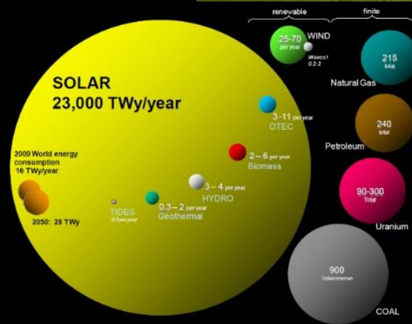
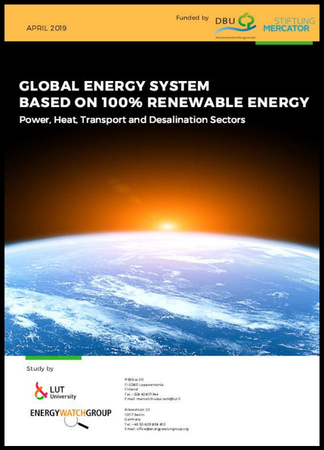


Impact of the transition towards 100% renewable energy systems on primary and final energy demand



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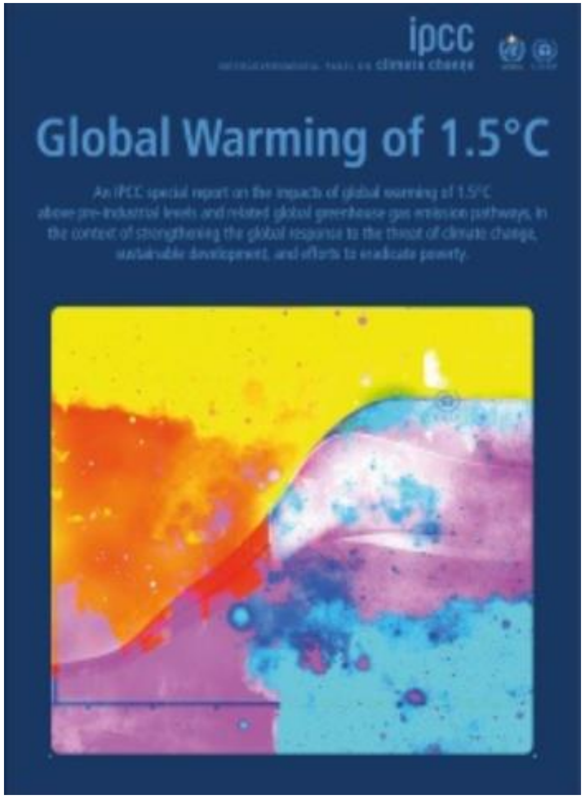
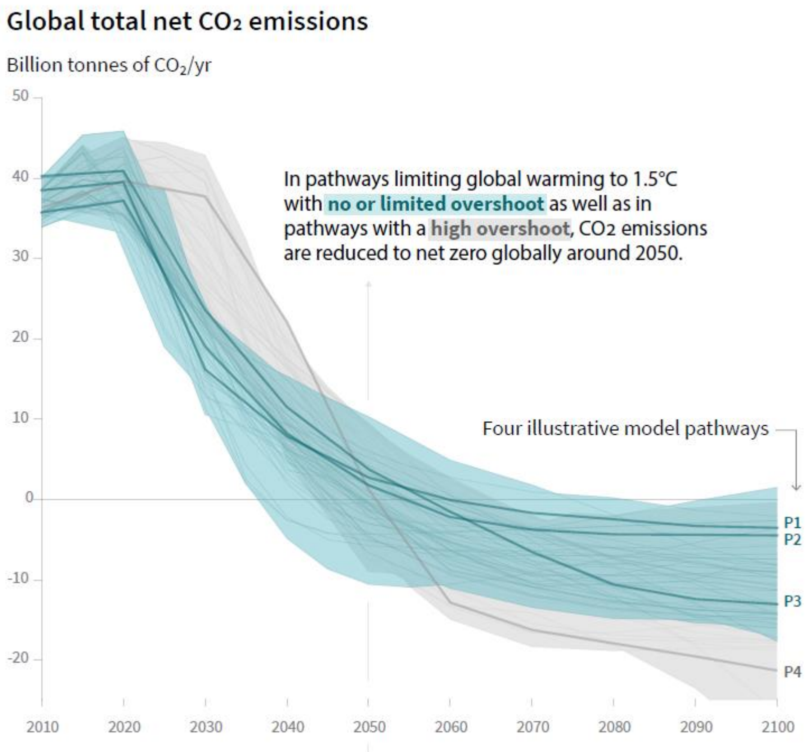
Christian Breyer, Dmitri Bogdanov,
Manish Ram, Arman Aghahosseini
LUT University, Lappeenranta, Finland

14th SDEWES
Dubrovnik, October 2, 2019

Latest insights for a 1.5°C world

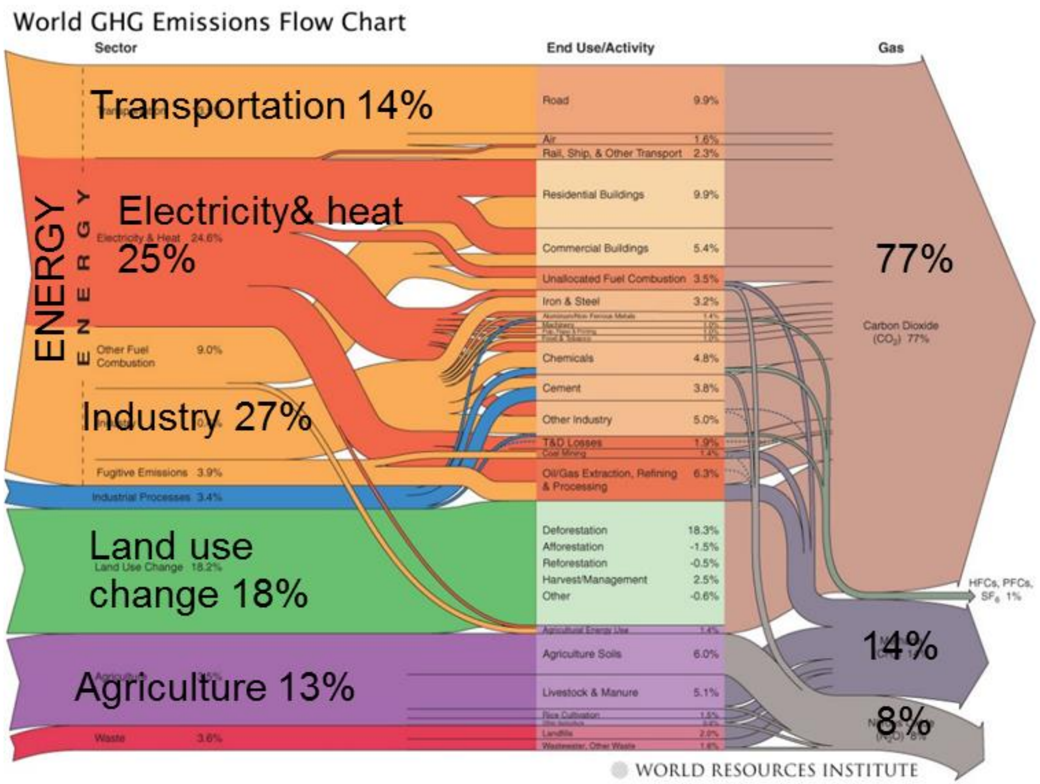




Key insights:

- very fast defossilisation is needed in any case
- zero GHG emissions in 2050s in all relevant scenarios
- net-negative CO_2 emissions from 2050s onwards
- 100% RE referenced in in the SR1.5 for the first time in IPCC history
- please be aware, a 1.5°C scenario still implies loss of most coastal cities in the world

Origin of GHG emissions



Key insights:
- Net zero emissions is mandatory for ALL GHG emissions
- To achieve net zero for the agricultural sector and land use changes is outstanding difficult
- Consequence 1: all energy sectors (Power, Heat, Transportation, Industry) HAVE to go to zero
- Consequence 2: all usage of fossil coal, oil, gas needs to be stopped
- Scientific debate on 'negative emission technologies' is intensifying
  - Afforestation may have a strong impact as constraint AND opportunity

Society changes. www.scientists4future.org

Five EU countries call for 100% renewable energy by 2050

By Sam Morgan | EURACTIV.com Mar 5, 2019 (updated: Mar 5, 2019)

Luxembourg's Claude Turmes speaks to media, 9 October 2018. [Photo: EPA-EFE/JULIEN WARNAND]

Languages: Français | Deutsch

The European Union's 28 energy ministers had their first public debate on the European Commission's 2050 climate plan on Monday (4 March) but five member states derided the lack of a 100% renewable energy scenario among the EU executive's proposed options.

The Commission's Clean Planet for All strategy, which debuted in November 2018, offers EU countries eight different emission-cutting scenarios to make Europe's economy compliant with the

Climate change

'The beginning of great change': Greta Thunberg hails school climate strikes

The 16-year-old's lone protest last summer has morphed into a powerful global movement challenging politicians to act

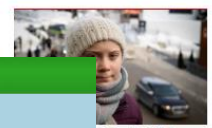
Taking part? Share your stories

Jonathan Watts
@jonathanwatts
Fri 15 Feb 2019 06.00 GMT

47,988

'I want you to panic': 16-year-old issues climate warning at Davos – video

Greta Thunberg is hopeful the student climate strike on Friday can bring about positive change, as young people in more and more countries join the protest movement she started last summer as a lone campaigner outside the Swedish parliament.



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source:
Hagedorn et al., 2019. The concerns of the young protesters are justified, GAIA, 28(2), 79-87

SCIENTISTS FOR FUTURE

#FFF Events / Graph Events / List

Scientists for Future

"Die junge Generation hat Recht"

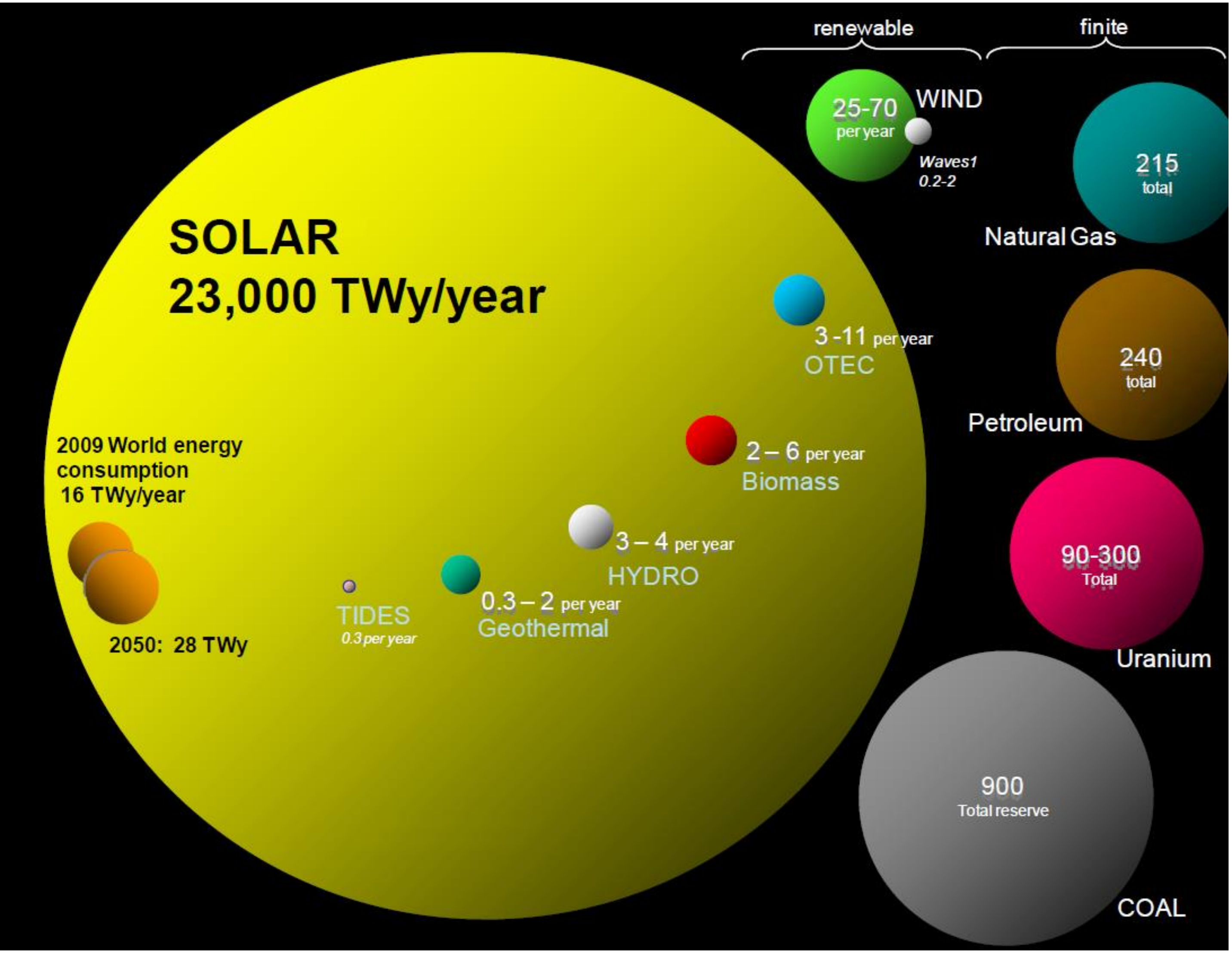
Stand: 12.03.2019 14:40 Uhr

Die Schüler, die jeden Freitag für das Klima auf die Straße gehen, bekommen Unterstützung aus der Wissenschaft. 12.000 "Scientists for Future" haben eine Petition gestartet.

Von Christopher Jähnert, ARD-Hauptstadtstudio

KORRESPONDENT

Resources and Energy Demand

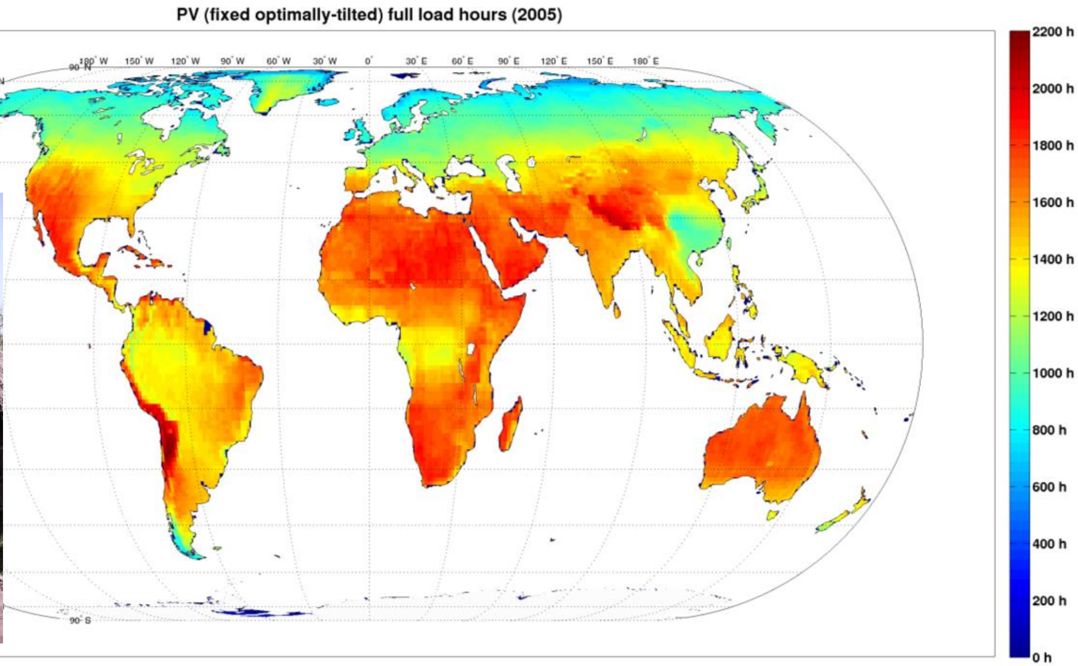


Key insights:
- no lack of energy resouces
- limited conventional resources
- solar and wind resources need to be the major pillars of a sustainable energy supply

Remark:
- conventional resources might be lower than depicted by Perez

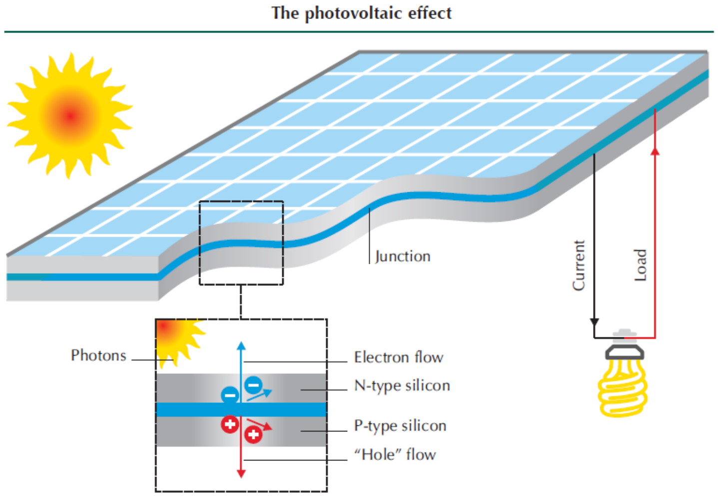
source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50

Solar Photovoltaics

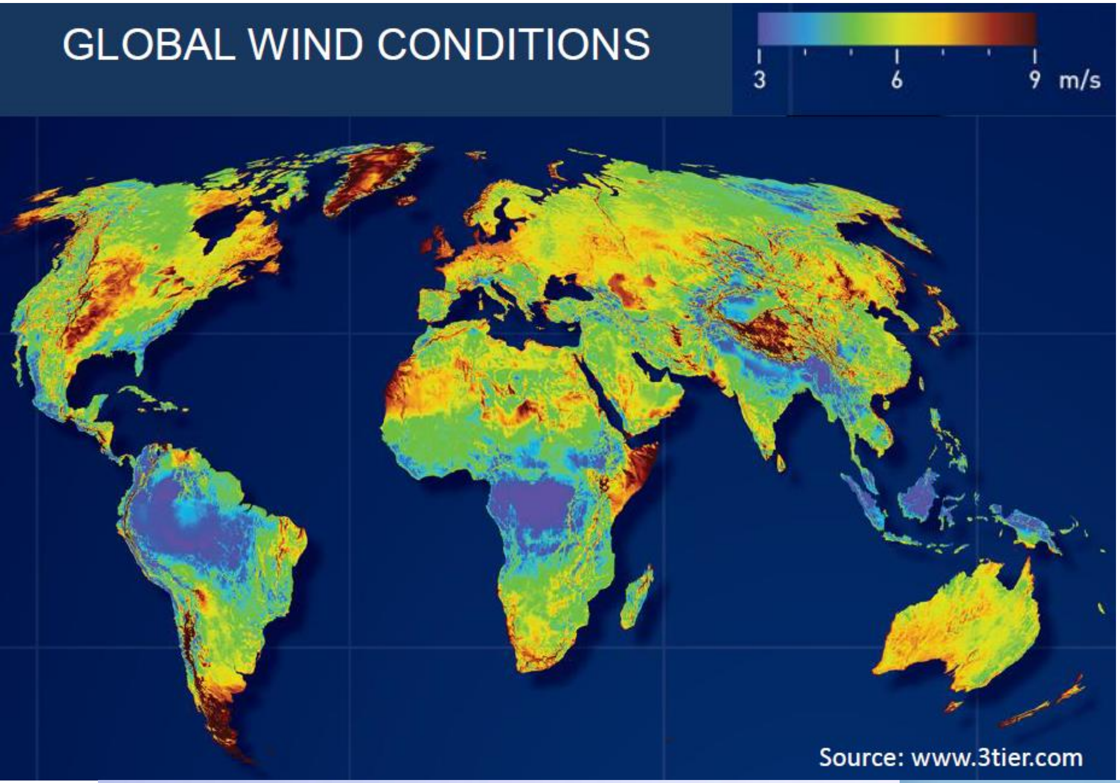


Key insights:

- accessible everywhere – no resource conflicts
- highly modular technology – off-grid, distributed roofs, large-scale
- high learning rate due to ’simple’ technology
- efficiency limit 86%, best lab efficiency 46%, best in markets ~20%
- high growth rate - >40% last 20 years – fast cost decline
- least cost electricity source in a fast growing number of regions
- 1st key enabling technology for survival of human civilization

