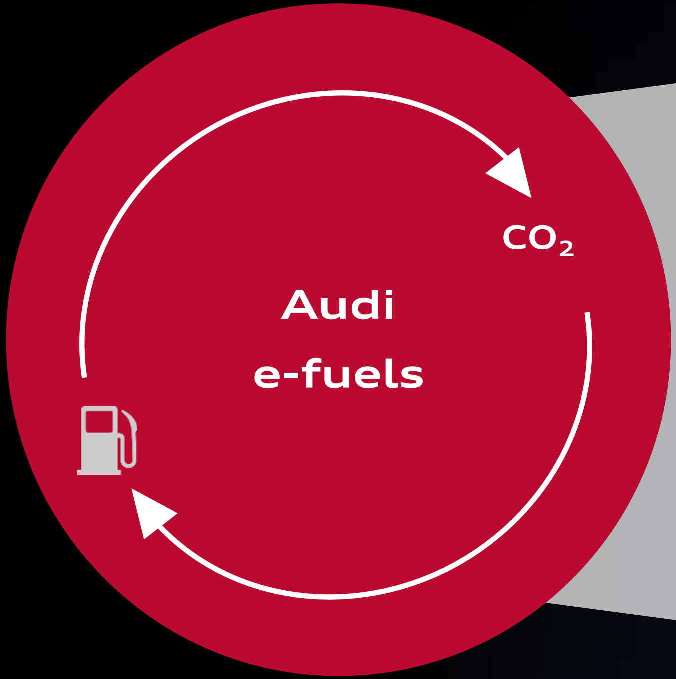
Decarbonization of the mobility sector: potential of Power-to-X technologies

Corentin Prié – AUDI AG – Sustainable Product Development

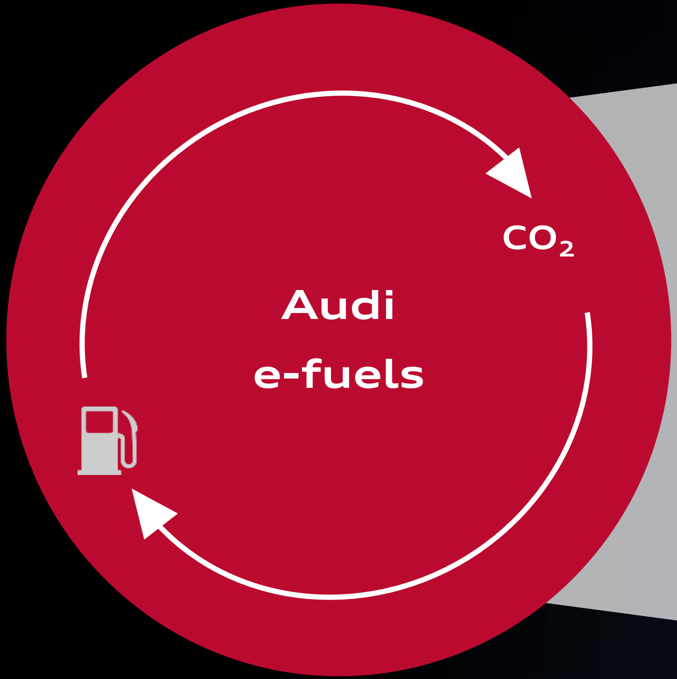
17.12.2019 – KIT – Seminar Combustion Engines

Source: CNBC

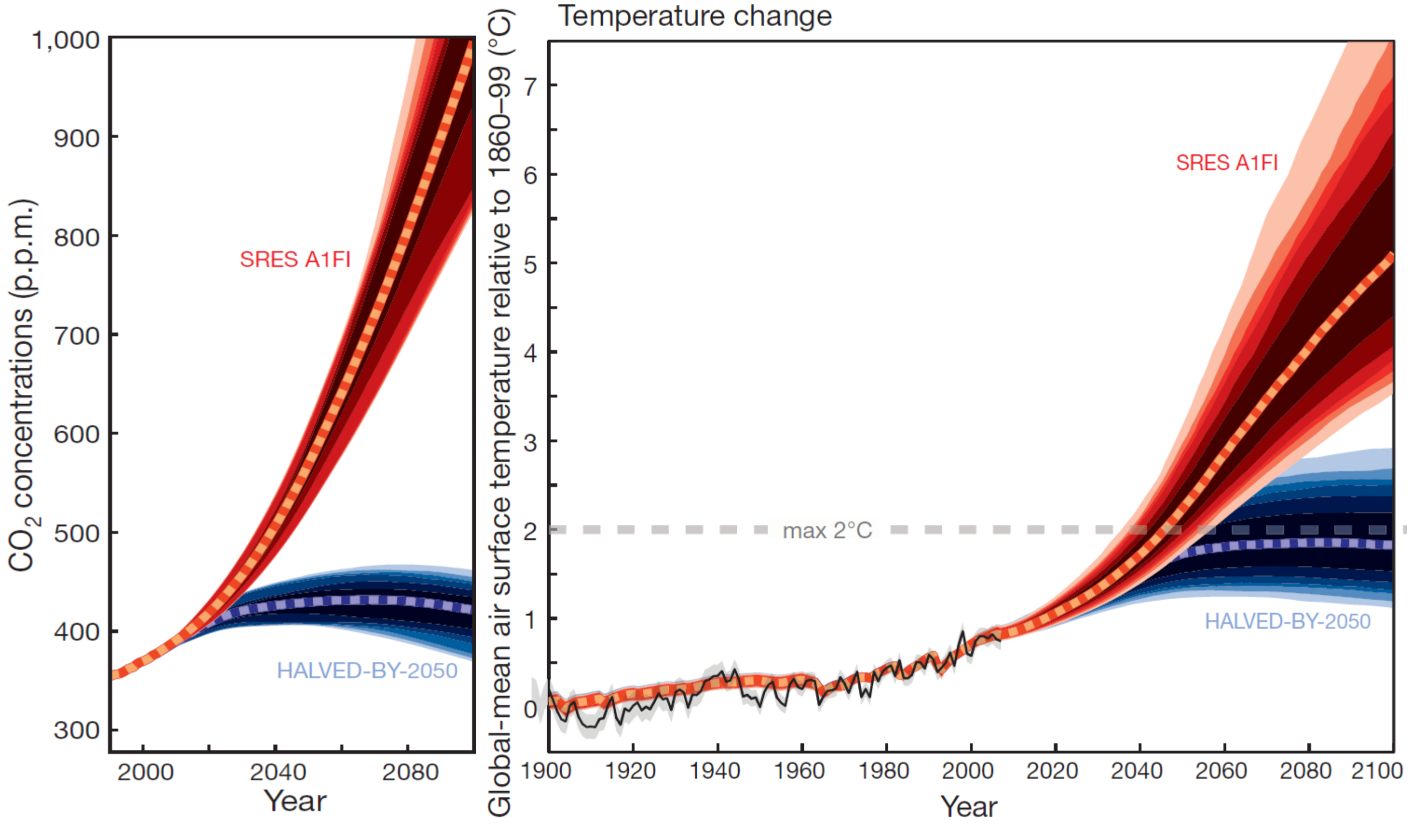
Content

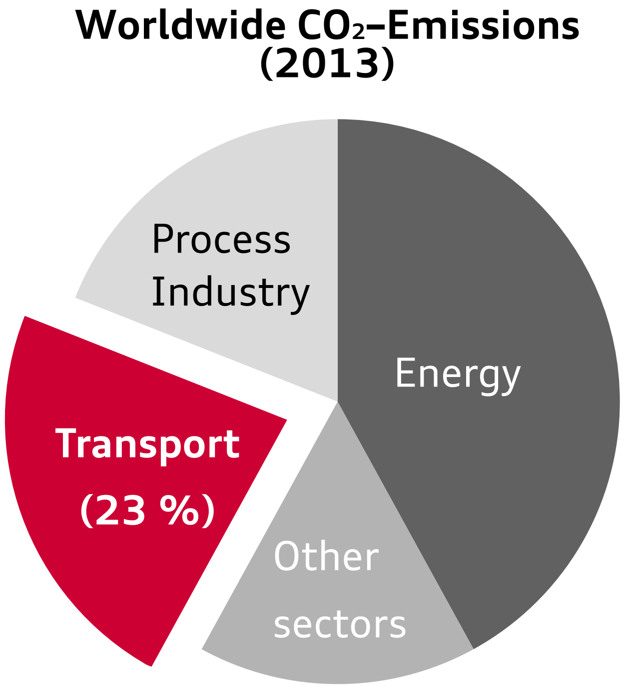


Content



The targets resulting from the climate agreement of Paris are not sufficient to sustain our environment…



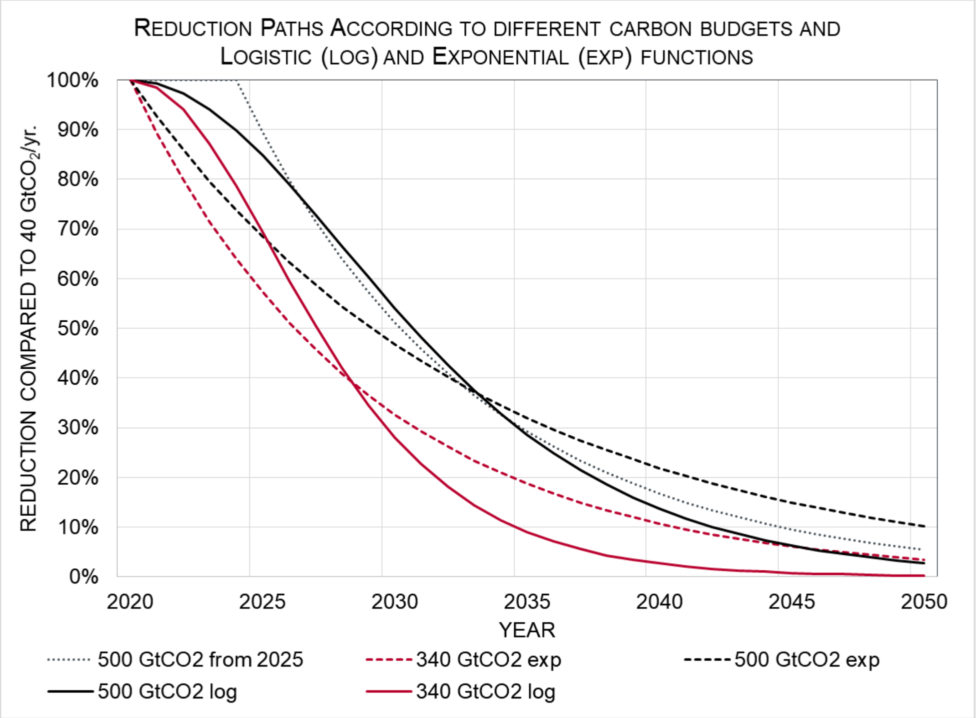


Source: Meinshausen (2009) „Greenhouse-gas emission targets for limiting global warming to 2 °C"; IEA (2015) „Key trends in CO2 emissions"; VW (2014) „Nachhaltigkeitsbericht" Scope 3 THG Emissions für 2013 321 Mio. t CO2

… and a responsible and fast response is essential in the transport sector which can only be possible by considering a large panel of options!

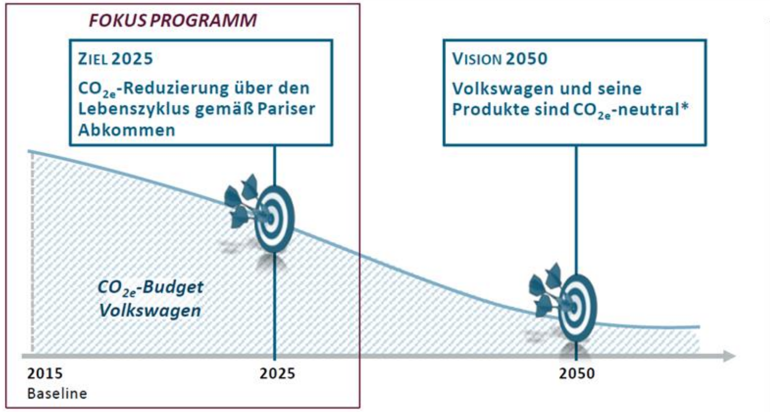
- CO_2 emissions have to be drastically reduced to have a chance stopping climate change
- The Volkswagen-Group needs to play a role of leader in the fight against climate change
- It implies a wide openness to all energy carriers and associated powertrain technologies

WORLD



Source: Rogelj et al., 2018; Rockström et al (2017); update Zapf, Pengg, Bütler, Bach, Weindl (2019)

VW-Group



Source: Volkswagen Group

Do we currently measure the complete consequences of mobility?

Current legislation

vehicle manufacturing

fuel production

exhaust pipe

recycling

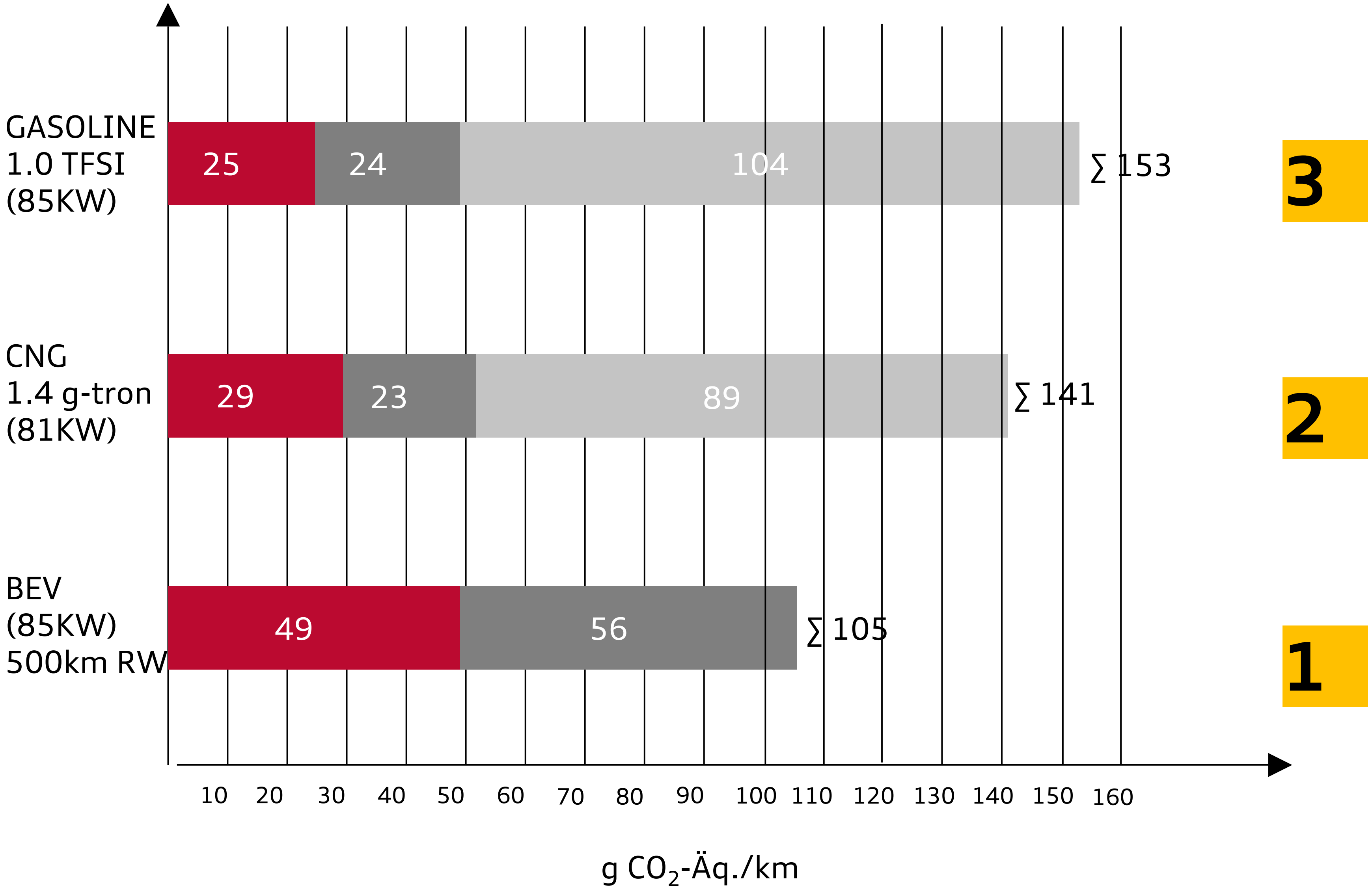
„well-to-tank“ „tank-to-wheel“

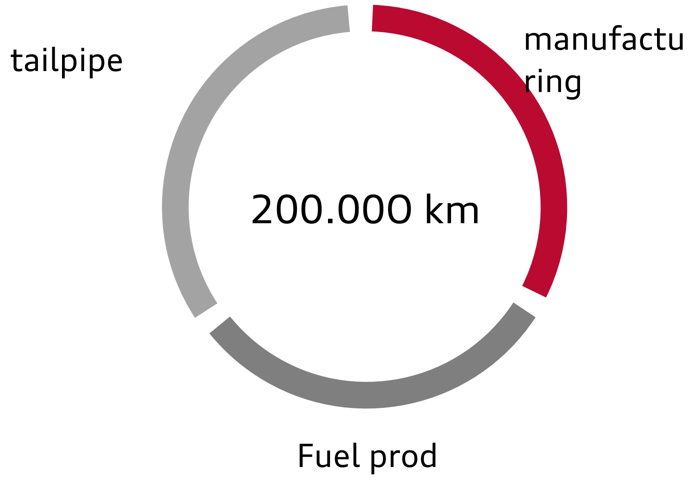
„well-to-wheel“

„cradle to grave“

Source: AUDI AG 2018

Who wins the „LCA race“?

