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Windstrom und Wasserstoff – Eine Alternative

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Future Energy Solutions need to be Existing Game Changers

Drivers

- Climate change
- Energy security
- Competitiveness
- Local emissions

Grand Challenges

- Renewable energy
- Electro mobility
- Efficient central power plants
- Fossil cogeneration

Goals

- Germany to reduce GHG emissions by 40% in 2020
  (w/o nuclear) 55% in 2030
  70% in 2040
  80-95% in 2050 with reference to 1990
- Danish distributed electricity and heat is to be fossil free by 2035 (no nuclear in DK)

http://www.bmu.de/english/energy_efficiency/doc/47609.php
http://www.stm.dk/publikationer/Et_Danmark_der_staar_sammen_11/Regeringsgrundlag_okt_2011.pdf

GHG Emissions Shares per Sector in Germany

Energy sector		37%
Thereof power generation	32%	
Transport (90% petroleum-based)		17%
Thereof passenger transport	11%	
Thereof goods transport	6%	
Residential		11%
Industry, trade and commerce		23%
Thereof industry	19%	
Thereof trade and commerce	4%	
Agriculture		8%
Others		4%
Total		100%

Absolute amount as of 2010: 920 m metric tonnes

Source: Emission Trends for Germany since 1990, Trend Tables: Greenhouse Gas (GHG) Emissions in Equivalents, without CO_2 from Land Use, Land Use Change and Forestry, Umweltbundesamt 2011

Transport-related values: supplemented with *Shell LKW Studie – Fakten, Trends und Perspektiven im Straßengüterverkehr bis 2030*.

CO_2 Equivalent Factors of Green House Gases

GHG1)	Equivalent Factors of GHG to CO_2 [1] for Three Timelines		
	20 Years	*100 Years*	*500 Years*
CO_2	1	1	1
CH_4	72	25	7,6
N_2O	289	298	153
HFC^2	437 – 12 000	124 – 14 800	38 – 12 200
PFC2)	5 200 – 8 630	7 390 – 17 700	9 500 – 21 200
SF_6	16 300	22 800	32 600

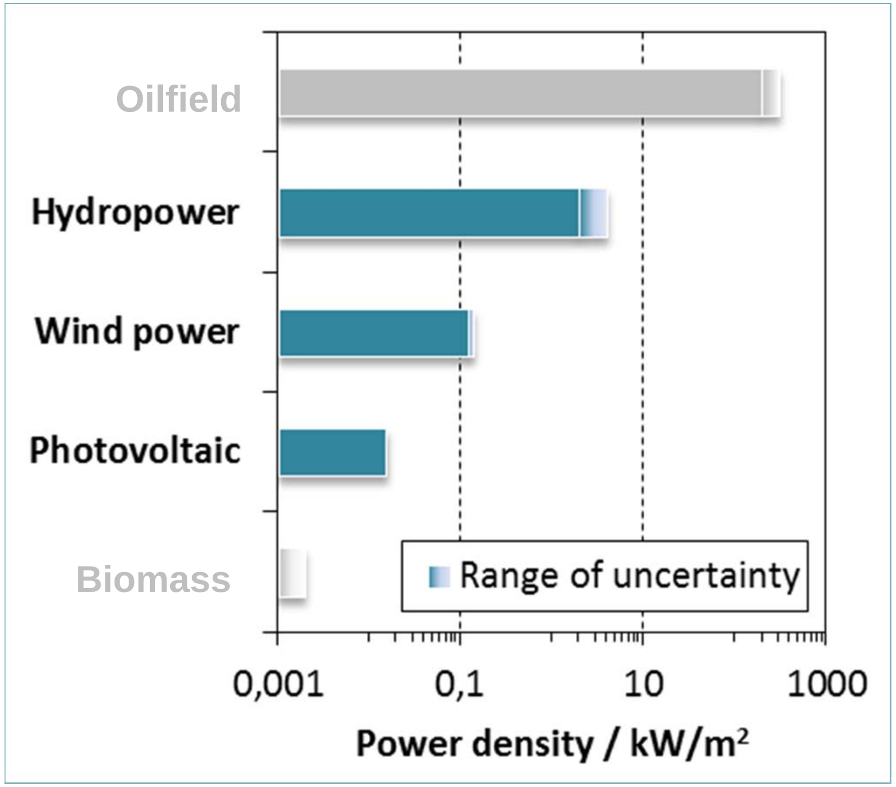
Average global radiative forcing [$W\ m^{-2}$] of green house gases [1]