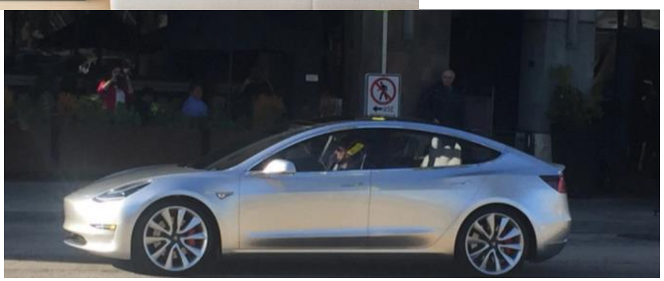


Wind energy

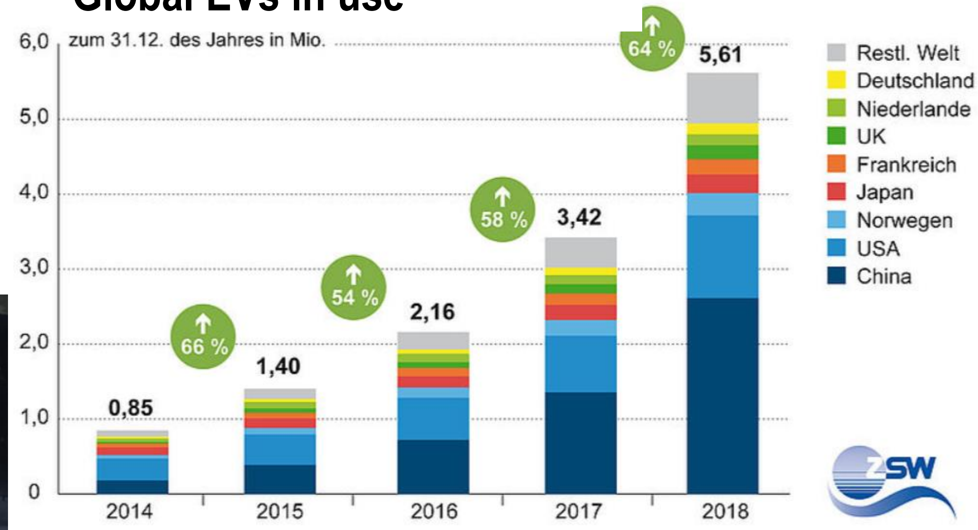


Key insights:
- accessible in all world regions – no resource conflicts
- modular technology – off-grid, community turbines, large-scale
- already on low cost level – 3 – 8 €ct/kWh
- least cost electricity source in wind resouce rich areas
- High full load hours due to 24/7 harvesting
- 2nd key enabling technology for survival of human civilization

Batteries and EVs – Very high dynamics



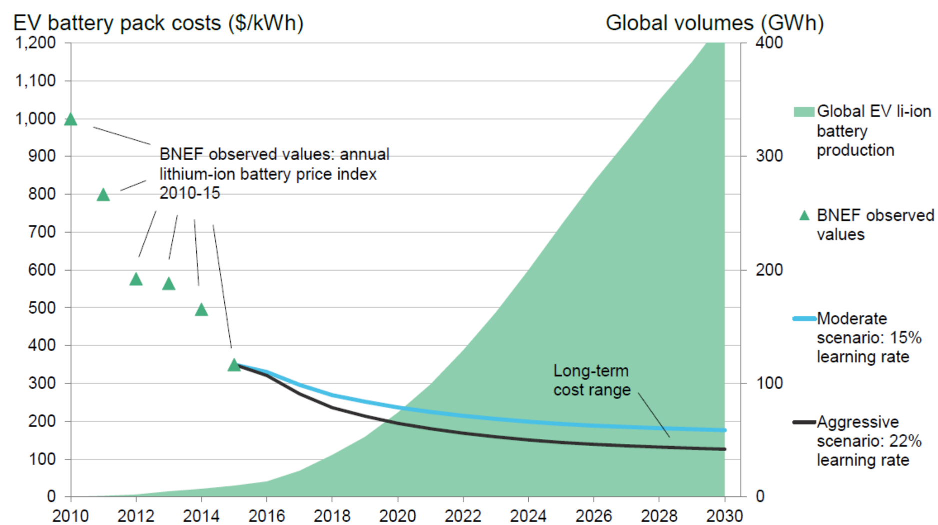
Global EVs in use



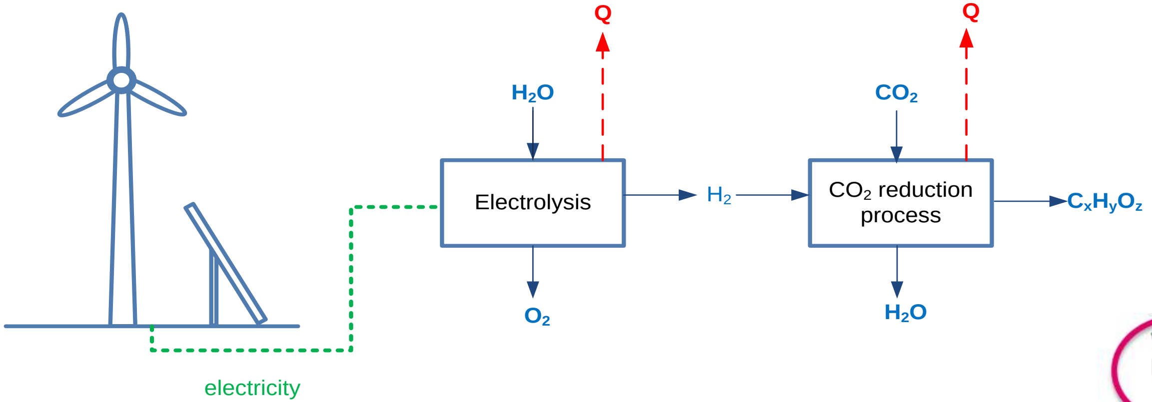
* Elektrofahrzeuge: ausgewertet wurden Pkw und leichte Nutzfahrzeuge mit ausschließlich batterieelektrischem Antrieb oder mit Range Extender sowie Plug-In Hybride.

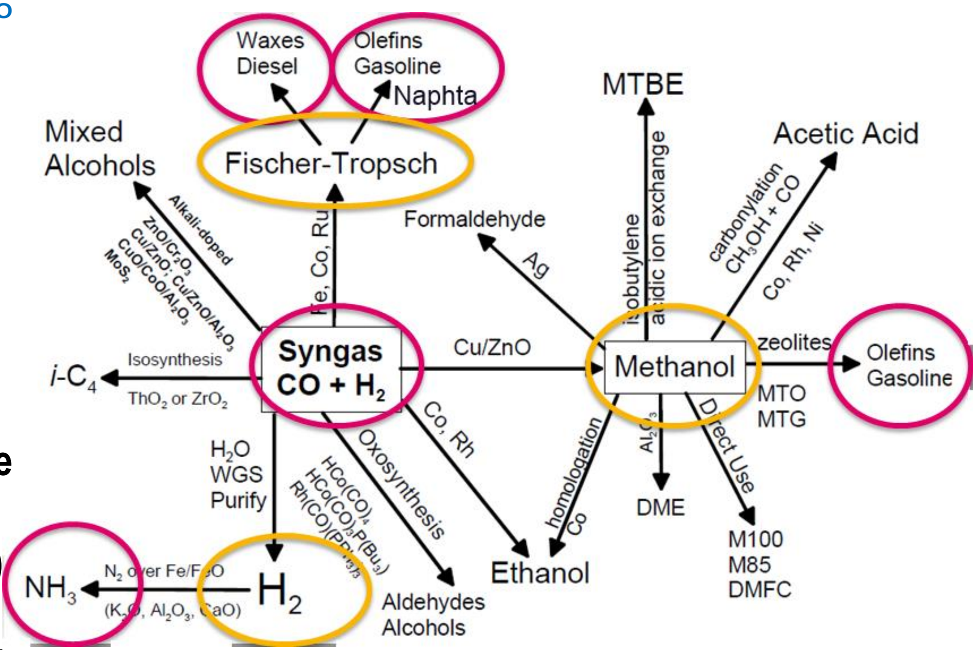
Key insights:

- Batteries convert PV into flexible 24/7 technology
- Batteries show same high learning rates as PV
- Highly module technology – phone to storage plant
- Extreme fast mobility revolution (fusion of renewables, modularity, digitalization, less complex)
- high growth rates – fast cost decline
- least cost mobility solution from 2025 onwards
- Key reason for collapse of western oil majors
- 3rd key enabling technology for survival of humankind



Power-to-X – covering hydrocarbon demand

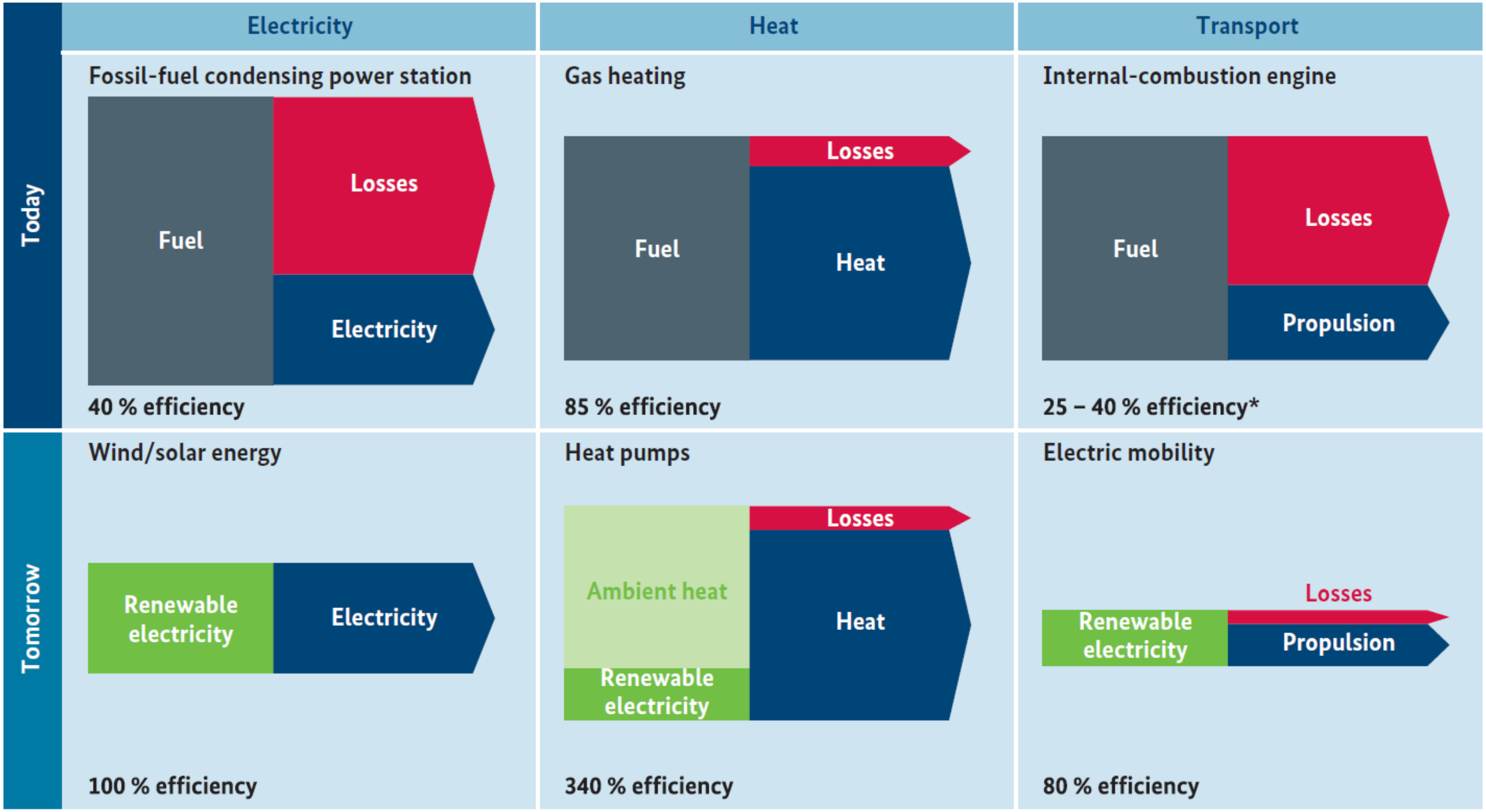




Key insights:

- PtX enables sustainable production of hydrocarbons
- Inredients: electricity, water, air
- w/o PtX Paris Agreement would be wishful thinking
- Profitability from 2030 onwards
- Flexible seasonal storage option
- Global hydrocarbon downstream infrastructure usable
- Most difficult sectors to decarbonise can be managed with PtX (aviation, chemistry, agriculture, metals, etc.)
- CO_2 direct air capture is part of PtX
- 4th key enabling technology for survival of humankind

Key rationale for electrification: Efficiency



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

source: [Brown et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847]

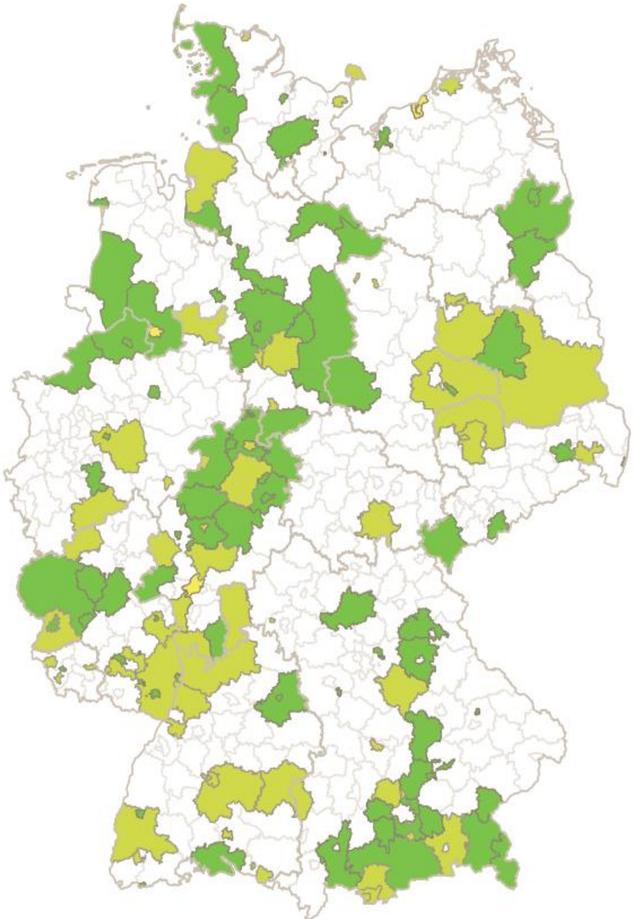
Preliminary insights for ET towards 100% RE

Increase of efficiency:
- substitution of thermal power plants by renewable electricity (wind, PV, hydro)
- introduction of heat pumps based on renewable electricity (wind, PV, hydro)
- substitution of combustion road vehicles by battery-electric vehicles
- substitution of thermal desalination by reverse osmosis desalination

Decrease of efficiency:
- curtailment of renewable electricity generation
- storage losses (power, heat; daily buffer and seasonal balancing)
- synthetic fuels of all kinds
- synthetic chemicals
- much of the Power-to-X chain is related to some losses

Key question:
Are the efficiency gains higher than the additional losses?

100% RENEWABLES
www.go100re.net



www.100-ee.de/

Nov 2016, COP-22, Marrakech:
48 countries (Climate Vulnerable Forum) decided for a 100% RE target

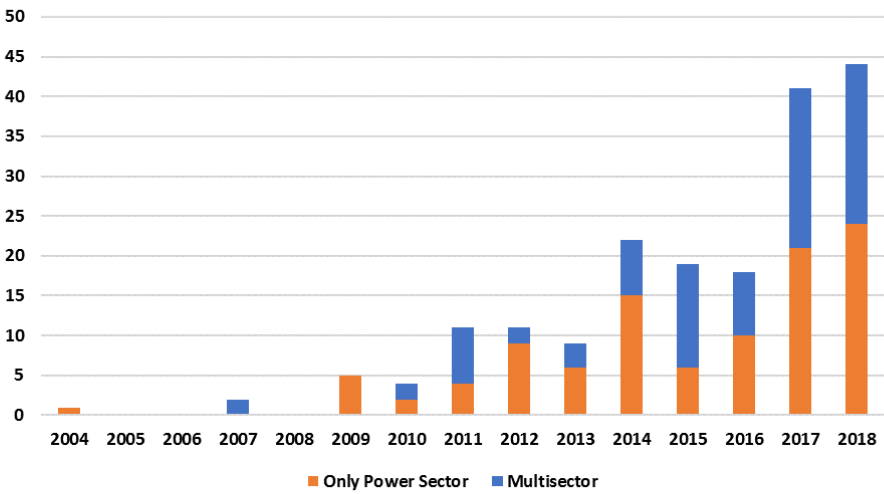
More Countries and States set 100% targets, e.g.:
Denmark, Sweden, **California**, Spain, Hawaii, …

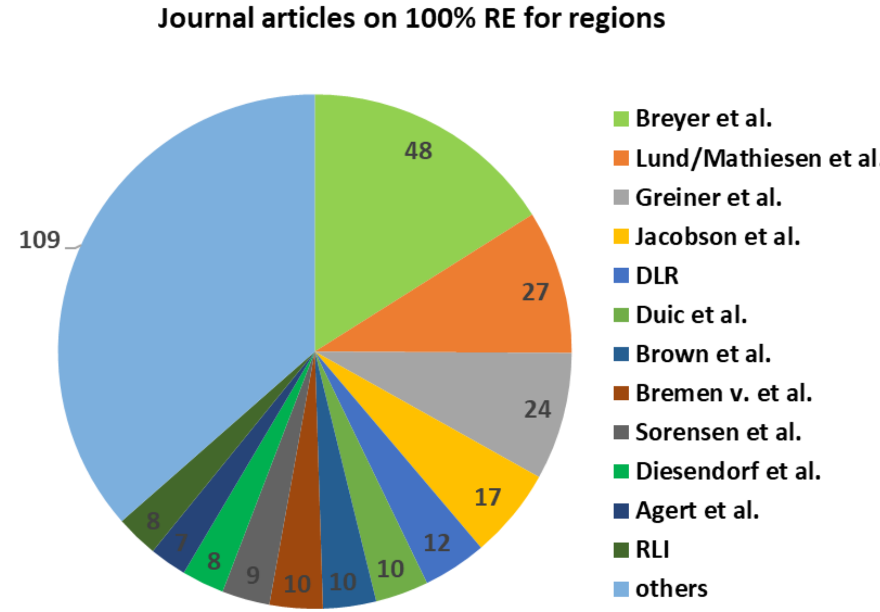
Some Countries are already around 100%, e.g.:
Norway, Costa Rica, Uruguay, Iceland, …

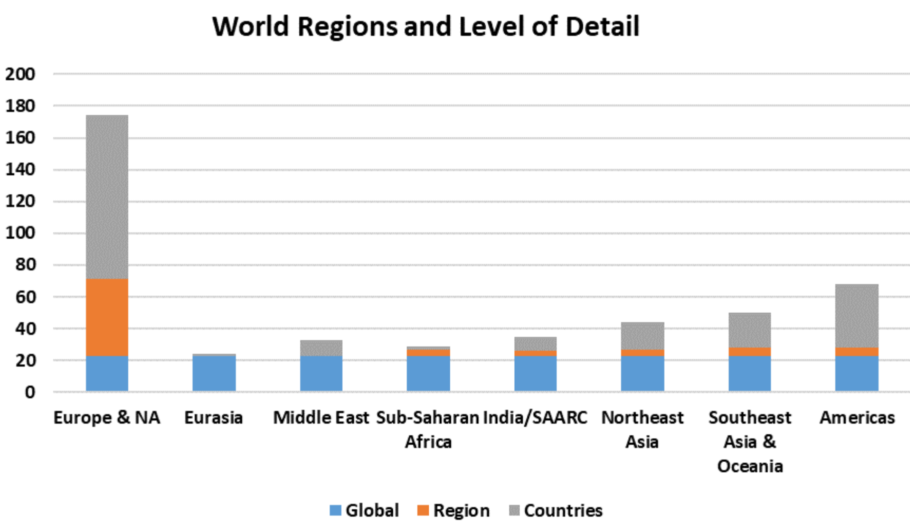
Cities with 100% RE targets, e.g.:
Barcelona, Masdar City, Munich, Masheireb, Downtown, Doha, Vancouver, San Francisco, Copenhagen, Sydney, …

Companies with 100% RE targets, e.g.:
Google, Microsoft, Coca-Cola, IKEA, Wärtsilä, Walmart, …

100% RE articles in recent years







Key insights:

- Research field exists since about 10 years
- Most publications are in hourly resolution
- More multisector publications
- Europe (FI, DK, DE) is hot spot of 100% RE research
- Gaps are in regional coverage and sectoral coverage (industry, NETs), temporal range (21st century)
- Community starts to get impact on neighbouring fields (e.g. IAMs, IPCC), but still ignored for major reports (IEA, IRENA, most governments)

source: Hansen, Breyer, Lund H., 2019. Energy, 175, 471-480

Key diagrams why there will be massive change

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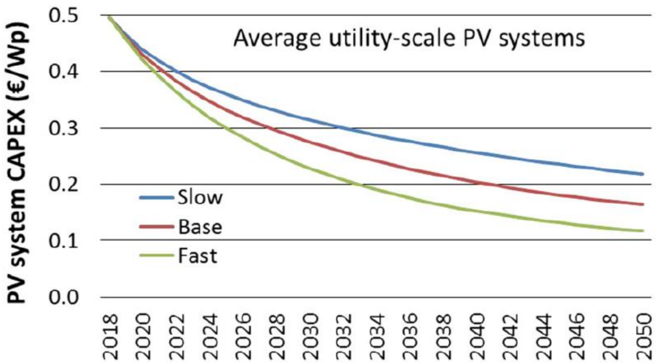
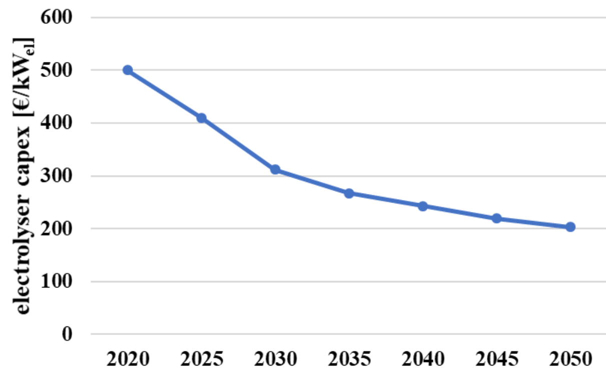
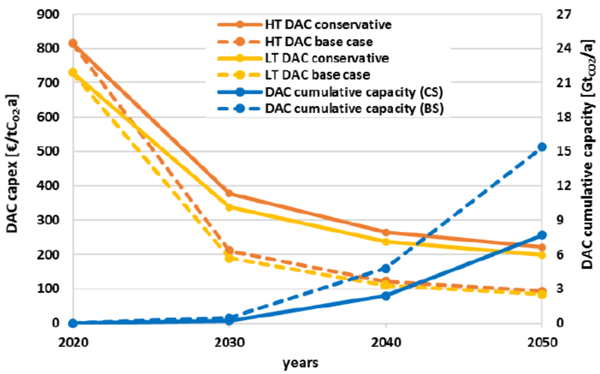
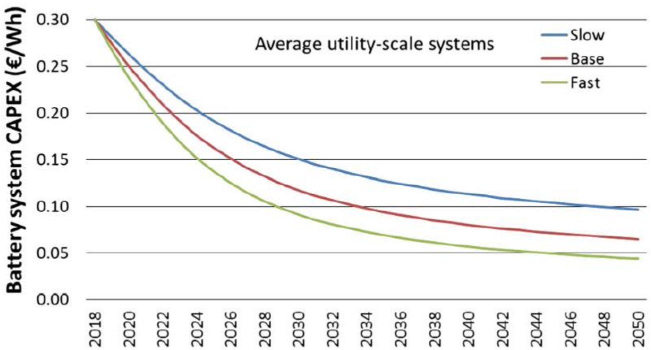
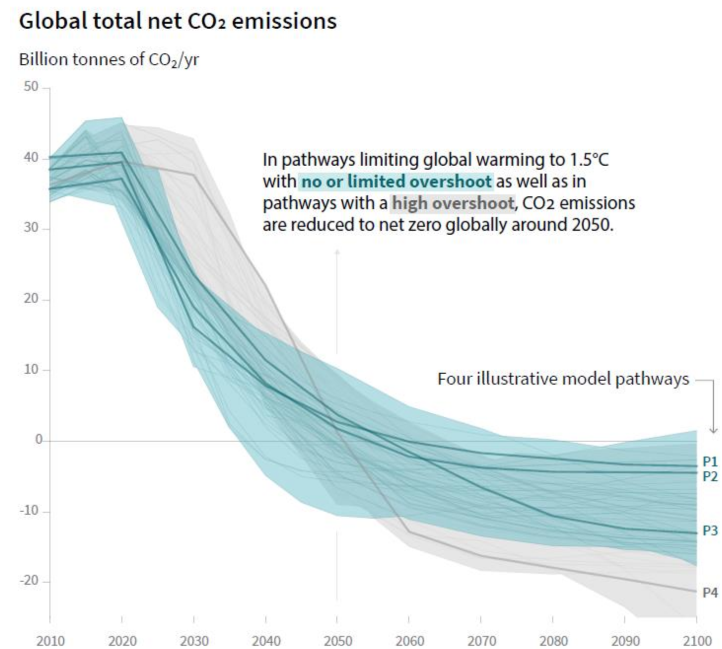








References:
PV, battery: [Vartiainen et al., Progress in PV]
Electrolyser: [LUT model assumptio, Nature]
CO_2 DAC: [Fasihi et al., J of Cleaner Prod]
CO_{2eq} decline: IPCC SR1.5



Key insights:

- **massive continued cost decline for solar PV, wind, battery, electrolysers, CO_2 DAC**
- **massive pressure to eliminate all fossil fuels**
- **massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand**

100% RE for Power Sector

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nature COMMUNICATIONS

ARTICLE

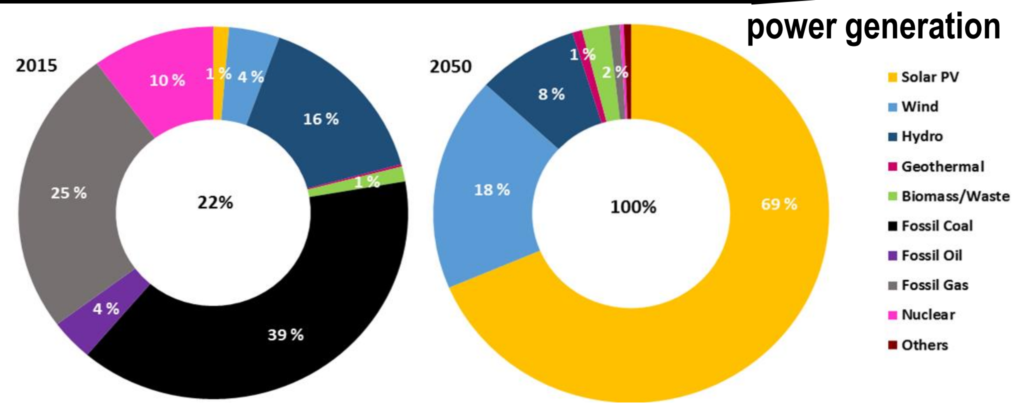
https://doi.org/10.1038/s41467-019-08855-1 OPEN

Radical transformation pathway towards sustainable electricity via evolutionary steps

Dmitrii Bogdanov[1], Javier Farfan[1], Kristina Sadovskaia[1], Arman Aghahosseini[1], Michael Child[1], Ashish Gulagi[1], Ayobami Solomon Oyewo[1], Larissa de Souza Noel Simas Barbosa[2] & Christian Breyer[1]

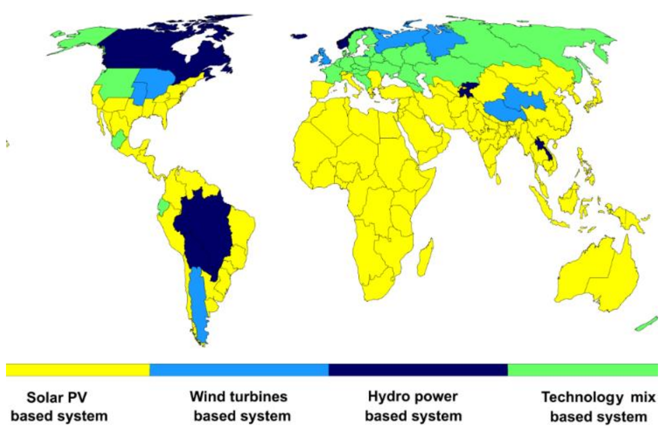
A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: greenhouse gas emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the optimal structure of future systems and potential transition pathways are still open questions. This research describes a global, 100% renewable electricity system, which can be achieved by 2050, and the steps required to enable a realistic transition that prevents societal disruption. Modelling results show that a carbon neutral electricity system can be built in all regions of the world in an economically feasible manner. This radical transformation will require steady but evolutionary changes for the next 35 years, and will lead to sustainable and affordable power supply globally.

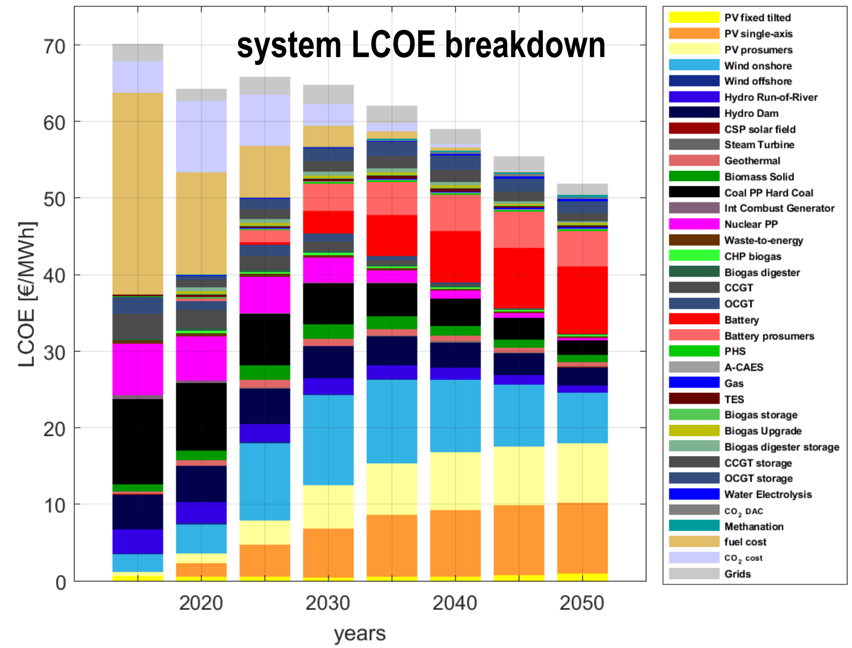
power generation



Area demand:

- Wind: 4% max per region; 0.3% of land area used
- Solar PV rooftop is zero impact area; ground-mounted is 0.14% of total global land area

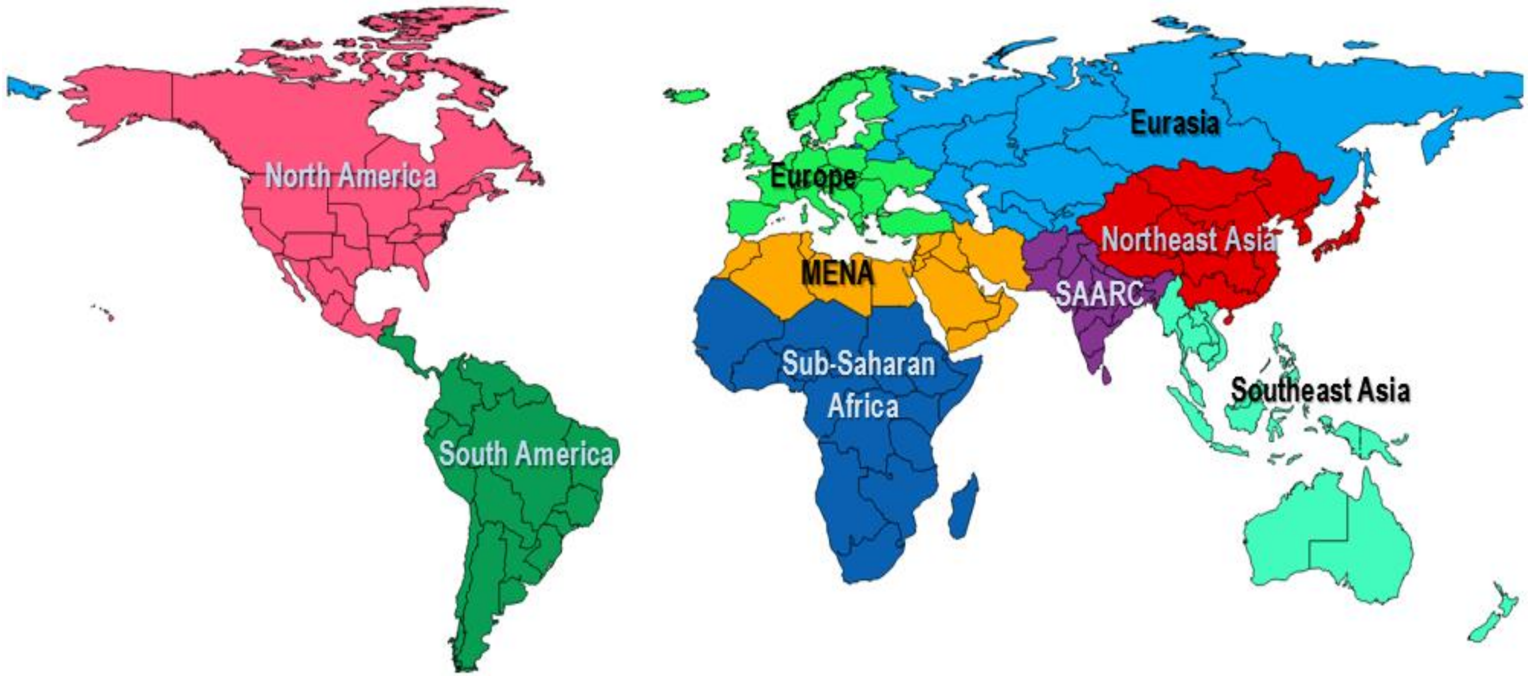




Impact of 100% RE on PED and FED
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

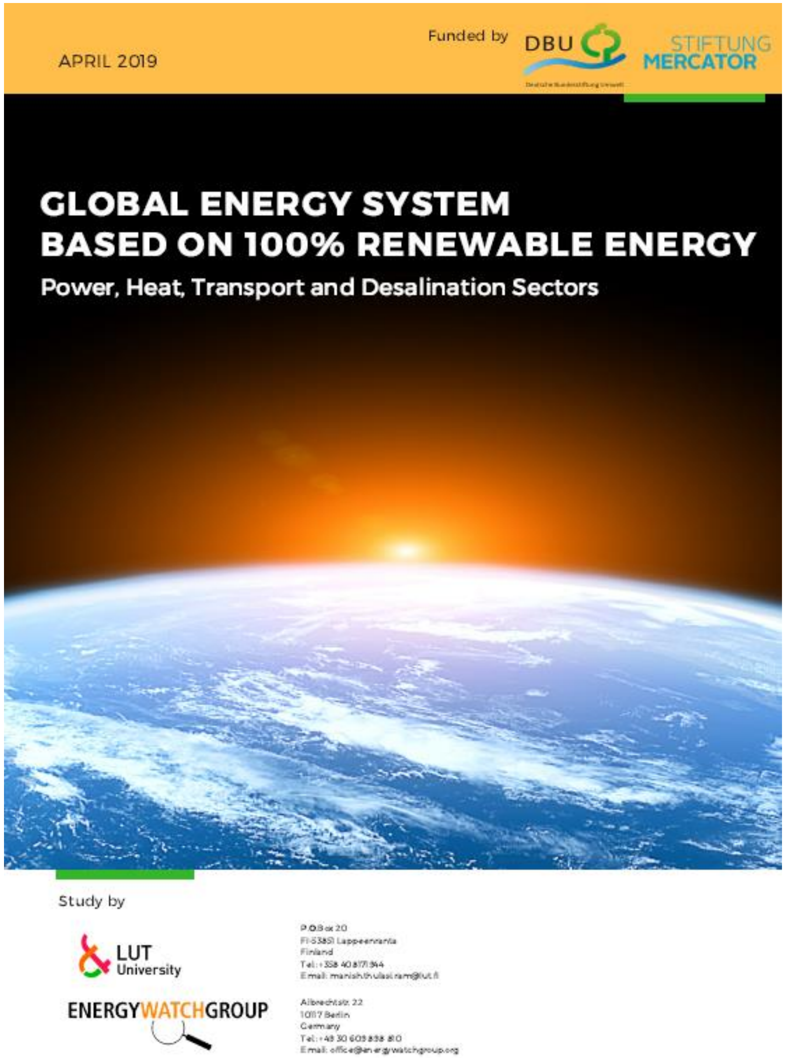
source: Breyer et al., 2018., Progress in Photovoltaics, 26, 505-523; Bogdanov et al., 2019. Nature Communications, 10, 1077

Global Overview



- The world is structured into 9 major regions, which are further divided to 145 sub-regions
- Some sub-regions represent more than one country, others parts of a larger country
- The sub-regions are interconnected by power lines within the same country
- The results shown are for the Power, Heat, Transport, Desalination sectors
- The energy transition scenario is carried out in full hourly resolution for all energy sectors
- In total 106 different technologies are applied

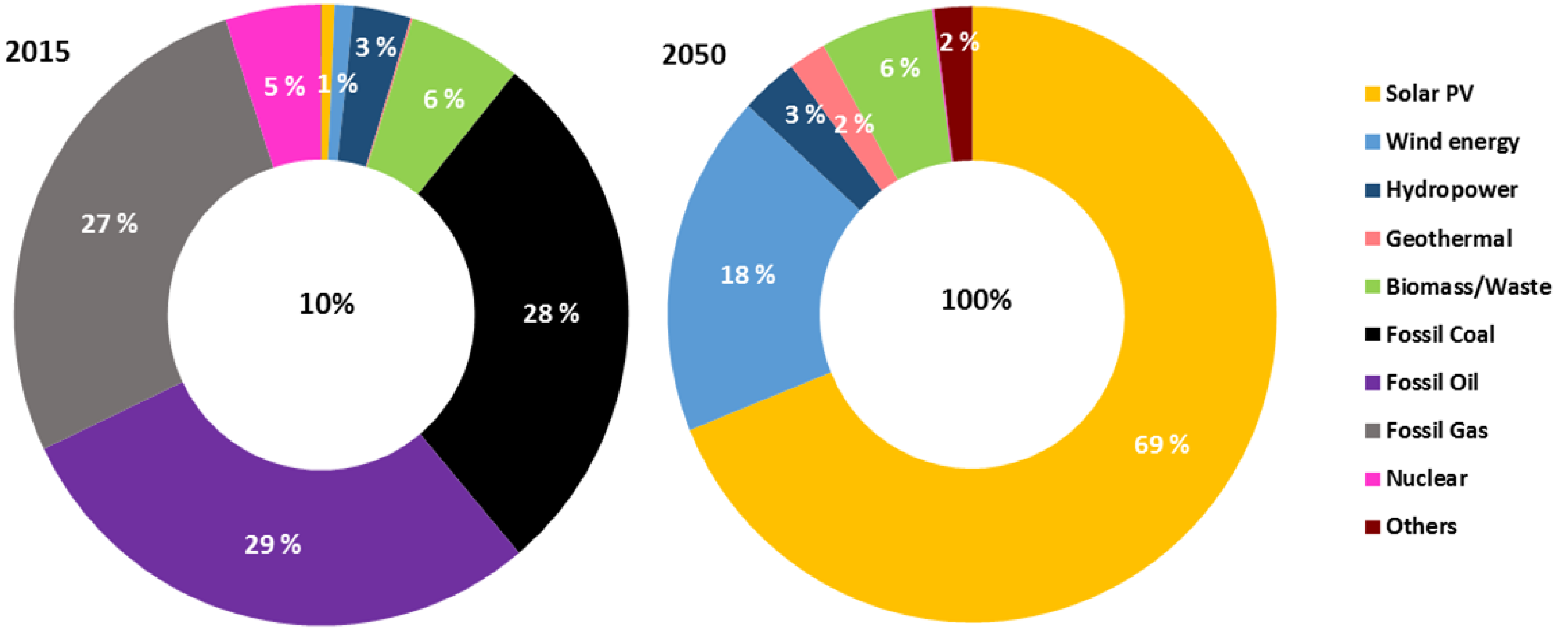
Reports: Europe (COP24), Global (April 2019)



Both reports are available for download

www.energywatchgroup.org

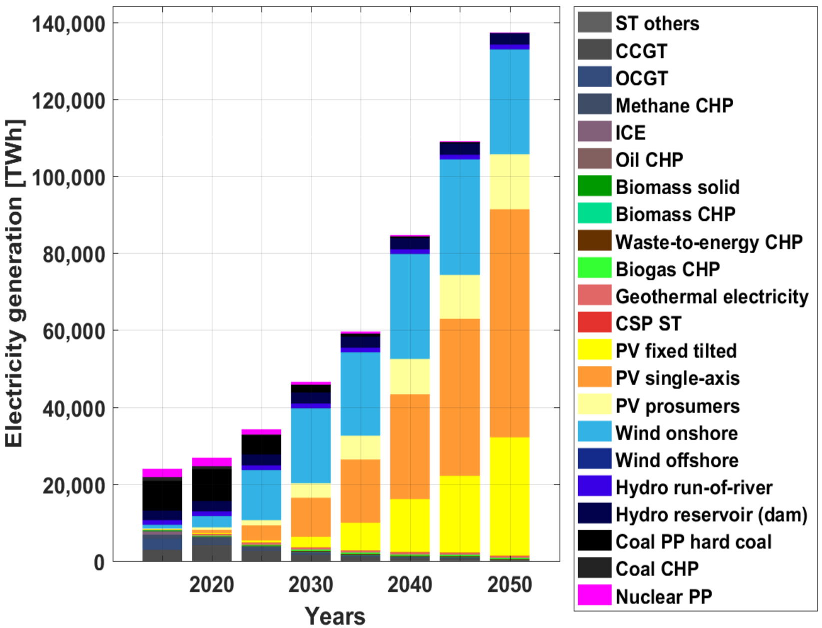
Total Primary Energy Demand Shares



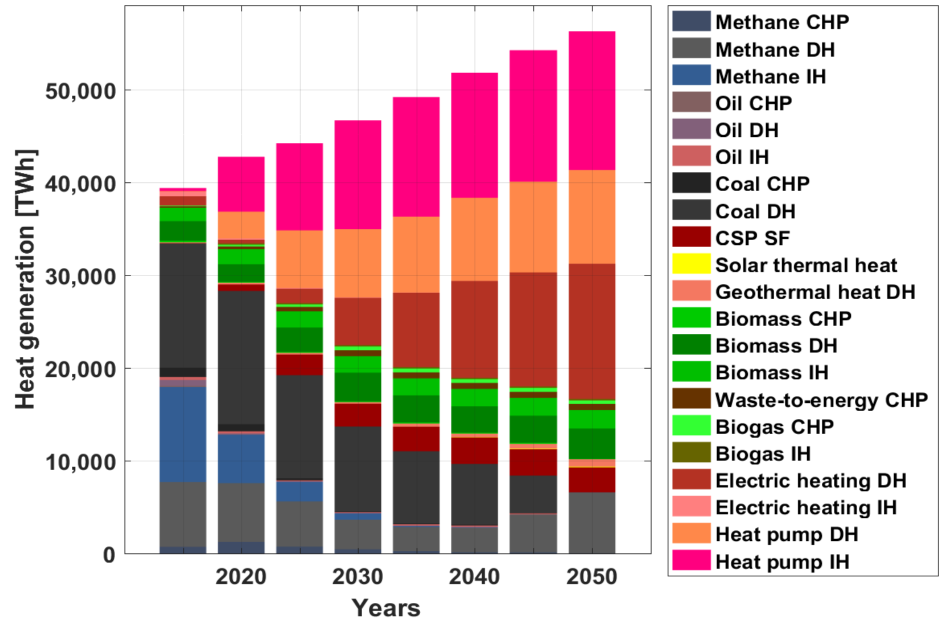
Key insights:
- TPED shifts from being dominated by coal, oil and gas in 2015 towards solar PV and wind energy by 2050
- Renewable sources of energy contribute just 22% of TPED in 2015, while in 2050 they supply 100% of TPED
- Solar PV drastically shifts from less than 1% in 2015 to around 69% of primary energy supply by 2050, as it becomes the least cost energy supply source