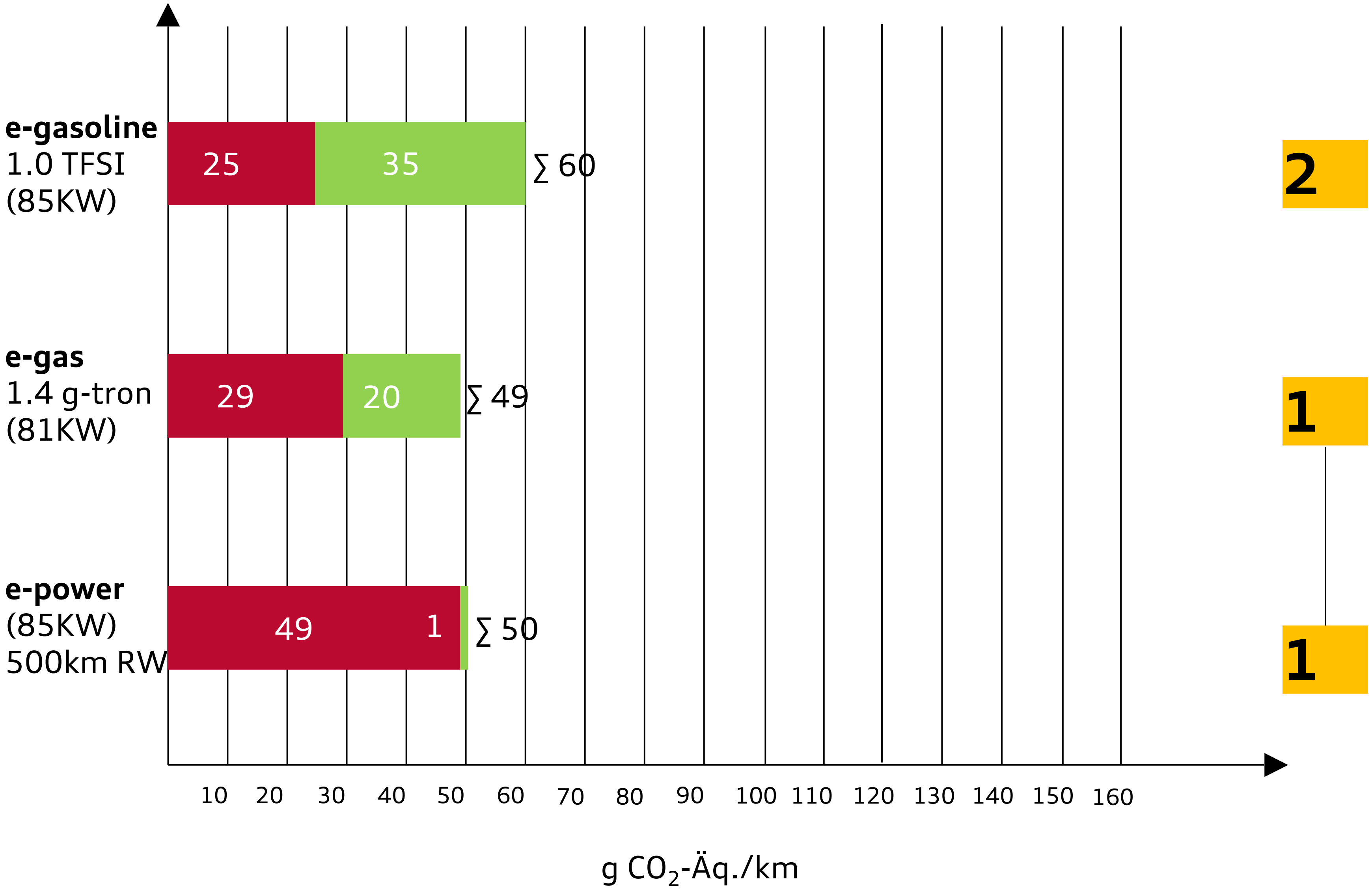


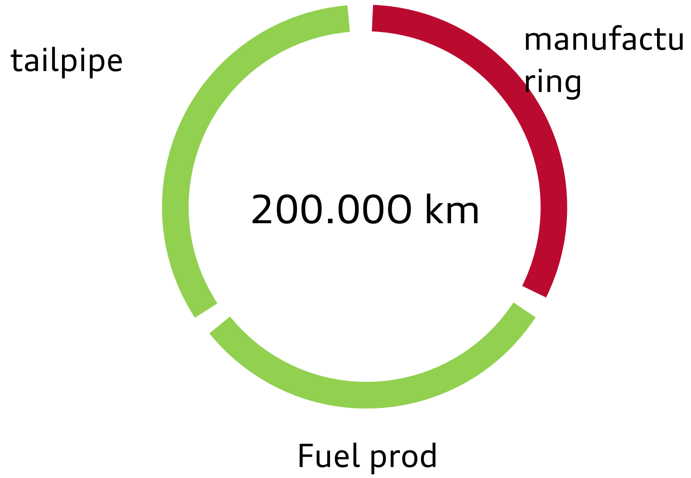


Assumptions:
Compact car (A3)
NEDC
All cars same range
Lifetime 200.000 km
Neglect recycling
Fossil gasoline & CNG / EU electricity mix

Source: AUDI AG 2018

LCA race with green energy

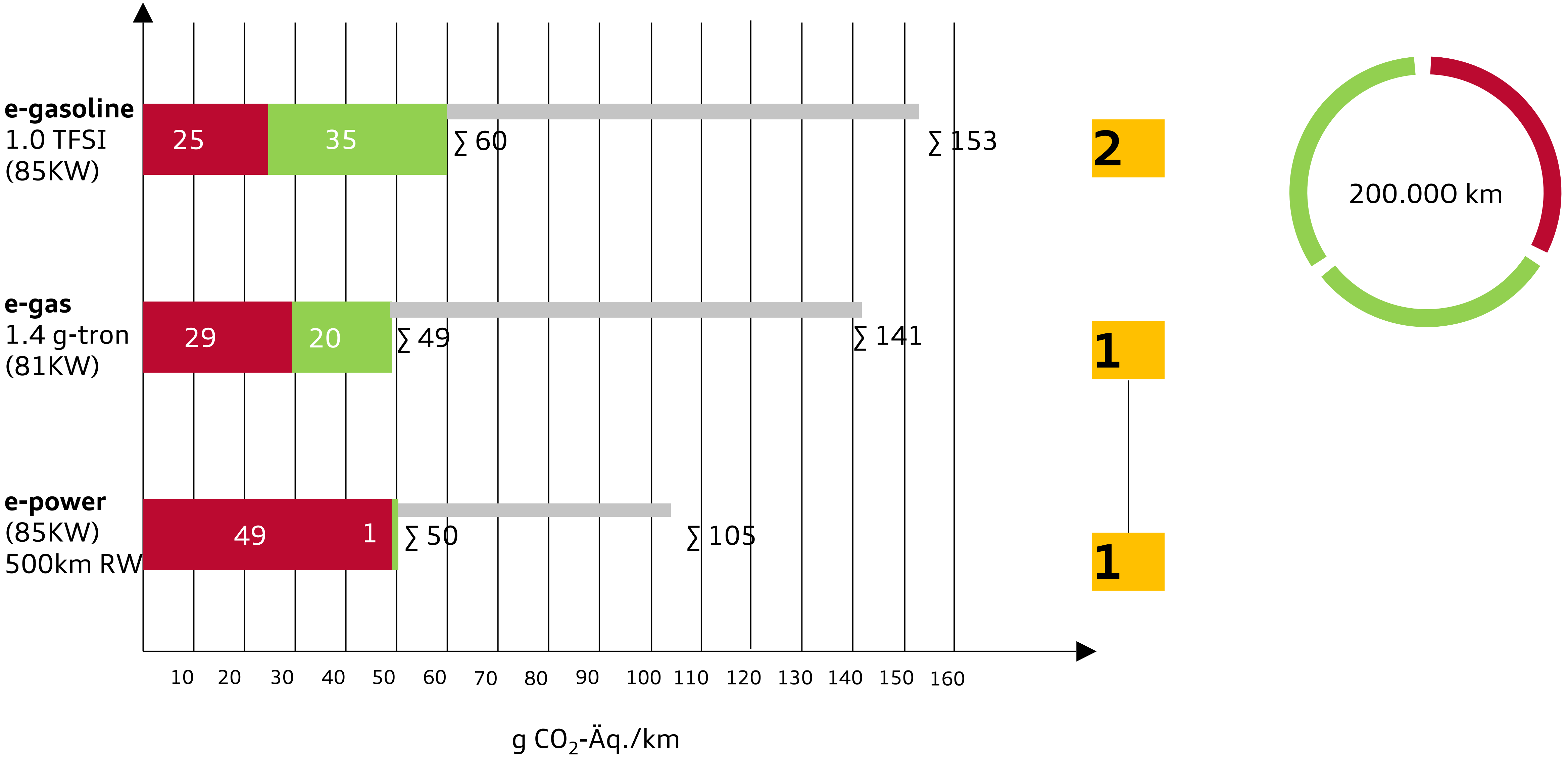




Source: AUDI AG 2018

Assumptions:
Compact car (A3)
NEDC
All cars same range
Lifetime 200.000 km
Neglect recycling
e-gasoline / e-gas / wind energy

Green energy – not powertrain - determines CO_2



Source: AUDI AG 2018

Evolution of fuels

Gen. 0	Gen. 1	Gen. 2	Gen. 3
Fossil fuels	Biofuels from crops	Audi e-fuels	
		Biofuels (waste based)	Electricity based fuels







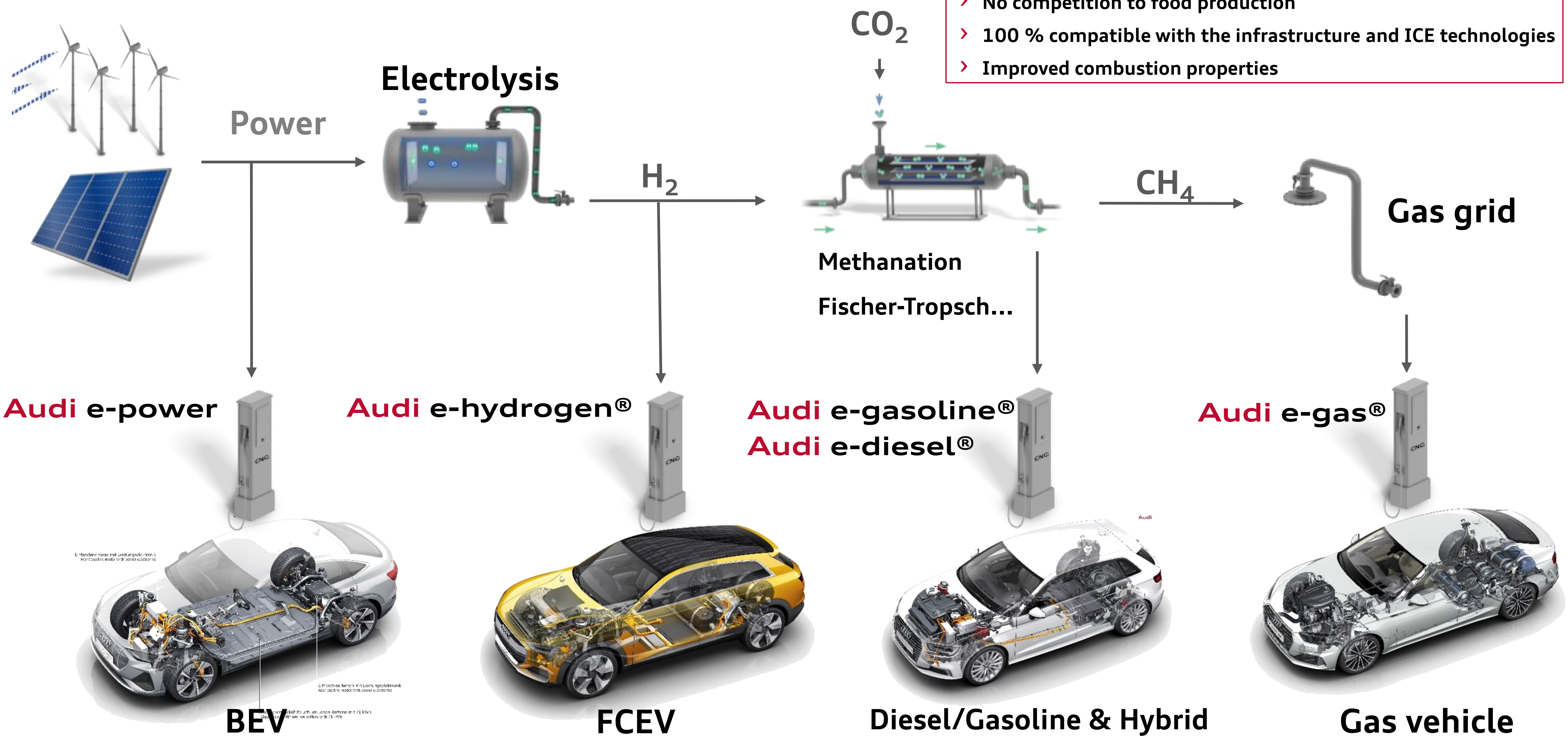





Audi e-fuels are advanced, renewable fuels of the 2nd and 3rd generation

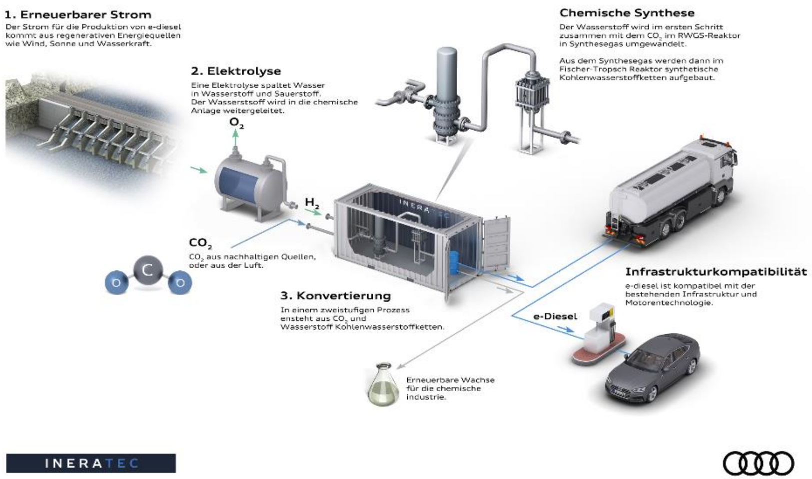
AUDI e-fuels enable the use of various powertrain technologies

- CO_2-reduction > 70% Well-to-Wheel
- No competition to food production
- 100 % compatible with the infrastructure and ICE technologies
- Improved combustion properties