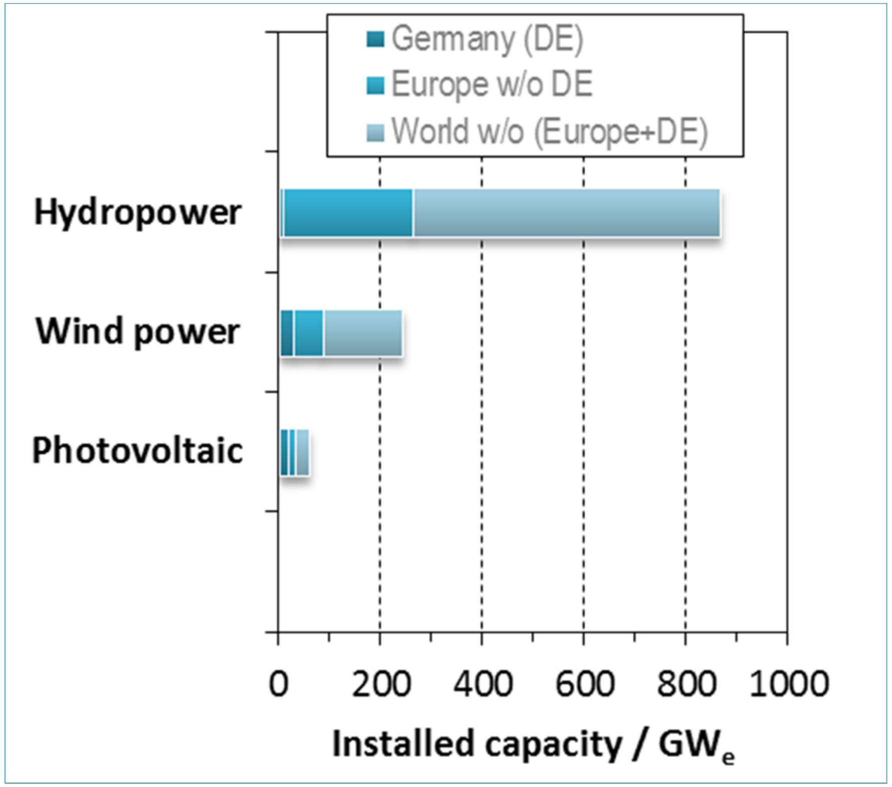
1) Selection of GHG according to [2]

2) Bandwidth according to systematics in [1]; HFC: flourinated Hydrocarbons; PFC: Perflourinated Carbons

Sources: [1] IPCC, 4th Assessment Report, Technical Summary, 2007, S. 32-33; literature usuallly refers to 100 years timeline
[2] Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 – 2009, Umweltbundesamt 2011

Renewable Energy: Energy Density & Installed Capacity





Sources:

- IEA Key World Energy Statistics (2011), Report www.iea.org, 6.10.2011.
- World Wind Association, http://www.wwindea.org/home/index.php, 6.10.2011.
- European Wind Association (2011), Wind in Power – 2010 Statistics. Report, Brussels, February 2011.
- European Phototvoltaic Industry Association (EPIA (2010)), Global Market Outlook 2015, Report, Brussels, 2010.
- ESTELA (2010), Solar Thermal Electricity 2025. Report, prepared by A.T. Kearney, June 2010.
- GREENPEACE (2009), Concentrating Solar Power – Global Outlook 09. Report published by Greenpeace International, Amsterdam 2009.
- IHA (2010), 2010 Activity Report. International Hydropower Association, London 2010.

Energy Density of Energy Carriers for Transportation

	Physical Storage Density		Technical Storage Density	
	$[MJ\ l^{-1}]$	$[MJ\ kg^{-1}]$	$[MJ\ l^{-1}]$	$[MJ\ kg^{-1}]$
Gasoline	32	43	~ 30	~ 35
Hydrogen	5 @ 700 bar	120	4 @ 700 bar	5 [§] ~ 2-3 [§§]
Li-Ion Batteries	1 – 1.8 [‡]	0.4 - 0.7	0,5 – 0,9 [†]	0.2 – 0.4 [†]
Li – air Batteries [#]		~ 40		~ 4

§ Existing system by Opel / GM
§§ Fuel cell system considered
‡ 250 – 500 Wh/kg
† Cooling cells and ΔSOC ≤ 50% considered
\# In early laboratory stage

