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JÜLICH FORSCHUNGSZENTRUM

Rolle chemischer Speicher für die Energiewende

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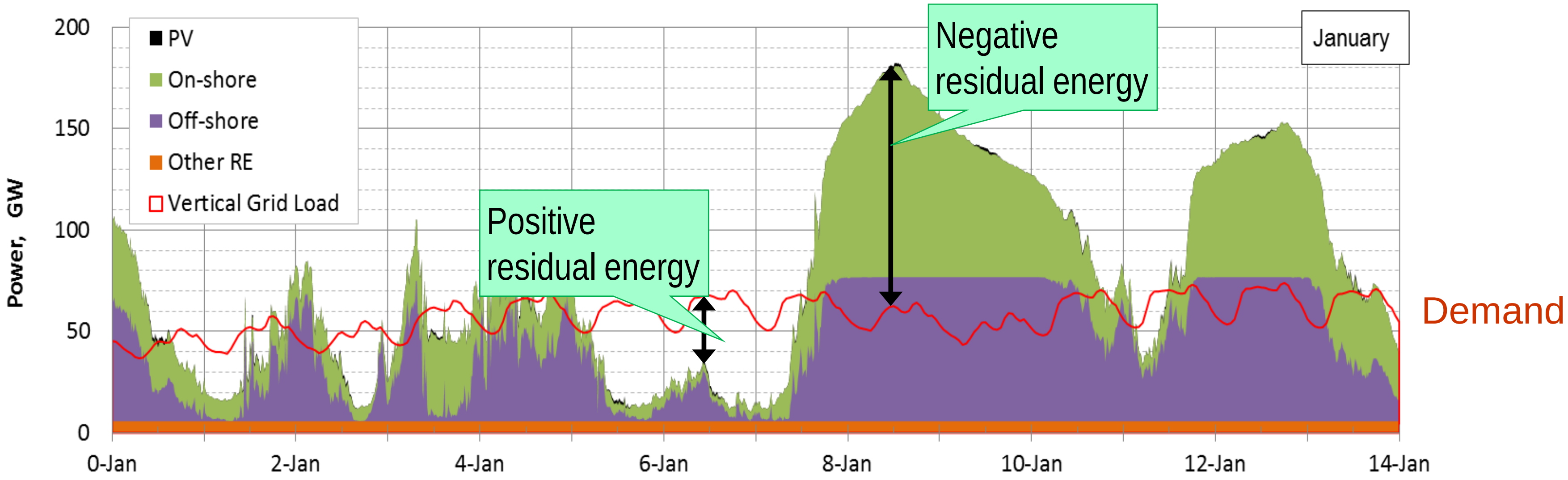
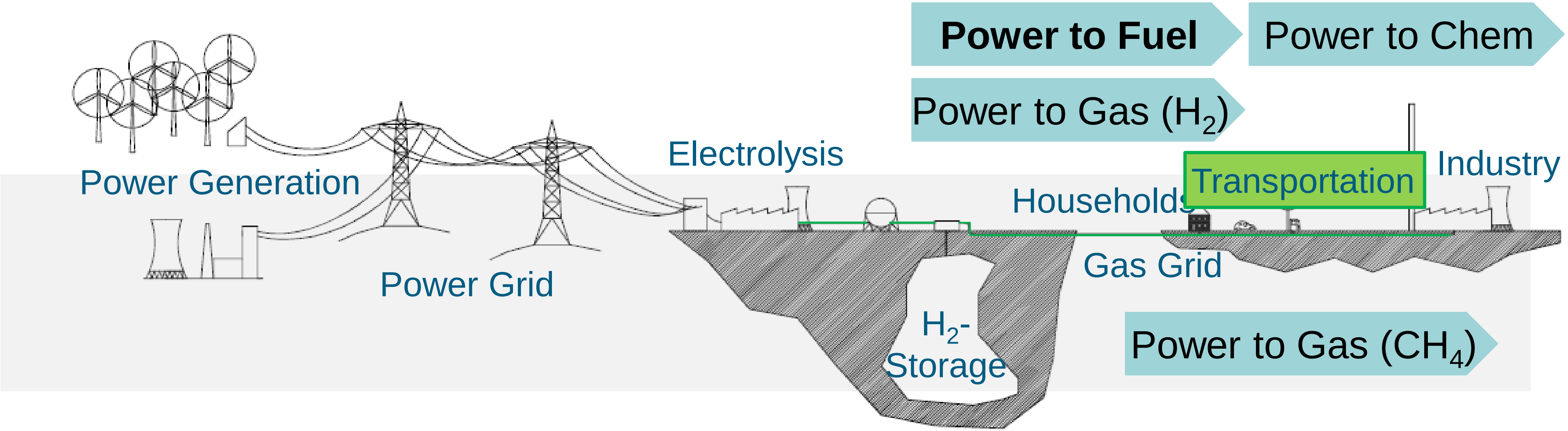
AKE Herbsttagung
Bad Honnef
19. Oktober 2017

Excess Power is Inherent to Renewable Power Generation





Power to Fuel

Power to Chem

Power to Gas (H_2)

Power to Gas (CH_4)

Overcapacity in Power is Inherent for Fully Renewable Energy Supply

renewable power needed = capacity factor x average power demand

- Averaged power demand for Germany: ~ 60GW (80 GW max)
- Capacity factor for full renewable power supply
  - Onshore wind → 4.4 based on 2,000 full load hrs
  - Offshore wind → 2.2 based on 4,000 full load hrs

@ no losses for reconversion considered

→ **Installed renewable power exceeds power demand on a regular basis**

→ Counteracting measures are

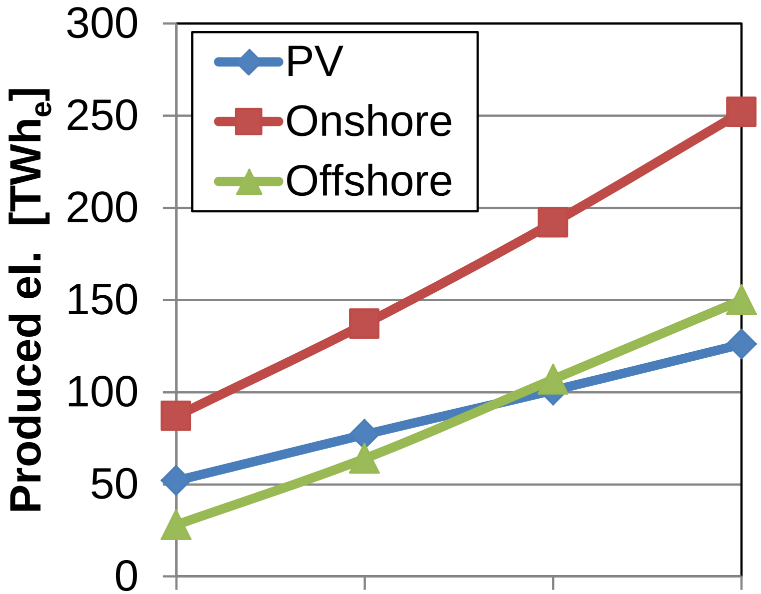
→ Curtailment

→ Interconnection of different climate zones

→ Introduction of new sinks

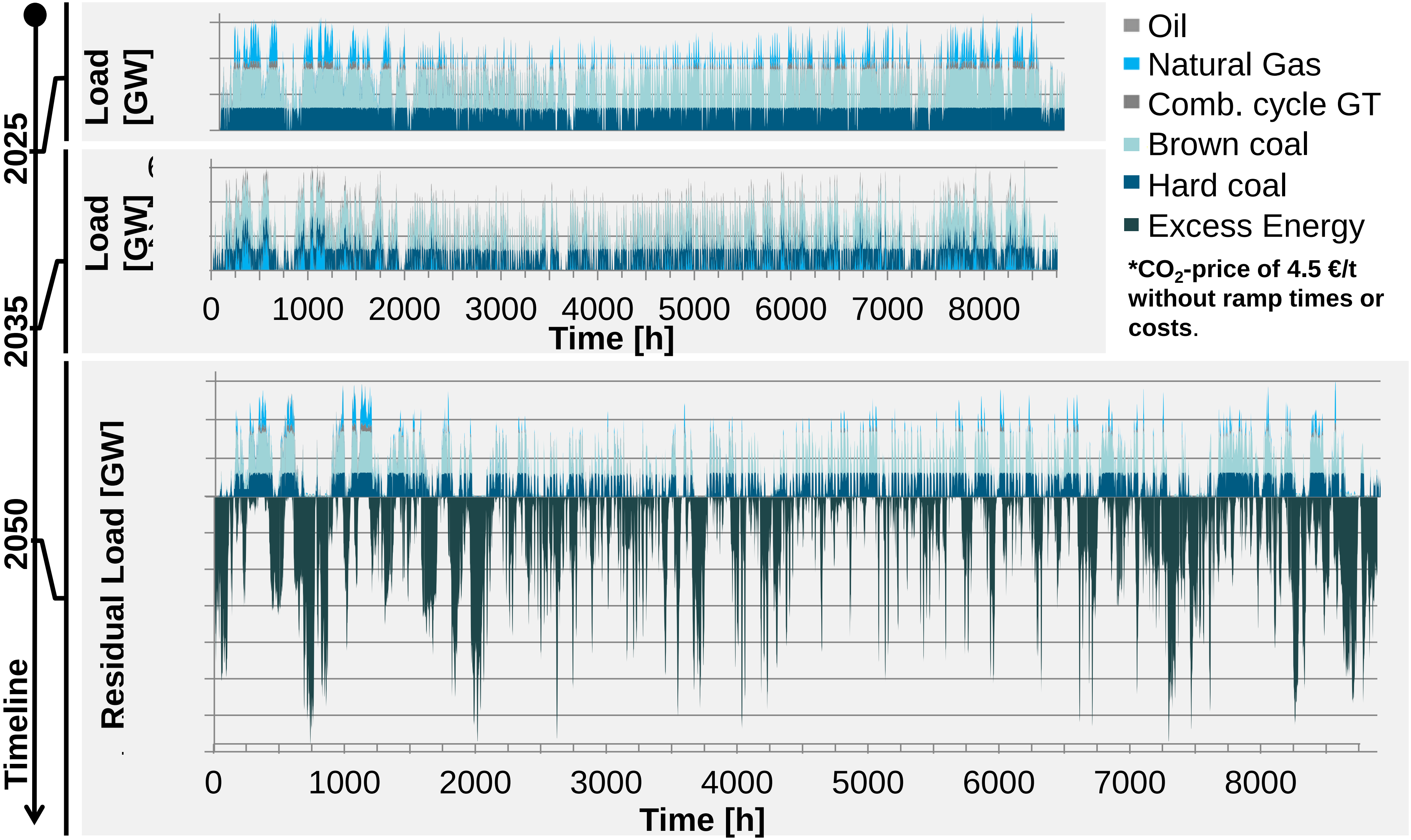
- Storage
  - Electrolysis
  - Power to heat
  - Mechanical sinks like hydropower, flywheels etc.
- Sector coupling
  - Transport (batteries, hydrogen, power-to-fuel)
  - Industry

Development of Renewables According to Current German Policy



		2020	**2030**	**2040**	**2050**
Peak excess power*	GW$_e$	22	55	90	125
Excess energy*	TWh$_e$	2,5	30	100	200
Minimum storage size**	TWh	0,9	6	12	17

Example of the Effect of an Increasing Share of Renewable Energy on the Residual Load based on Real Weather Data



***CO_2-price of 4.5 €/t without ramp times or costs**.

Installed capacity regarding to [1] Übertragungsnetzbetreiber (2015): Netzentwicklungsplan Strom 2025

[2] Bartels, S (2016): Simulationsmodell regional aufgelöster Residuallasten in Deutschland, Masterthesis