Quelle: Ineratec GmbH

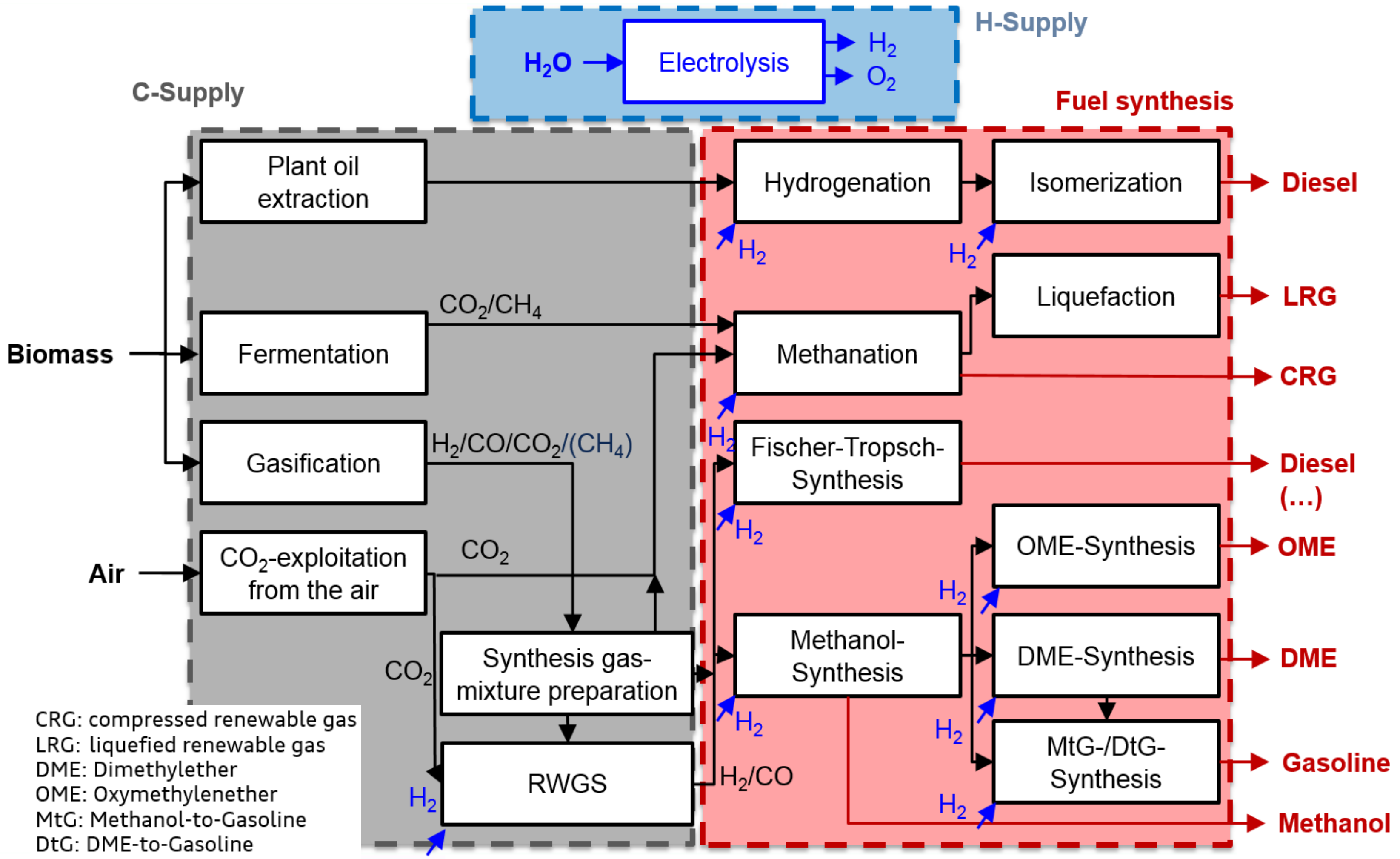
Audi e-diesel®



Audi e-benzin®

Audi e-gas®

But what is the worldwide potential of e-fuels when it comes to competing with fossil fuels?



CRG: compressed renewable gas
LRG: liquefied renewable gas
DME: Dimethylether
OME: Oxymethylenether
MtG: Methanol-to-Gasoline
DtG: DME-to-Gasoline
RWGS: Reverse Water Gas Shift

Overview of e-fuel processes

Needed energies/material:

- Electricity (renewable)
- Water
- Carbon dioxide

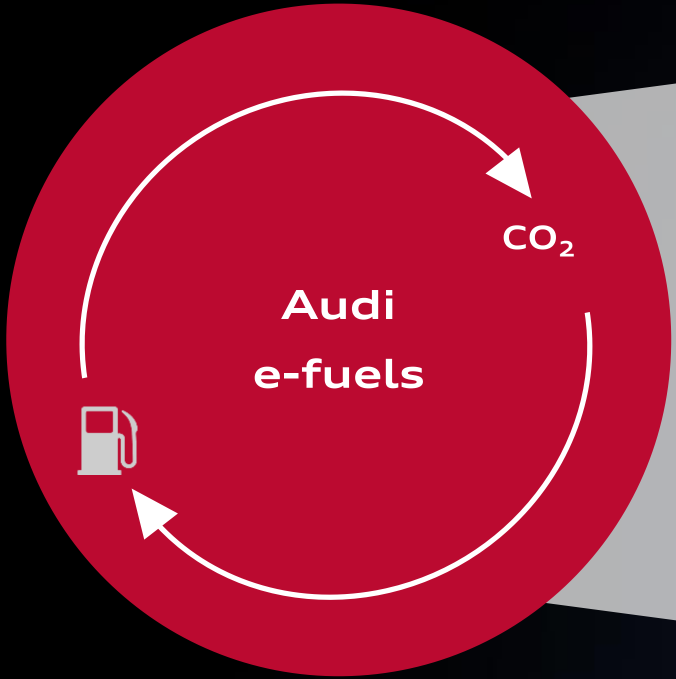
Which regions could contribute to provide these energy sources ?

What are their technical/financial potential?

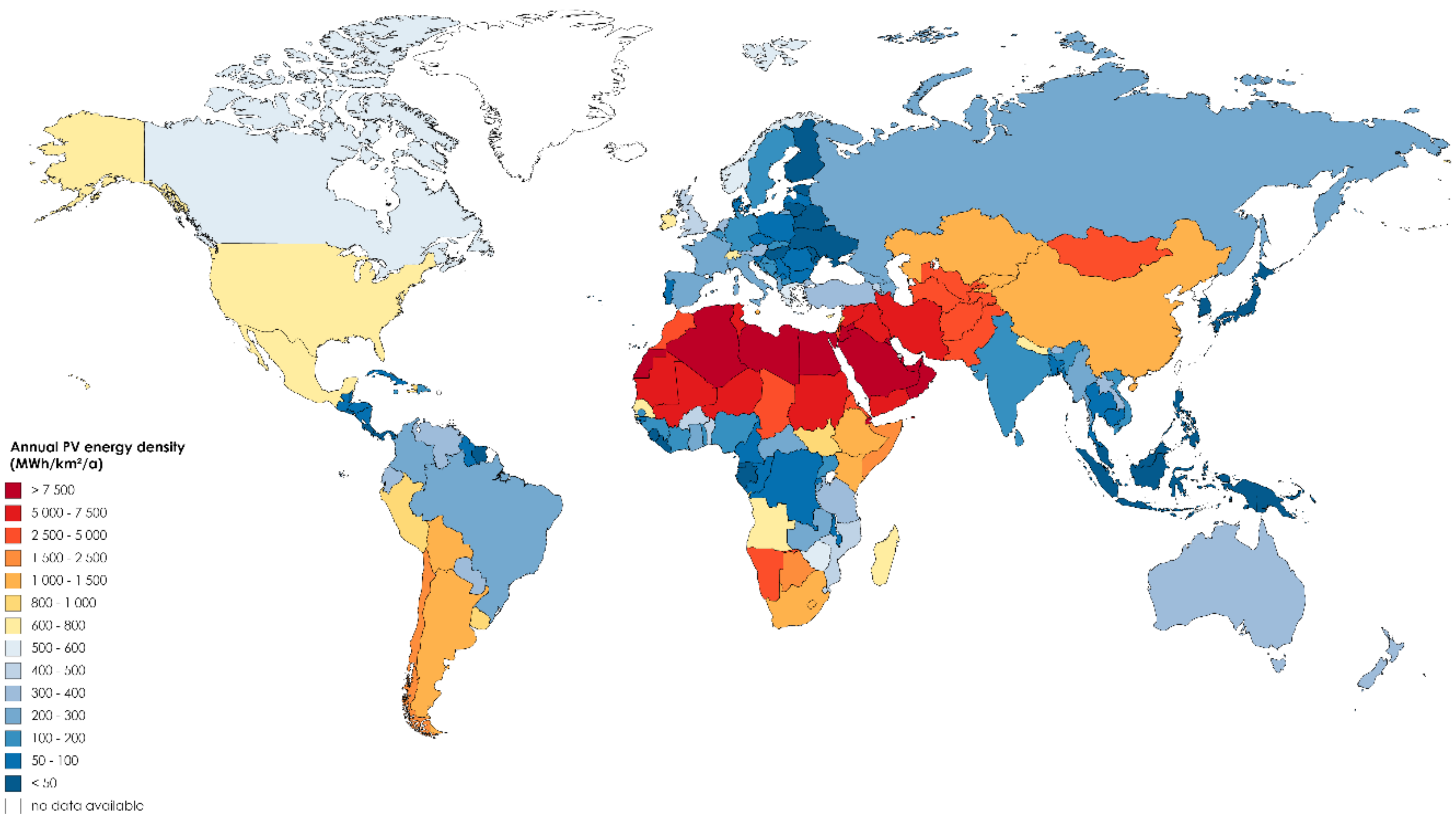
Goal: Build a renewable energy landscape assigning technologies to regions

Source: DVGW-EBI, Engler-Bunte-Institut (KIT-EBI), Institut für Katalyseforschung und -technologie (KIT-IKFT) “Vergleichende Bewertung von PtX-Prozessen zur Bereitstellung von Kraftstoffen aus erneuerbaren Quellen”, sl. 22

Content



Energy generation potential of utility-scale PV power

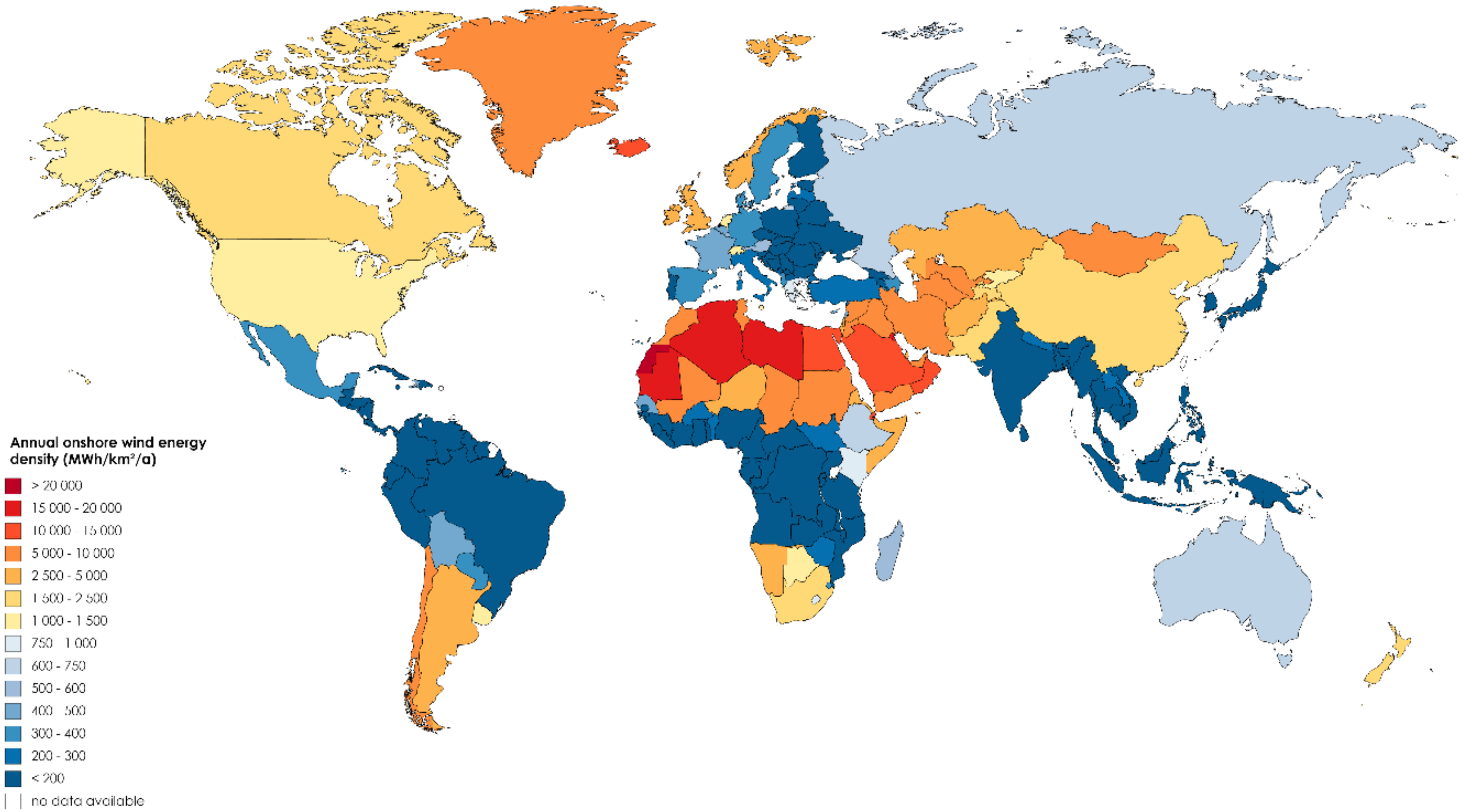


- Largest potential producers: MENA countries with > 7,500 MWh/km²/a.
- Algeria alone could cover 5 times the current European electricity demand
- Inside large countries, local potentials are hidden by country average values.

$$Solar\ energy\ density\ \left(\frac{MWh}{km^2 a}\right) = \frac{Solar\ energy\ output\ (MWh/a)}{Ground\ area\ (km^2)}$$

Source: AUDI AG 2019

Energy generation potential of onshore wind power

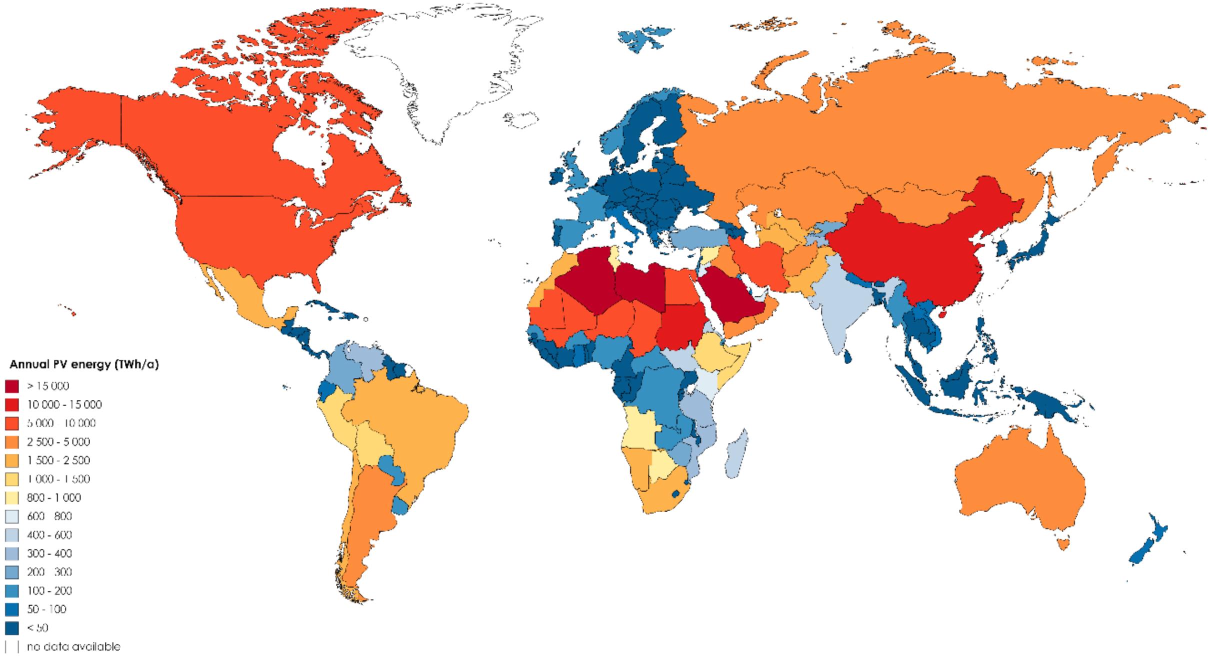


- Largest potential producers: Western Sahara with > 30,000 MWh/km²/a.
- MENA countries, the regions sharing the North Sea, as well as New Zealand, Chile, Argentina and Norway have a great wind potential.
- Denmark is currently a step ahead with a 44% rate of wind energy based electricity in the power grid.
- Again, inside large countries, local potentials are hidden by country average values.