Concept for a Novel Energy System

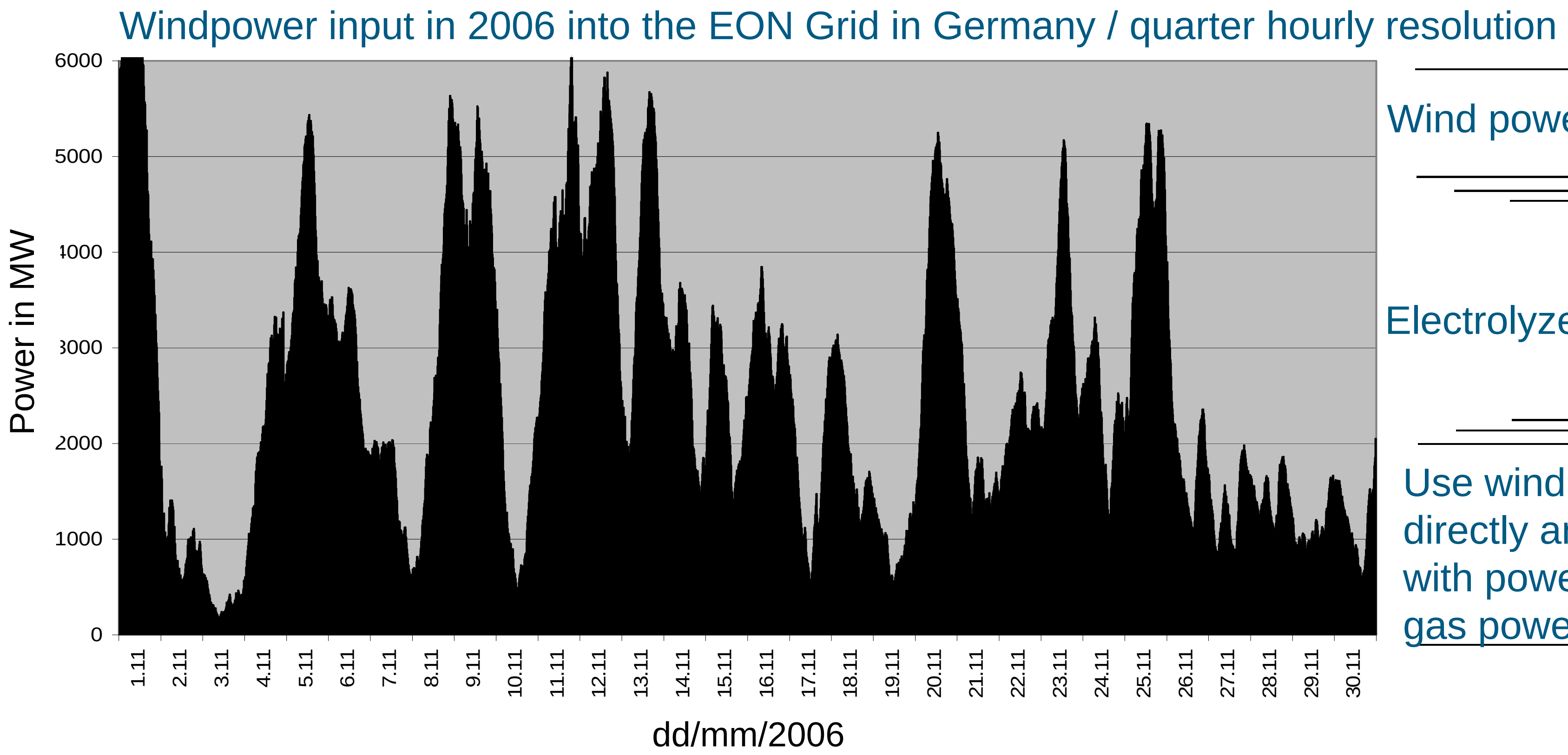
1. Timeline requires focus on Existing Game Changers and Missing Links
2. Only renewables can deliver on the GHG reductions required
3. Only electromobilty can deliver on the GHG requirements
4. Wind power, electrolysis, hydrogen and fuel cells for transportation are potential game changers
5. Renewables require dynamic bulk storage like geologic H_2 storage
6. Cost efficiency is paramount

Scenario of the Energy System for Germany in View of 55% CO_2 Reduction

Onshore Wind Power	Same number of wind mills as of end 2011 (22500 units) Repowering from Ø 1.3 MW to 7,5 MW units => Σ 167 GW Averaged nominal operating hours: 2000 p.a. [1]
Offshore Wind Power	70 GW (potential according to BMU 2011[2], Fino => 4000 h)
Photovoltaik	24,8 GW as status of 12/2011[3], volatitilty considered
Other Renewables	Constant as of 2010[4]
Excess Energy	Water electrolysis $\eta_{LHV} = 70\ \%$[5]; > 1000 operating hours Pipeline transport + storage in salt caverns
Transportation	Hydrogen for fuel cel cars: cruising range 14900 km/a[6], consumption 1kg/100km
Residential Sector	50% savings on natural gas as of 2010
Back-up Power	Open gas turbines; combined cycles > 700 operating hours/a Part load considered by 15% reduction on nominal efficiency

