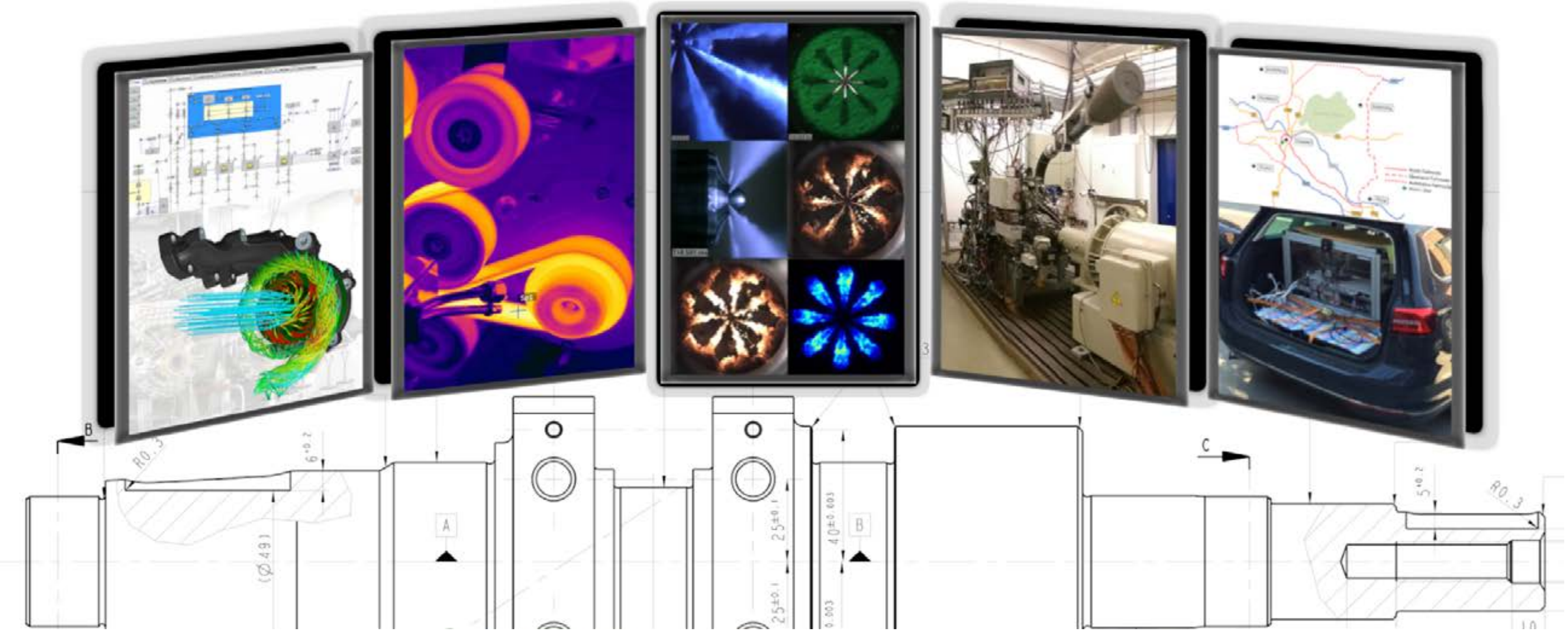

Transition of Energy and Mobility Systems
How will we move about tomorrow?

Chair of Combustion Engines and Powertrain Systems, Prof. Dr.-Ing. F. Atzler

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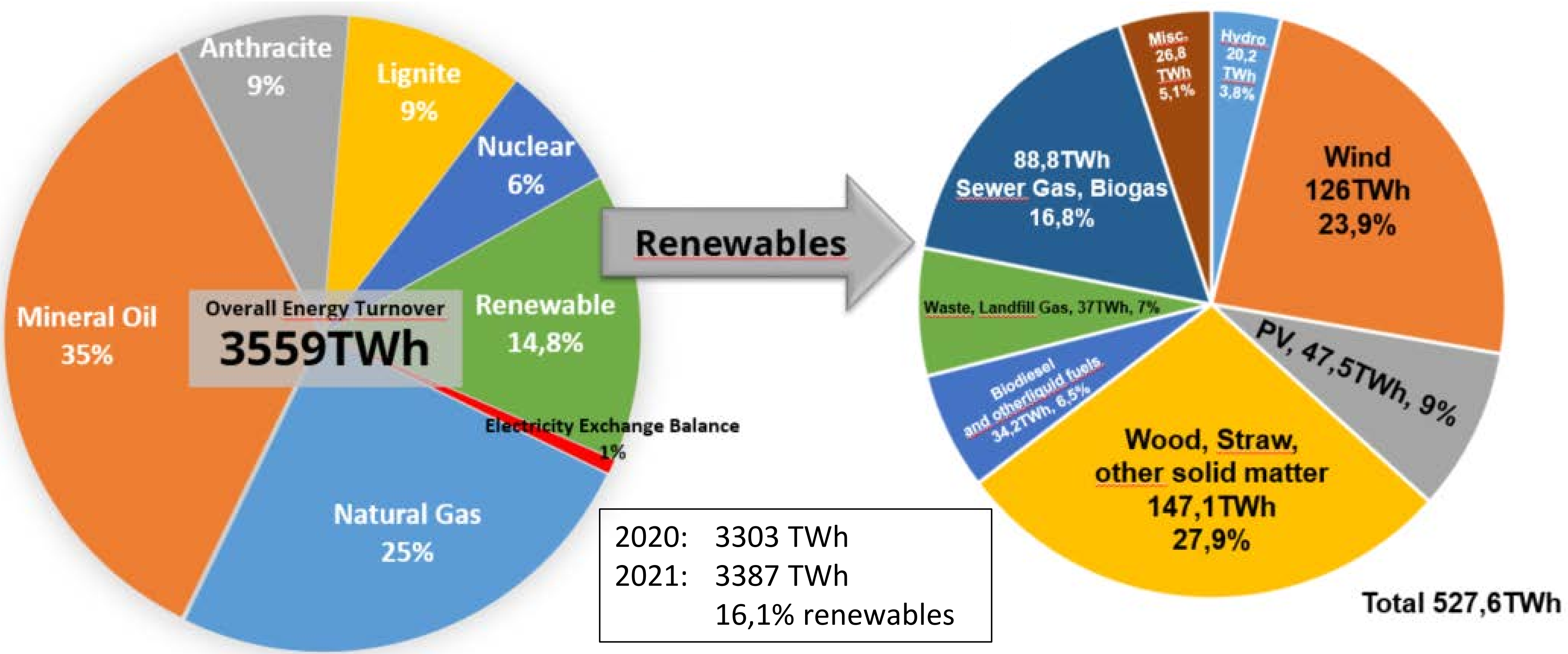
Primary Energy Consumption in Germany

Source: Arbeitsgemeinschaft Energiebilanzen, 2019* https://www.ag-energiebilanzen.de/



2020: 3303 TWh
2021: 3387 TWh
16,1% renewables

1) only 14,8% (2020: 16,8%) of the overall primary energy consumtion are covered by renewables

2) only 5% of the overall primary energy consumtion are supplied by wind and photovoltaics

3) Germany/Europe will always be dependent on energy imports, 2019 nearly 70% of primary energy (destatis.net)

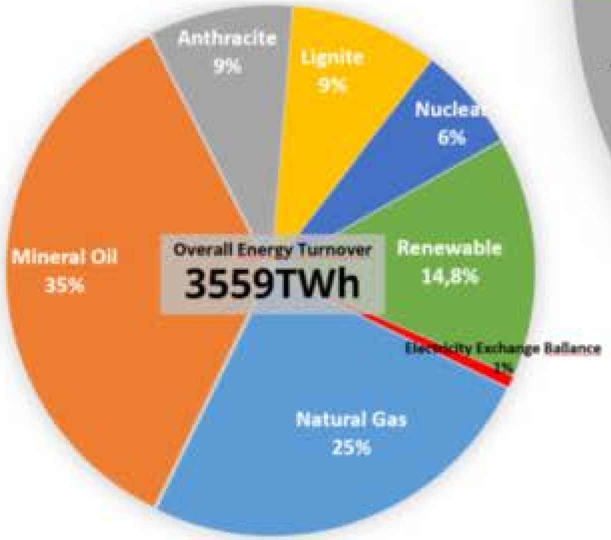
4) Which energy carrier is suitable for long distance transport → Electricity, H_2, liquid reFuels?

