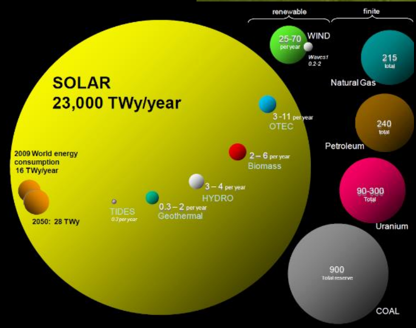




Complementarity of Hydro, Solar and Wind as Basis for 100% Renewables in Latin America

Open your mind. LUT.
Lappeenranta University of Technology

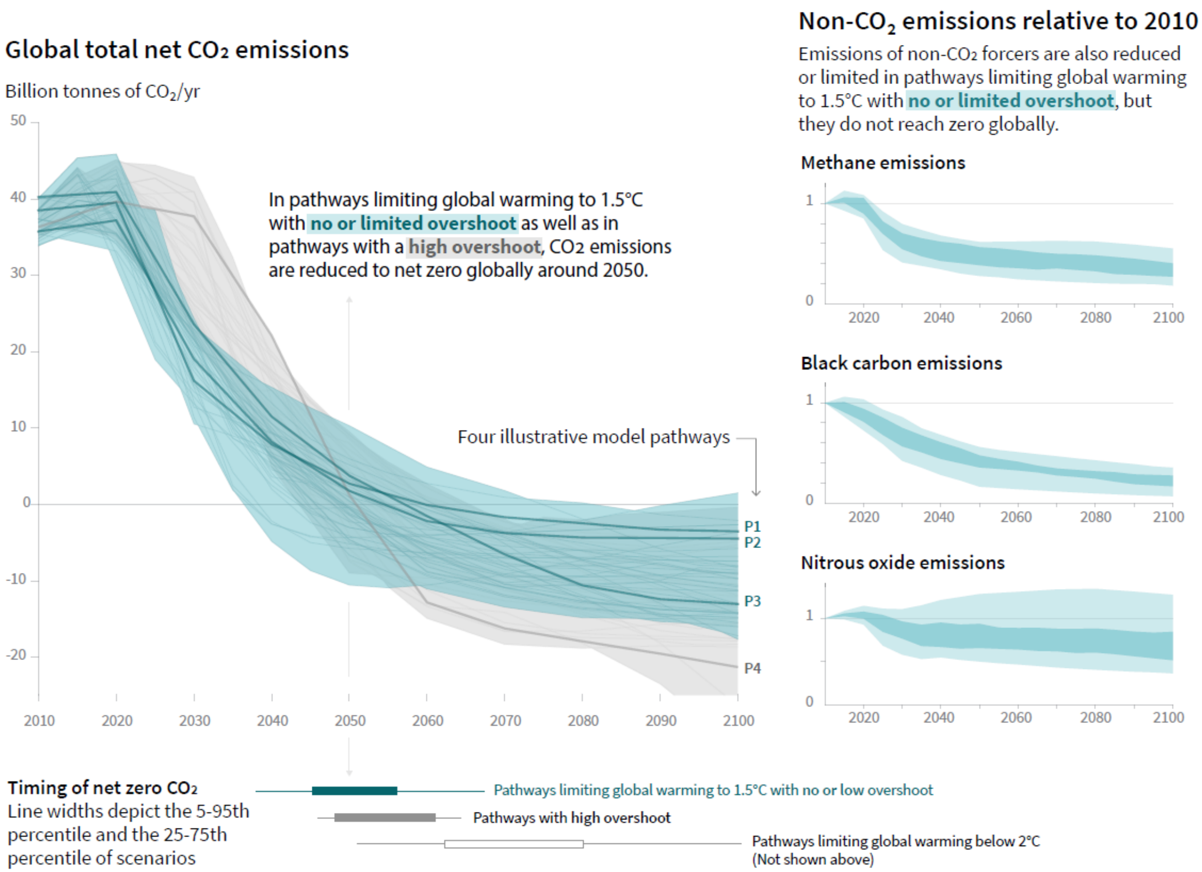
Christian Breyer, professor for Solar Economy
Lappeenranta University of Technology

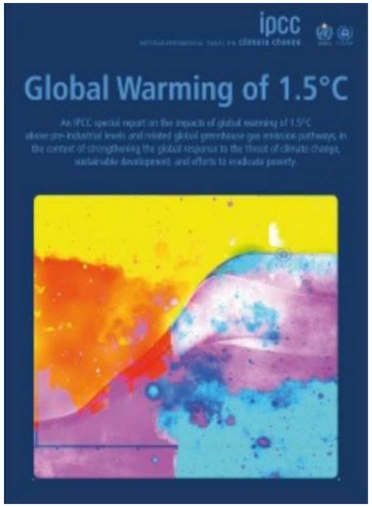
CONGRESO Internacional Mecanismos de incentivo para energías renovables en América Latina
Cochabamba, October 15, 2018

Key takeaways

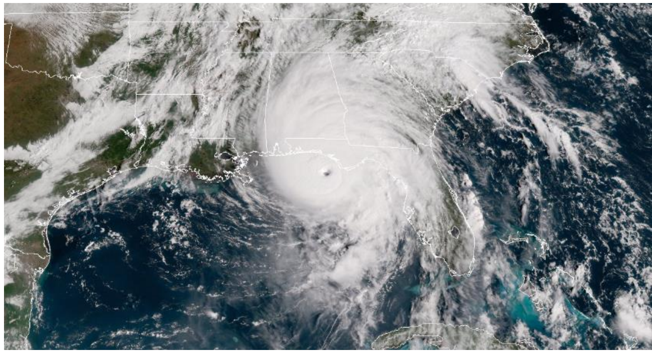
- Climate Change forces a drastic and fast change of the energy system
- 100% renewable energy is technically feasible and economically viable
- Full hourly resolved modeling ensures energy supply throughout the year
- Key energy system components are solar PV, wind energy, batteries, PtX (incl. CCU)
- PV will emerge to the dominating source of energy in this century
- Energy transition to 100% RE eliminates GHG emissions, reduces cost and creates jobs
- Electricity demand will drastically rise due to broad electrification of the energy system
- Latin America owns the best resources in the world for solar, wind, hydro and lithium!!
- Energy-intensive products have the least cost globally in Latin America in 21st century!!
- Almost no one understood so far what 10 USD/MWh electricity cost really means
- Enormous economic rise is possible, if good governance allows harvesting of benefit
- Substantially more studies are needed to better understand the comparative competitiveness

Latest insights for 1.5°C world





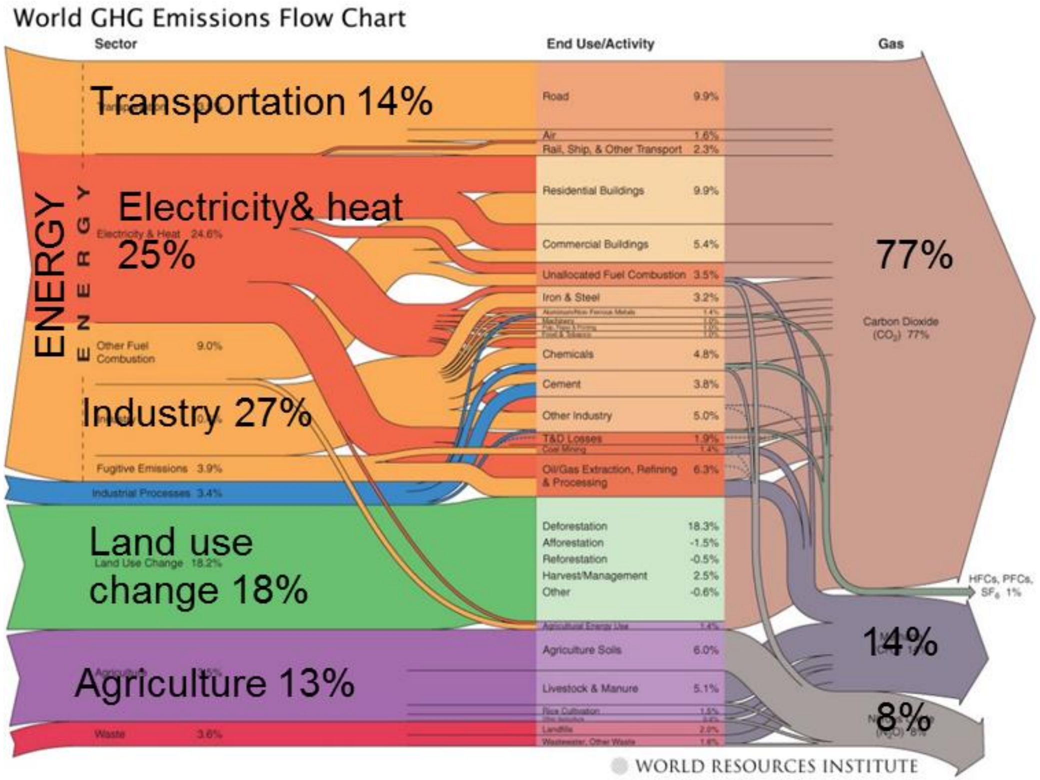
source:
IPCC, 2018. Global Warming of 1.5ºC, released October 8



Key insights:

- very fast defossilisation is needed in any case
- zero GHG emissions in 2050s in all relevant scenarios
- <u>net negative</u> CO_2 emissions from 2050s onwards (ramp-up of NETs to be started in 2030s/2040s)

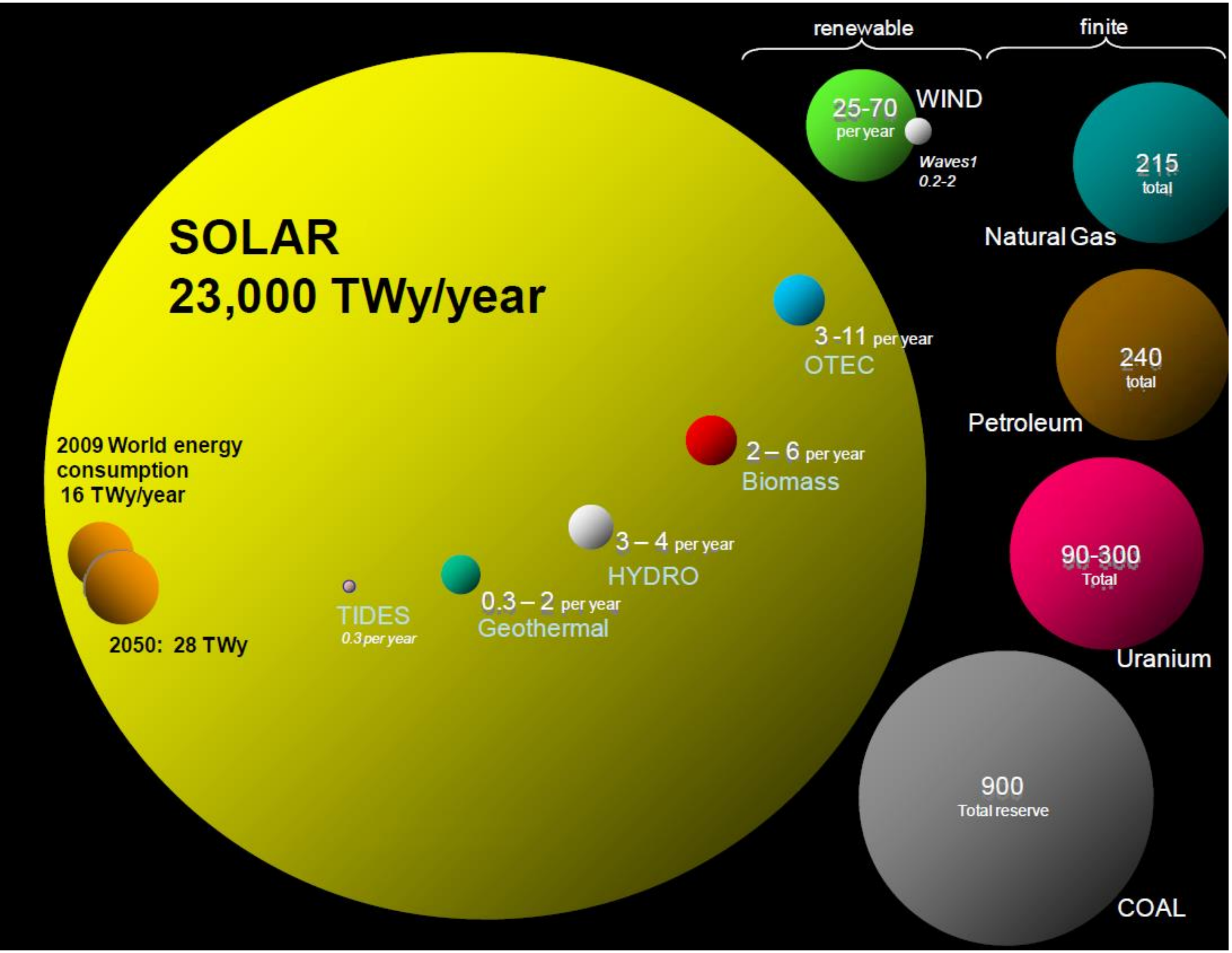
Origin of GHG emissions



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

Resources and Energy Demand

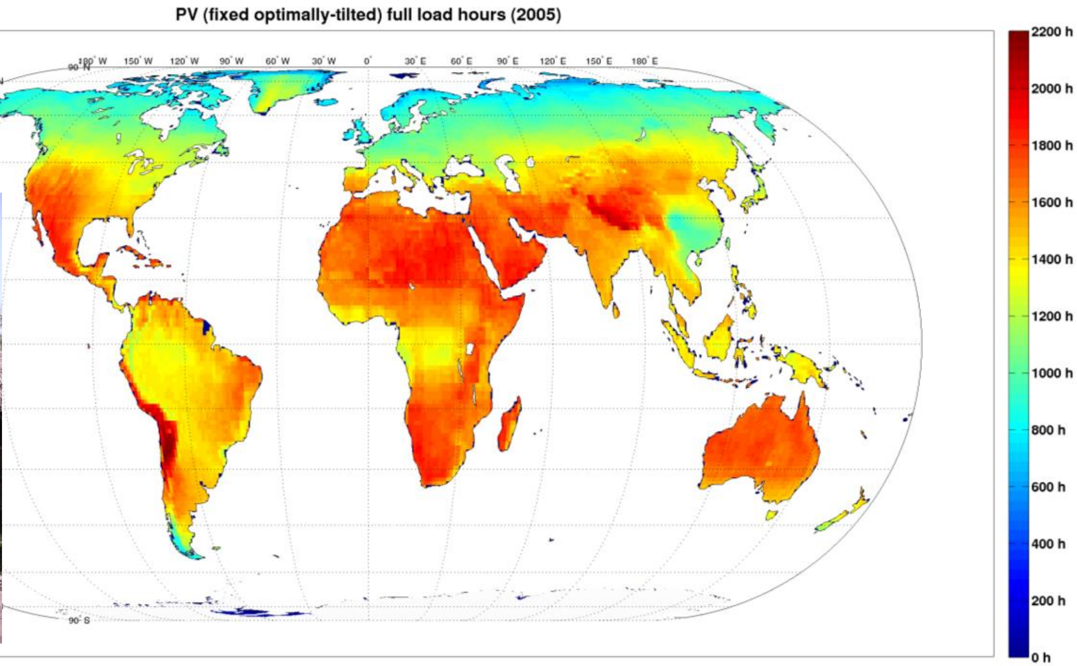


Key insights:
- no lack of energy resouces
- limited conventional resources
- solar and wind resources need to be the major pillars of a sustainable energy supply

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

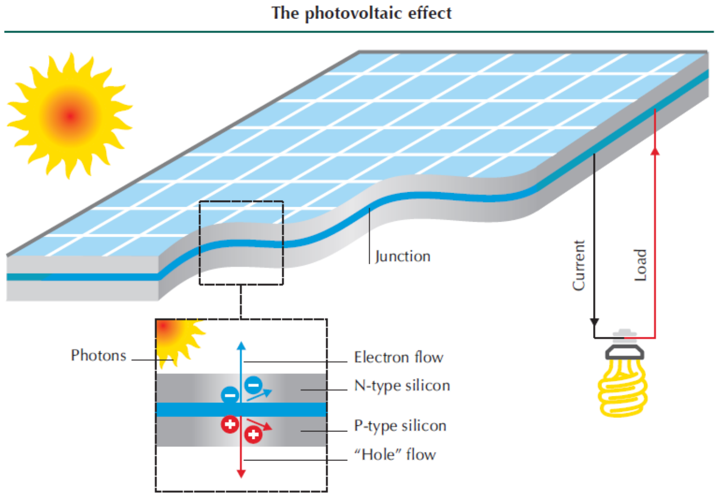
source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50

Solar Photovoltaics

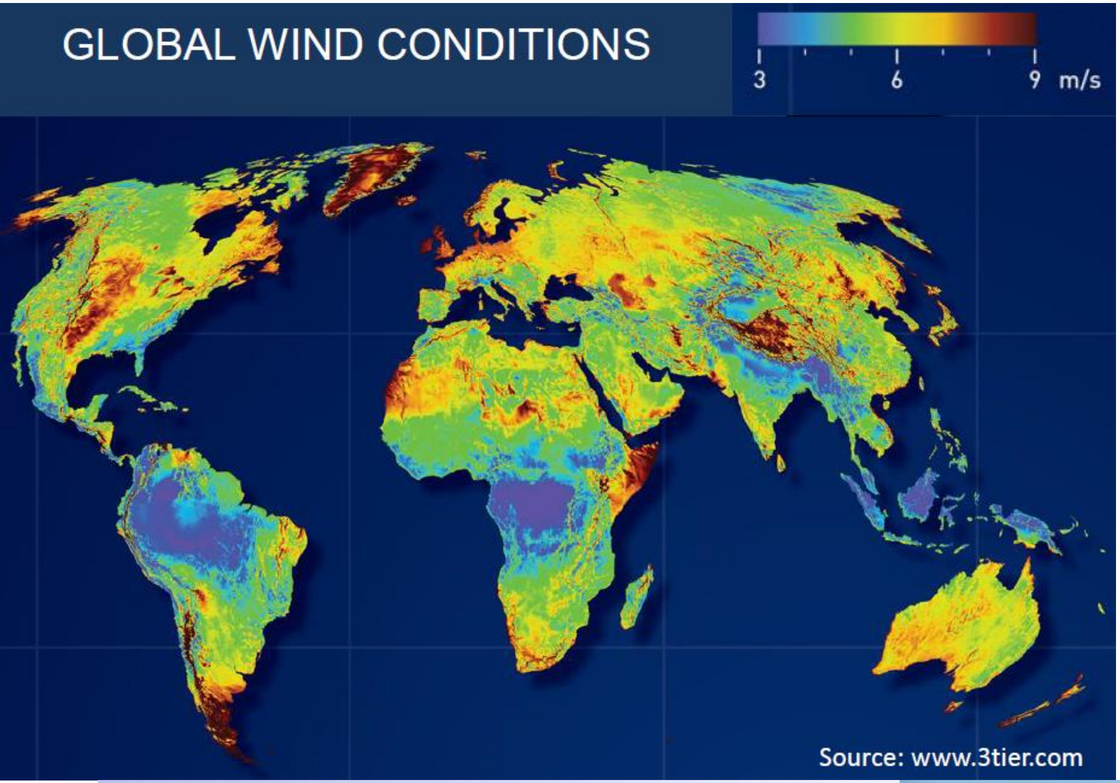


Key insights:

- 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



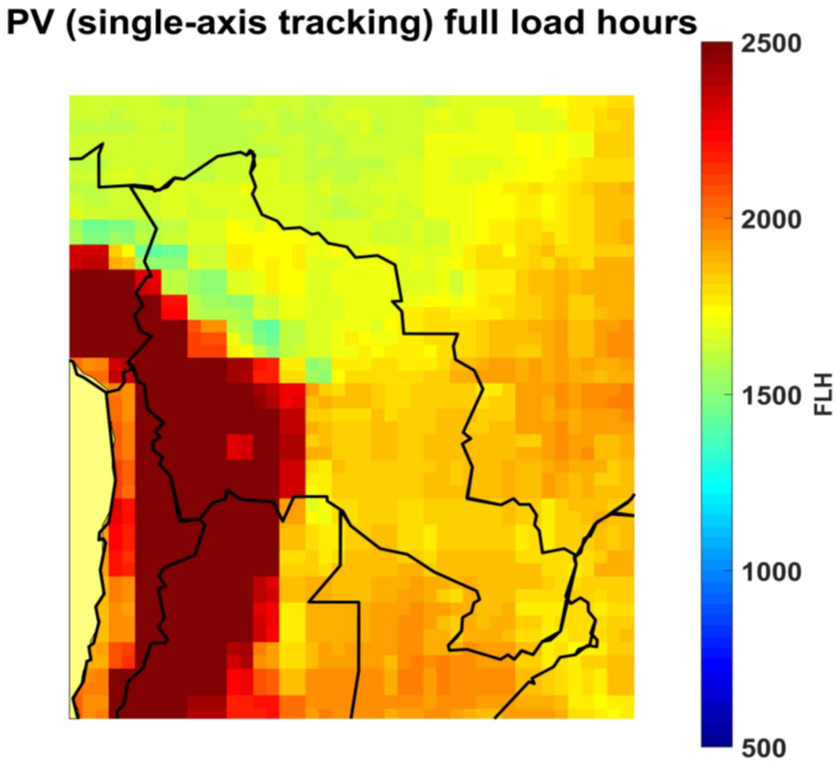
Wind energy

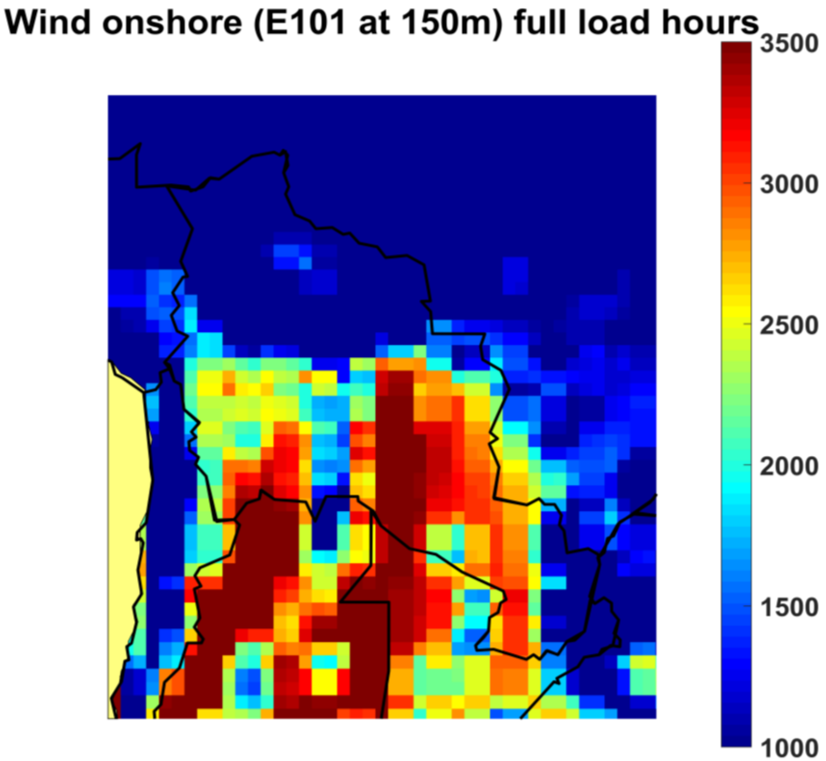


Key insights:

- 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

Bolivia, Paraguay - Full Load Hours





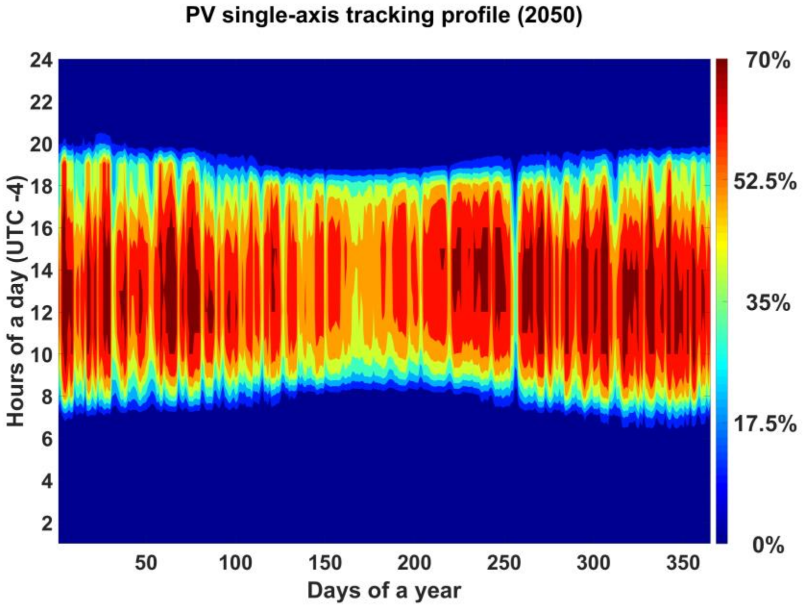
Key insights:

- Wind: Resource distribution is uneven throughout the region
- Solar PV: Good to excellent PV conditions in the entire region

Bolivia, Paraguay (Solar, Wind)

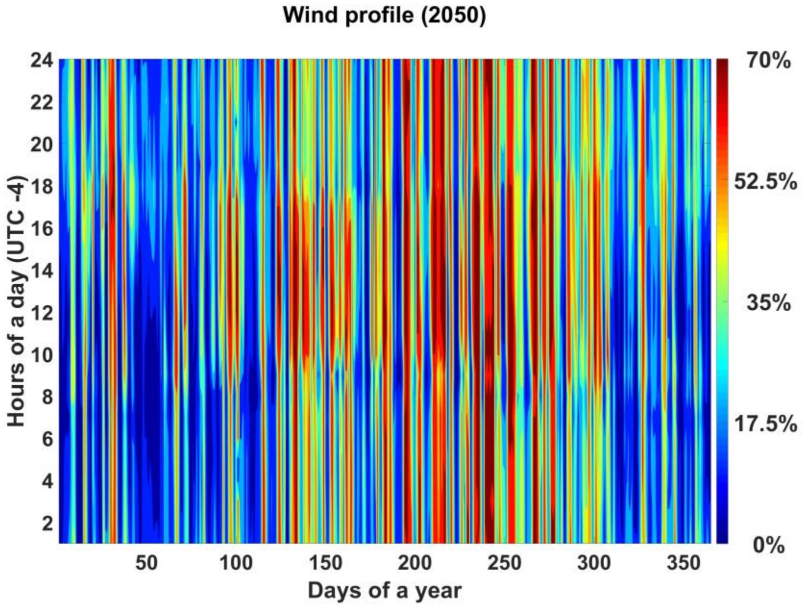
Solar PV generation profile

Aggregated PV feed-in profile computed using the weighed average rule



Wind generation profile

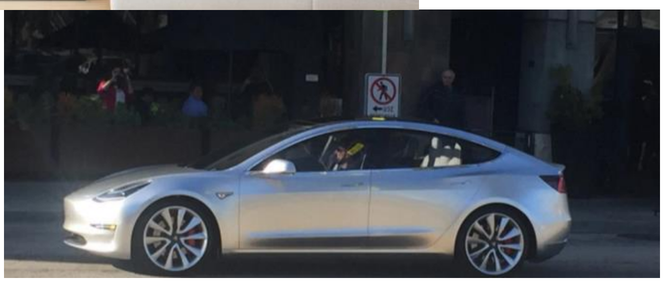
Aggregated wind feed-in profile computed using the weighed average rule

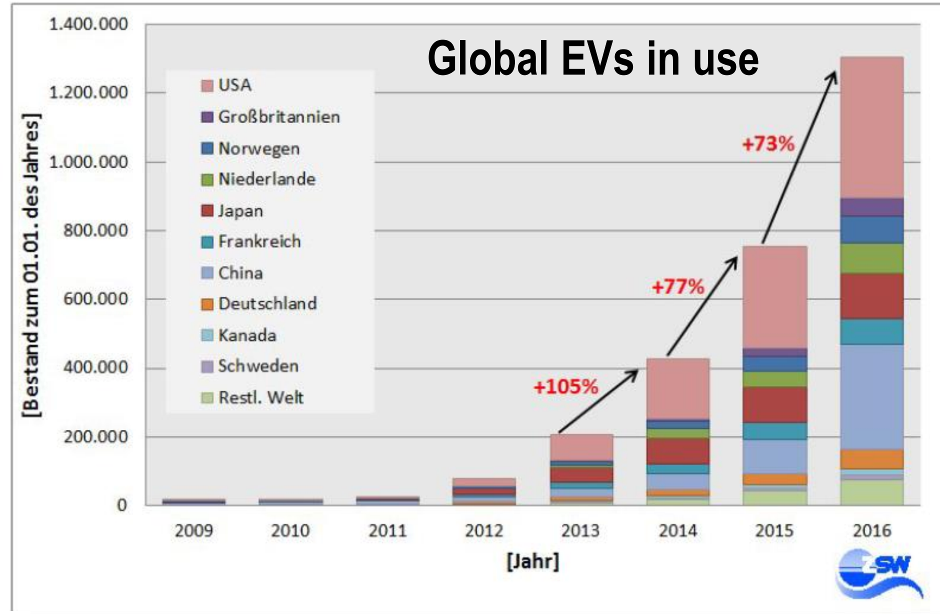


Key insights:

- Wind: Moderate seasonal variability and uneven distribution. Excellent resource availability in the middle and towards the end of the year
- Solar PV: Excellent potential throughout the year
- Seasonal and hourly complementarity of PV and wind

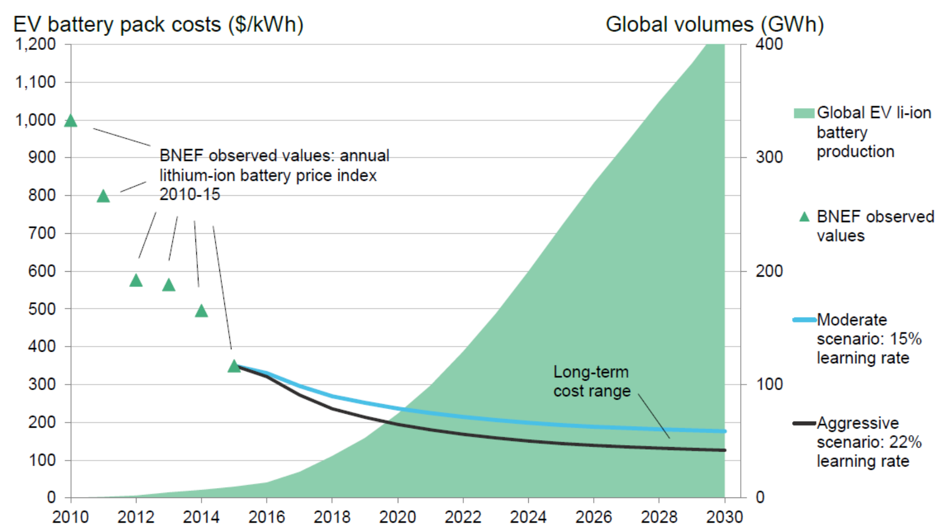
Batteries and EVs – Very high dynamics



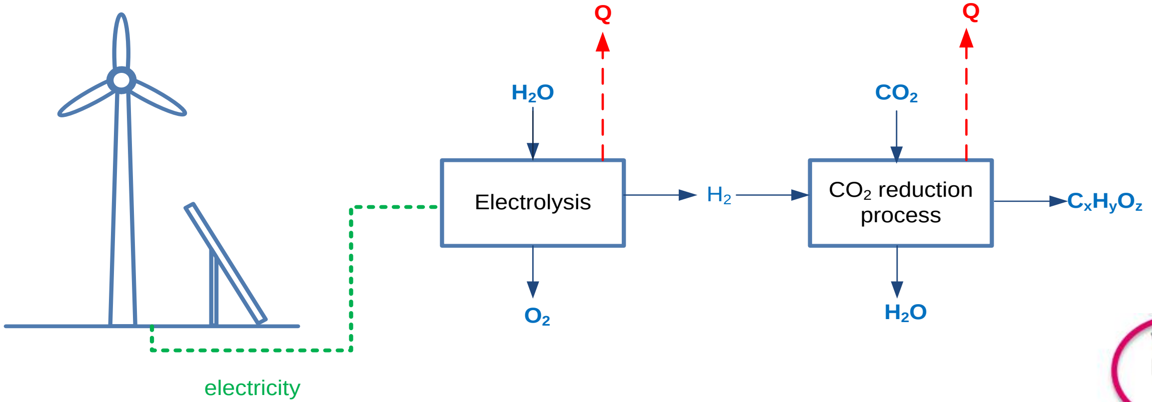


Key insights:

- 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

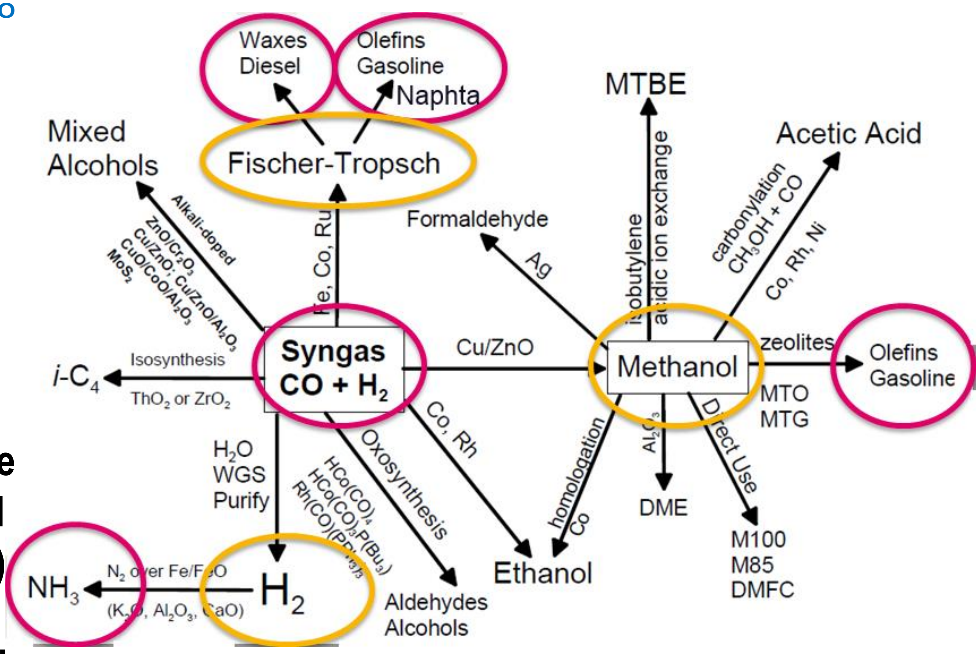


Power-to-X – covering hydrocarbon demand

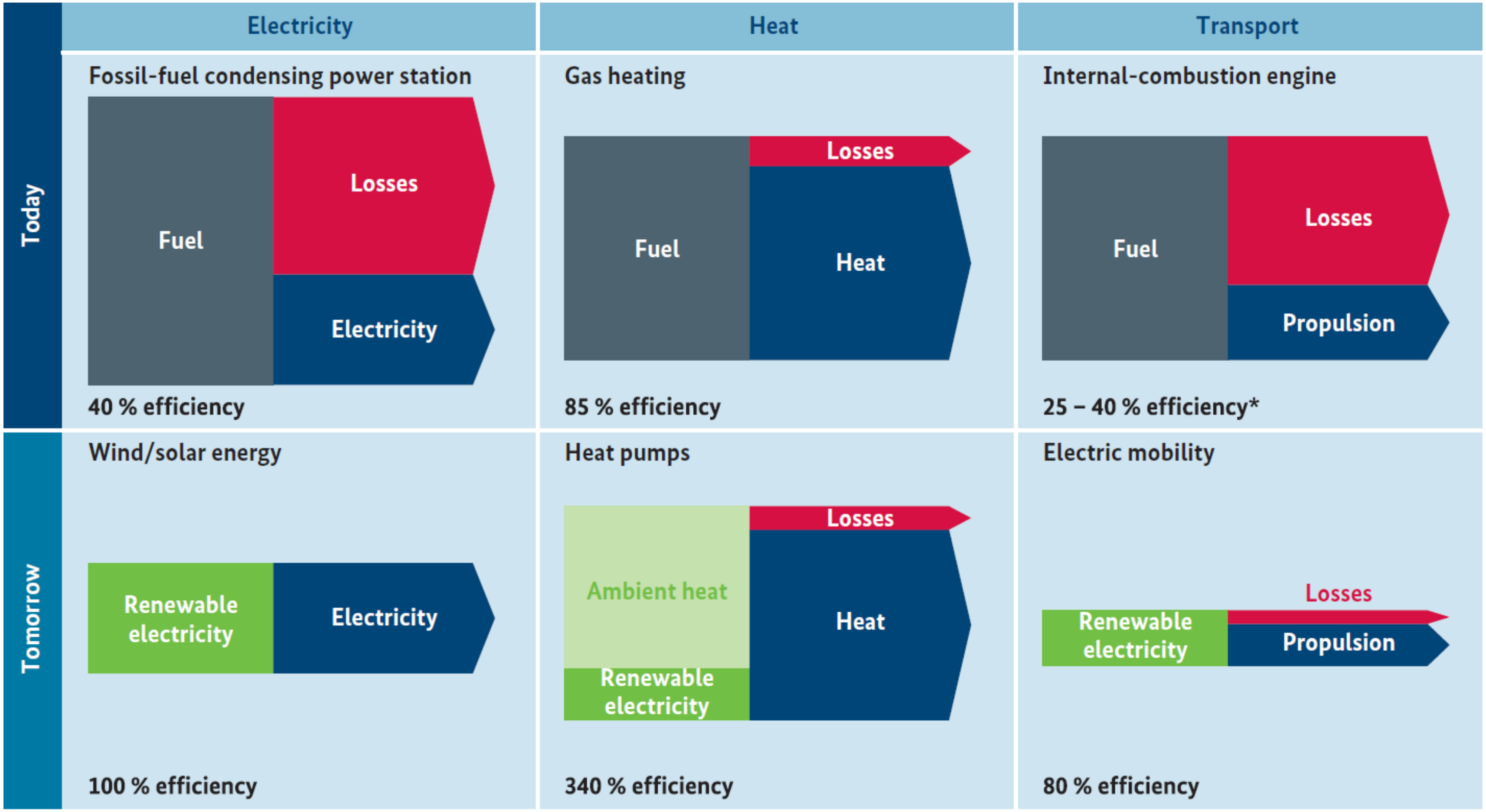


Key insights:

- PtX enables sustainable production of hydrocarbons
- Inredients: electricity, water, air
- w/o PtX COP21 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

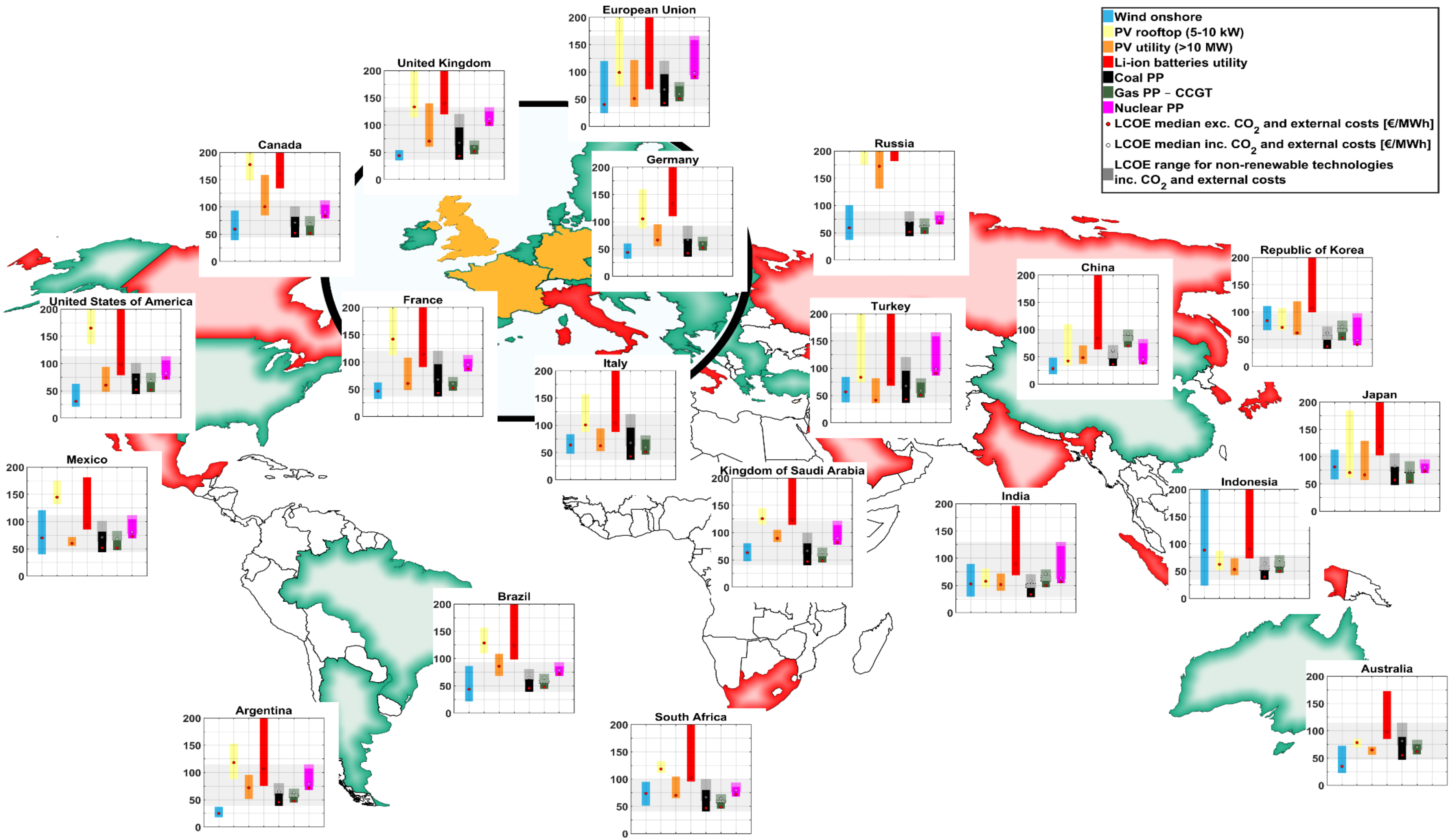


Key rationale for electrification: Efficiency



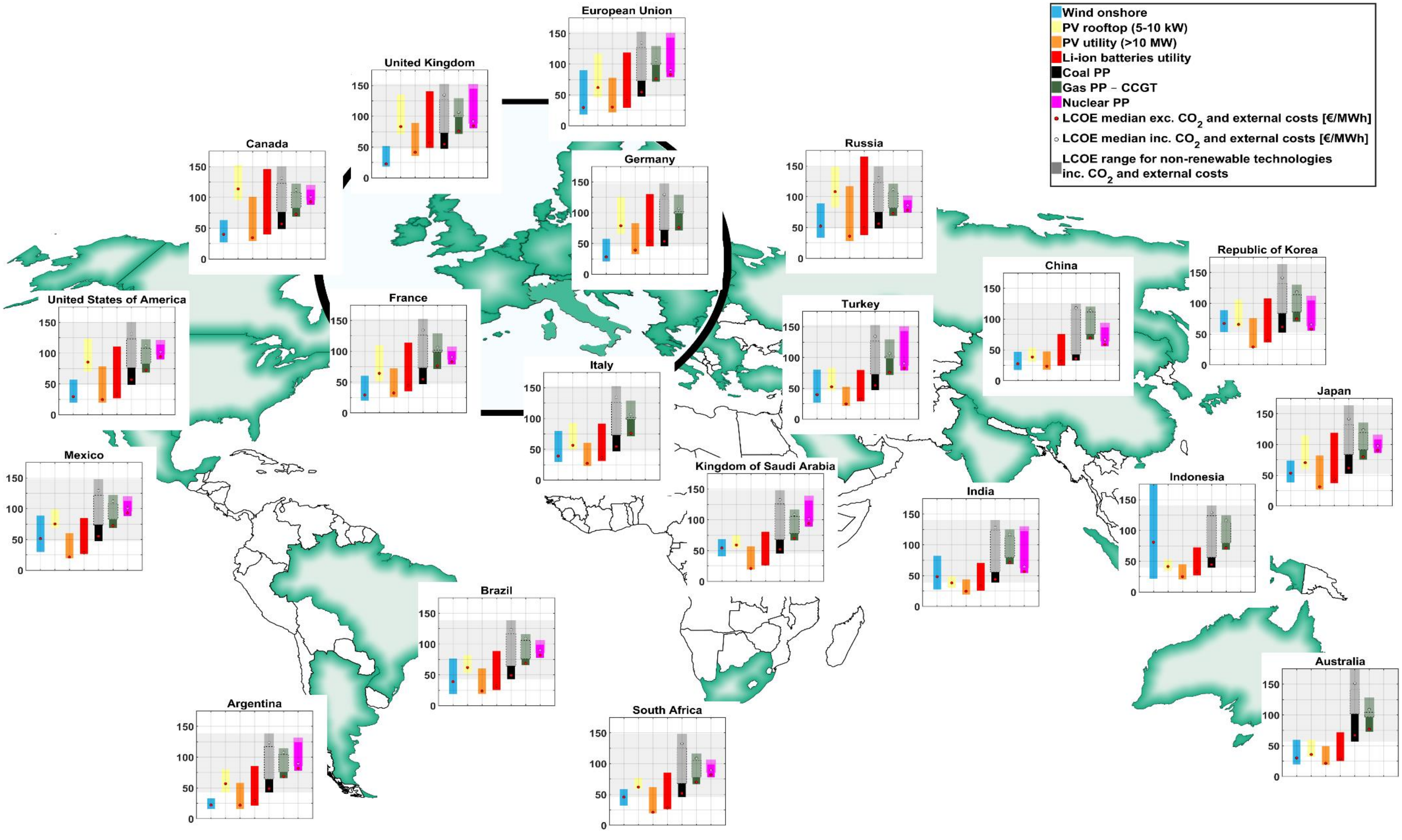
* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