KBB

Water Electrolysis as an Enabler for Renewables

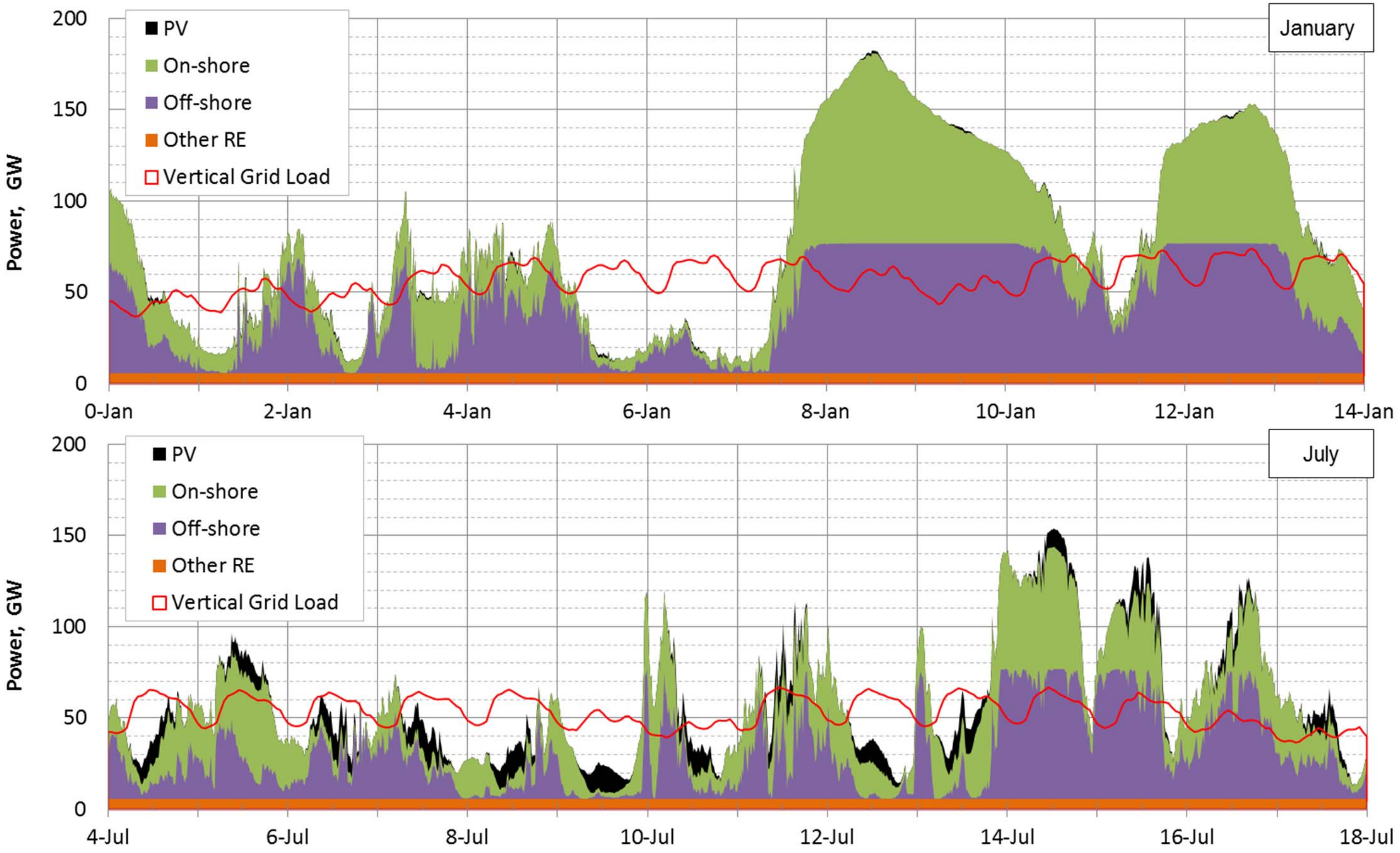

Windpower input in 2006 into the EON Grid in Germany / quarter hourly resolution

Wind power curtailment

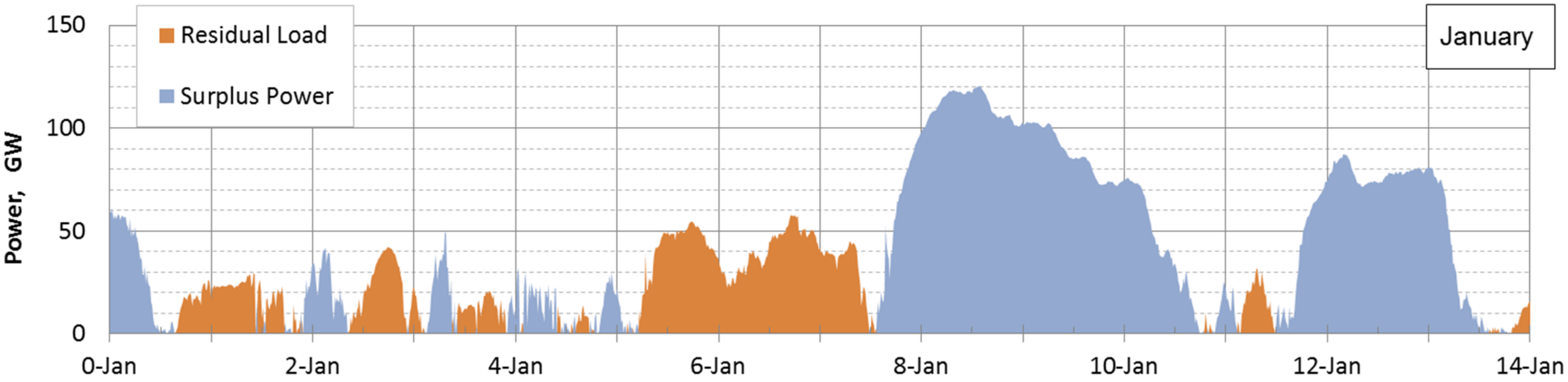
Electrolyze wind peaks

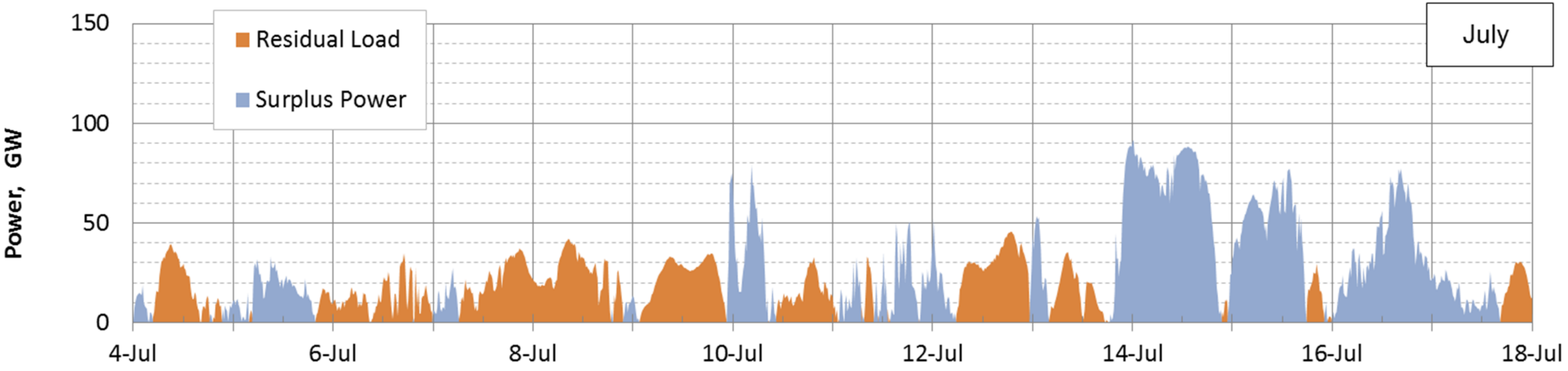