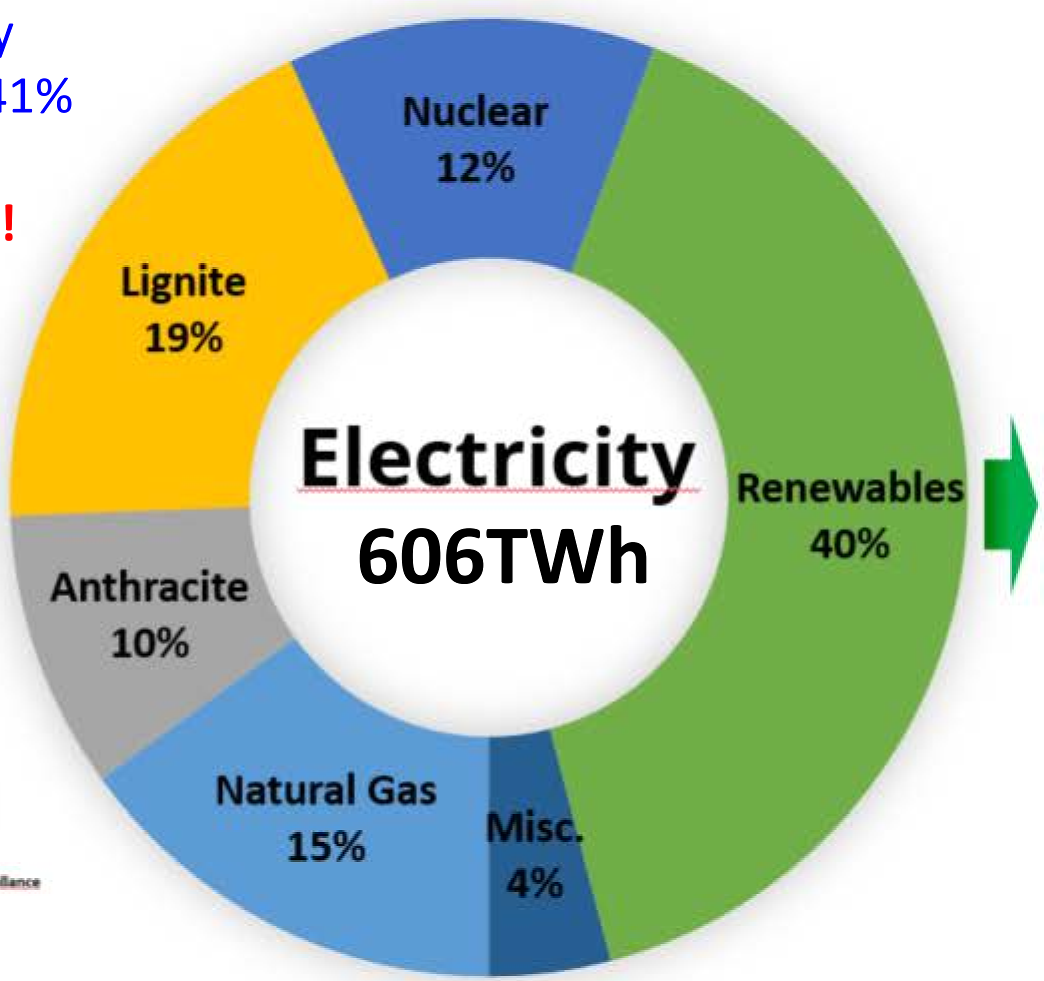
Electricity Generation in Germany 2019

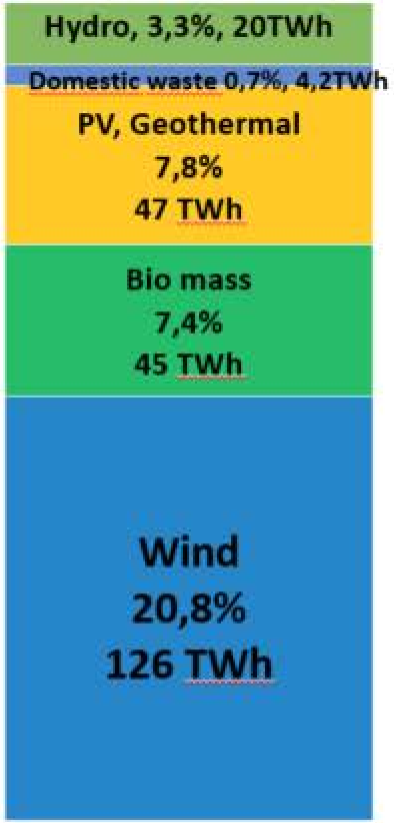
Source: Arbeitsgemeinschaft Energiebilanzen, Stand 2019 https://www.ag-energiebilanzen.de/

How will we replace 31% of electricity generation (Lignite + Nuclear), resp. 41% incl. Anthracite……….?

Through the import of green energy !







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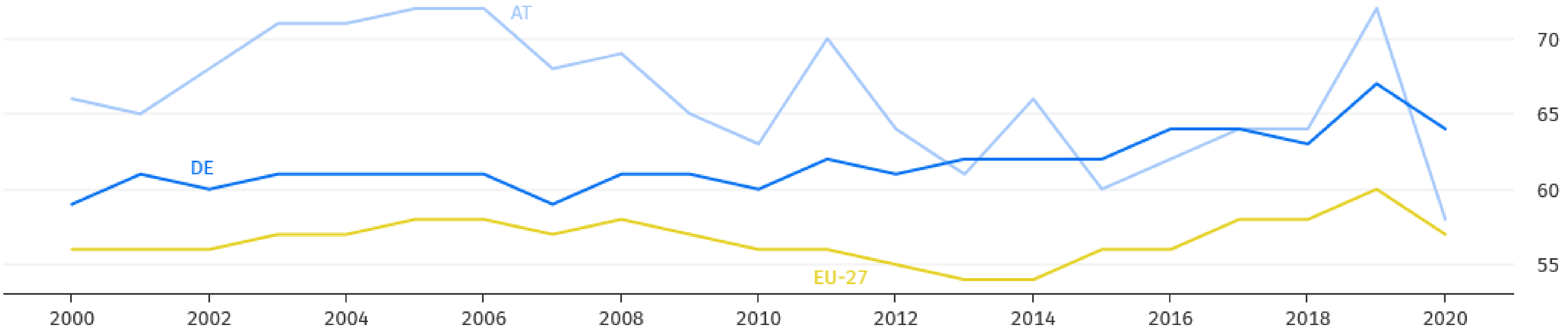
Energy imports to Germany, Austrian, EU-27; Fraction of the primary energy demand

https://www.destatis.de/Europa/DE/Thema/Umwelt-Energie/_inhalt.html → Grafiken



Energy imports need to include easily and long term storable media, e.g. methanol, in order to cater for all kinds of import fluctuations (market, political, geo-strategical….) !

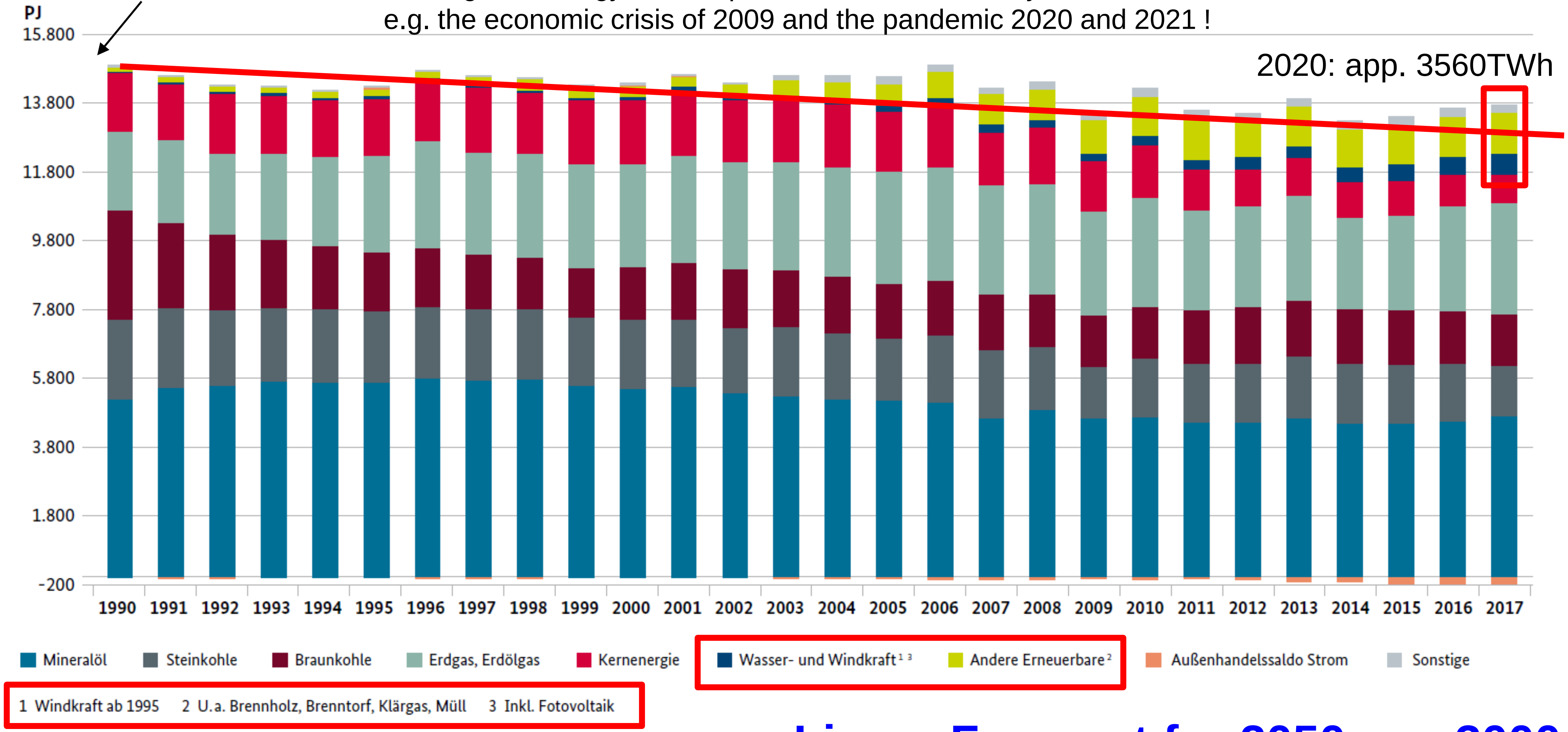
For an industrialised Germany a complete independence of energy imports is not possible!

Primary Energie Consumption in Germany 1990 - 2017

app.4100TWh

„Savings“ in energy consumption often are caused by economic fluctuations, e.g. the economic crisis of 2009 and the pandemic 2020 and 2021 !

2020: app. 3560TWh

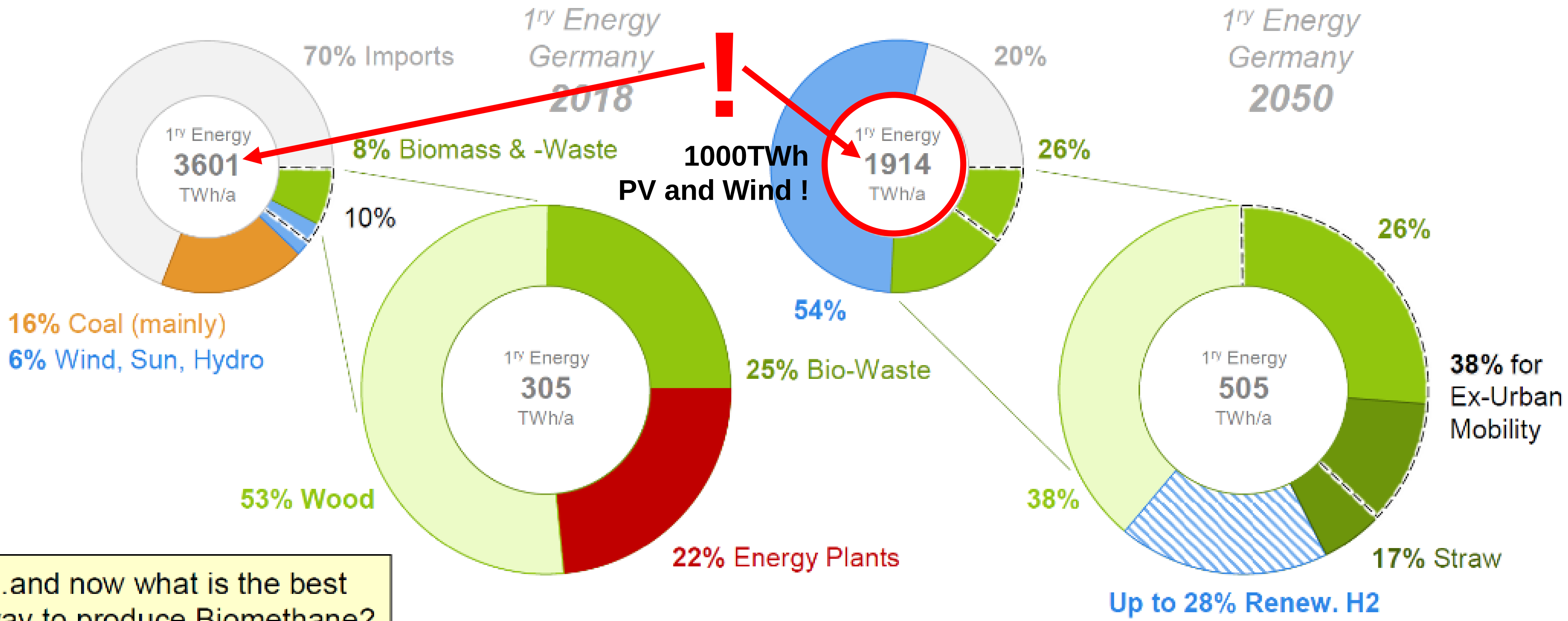


Quelle: Arbeitsgemeinschaft Energiebilanzen (AGEB)

Linear Forecast for 2050: ca. 3000 TWh

Forecast, Energy supply in 2050

Quellen: Sens, Brauer et al, IAV, in SAE ICE 9/2019 und FNR e.V., eigene Rechnungen



…and now what is the best way to produce Biomethane?