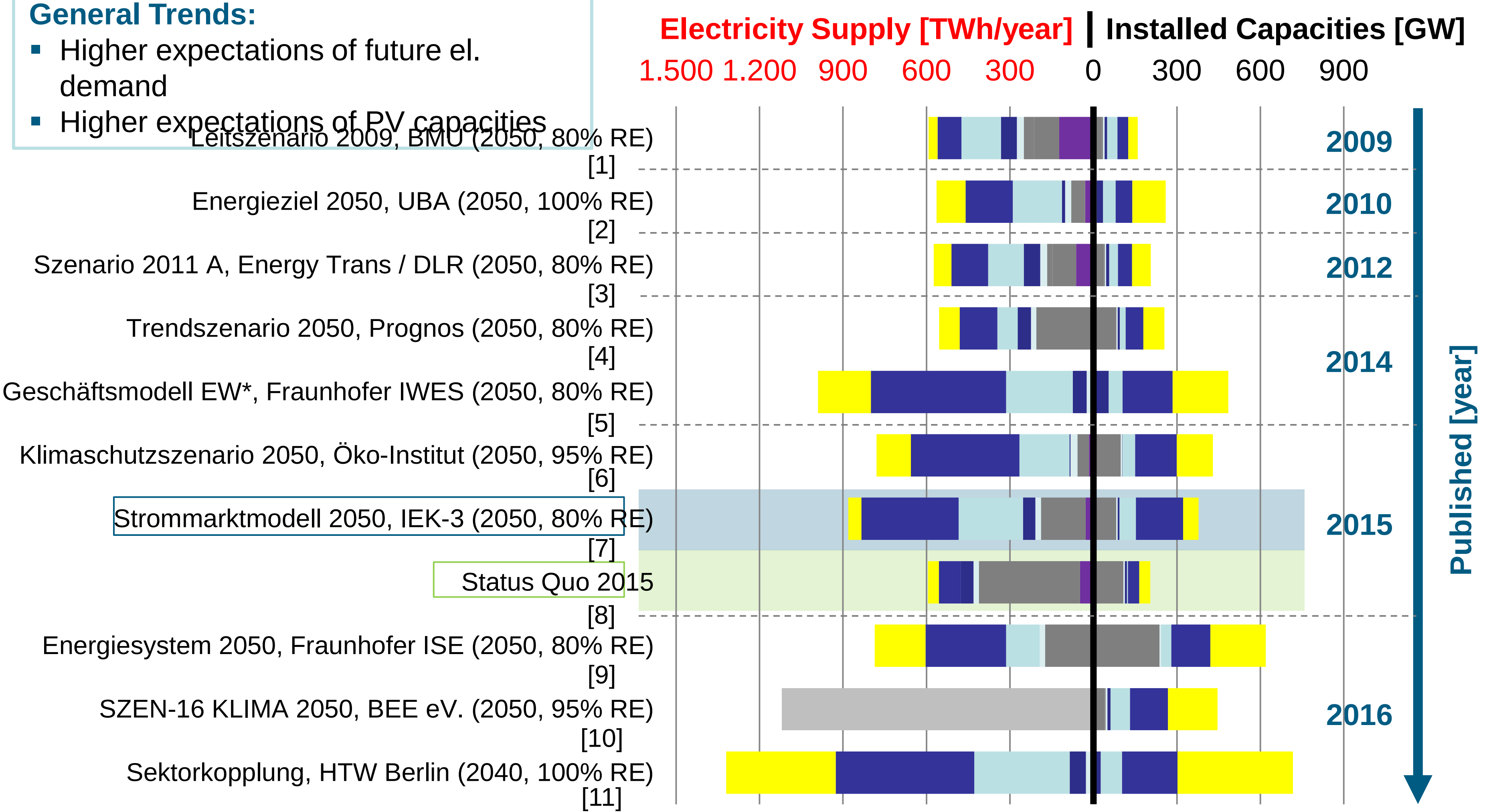
[3] Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.

Installed Capacities and Electricity Supply of German Energy Scenarios achieving ≥80% CO_2 Reduction across all Energy Sectors***

- ⬜ Sum
- ⬛ Others (FF**, Other RE, Storage Cap.)
- ⬜ Hydropower
- ⬜ Wind (Offshore)
- 🟪 Import
- ⬛ Geothermics
- 🟦 Bioenergy
- 🟦 Wind (Onshore)

General Trends:

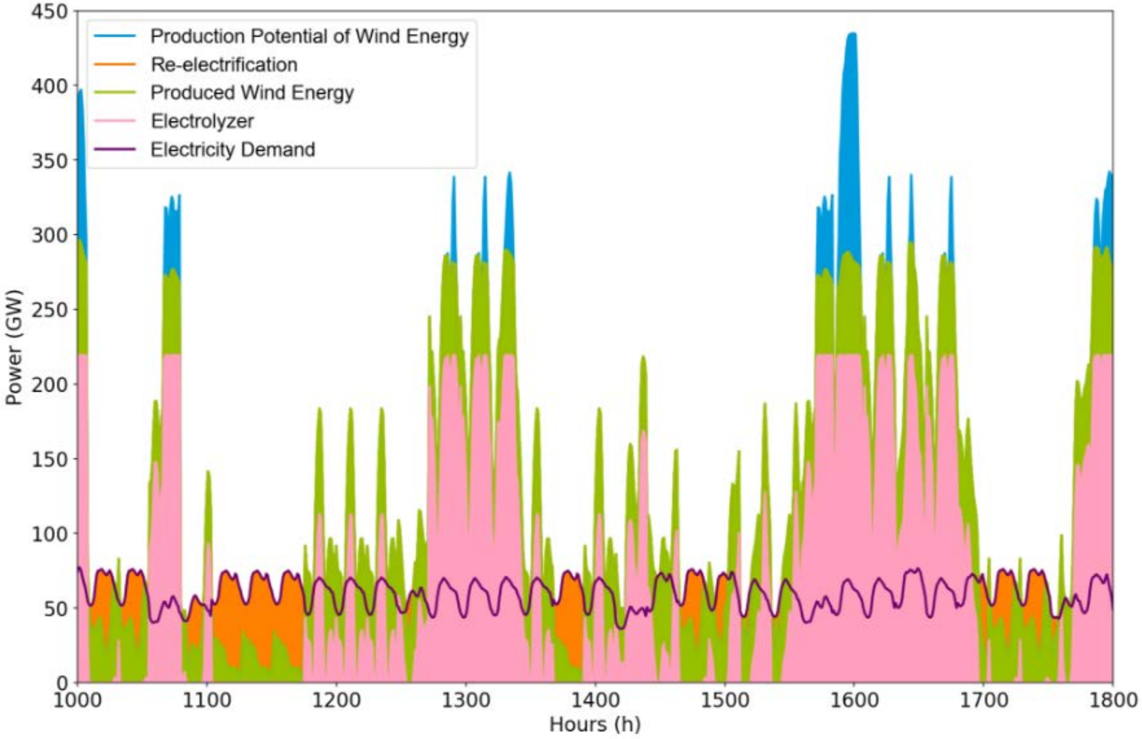
- Higher expectations of future el. demand
- Higher expectations of PV capacities



* Energiewende; ** Fossil Fuels; *** compared to 1990

Schematic of a Potential Renewable Energy System

- Potential of Wind Energy → Before curtailment
  - Maximum amount of energy that we can produce if we operate all wind turbines
- Produced Wind Energy → Actual amount of energy that is produced
  - Part of this energy is used to supply the electricity demand
  - Remaining is used in electrolyzer to produce hydrogen
- When the amount of produced wind energy is less than the demand → Re-electrification



Overcapacity in Power is Inherent for Full Renewable Energy Supply

$$\text{Capacity factor} = \frac{\textbf{energy harvested}}{\textbf{nameplate harvest}}$$

Average power demand for Germany: ~ 60 GW (based on **528 TWh** grid electricity)

	Capacity factor	**Necessary Power, if just one Technology is applied**	**Reasonable power mix DE 2050** (DE gov. Installation plans extrapolated)	**Reasonable electricity mix DE 2050**	**Electricity to be converted to H_2** (serving 75% of passenger vehicles in DE)
Offshore wind	0.46	120 GW	59 GW	236 TWh	
Onshore wind	0.23	230 GW	132 GW	267 TWh	
PV	0.12	460 GW	120 GW	126 TWh	
Total	--------	----------	311 GW	**629 TWh**	101 TWh (**2,1 mt H_2**)
Untimely produced electricity				≈ 200 TWh (to be stored)	
CO_2 cut Ø 80%				90% (10% power by NG)	54% of passenger cars

Issues of Integrating Renewables into the Power Grid

Just replacing the power production of fossils by renewables cannot work because

- Renewable energy is inherently subject to strong fluctuations
    - Day/night shifts
    - Weather
    - Seasons
- Renewable energy is more site dependent for its low energy density
    - Photovoltaics is very distributed
    - Offshore wind power will be much more centralized than conventional power plants

Drivers for Storing Intermittent Renewable Energy

Grid Stabilization

- Primary control (currently covered by inertia of power plant generators, seconds, minutes)
- Secondary control (on-demand power on a 15 minutes basis)
- Tertiary control (purchase of traded power on the markets)
- Cost reduction

Utilization of Renewable Power

- Low energy density → spatial restrictions
- Reduction of curtailment
- Seasonal levelling of renewable energy input
- Optimization criterion is overall cost reduction

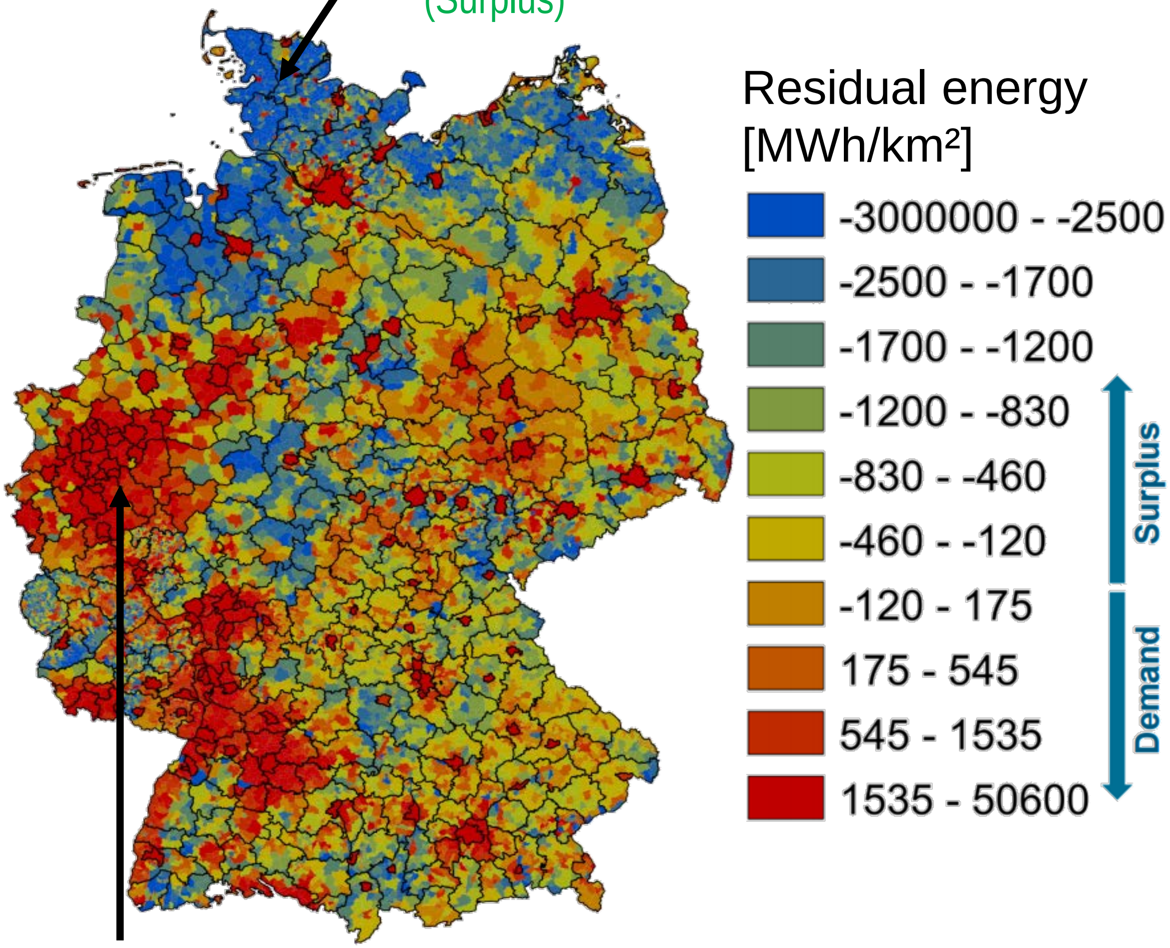
Disjunction of Power and Energy – Economic Aspects

1. Power and energy scales together
    - E.g.: batteries, super capacitors, fly-wheels etc.
    - Installation size direcly translates into power and energy
    - Costs to he most extent scale linearly installation size
    - Energy scales with expensive components like battery chemistry
    - E.g.: Storage w/ battery costs 12 ct/kWh @ 365 cycles, 44 ct/kWh @ 100 cycles

2. Power scales less than energy: saves cost for long-term storage
    - Electrolyzer (expensive) controls power, gas cavern (cheap) controls energy
    - Pumped hydro power plants (turbine vs. lake)
    - Compressed air storage (turbine, heat storage if applicable vs. Ga cavern)
    - Decoupled markets like transportation gets accessible

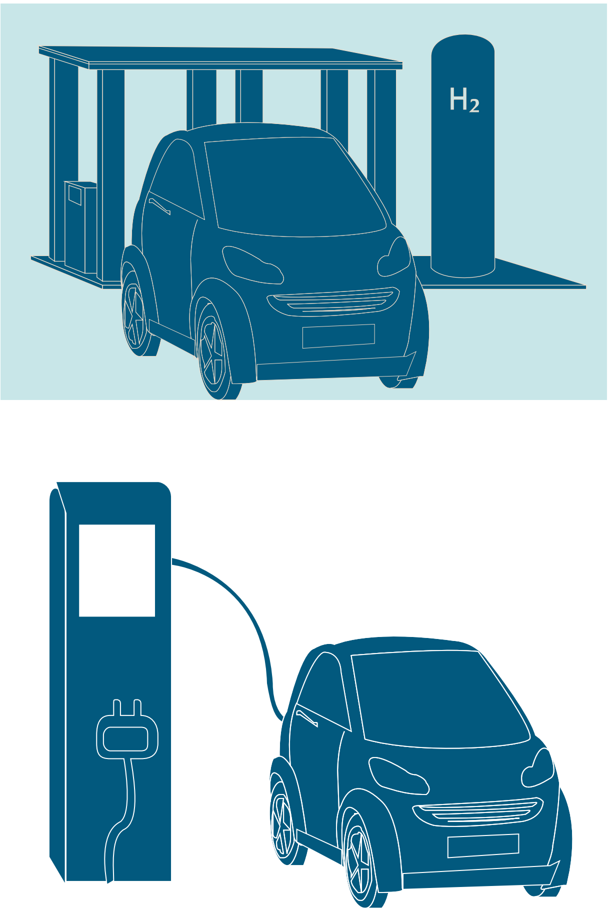
3. Power scales more than energy
    - Technology from 2. can deliver
    - Economic grounds questionable