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

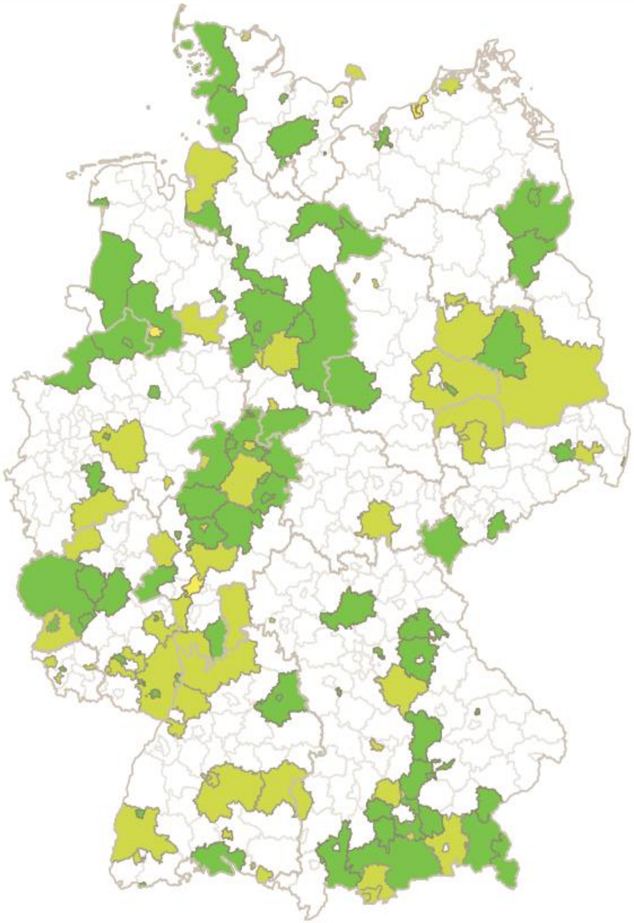
LCOE across G20 in 2030



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

100% RENEWABLES

www.go100re.net



Nov 2016, COP22, Marrakech:
48 countries (Climate Vulnerable Forum) decided for a 100% RE target

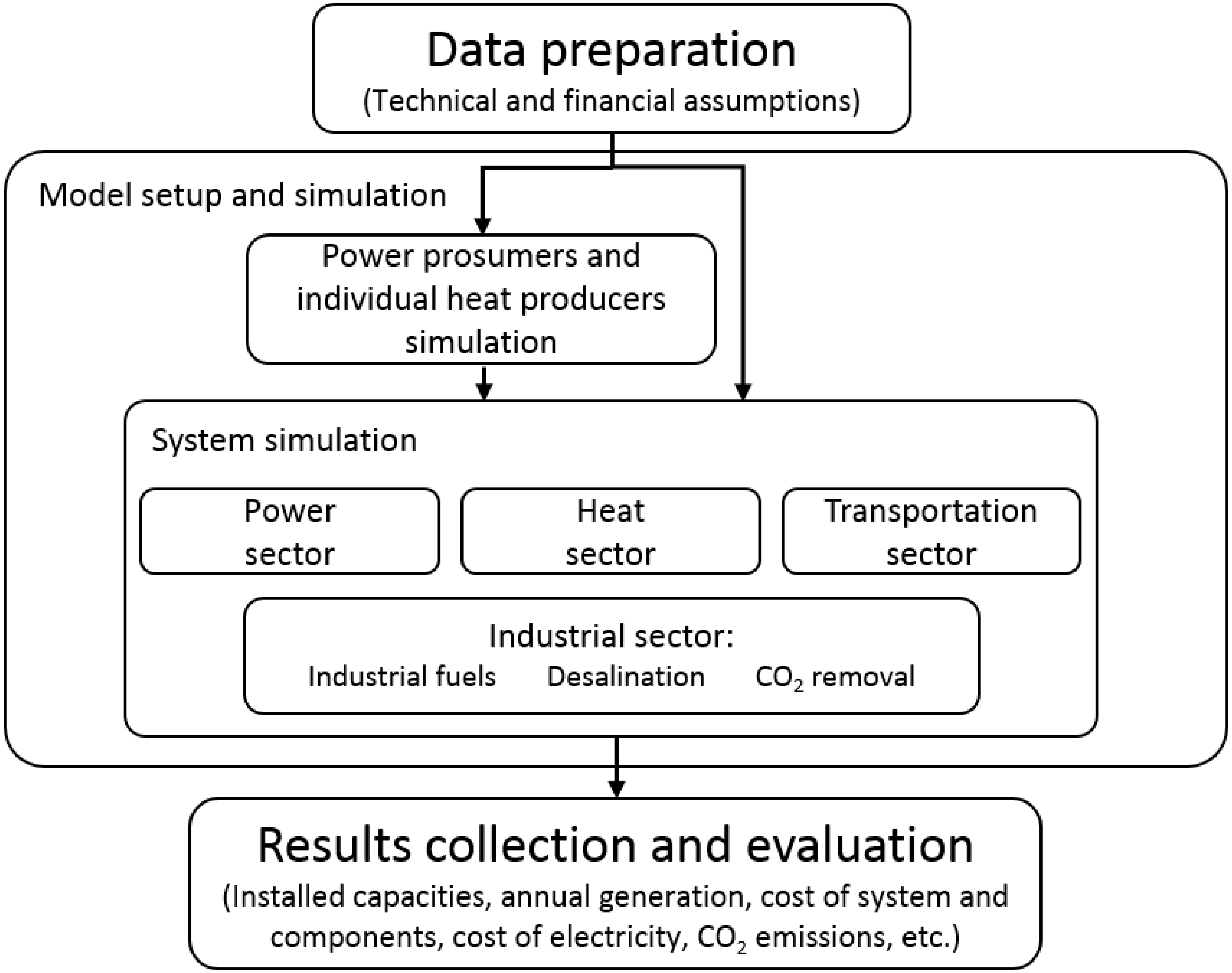
More Countries and States set 100% targets, e.g.:
Denmark, Sweden, California, Costa Rica, Iceland, …

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

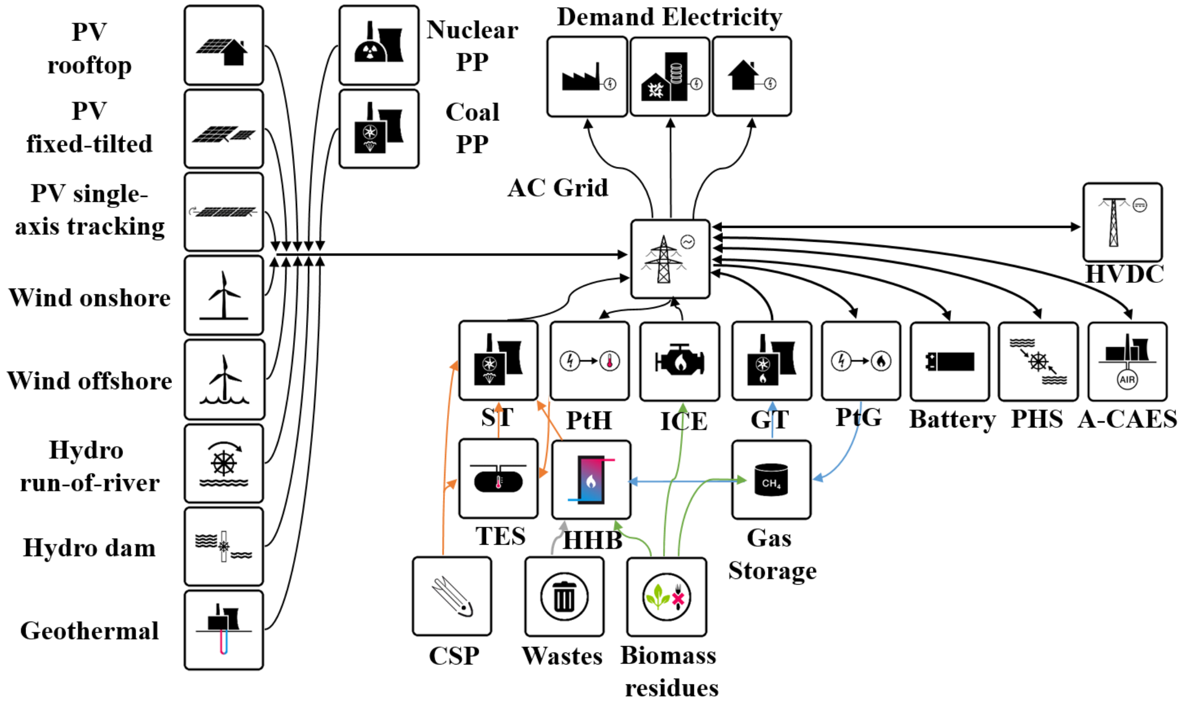
Companies with 100% RE targets, e.g.:
Google, Microsoft, Coca-Cola, IKEA, Wärtsilä, Walmart, …

www.100-ee.de/

LUT model: fundamentals

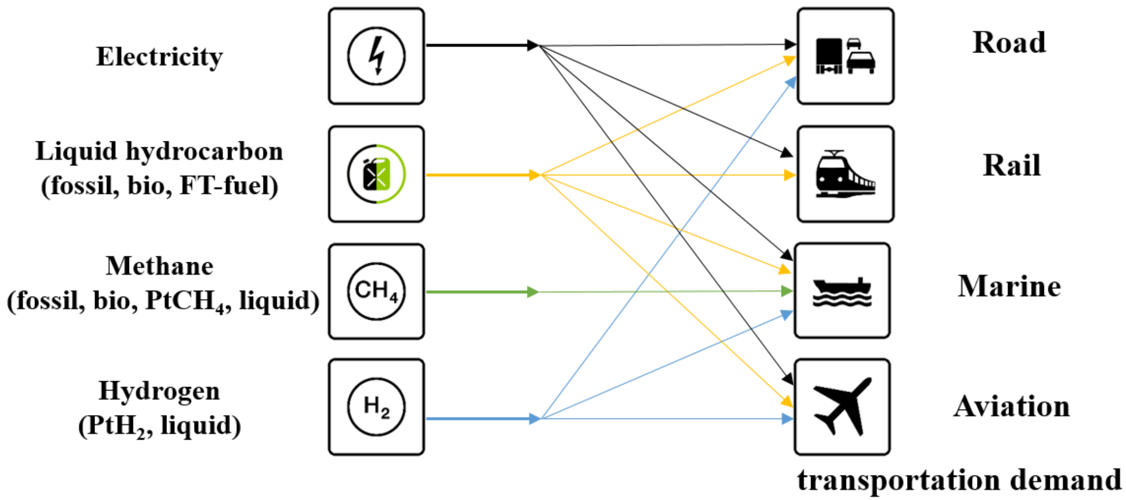


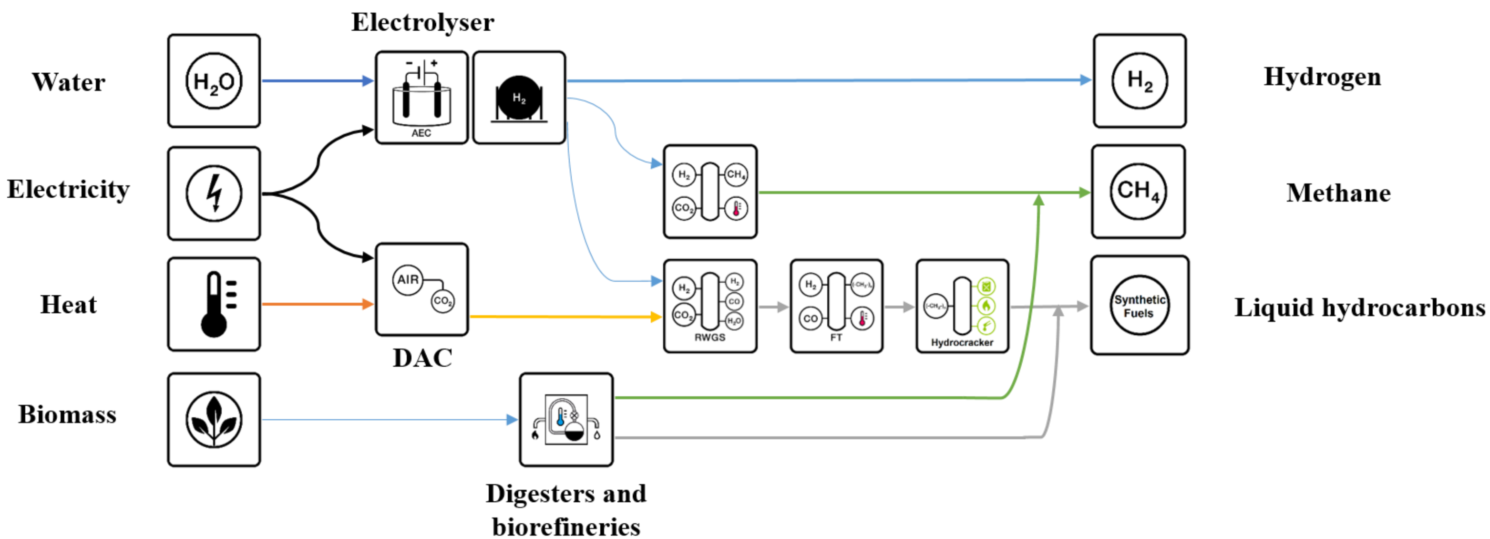
LUT Energy System Transition model



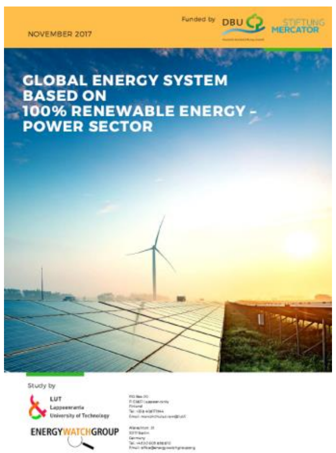
- The technologies applied for the energy system optimisation include those for electricity generation, energy storage and electricity transmission
- The model is applied at full hourly resolution for an entire year
- The LUT model is currently expanded to all energy sectors

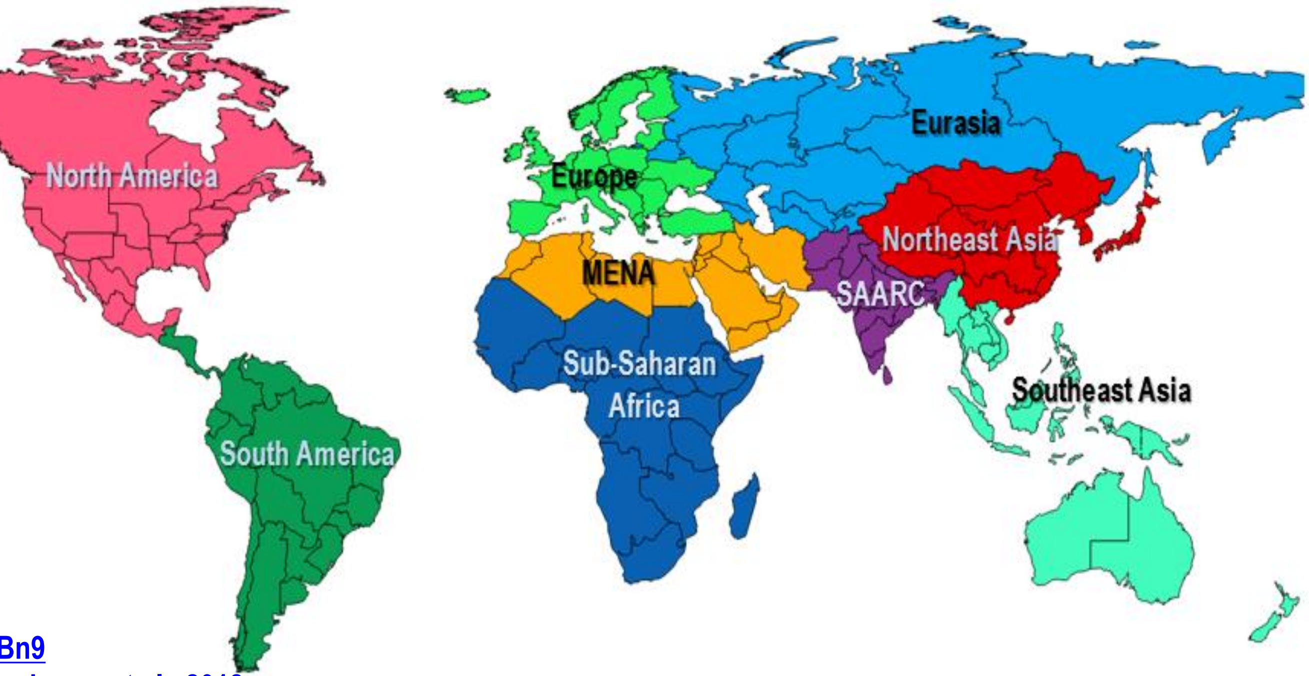
LUT model: sector transportation





Modelling of 100% RE Global Power System

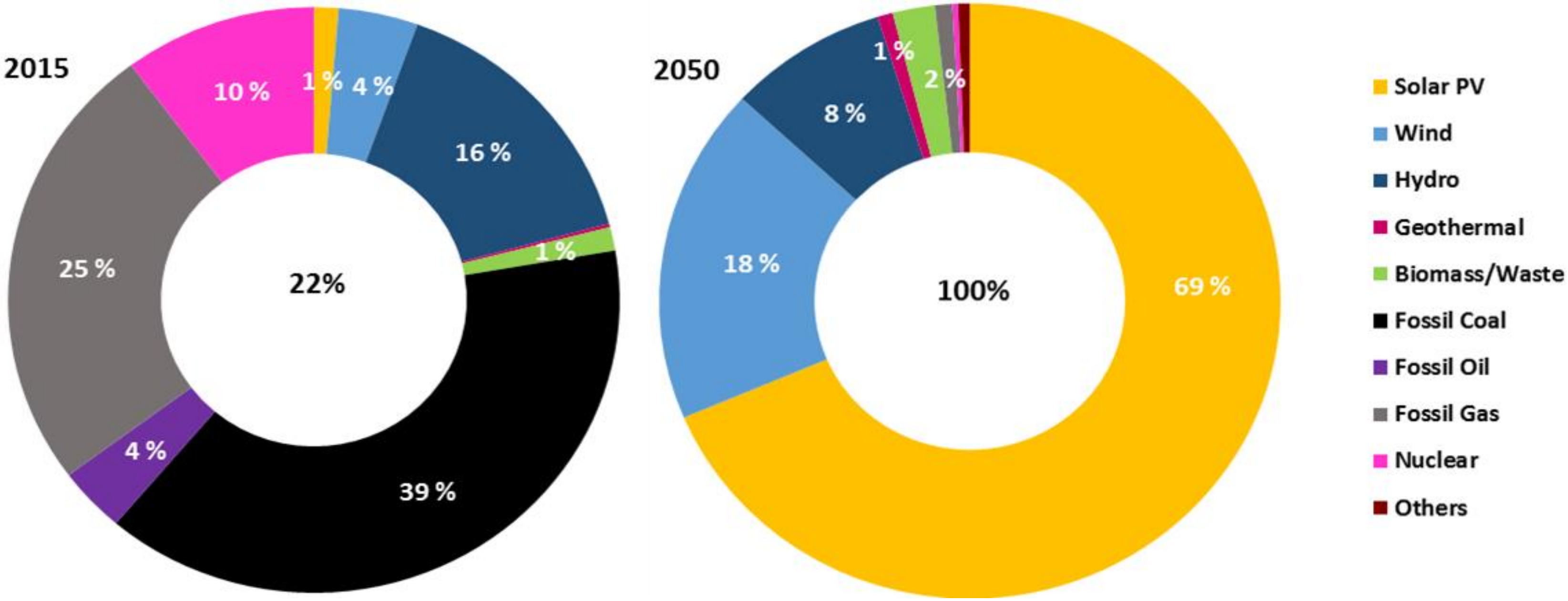


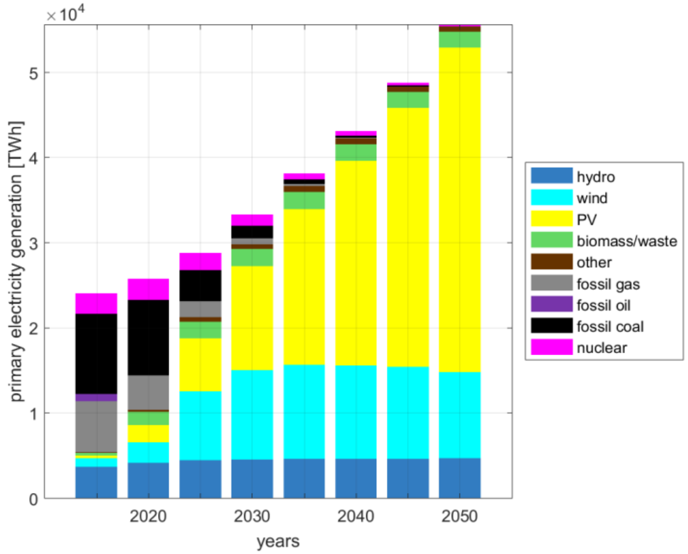


full study http://bit.ly/2hU4Bn9
scientific article Breyer, Bogdanov, et al., 2018

- The modelling by the Lappeenranta University of Technology as of 2017 is the only one to run at full hourly resolution on a global-local scale.
- Real weather data were used for assessing the solar, wind and hydro resources.
- By 2050, the world population is expected to grow from 7.3 to 9.7 billion.
- The global electricity demand for the power sector is set to increase from 24,310 TWh in 2015 to around 48,800 TWh by 2050.