Use wind power directly and fill gaps with power from gas power plants

Renewable Production in Scenario & Vertical Grid Load 2010



Surplus Power & Residual Load in Scenario



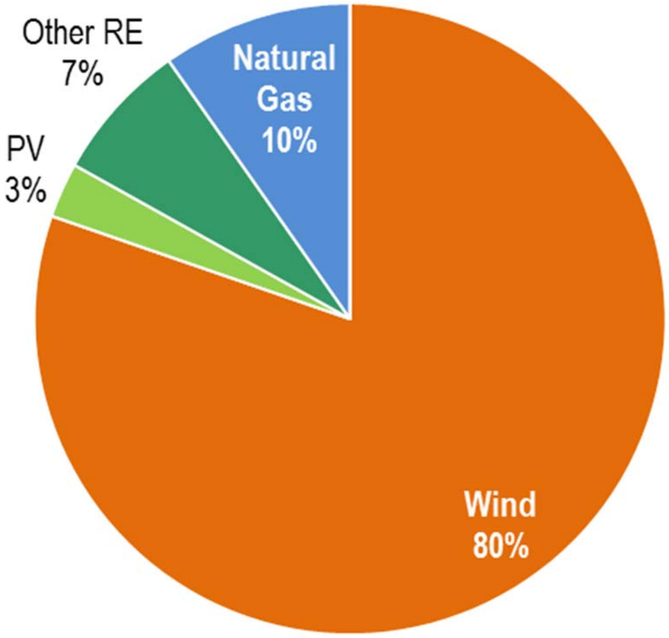


Results for Scenario of 55 % of CO_2 Savings

Total amount of electricity produced; includes electricity for hydrogen production 745 TWh

