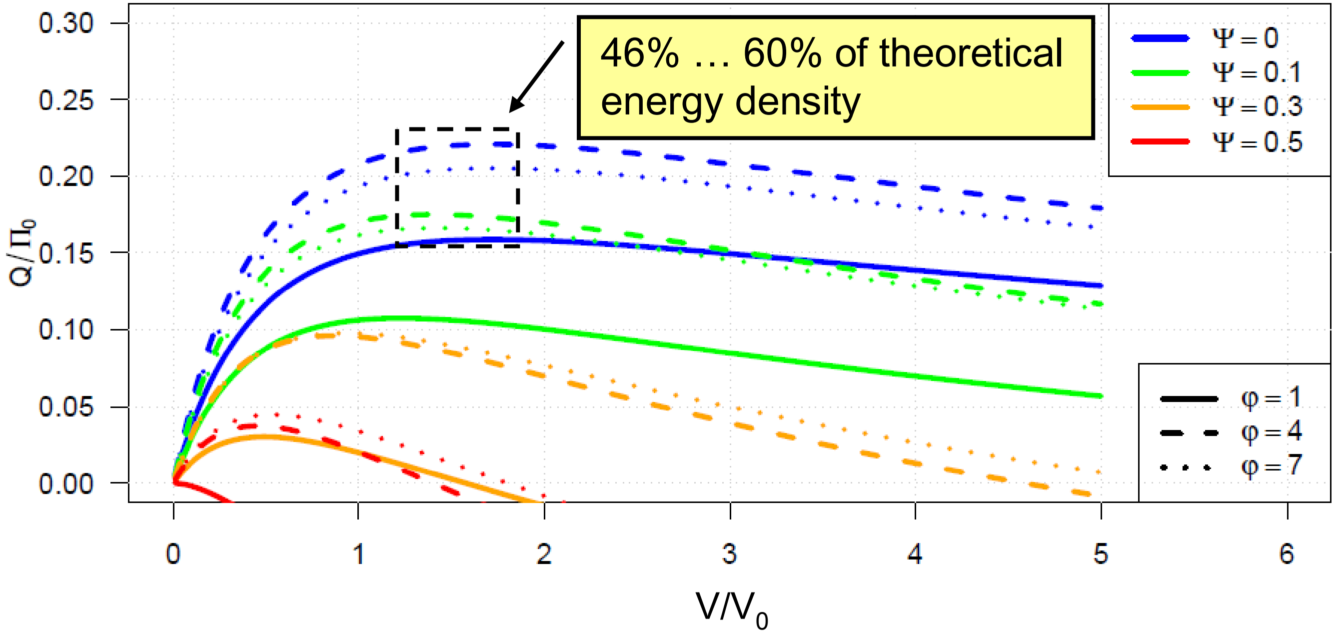
Pressure exchanger efficiency $\eta_{PX} = 0.97$

Booster pump efficiency
$\eta_P = 0.9$



φ: Ratio between flow through the pressure exchanger and membrane flow

$\Psi = \Delta p_J/\Pi_0$: Fraction of membrane pressure drop from total osmotic pressure.



46% … 60% of theoretical energy density