Electricity Generation in 2015 and 2050





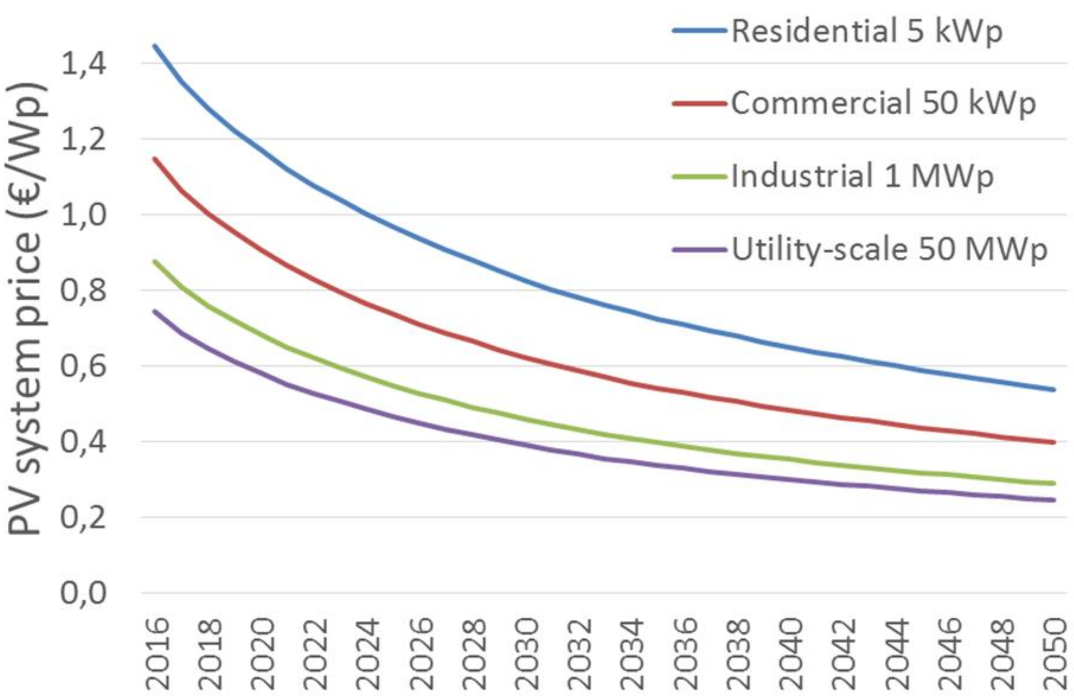
- In 2050, solar PV accounts for 69%, wind energy 18%, hydropower 8% and bioenergy 2% of the total electricity mix globally.
- Gas generation is only from renewable energy based gas (bio-methane and power-to-gas)
- Nuclear power still accounts for negligible 0.3% of the total electricity generation, due to the end of its assumed technical life, but could be phased out earlier.

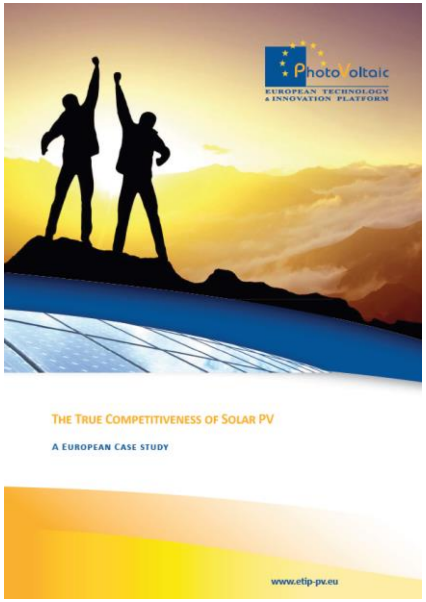
source: Breyer et al., 2017. Solar PV Demand for the Global Energy Transition in the Power Sector, Progress in Photovoltaics; Ram et al., 2017. Global Energy System based on 100% Renewable Energy - Power Sector, report

ChristianOnRE

LUT Energy System Model

Data – Financial Assumptions: PV update

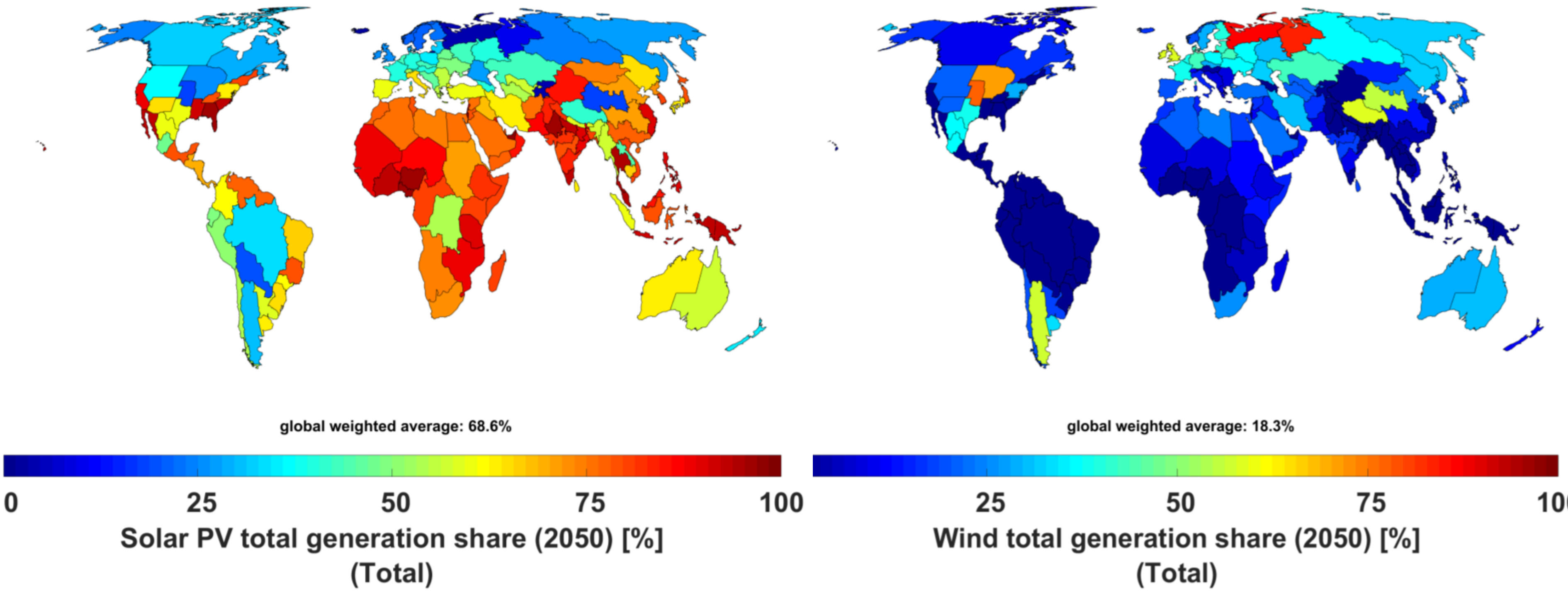




source: ETIP-PV, 2017. The True Competitiveness of Solar PV – A European Case Study

- capex variation based on learning curves, market growth
- PV capex had been continuously wrong in own work during the last 10 years
- PV most important in energy transition scenarios, hence very good capex understanding required
- now split into 5 types of PV segments (rooftop RES/ COM/ IND, ground-mounted fixed, tracking)

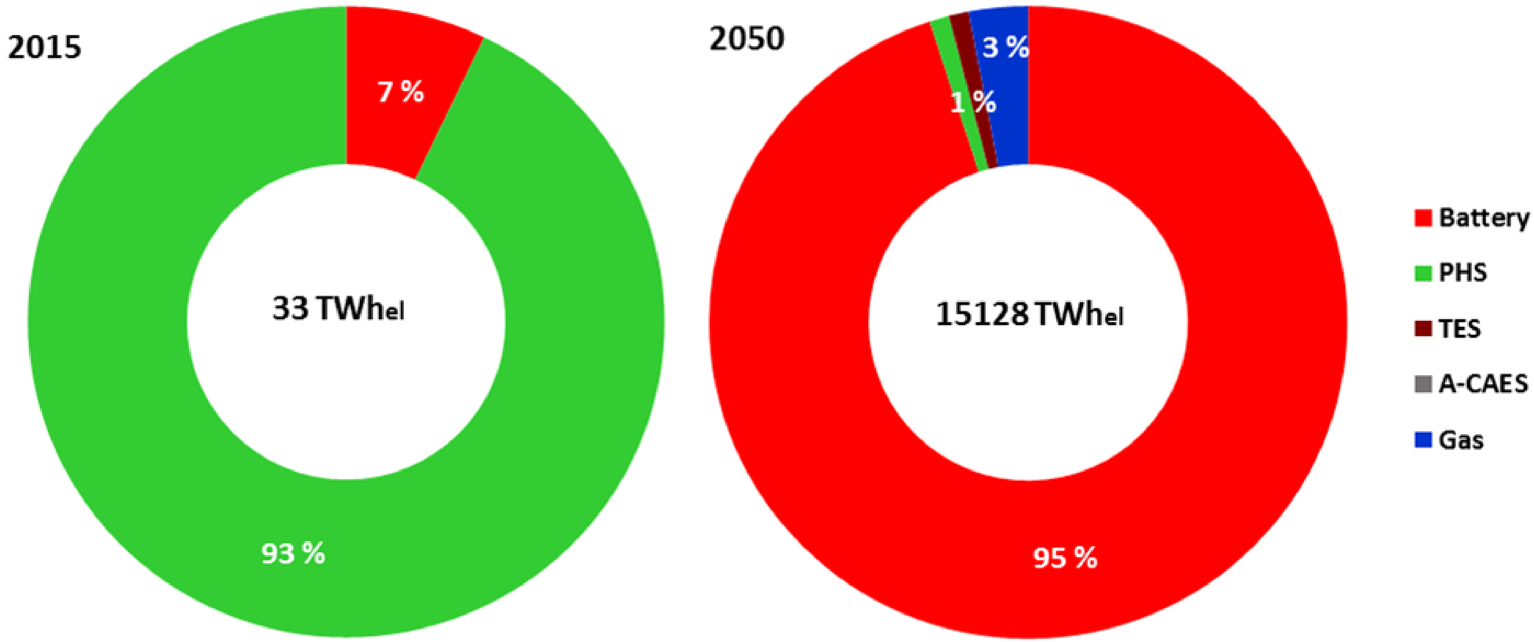
Regional Variation – Solar PV and Wind

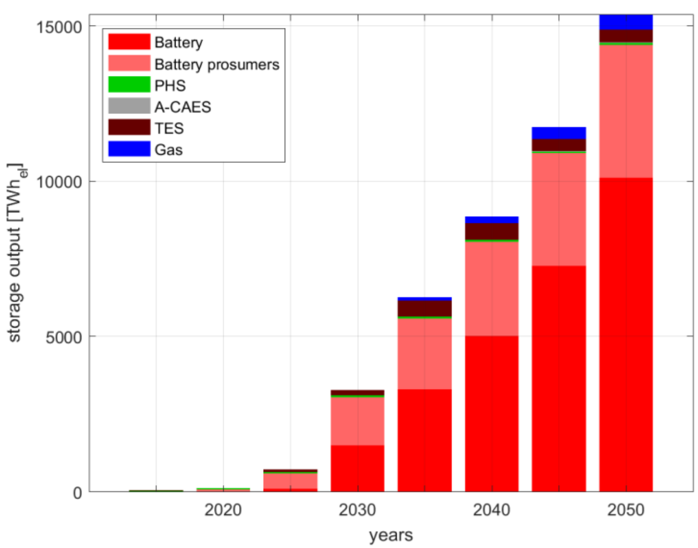


- Solar PV is the dominating source of electricity in the Sun Belt
- Wind energy is very important in the North
- In regions of less solar PV and wind energy the contribution of hydropower is excellent

Christian Breyer ▸ christian.breyer@lut.fi @ChristianOnRE
source: Breyer et al., 2017. Solar PV Demand for the Global Energy Transition in the Power Sector, Progress in Photovoltaics; Ram et al., 2017. Global Energy System based on 100% Renewable Energy - Power Sector, report

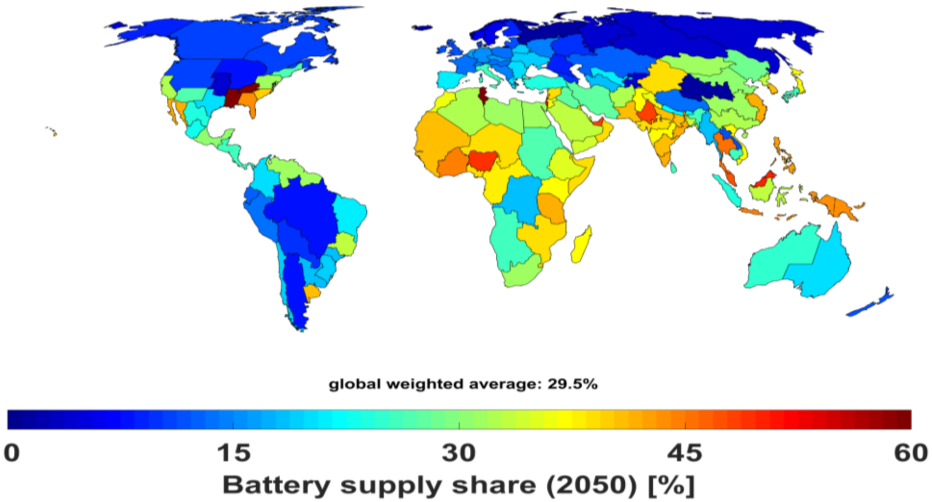
Electricity Storage Output in 2015 and 2050

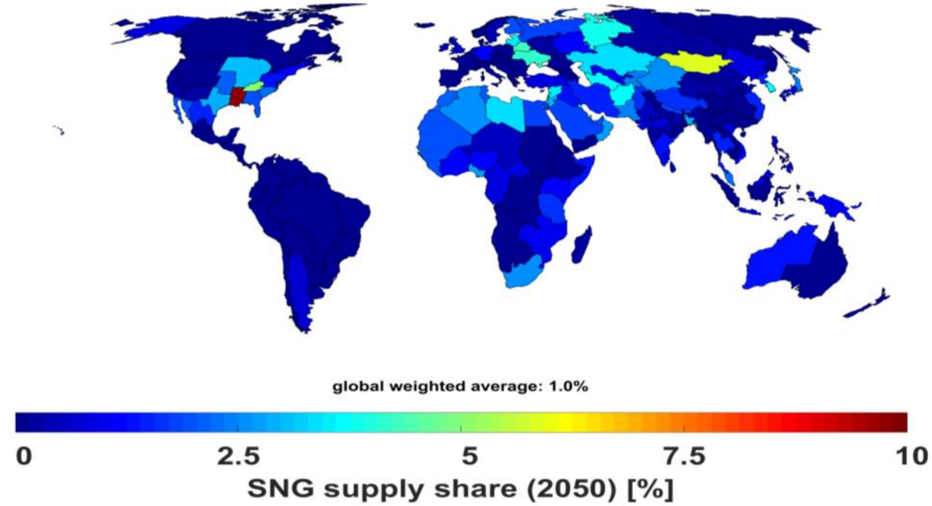




- Batteries are the key supporting technology for solar PV.
- Storage output covers 31% of the total demand in 2050, 95% of which is covered by batteries alone.
- Battery storage provides mainly diurnal storage, and renewable energy based gas provides seasonal storage.

Storage Supply Shares in 2050

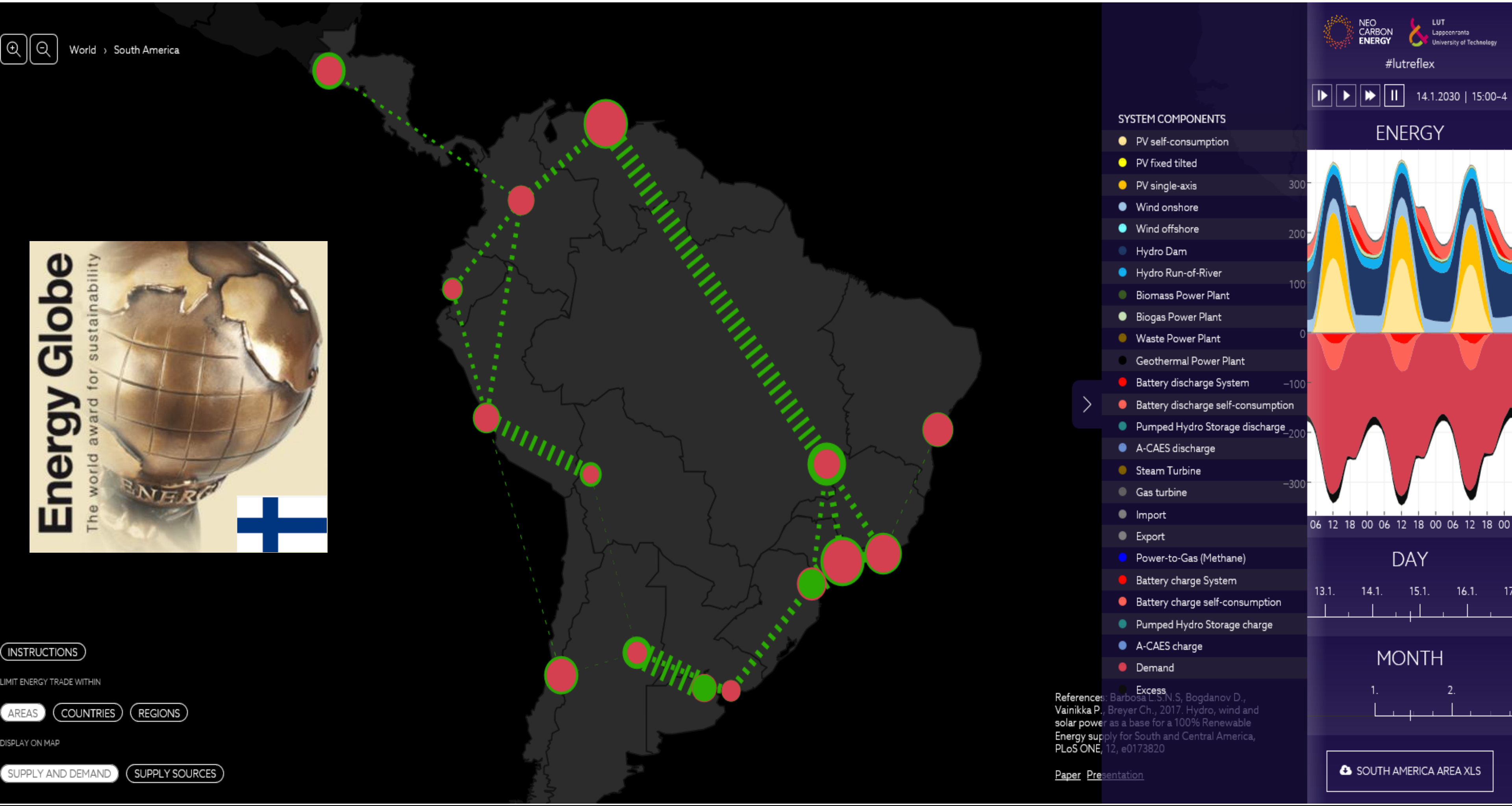




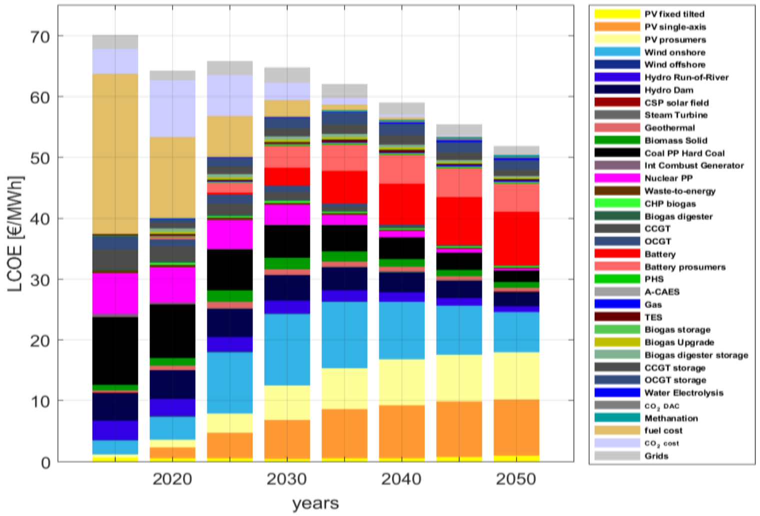
- Battery storage mainly plays a role in providing diurnal storage with around 31% of the total supply
- Gas storage mainly plays a role in providing seasonal storage with just 2% of total supply (1% from synthetic natural gas and 1% from bio-methane – both RE-based)
- Prosumers play a significant role and hence a large portion of batteries can be observed in 2050, also with low costs of solar PV and batteries

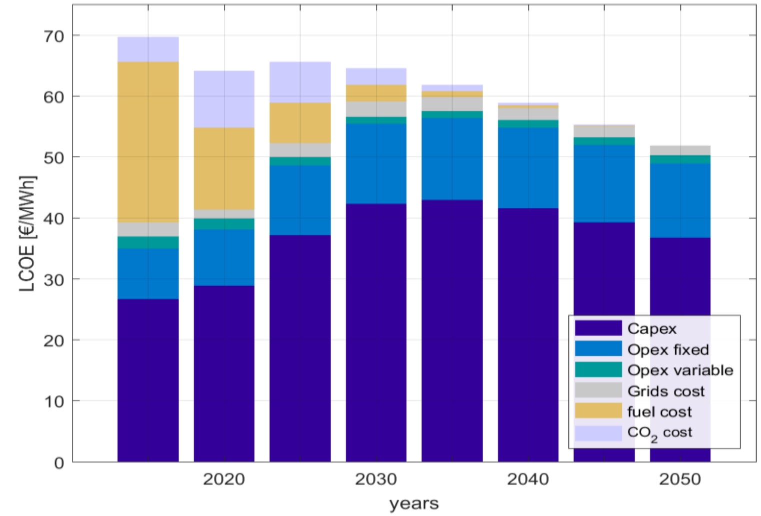
Impact: Energy Globe Award

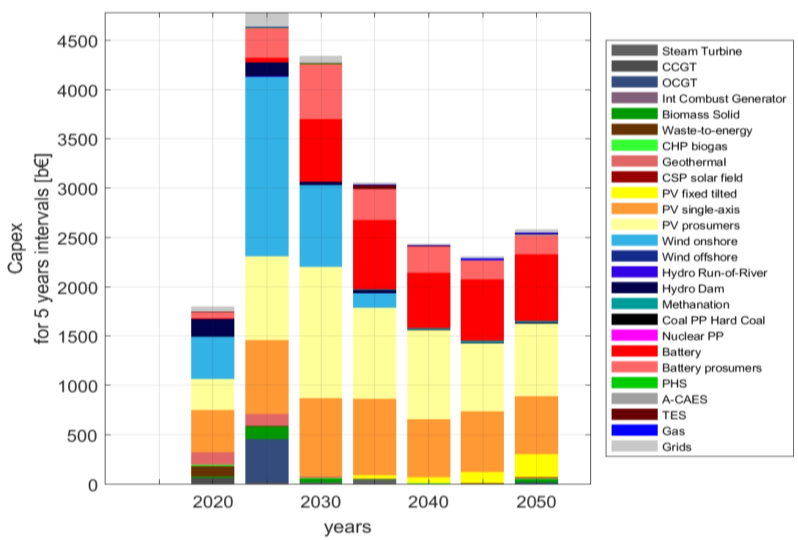
Global Internet of Energy: http://neocarbonenergy.fi/internetofenergy/#