Transmitted electricity (vertical grid load) 488 TWh

Electricity for hydrogen production 257 TWh => 5.4 m tonnes H_2

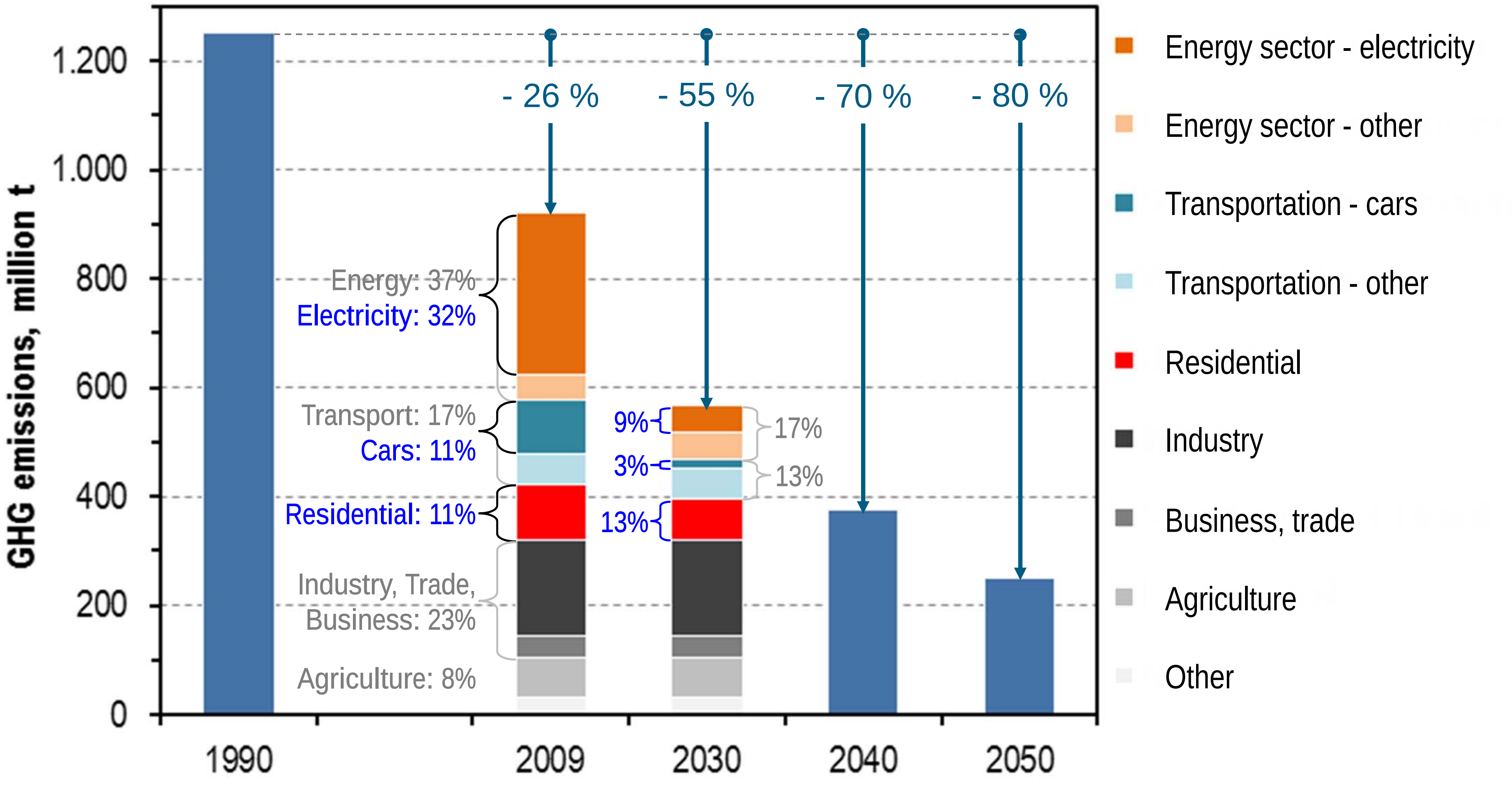


Power sector:
All nuclear, coal, lignite and oil is substituted
Natural gas used for compensating fluctuations in Renewable energy

Electricity for hydrogen procduction in transportation:
28.5 m vehicles
2.1 m light duty vehicles
50,000 buses

Mix of vehicles according to the study German Hy
Other than in German Hy all vehicles are FC vehicles

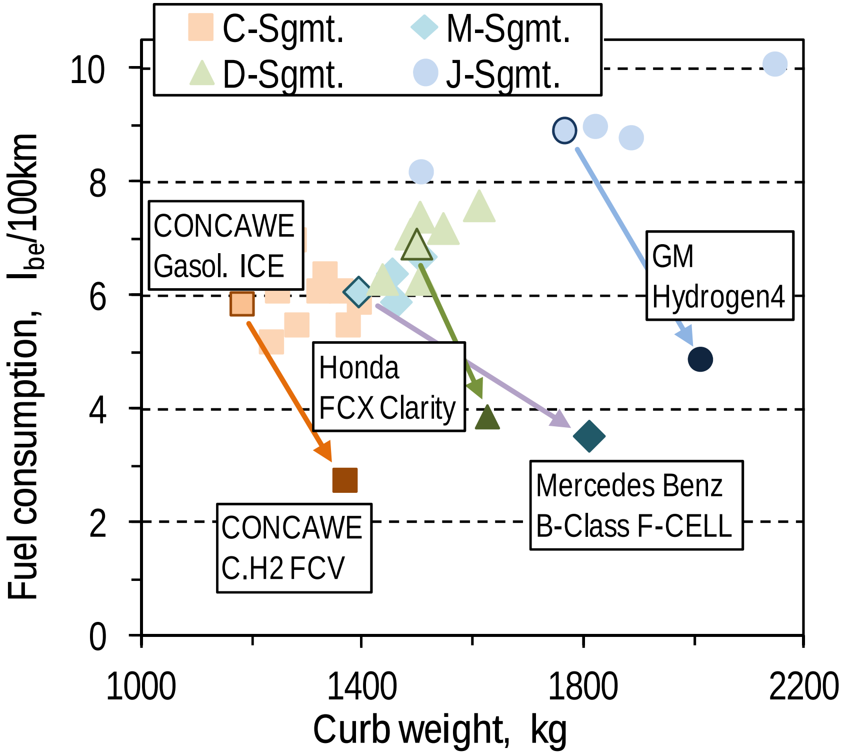
GHG Emissions According to Scenario



2030 target is achieved. Further reductions are feasible.