Energy Supply

Electricity Generation



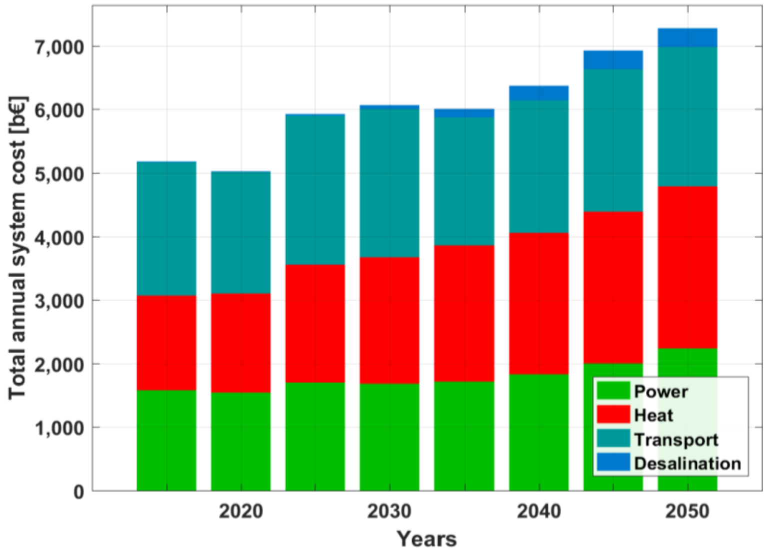
Heat Generation

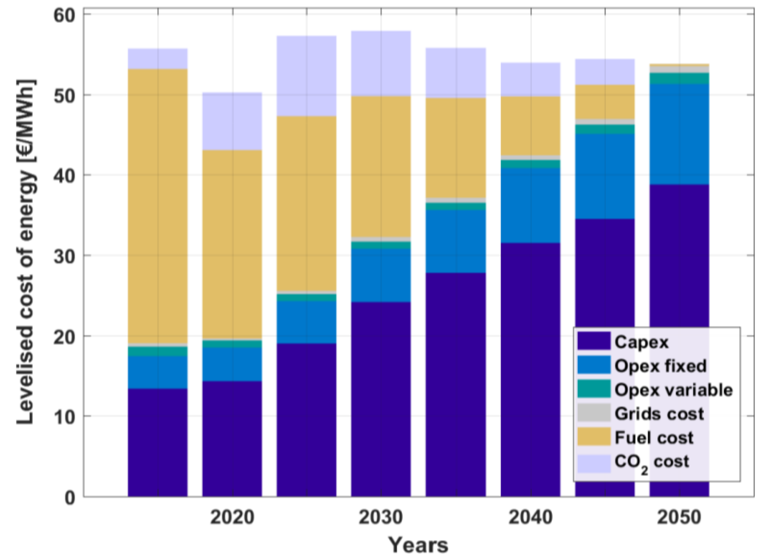


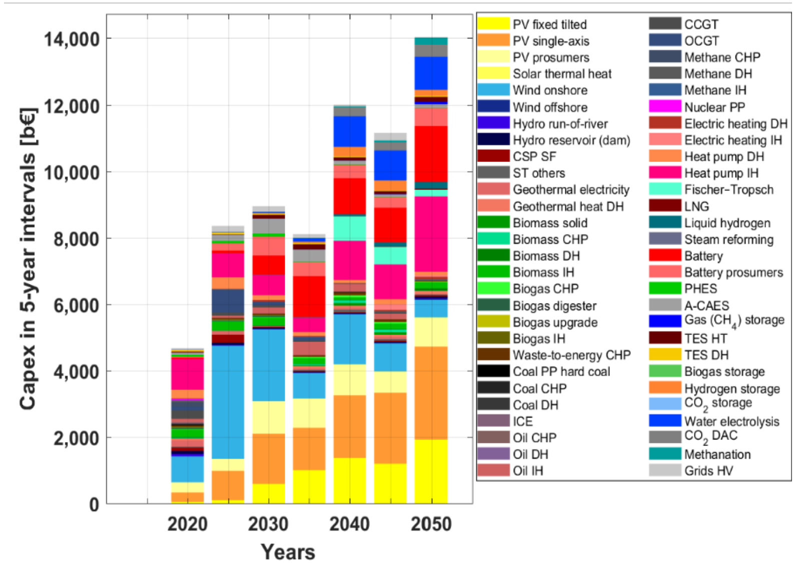
Key insights:

- Electricity generation is comprised of demand for all sectors (power, heat, transport, desalination)
- Solar PV supply increases from 32% in 2030 to about 73% in 2050 becoming the main energy source
- Wind energy increases to 43% by 2030 and steadily declines to about 20% till 2050
- Heat pumps play a significant role in the heat sector with a share of over 40% of heat generation by 2050 coming from heat pumps on district and individual levels with some shares of non-fossil gas and biomass based heating
- Gas-based heating decreases through the transition from above 40% in 2015 to around 11% by 2050

Energy System Cost





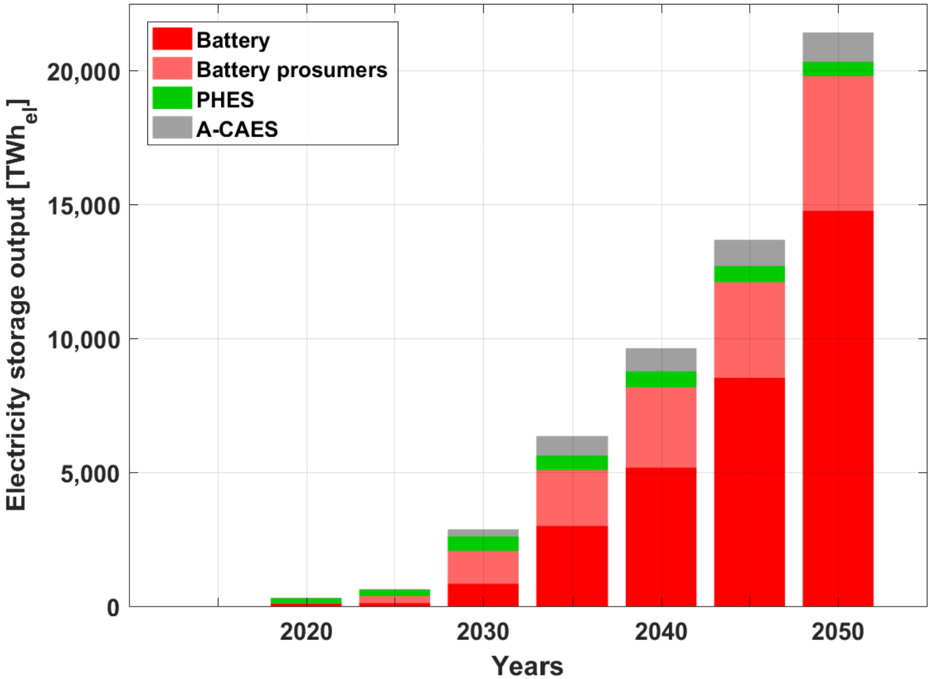


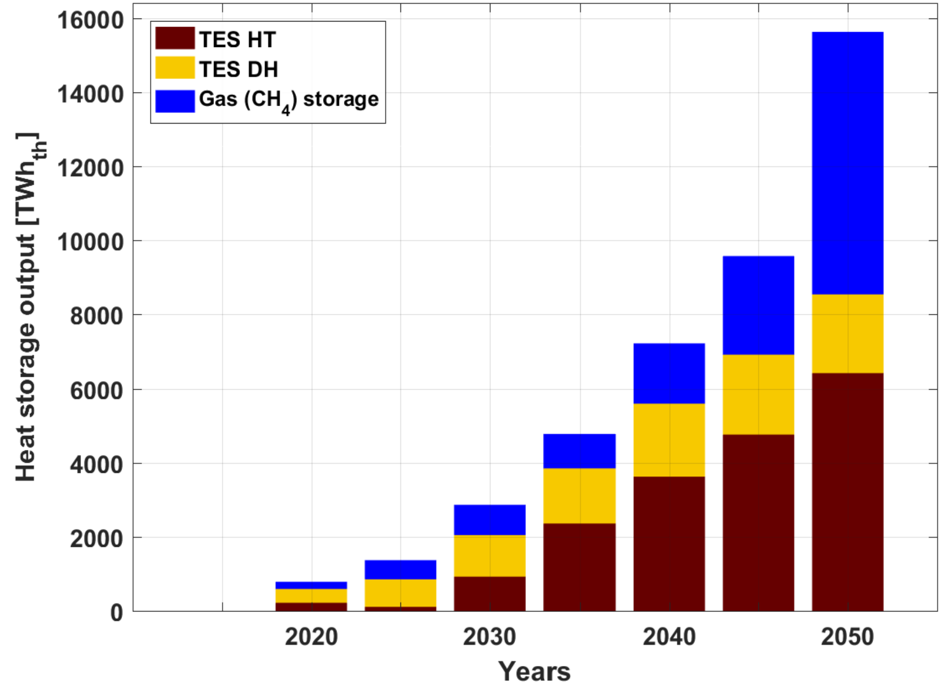
Key insights:

- The total annual costs are in the range of 5100-7200 b€ through the transition period and well distributed across the 3 major sectors of Power, Heat and Transport
- LCOE remains around 50-57 €/MWh and is increasingly dominated by capital costs as fuel costs lose importance through the transition period, which could mean increased self-reliance by 2050
- Costs are well spread across a range of technologies with major investments for PV, wind, batteries, heat pumps and synthetic fuel conversion up to 2050
- The cumulative investment costs are about 67,200 b€

Sectoral Outlook

Power & Heat – Storage Output

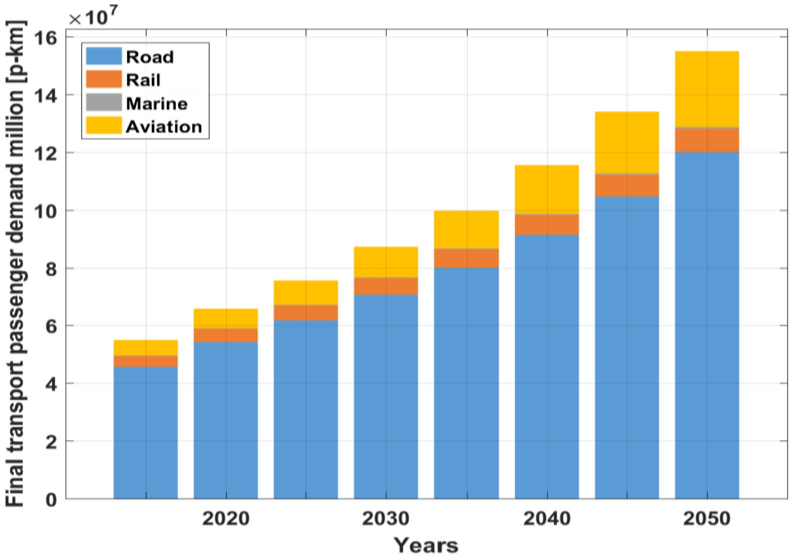


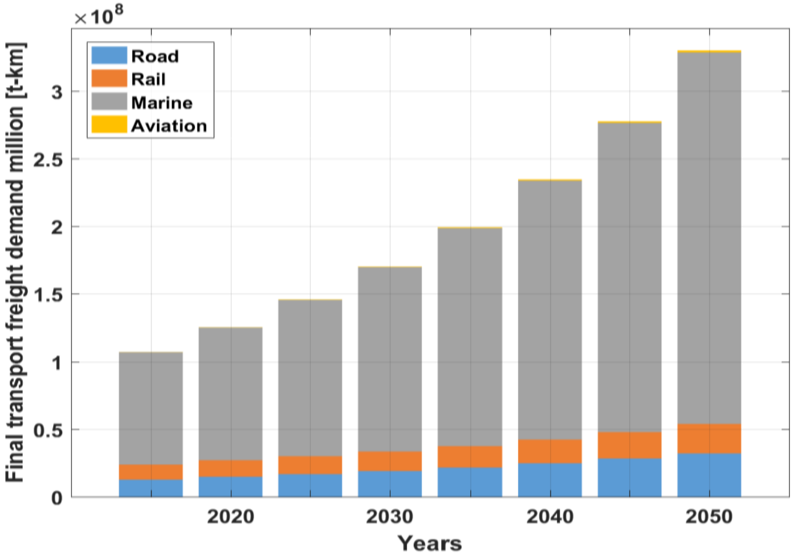


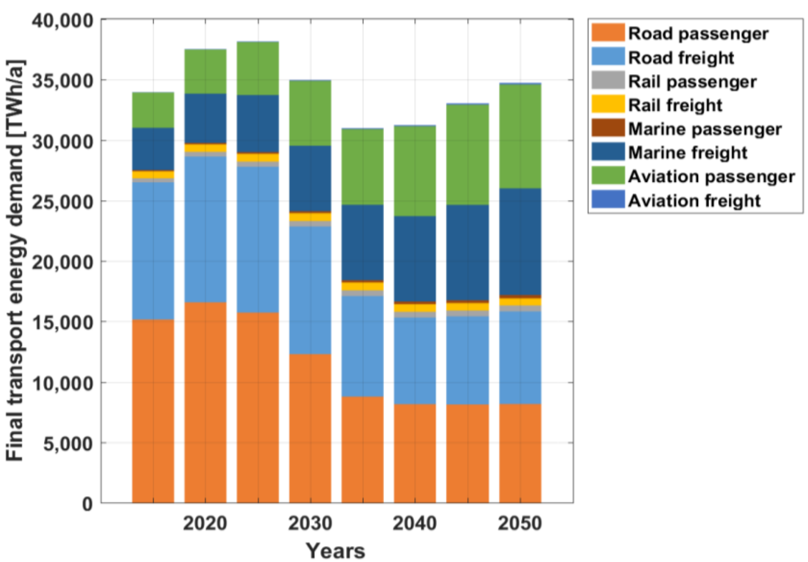
Key insights:

- Utility-scale and prosumer batteries contribute a major share of the electricity storage output with nearly 92% by 2050
- Pumped hydro energy storage and compressed air energy storage contribute through the transition
- Thermal energy storage emerges as the most relevant heat storage technology with about 61% of heat storage output by 2050
- Gas storage contributes around 39% of the heat storage output in 2050 covering predominantly seasonal demand, which was covered by fossil gas before 2050

Sectoral Outlook
Transport – Demand



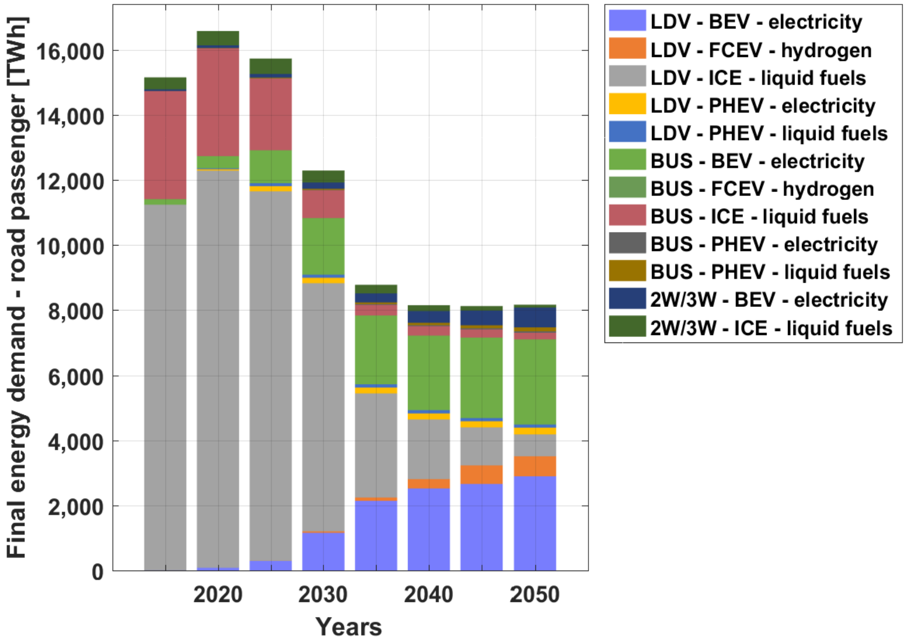


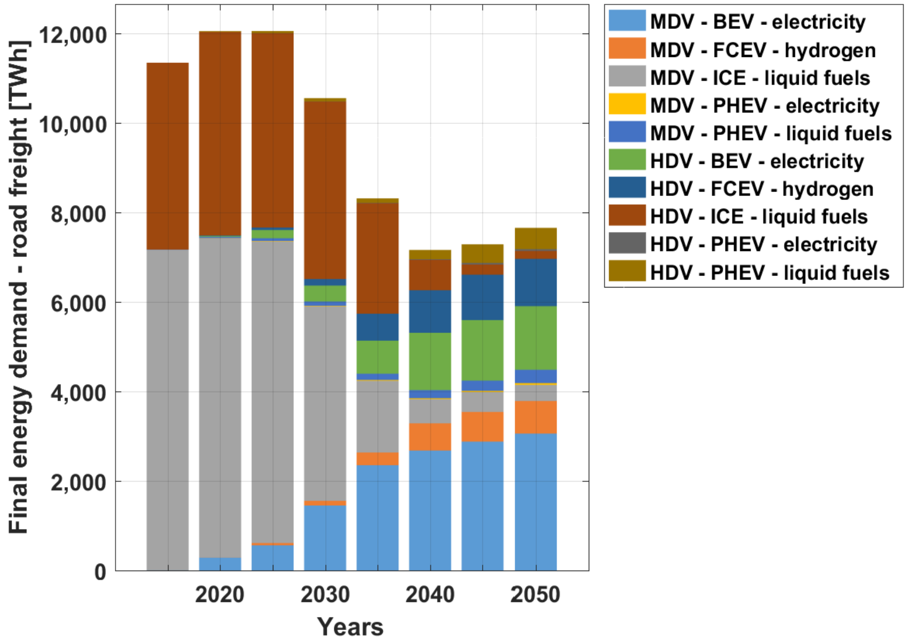


Key insights:

- The final transport passenger demand increases from around 50.8 million p-km to around 150.8 million p-km
- The final transport freight demand also increases from around 110 million t-km to around 330 million t-km
- Whereas, the final energy demand for overall transport increases slightly from 34,000 TWh/a in 2015 to 35,000 TWh/a by 2050, enabled by high efficiency of electric vehicles
- Marine freight is aligned to the scenario with a drastic decline in fuels transportation during the transition

Sectoral Outlook
Transport – Road Demand



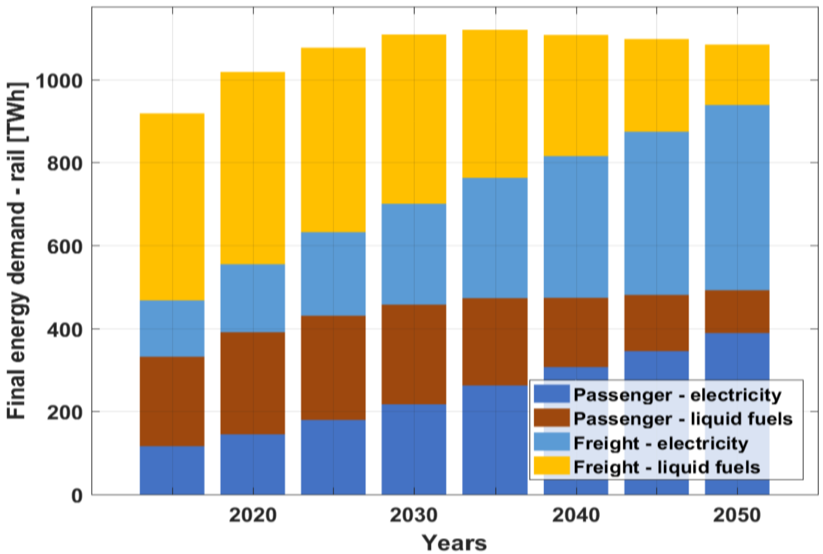


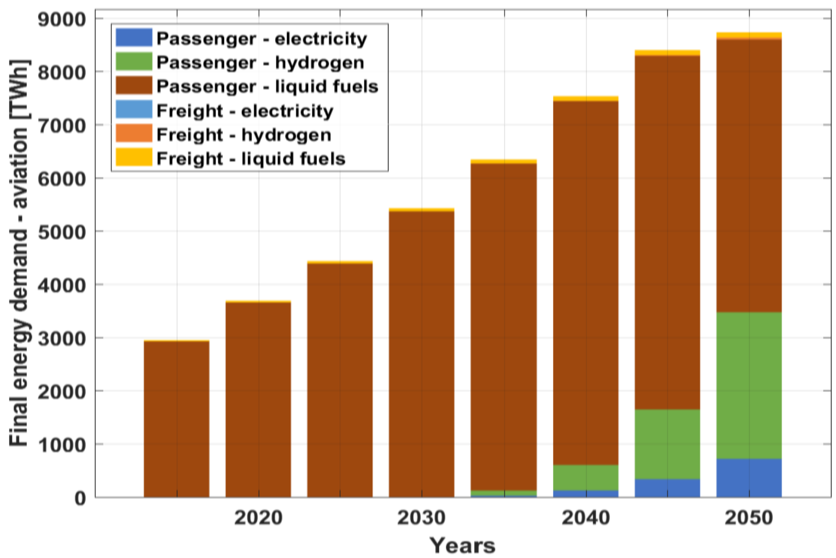
Key insights:

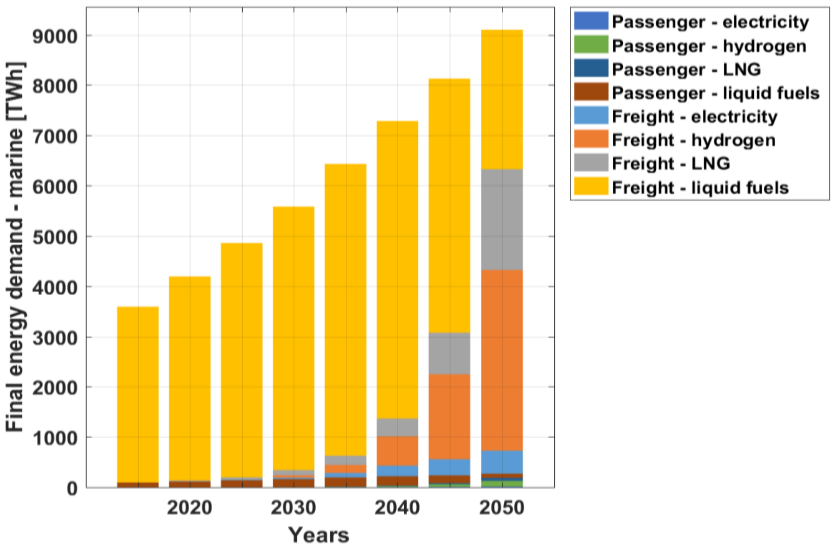
- The final energy demand for road passengers decreases significantly from around 14,500 TWh in 2015 to just around 8000 TWh by 2050
- The final energy demand for road freight decreases substantially from around 11,500 TWh in 2015 to around 7700 TWh by 2050
- The significant decrease in final energy demand for overall road transport is primarily driven by the massive electrification

Sectoral Outlook

Transport – Rail, Marine and Aviation Demand



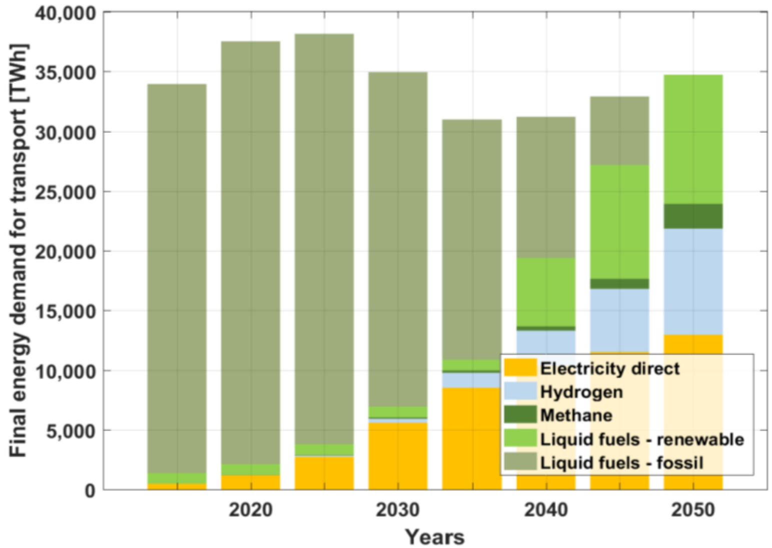


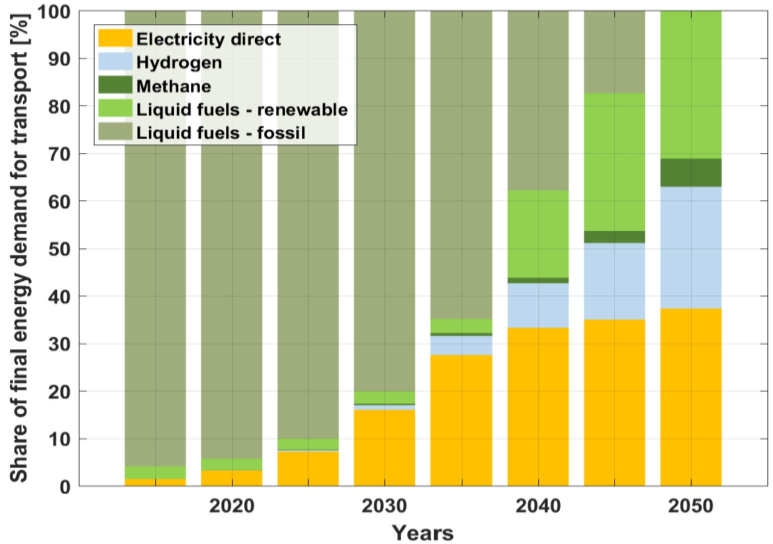


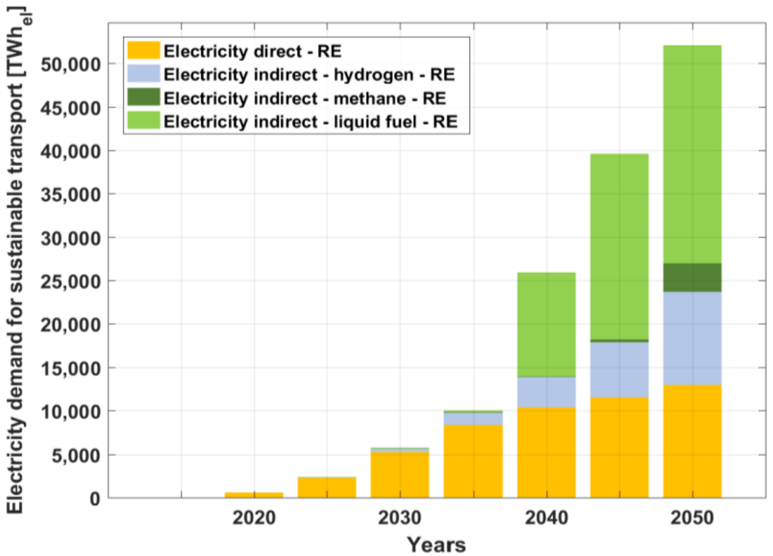
Key insights:

- The final energy demand for rail transport increases from around 860 TWh in 2015 to around 1100 TWh by 2050
- The final energy demand for marine transport increases steadily from around 3600 TWh in 2015 to around 9000 TWh by 2050
- The final energy demand for aviation transport increases significantly from nearly 3000 TWh in 2015 to around 8800 TWh by 2050

Sectoral Outlook
Transport – Defossilisation and Electrification



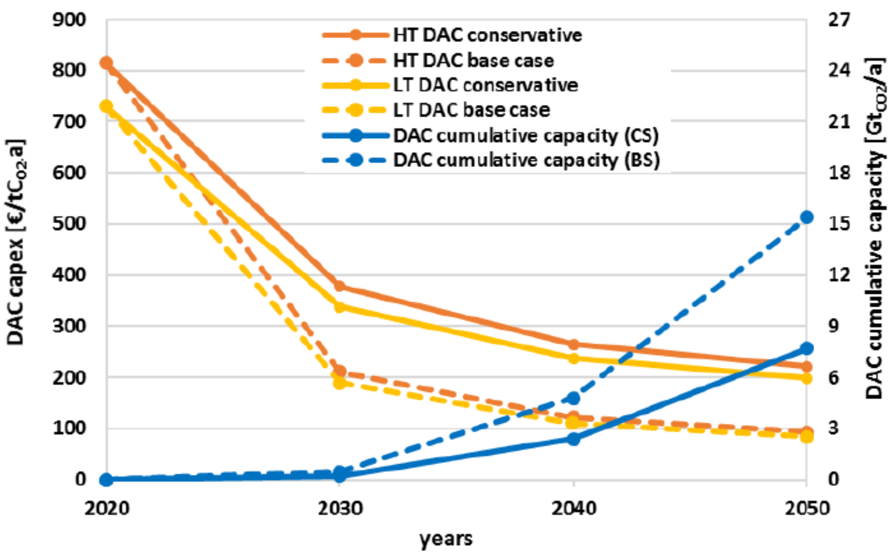


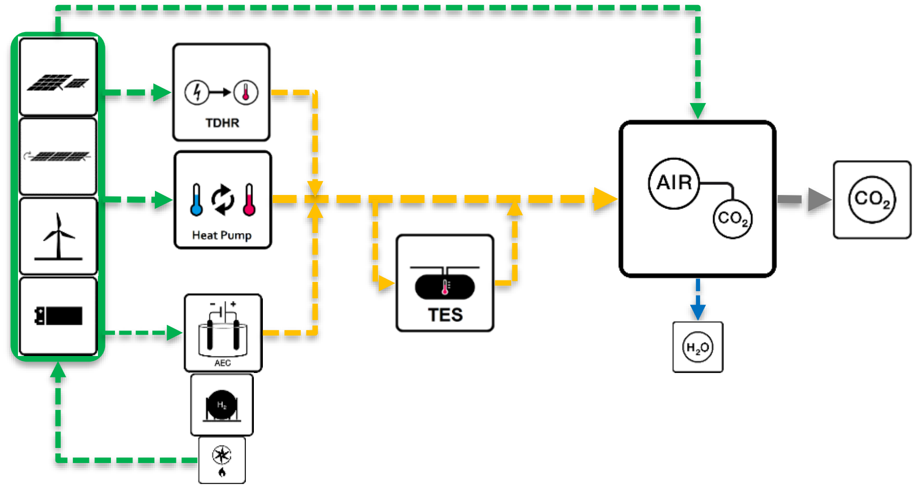


Key insights:

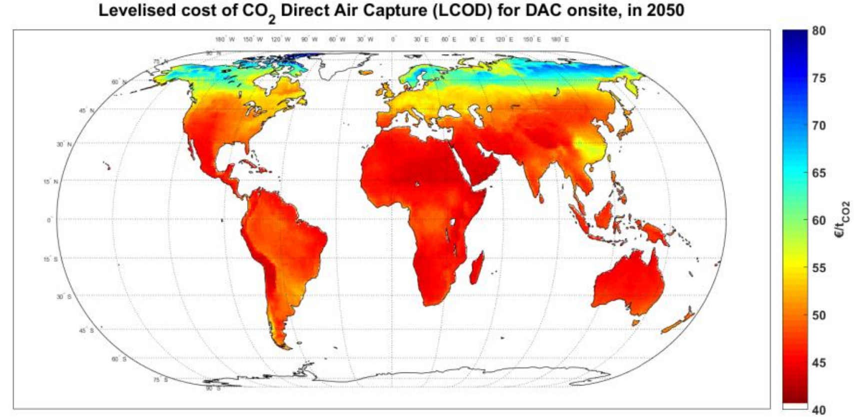
- Fossil fuel consumption in transport is observed to decline through the transition from about 97% in 2015 to zero by 2050
- Liquid fuels produced by renewable electricity contribute around 31% of the final energy demand in 2050
- Hydrogen constitutes more than 26% of final energy demand in 2050
- Electrification of the transport sector creates an electricity demand of around 50,000 TWh$_{el}$ by 2050
- Massive demand for liquid fuels kicks in from 2040 onwards up to 2050

CO_2 DAC is a central technology





Levelised cost of CO_2 Direct Air Capture (LCOD) for DAC onsite, in 2050



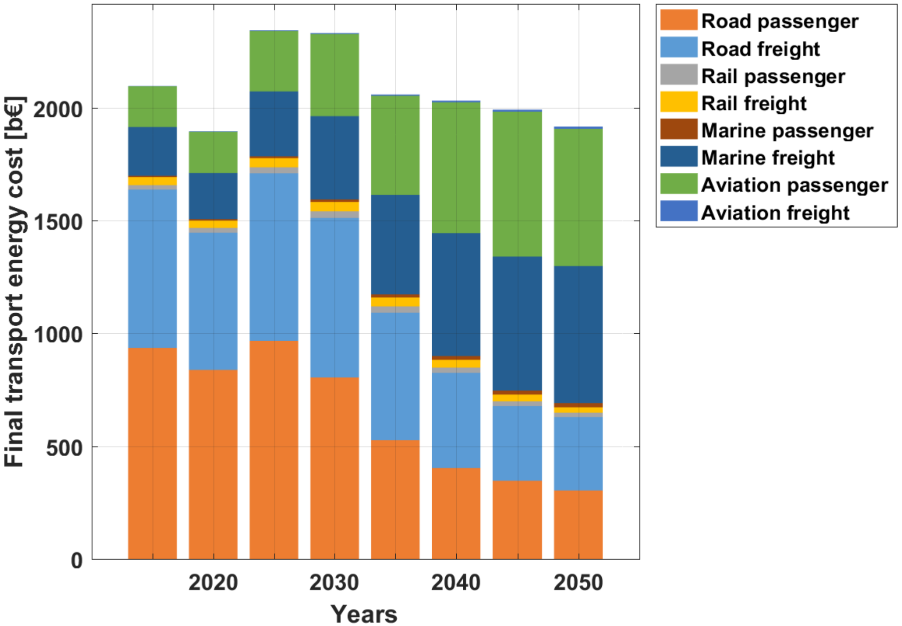
Key insights:

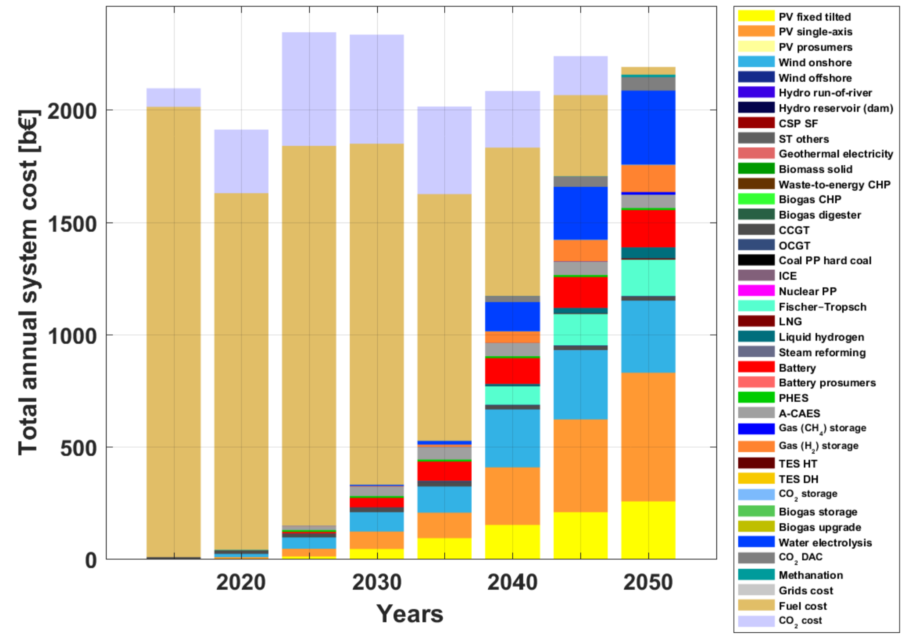
- DAC capex decline is driven by learning rate (10-15%) and capacity demand
- Half of DAC capacity demand can be expected from the energy system
- Half of DAC capacity demand can be expected from CDR
- DAC business will become most likely a triple digit billion industry by 2050

source: Fasihi M., et al., 2019. Journal of Cleaner Production, 224, 957-980; Breyer et al., 2019. Mitigation and Adaptation Strategies for Global Change, online ; Breyer et al., 2019. Joule, 3, 2053-2057

Sectoral Outlook

Transport – Annual Energy Costs

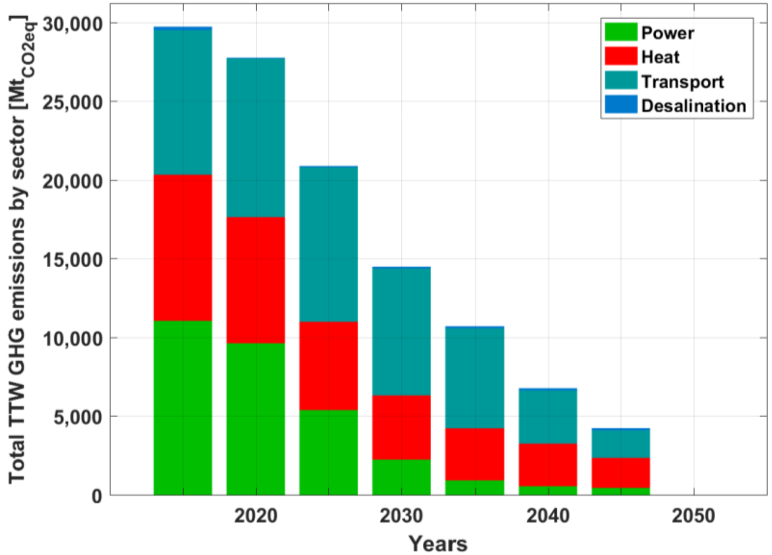




Key insights:

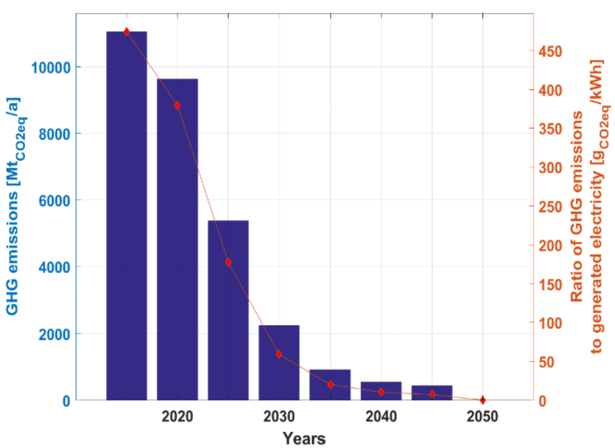
- The total annual energy costs for transport are in the range of 1900-2190 b€ through the transition period with a slight increase from around 2090 b€ in 2015 to about 2190 b€ by 2050
- Road transport forms a major share of the costs in the initial years up to 2030, beyond which the aviation mode dominates the share of costs as cost in the road mode declines through the transition up to 2050
- Rail and marine mode costs remain more steady through the transition
- Annual system costs transit from being heavily dominated by fuel costs in 2015 to a very diverse share of costs across various technologies for electricity, synthetic fuels and sustainable biofuel production by 2050
- FT units produce naphtha as by-product, which is included in overall system costs but not in transport cost

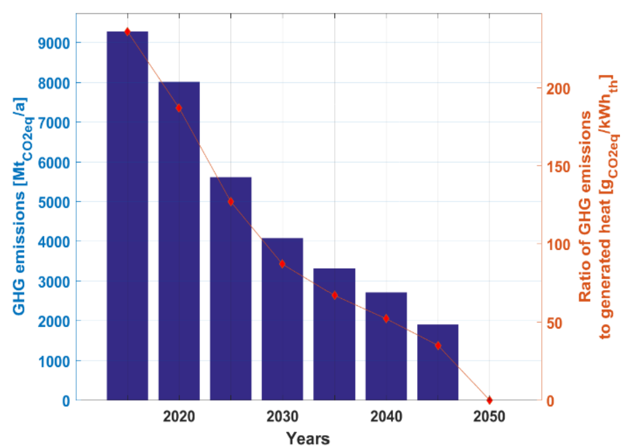
GHG Emissions Reduction

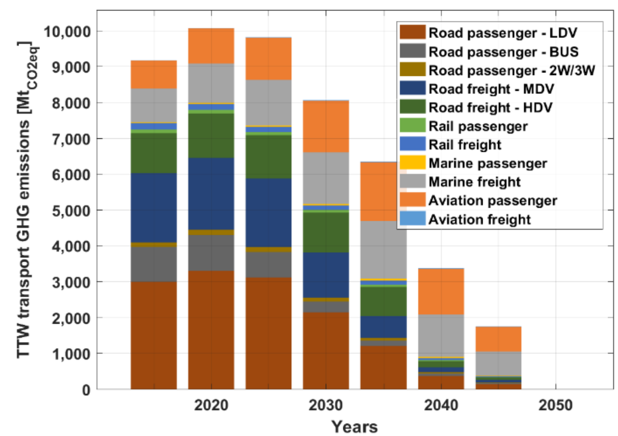


Key insights:

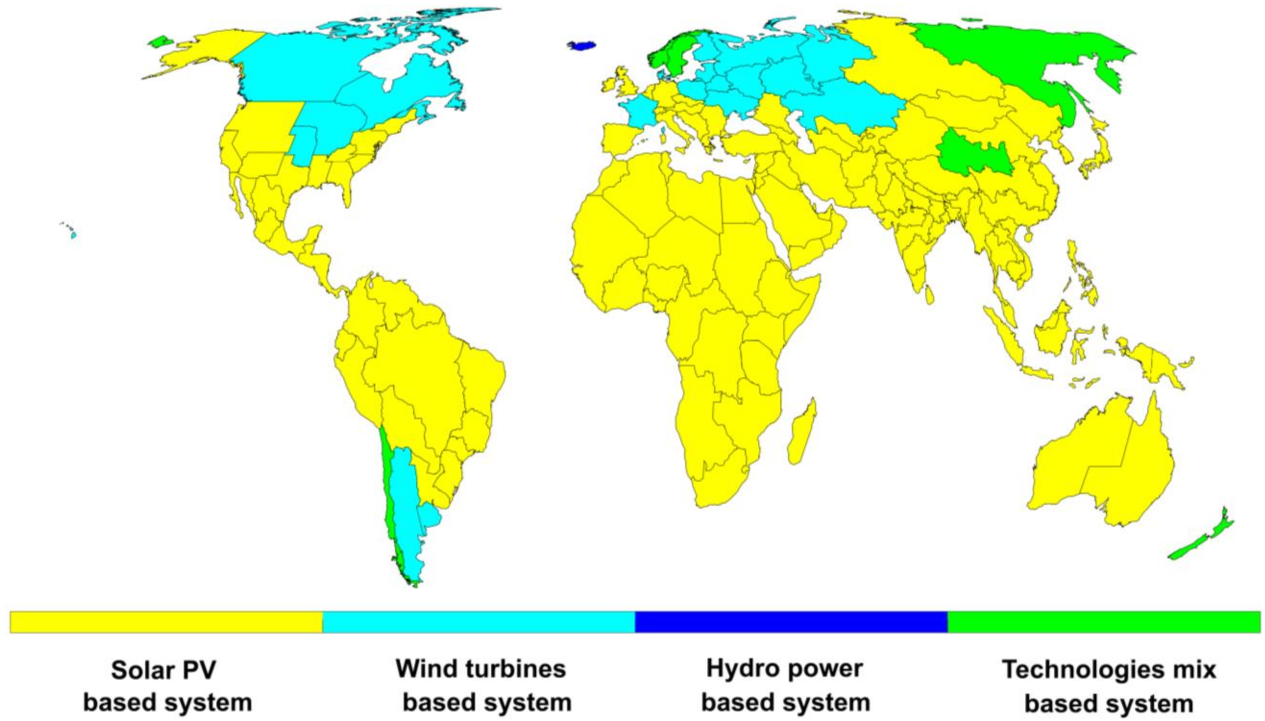
- GHG emissions can be reduced from around 30,000 $MtCO_{2eq}$ in 2015 to zero by 2050 across all energy sectors
- The remaining cumulative GHG emissions comprise around 422 $GtCO_{2eq}$ from 2018 to 2050.
- The presented 100% RE scenario for the global energy sector is compatible with the Paris Agreement for 1.5ºC
- Deep defossilisation of the power and heat sectors is possible by 2030, while the transport sector is lagging and a massive decline of emissions is possible beyond 2030 up to 2050







Regional Variation in 2050



Key insights:

- Solar PV dominates most of regions around the world and particularly in the Sun Belt
- Wind energy drives systems in the Northern and Southern hemispheres with excellent wind conditions and lacking seasonal solar energy
- Some regions are further complemented with hydropower to form a mixed system

Comparison to Teske/DLR et al. and Jacobson et al.

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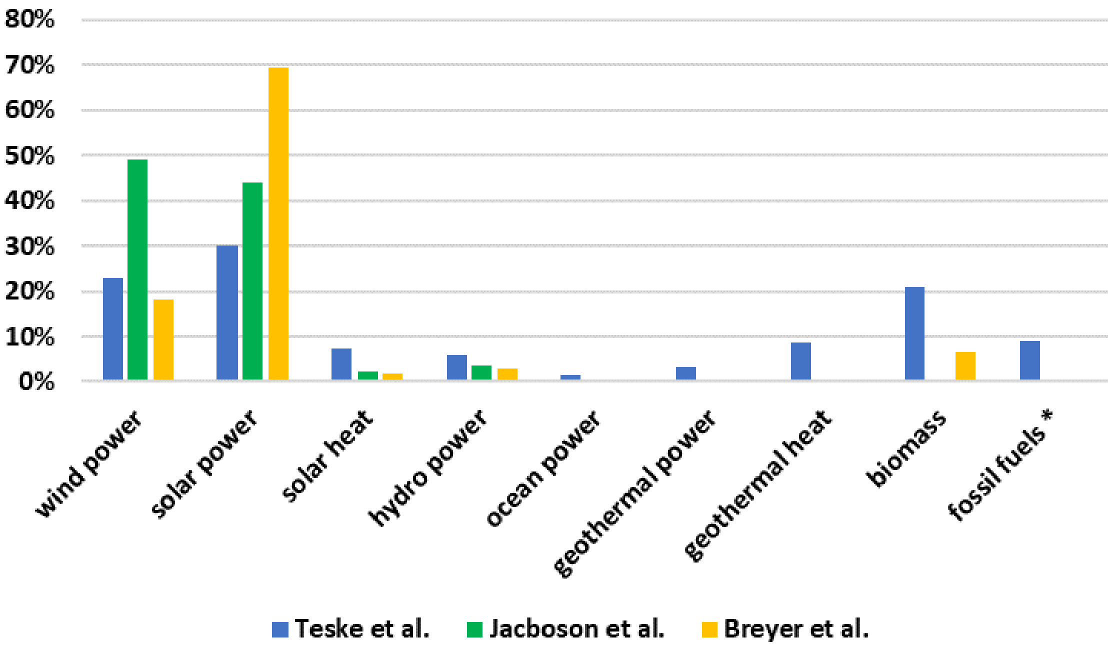
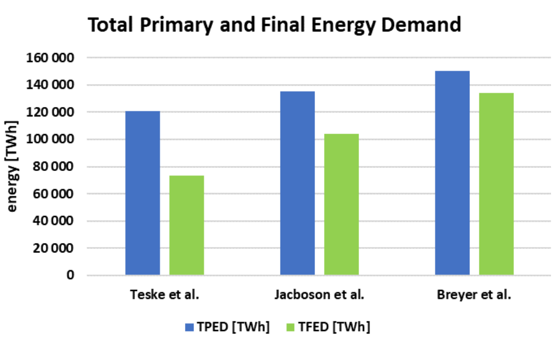
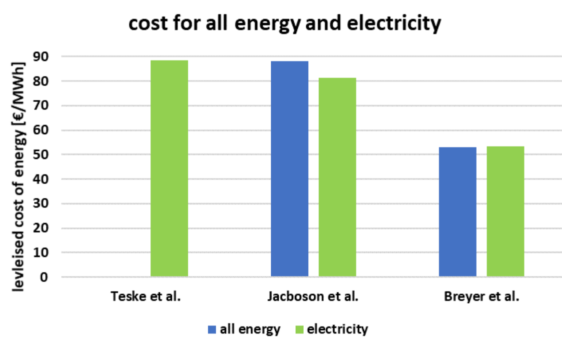






- All three leading highly renewable energy scenarios agree that its possible
- Breyer et al. find the highest solar PV demand
- PV capex relevant for results
- Optimisation vs simulation modeling relevant
- Full optimisation and realistic cost lead to least cost solutions
- Energy demand projections vary
- Without bioenergy would be possible (Jacobson et al.)
- CSP is still under discussion, however cost_{CSP} > $\text{cost}_{\text{PV-battery}}$
- studies available as articles (peer-reviewed), and reports/ books

Overview on transport sector transition

										TFED share in 2050 *			
Source	Publication year	Unit	2015	2020	2025	2030	2035	2040	2045	2050	fossils	biofuels	synfuels	electricit
this study	2019	TWh/a	31613	34799	35848	35609	33761	32177	31758	32542	0 %	1 %	63 %	35 %
Greenpeace [E]R	2015	TWh/a	-	26129	25599	25070	-	21808	-	19159	29 %	14 %	20 %	38 %
Greenpeace [E]R adv.	2015	TWh/a	-	25850	24897	23207	-	18020	-	14836	0 %	14 %	35 %	51 %
Teske, 1.5 °C	2019	TWh/a	30752	-	29411	25606	-	19604	-	17001	0 %	16 %	36 %	48 %
Teske, 2 °C	2019	TWh/a	30752	-	26142	20371	-	15919	-	14279	0 %	25 %	29 %	46 %
Jacobson et al.	2018	TWh/a	-	-	-	-	-	-	-	13113	0 %	0 %	33 %	67 %
Löffler et al.	2017	TWh/a	31298	32434	28910	24069	20258	16706	13326	10414	0	15 %	44 %	41 %
Pursiheimo et al.	2019	TWh/a	-	-	-	-	-	-	-	23480	0 %	30 %	33 %	37 %
García-Olivares et al.	2018	TWh/a	-	-	-	-	-	-	-	28383	n/a	n/a	n/a	n/a
WWF / Deng et al.	2011	TWh/a	29102	29598	28714	25940	24420	19533	17998	17741	0 %	74 %	0 %	26 %
World Energy Council	2016	TWh/a	-	31842	-	35471	-	37018	-	37169	77 %	15 %	2 %	6 %
DNV GL	2018	TWh/a	29513	30555	31945	31388	30555	28472	25694	25000	42 %	16 %	2 %	40 %
IEA, WEO NPS	2018	TWh/a	31308	-	36564	38530	40088	42065	-	-	90 %	6 %	0 %	4 %
IEA, WEO SDS	2018	TWh/a	31308	-	34250	33668	-	30703	-	-	73 %	13 %	0 %	14 %
Luderer et al. B200	2018	TWh/a	-	-	-	-	-	-	-	31945	32 %	29 %	18 %	21 %
Luderer et al. B800	2018	TWh/a	-	-	-	-	-	-	-	36110	47 %	26 %	12 %	15 %
Shell, Sky	2018	TWh/a	30812	33019	34989	34611	36290	37686	38837	40630	67 %	13 %	2 %	18 %
BP Energy Outlook	2019	TWh/a	29656	32564	34890	36053	37216	37099	-	-	89 %	7 %	0 %	4 %
ExxonMobil	2017	TWh/a	32530	-	36633	-	-	40736	-	-	94 %	4 %	0 %	2 %
US DoE EIA	2017	TWh/a	32823	33703	35168	37806	40736	44400	-	-	98 %	0% **	0 %	2 %

- no consolidated view on transport sector transition: range from US DoE (98% fossils) to 100% RE group
- different bets on biofuels, but many do not factor in sustainability limits
- synthetic fuels is still very often only hydrogen
- LUT has the highest synthetic fuel share among all groups in the world
- IEA deserves massive pressure from civil society, but also IPCC for being laggard in progressive options
- Oil majors will go for bankruptcy, if they follow their own scenarios – for Shell might be hope

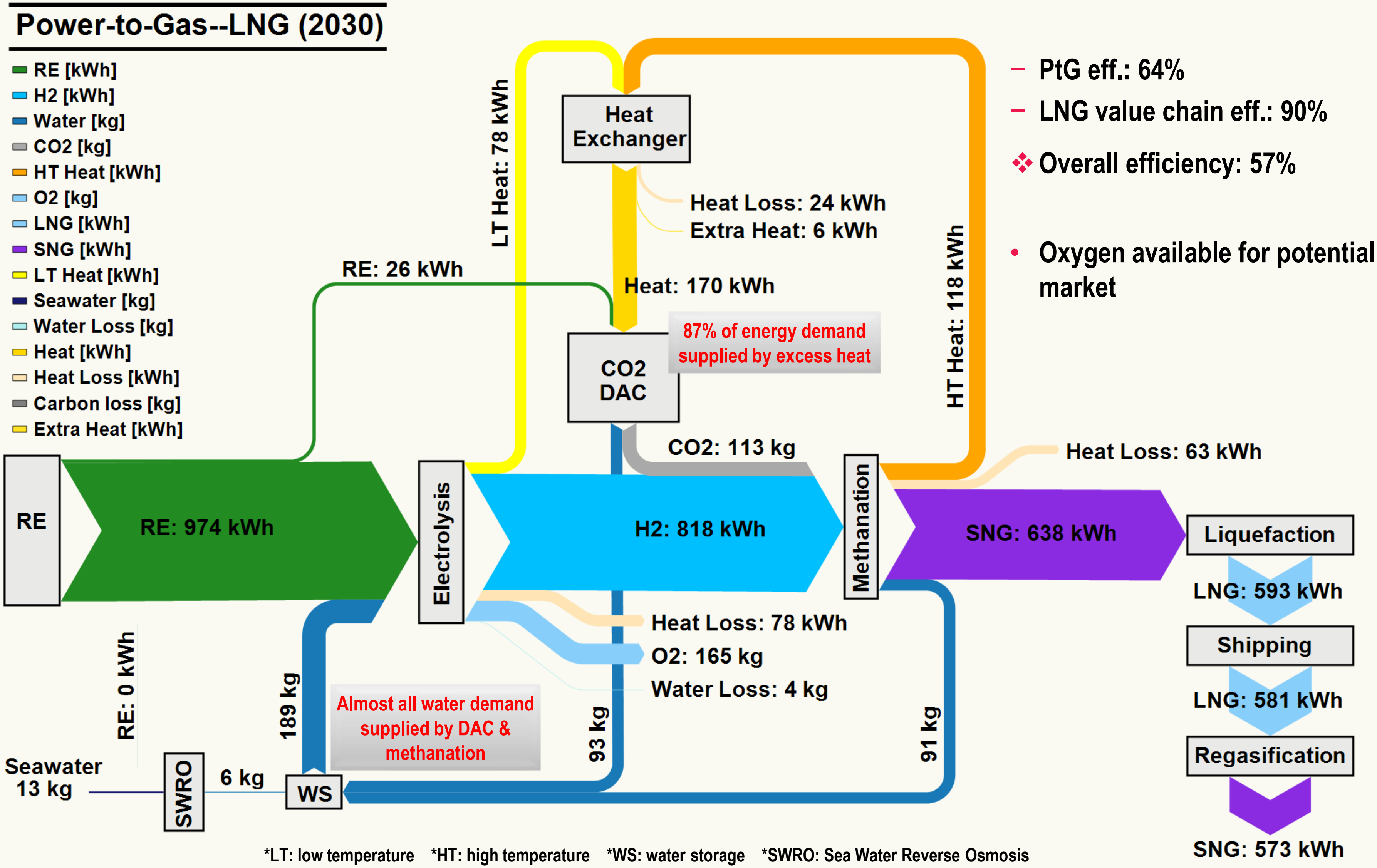
Role of Sector Coupling

Key insights:

- **Power-to-X is the central element of a future energy system, since electricity is the universal platform**
- Electricity-based hydrogen emerges to the 2nd relevant energy carrier (for fuels, chemicals)
- Flexibility in the energy system is key:
  - Supply response (hydro reservoirs, bioenergy) for indirect balancing of solar and wind
  - Grid interconnections, in particular for balancing wind energy
  - Smart demand response: BEV (smart charging, V2G), heat pumps, electrolysers
  - Storage (hours, days, weeks, seasons; electricity, heat, fuels)
- **Cross-border integration may be less important than cross-sectoral cost reduction**
- **Efficient sector coupling substantially reduces curtailment**
- Low-capex batteries and low-capex electrolysers are key for the energy transition
- No flexibility from CO_2 direct air capture units, H_2-to-X synthesis and desalination

Methodology

PtG-LNG Value Chain Energy Flow & Mass Balance



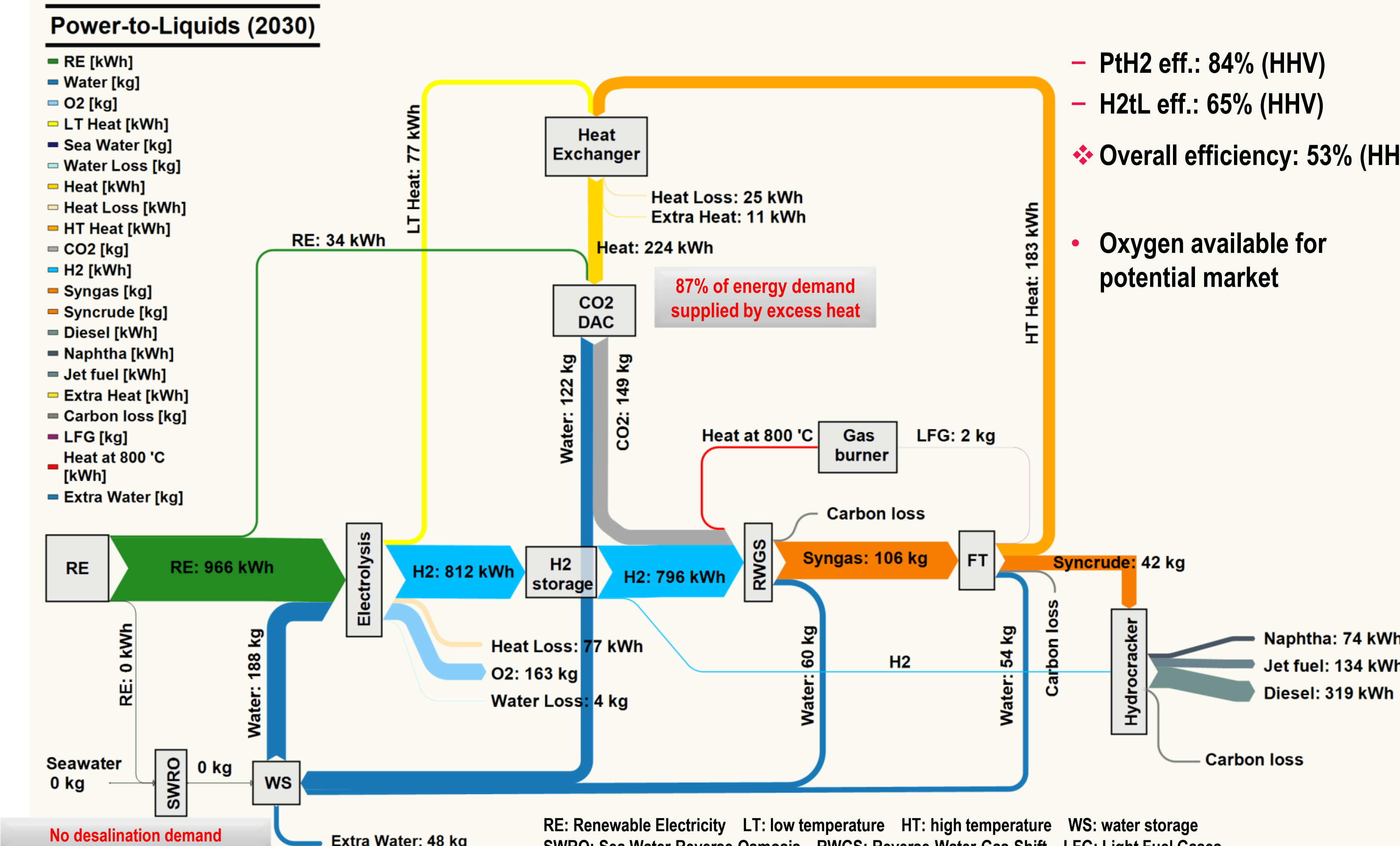
- PtG eff.: 64%
- LNG value chain eff.: 90%
- Overall efficiency: 57%

- Oxygen available for potential market

*LT: low temperature *HT: high temperature *WS: water storage *SWRO: Sea Water Reverse Osmosis