Electricity System Cost during Transition

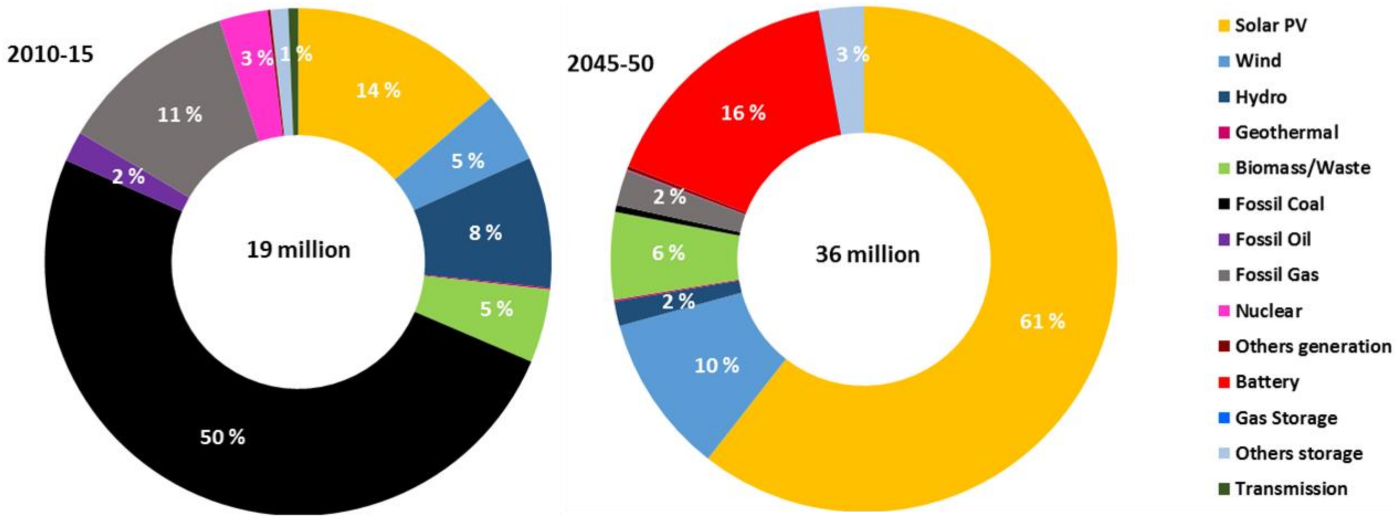






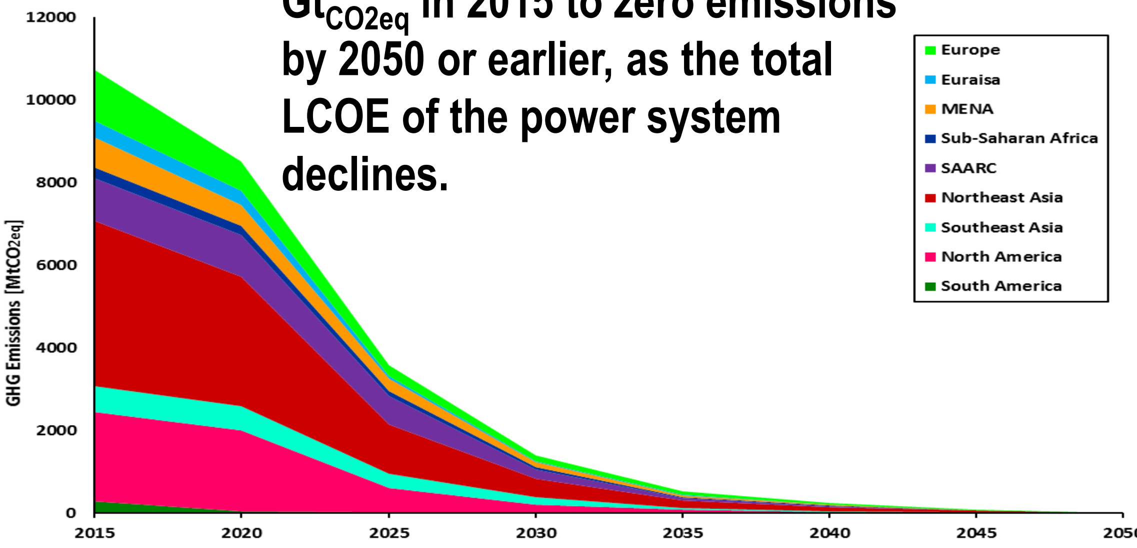
- The global power system LCOE remains stable for the first periods, showing a gradual decline from 70 €/MWh to 59 €/MWh from 2015 to 2040, including all generation, storage, curtailment and parts of the grid costs
- Beyond 2040 the LCOE further declines to 52 €/MWh by 2050, signifying that larger capacities of RE addition result in reduction of energy costs
- After an initial increase, the investment requirements decline after 2030 to stabilise between 2040 to 2050

Job Opportunities - GHG Emissions to zero



- The global energy transition to a 100% renewable electricity system creates 36 million jobs by 2050 in comparison to 19 million jobs by 2015.
- Governments should start programmes to convert coal jobs to jobs for renewable energy.

- Global greenhouse gas emissions significantly reduce from about 11 Gt_{CO2eq} in 2015 to zero emissions by 2050 or earlier, as the total LCOE of the power system declines.



Overview Global Energy Scenarios

	Current Status	IEA	Exxon	Greenpeace	Greenpeace	WWF	MIT	Shell	IEA-PVPS	WBGU	IPCC
	today	2040	2040	2050	2050	2050	2050	2060	2100	2100	2100
Energy resource base	red	red	red	yellow	green	yellow	red	red	red	yellow	red
Climate change impact	red	red	red	yellow	green	green	red	yellow	red	yellow	yellow
Societal cost	red	red	red	yellow	green	green	red	red	red	green	yellow
Energy access for all	red	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	green
Coverage of energy sectors	green	green	green	green	green	green	green	green	green	green	green

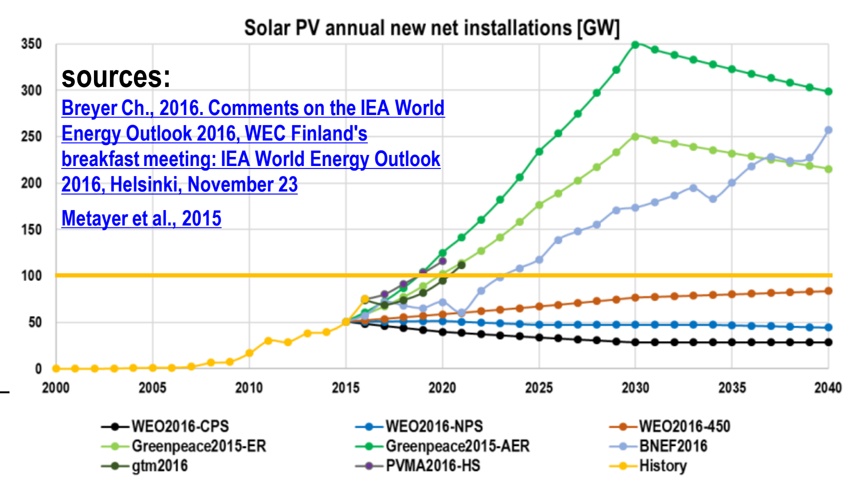
Key insights and general remarks:

- climate change as a major challenge accepted by all energy scenarios (lagging behind: Exxon)
- increasing share of RE is accepted by all scenarios (lagging behind: Exxon)
- assumptions of future energy demand and energy efficiency efforts differ widely
- NO scenario discusses impact of peak-oil, -gas, -coal and -uranium and respective price impacts
- dominance of power sector in future only understood by WWF and Greenpeace
- cost advantage of solar PV vs CSP reflected only by IEA-PVPS
- role of storage and long distance grids reflected by NO scenario
- power-to-gas technology as storage and bridging technology reflected by NO scenario
- coupling of energy sectors reflected by WWF, Greenpeace, IEA-PVPS but no cost transparency
- progressive: Greenpeace, WWF, WBGU

PV Capacity Expectations in Major Reports

	LUT [GW]	E[R] [GW]	AE[R] [GW]	BNEF [GW]	ITRPV (m) [GW]	ITRPV (h) [GW]	REmap [GW]	Roadmap [GW]	2DS hi-Ren [GW]	NPS [GW]	450 [GW]
2030	6980	2839	3725	1799	4050	4600	2921	1721	1927	949	1278
2040	13810	4988	6678	3687	6440	8500	-	3199	3277	1405	2108
2050	21960	6745	9295	-	6850	9100	6348	-	-	-	-

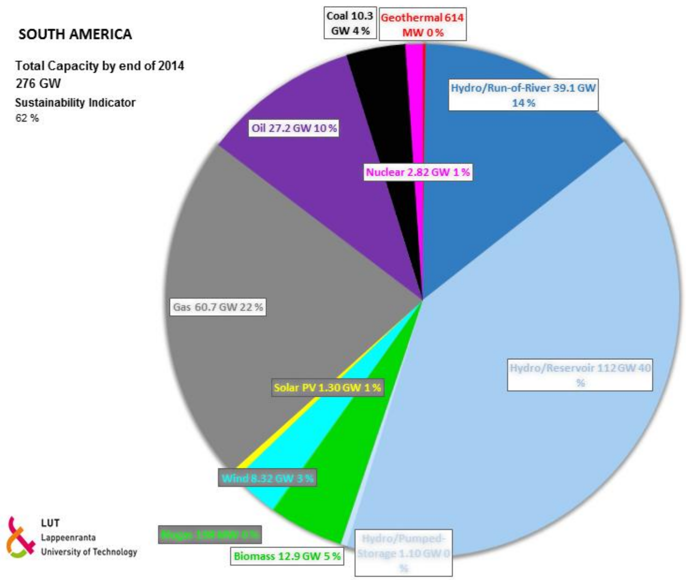
Key insights:
- Greenpeace and BNEF had been close to real numbers in the past 10 years leading reports show 2-3 times higher numbers than IEA WEO for 2030 and 2040
- IEA WEO is lagging behind due to assuming wrong growth
- LUT results are far beyond the major reports



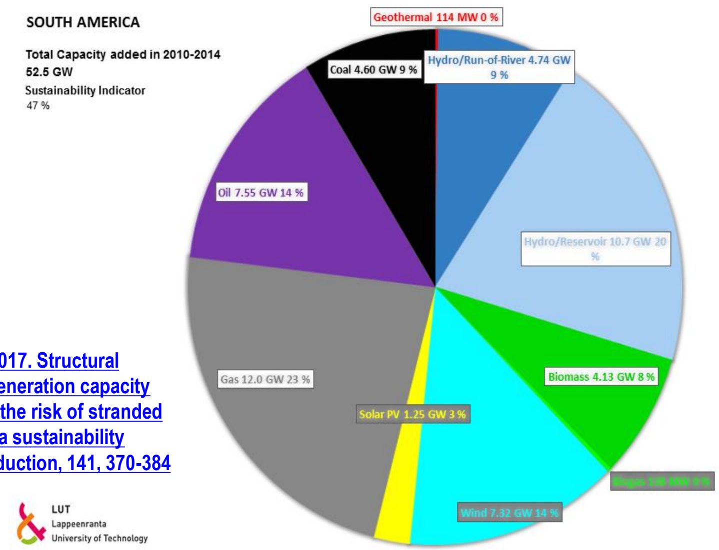
South America - Overview

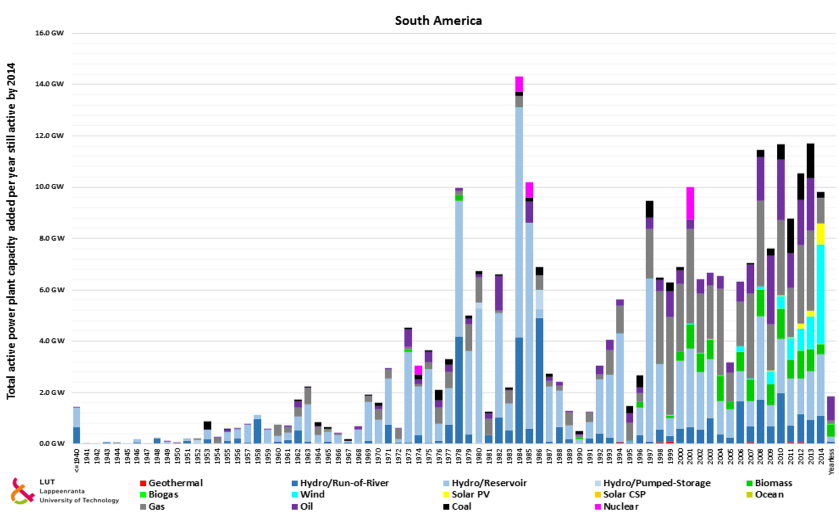
- The South America is structured into 15 regions.
  - Central America (Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Belize)
  - Venezuela, Colombia, Ecuador, Peru and Chile
  - Bolivia, Paraguay
  - Brazil (North, Northeast, Southeast, São Paulo, South)
  - Argentina (West, East, Northeast, Uruguay)

South America - Power Plant Infrastructure



source:
[Farfan J. and Breyer Ch., 2017. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator; J of Cleaner Production, 141, 370-384]





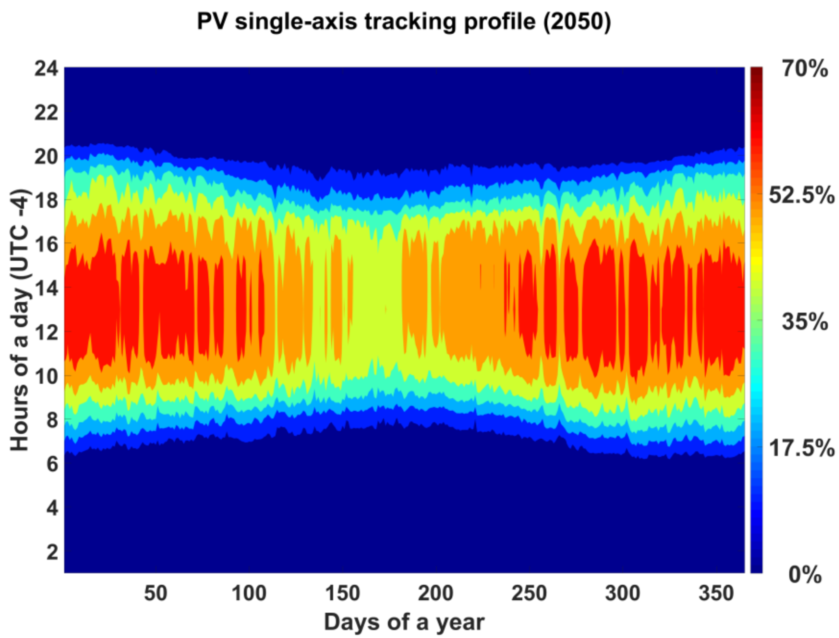
Key insights:

- Significant share of hydropower in the generation mix is observed
- After hydropower, biomass has the highest share among RE installed capacities by end of 2014
- Gas and oil are the major fossil fuel contributors with a share of 32% of the total power capacity today

South America (Solar, Wind)

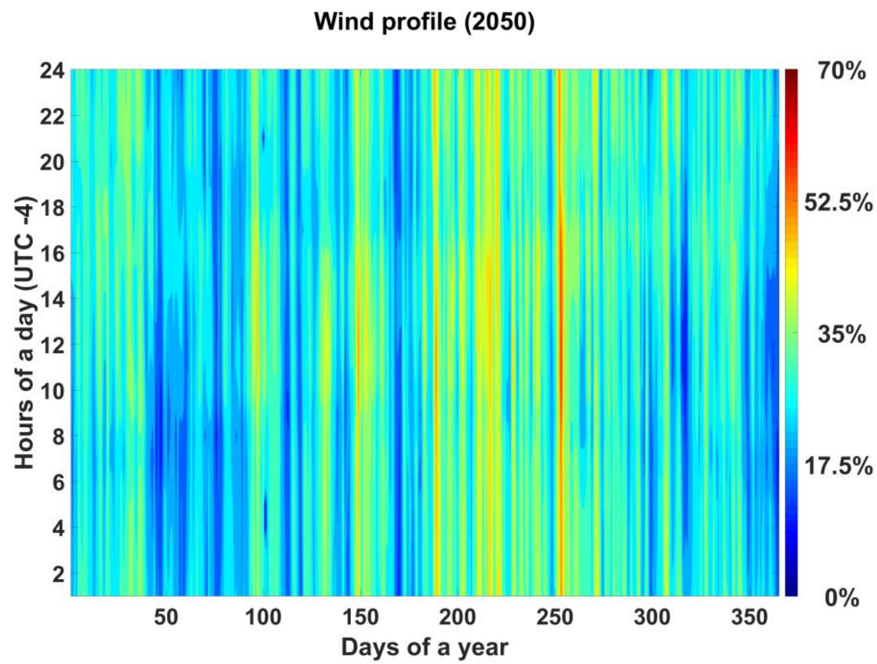
Solar PV generation profile

Regional aggregated PV feed-in profile computed using the weighed average rule



Wind generation profile

Regional aggregated wind feed-in profile computed using the weighed average rule

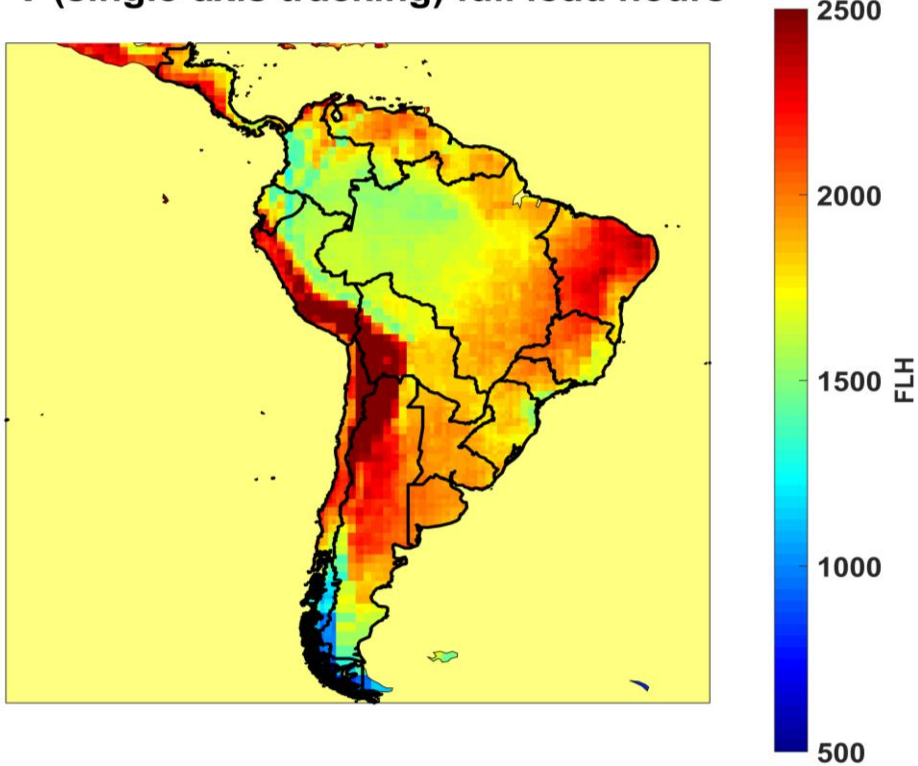


Key insights:

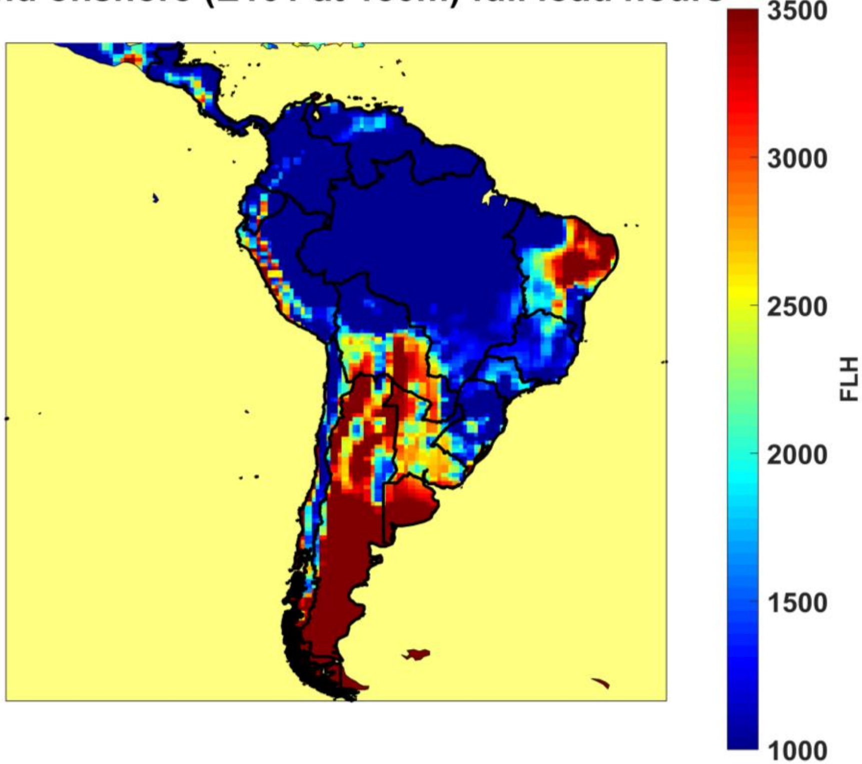
- Solar PV can generate electricity throughout the year
- Perfect wind conditions at the beginning of the year in almost all hours of a day
- Seasonal and hourly complementary of solar PV and wind energy

South America - Full Load Hours

PV (single-axis tracking) full load hours



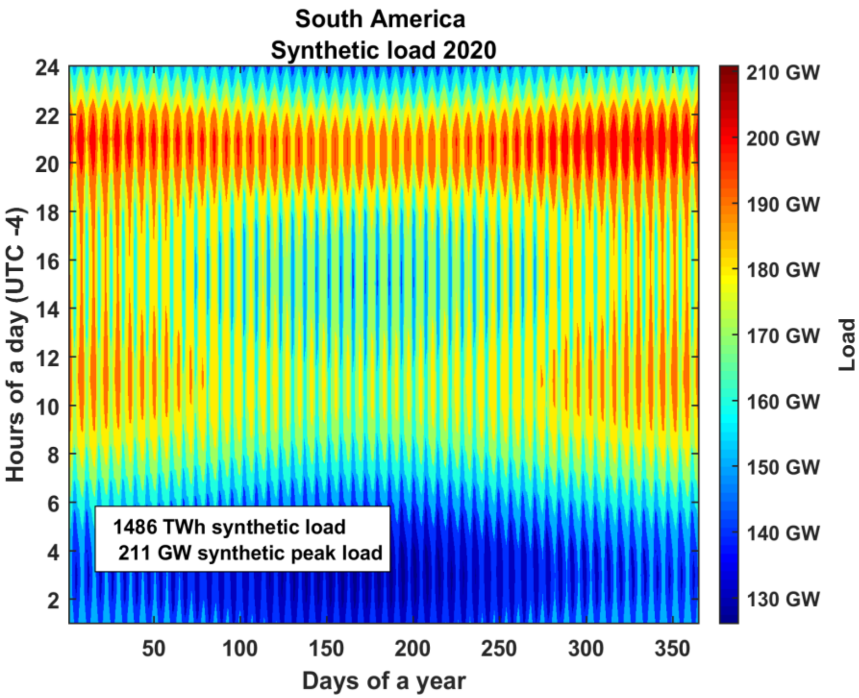
Wind onshore (E101 at 150m) full load hours