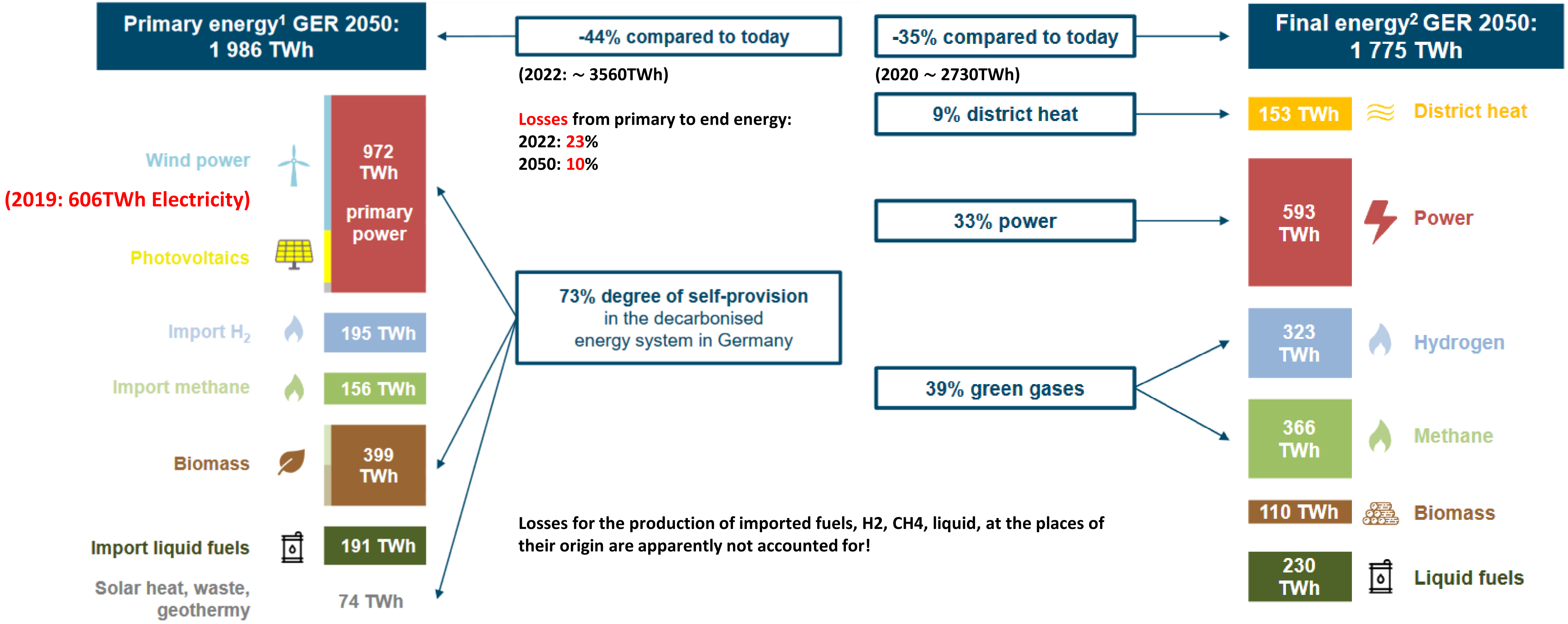
Sources: FNR 2018, EU 2019, "Energiekonzept 2050" Bundesregieung 2019 , own calculations

→ Biomass used for Sustainable Mobility shall not compete with the Food Supply!

Is a reduction to 1914TWh in 2050 from 3600TWh in 2019 of primary energy possible?

Simulation 2050, WECOM, Wagner, Elbling & Company

Presented at FVV Autumn Conference October 6th, 2022



[1] excl. ambient heat and decentral solar thermal heat (230 TWh), excl. grid connection losses; [2] excl. ambient heat and decentral solar thermal heat (186 TWh);
Picture source: (licensed by Creative Commons BY 3.0): DinosoftLabs, Freepik, Hand Drawn Goods, Iconnice, Smashicons - Flaticon.com

In 2050 73% of primary energy are assumed to be produced domestically → 27% imports

Savings against the linear estimate of 3000TWh: **direct electricity generation** (from PV and wind, without conversion loss from steam generation and turbine), massively improved building insulation, heat pumps, efficiency of nationally fed electric cars, (hopefully) the efficiency of future hybrid/combustion powertrains

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Energy logistics across the world
The challenge of volumetric Energy Density for logistics

Fuel, state of matter	**Energy / Litre**	**volumetric Factors with reference to Diesel**	
Diesel, liquid at 20°C, 1013 mbar	9,74 kWh	1 / 1	
Gasoline, liquid at 20°C, 1013 mbar	9,25 kWh	0,95 / 1,05	
Methanol, liquid at 20°C, 1013 mbar	4,43 kWh	0,45 / 2,2	Production efficiency 52%
Ammonia, liquid at 20°C, **8,6 bar**	3,17 kWh	0,33 / 3	
Hydrogen, liquid at **-253°C**, 1013 mbar	2,34 kWh	0,24 / 4,16	Production + liquefaction efficiencies: 0.7 x 0.72 = 0.50 !!
Hydrogen, gaseous at 20°C, **700 bar**	1,42 kWh	0,15 / 6,86	Production + compression efficiencies: 0.7 x 0.88 = 0.62 !!
Hydrogen, gaseous at 20°C, **350 bar**	0,85 kWh	0,09 / 11,45	

Hydrogen poses a transport problem ! not only in terms of molecular diffusion.

- **liquefaction at -253°C is expensive. ~28….46% of ist own heating value are lost for this process + facility cost.**
  Source: Bossel, *Wasserstoff löst keine Energieprobleme; Technikfolgenabschätzung – Theorie und Praxis.* Karlsruher Institut für Technologie, 2006
- **pressurising hydrogen to 700bar is also expensive, ~12% of ist own heating value are lost for this process + facility cost**
  Source: Peter Kurzweil, Otto K. Dietlmeier: *Elektrochemische Speicher*. 2. Auflage. Springer Fachmedien, Wiesbaden 2018, ISBN 978-3-658-21828-7, 8.2 Wasserstoffspeicherung
- **handling substances at -253°C or at 700/350bar is expensive**

In any case it is impossible to carry large quantities in weight and, hence, in energy ! → range and refilling → H_2 is best used in applications with pipeline!

H_2 Transport

Source: https://www.energieundmittelstand.de/2-21

Average Tanker:

Liquid Diesel, Petrol or Methanol
250000 m^3
210000 t Diesel, 2.435.000 MWh
198000 t Methanol, 1.107.500 MWh

Largest H_2-Tanker (2021)
Liquid Hydrogen
1250 m^3 H_2, 293 MWh

	kWh/l	kWh/m3	m3	kWh	MWh
Diesel	9,74	9740	250000	2435000000	2435000
Methanol	4,43	4430	250000	1107500000	1107500
LH2	2,34	234	1250	292500	292,5

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Self-sufficient Germany?

Number of wind turbines in Germany 2018: **30518 → 126TWh yield in 2019**

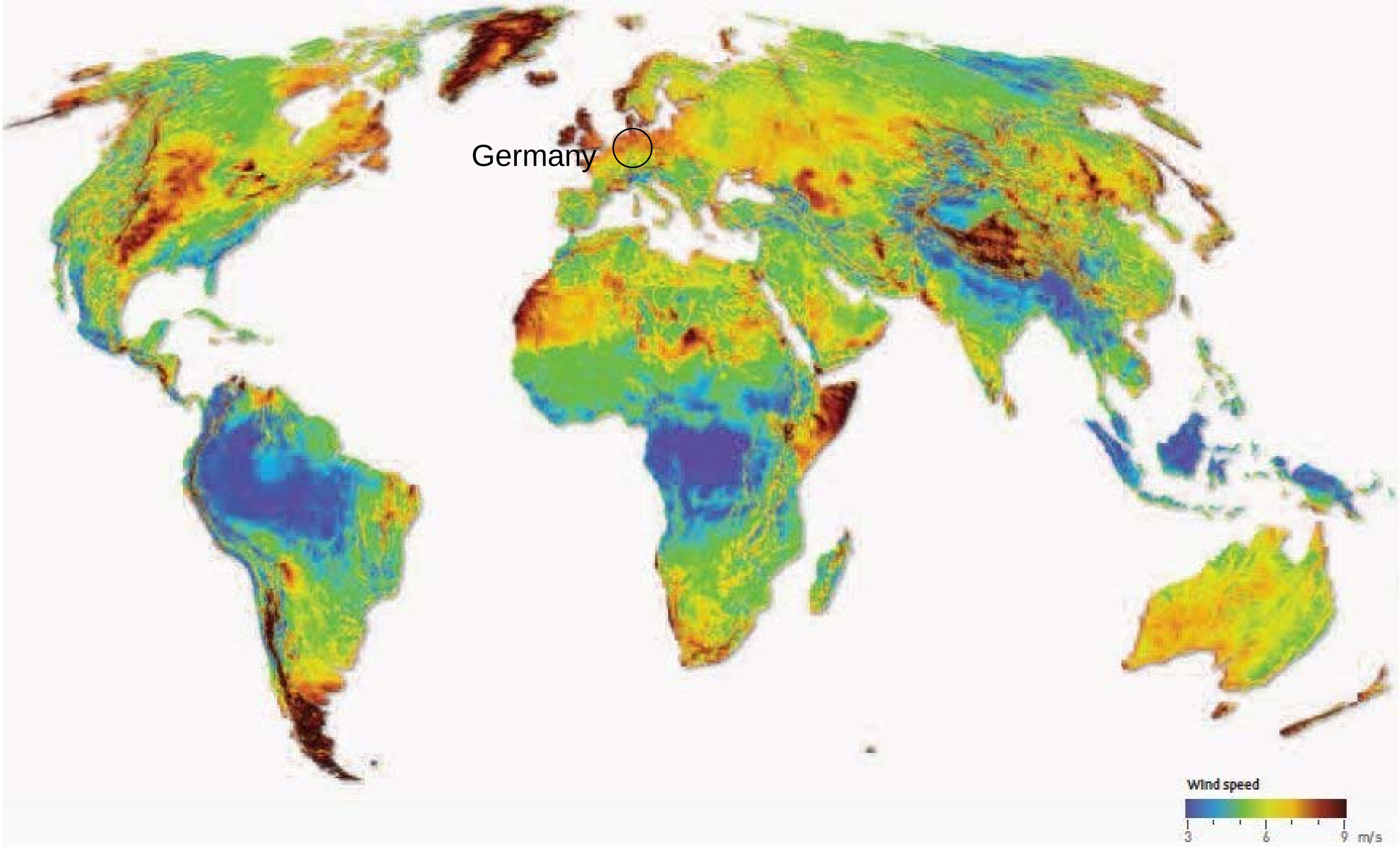
Basis: Primary Energy Consumption in Germany 2021, estimate app. 3500TWh					
No of plants	Full Load Power	Overall Power	Load Factor	Energy harvest	Fraction of 3500TWh
n	MW	MW		TWh/a	%
60000	6	360000	0,23	725	20,7%
	Turbines per Windpark	Surface of Gemany	Surface Square per Park	Distance between Windparks	
	-	km2	km2	km	
60000	10	357000	59,5	**7 to 8km**	

60000 wind turbine on shore are relatively unlikely with the frequency of a windpark every 7 – 8 km.
Off shore offers additional surface potential a higher degree of usage.