Linking the Power and the Transport Sector



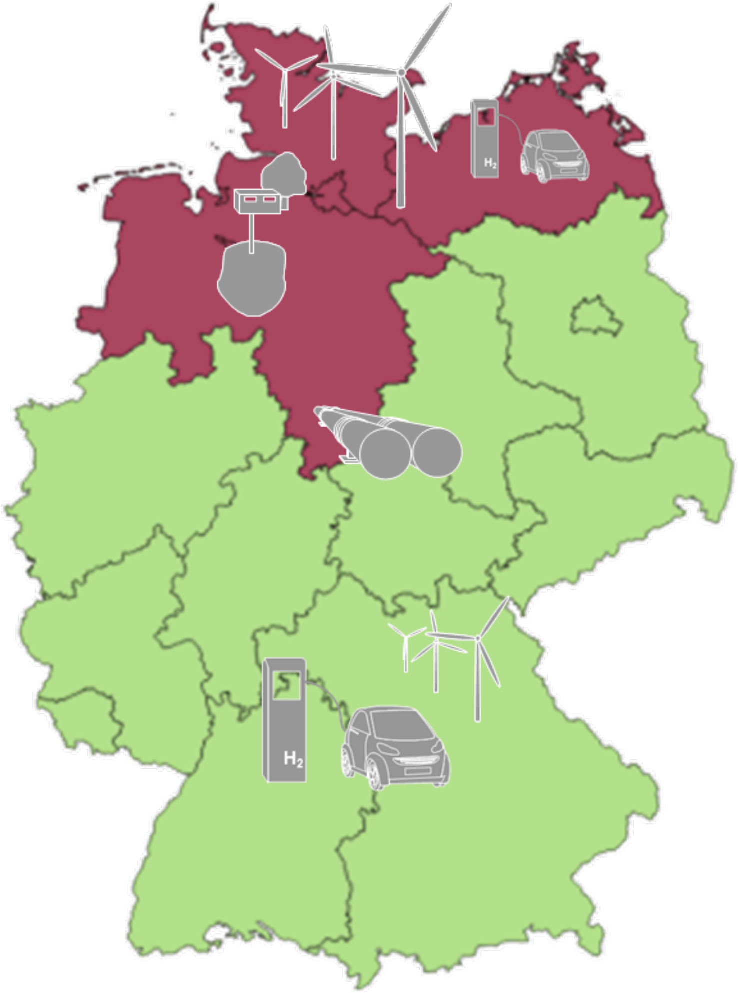
Negative residual energy (Surplus)

Positive residual energy



Simple Model to Illustrate the Impact of Cost Considerations

		Base Case	**The Value of Transport**
Energy transport		Pipeline	Not connected
North	Onshore wind	49.9 GW	8.1 GW
	Inst. electrolyzers	40.8 GW	7.3 GW
	Storage capacity (UGS)	8.8 TWh	1.6 TWh
South	Onshore wind	0 GW	75.8 GW
	Inst. electrolyzers	0 GW	34.9 GW
	Storage capacity (Large vessel)	0.3 TWh	12.3 TWh
Total annual cost (TAC)		**TAC_{bc}**	**199% of TAC_{bc}**



Decouple Power and Energy for Long-term Storage

Assumption: storage may add about the same price tag to the energy delivered, be it

- Short-term storage, or
- Long-term storage

	Storage cycles / a [1/a]	Relative allowable invest / kWh* [%]	Energy required [GWh]	Energy specific investment cost [€ / kWh]	Power required [GW]	Additional cost for conversion units (electrolyzer) [€/kW]
Short-term	100 - 1000	100%	some GWh	Batteries 100-200	some 10GW	none
Long-term	1 - 10	1%	some 1000 GWh	Salt cavern << 1 (approx. 0.25)	some 10GW	500 €/kW

Disjunction of Power and Energy

Batteries : Power and energy scale linearly with unit size

Hydrogen: **Power** scales less than **energy for loading; quick unloading feasible**

↓ **Electrolyzers**

↓ **Gas caverns**

Disjunction of Power and Energy – Economic Aspects

1. **Power and energy scale linearly with unit size**
   - E.g.: batteries, super capacitors, fly-wheels etc.
   - Installation size directly translates into power and energy
   - Costs to he most extent scale linearly installation size
   - Energy scales with expensive components like battery chemistry
   - E.g.: Storage w/ battery costs 12 ct/kWh @ 365 cycles, 44 ct/kWh @ 100 cycles

2. **Power scales less than energy: allows for cheap storage** (e.g. rock salt caverns)
   - Electrolyzer (expensive) controls power, gas cavern (cheap) controls energy
   - Pumped hydro power plants (turbine vs. lake)
   - Compressed air storage (turbine, heat storage if applicable vs. gas cavern)
   - Time-wise decoupled markets like transportation get accessible
   - Improved economics for seasonal storage

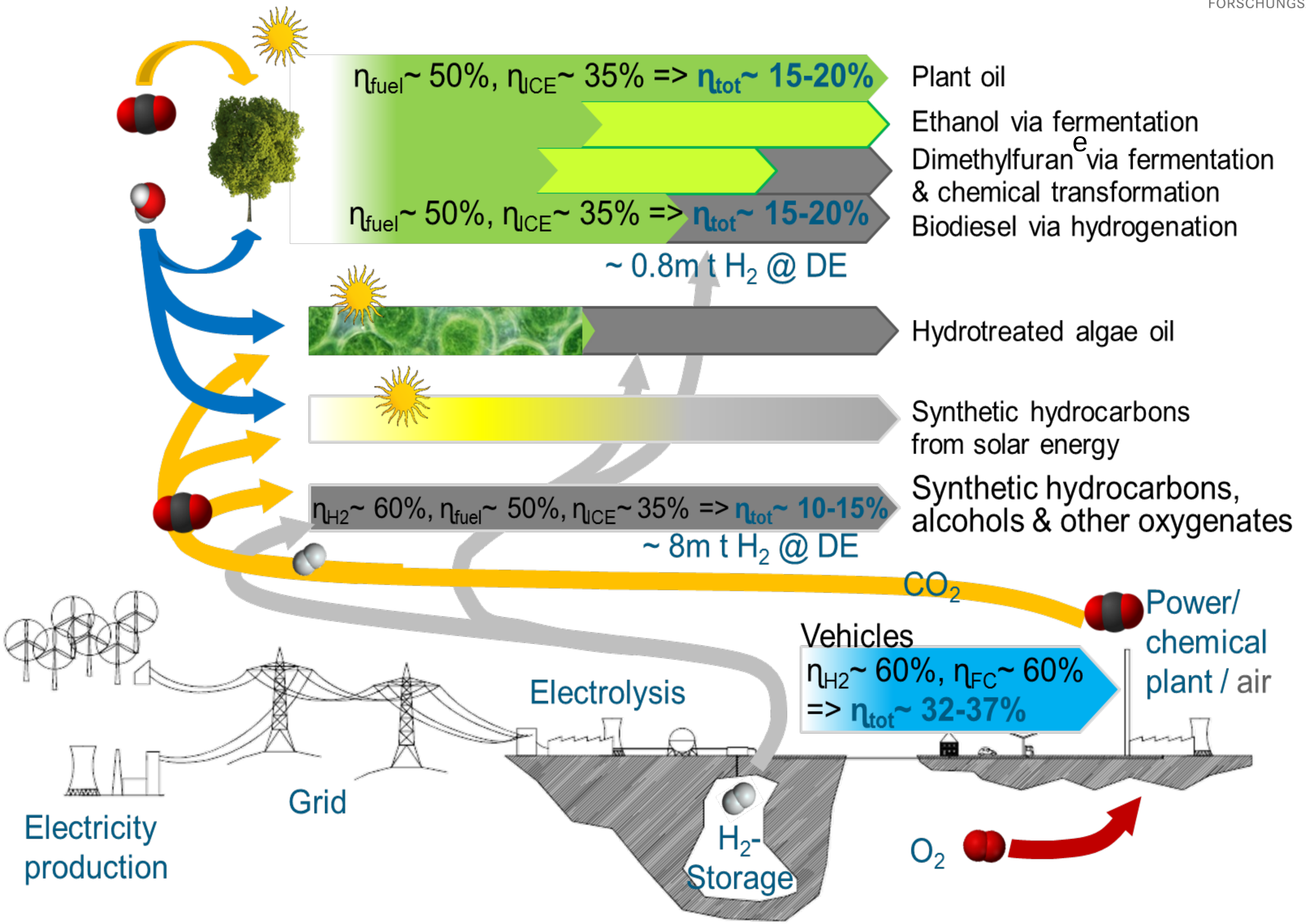
3. Power scales more than energy
   - Technology from 2. can deliver
   - Economic grounds questionable

Storage Densities

Medium		Storage Density
Electricity storage		0,3 -0,9 MJ/l
Mechanical storage		0,001 – 0,01 Pumped hydro; compr. Air)
Gas storage (Electrolysis + storage)		0,9 – 3,7 H_2 – CH_4/Δ100bar
Liquid storage		approx. 40 MJ/kg gasoline: 32 MJ/l

* @ comparable specific cost

Power to Fuel: Option or Necessity for Heavy Transportation?



η_{fuel}~ 50%, η_{ICE}~ 35% => η_{tot}~ 15-20%

Plant oil

Ethanol via fermentation

Dimethylfurane via fermentation
& chemical transformation

η_{fuel}~ 50%, η_{ICE}~ 35% => η_{tot}~ 15-20%

Biodiesel via hydrogenation

~ 0.8m t H_2 @ DE

Hydrotreated algae oil

Synthetic hydrocarbons
from solar energy

η_{H2}~ 60%, η_{fuel}~ 50%, η_{ICE}~ 35% => η_{tot}~ 10-15%

Synthetic hydrocarbons,
alcohols & other oxygenates

~ 8m t H_2 @ DE

CO_2

Power/
chemical
plant / air

Vehicles

η_{H2}~ 60%, η_{FC}~ 60%
=> η_{tot}~ 32-37%

Electrolysis

Grid

Electricity
production

H_2-
Storage

O_2

Passenger car-based transport in 2050

Battery vehicle (renewable electricity)

Efficiency:	80 % x 85 % = 68 % (WTT) (TTW)
Vehicle cost:	⊖⊖
Fuel production:	⊕
Storage & distrib.:	⊖⊖⊖
Operating range:	low
Resources:	sufficient
Soot/NOx emissions:	none

Fuel cell vehicle (renewable electricity)

Efficiency:	63 % x 60 % = 38 % (WTT) (TTW)
Vehicle cost:	⊖⊖
Fuel production:	⊖
Storage & distrib.:	⊖⊖
Operating range:	medium
Resources:	sufficient
Soot/NOx emissions:	none

Combustion engine (CO$_2$-based fuels)

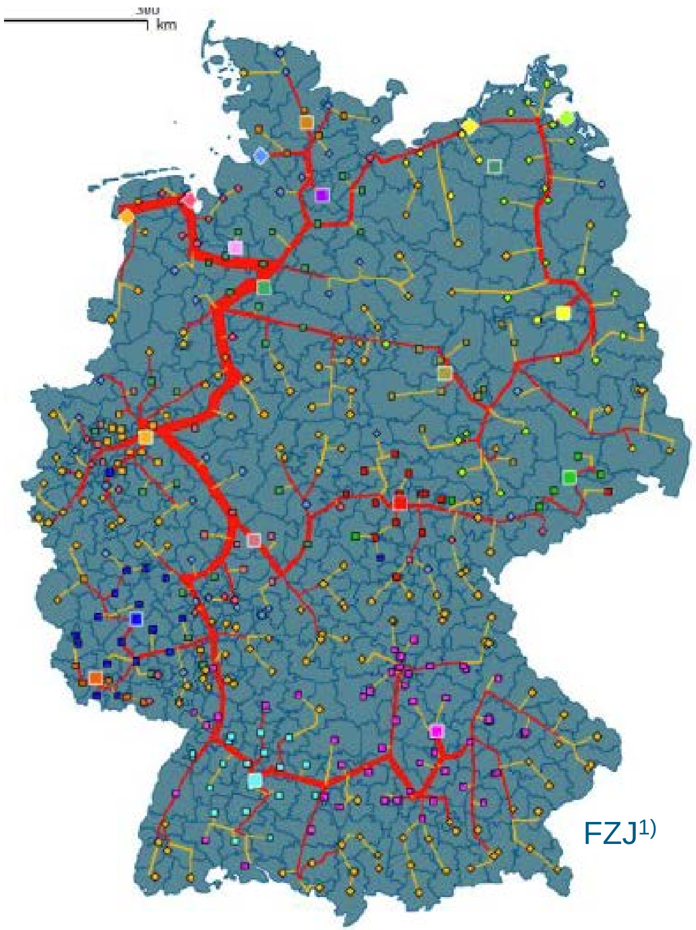
Efficiency:	70 % x 50 % x 25 % = 9 % (H$_2$) (plant) (TTW)
Vehicle cost:	⊖
Fuel production:	⊖⊖
Storage & distrib.:	⊕
Operating range:	high
Resources:	sufficient
Soot/NOx emissions:	medium