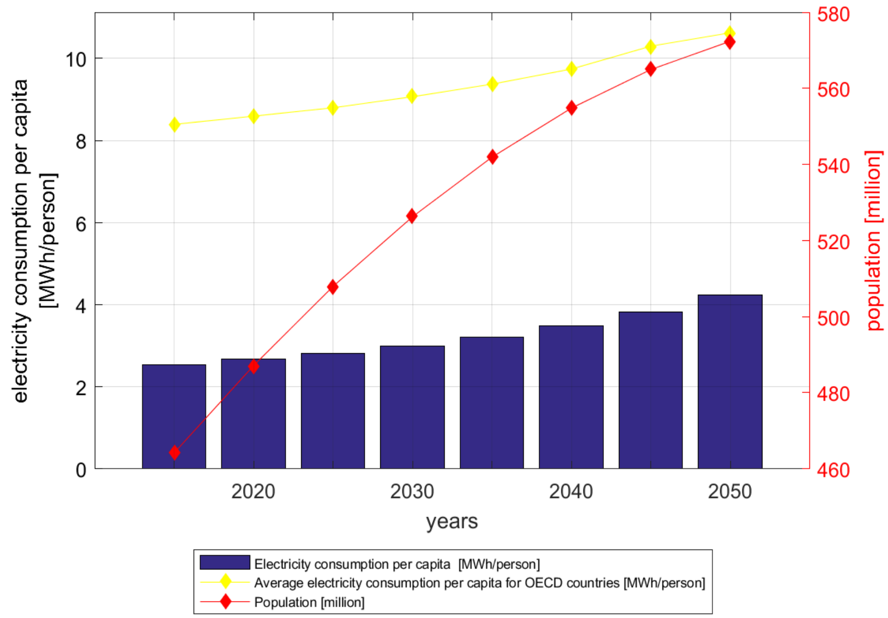


Key insights:

- **Wind: Very high potential in the southern regions and low potential in the Northern regions**
- **Solar PV: Excellent PV condition in almost all the countries/regions, especially in Peru, Chile, Central South America, Northwest Argentina and Northeast Brazil**

Hourly Resolved and Long-term Demand





Key insights:

- A cumulative average annual growth rate electricity demand is assumed to be 2.1% in the energy transition period; growth might be higher in some countries than in others
- The South American population is expected to grow from 464.2 to 572 million, while the average per capita electricity demand rises from 2.5 to 4.2 MWh
- The electricity demand is assumed to increase from 1015 TWh in 2015 to around 2260 TWh in the year 2050

Energy Transition in Capacity and Generation

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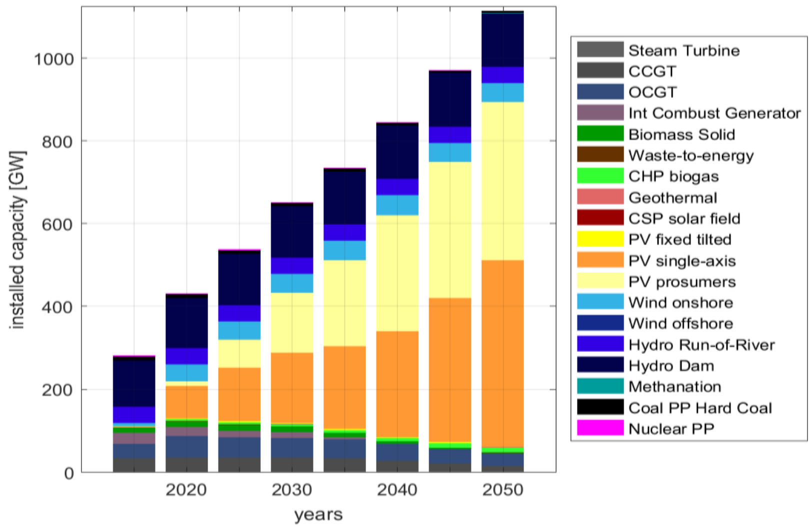
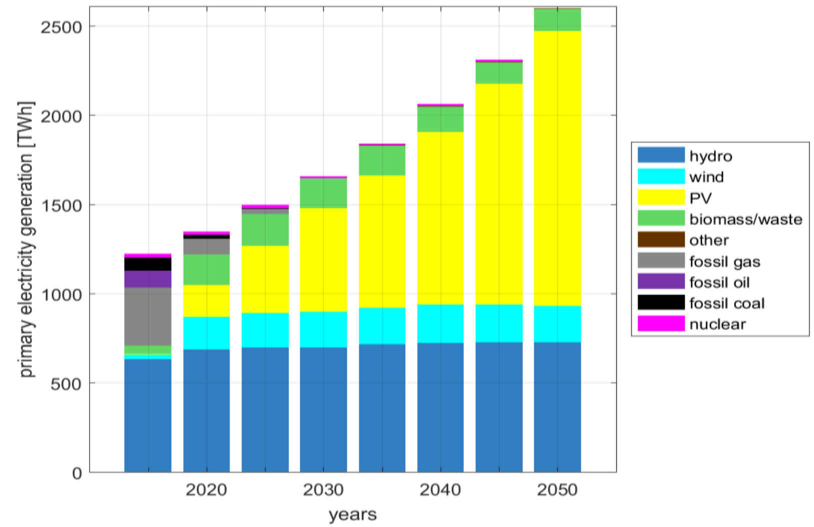
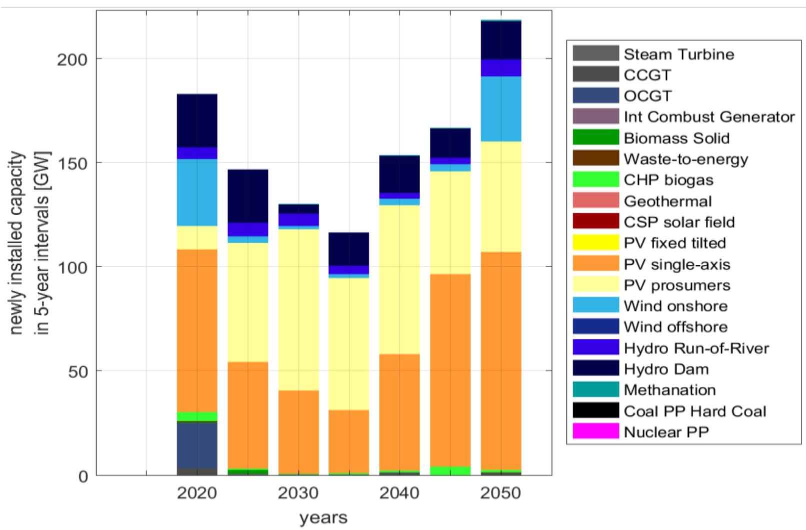
Installed Capacity



Electricity Generation

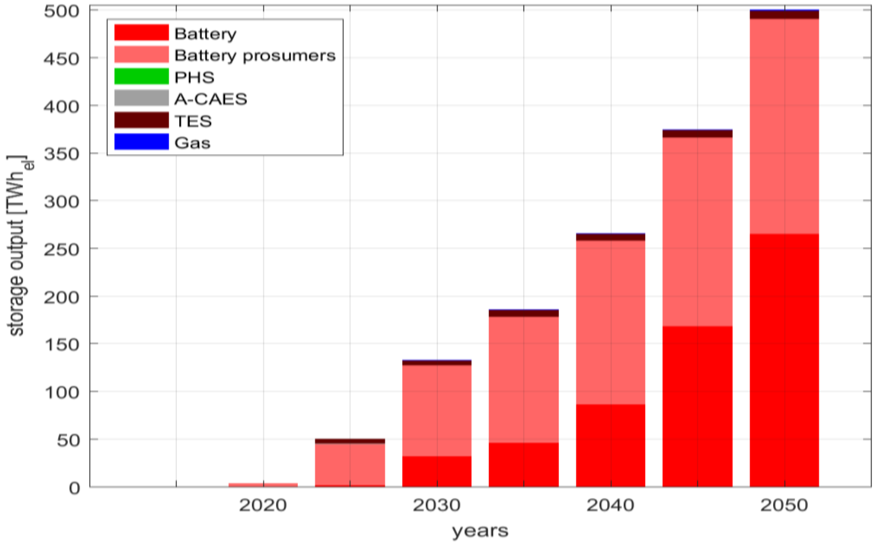


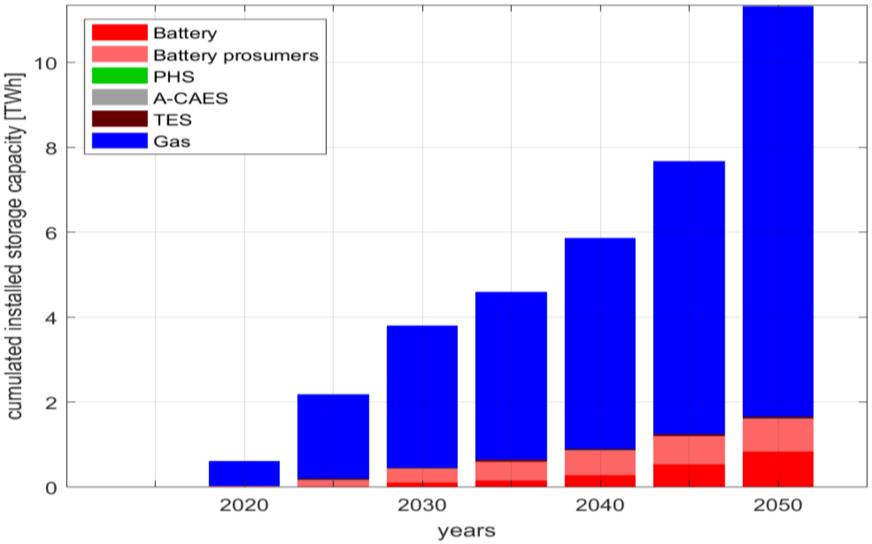


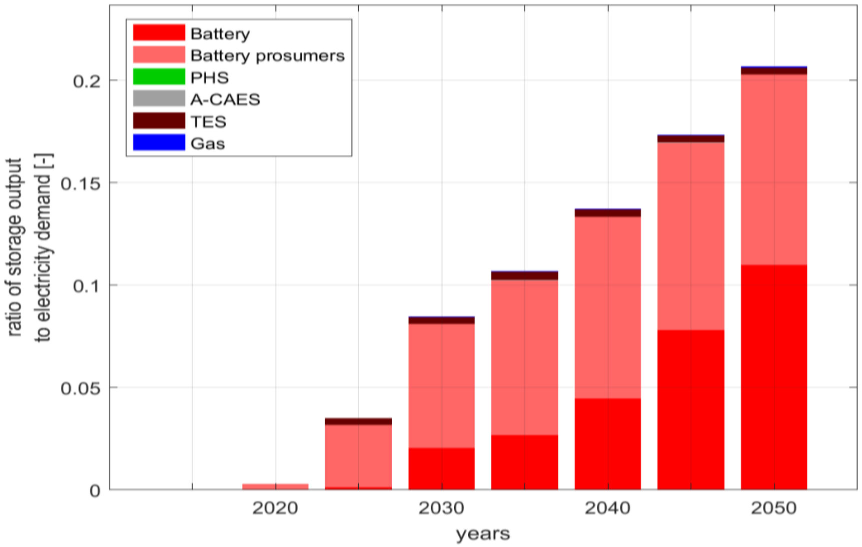
Key insights:

- Solar PV increasingly drives most of the system, strong influence of hydropower and wind energy complement
- Solar PV supply share increases from 35% in 2030 to about 60% in 2050 becoming the least cost energy source
- Share of hydropower is more significant than wind energy by 2050 due to the historically installed capacity and very long lifetime of plants

Storage Requirements



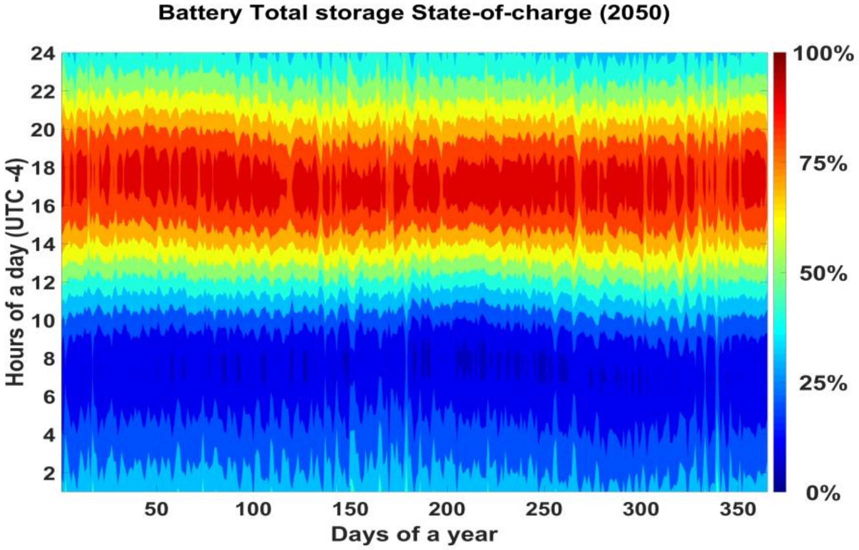


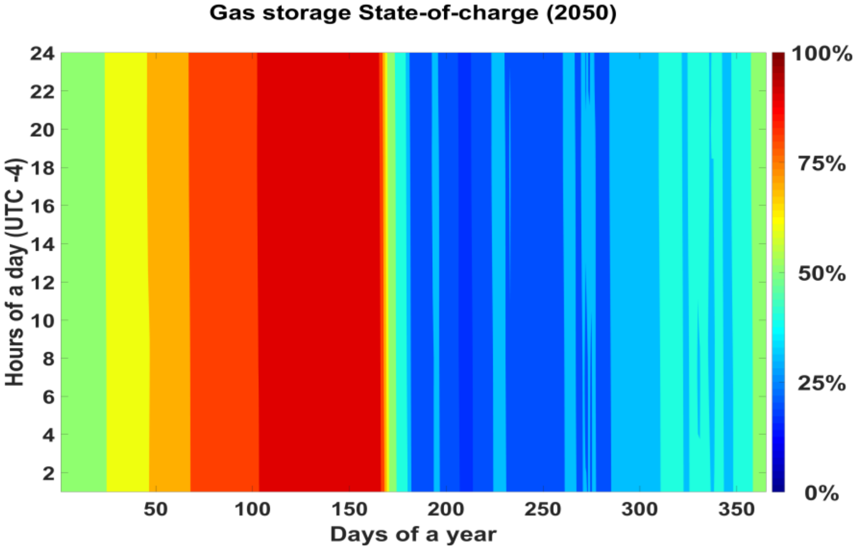


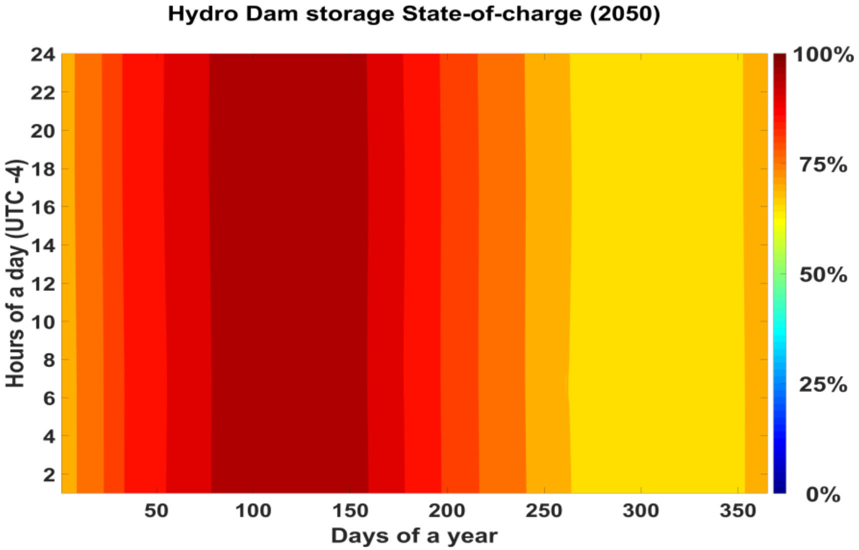
Key insights:

- Batteries are the most important supporting technology for solar PV, particularly for PV prosumers
- A significant share of gas storage is installed to provide seasonal storage
- However, gas storage output is substantially lower than battery output
- Gas storage dominates the capacities, which is used for SNG (6%) and bio-methane (94%), which is not accounted in the storage output diagrams but as bioenergy generation

Storage Operation Modes (2050)







Key insights:

- Battery storage balances on a daily basis
- Gas storage reacts in a very flexible way
- Hydro reservoirs provide complementarity with solar and wind but are also used as seasonal storage

Electricity System Cost during Transition

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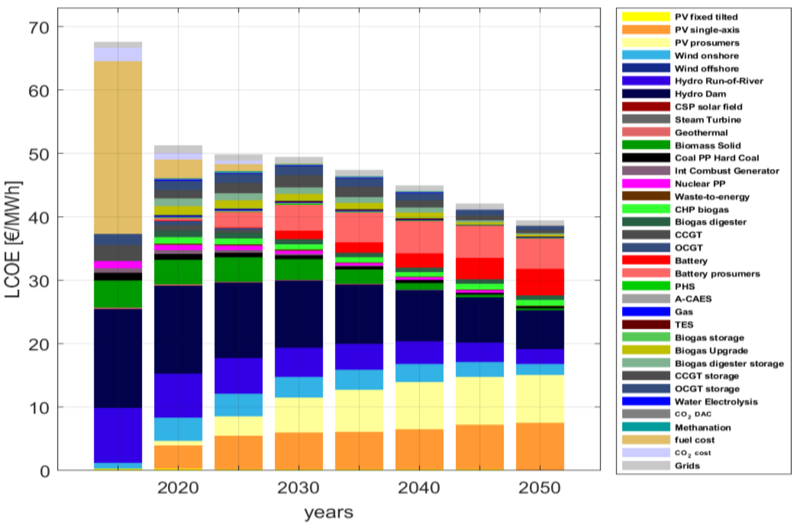
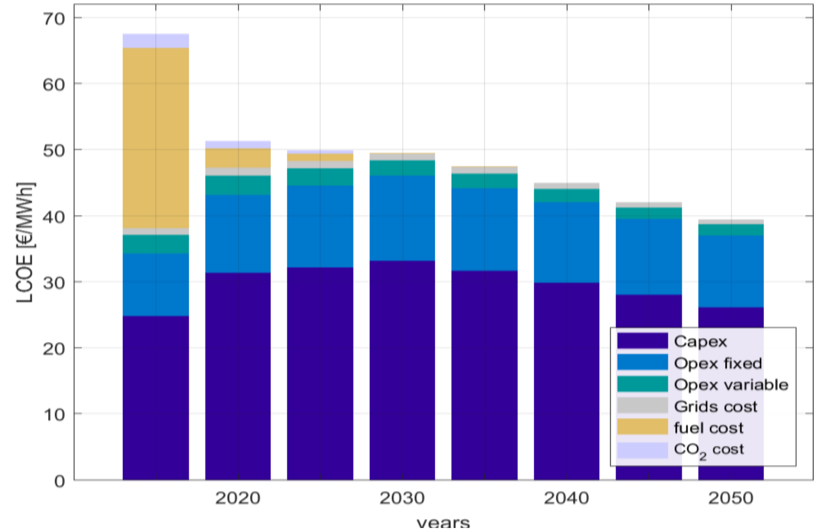
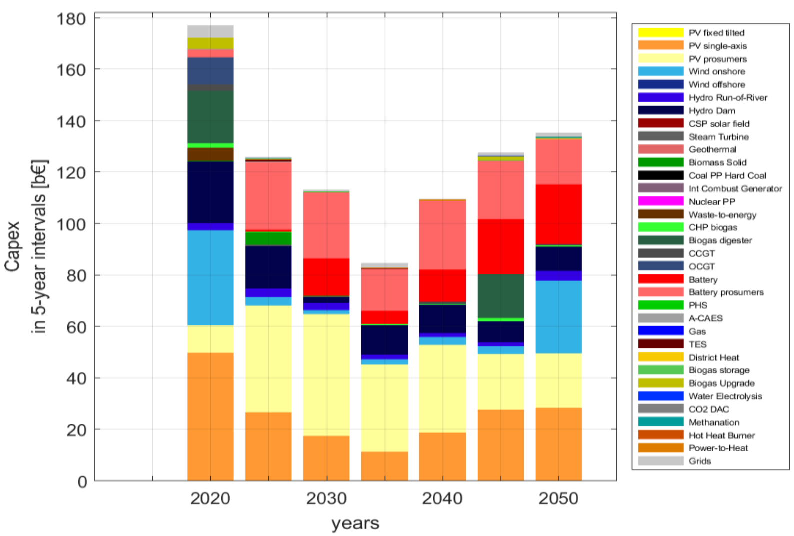




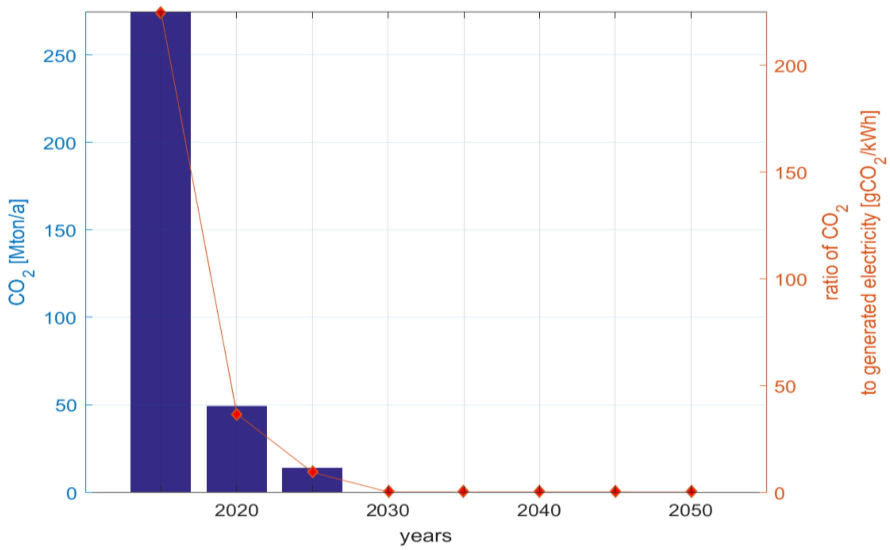


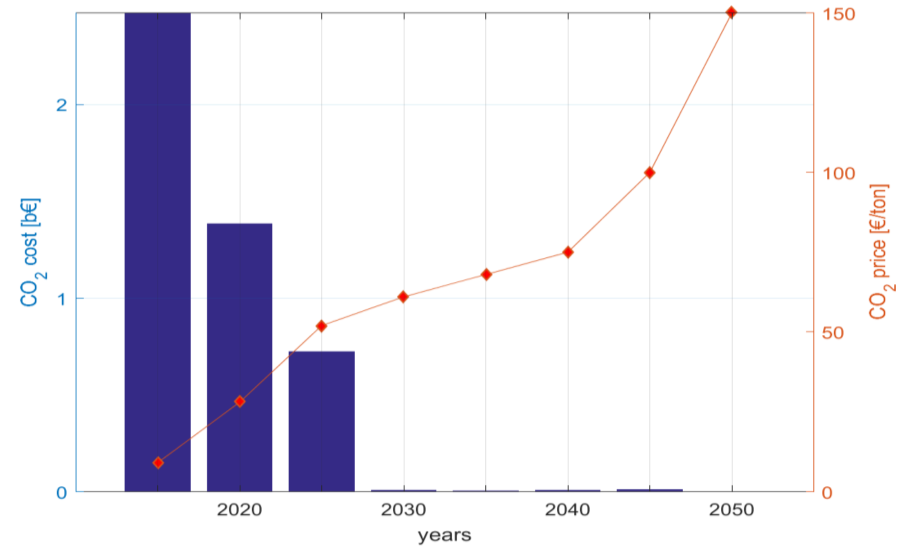
Key insights:

- The power system LCOE decline from 67.5 €/MWh to 39.4 €/MWh from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs
- Beyond 2030 the LCOE further declines up to 2050, signifying that larger capacities of RE addition result in reduction of energy costs
- After an initial increase, the investment requirements decline after 2030 to stabilise between 2040 to 2050

Christian Breyer ▸ christian.breyer@lut.fi @ChristianOnRE

CO_2 Emissions Reduction

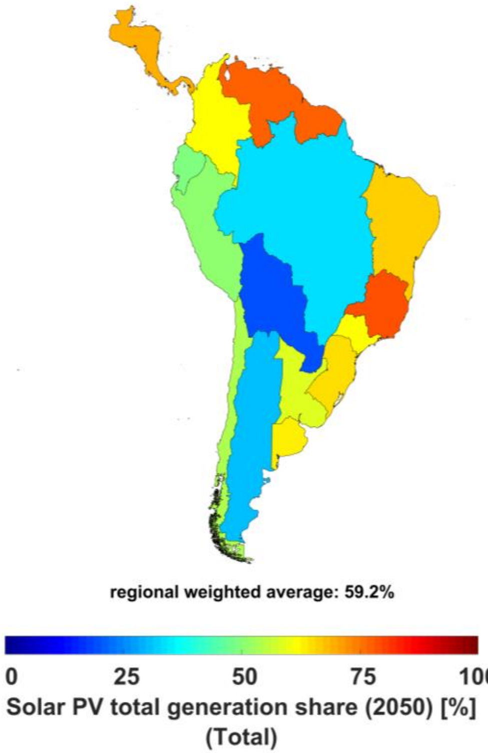


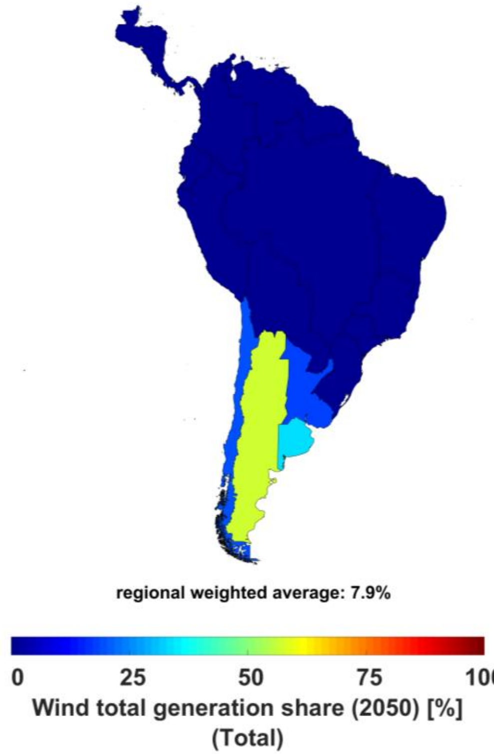


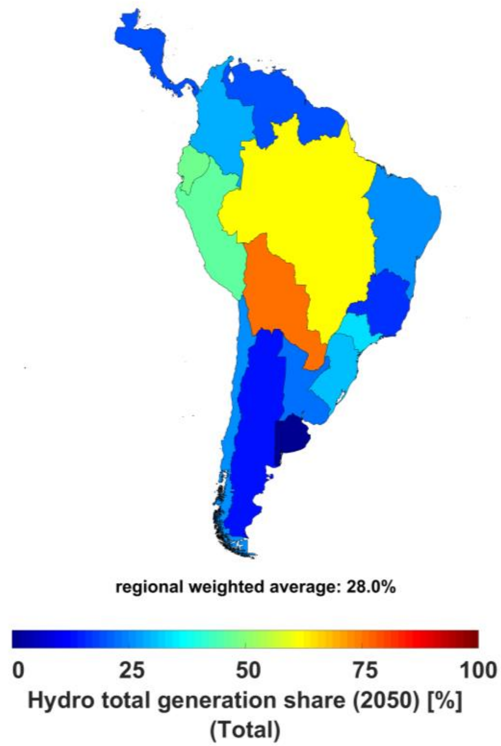
Key insights:

- GHG emissions can be reduced from about 275 $MtCO_{2eq}$ in 2015 to zero by 2050, while the total LCOE of the power system declines
- GHG emissions decline as fossil fueled power plants are eliminated from the system.
- By 2030 carbon emission is zero, which gradually lowering the energy system LCOE
- The results also indicate that a 100% RE based energy system is much more efficient in comparison to the current energy system

Major RE Supply Shares in 2050







Key insights:

- Solar PV dominates the total generation
- Supply shares in 2050
  - Solar PV at about 59% as the least cost source
  - Hydropower at about 28%
  - Wind energy at about 8%
  - Bioenergy at about 4%

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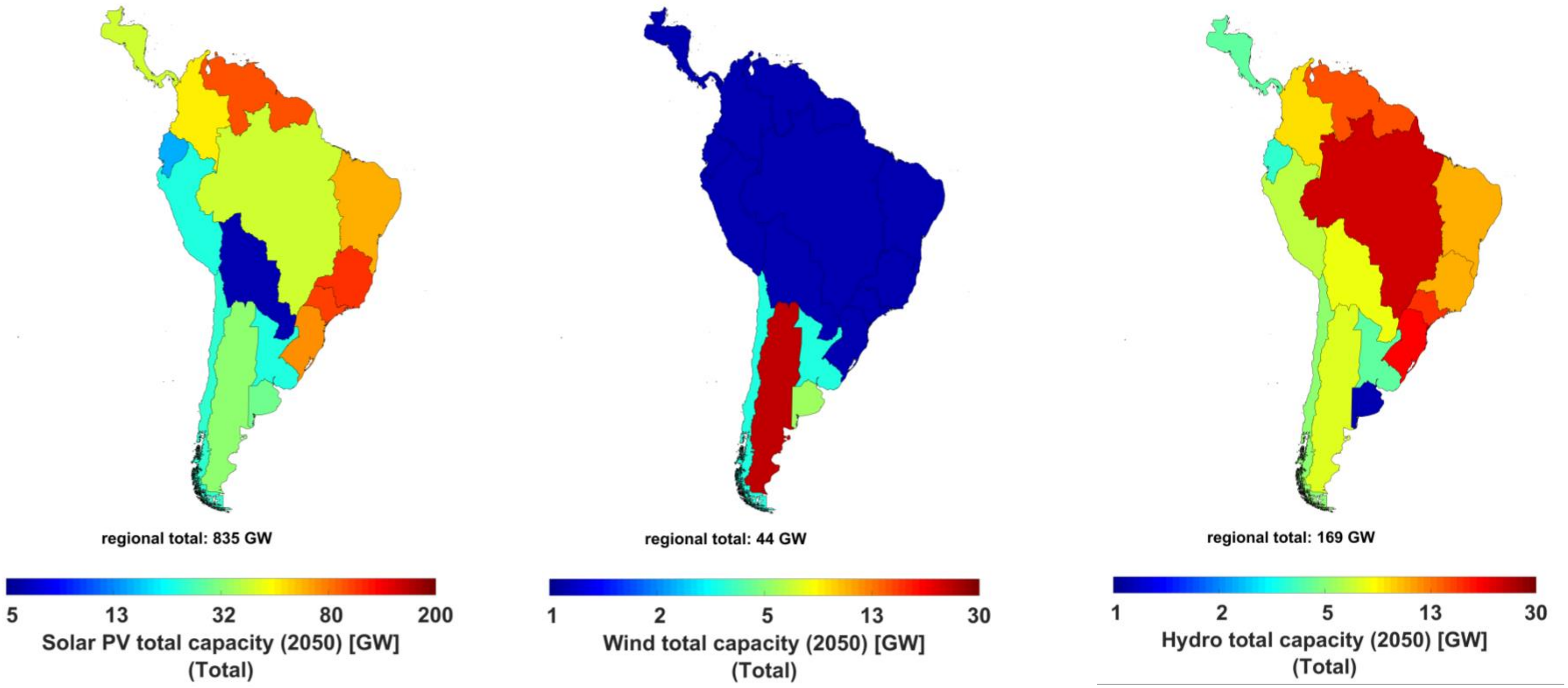
Major RE Capacities in 2050



Key insights:

- Solar PV dominates the total generation capacity
- Capacity shares in 2050
  - Solar PV: 835 GW
  - Hydropower: 169 GW
  - Wind energy: 44 GW
  - Bioenergy: 15 GW

Storage Supply Shares in 2050

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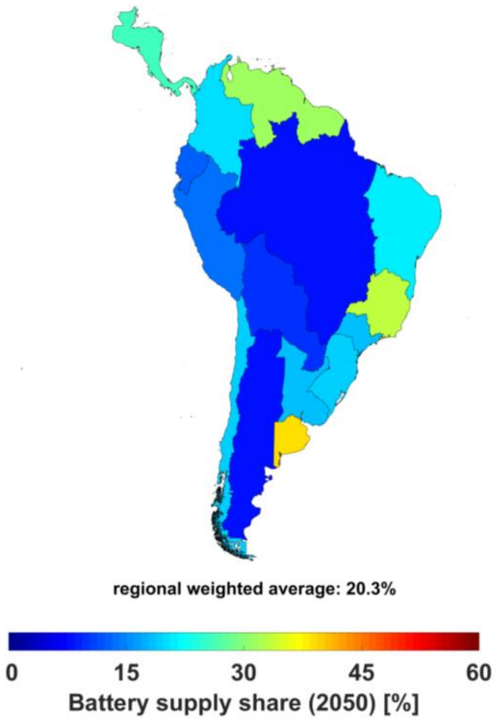
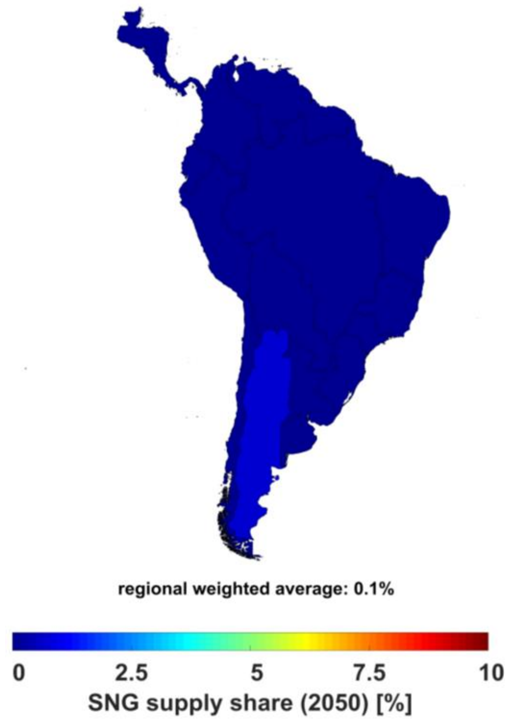
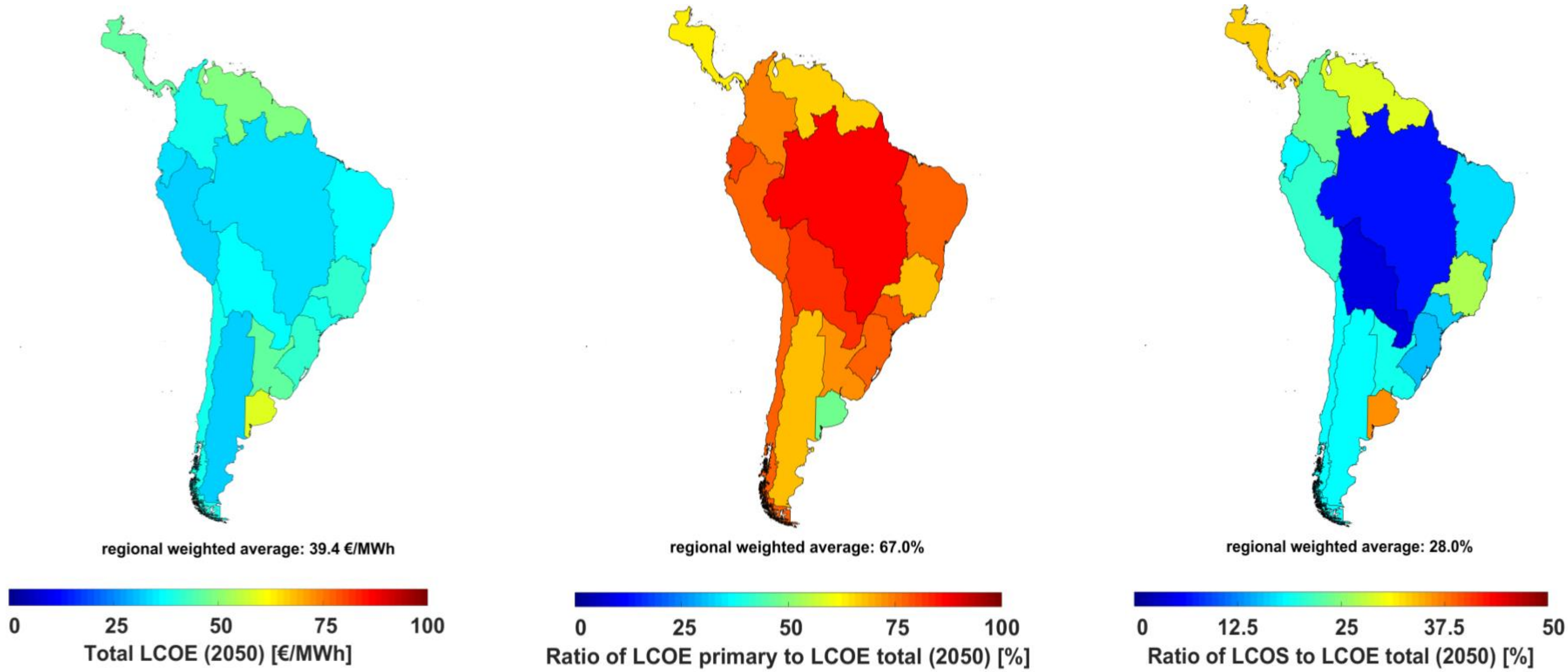




Key insights:

- Battery storage mainly plays a role in providing diurnal storage with around 20.3% of the total supply
- Gas storage mainly plays a role in providing seasonal storage with just 0.1% of total supply
- Prosumers play a significant role and hence a large portion of batteries can be observed in 2050, also with low costs of solar PV and batteries

Total Cost and Share of Primary Generation



Key insights:

- **Total LCOE by 2050 is around 39.4 €/MWh (including generation, storage, curtailment and some grid costs), the range for 75% of regional power demand is 34 – 45 €/MWh**
- **A 67% ratio of the primary generation cost to the total LCOE can be observed, in a range of 61% – 80% for 75% of regional power demand**
- **Cost of storage contributes substantially to the total energy system LCOE, within a range of 5 – 14 €/MWh for 75% of regional power demand**

Energy Transition for Power

- South America can reach 100% RE and zero GHG emissions by 2050
- The LCOE obtained for a fully sustainable energy system for South America is 39.4 €/MWh by 2050
- Solar PV emerges as the most prominent electricity supply source with around 59% of the total electricity supply by 2050
- Batteries emerge as the key storage technology with 99% of total storage output
- Cost of storage contributes substantially to the total energy system LCOE, which is 28%
- GHG emissions can be reduced from about 200 $MtCO_{2eq}$ in 2015 to zero by 2050
- A 100% RE system is more efficient and cost competitive than a fossil based option

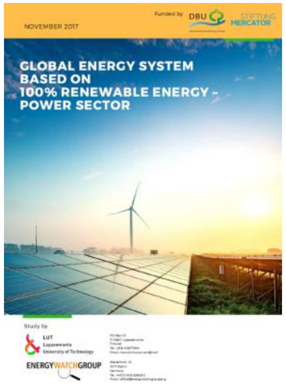
Further Findings

Results for all countries in South America and a Global Overview are available :

- Central America http://bit.ly/2ikbrlr
- Venezuela, Guyana, Fr. Guiana, Suriname http://bit.ly/2ykuFCk
- Colombia http://bit.ly/2z9FHcP
- Ecuador http://bit.ly/2A4NPJu
- Peru http://bit.ly/2huf2xs
- Chile http://bit.ly/2ijqCuW
- Bolivia, Paraguay http://bit.ly/2lBNxGZ
- Brazil http://bit.ly/2zW0q0V
- Argentina, Uruguay http://bit.ly/2A2T7oZ

Global Overview http://bit.ly/2gQIY6p

full study http://bit.ly/2hU4Bn9



full study http://bit.ly/2hU4Bn9
scientific article Breyer, Bogdanov, et al., 2018

Power lines connecting North and South

Theoretical consideration of Grossmann et al.

- It may make sense to link North and South America with long-distance power lines
- Seasonal balance of solar resource variation may be attractive
- In practical terms: power lines connecting US Southwest (Mojave) and Chile/Bolivia/Argentina (Atacama) may balance seasonal solar deficits, thus generating benefits

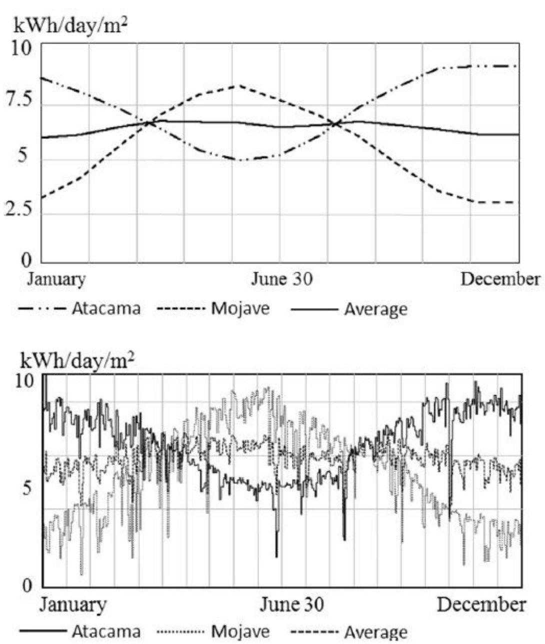
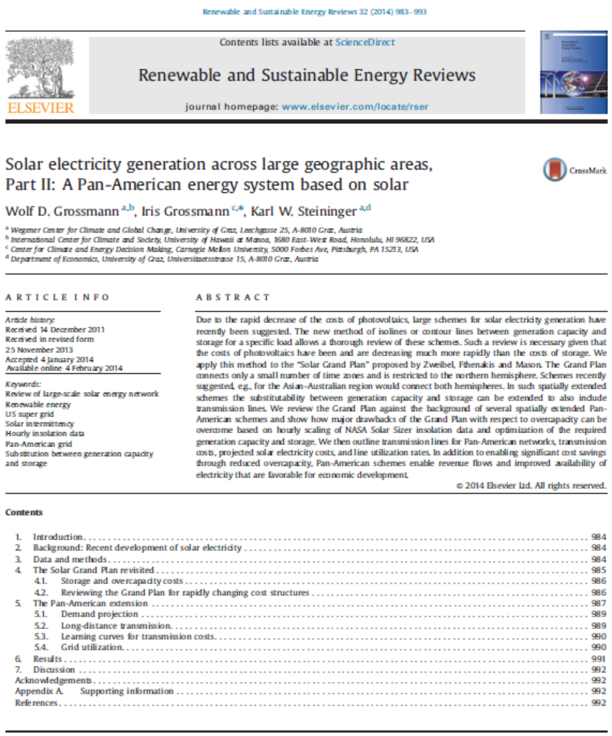


Fig. 5. Top: 23-year average of daily insolation in kW h/m^2 in the Atacama and Mojave and the average of the two locations (data from [17]). Bottom: Actual insolation for one year (1986).



Renewable and Sustainable Energy Reviews 32 (2014) 983–993

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Solar electricity generation across large geographic areas, Part II: A Pan-American energy system based on solar

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ARTICLE INFO

Article history:
Received 14 December 2011
Received in revised form
25 November 2013
Accepted 4 January 2014
Available online 4 February 2014

Keywords:
Review of large-scale solar energy network
Renewable energy
US super grid
Solar intermittency
Hourly insolation data
Pan-American grid
Substitution between generation capacity and storage

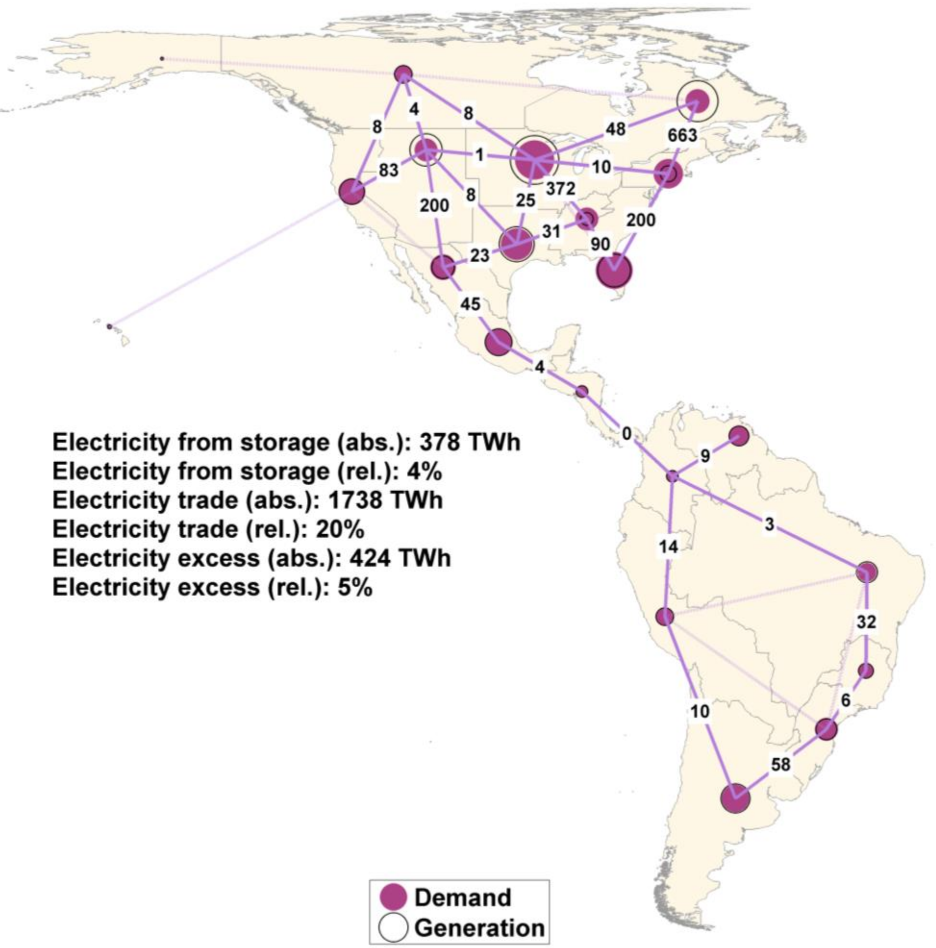
ABSTRACT

Due to the rapid decrease of the costs of photovoltaics, large schemes for solar electricity generation have recently been suggested. The new method of isolines or contour lines between generation capacity and storage for a specific load allows a thorough review of these schemes. Such a review is necessary given that the costs of photovoltaics have been and are decreasing much more rapidly than the costs of storage. We apply this method to the "Solar Grand Plan" proposed by Zweibel, Fthenakis and Mason. The Grand Plan connects only a small number of time zones and is restricted to the northern hemisphere. Schemes recently suggested, e.g., for the Asian–Australian region would connect both hemispheres. In such spatially extended schemes the substitutability between generation capacity and storage can be extended to also include transmission lines. We review the Grand Plan against the background of several spatially extended Pan-American schemes and show how major drawbacks of the Grand Plan with respect to overcapacity can be overcome based on hourly scaling of NASA Solar Sizer insolation data and optimization of the required generation capacity and storage. We then outline transmission lines for Pan-American networks, transmission costs, projected solar electricity costs, and line utilization rates. In addition to enabling significant cost savings through reduced overcapacity, Pan-American schemes enable revenue flows and improved availability of electricity that are favorable for economic development.