Methodology

PtL Energy Flow & Mass Balance



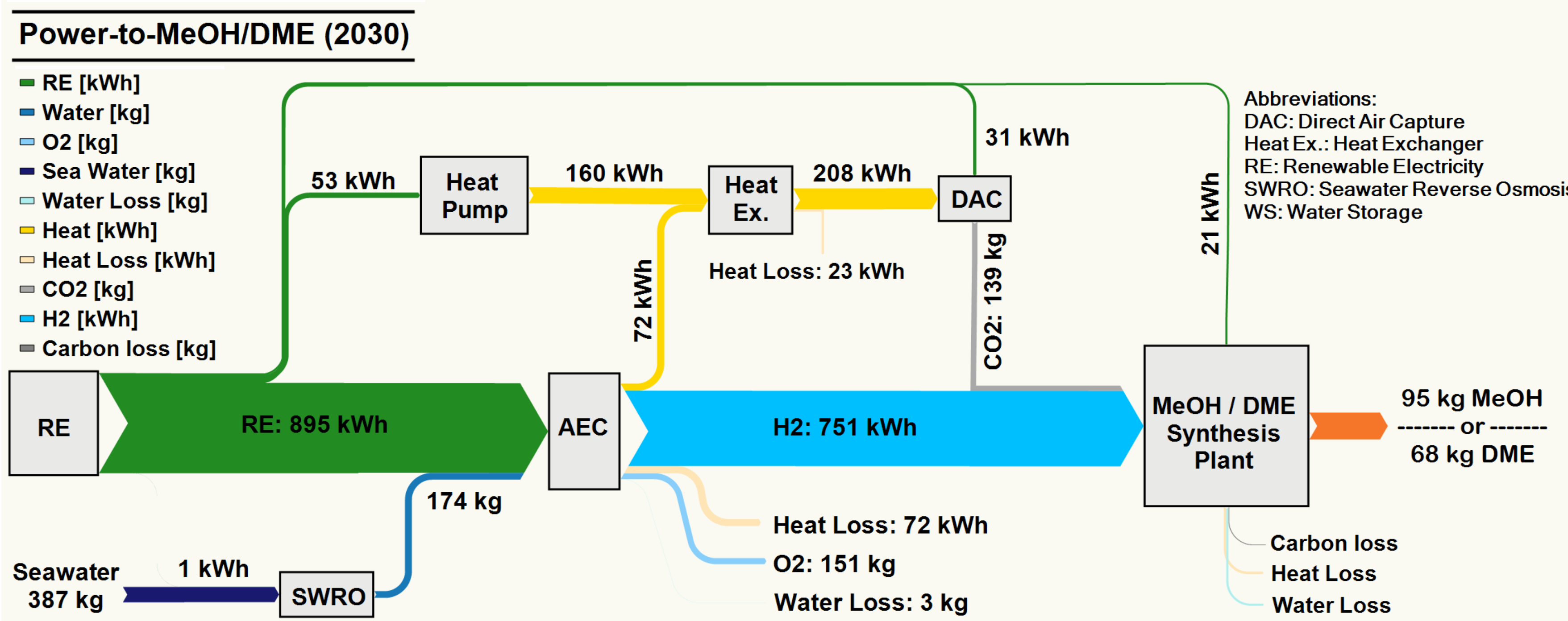
- PtH2 eff.: 84% (HHV)
- H2tL eff.: 65% (HHV)
- Overall efficiency: 53% (HHV)
- Oxygen available for potential market

RE: Renewable Electricity LT: low temperature HT: high temperature WS: water storage
SWRO: Sea Water Reverse Osmosis RWGS: Reverse Water-Gas Shift LFG: Light Fuel Gases

source: [Fasihi et al., 2016, Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, Energy Procedia, 99, 243-268]

Methodology

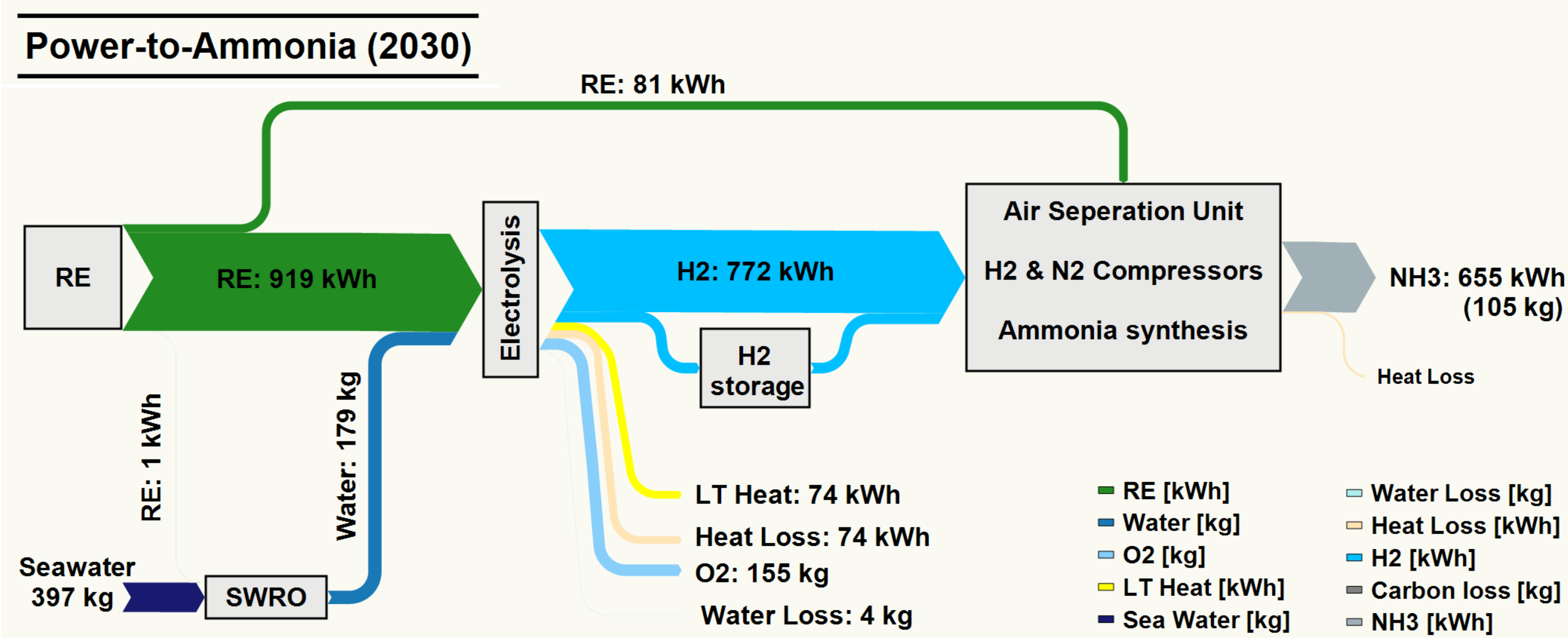
PtMeOH/DME Energy Flow & Mass Balance



- Electrolyser is the main electricity consumer
- PtH_2 eff.: 84% (HHV)
- PtMeOH overall efficiency eff.: 60.4% (HHV)
- PtDME overall efficiency eff.: 60.5% (HHV)
- Oxygen available for sale on respective O_2 markets
- Heat pump decreases direct electricity consumption

Methodology

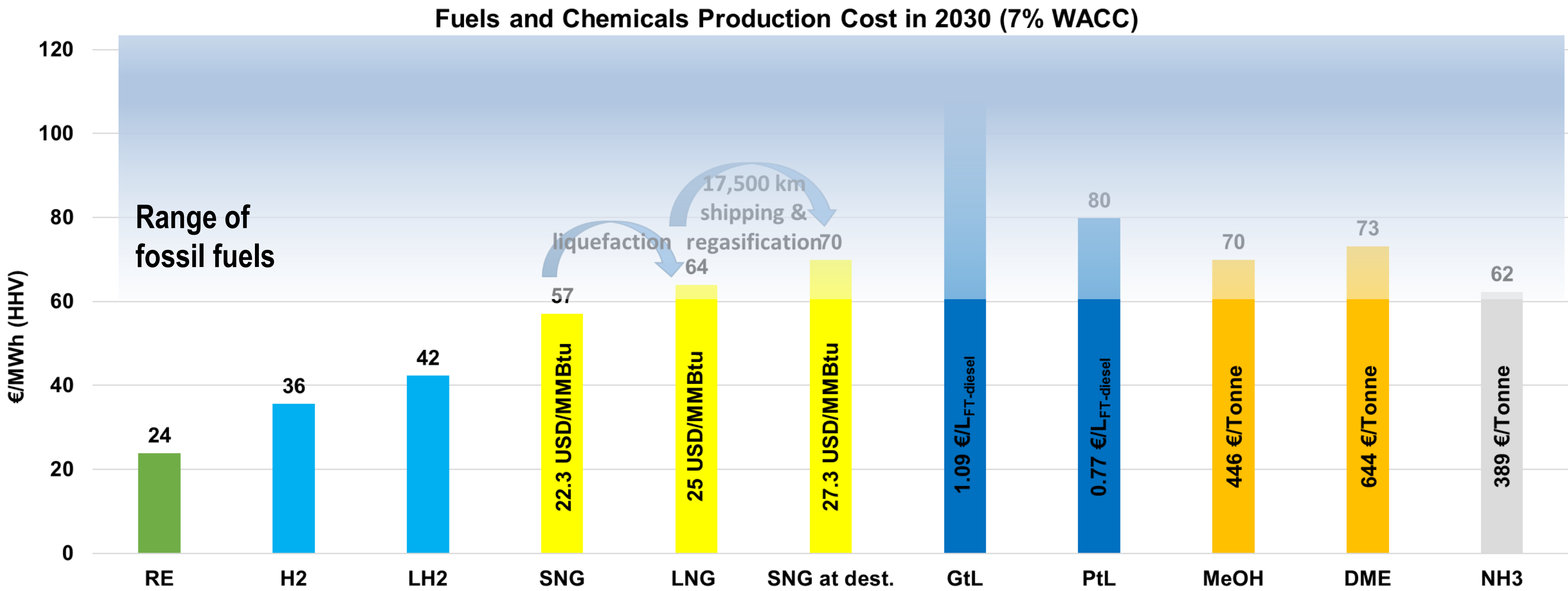
$PtNH_3$ Energy Flow & Mass Balance



RE: Renewable Electricity LT: low temperature SWRO: Sea Water Reverse Osmosis

- Electrolyser is the main electricity consumer
- PtH_2 eff.: 84% (HHV)
- $PtNH_3$ overall eff.: 65.5% (HHV)
- Oxygen available for sale on respective O_2 markets
- Excess utilisable heat available from electrolyser and synthesis plant

PtX
Cost of Power-to-Fuel/Chemical Options



- For conditions in Patagonia
- SNG and PtG-GtL are the cheapest and the most expensive synthetic fuel, respectively.
- the production cost of RE-diesel, RE-methanol and RE-DME are close to each other, however the fuel-parity (cost competitiveness) depends on their respective market price and CO_2 emission cost.
- Sensitivities (rough rules of thumb):
  - -10% of RE capex: -6% of output fuel/chemicals cost
  - -10%rel of WACC: -5% of output fuel/chemicals cost (5% WACC: -15% of output cost)

Various losses in a 100% RE system

Key insights:

- electricity storage losses are surprisingly low, only 28% of generation has to be stored, and batteries can store 92% of all stored electricity and that at high efficiency
- seasonal storage can be at negligible loss for hydro reservoirs and biomethane, Power-to-Gas-to-Power is needed only for 0.3% of total electricity demand (in global average), thanks to sector coupling
- curtailment across all sectors is surprisingly low, at about 3.5% of generation
- Power-to-Fuels efficiency is about 50-60%, BUT generated electricity can be used with low curtailment and little battery storage (due to flexible electrolysers) and storage efficiency of liquids is high

Flexibility supports loss reduction

- electrolysers follow generation supported by hydrogen buffer storage
- thermal energy storage provides additional flexibility, in addition to heat pumps, both leading to a reduced curtailment in electricity generation
- smart charging of battery-electric vehicles is a further highly valuable flexibility option and can reduce seasonal storage demand

Efficiency development in transport sector

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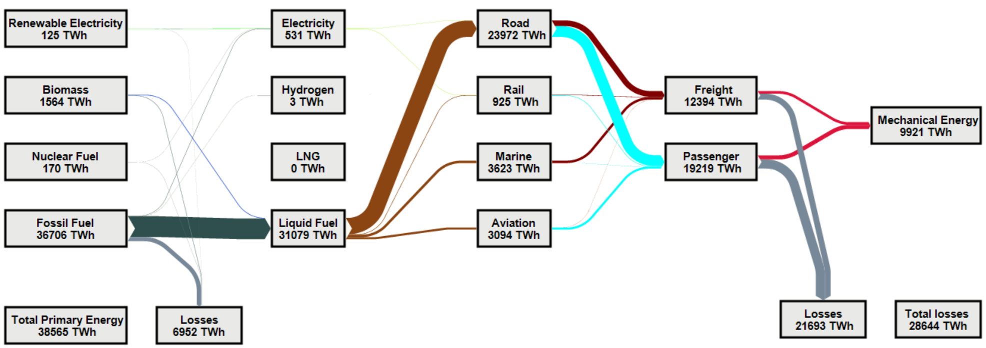
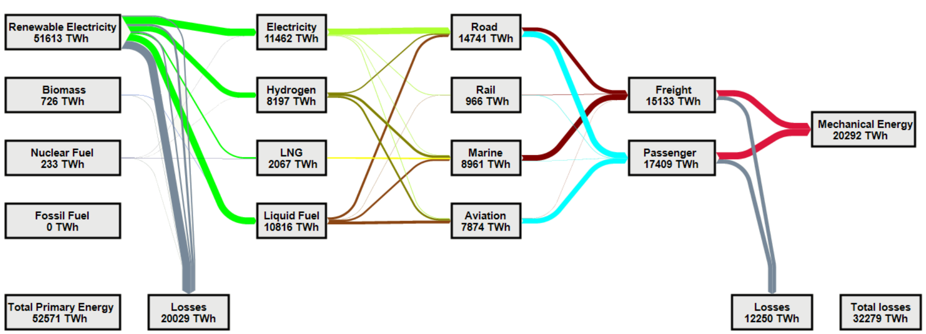
Year	Primary Energy	Final Energy	Mechanical Energy	Transport Activity Passenger	Transport Activity Freight
	TWh	TWh	TWh	b p-km	b t-km
2015	38,565	31,613	9921	181,273	108,006
2050	52,571	32,542	20,292	646,522	332,405
relative change	36.3%	2.9%	104.5%	257%	208%

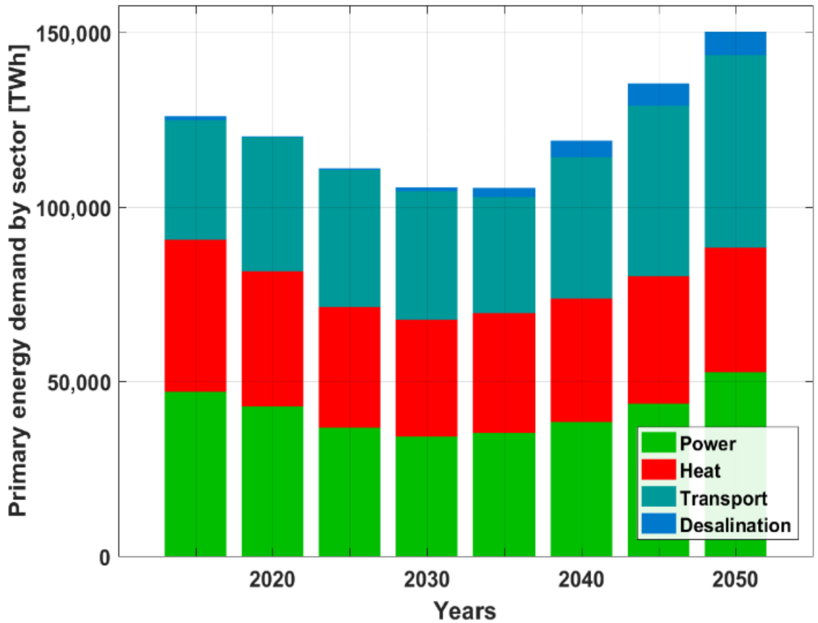


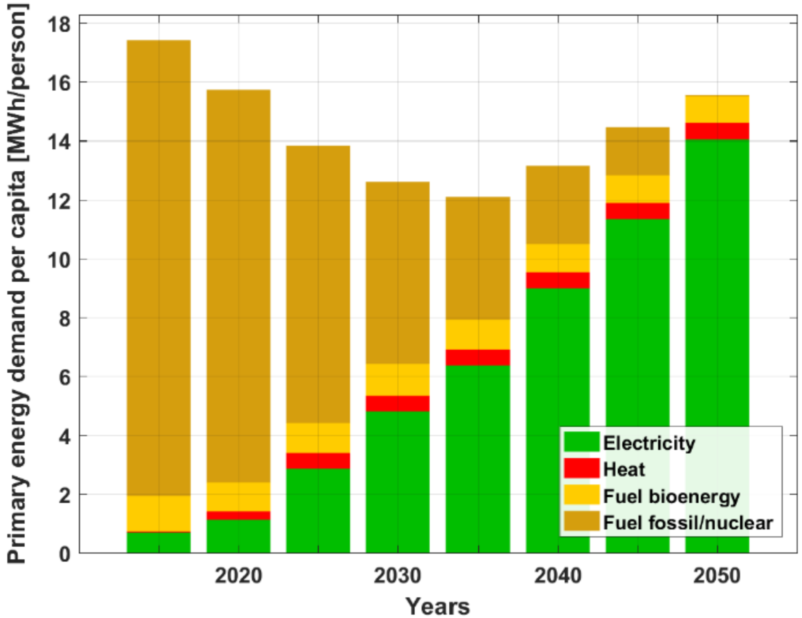


Key insights:

- energy services grow substantially
- final energy remains practically unchanged
- primary energy increases moderately
- losses increase by 13% while used energy increases by 105%
- massive efficiency gain in road transport
- PtX efficiency acceptable

Long-term Energy Demand

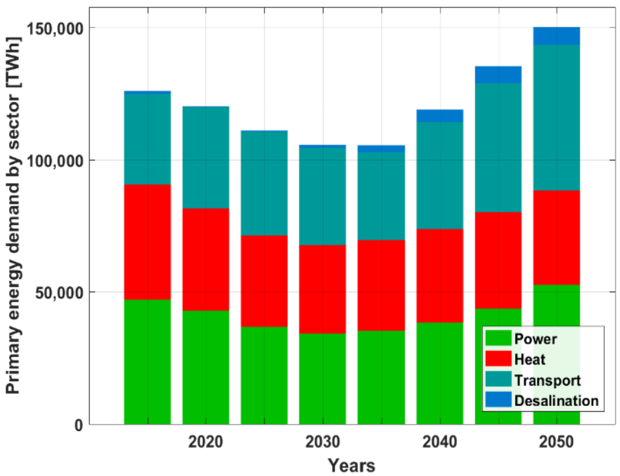


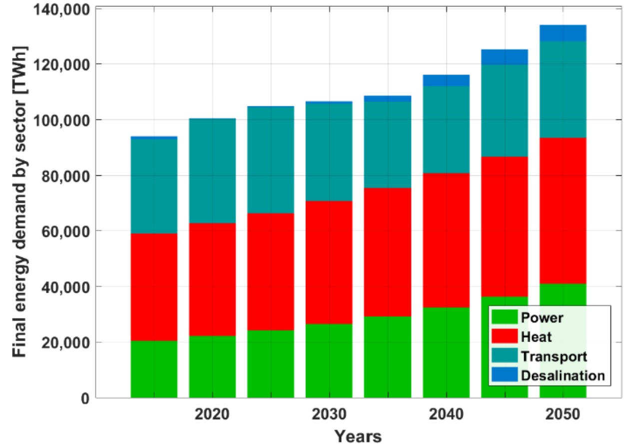


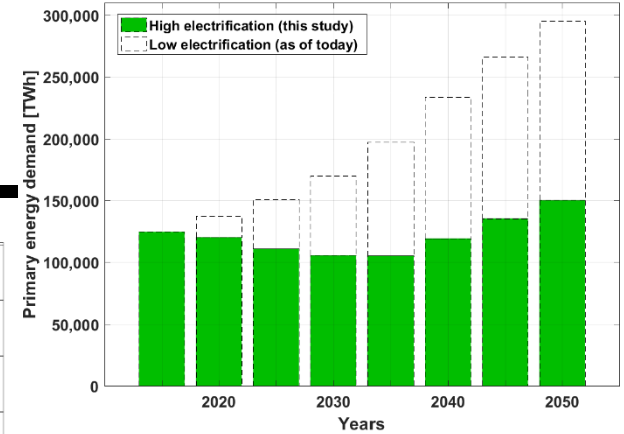
Key insights:

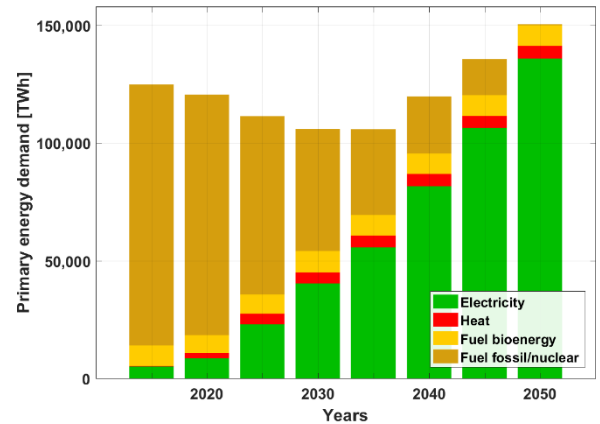
- A global compound average annual growth rate of about 1.0% in final energy demand drives the transition. This is composed by final energy demand growth for power and heat, desalinated water demand and transportation demand linked to powertrain assumptions. This leads to a comprehensive electrification, which massively increases overall energy efficiency, to an even higher growth rate in provided energy services.
- This results in an average annual growth rate of about 0.5% in total primary energy demand (TPED).
- World population is expected to grow from 7.2 to 9.7 billion, while the average per capita PED decreases from around 17 MWh/person in 2015 to 12 MWh/person by 2035 and increases up to around 15 MWh/person by 2050.