Sources: Load Factor: http://windmonitor.iee.fraunhofer.de/windmonitor_de/3_Onshore/5_betriebsergebnisse/1_vollaststunden/ → 0,23
Wikipedia, „Volllaststunden“: 21% on-shore, 24,5% off-shore
Atzler, own calculations, Stat. Bundesamt 2019, Bundesverband Windenergie, Umweltbundesamt, Bundesnetzagentur + www.smard.de

Wind map of the world, wind speed 80m above ground

https://crushtymks.com/wind-power/1607-what-about-the-worlds-wind-resources.html



Areas with elevated wind potential: near coastal regionen of Europe (Atlantic, north sea, baltic sea),

- German Northern Plains, ~7m/s
- **Greenland**, **Patagonia**
- Australia, South Africa,
- **North-West-Africa**
  Horn of Africa (Ethiopia, Somalia)
- Central USA, Alaska, Canada
- Russia, for land surface

Potential areas: > 9 m/s

Electricity production: Photovoltaics
Self-sufficient Germany? Surface demand / Flächenbedarf

Germany, km2	Germany, m2	Average Solar Irradiation in kWh/m2/a*	Average Photovoltaiks yield at 20% PV conversion efficincy	Considered Surface Fraction	Surface in km2	Electricity Yield of considered surface in kWh	Conversion kWh in TWh, 10^-9
357000	3,57E+11	1100	220	5,0%	17850	3,927E+12	3927
357000	3,57E+11	1100	220	2,5%	8925	1,964E+12	1964

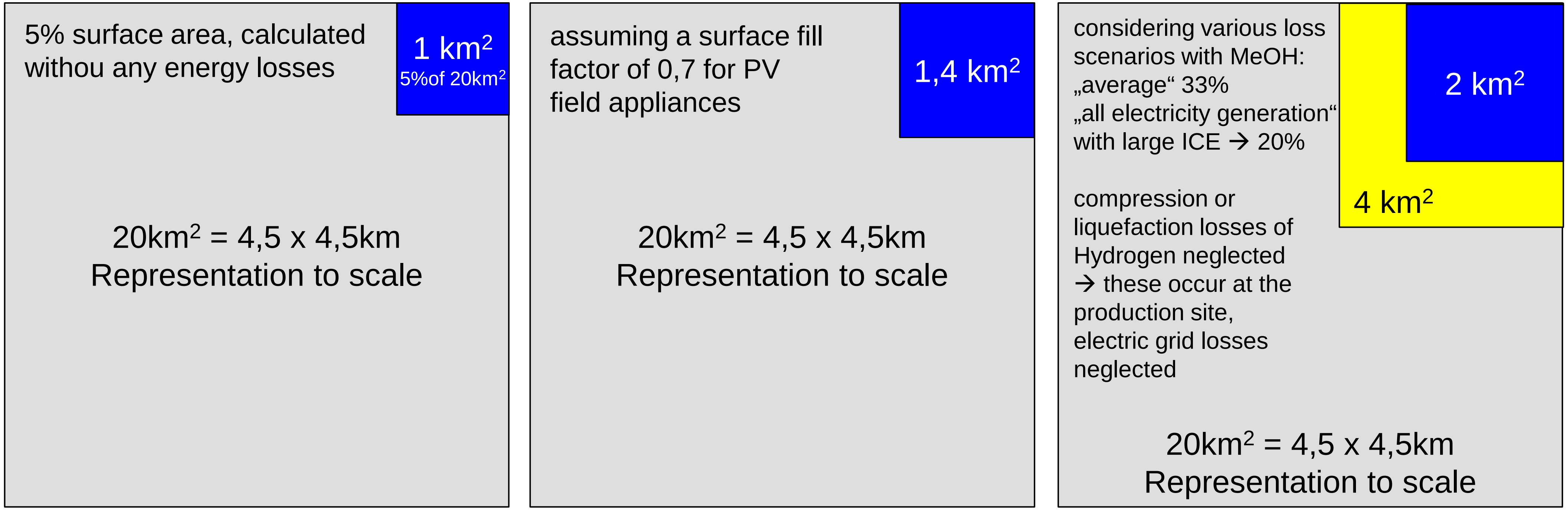
- **Lossless calculation !**
- **For heat generation, including process heat, MeOH can be used directly**
- **Electricity generation: production efficiency of Methanol ~50%, large combustion engines, large steam turbines >40% → overall eficiency ~20%**
- **Coarse estimate for a mixed scenario:**
  Energy in Germany is used for: 53% heat incl. process heat, 38% mechanical movement incl. 22%pts transport, 9% other (lighting, communication, etc.)

- **4 scenarios: 2 Overall efficiencies: 33% (50% heat/50%mech), 20% (ALL electricity generation from eFuel) → 33% is more realistic, than 20%**
- **2 demand scenarios: 2022: 3600TWh, 2050: 2000TWh**
- **Assumption: all field PV, surface fill factor 0,7**
- **Other losses are neglected: compression and liquefaction losses of H_2, grid losses, etc.**

Demand in TWh	surface in km2 "lossless" calculation	Overall energy efficiency	Surface fill factor	Effective surface in km2	Effective Surface in % of Germany	surface within 20km2	length of square, km
3600	16000	0,33	0,70	69264	19%	3,88	1,97
2000	9000	0,33	0,70	38961	11%	2,18	1,48
3600	16000	0,2	0,70	114286	32%	6,40	2,53
2000	9000	0,2	0,70	64286	18%	3,60	1,90

Electricity production: Photovoltaics
Self-sufficient Germany? Surface demand / Flächenbedarf

- **Photovoltaics yield app. 220kWh per m² each year**
- **5% of Germany´s surface yield 3900TWh = app. 100% of Germany´s primary energy demand (no grid losses and other losses included)**
- **for Methanol Production the energetic efficiency is app. 50%. Additionally other energy losses must be considered**



It is not possible to supply all of Germany‘s primary energy demand from national PV sources, not even for low forecast of 2000TWh in 2050! However, a significant fraction could nevertheless be produced nationally!

Sources: Atzler, own calculations,
Fraunhofer ISE, Stromgestehungskosten erneuerbare Energien, Juni 2021, energy yield Germany 950 (north) to 1300kWh/m²/a (south) → mean 1125

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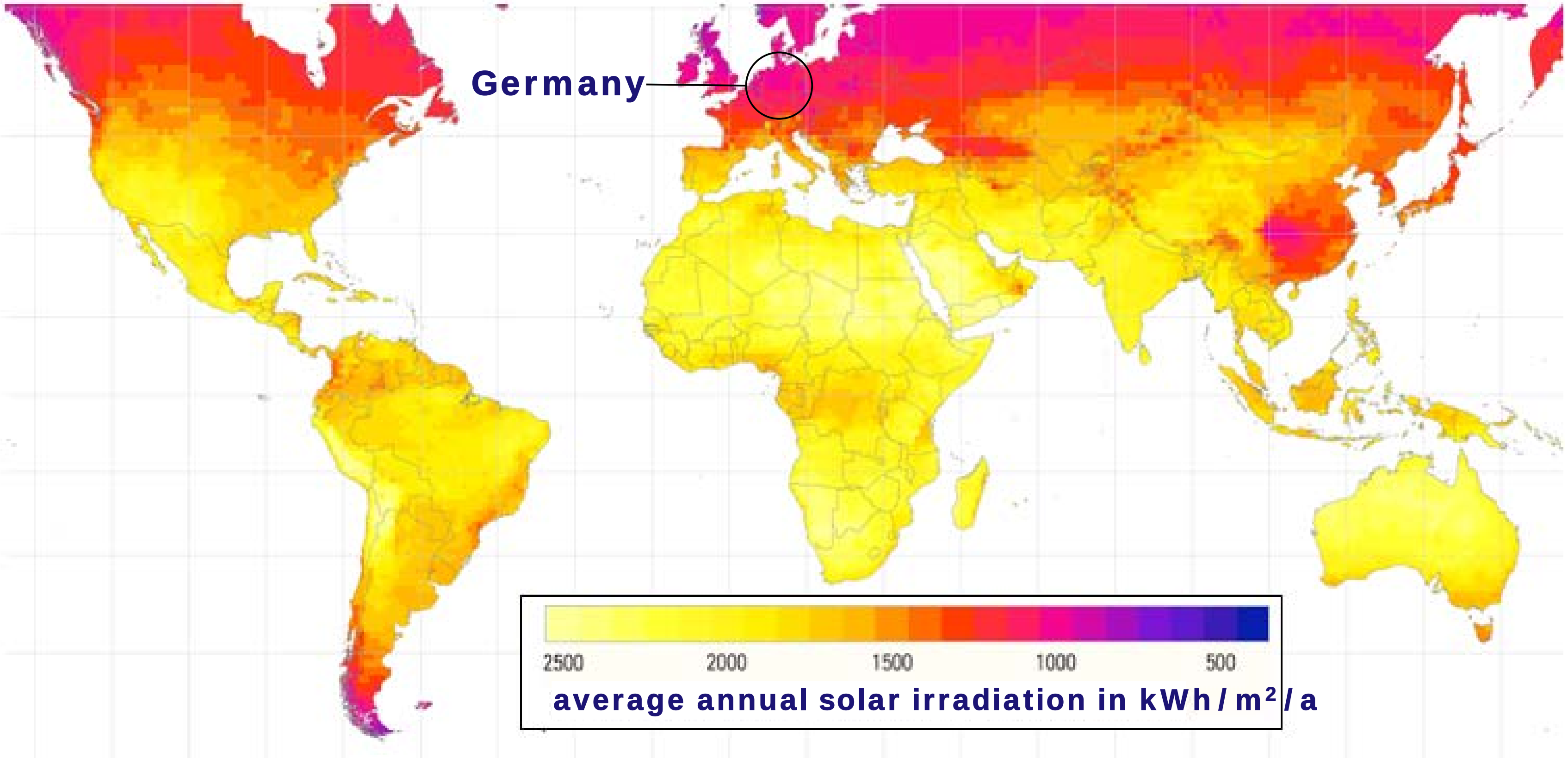
Photovoltaics, world map of sun energy