Combustion engine (bio-fuels)

Efficiency:	50 % x 25 % = 13 % (WTT) (TTW)
Vehicle cost:	⊖
Fuel production:	⊖⊖
Storage & distrib.:	⊕
Operating range:	high
Resources:	limited
Soot/NOx emissions:	medium

TTW: Tank-to-wheel
WTT: Well-to-tank

Hydrogen Pipeline Network designed for Fueling Stations



FZJ[1)]

Data of designed H_2 pipeline network

	Length / km	Cost / billion €
Transmission Pipeline	12,000	6 - 7
Distribution Pipeline	31,000 – 47,000	13 - 19

5.4 mn tons/a hydrogen result from by renewable power input

9800 fueling stations @1500 kg H_2/d result from hydrogen input

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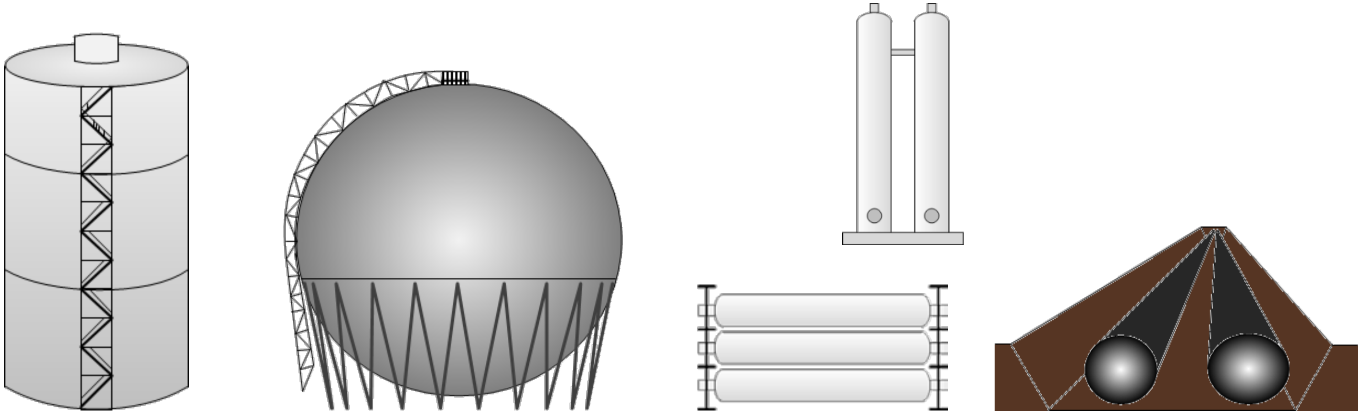
1) Baufume, Grube, Krieg, Linssen, Weber, Hake, Stolten (2012) 12. Symp. Energieinnovation, Graz, 15-17.3. (values adapted here to larger total amount of H_2)
2) incl. compressors for compensation of pressure losses

Geologic Gas Storage Facilities

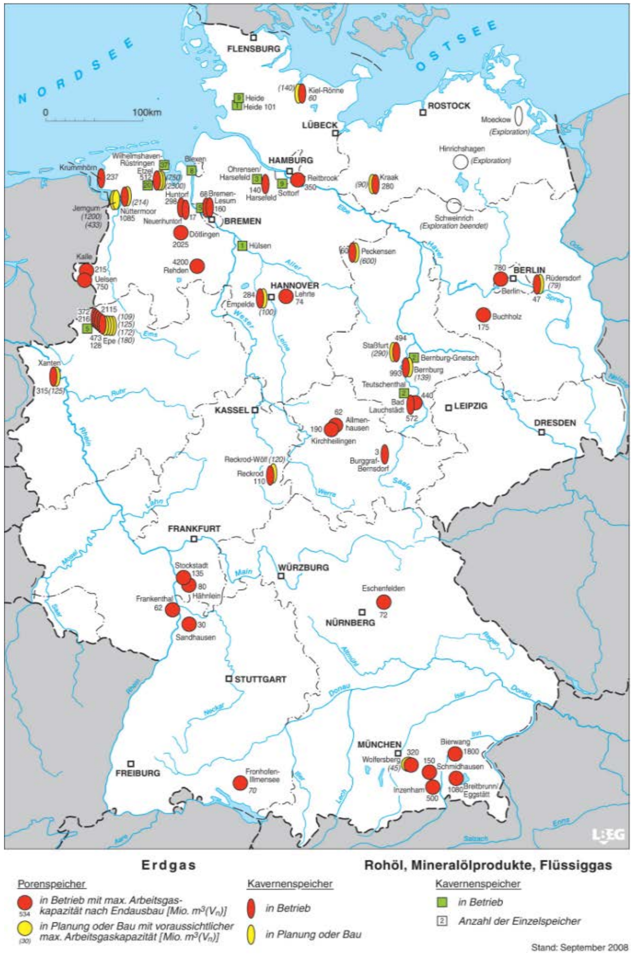
	Depleted oil / gas fields	**Aquifers**	**Salt caverns**	**Rock caverns / abandoned mines**
Working volume [scm]	10^{10}	10^{8}	10^{7}	10^{6}
Cushion gas	50 %	up to 80 %	20 - 30 %	20 - 30 %
Gas quality	reaction and **contamination** with present gases, microorganism and minerals		saturation with water vapor	
Annual cycling cap.	only seasonal		seasonal & frequent	

Near-Surface Gas Storage Facilities

	Gas holders	Spherical gas vessels	Ground storage assemblies	Pipe storage facilities
Maximum pressure [bar]	1.01 - 1.5	5 - 20	40 - 1000	20 - 100
Storage capacity [scm]	$< 6 \times 10^4$	$< 3 \times 10^5$	$< 1 \times 10^4$	$< 9 \times 10^5$
Invest/ storage capacity ‡ [€/scm]	?	20 - 50	50 - 180	20 - 50



Infrastructure: Electrolysis & Large Scale Storage



Estimated seasonal storage capacity	**27 TWh$_{LHV}$**
Storage capacity 60 day reserve	**90 TWh**
Storage capacity until 2040	**40 TWh**

regularly over weeks and months;

DB research, Josef Auer, January 31, 2012

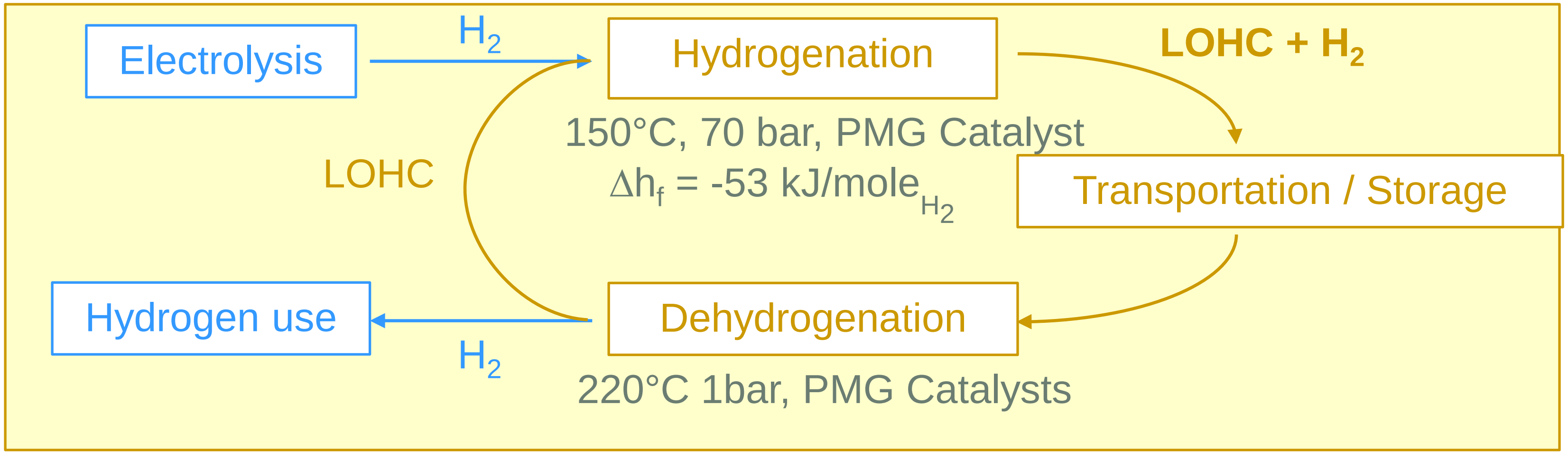
(Pumped Hydro Power in Germany:	*0.04 TWh$_e$)*

Seasonal storage capacity required:	9 bn scm
Existing NG-storage in Germany :	20.8 bn scm
thereof salt dome caverns in use:	8.1 bn scm
Salt cavern in construction/planned :	12.9 bn scm

Source: Sedlacek, R: Untertage-Gasspeicherung in Deutschland;
Erdöl, Erdgas, Kohle 125, Nr.11, 2009, S.412–426.

Liquid Organic Hydrogen Carriers (LOHC)

- Liquid, heterocyclic, aromatic hydrocarbon as carriers
  - Hydrogenation: saturation of aromatic rings with hydrogen
- **Chemicals:** N-ethylcarbazole, toluene and other aromatics
- Degradation by formation of unintended by-products



- Hydrogen storage density: 6 - 8 wt% [1,2]
- Transportation cost ≈ 0.2 €/kg$_{H_2}$ via ship (5000 km) [3]
- Japan seeks produce H_2 in Patagonia and transport it home (distance ≈ 20,000 km)

Power Line and Gas Pipelines Compared

	380 kV overhead line	**Natural gas pipeline §**	**Hydrogen gas pipeline**
Type	4 x 564/72 double circuit	DN 1000 p_{in} = 90 bar	
Energy transport capacity	1.2 GW_{el}	16 GW_{th}	12 GW_{th}
Investment cost in M€/km	1 - 1.5	1 - 2	1.2 - 3

Spatial Requirements for Transmission

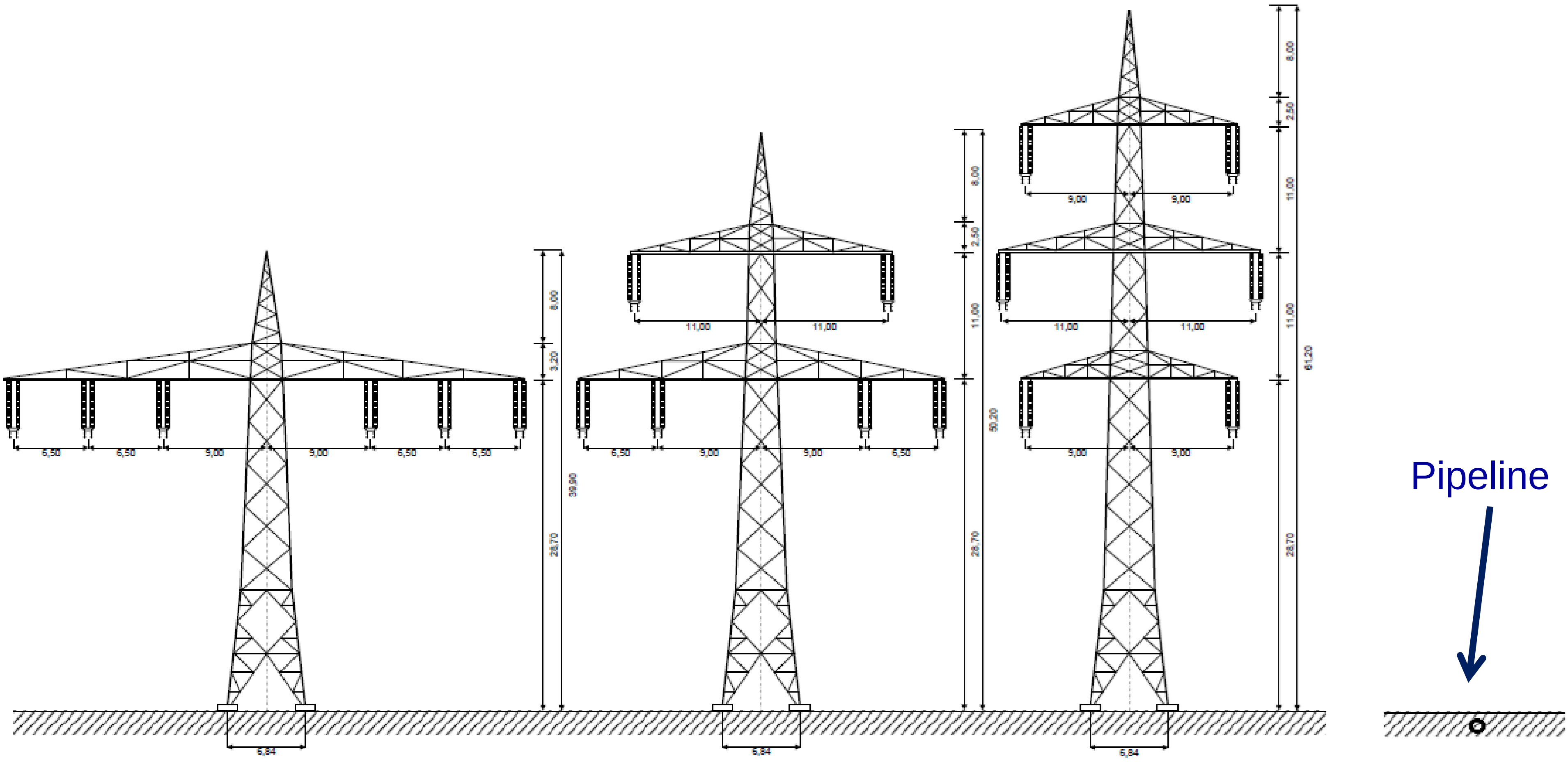
Width of protective strips

70 m

57 m

48 m

10 m



Picture of power poles from Hofman: Technologien zur Stromübertragung, IEH,
http://nvonb.bundesnetzagentur.de/netzausbau/Vortrag_Hofmann.pdf