Hydrogen avoids more CO_2 in Road Transport than in Electric Re-conversion

Fuel consumption ratio ICE / FCEV	2,0
CO_2 emissions of substituted fuel in MJ gasoline / natural gas	1,25
CO_2 avoidance through H_2 utilization transport / re-conversion	**2,5**



Constraints:
Re-conversion: combined cycle PP after transport in NG pipelines, efficiency ~= NG CCPP
Road transport: replacement of (1) less efficient power trains & (2) more carbon-rich fuel

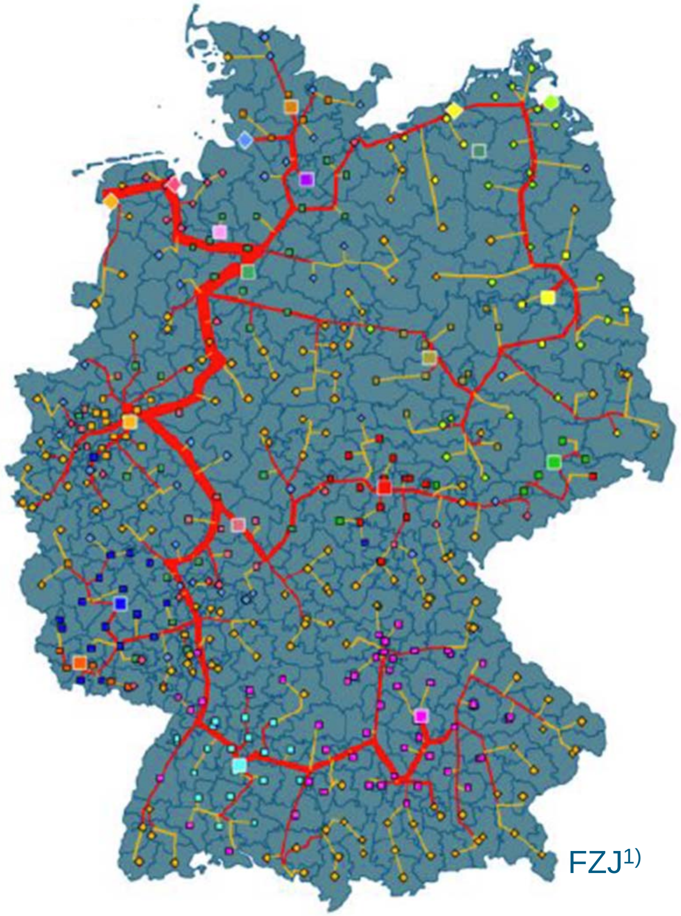
Daimler B-class F-Cell as an Example

- Small scale production started
- Delivery of 200 vehicles beginning of 2010

http://media.daimler.com/dcmedia/
Stuttgart 28.8.2009

Drive train	Electric motor with fuel cell
Net power (kW/PS)	100/136
Nominal torque (Nm)	290
Top speed (km/h)	170
Fuel consumption NEDC (l Diesel equivalent/100 km)	3,3
CO2 total (g/km min.–max.)	0,0
Cruising range (km) NEDC	385
Capacity/ power lithium ion battery (kWh/kW)	1,4 /35
Freeze start-up capability	Down to -25 °C

Infrastructure: Pipeline Network


FZJ[1)]

Annual hydrogen production: 5.4 m tons

Transmission grid to German districts (Landkreise)

- Length: 12,000 km
- Investment: 6-7 bn €[2)]

Distribution to 9800 refueling stations w/ 1500 kg H_2/d

- Length: 31-47,000 km
- Investment: 13-19 bn €[2)]