Source: Konrad Mertens, "Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis", Hanser Verlag, 2020



Average yield in Germany app. 1100kWh/m²/a

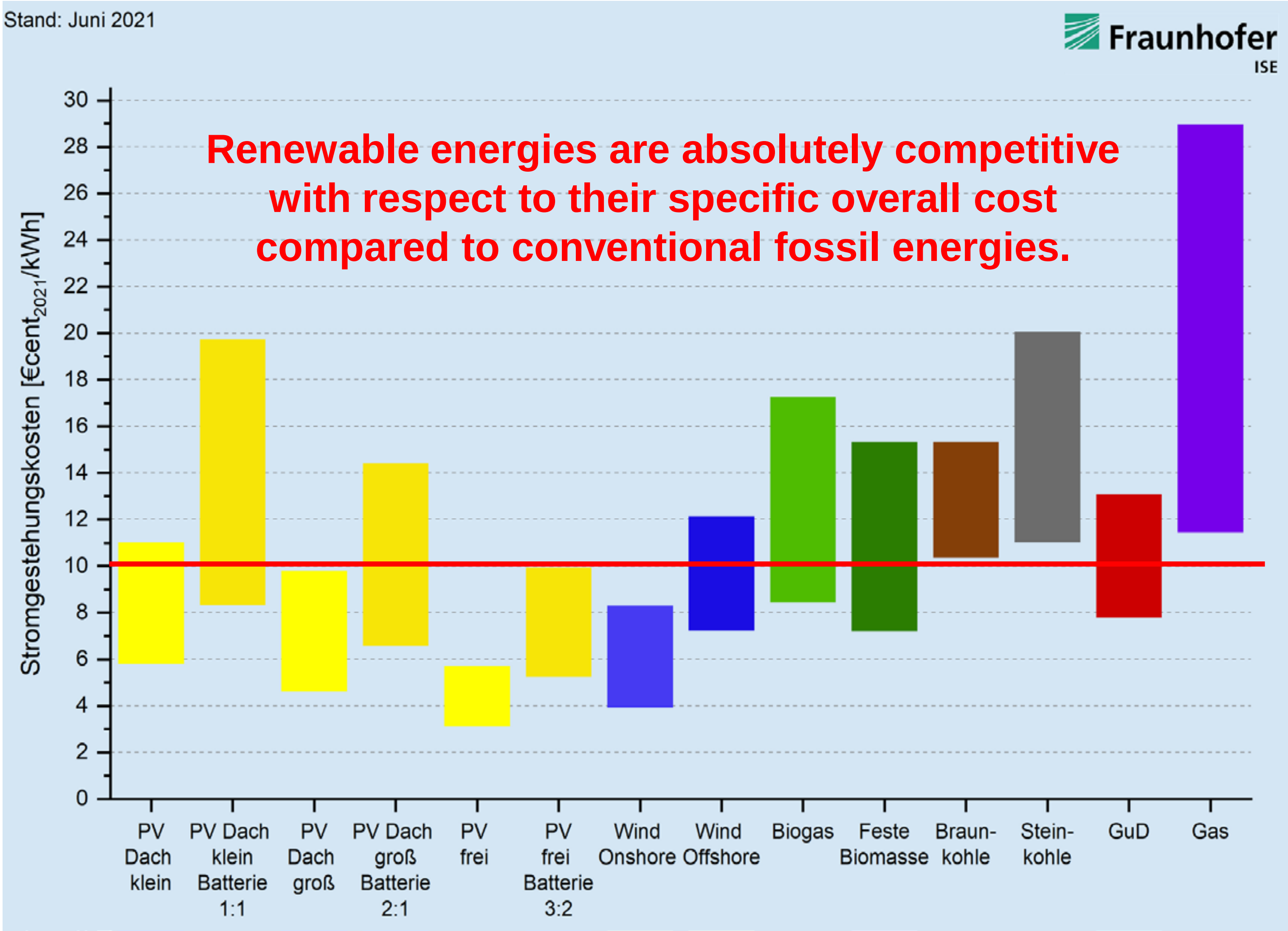
Yield in the „sun belt“ of the world: up to 2500kWh/m²/a → Factor 2,27 → economical production!

Geopolitical implications: Spain, Portugal, South of Italy, Greece → stable partners within the EU

Turkey, Australia, Brasil, Chile, Argentine ? Regions of Africa?

USA, China and India will probably use their ressources themselves

Comparison Overall Energy Cost Germany 2021, Fraunhofer ISE



Legend:

PV = photovoltaics
Dach = roof
klein = small
groß = large

„Batterie“, means the addition of a battery storage to a photovoltaic appliance

frei = open land
Braunkohle = lignite
GuD = gas and steam combined process
Steinkohle = anthracite

PV and wind (and much more so biomass) need large surface areas.

They have much smaller specific energy densities (w.r.t. surface area) than thermal power plants!

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Example: Photovoltaics can cover the primary energy demand of Germany / the World !

- **about 40000……70000km² are enough to supply the total primary energy demand for Germany**
  (at an assumed overall efficiency of 33%, fill factor 0.7, 2000TWh……..3600TWh scenario)
- **50% is the app. efficiency for Methanol production,** the rest is for losses in the logistic chain and other losses

- **2……3,5 Mio km² are enough to supply the total primary energy demand of the worlds** (same assumptions as above, Germany x 50)

- **Desert surfaces across the world in Mio. km²:**
  Sahara ~9; Australian deserts 1,37; Tharr and Colistan (India and Pakistan) 0,27; Gobi 2,35; New Mexico USA 0,3; (data from Wikipedia)
- **a detailed analysis of suitable surfaces is given in the Fraunhofer IEE PTX Atlas**
- **Current cost per kWh für photovoltaics and windpower are below that of conventional fossile power plants and far below the total cost of nuclear power → see Fraunhofer ISE, Stromgestehungskosten erneuerbare Energien, Juni 2021**

International cooperation is inevitable to harvest the energy economically, i.e. in the „sunbelt of the earth"

- **Methanol is liquid at ambient pressure and temperature → suitable for SIMPLE and CHEAP transport, storage and use !**
  (and further processing at industrial scale)

Fraunhofer IEE PtX Atlas

https://www.iee.fraunhofer.de/de/presse-infothek/Presse-Medien/Pressemitteilungen/2021/neuer-atlas-power-to-x-potenziale.html

Findings: in the long term there is a potential overall for:

- 109.000 TWh of liquid Hydrogen or 87.000 TWh reFuels (PtL)
- **realistically not all of this can be used →** **geopolitical aspects**
- 69.100 TWh liquid Hydrogen resp. 57.000 TWh reFuels (PtL)

PtX only, excluding the wind and PV potential directly used !

- For comparison, demand in PtL for global aviation in 2050 app. **6.700** TWh, global shipping **4.500** TWh
- German overall primary energy demand **2000…3000**TWh
- World primary energy demand: 3600TWh x 50 = **180.000**TWh, 2000TWh x 50 = **100.000**TWh

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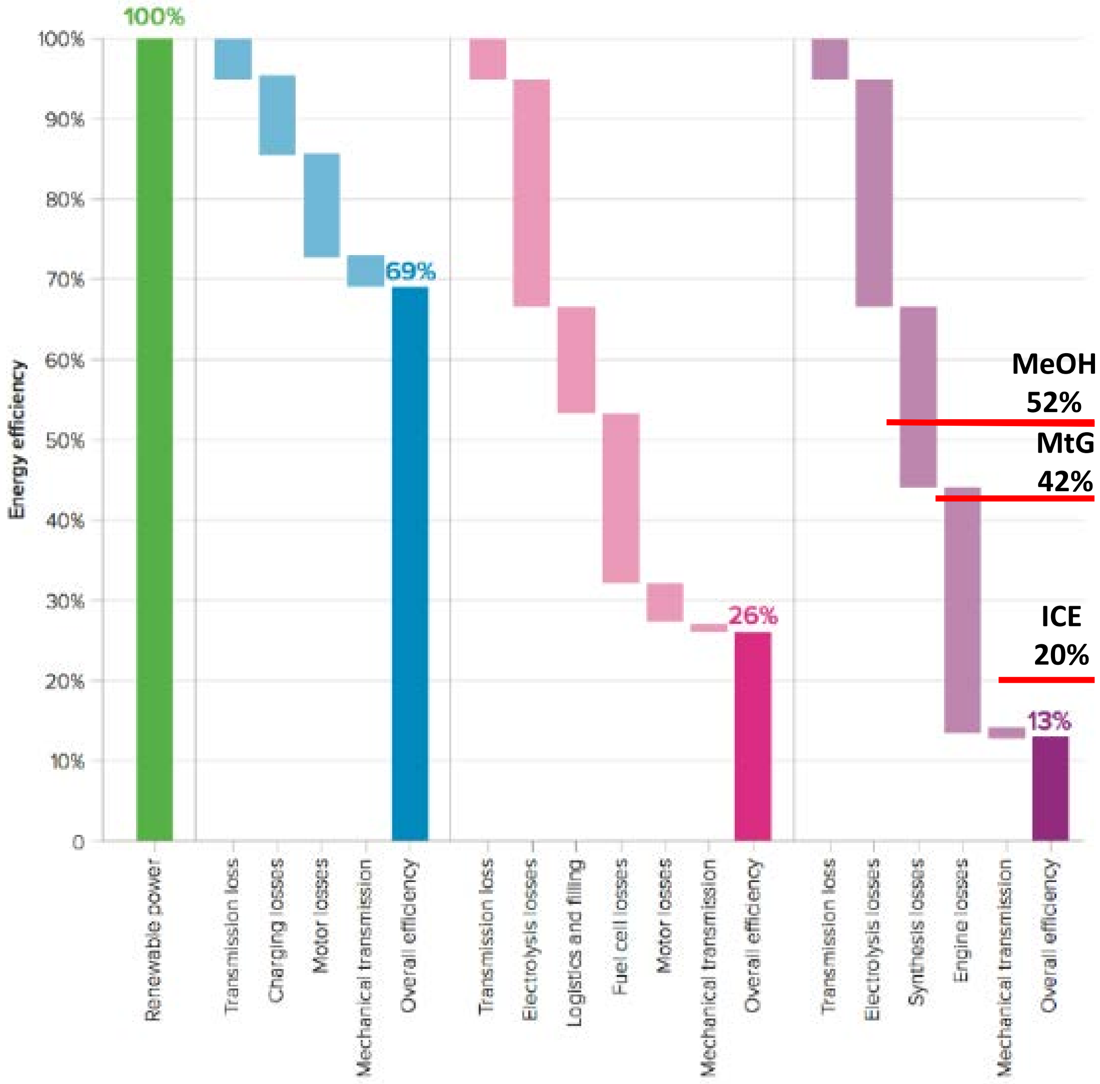
Efficiency of reFuels production and efficiency of application

Assumption: 100% energy (green column) is used to:

- drive a battery electric vehicle (blue)
- to run a fuel cell vehicle with hydrogen (red)
- to run a Diesel vehicle with synthetic Diesel (purple)

In all of these scenarii the production and disposal of the vehicle and in particular the CO_2 intensive production of the battery is not included, nor is the infrastuctur to produce the necessary amount of green energy !