Hydrogen can be Efficiently Transported and Effectively Stored

Transport of energy

	Energy demand
Gaseous hydrogen transport	3% / 1000 km (distributed input-/output)
High voltage DC-DC power line	3% / 1000 km, conversion 4-6%; (point-to-point only)
Conventional AC power line	9% / 1000 km @ 400 kV; Source EoN
	5% / 1000 km @ 765 kV; Source EoN

Storage of energy

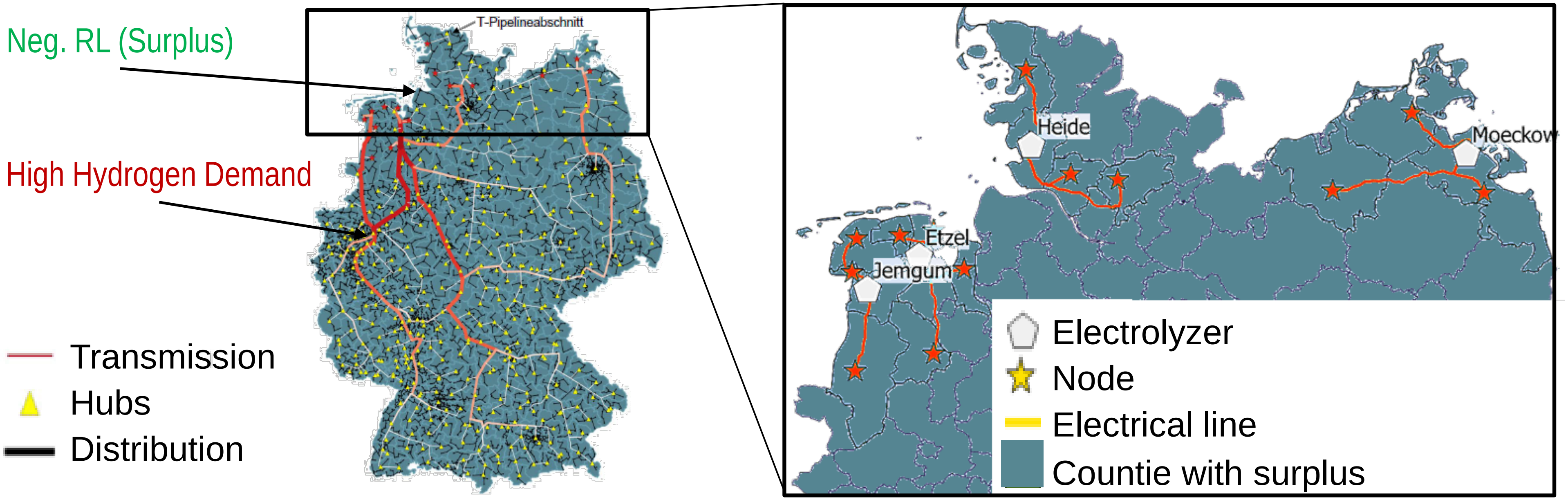
Hydrogen	Caverns, no-self discharge; short- & long-term storage
Electrical energy	Batteries, effective for short-term storage

Energy Concept 2.0

Assessment based on county level

Results

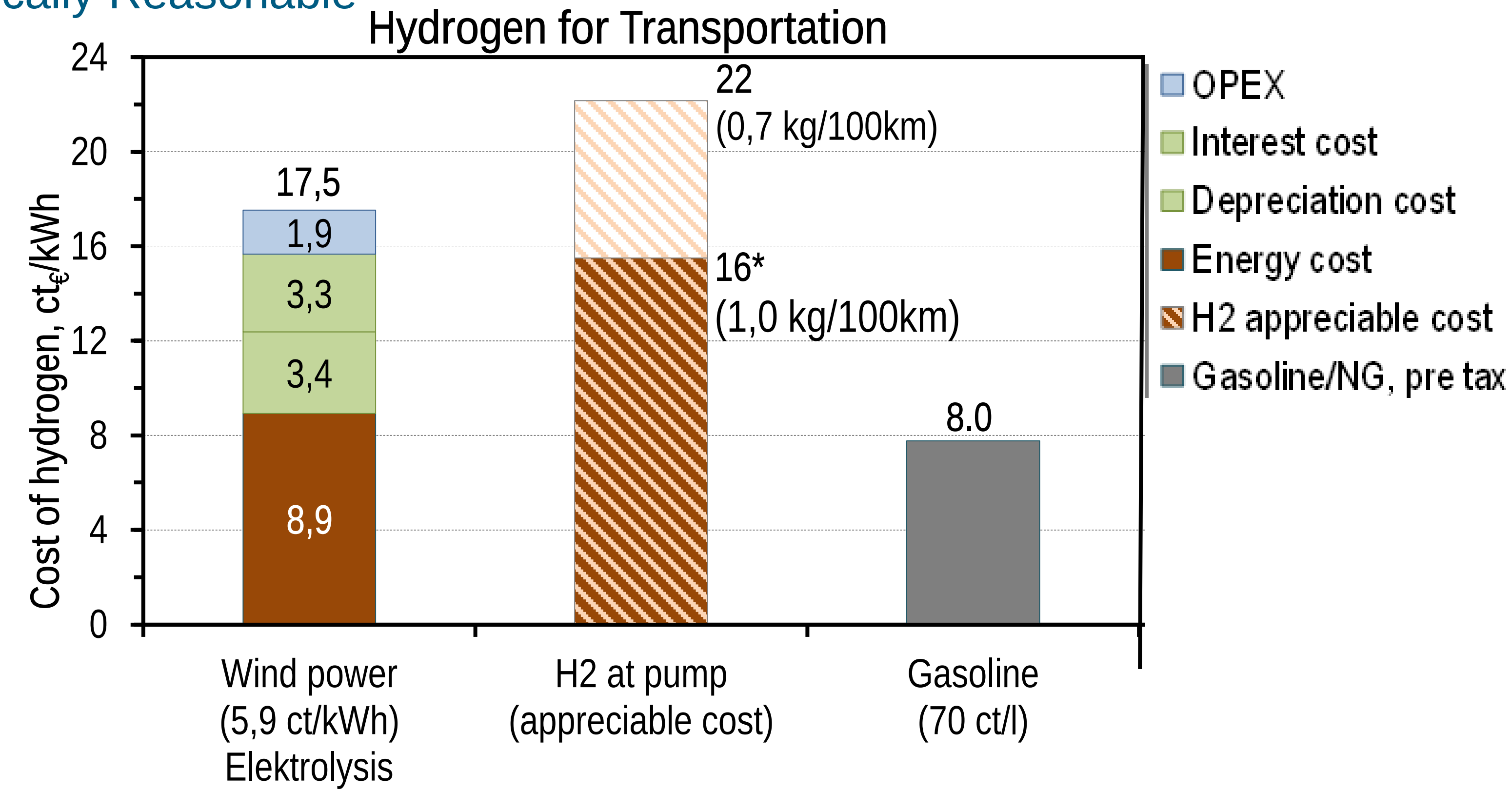
H_2 sources:	28 GW electrolysis power in 15 districts in Northern Germany, **15 billion €**
H_2 sinks:	**9,968 refueling stations** with averaged sales of 803 kg/d, **20 billion €**
H_2 storage:	48 TWh (incl. 60 day reserve), **8 billion €**
Pipeline invest [3]:	**6.7 billion €** (12,104 km transmission grid); **12 billion €** (29,671 km distribution grid)
Electricity cost:	LCOE Onshore: **5.8 ct/kWh**;
Total H_2 cost (pre-tax):	17.5 ct/kWh WACC: 8 %



All values after Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation RWTH Aachen University, ISBN: 978-3-95806-110-1; except: [3] Krieg, D. (2012), Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Forschungszentrum Jülich IEK-3

Cost Comparison of Power to Gas Options – **Pre-tax**

Hydrogen for Transportation with a Dedicated Hydrogen Infrastructure is Economically Reasonable



CAPEX via depreciation of investment plus interest

- 10 a for electrolysers and other production devices
- 40 a for transmission grid
- 20 a for distribution grid and refueling stations
- Interest rate 8.0 % p.a.

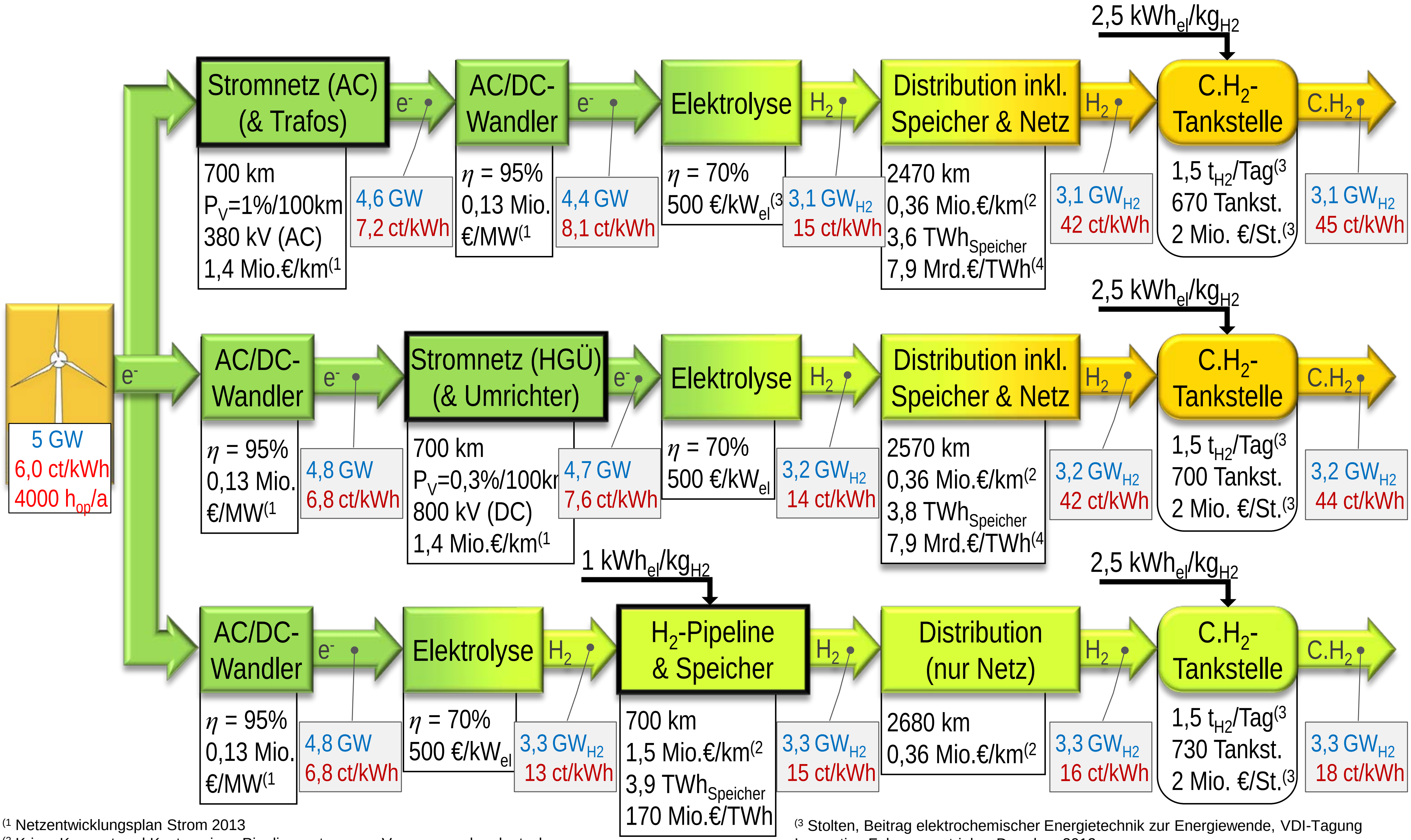
Other Assumptions:

- 2.9 million t_{H2}/a from renewable power via electrolysis
- **Electrolysis: η = 70 %**$_{LHV}$, 28 GW; investment cost 500 €/kW
- **Methanation: η = 80 %**$_{LHV}$