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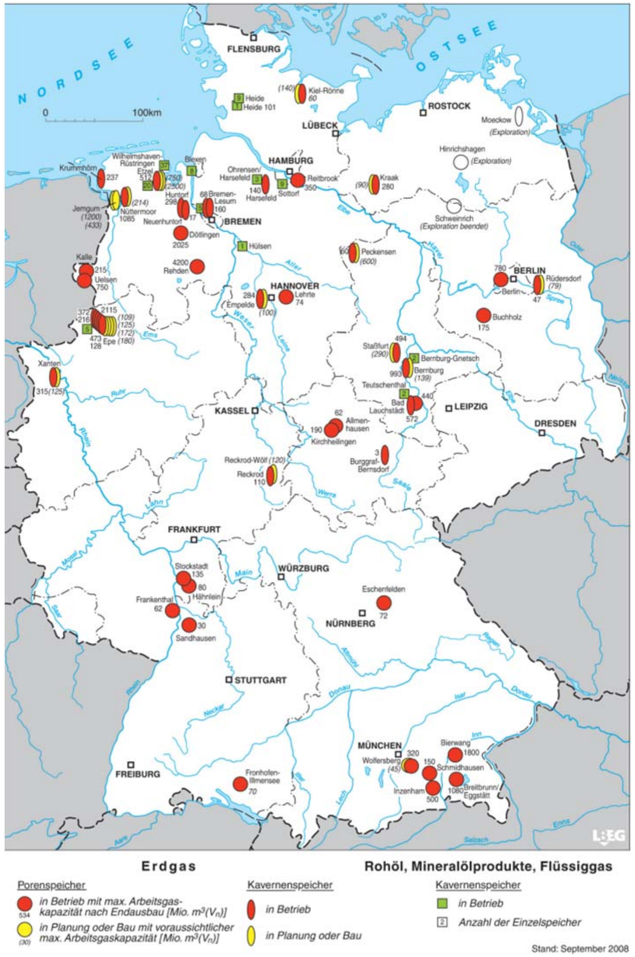
1) Baufume, Grube, Krieg, Linssen, Weber, Hake, Stolten (2012) 12. Symp. Energieinnovation, Graz, 15-17.3. (values adapted here to larger total amount of H_2)

2) incl. compressors for compensation of pressure losses

Infrastructure: Electrolysis & Large Scale Storage



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

Hydrogen production: 5.4 million t/a

Max power over 1000 h: 84 GW

Storage capacity required at constant discharge:

0.8 m tons

9 bn scm

27 TWh_{LHV}

Storage capacity for 60 day reserve approx. 90 TWh

(Pumped Hydro Power in Germany: 0.04 $\textit{TWh}_e$*)*

Existing NG-storage in Germany:

- 20.8 bn scm

thereof salt dome caverns:

- 8.1 bn scm (in use)
- 12.9 bn scm (in planning/construction phase)

=> Twice the existing storage capacity in salt domes needed

Cost Estimation for 55% Scenario in bn €

Water electrolyzers	42
Hydrogen pipeline grid	19 – 25
Gas caverns (compensating annual fluctuation)	5§ - 15&
Fueling stations (9 800 units)	20
Additional peak power plants (GT, CC)	24
Total	110 – 126

§ compensating annual fluctuation

& strategic reserve for 60 days

Why should Hydrogen go to Transportation and better not be Re-converted to Electricity?

Direct cost of hydrogen production from wind:

6 ct/kWh$_e$ / 70% = 8,6 ct/kWh$_{H2,LHV}$ = **77 ct/l$_{gasoline}$**

(1ℓ gasoline ≙ 9 kWh[1])

Revenues for hydrogen in case of road transportation:

70 ct/l$_{gasoline}$ * 2 (= efficiency ratio FCV/ICE) = **140 ct/l$_{gasoline}$** **=> margin + 63 ct/l$_{gasoline}$**

tax margin 100%; ~ 1.4 €

Revenues for hydrogen fed into the gas grid:

NG purchase price: 4 ct/kWh = 36 ct/l $_{gasoline}$ = **36 ct/l$_{gasoline}$** **=> margin - 41 ct/l$_{gasoline}$**

tax margin max 18 ct

Revenues for hydrogen in case of methanation:

NG purchase price: 4 ct/kWh = 36 ct/l$_{b.\text{-}eq.}$

Mass balance: $4\ H_2 + CO_2 \leftrightarrow 2\ H_2O + CH_4$

Effciency: ≈ 75% => 36 ct/l$_{b.\text{-}äq.}$ * 75 % = **27 ct/l$_{gasoline}$** **=> margin – 50 ct/l$_{gasoline}$**

[1] JEC - Joint Research Center EUCAR CONCAVE (2011) *Well-to-Wheels analysis of future Automotive fuels and powertrains, WtT-Appendix 1, Version 3c.*

Conclusions

- Wind power bears the potential to transform the German energy sector
- The proposed reduction potential of 55% is achievable; the timeline until 2030 is to be clarified
- Hydrogen as a means of energy storage is indispensable since
  - *Methanation is economically not viable*
  - *Other means of storage like pumped hydro or batteries fail capacity-wise*
- There is no such thing as surplus wind power; i.e. it is not for granted and should be used most economically in transportation
- Capital cost is manageable
- The CO_2 reduction measures draw on:
  - *Power production: -20%*
  - *Transportation: -6,5%*
  - *Residential heating: -2,2%*
- Further reduction potential through:
  - *Biofuels as surrogates for liquid fuels*
  - *Energy conservation measures*
  - *Incorporation of contributions of other concepts like smart grids, heat pumps etc.*

Thank You for Your Attention!

3rd ICEPE 2013
International Conference on Energy Process Engineering

Transition to Renewables
June 3-5, 2012
Frankfurt, Dechema Haus

Call for abstracts to come September 1, 2012