Legend:
Transmission loss → losses in the electric Grid
Motor losses → losses in the electric motor, efficiency of the eMotor
Logistics and filling → storage, transport of H_2, both liquid and gaseous, consume energy. The filling process (of tanks), i.e. the transfer of H_2 from one vessel to another requires energy and incurs loss of H_2 (leakage, boiling losses, ….)
Synthesis losses: are a matter of debate and depend very much on the synthesised fuel. E.g. H_2+CO_2 → Methanol is an exothermic reaction, CO_2 can be captured „out of the air“ (400ppm vol → very energy consuming!) or „from industrial combustion“ (5 to 15% vol!)

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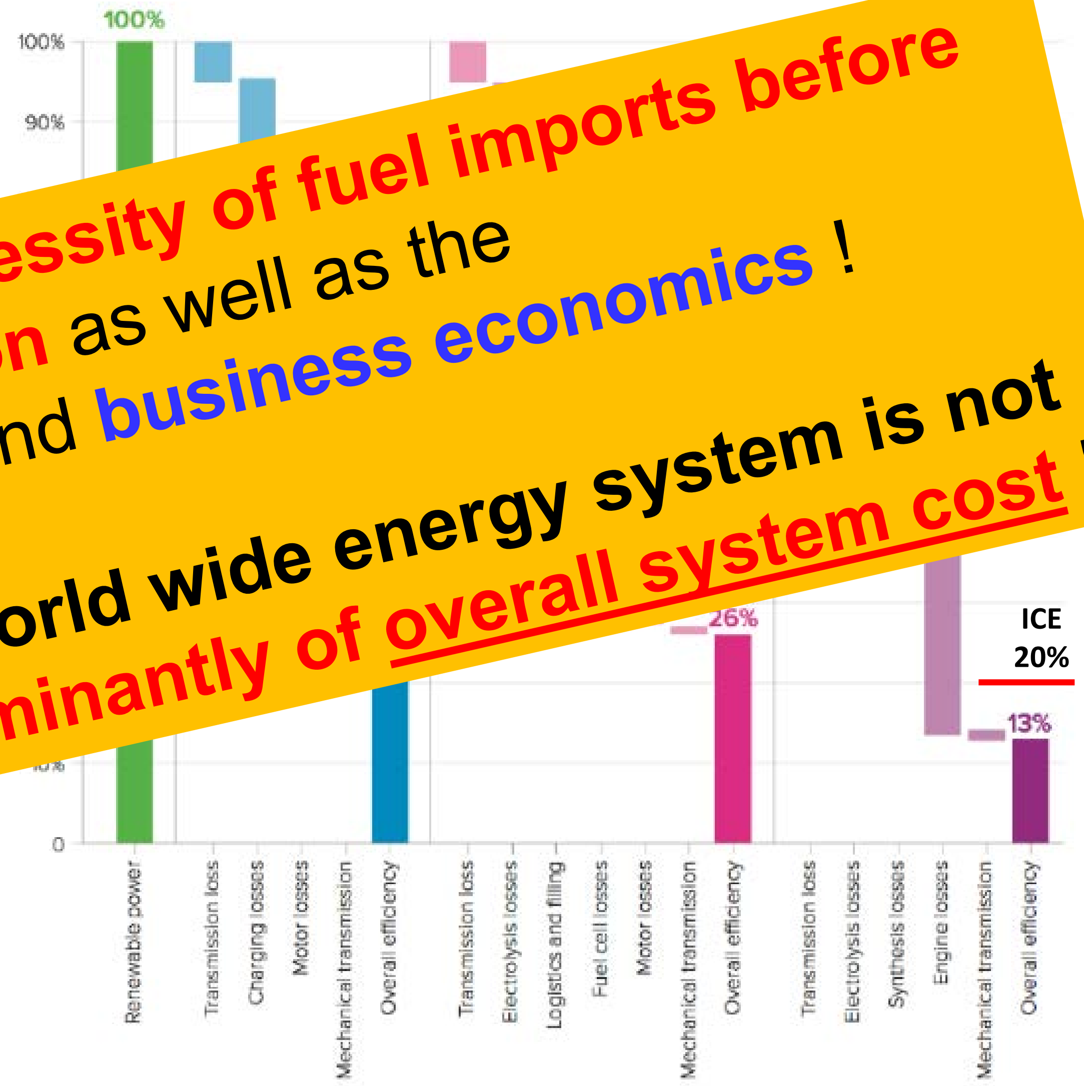
These consideration disregards the **necessity of fuel imports before the electricity generation** as well as the **basic rules of industrialisation** and **business economics** !

The optimum solution for a green world wide energy system is not only a question of efficiency but dominantly of overall system cost !



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Industrial Production

Mass production = <u>good quality at a low price → industrialised process</u>

- **Cost** = (development cost + production cost + production facility cost + logistics, warehouse, distribution cost + desired profit) divided by number of units produced

Attributes of an industrial process: Robustness, Cost, Scalability

- **Robustness**: production availability 8500h/a, output error rate below 100ppm (this may vary for different products, markets and prices)
- **Cost**: Production facilities need to be based on „inexpensive“ and/or very efficient methods to keep the cost down, i.e. productivity must be high. Examples: production of PEM-membranes, synthesis of Methanol : the catalyst must be cheap and robust, i.e. without precious metals
- **Scalability**: The robust and cheap process must deliver several million units (i.e. not lab scale)

- **Efficiency** does not play a dominant role. The process must delivers reliably for a low price, and obviously the efficiency must not be too low! **A sofisticated, high-efficiency process with frequent downtimes is useless. There is by far enough renewable energy available on the earth to cover for (slightly) less efficient but robust processes! with high yield !**
- **Ecology**: the production process should avoid (too many) materials, the production of which causes a big environmental impact or ethical issues anywhere in the world. But this unfortunately often is a matter of perspective in different pats of the world.

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Cost No.1: Is electrolysis expensive?

Cost per unit Input Power	Electrolyser Unit	Total Cost per Electrolyser		Nuclear Power e.g. Olkiluoto Finland	Net Power Output	specific Cost
€/kW	kW	€		Estimated Cost, €**	W	€/W
2000	20000	40000000		8,50E+09	1,60E+09	5,31
		Mio €		Mia €	MW	€/kW
		40		8,5	1600	5312,5
* currently only piece by piece manufacture, scaling effects are assumed to reduce the cost to some 200€/kW input power						
**https://de.wikipedia.org/wiki/Kernkraftwerk_Olkiluoto						

Cost for Electrolysers and Power Input:
2000€ per kW PEM electrolyser capacity = top value, from Fraunhofer Zittau
Source: Prof. Ed Bodmer https://edbodmer.com/levelized-cost-of-hydrogen-and-biomass/

Comparison from Machhammer*: Haru Oni in Chile, 2500MW, 3,75Mia€ → 1500€/kW ✓

The price per kW electrolyser capacity is expected to reduce from 2000€/kW (2020) to some 200€/kW in 2025……2030 in industrial series production
This agrees with the forecast from EKPO for 2026 of app. 150€/kW for the fuel cell (→ „reverse electrolyser“), however for automotive/commercial vehicle use. (Emission Control, Dresden 2021)

Source: Regenerativer Strom aus Deutschland oder e-Fuels aus Chile: Worauf sollte die zukünftige Mobilität bauen? Otto Machhammer DOI: 10.1002/cite.202100003
in Chemie Ingenieur Technik 2021, 93, N0.4, pp 641 – 654; *m+@machhammer.consulting, M+ machhammer consulting, Bruchsaler Straße 36, 68219 Mannheim, Deutschlandc

Cost No.2: How many electrolysers are needed ? → Industrial Production → Cost

Grid Input Power	Efficiency of H2 production	Load Factor (per year)	Hours/Year	Energy output in Hydrogen per year	Energy demand, Germany	Number of Elektrolysers
MW				MWh H2/y	TWh	
20	70%	90%	8760	110376	3600/2000	
W				Wh H2/y	Wh	
2,00E+07	0,7	0,9	8760	1,10376E+11	3,60E+15	32616
2,00E+07	0,7	0,9	8760	1,10376E+11	2,00E+15	18120

For the supply of Germany in an „all Hydrogen“ scenario:

- **for app. 3600TWh nearly 33000 electrolysers are needed**
- **for the forecast 2050 of app. 2000TWh some 18000 electrolysers would be necessary.**

This is large scale industrial production → reduction of cost from currently app. 2000€/kW to 200€/kW likely.

Also, this could be one of the future top exports of Germany, including desalination technology.

However, this will be one of the obvious bottlenecks for some years to come!

Cost No.3: Electrolyser Cost per unit H_2 and Write Off per kWh H_2-energy from the 20MW electrolyser

Electricity CAPEX and OPEX	Electricity cons. for a 20MW Electrolyser*	Energy cost per year	Elektrolyser WriteOff	**WriteOff per kWh H2 output****	Total cost	Cost / Unit Energy H2	Cost kg H2 (33kWh/kg)
Renewable electricity, 2000€/kW Electrolyser Cost, linear write off 5 years, 45000h --> Bipolar Plates Durability ?							
€c/kWh	kWh/year	€	Mio €/y	€c/kWh H2		€cent	
4	157.680.000		8	7,25		12,96	
€/Wh	Wh/year		€/y	€/kWh H2	€/y	€/kWh	€/kg
0,00004	1,58E+11	6.307.200 €	8.000.000 €	0,0725	14.307.200 €	0,1296	4,28
Renewable electricity, 200€/kW Electrolyser Cost, linear write off 5 years, 45000h --> Bipolar Plates Durability ?							
€c/kWh	kWh/year	€	Mio €/y	€cent/kWh H2		€cent	
4	157.680.000		0,8	0,72		6,44	
€/Wh	Wh/year		€/y	€/kWh H2	€/y	€/kWh	€/kg
0,00004	1,58E+11	6.307.200 €	800.000 €	0,0072	7.107.200 €	0,0644	2,12
Renewable electricity, 200/€kW Electrolyser Cost, linear write off 5 years, 45000h --> Bipolar Plates Durability ?							
€c/kWh	kWh/year	€	Mio €/y	€cent/kWh H2		€cent	
1	157.680.000		0,8	0,72		2,15	
€/Wh	Wh/year		€/y	€/kWh H2	€/y	€/kWh	€/kg
0,00001	1,58E+11	1.576.800 €	800.000 €	0,0072	2.376.800 €	0,0215	0,71

*Energy consumption: 20MW x Load Factor 90% x 8760h/a = 157.680 MWh; **based on H2 output of 110.376MWh H2 = 157.680 x 70% efficiency

At 2000€ per kW → total electrolyser cost = 40Mio€ → for 5 years write off = 8Mio
At 200€/kW → 4 Mio€ → 5 years write off → 800.000€/a

Lehrstuhl VERBRENNUNGSMOTOREN und Antriebssysteme

TECHNISCHE UNIVERSITÄT DRESDEN

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- Can Germany / Europe supply ist own renewable energy ? Wind, PV, Biomass, Cost comparison
- Can the world be supplied with renewable energy ?
  Simple assessment based on PV + Fraunhofer PTX Atlas
- Efficiency of use
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- eFuels cost
- eFuels cost including TRANSPORT
- Efficiency and cost per kilometre
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Cost No.4: How much is one litre of Methanol?