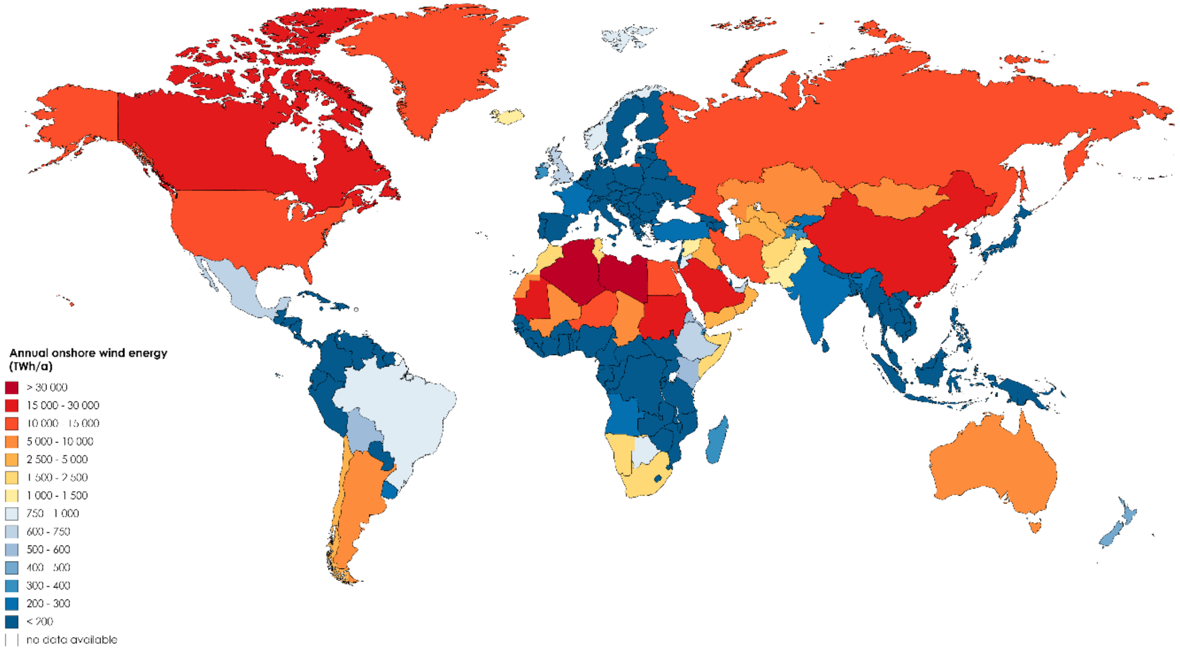
$$Wind\ energy\ density\ \left(\frac{MWh}{km^2 a}\right) = \frac{Wind\ energy\ output\ (MWh/a)}{Ground\ area\ (km^2)}$$

Source: AUDI AG 2019

Potential renewable energies vs. energy demand



Potential photovoltaic energy

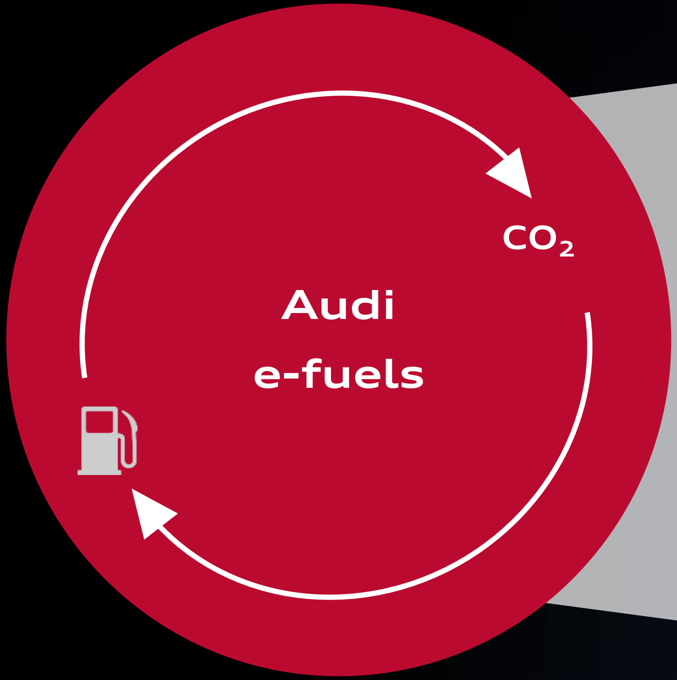


Potential onshore wind energy

Energy [TWh/a]	Potential PV	Potential Onshore Wind	Energy demand 2016
World	206,670	347,750	160,056
EU	1,050	19,500	18,583
USA	6,540	10,160	24,861
Germany	40	120	3,638

Sources: AUDI AG 2019, Dena „The potential of electricity-based fuels for low-emission transport in the EU, Dena Leitstudie „Integrierte Energiewende, BMWI, en:former, Statista

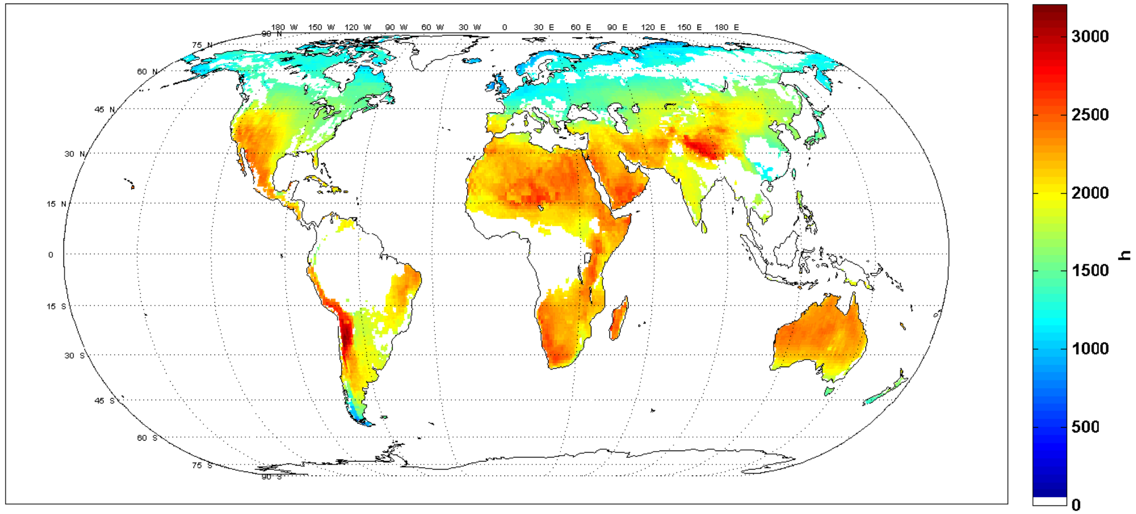
Content



- Motivation: why e-fuels? 1
- What is the worldwide potential of renewable energies? 2
- What is the worldwide potential of e-fuels? 3
- Conclusions 4

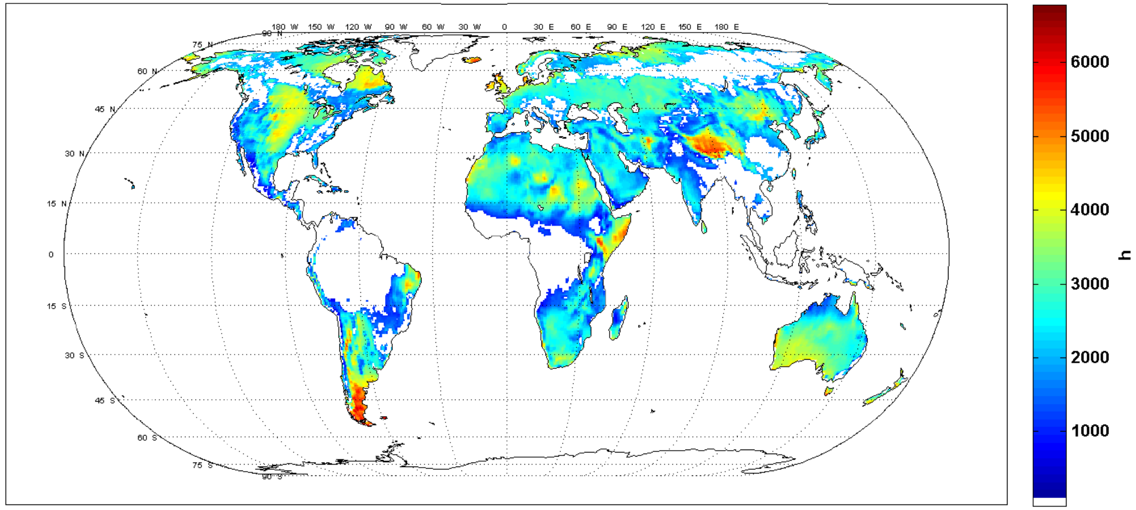
Worldwide PtX potential: Power full-load hours in 2030

PV (1-axis tracking) FLh for cost year 2030

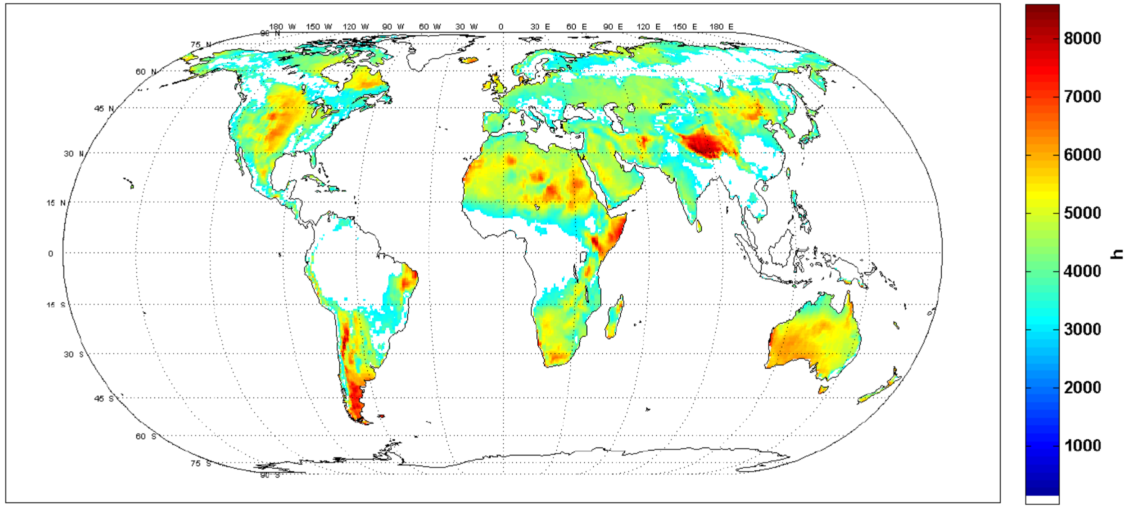


- Assumptions:
  - Only sites with cumulative FLh higher than 3,000 are considered.
  - Fixed tilted PV systems are not installed in 2030 (lower FLh).
- PV champions: Atacama Desert, Sahara Desert, Tibet (> 2,500 FLh).
- Wind champions: Patagonia, Tibet (6,000 - 5,500 FLh).
- Hybrid champions: Patagonia and Tibet (> 7,000 FLh).

Wind FLh for cost year 2030



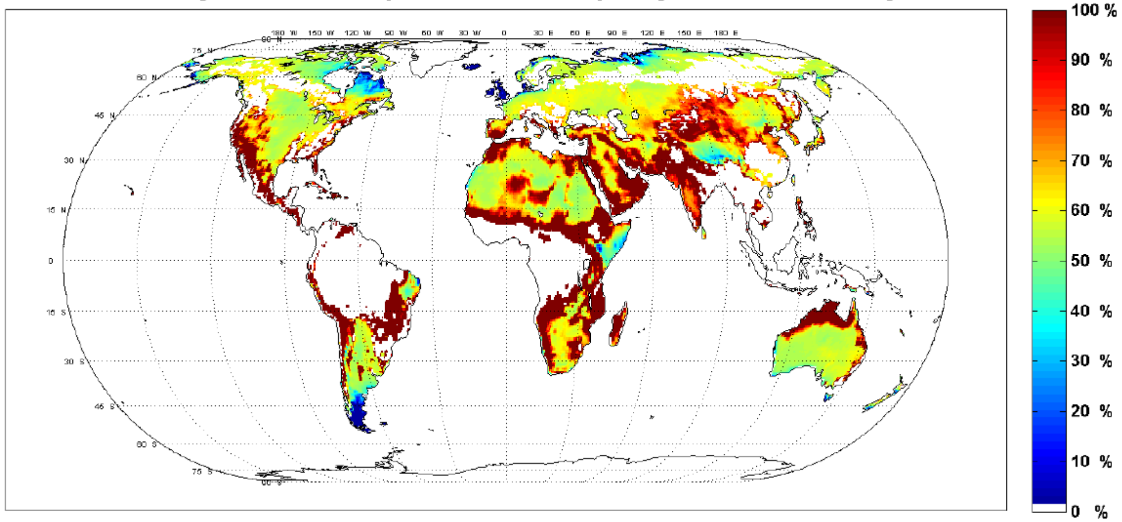
Hybrid PV1-Wind cumulative FLh for cost year 2030



Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer, Lappeenranta University of Technology

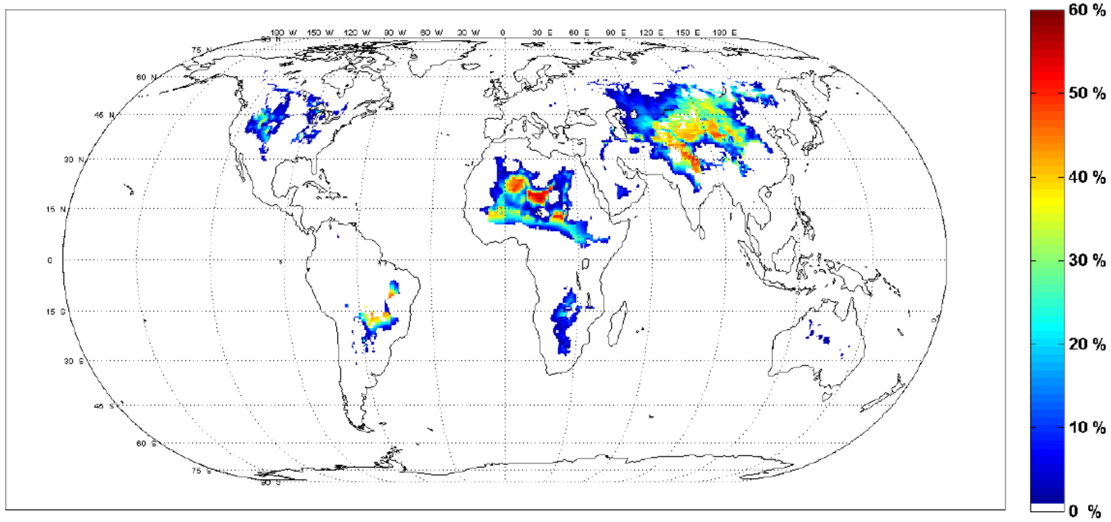
Worldwide PtX potential: Storage demand & excess electricity in 2030

Ratio of PV to hybrid PV-Wind plant installed capacity for PtG, for cost year 2030

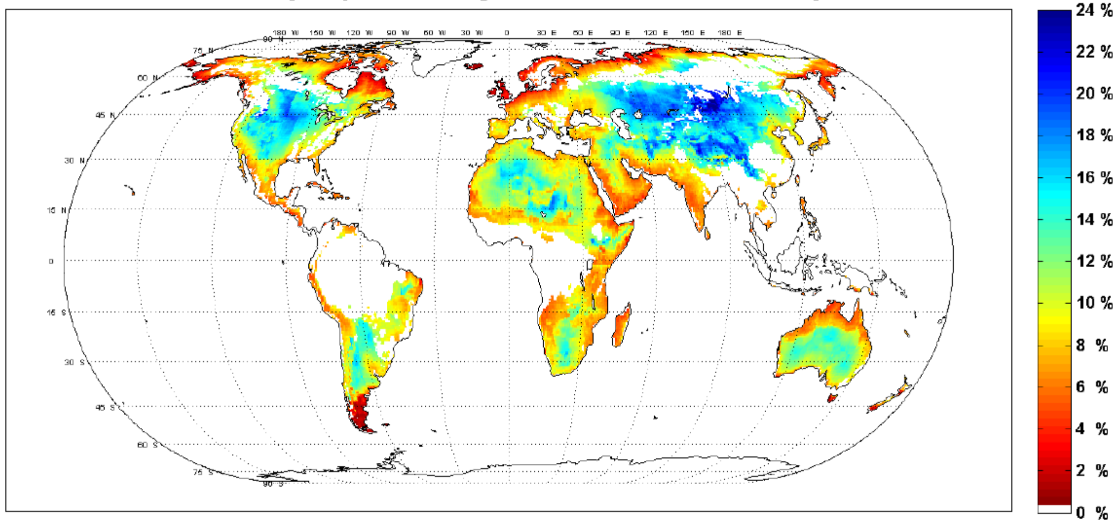


- The PV-Wind share has to be optimized according to LCOE/FLh.
- Additional electricity costs for PtX depend or certain factors:
  - Long distance to the coast, where PtX have to be introduced
  - High storage costs in order to balance the system for lower electricity transmission cost, especially crucial with a high share of PV, such as Tibet.
  - Excess electricity due to overlap and curtailments.