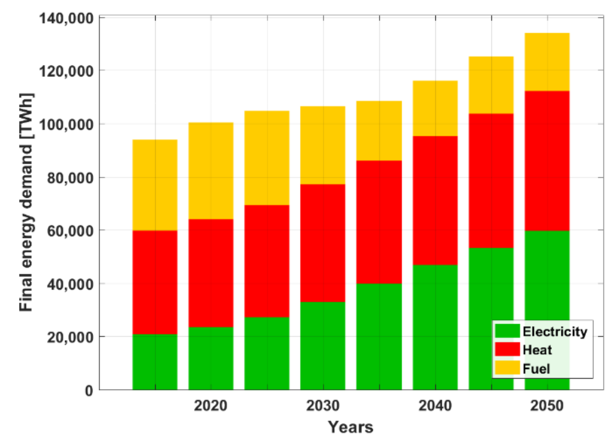
Long-term Energy Demand











Key insights:

- TFED increases continuously by 43% from 94,000 TWh to 134,000 TWh while energy services grow faster
- TPED decreases from almost 130,000 TWh in 2015 to around 105,000 TWh by 2035 and increases up to 150,000 TWh by 2050 in this study (which assumes high electrification). Total growth is around 21%.
- In comparison, current practices (low electrification) would result in a TPED of nearly 300,000 TWh by 2050.
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 90% in 2050, saving nearly 150,000 TWh compared to the continuation of current practices (low electrification).
- TFED structure changes moderately with higher electricity shares
- TPED changes structurally and massively to dominance of electricity

Special note on solar PV

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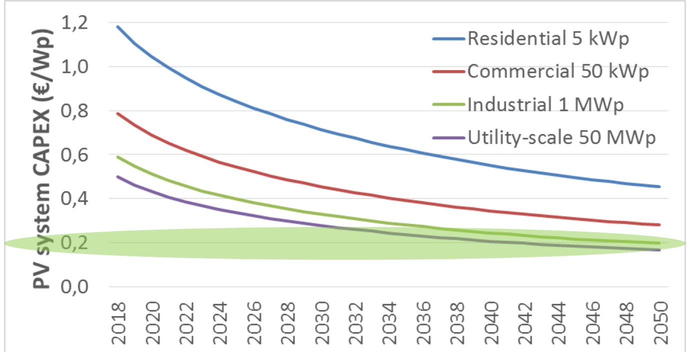
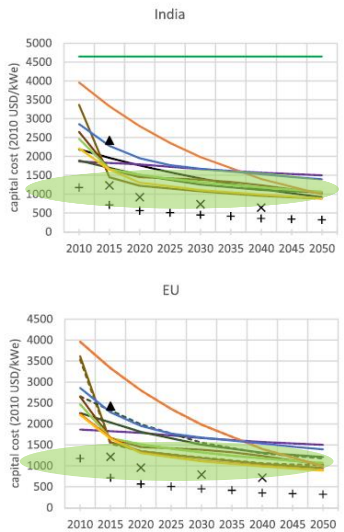
Key insights:

- **Solar PV emerges to the major source of energy till 2050, in Europe and globally**
- Practically ALL global scenarios dramatically fail in the right role of solar PV
- **Fast cost decline of the last 10 years is ignored by IEA, IPCC (based on IAMs), and others**
- Climate change mitigation could be more powerful, if major institutions would perform better
- Massive and fundamental re-thinking on solar PV, plus supporting batteries, is needed
- Fridays For Future increase pressure and massively punish low-performing parties
- We witness the dawn of the Solar Age and should take benefits instead of destroying the future

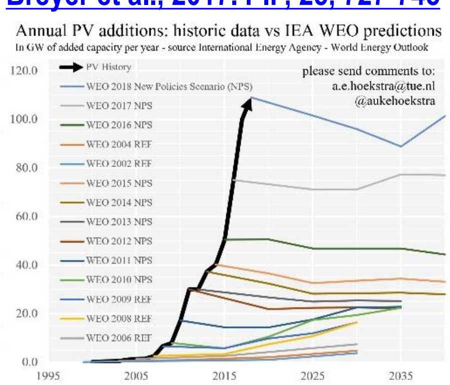


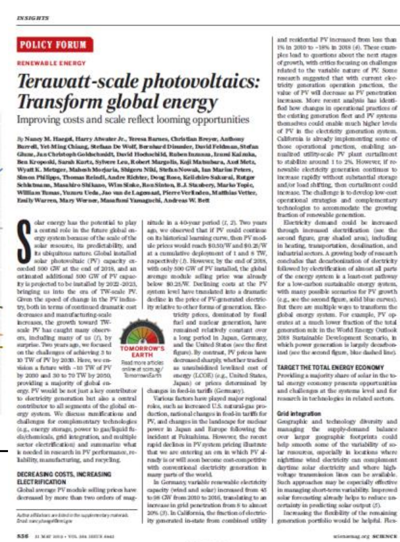
numbers by ETIP PV https://bit.ly/2K0sFV7
power plants: [Vartiainen et al., Progress in PV](#)



IAM assumptions in IPCC
[Krey et al., 2019. Energy, 172, 1254-1267](#)

articles based on real PV cost
[Heagel et al. 2019. Science, 364(6443), 836-838](#)
[Vartiainen et al., 2019. PIP](#)
[Breyer et al., 2018. PIP, 26, 505-523](#)
[Breyer et al., 2017. PIP, 25, 727-745](#)



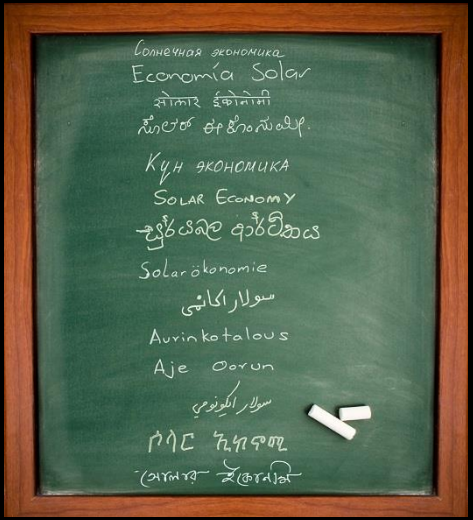


Impact of 100% R
Christian Breyer

Summary

- 1.5°C scenario with zero GHG emissions in 2050 is possible
- Specific energy cost shrink slightly
- Broad electrification of the entire energy system
- Overall storage losses are small, since bulk storage is battery and fuels (hydrogen, liquid fuels) which are both at high levels of efficiency
- Thermal conversion processes are a consequence of fossil fuels and inherently low efficient, compared to electricity-based solutions, including PtX where needed
- Energy services expand, while primary energy grows slowly
- Gain in overall efficiency can be quantified by a factor of 2
- More research required for net energy/ EROI considerations
- Solar photovoltaic, wind energy, batteries, heat pumps and synthetic fuel conversion technologies are central
- No risk technologies required
- Political will and ambitious execution drive transition

Thank you for your attention …
… and to the team!



SCIENTISTS FOR FUTURE

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all publications at: www.researchgate.net/profile/Christian_Breyer
new publications also announced via Twitter: @ChristianOnRE

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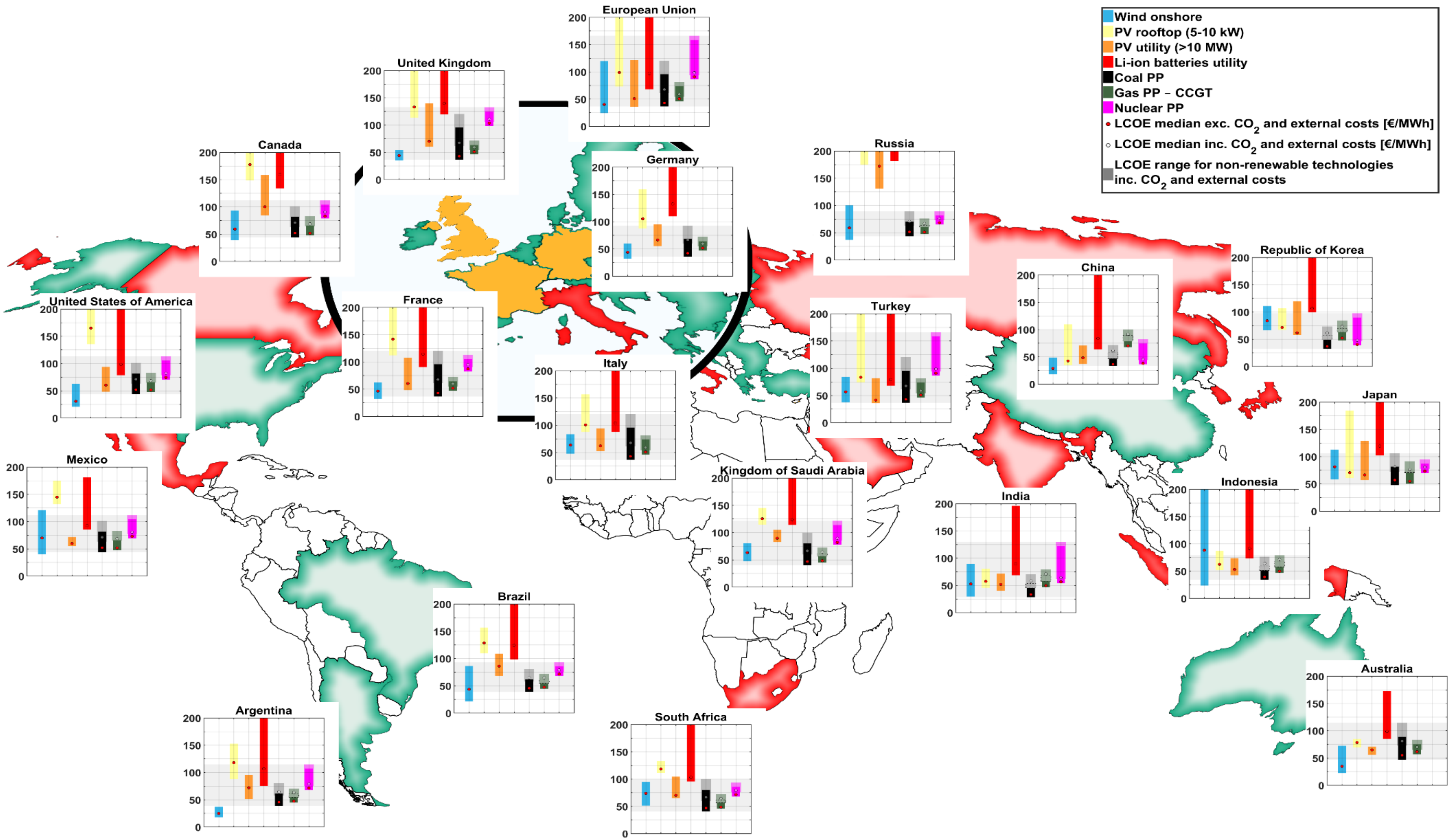
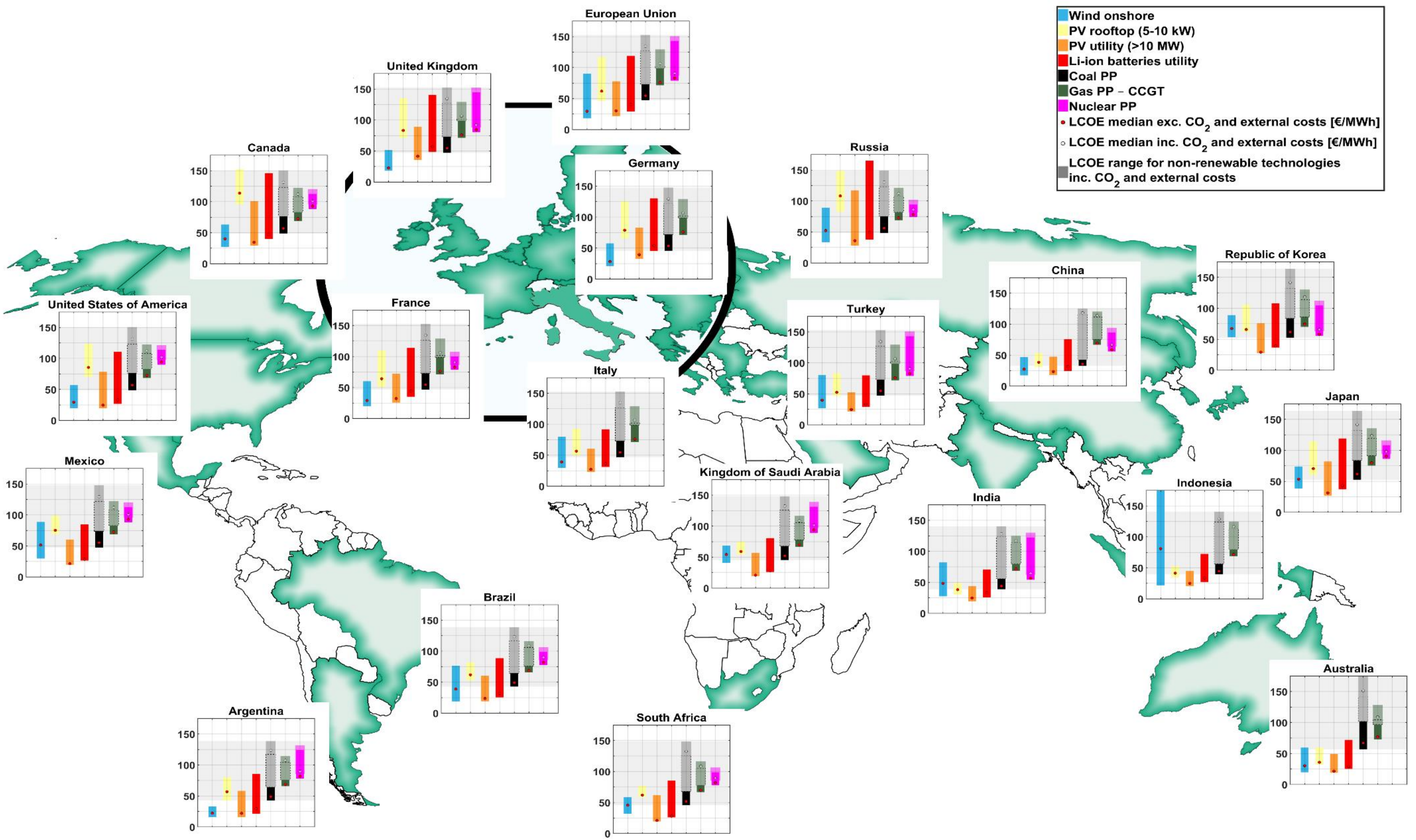
LCOE across G20 in 2015



source: Ram M., et al., 2018. A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030, J of Cleaner Production, 199, 687-704

LCOE across G20 in 2030



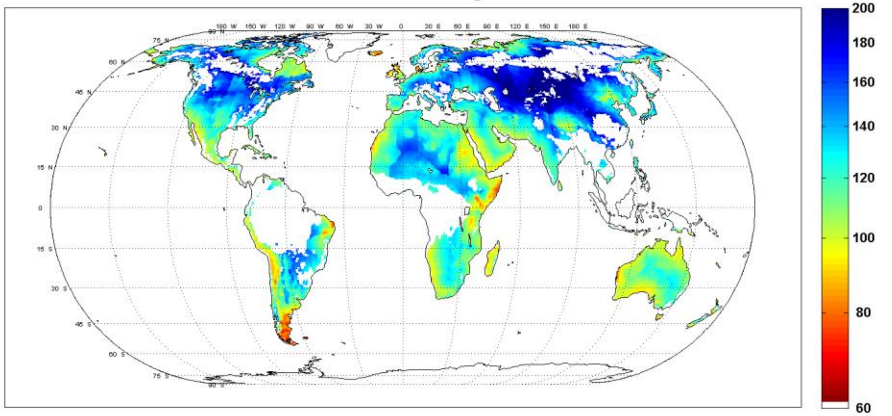
Impact of 100% RE on PED and FED
Christian Breyer ► christian.breyer@lut.fi

source: Ram M., et al., 2018. A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030, J of Cleaner Production, 199, 687-704

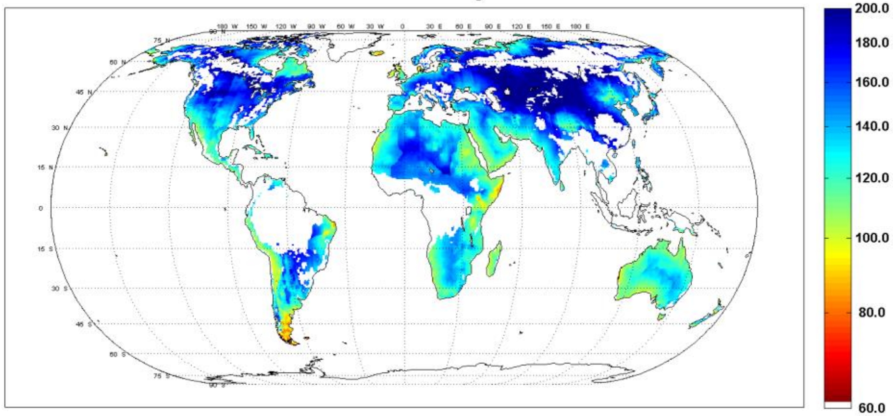
Results

Levelised Cost of Fuels (LCOF) at Coast in 2030

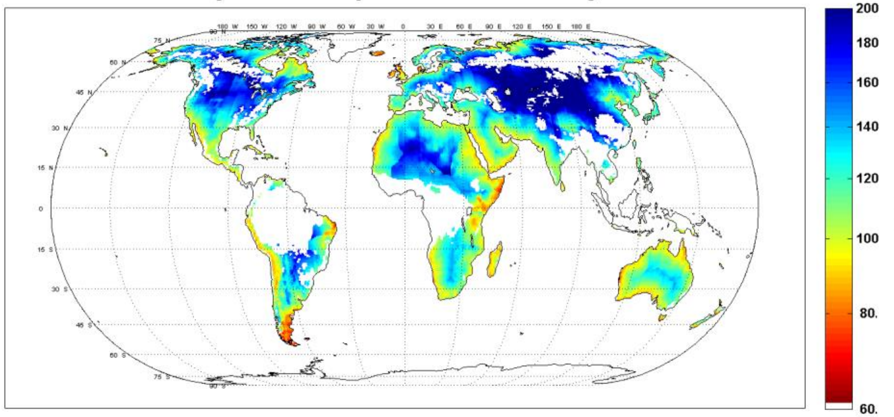
Cost of SNG for cost year 2030



Cost of LNG for cost year 2030



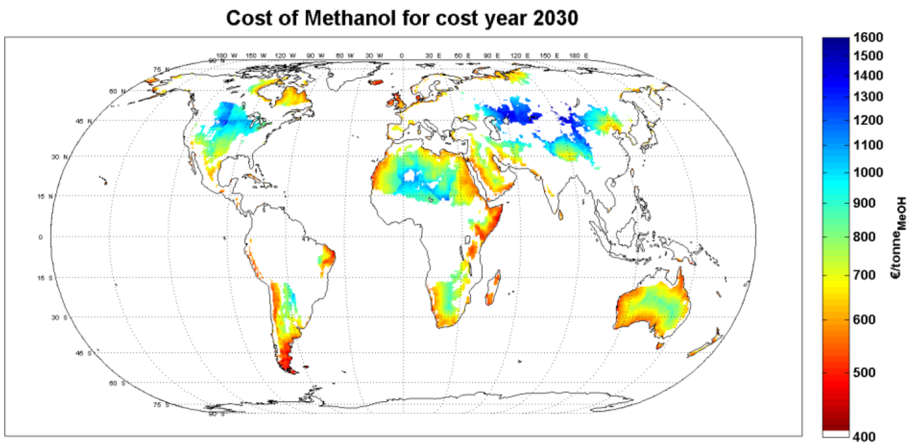
Cost of Synthetic Liquid Fuels for cost year 2030

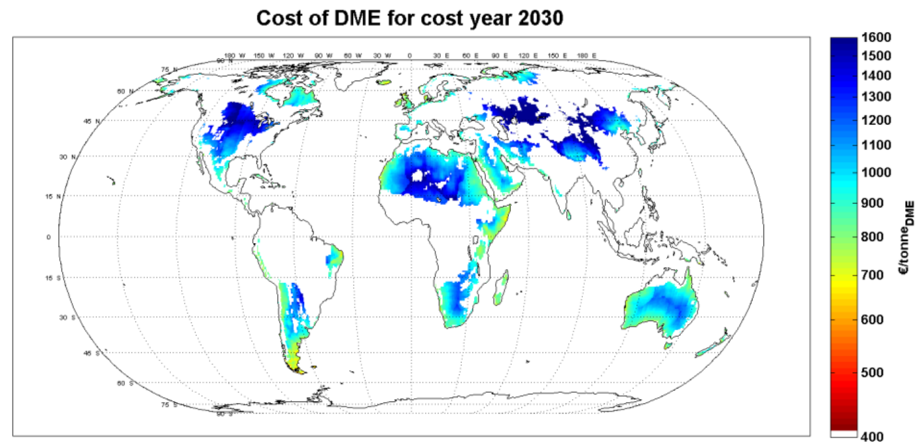


- LCOF as a function of LCOE and FLh of plants' components
- in 2030, top sites in the world reach LCOF of 70 – 80 €/MWh (0.68 - 0.77 €/l for diesel and 27.4 - 31.3 USD/MMBtu for SNG)
- LNG value chain adds 15-20 €/MWh to delivered SNG cost
- regions not so far from coast are generally a better place due to lower electricity transmission cost

Results

Levelised Cost of Fuels (LCOF) at Coast in 2030





- Patagonia, Somalia, Western Sahara and the coasts of Australia and Brazil produce the cheapest methanol within the range of 400-600 €/tonne.
- DME production cost is about 200-300 €/tonne more expensive for each site, depending on the corresponding LCOE.
- The difference in ammonia production cost at coast and remote areas is smaller than the methanol case, due to lower transmission line cost assumption