- Currently the cheapest PV electricity comes from Saudi Arabia → 0,88€cents per kWh → ~1€cent/kWh
- There are 4,4kWh in one litre of Methanol → 4,4€cents per litre → ~ 5€cents electricity
- Methanol → production efficiency of app. 50% from electricity → ~ 10€cents electricity
- Methanol contains half the energy of gasoline → double the volume is needed → ~ 20€cents electricity
- For the **cost of the electrolyser** to produce the Hydrogen

  → **expensive case 2022** ~7€c/kWh → gasoline equivalent ~10kWh → 70€cent

  → **future estimate 2035?** ~0,7€c/kWh x 10kWh → 7€cent

- **catalyst to produce Methanol → negligible compared to the electrolyser cost**

  → between 27 and 90€cent for the energy equivalent of one litre of gasoline (before profit)

  → Educated guess: 50€cents gasoline equivalent (~10kWh) or **5€cents per kWh** (2,7€c/kWh minimum + transport) (before profit)

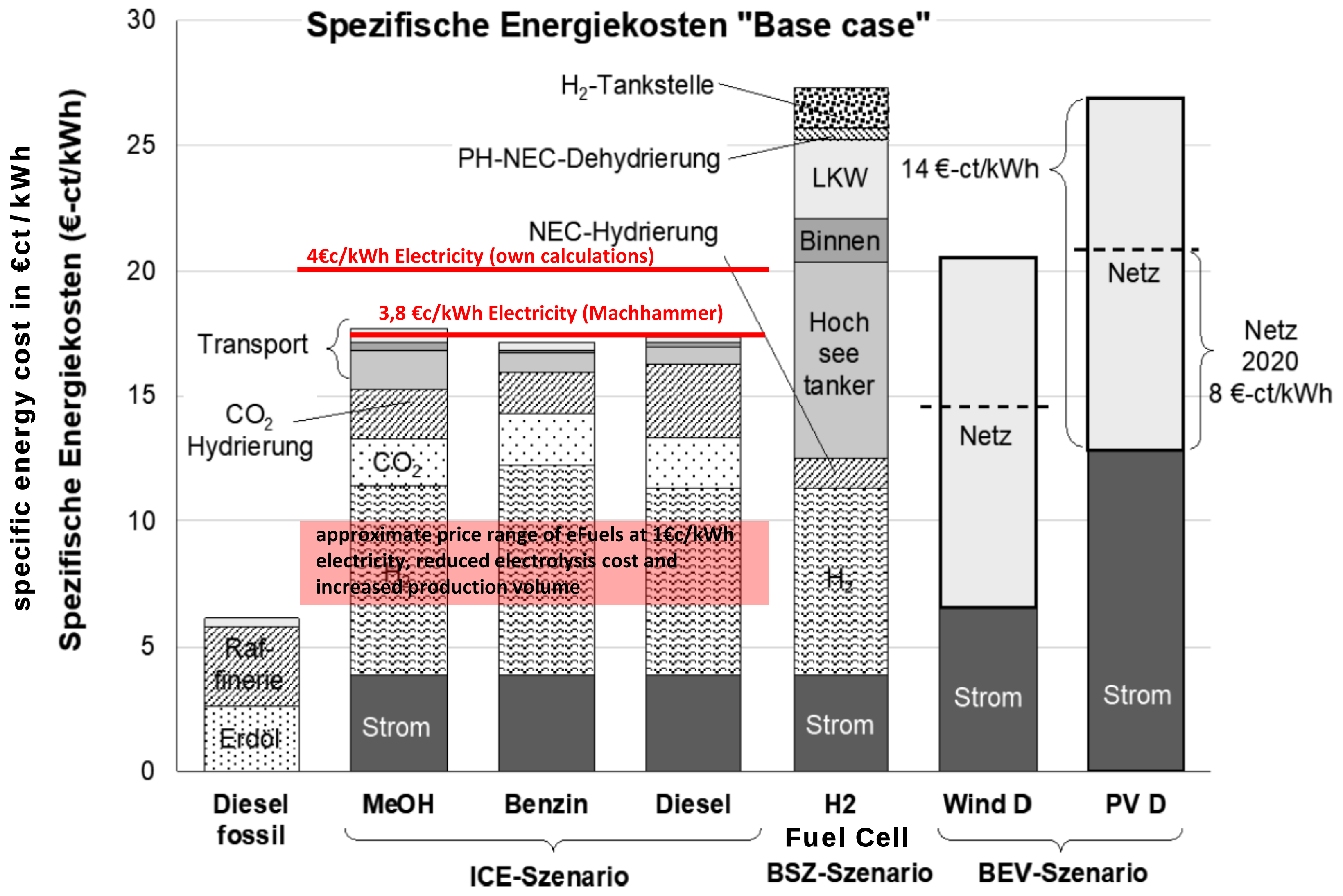
  → if electricity costs 4€c/kWh → 20€c/kWh (comparison to Machhammer paper → 3,8€c/kWh)

- prices of gasoline and diesel **ex refinery without taxes in April/May 2022 were at app. 1€ per litre at a pump sales price of 2€/litre**

  (refinery price + VAT + CO_2tax + energy tax + procurement tax = pump sales price)

Cost No.5: Specific energy cost in Ect/kWh, Source: Machhammer 2021

eFuels from Patagonia incl transport versus directly consumed electricity supplied within Germany



Only liquid „fuels" were considered

Methanol
MtG Gasoline
(Fischer Tropsch Diesel)
H_2LOHC (Liquid Organic Hydrogen Carrier)

Electricity cost, Chile: 3,8€c/kWh

Windpower and PV from Germany, direct use in BEVs, 2 scenarios for grid cost (8 / 14€c/kWh)

For comparison:
fossil fuel costs only 6 to 7€c/kWh

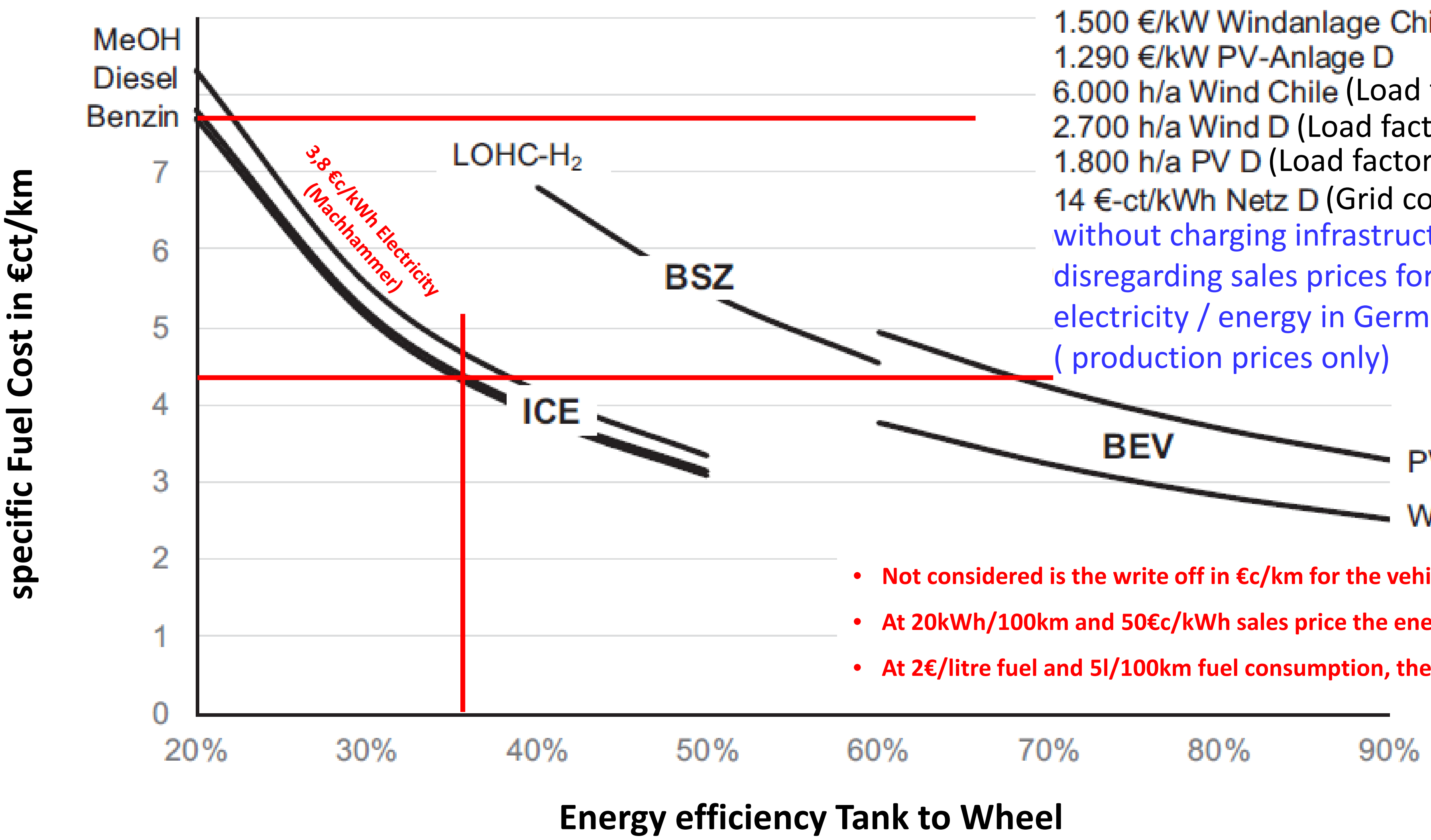
Lower Price range for MeOH:
~1€c/kWh electricity
~ 3€c/kWh electrolysis (see „write off electrolyser)
~ 4€c/kWh CO_2+MeOH synthesis
~ 2€c/kWh Transport

~ 10€c/kWh with margin for cost reductions

The pump sales price is mostly a matter of profit margin and taxation !