- Appreciable cost @ half the specific fuel consumption

[1] Energy Concept 2.0

Vergleich Transportoptionen am Beispiel Nord-Süd



5 GW
6,0 ct/kWh
4000 h_{op}/a

e^-

Stromnetz (AC) (& Trafos)
700 km
P_V=1%/100km
380 kV (AC)
1,4 Mio.€/km[1]

e^-
4,6 GW
7,2 ct/kWh

AC/DC-Wandler
η = 95%
0,13 Mio. €/MW[1]

e^-
4,4 GW
8,1 ct/kWh

Elektrolyse
η = 70%
500 €/kW_{el}[3]

H_2
3,1 GW_{H2}
15 ct/kWh

Distribution inkl. Speicher & Netz
2470 km
0,36 Mio.€/km[2]
3,6 $TWh_{Speicher}$
7,9 Mrd.€/TWh[4]

H_2
3,1 GW_{H2}
42 ct/kWh

2,5 kWh_{el}/kg_{H2}

C.H_2-Tankstelle
1,5 t_{H2}/Tag[3]
670 Tankst.
2 Mio. €/St.[3]

C.H_2
3,1 GW_{H2}
45 ct/kWh

AC/DC-Wandler
η = 95%
0,13 Mio. €/MW[1]

e^-
4,8 GW
6,8 ct/kWh

Stromnetz (HGÜ) (& Umrichter)
700 km
P_V=0,3%/100kr
800 kV (DC)
1,4 Mio.€/km[1]

e^-
4,7 GW
7,6 ct/kWh

Elektrolyse
η = 70%
500 €/kW_{el}

H_2
3,2 GW_{H2}
14 ct/kWh

Distribution inkl. Speicher & Netz
2570 km
0,36 Mio.€/km[2]
3,8 $TWh_{Speicher}$
7,9 Mrd.€/TWh[4]

H_2
3,2 GW_{H2}
42 ct/kWh

2,5 kWh_{el}/kg_{H2}

C.H_2-Tankstelle
1,5 t_{H2}/Tag[3]
700 Tankst.
2 Mio. €/St.[3]

C.H_2
3,2 GW_{H2}
44 ct/kWh

AC/DC-Wandler
η = 95%
0,13 Mio. €/MW[1]

e^-
4,8 GW
6,8 ct/kWh

Elektrolyse
η = 70%
500 €/kW_{el}

H_2
3,3 GW_{H2}
13 ct/kWh

1 kWh_{el}/kg_{H2}

H_2-Pipeline & Speicher
700 km
1,5 Mio.€/km[2]
3,9 $TWh_{Speicher}$
170 Mio.€/TWh

H_2
3,3 GW_{H2}
15 ct/kWh

Distribution (nur Netz)
2680 km
0,36 Mio.€/km[2]

H_2
3,3 GW_{H2}
16 ct/kWh

2,5 kWh_{el}/kg_{H2}

C.H_2-Tankstelle
1,5 t_{H2}/Tag[3]
730 Tankst.
2 Mio. €/St.[3]

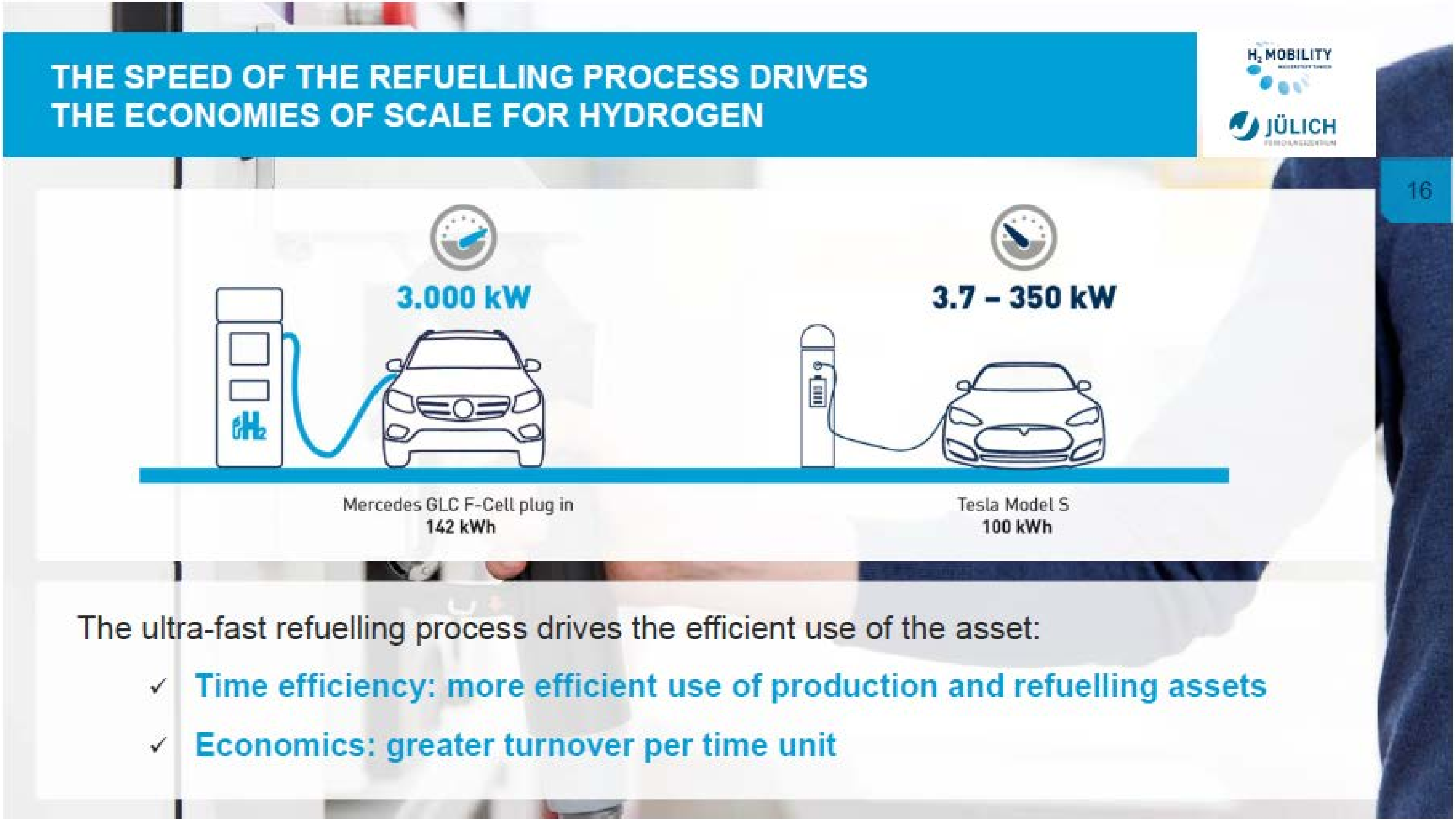
C.H_2
3,3 GW_{H2}
18 ct/kWh

[1] Netzentwicklungsplan Strom 2013

[2] Krieg, Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff, 2012

[3] Stolten, Beitrag elektrochemischer Energietechnik zur Energiewende, VDI-Tagung Innovative Fahrzeugantriebe, Dresden, 2012

[4] Tietze, Near-Surface Bulk Storage of Hydrogen, in: Transition to Renewable Energy Systems, 2013



THE SPEED OF THE REFUELLING PROCESS DRIVES THE ECONOMIES OF SCALE FOR HYDROGEN

3.000 kW

Mercedes GLC F-Cell plug in
142 kWh

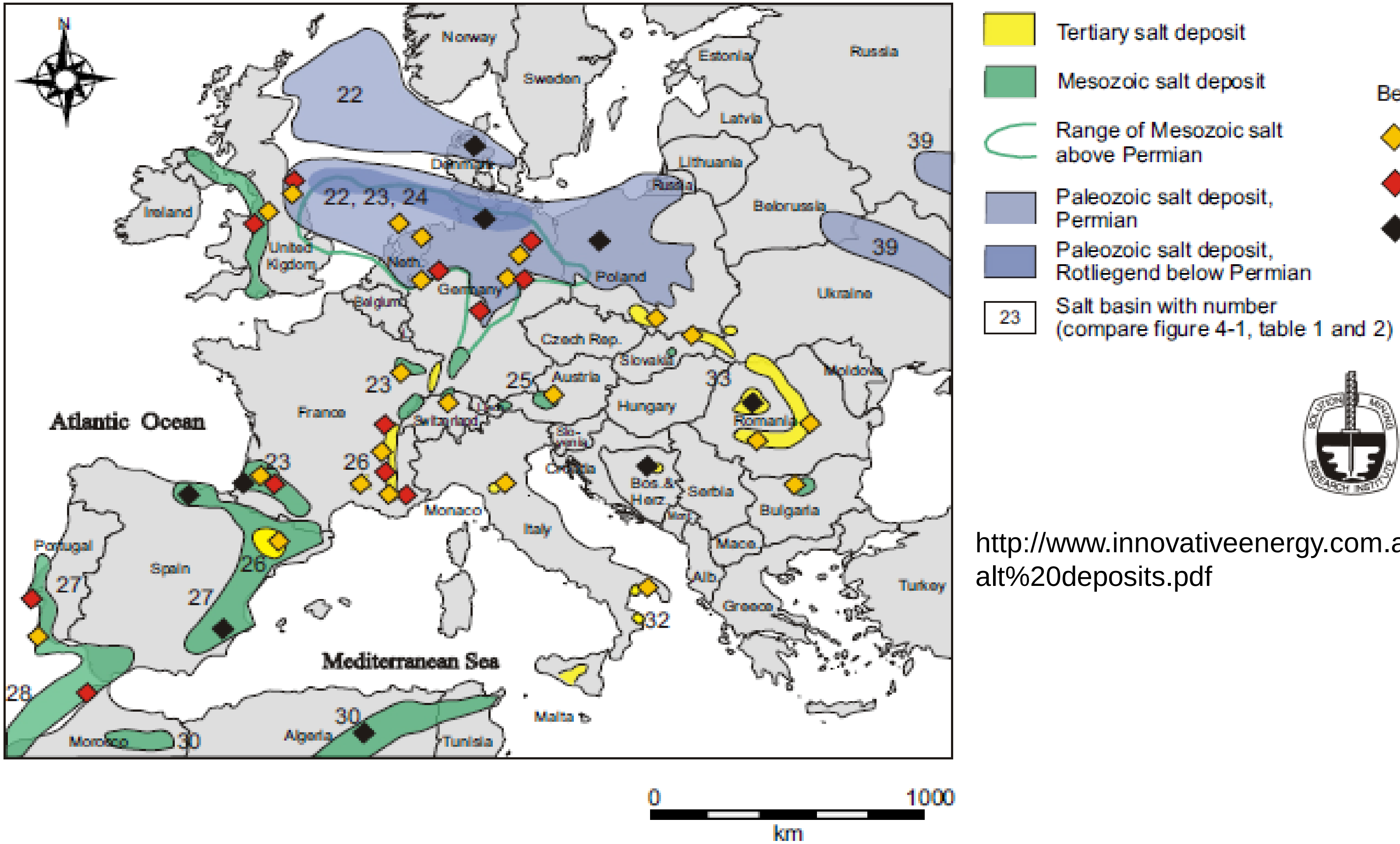
3.7 – 350 kW

Tesla Model S
100 kWh

The ultra-fast refuelling process drives the efficient use of the asset:

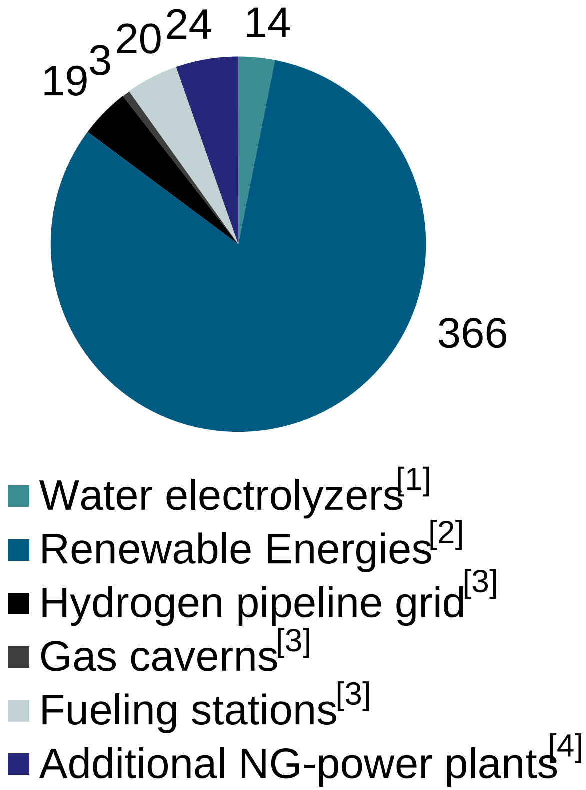
- ✓ Time efficiency: more efficient use of production and refuelling assets
- ✓ Economics: greater turnover per time unit

Salt Deposits in Europe



http://www.innovativeenergy.com.au/saltcavern/world%20salt%20deposits.pdf

Infrastructure Analysis (simplified)