Ratio of battery to hybrid PV-Wind plant installed capacity for PtG, for cost year 2030



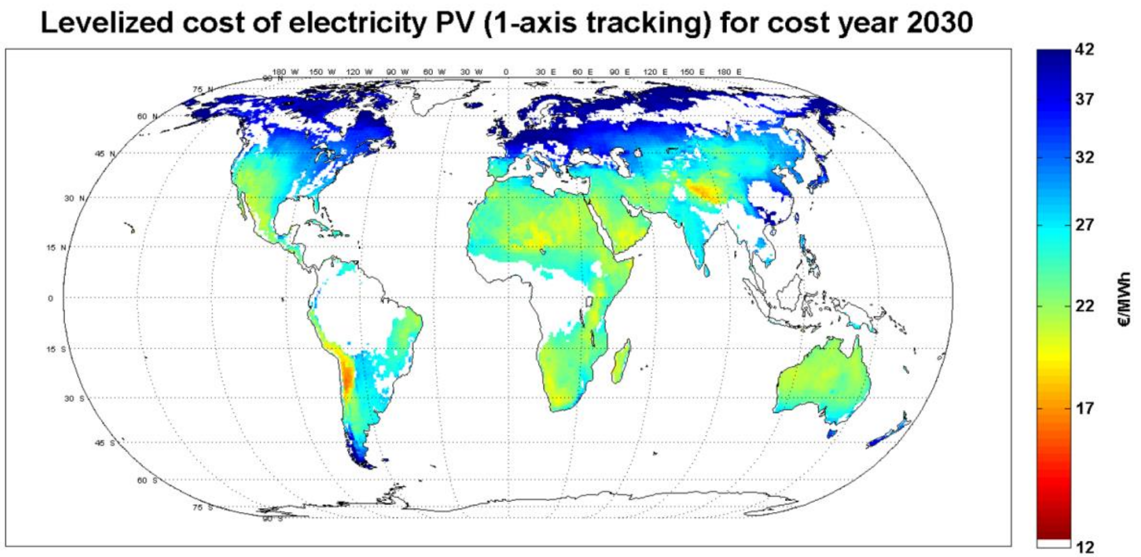
Excess electricity in percent of generationfor PtL, for cost year 2030



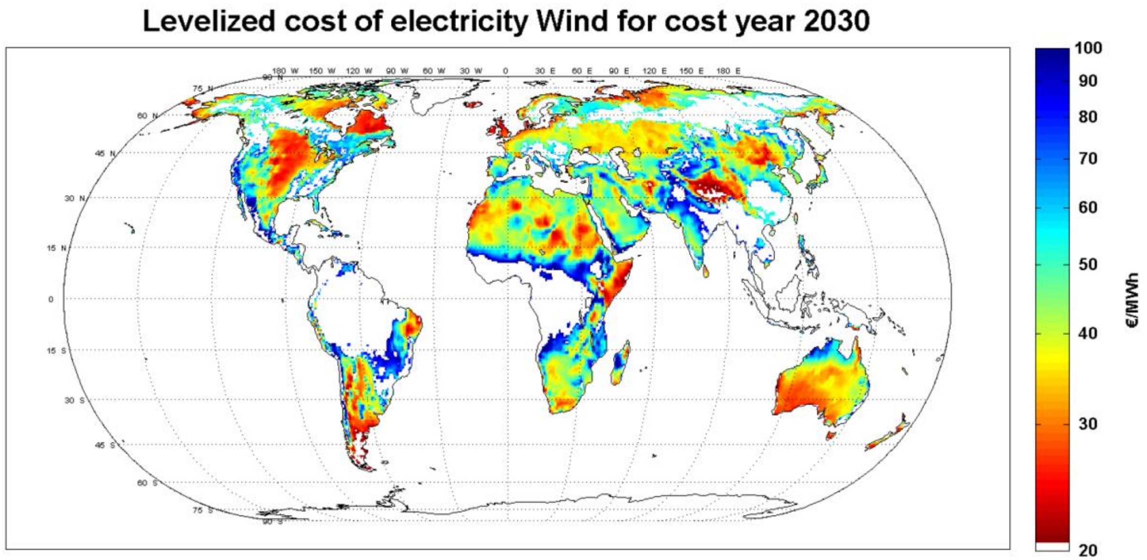
Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer, Lappeenranta University of Technology

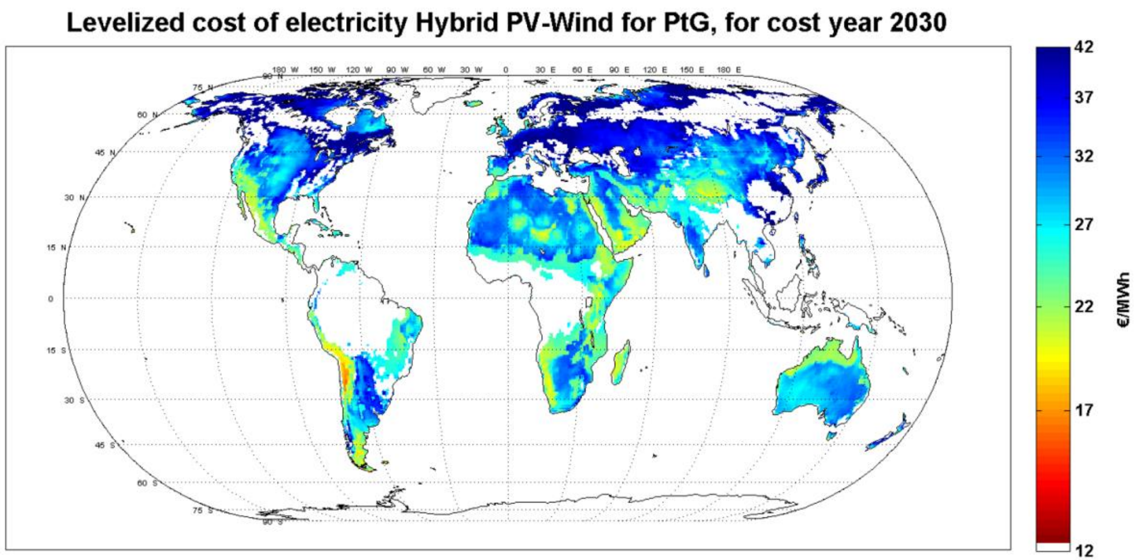
LCOE = Levelized Cost of Electricity

Worldwide PtX potential: LCOE in 2030



- Top site 1-axis PV LCOE: Atacama Desert **~ €ct1.6/kWh**.
- Top site Wind LCOE: Patagonia **~ €ct1.9/kWh**.
- Top site hybrid PV-Wind LCOE: **~ €ct1.7-2.0/kWh**.

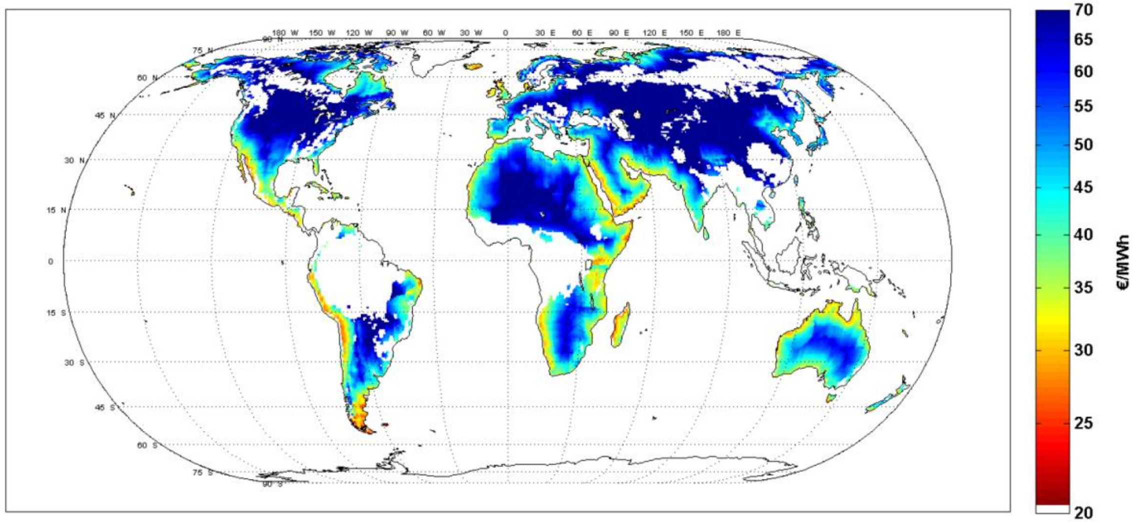




LCOE = Levelized Cost of Electricity
LCOF = Levelized Cost of Fuel

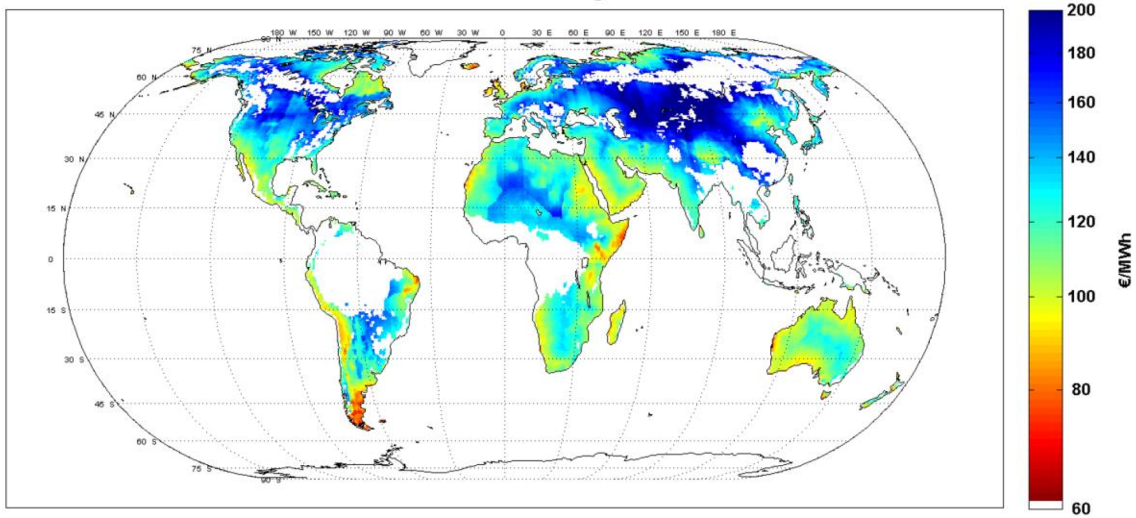
Worldwide PtX potential: LCOE & LCOF in 2030

Levelized cost of delivered electricity for PtG, for cost year 2030

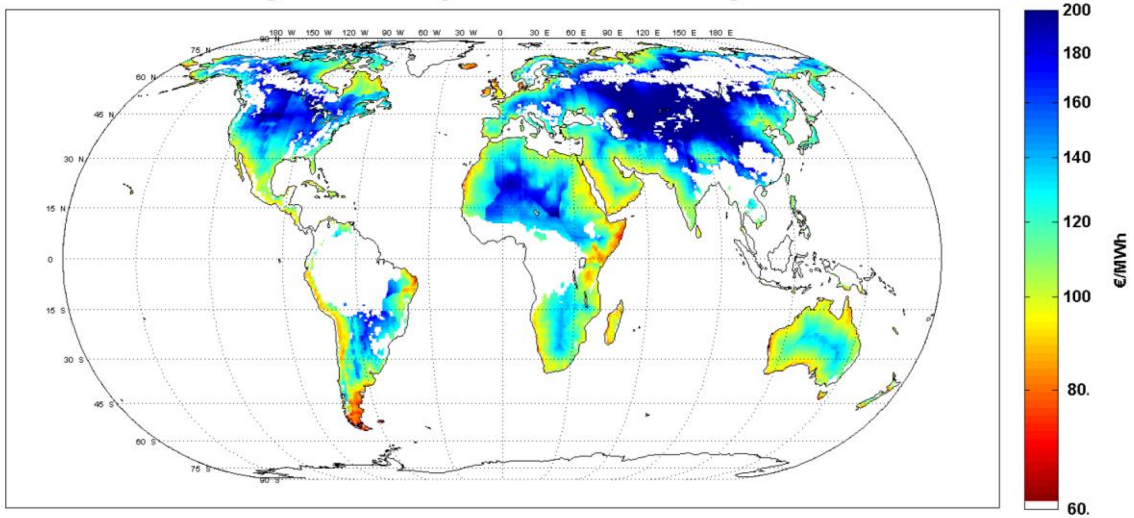


- Top site 1-axis PV LCOE: Atacama Desert **~ €ct1.6/kWh**.
- Top site Wind LCOE: Patagonia **~ €ct1.9/kWh**.
- Top site hybrid PV-Wind LCOE: **~ €ct1.7-2.0/kWh**.
- Top sites could deliver electricity to PtX plants at **€ct2.5-3.0/kWh**.
- Assumption: CO_2 is supplied by a Direct Air Capture (DAC) plant.
- Top sites in the world could reach LCOF of **€70-80/MWh** in 2030.
- Additional cost to SNG cost for LNG value chain: **€15-20/MWh**.

Cost of SNG for cost year 2030

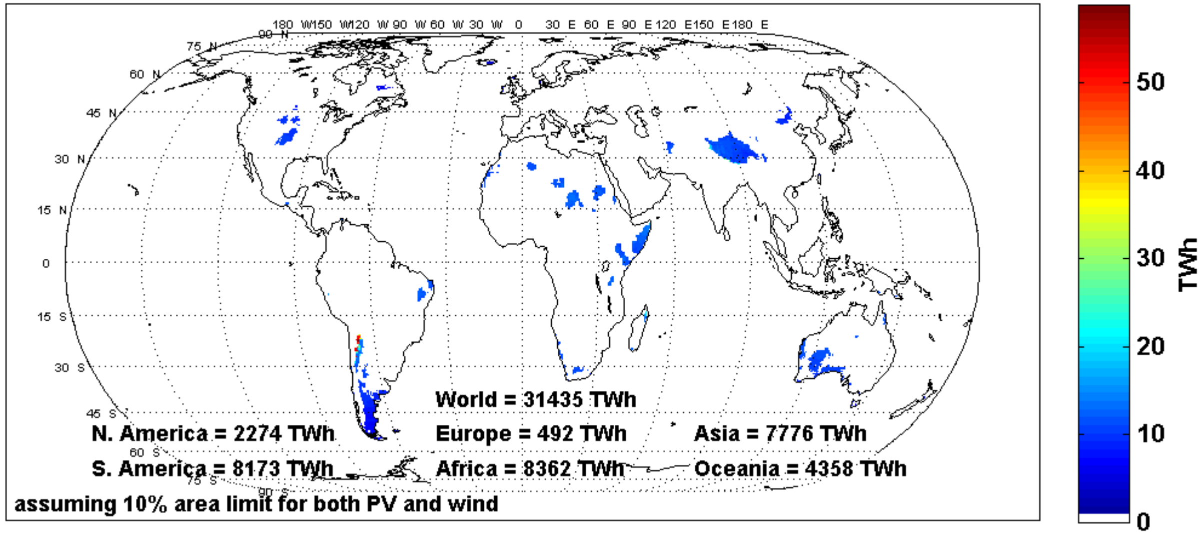


Cost of Synthetic Liquid Fuels for cost year 2030

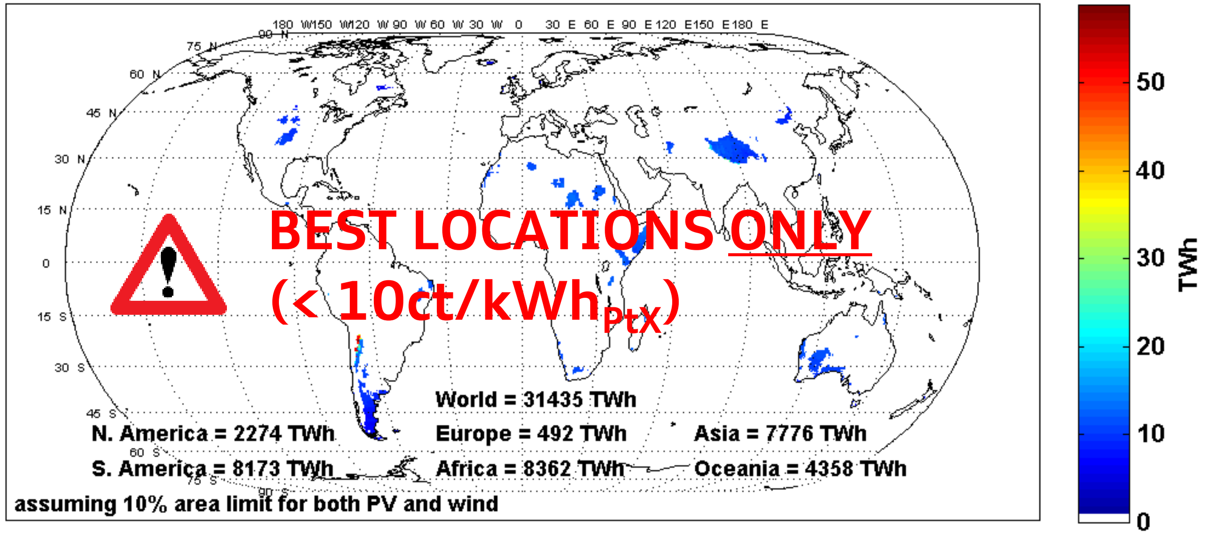


Source: Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants, M. Fasihi, D. Bogdanov & C. Breyer, Lappeenranta University of Technology