1€c/kWh Electricity (own calculations)

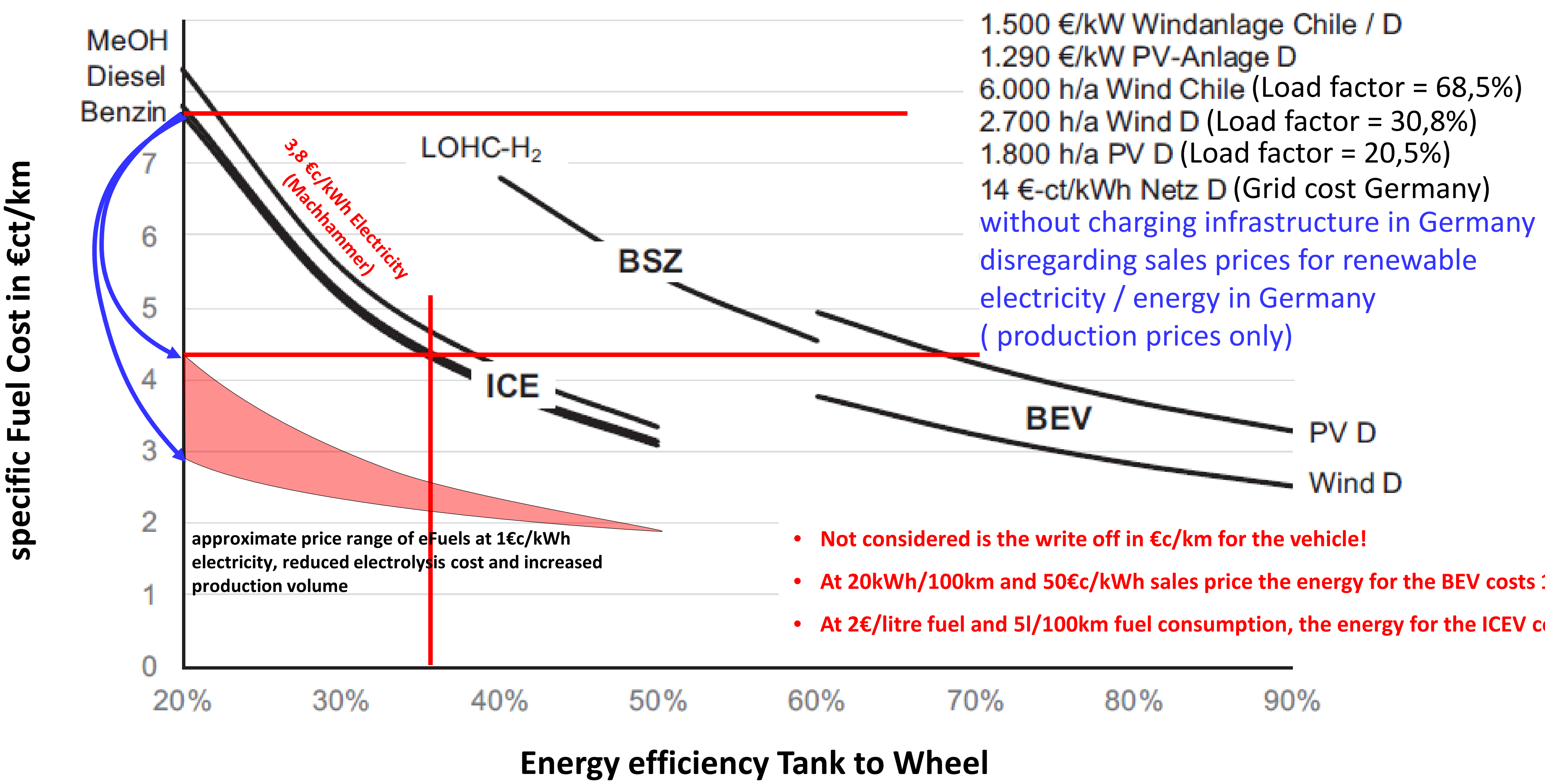
Cost No.6: specific energy cost in €ct/km, Source: Machhammer 2021
eFuels from Patagonia incl transport versus directly consumed electricity supplies from within Germany



1.500 €/kW Windanlage Chile / D
1.290 €/kW PV-Anlage D
6.000 h/a Wind Chile (Load factor = 68,5%)
2.700 h/a Wind D (Load factor = 30,8%)
1.800 h/a PV D (Load factor = 20,5%)
14 €-ct/kWh Netz D (Grid cost Germany)
without charging infrastructure in Germany disregarding sales prices for renewable electricity / energy in Germany (production prices only)

- **Not considered is the write off in €c/km for the vehicle!**
- **At 20kWh/100km and 50€c/kWh sales price the energy for the BEV costs 10€/100km**
- **At 2€/litre fuel and 5l/100km fuel consumption, the energy for the ICEV costs 10€/100km**

Cost No.6: specific energy cost in €ct/km, Source: Machhammer 2021
eFuels from Patagonia incl transport versus directly consumed electricity supplies from within Germany



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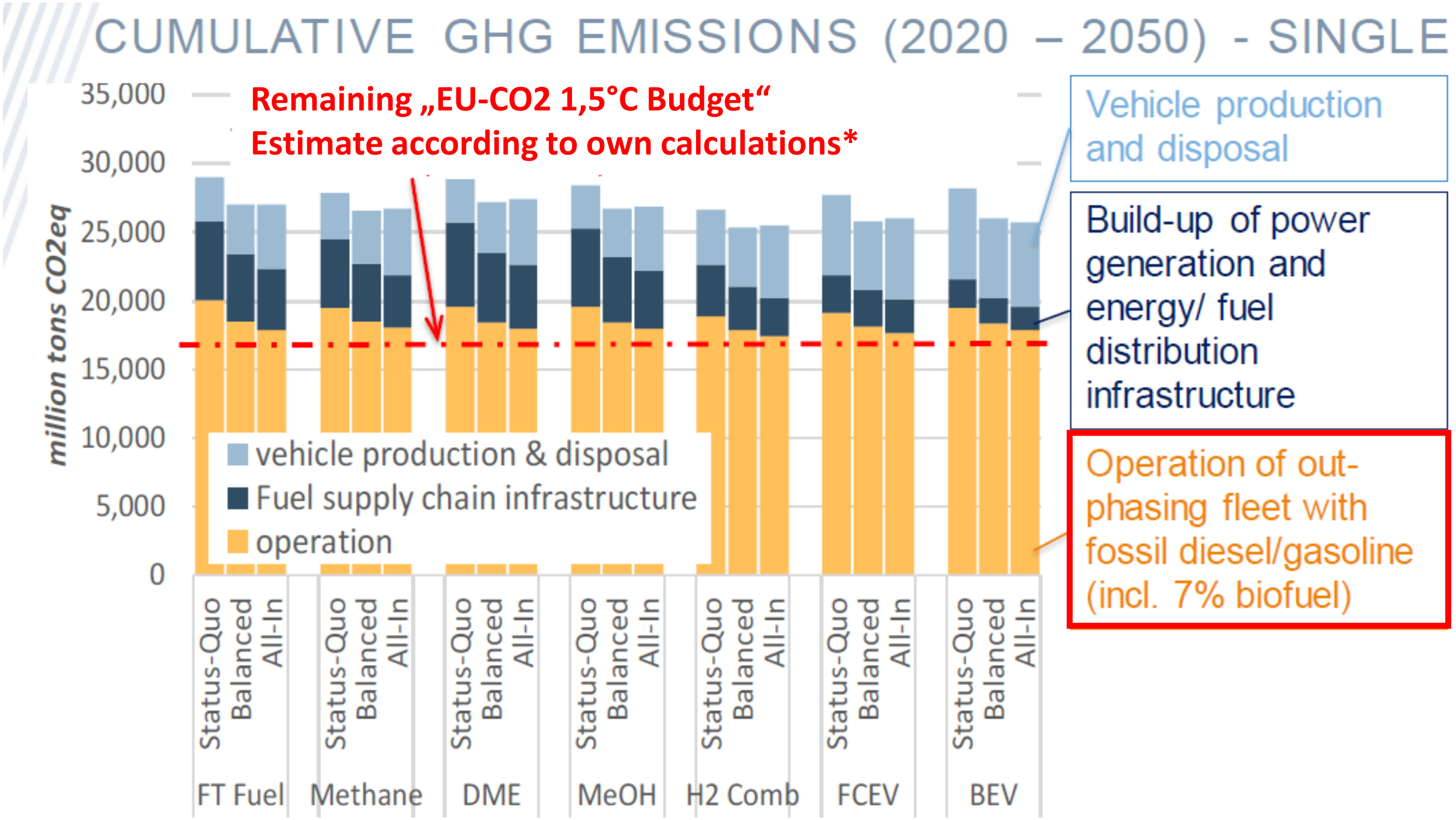
FVV Fuel Study IVb, Essentials

Without defossilisation of the existing fleet the 1,5°C limit cannot be achieved !



Global warming is determined by cumulative GHG emissions:

- **Vehicle operation** of out-phasing fleet with fossil fuels dominates cumulative GHG emissions with ≈ **70%** in all single technology scenarios.
- ≈ **30%** of cumulative GHG emissions are from **vehicle production/disposal** and **building up the complete renewable energy infrastructure** in all 100% scenarios
- **55-60%** of the cumulative GHG emissions are emitted before **2030**

*estimate of an EU share corresponding to the comparison of EU and world Gross Domestic Product (using data from destatis.net and EUROSTAT)

Fast replacement of fossil fuels for vehicle operation is essential for reducing cumulative GHG emissions!

* GHG targets for Europe and for transport are not existing, therefore a theoretical target was assumed : 1.5°C 67th TCRE European share according to population share (6.5%) for EU27+UK; cumulative GHG from transport on C2G basis: including build-up of FSC infrastructure + vehicle production/disposal)

Summary and Conclusions

- There is enough renewable energy for the whole world. **Electricity, Hydrogen and Methanol are the "new oil".**
- **Surface area** is the most important resource for PV and windpower (apart from suitable solar irradiation and wind intensity)
- As long as **green electricity and Hydrogen are not available in abundance** in Europe, it would be sensible to use **imported eFuels in mobile applications** and **locally produced electricity and H_2 economically in stationary applications**. However, BEVs are very suitable for short distances of up to app. 100….200km and facilitate local emission free transport.
- **Methanol** is a very suitable base substance for transport fuels, but can also be used directly as fuel, e.g. in high efficiency ICE concepts.
- The **Methanol-to-Gasoline** process allows for the **efficient defossilisation of 2/3 of the existing vehicle fleet**, i.e. of SI-ICE passenger cars. The production of Diesel and Kerosene through Fischer-Tropsch-Synthesis requires a higher technical effort.
- Although the **investments** into the "new green world energy system" are humongous, they are very likely to **pay back in the mid term**. Politics need to set a reliable framework to enable these industrial engagements.
- On the basis of the actual electricity production cost for wind and PV it appears realistic, that the **future energy cost in a renewable energy system not necessarily need to be higher than today**. Pricing is dominantly a matter of desired profits and taxation, not of the product cost!
- All of the population(s) need to be included, needs to have the liberty to travel!
- Geopolitical implications and their repercussions on raw materials may obstruct progress. Smart industrial policy is needed to circumvent these challenges.
- **For the reduction of Green House Gas emissions the defossilisation of the existing fleet is imperative.**
  → For this, the introduction of refuels is necessary.