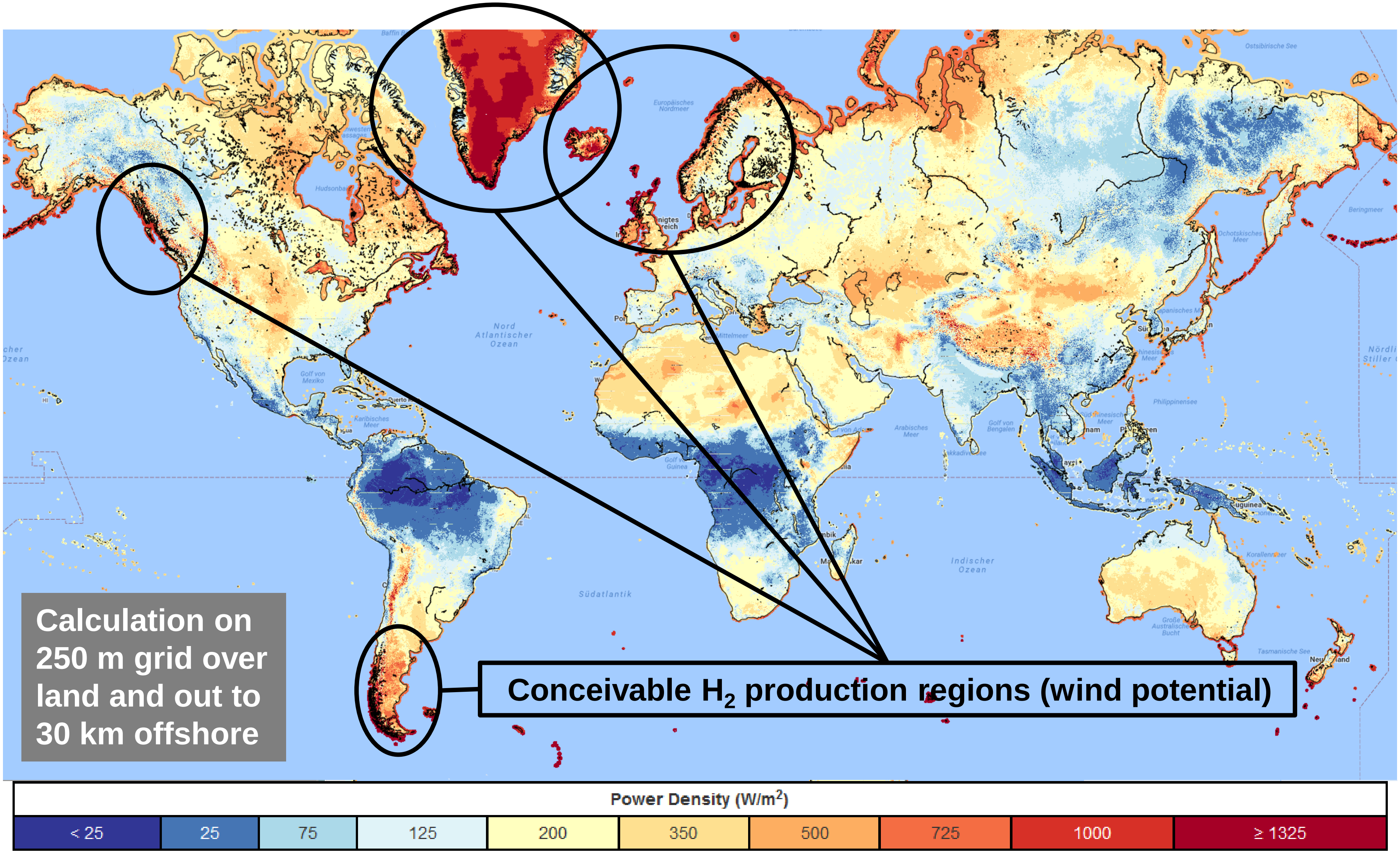


Infrastructure of Energy Concept 2.0
Cost Aanalysis [Bn €]

[1] Electrolyzer @ 500 €/kW

[2] PV @ 1000 €/kW; wind onshore @ 1400 €/kW; offshore @ 3000/kW; Installed capacities after **[3]** Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation RWTH Aachen **[4]** 42 GW GT + comb. Cycles, 23 GW already in place **[5]** Zeitreihen zur Entwicklung Erneuerbarer Energien, BMWi, August 2016 [6] Netzentwicklungsplan NEP 2025 BNA

Global wind power density (aggregated mean 100m height)

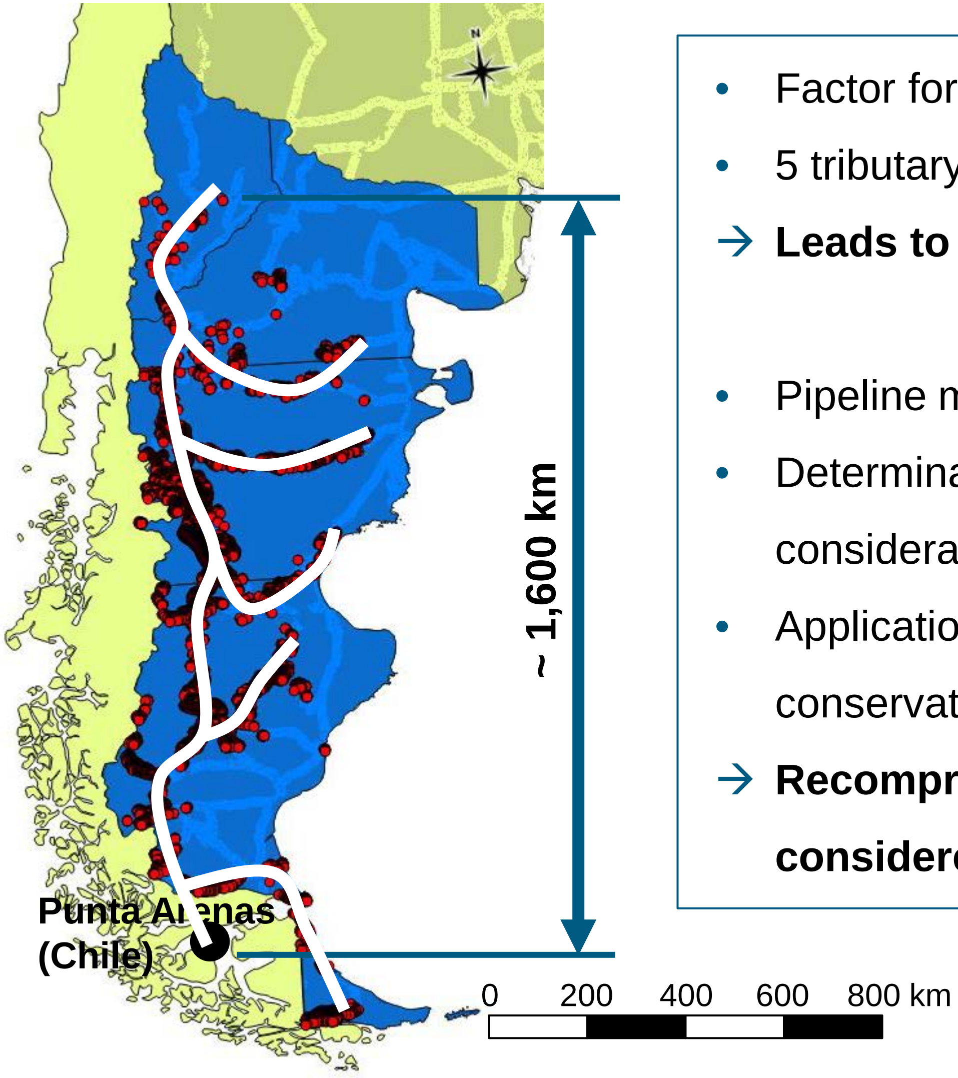


Calculation on 250 m grid over land and out to 30 km offshore

Conceivable H_2 production regions (wind potential)

Global Wind Atlas. DTU Wind Energy. URL: http://globalwindatlas.com/map.html

Pipeline through Patagonia to Punta Arenas (simplified)



- Factor for indirect route of 1.2 is considered
- 5 tributary pipelines, 500 km each

→ **Leads to pipeline length of about 4,500 km**

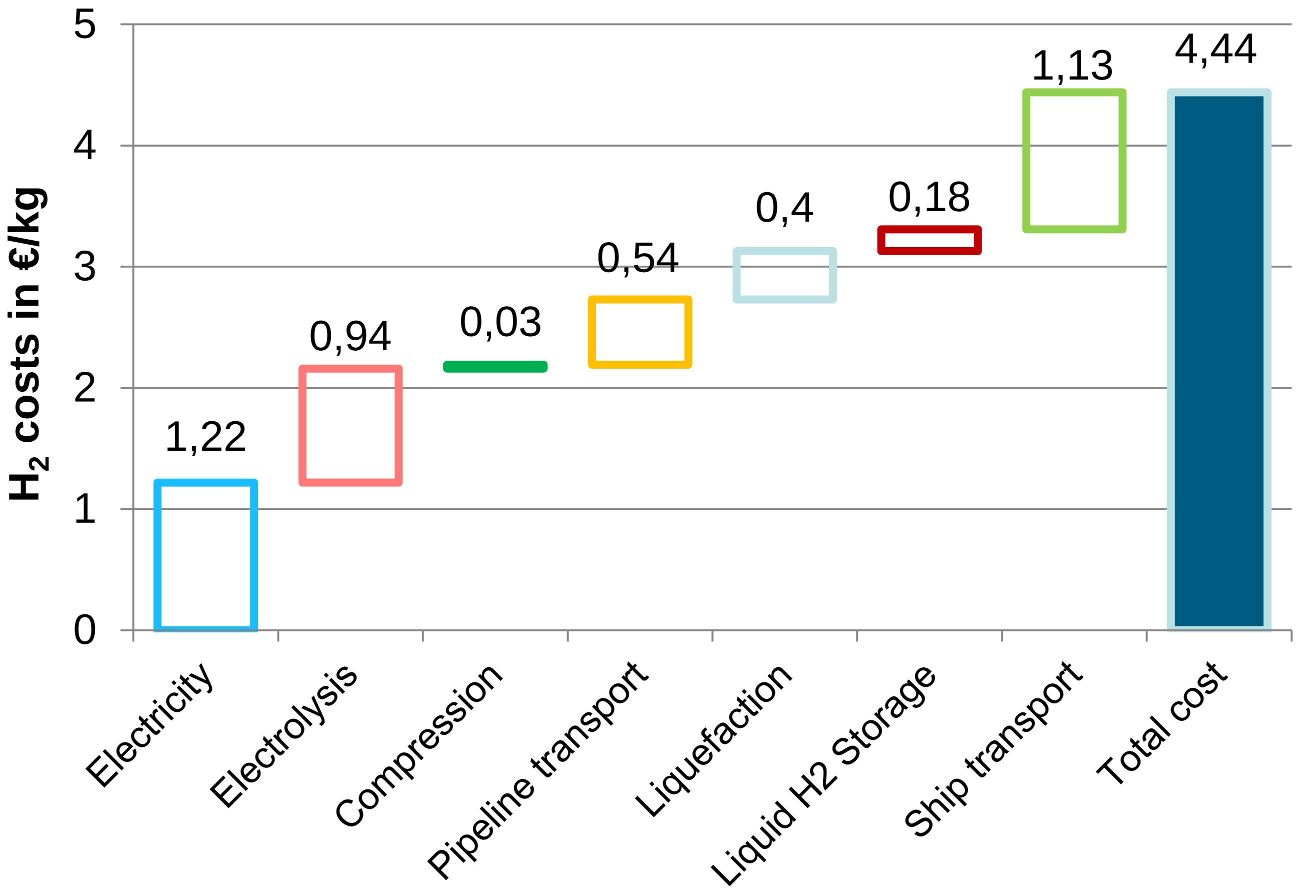
- Pipeline model from V. Tietze, cost data from D. Krieg [1]
- Determination of pipeline quantity and diameter without consideration of recompression
- Application of Krieg's cost data (published) leads to more conservative cost estimation

→ **Recompression and associated costs are to be considered in prospective analysis**

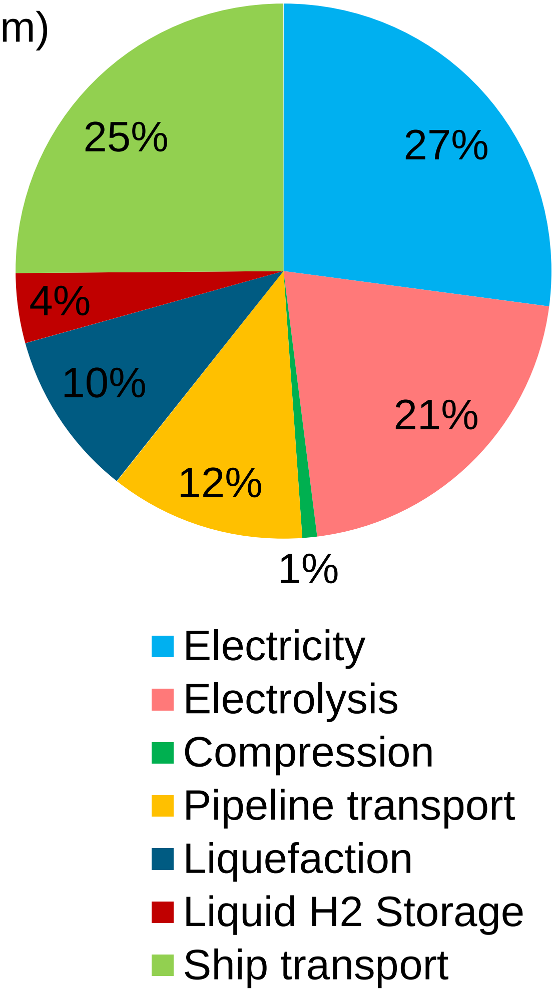
[1] Krieg, D. (2012). Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.RWTH Aachen University.