Worldwide PtX potential vs. energy demand



Power generation potential in best areas for PtX in 2030
Potential Hybrid PV-Wind power plant: 31.435 TWh/a



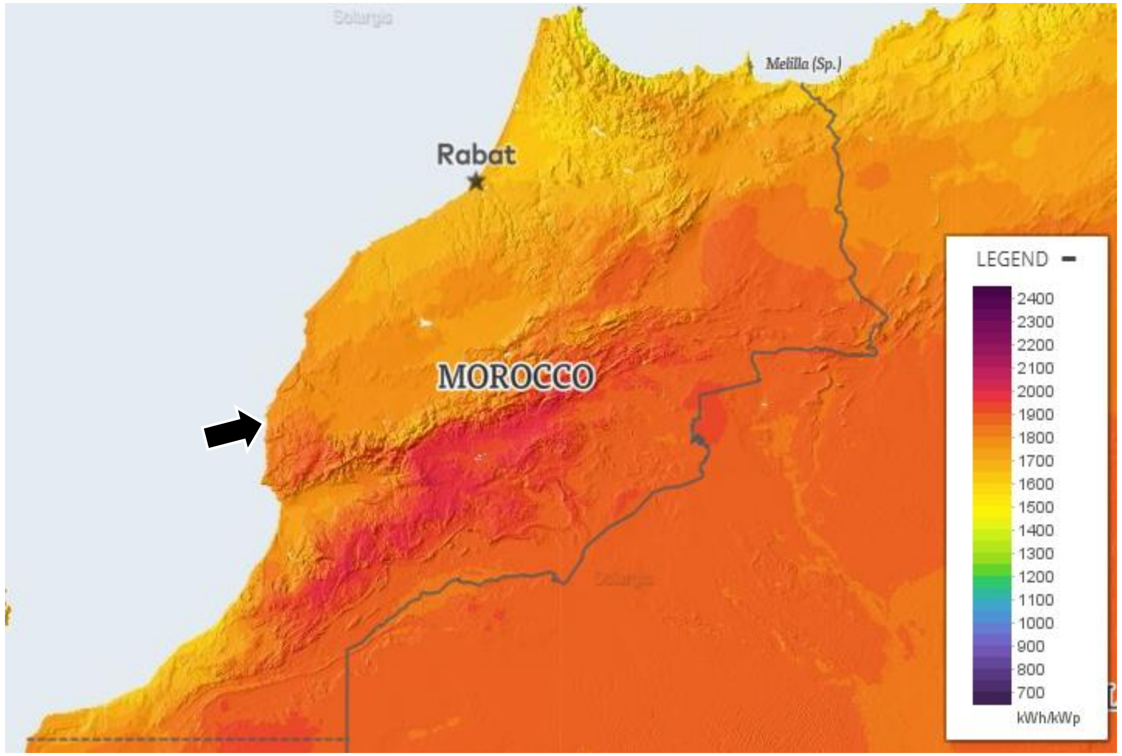
PtX production potential in 2030: **17.557 TWh/a**

Best Locations could cover the PtX demand of 23-33 Germanys!

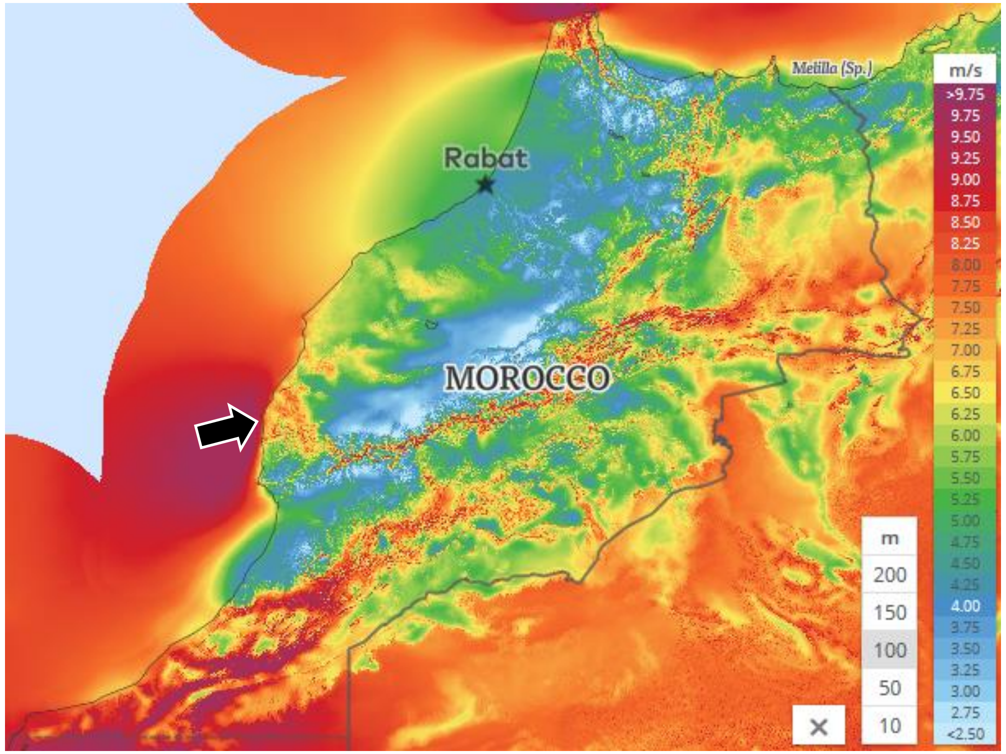
Germany 2050	EL 95	TM 95
Primary energy demand [TWh/a]	1,861	2,007
Renewable energy demand [TWh/a]	1,139	1,029
PTX-Demand [TWh/a]	533	744

Sources: Dena „The potential of electricity-based fuels for low-emission transport in the EU, Dena Leitstudie „Integrierte Energiewende, BMWI, Dmitrii Bogdanov, Mahdi Fasihi and Christian Breyer, *Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants*

Simulation for an attractive spot in Morocco in 2030



Full-load hours of fixed tilted PV panels in Morocco



Average wind speed in Morocco

Chosen location

- Wind and solar conditions both optimal → Hybrid PV-Wind power plant with 7,000 FLh
- Access to the ocean with a harbor located 20 km in the South (Agadir) → export is possible
- Water available from the ocean with additional desalination
- Desert region without natural or urban restraints

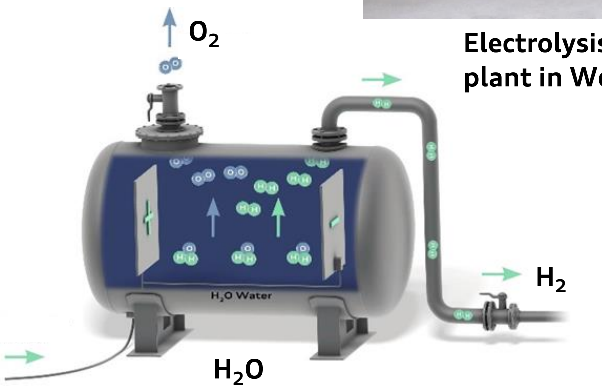
Source: Global Solar Atlas, Global Wind Atlas

Simulation for an attractive spot in Morocco in 2030

+

→

Renewable energy



H_2O

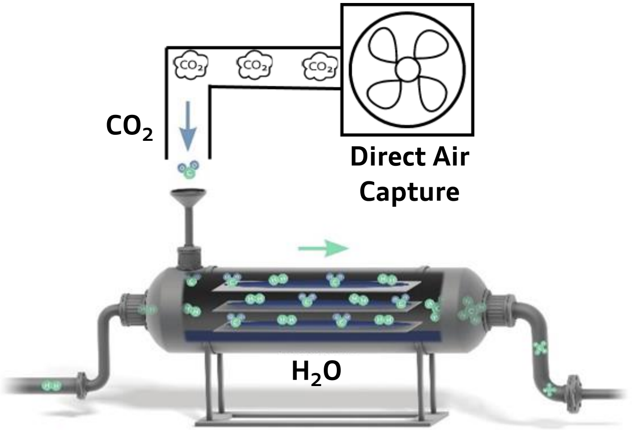
↑

Water desalination (SWRO)

Electrolysis of the AUDI PtG plant in Werlte, Germany

→

Climeworks' Carbon Air Capturing plant in Switzerland captures about 1,000 tons CO_2 per year



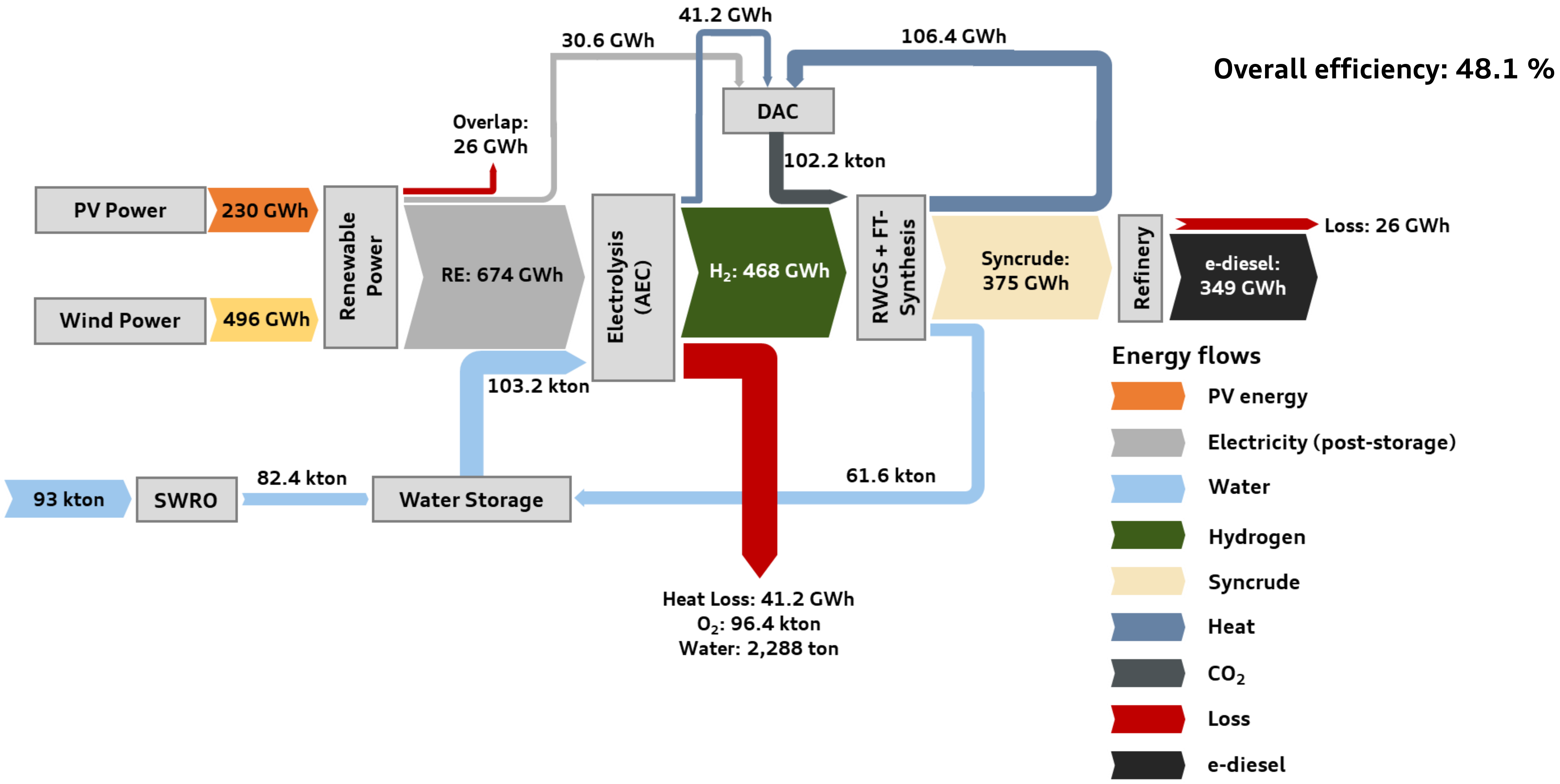
H_2 → PtL / PtG

The Ashkelon SWRO desalination facility (IDE) produces 13% of Israel's domestic consumer demand: 100 million m³/a, for $0.52/m³

Methanation of the AUDI PtG plant in Werlte, Germany

Source: AUDI AG 2019, Climeworks AG, The Times of Israel, James Galfund, https://blogs.timesofisrael.com/israels-innovative-water-solutions-from-striking-a-rock-to-desalination/

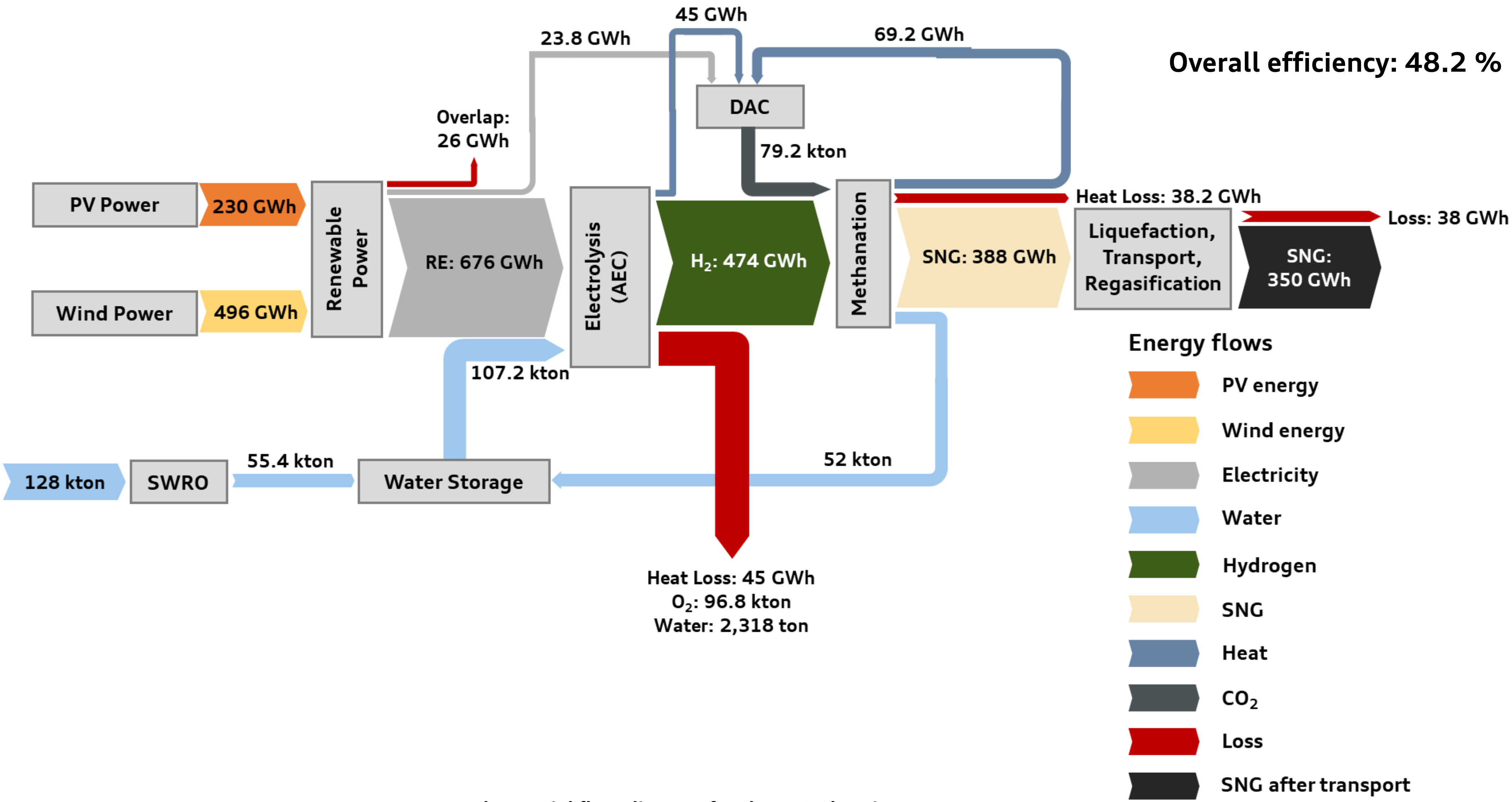
Simulation for an attractive spot in Morocco in 2030



Energy and material flow diagram for the PtL plant in Morocco

Source: AUDI AG 2019, Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants - Mahdi Fasihi*, Dmitrii Bogdanov, Christian Breyer

Simulation for an attractive spot in Morocco in 2030



Energy and material flow diagram for the PtG plant in Morocco

Source: AUDI AG 2019, Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants - Mahdi Fasihi*, Dmitrii Bogdanov, Christian Breyer

Simulation for an attractive spot in Morocco in 2030

	Assumptions H_2tX	e-diesel 1.14 €/$l_{e\text{-}diesel}$ (1)	SNG 1.58 €/kg_{SNG} (1)
	Cost of capital [%]	5	
PV	Full Load hours [h/a]	2,300	
PV	Power capacity [MW_p]	100	
PV	LCOE [ct/kWh]	1.49	
Onshore Wind	Full Load hours [h/a]	4,955	
Onshore Wind	Power capacity [MW]	100	
Onshore Wind	LCOE [ct/kWh]	2.23	
Hybrid Power	Overlap PV7Wind [%]	3.5	
Hybrid Power	Full Load hours [h/a]	7,000	
Hybrid Power	LCOE [ct/kWh]	2.07	
SWRO	Cost of water [€/m^3]	0,21	
Electrolysis	Capacity [MW_{el}]	100	
Electrolysis	Full Load hours [h/a]	7,000	
Electrolysis	Cost of H_2 [€/kg H_2]	1.60	
DAC	CO_2 costs [€/t CO_2]	83	
FT / Meth.	Capacity [MW_{PtX}]	48	55
FT / Meth.	Full Load hours [h/a]	7,800	7,000
	Hydrocracking cost [ct/$l_{e\text{-}diesel}$]	5.25€ct/l eDiesel	-
	Transport costs [ct/l or ct/kg]	4.2 (2)	32 (3)
	Overall investment [Mio.€]	325	284
	Volume [$l_{e\text{-}diesel}$] or [ton_{SNG}]	35,086,000	25,200

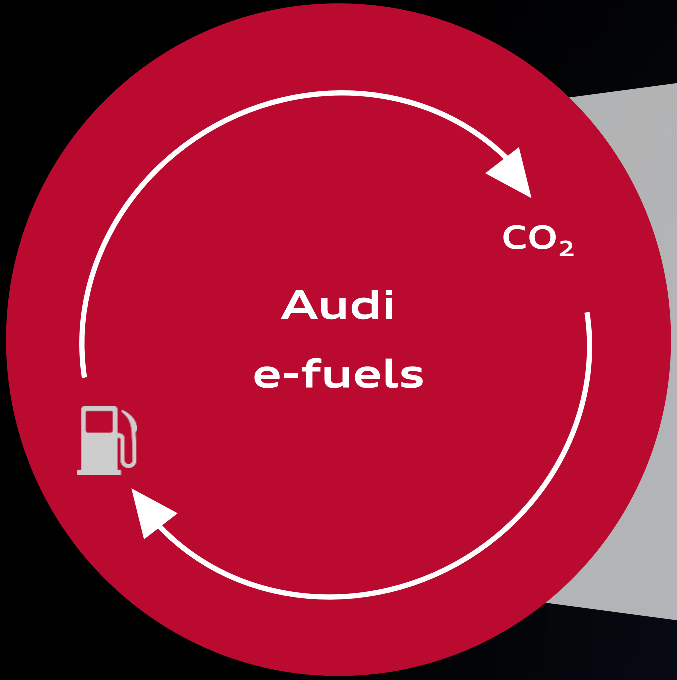
→ 35,000 vehicles

Overall efficiency: 48 %
for both PtL and PtG including transport to filling stations

(1) Cost at the gas station
(2) Import shipping + pipeline and transport to gas stations
(3) incl. local liquefaction, transport with LNG-tanker ship, regasification and gas grid expenses (Source: Agora 2018)

Source: AUDI AG 2019, Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants - Mahdi Fasihi*, Dmitrii Bogdanov, Christian Breyer

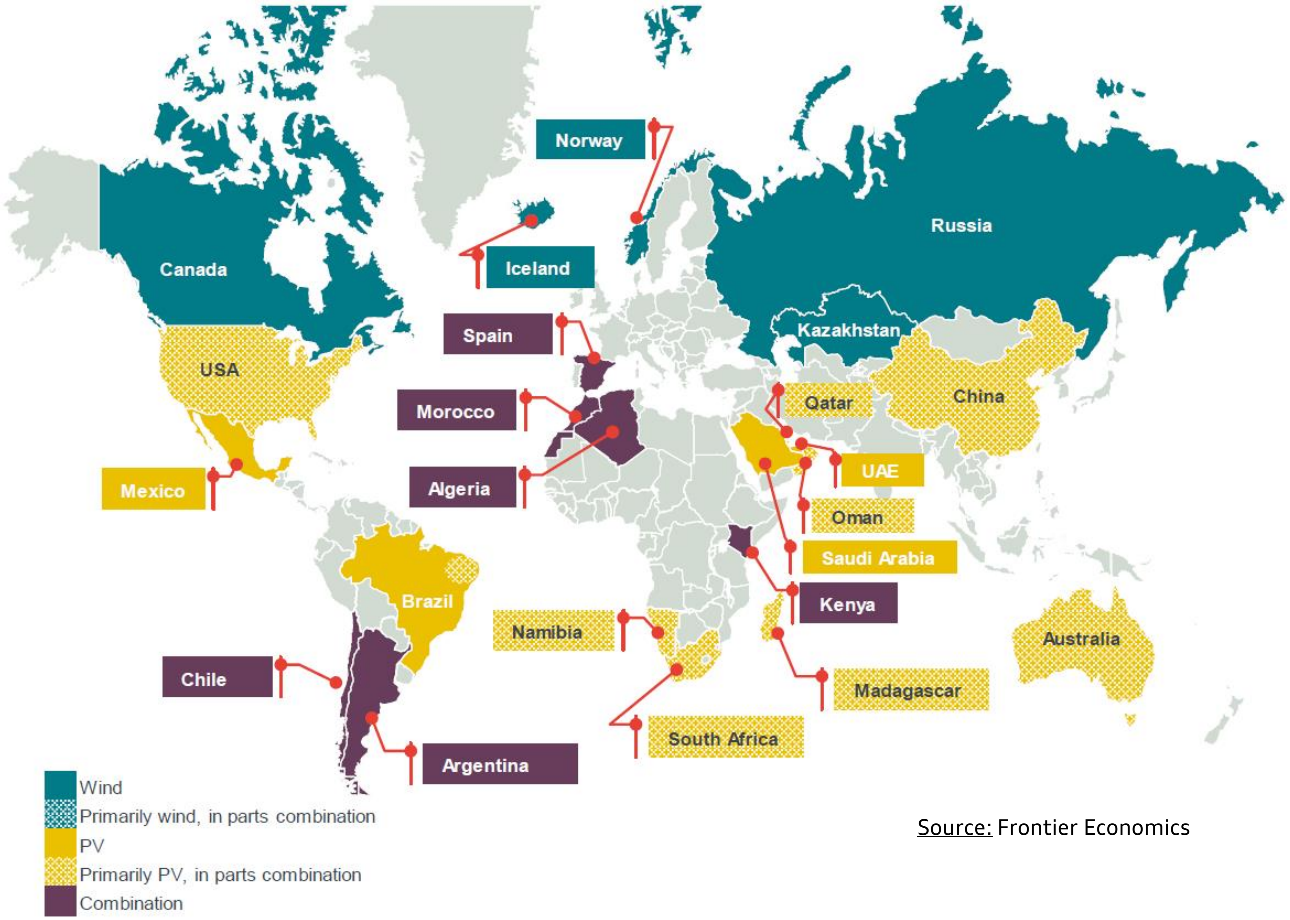
Content



Conclusions

- Renewable energies have an extremely high potential in some regions → energy export to other markets with PtX energy carriers.
- The main cost factors for PtX are the LCOE and the number of FLh for operating the PtX plant → a PV-Wind combination is often necessary to reach competitive costs.
- PtX technologies have a high potential in terms of possible rising volume and cost decrease over time. A further PtG cost decline could be enabled by the development of the gas grid.

Morocco / Patagonia = 



Source: Frontier Economics

Snapshot of the variety and diversity of potential PtX producing countries

Questions?

Source: Business Wire

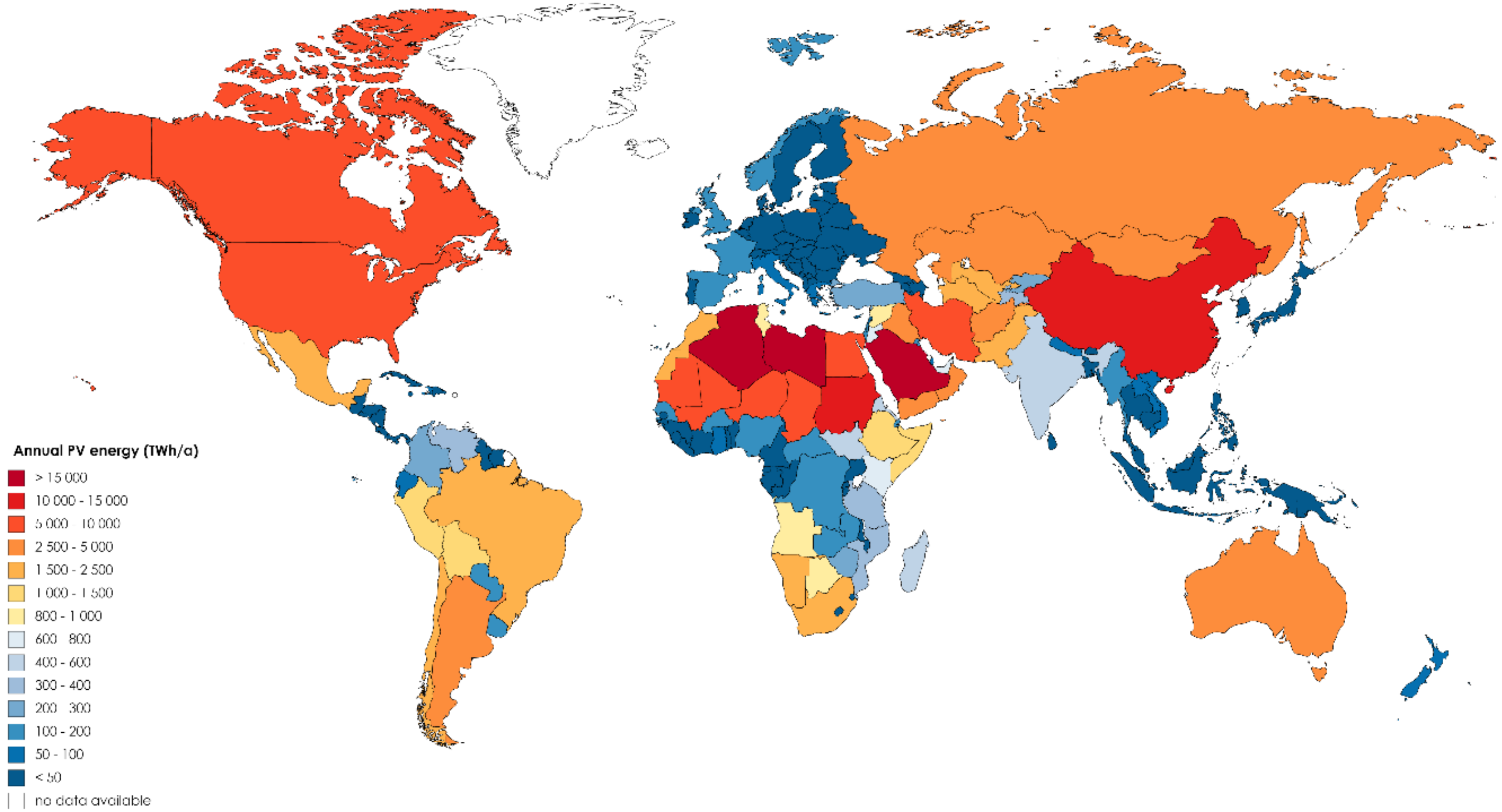
Back-UP: Decarbonization of the mobility sector: potential of Power-to-X techologies

Corentin Prié – AUDI AG – Sustainable Product Development

17.12.2019 – KIT – Seminar Combustion Engines

Source: CNBC

Energy generation potential of utility-scale PV power: Results

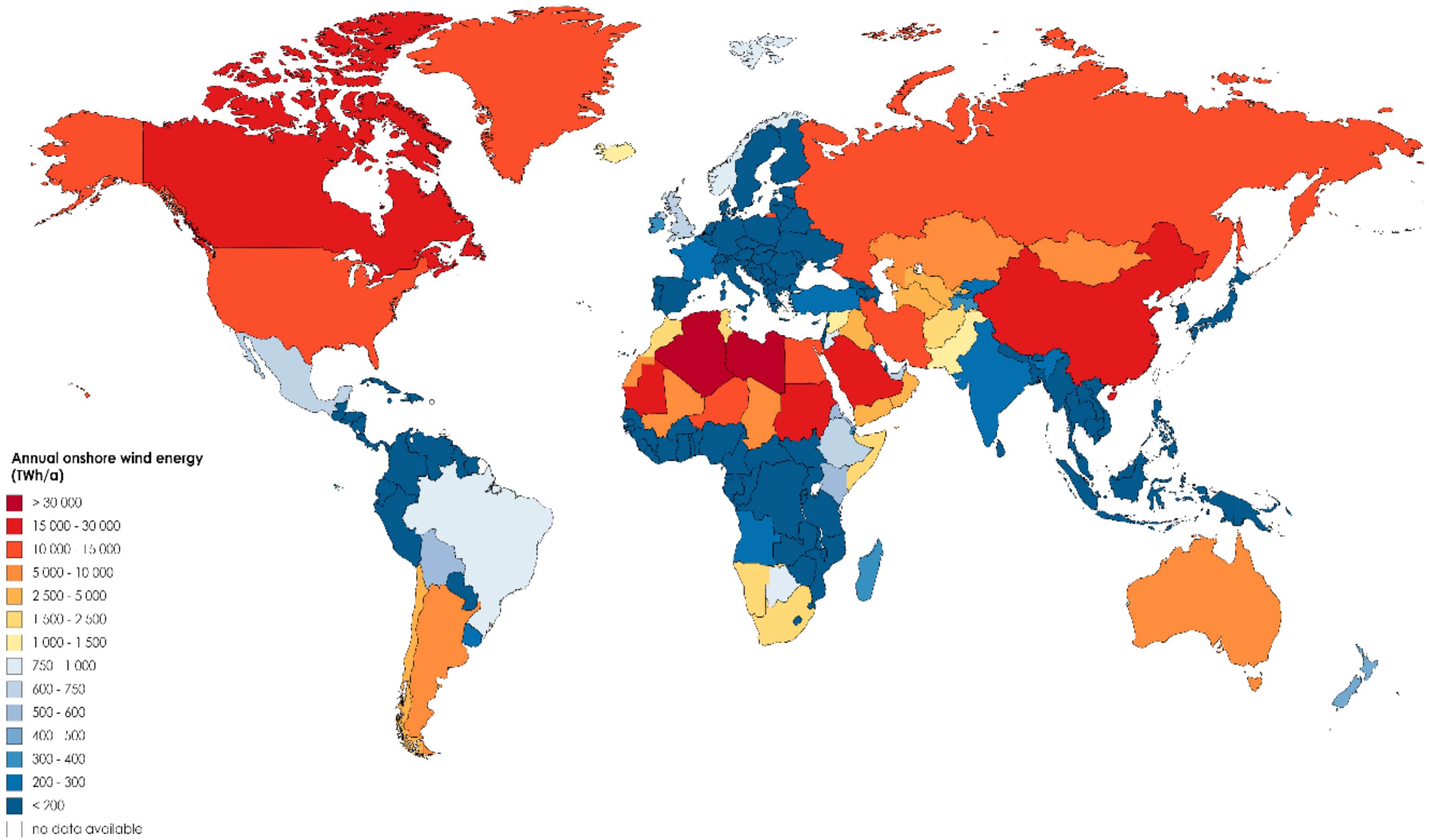


- Largest potential producers: Algeria, Saudi Arabia, and Libya with > 15,000 TWh/a.
- The largest PV power generation potential is measured in Northern Africa and the Middle East but the development of PtX facilities could strongly depend on the local political situation.
- Giant countries like Canada, the USA, China and Australia benefit from large bare spaces to install PV power plants.
- The potential of small countries is hidden by the surface difference with large countries

$$Electric\ energy\ output: E_{PV}\left(\frac{kWh}{a}\right) = Iradiation\left(\frac{kWh}{m^2 a}\right) \times Efficiency_{PV} \times Suitable\ Area\ (m^2)$$