Cost Results for H_2 provision – Patagonia to Japan

- H_2 Production of 8.8 Mt/a in Patagonia (use of wind energy)
- Domestic transport via Pipeline (4,500 km)
- Liquefaction and storage in domestic harbor (Cap.: 113,600 tons)
- International transport via ship (Punta Arenas to Yokohama: 17,712 km)



Cost distribution



World Map of Salt Deposits

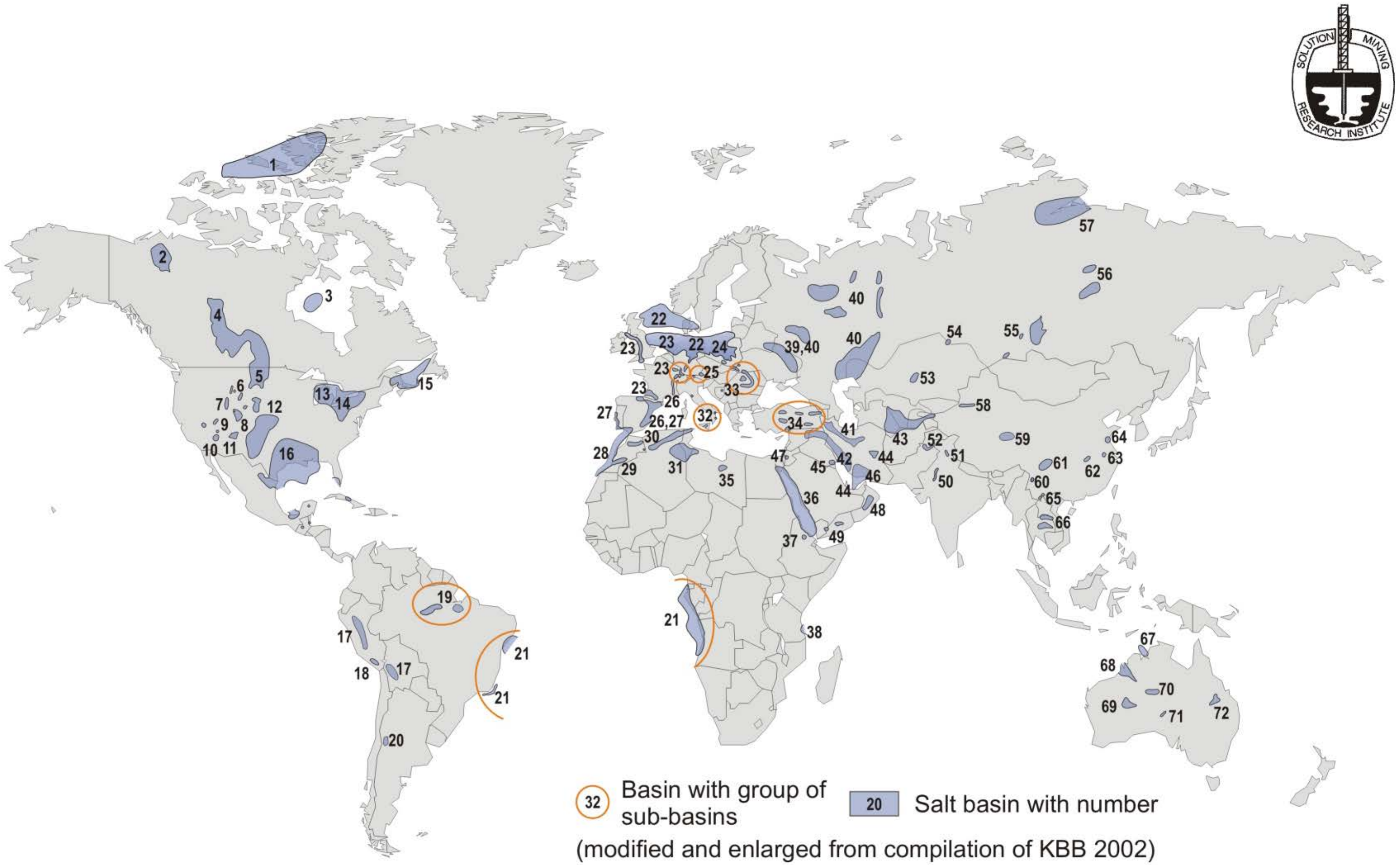


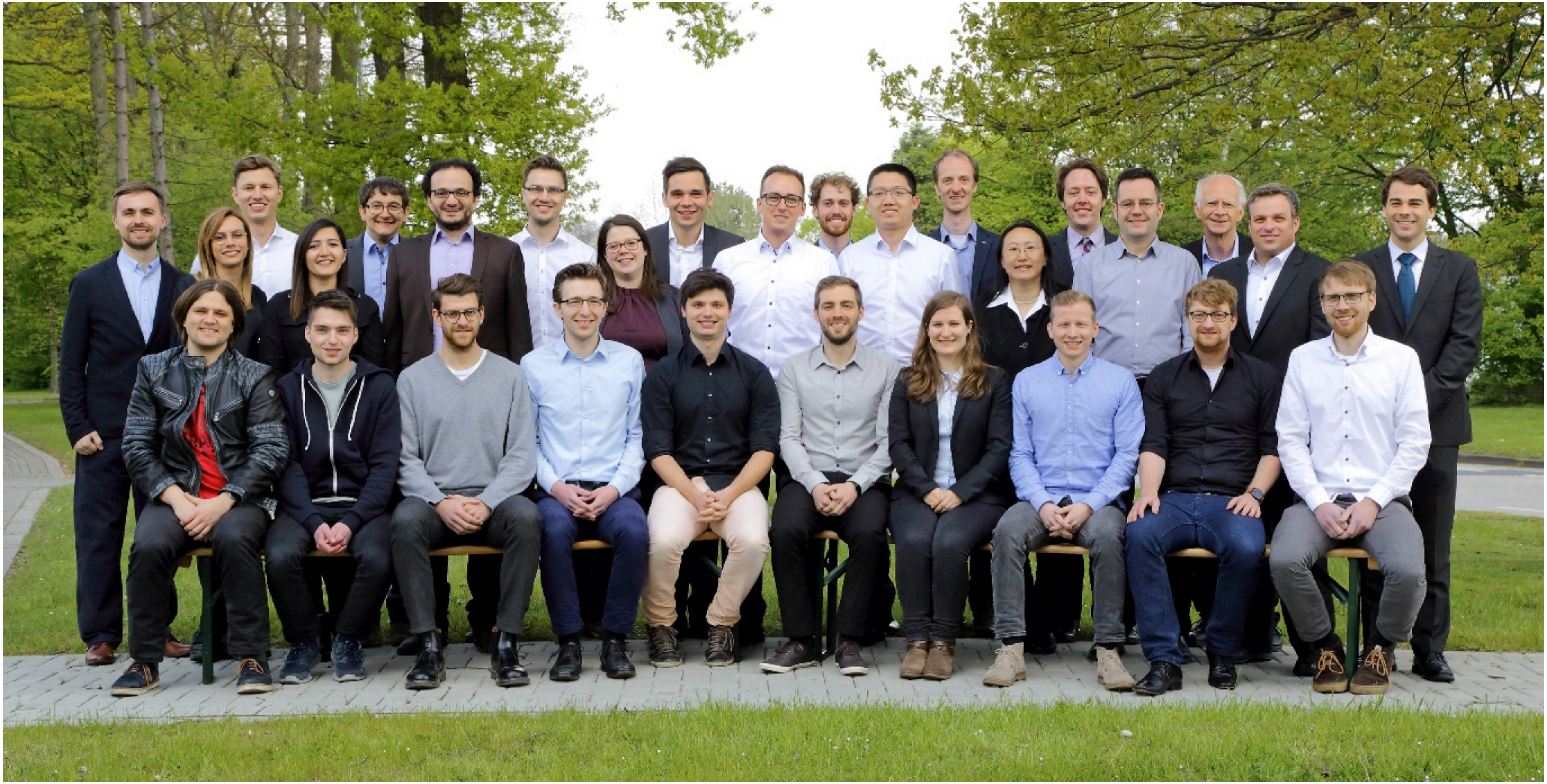
Figure 4-1
World map of underground salt deposits.
Name and stratigraphy of numbered salt basins as listed in tables 1 and 2.
7007-01\Ausgang\060905\050926_world-salt-map_rev01.cdr

Conclusions

- **Direct use of power** has the highest efficiency and is to be preferred, if possible.
- Direct **hydrogen pathways** with fuel cells are **second most efficient.**
- **Hydrogen** generation from „excess power“ **delivers** a notable **grid service.**
- Owing to the inherently high quantities of excess power of renewable concepts **„excess power“ is** to be treated as **a valuable good**. There is **no** such thing as a **low or negative power price** if the system is adjusted appropriately.
- All **PtF concepts use hydrogen**; the less oxygen in carbon precursors the higher the efficiency.
- Renewable **hydrogen is most cost effective in transportation**, substituting liquid fuels
- Methanation economically is no option
- **Distribution infrastructure for fuels** including H_2 amounts to about **20% max. of the investment** cost incl. generation; **distribution infrastructure issue** is **currently overrated**.
- Battery and fuel cells are much better in efficiency than bio-fuel and power to fuel concepts
- **Battery infrastructure is cheap at low market penetration**; **hydrogen infrastructure is much more cost effective** than battery infrastructure **at high market penetration.**
- **Renewable energy is** (getting) **competitive.**
- The moderate efficiency of the combustion engine makes alternate liquid fuel concepts expensive.

Renewable Transportation has a bright future if the right choices are being made timely

The team



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Thank You for Your Attention!

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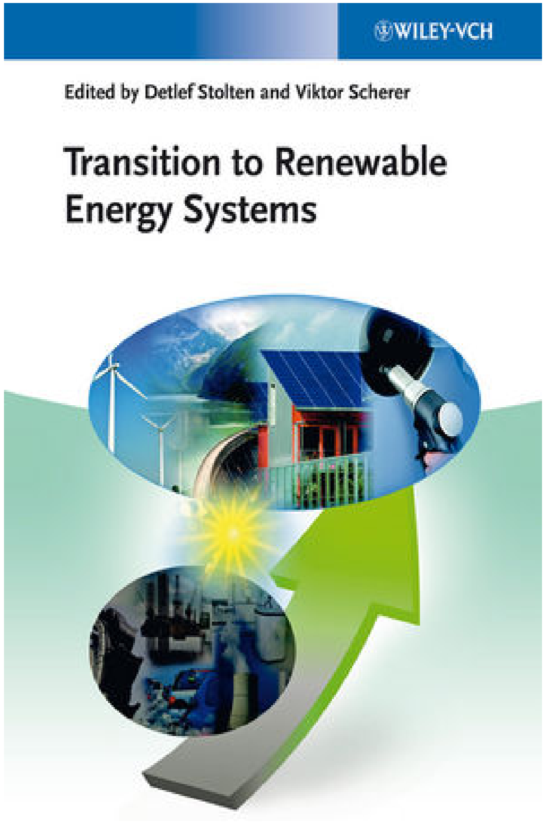

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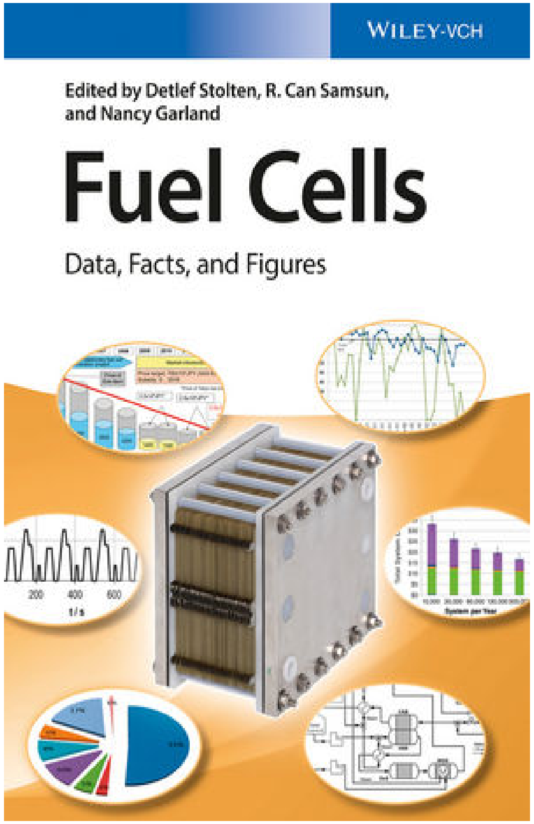
Transition to Renewable Energy Systems



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Fuel Cells

Data, Facts, and Figures