Source: AUDI AG 2019

Energy generation potential of onshore wind power: Results

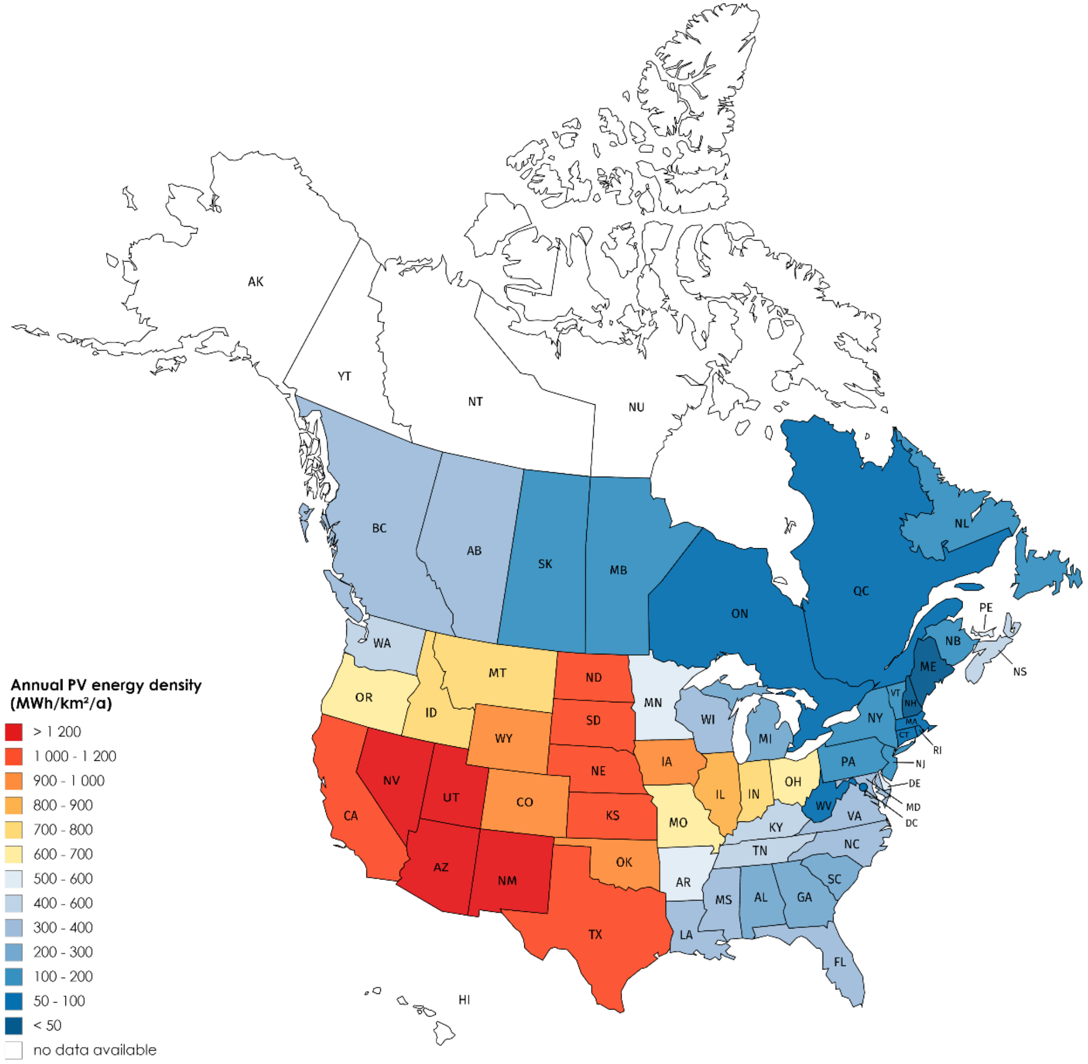


$$\textit{Electric energy output:}\ E_{Wind}\left(\frac{kWh}{a}\right) = \frac{P_{W,el}}{A_G} \times A_{suitable} \times 8760$$

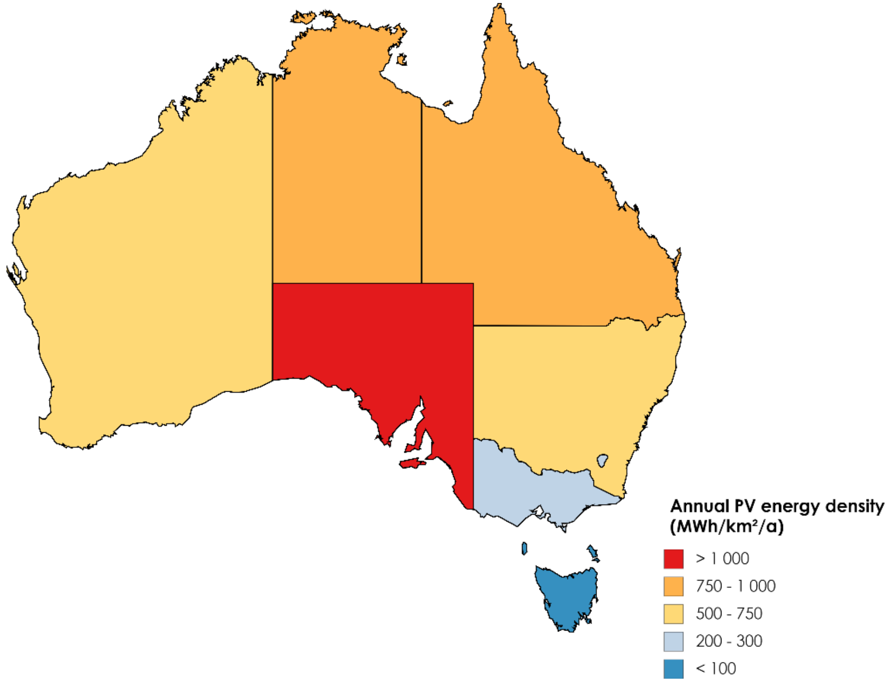
- Largest potential producers: Algeria and Libya with > 30,000 TWh/a.
- Large countries like Canada, China, the USA and Russia could exploit bare areas to produce onshore wind energy.
- Countries with wide forests like in Central Africa and countries sharing the Amazon don't have the space required to install onshore wind parks.
- The potential of small countries is hidden by the surface difference with large countries

Source: AUDI AG 2019

Energy generation potential of utility-scale PV power: Results



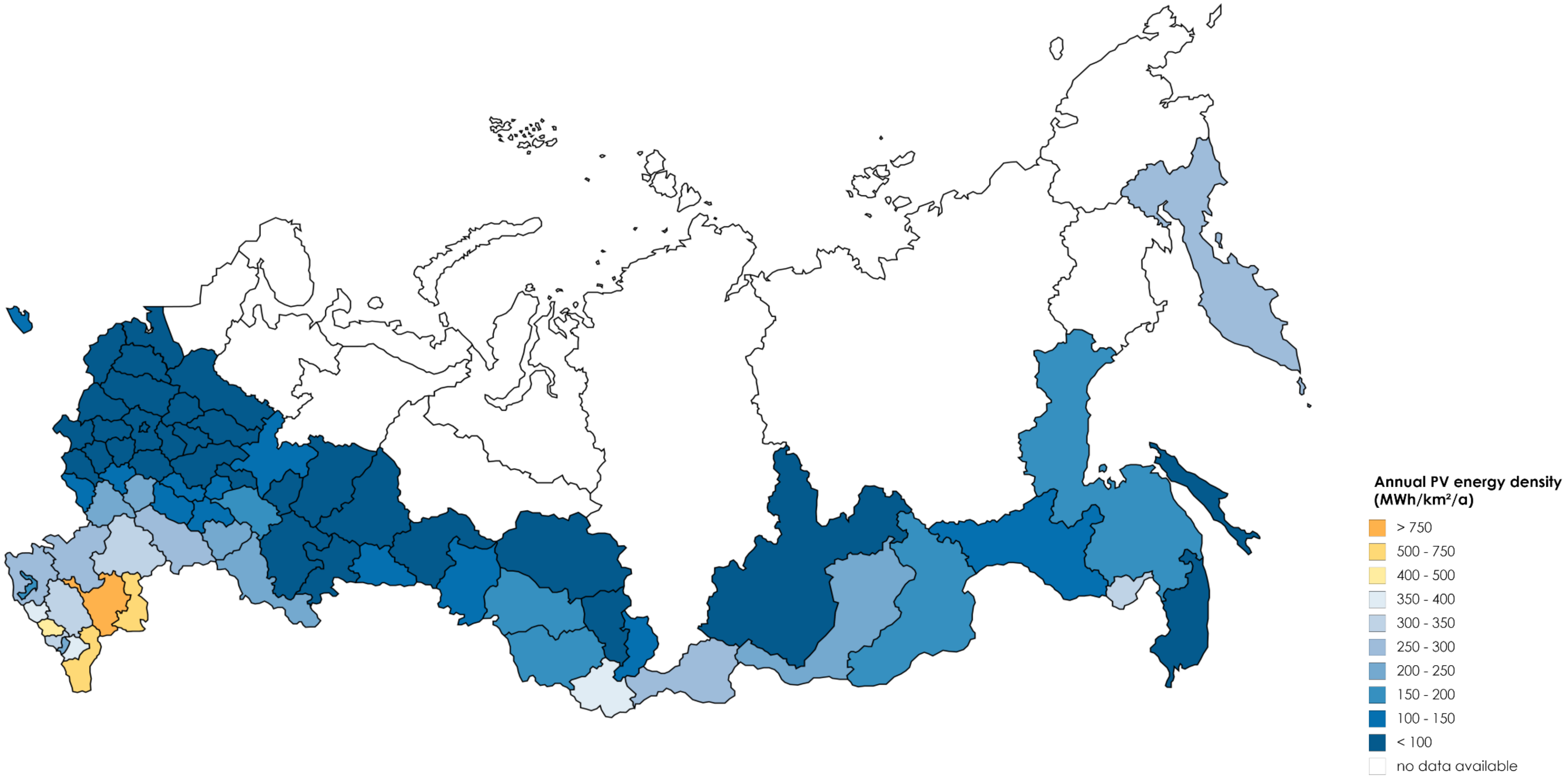
Potential annual energy output density of centralized PV in North America



Potential annual energy output density of centralized PV in Australia

Source: AUDI AG 2019

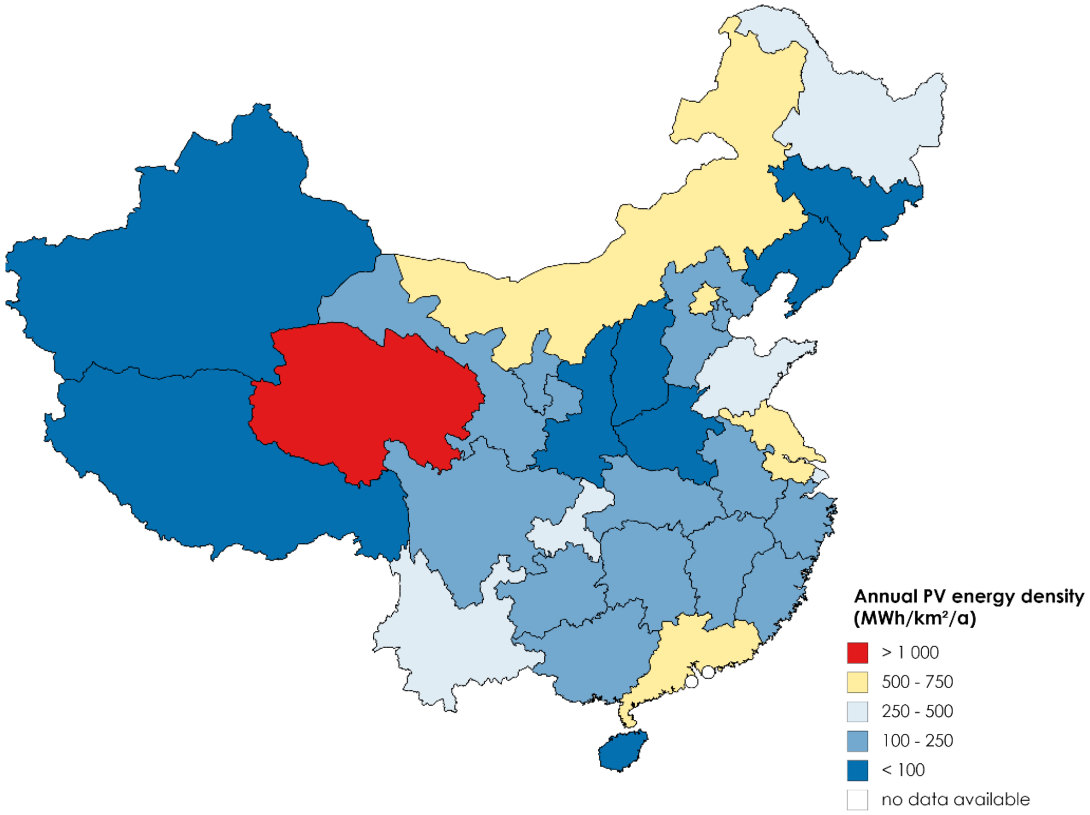
Energy generation potential of utility-scale PV power: Results



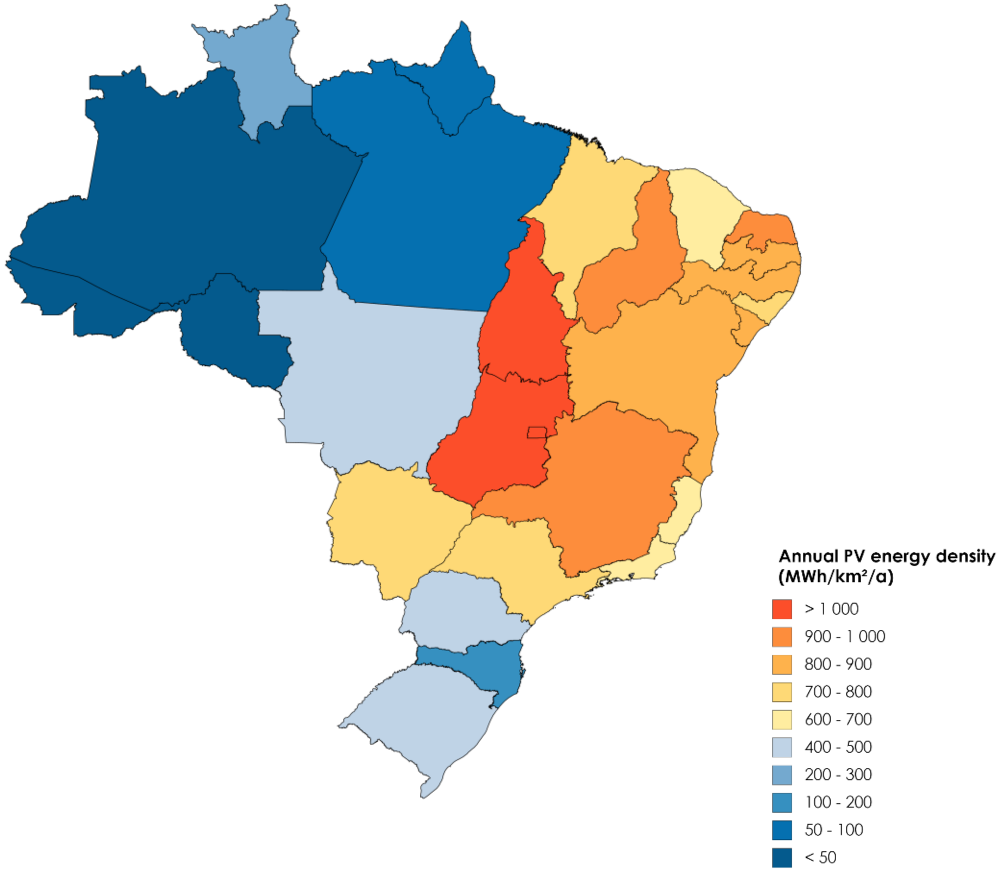
Potential annual energy output density of centralized PV in Russia

Source: AUDI AG 2019

Energy generation potential of utility-scale PV power: Results



Potential annual energy output density of centralized PV in China



Potential annual energy output density of centralized PV in Brazil

Source: AUDI AG 2019