Contents

Americas link – an energy system view

Annual imported and exported electricity (TWh)



Insights with LUT model

- Sectors considered: power, desalination, non-energetic gas demand
- Cost assumptions for year 2030 cannot confirm substantial benefit of linking Northern and Southern Hemisphere
- Substantial balancing effect in North America (driven by wind energy from Canada East and US Midwest)
- Energy system solution with surprisingly low amount of excess and low storage, but still limited electricity trade
- Total annualised cost of linked Americas can be reduced from 49.5 to 48.8 €/MWh for integrated Americas vs separated North and South America, thus by 1.4%

- What may be the reason for limited value of hemispherical linking power lines?

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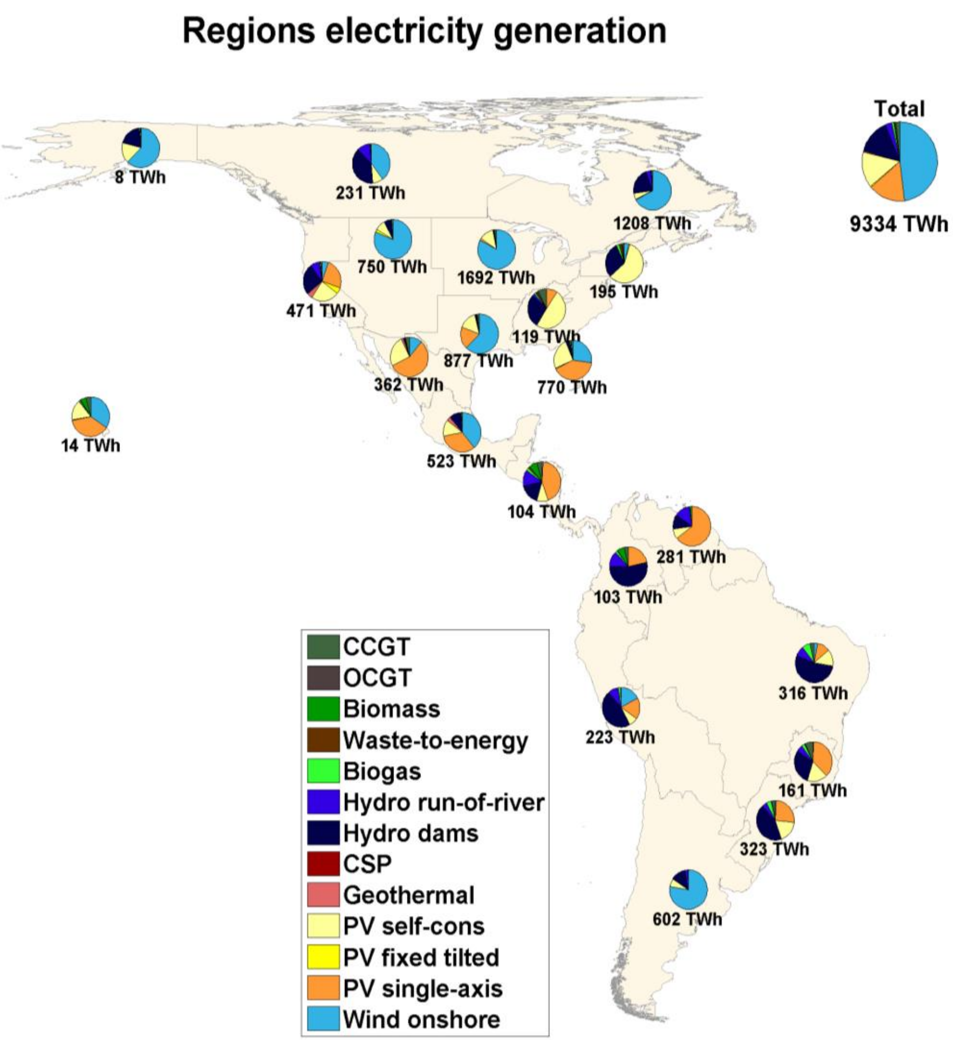
source: Aghahosseini A., Bogdanov D., Barbosa L.S.N.S., Breyer Ch., 2018. Analysing the feasibility of powering the Americas using solely renewable energy and a wide area synchronous transmission network by 2030, under review

Americas link – an energy system view



Insights with LUT model

- Silo thinking is dangerous!
- The Americas have excellent resources for solar AND wind AND hydro
- The regional complementarity for balancing of solar, wind and hydro is MUCH more valuable than power lines of many thousands of kilometres can ever be

Strong disclaimer:

- We have calculated a 2030 case
- For 2050 assumptions the solar share will be higher due to further reduced cost of PV
- However, the complementarity of solar, wind and hydro will be still most valuable

- Do not forget:
- The best solar, wind and hydro resources in the world, are all in Latin America!!

source: Aghahosseini A., Bogdanov D., Barbosa L.S.N.S., Breyer Ch., 2018. Analysing the feasibility of powering the Americas using solely renewable energy and a wide area synchronous transmission network by 2030, under review

Energy Transition in Transport Sector

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Table 2.3 • Announced sales bans for ICE vehicles

Country	2025	2030	2032	2040	2045
France				ICE access restrictions	
Ireland		ICE access restrictions			
Netherlands		ICE access restrictions			
Norway	ICE access restrictions				
Slovenia		ICE access restrictions			
Sri Lanka				ICE sales ban	
Sweden					ICE sales ban
Scotland			ICE access restrictions		
United Kingdom				ICE access restrictions	

Table 2.4 • Announced access restriction mandates in local jurisdictions

Local jurisdiction	2024	2025	2030	2035	2040
Athens		Diesel access restrictions			
Auckland			Fossil-Fuel-Free Streets Declaration		
Balearic Islands		Diesel access restrictions		ICE access restrictions	
Barcelona			Fossil-Fuel-Free Streets Declaration		
Cape Town			Fossil-Fuel-Free Streets Declaration		
Chinese Taipei					ICE sales ban
Copenhagen			Fossil-Fuel-Free Streets Declaration		
London			Fossil-Fuel-Free Streets Declaration		
Los Angeles			Fossil-Fuel-Free Streets Declaration		
Madrid		Diesel access restrictions			
Mexico City		Diesel access restrictions	Fossil-Fuel-Free Streets Declaration		
Milan			Fossil-Fuel-Free Streets Declaration		
Oxford			Fossil-Fuel-Free Streets Declaration		
Paris	Diesel access restrictions		ICE access restrictions; Fossil-Fuel-Free Streets Declaration		
Quito			Fossil-Fuel-Free Streets Declaration		
Rome	Diesel access restrictions				
Seattle			Fossil-Fuel-Free Streets Declaration		
Stockholm			ICE access restrictions		
Vancouver			Fossil-Fuel-Free Streets Declaration		

● Diesel access restrictions ● ICE access restrictions
● Fossil-Fuel-Free Streets Declaration ● ICE sales ban

- **2030 onwards seems to be the time, when new sales of ICE cars will collapse, latest**
- **ICE bans are declared in Europe, Americas, Asia-Pacific**
- **If major cities of a country start to ban ICE cars, probability is high that this triggers a trend for the entire country**

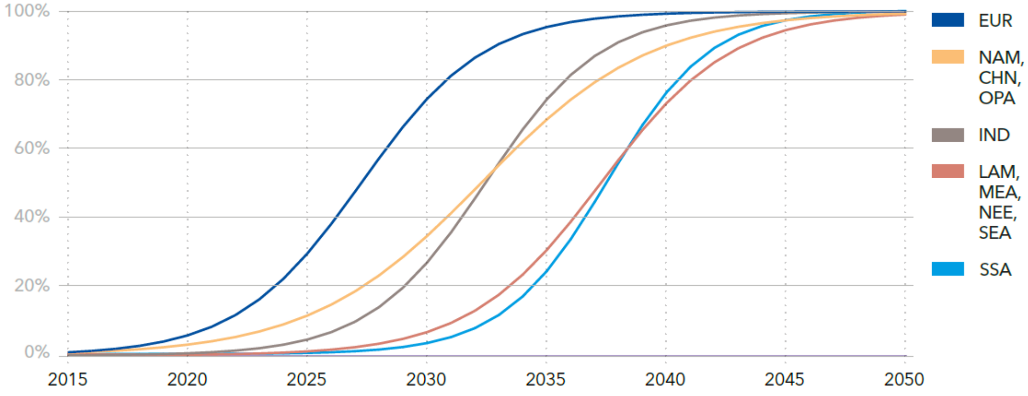
source: IEA, 2018. Global EV Outlook 2018

Energy Transition in Transport Sector

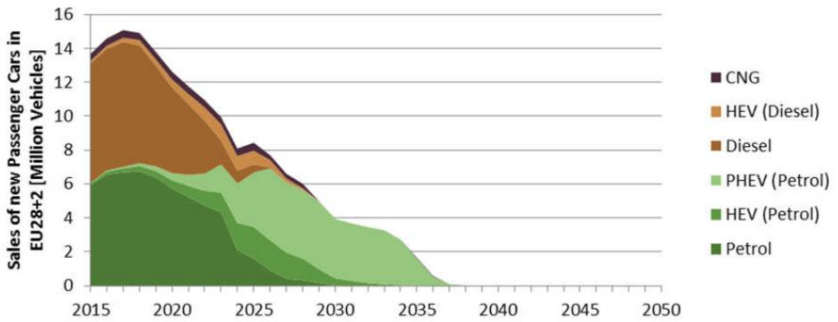
FIGURE 4.1.3

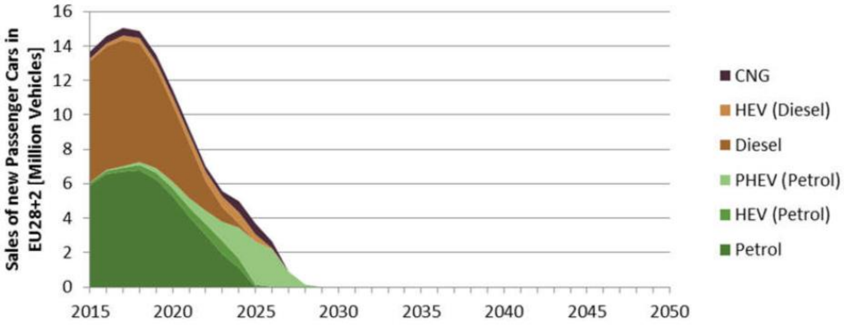
Market share of non-combustion light vehicles by region

Units: Percentages



source: DNV GL, 2018. Energy Transition Outlook 2018





source: DLR, 2018. Development of the car fleet in EU28+2 to achieve the Paris Agreement target to limit global warming to 1.5C

DNV GL

- Europe is expected to lead soon the market in relative newly sold non-ICE cars
- 2030: 75% market share of non-ICE cars expected in Europe
- 2040: >80% market share of non-ICE cars expected globally, rather close to 100%

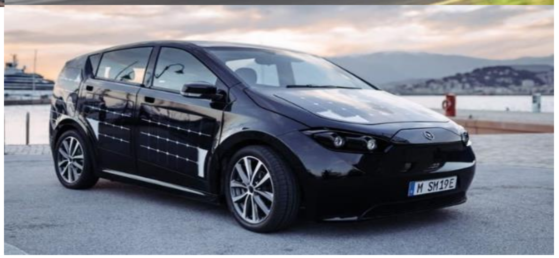
DLR

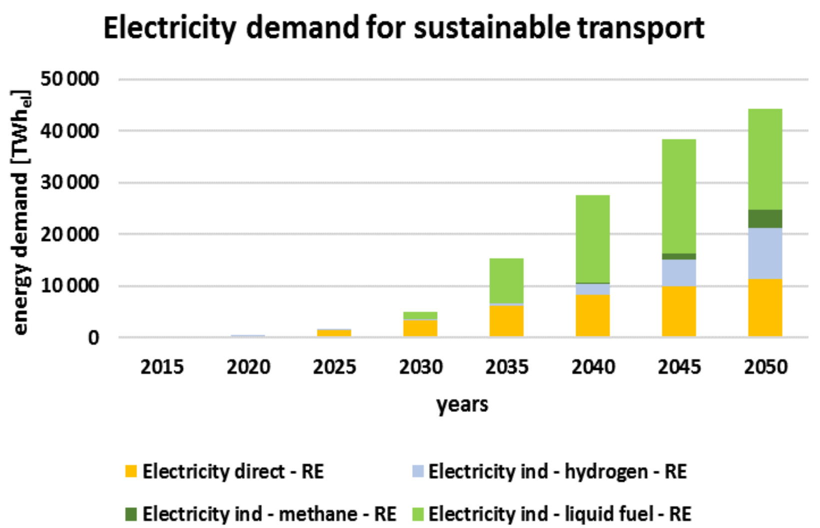
- 1.5°C target (in 50% probability) confirms the DNV GL scenario
- 1.5°C target (in 66% probability) requires even more tough policy measures

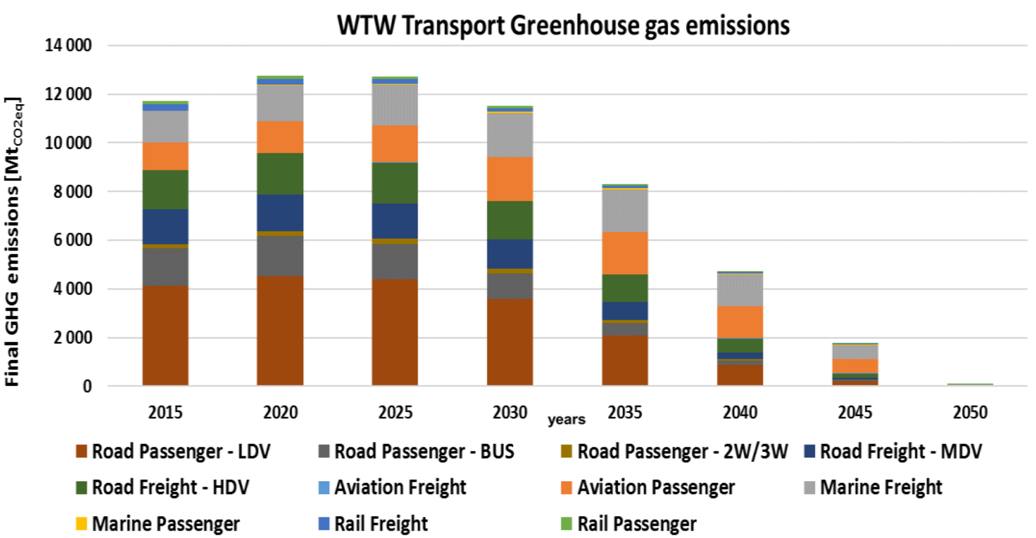
Sustainable Transport



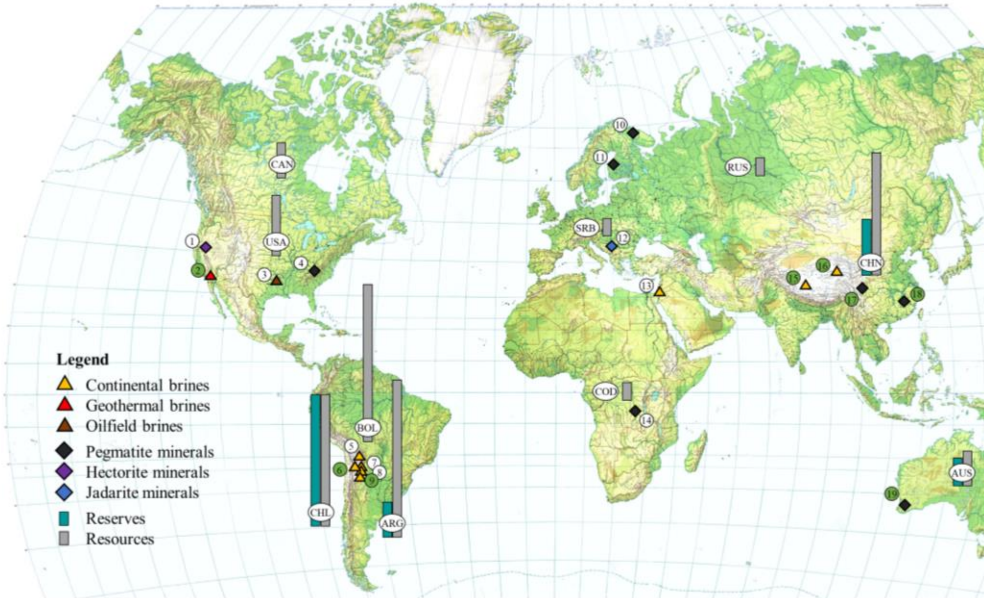

- Almost everything will be electrified (directly and indirectly)
- Massive extra electricity demand
- GHG emissions can go to zero by 2050



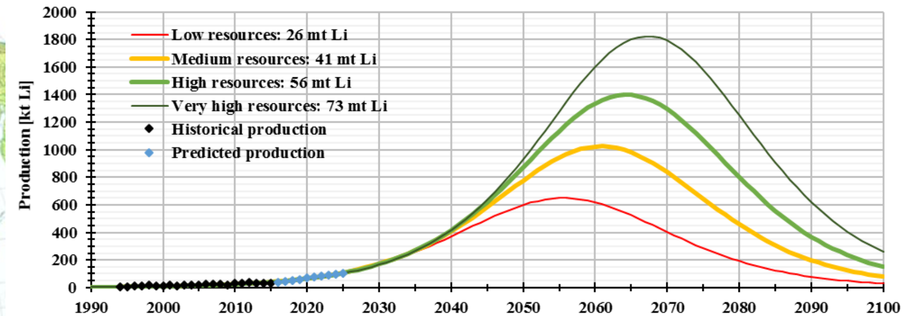


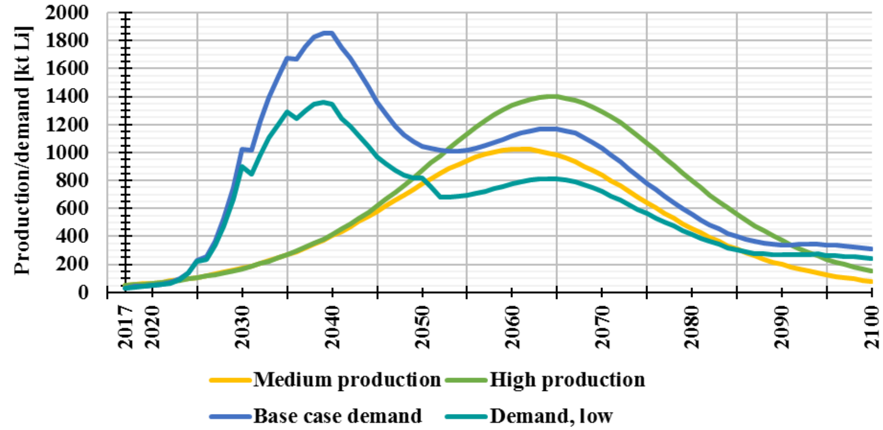


Lithium resources vs demand profile



① Kings Valley, U.S.
② Salton Sea, U.S.
③ Smackover, U.S.
④ Kings Mountain Belt, U.S.
⑤ Salar de Uyuni, Bolivia
⑥ Salar de Atacama, Chile
⑦ Salar de Cauchari, Argentina
⑧ Salar del Rincón, Argentina
⑨ Salar del Hombre Muerto, Argentina
⑩ Kolmozerskoe, Russia
⑪ Läntää, Finland
⑫ Jadar Valley, Serbia
⑬ Dead Sea, Israel
⑭ Manono/Kitolo, Congo
⑮ Lake Zabuye, China
⑯ Qaida
⑰ Gajika
⑱ Yichu
⑲ Green

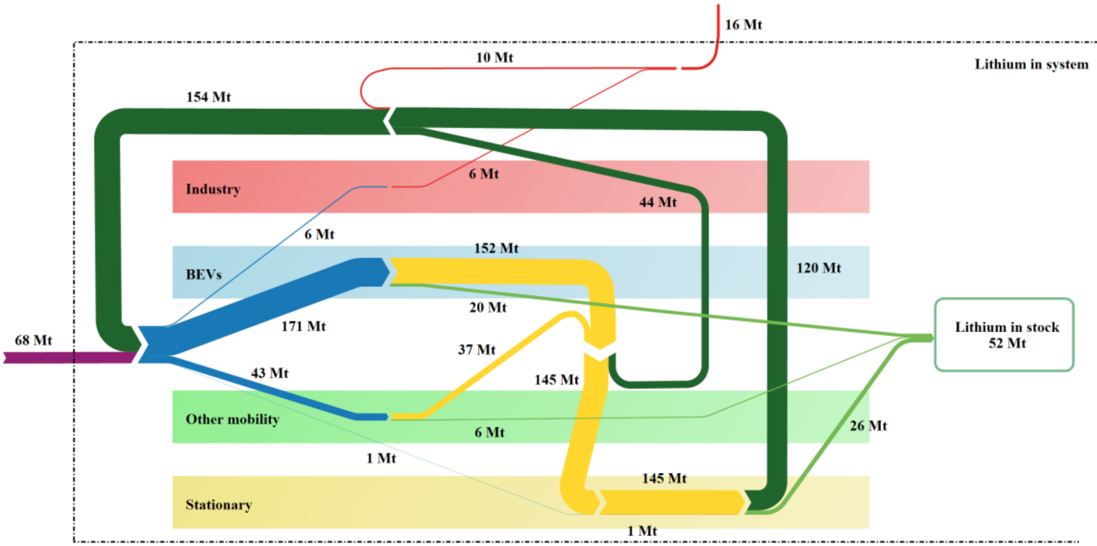


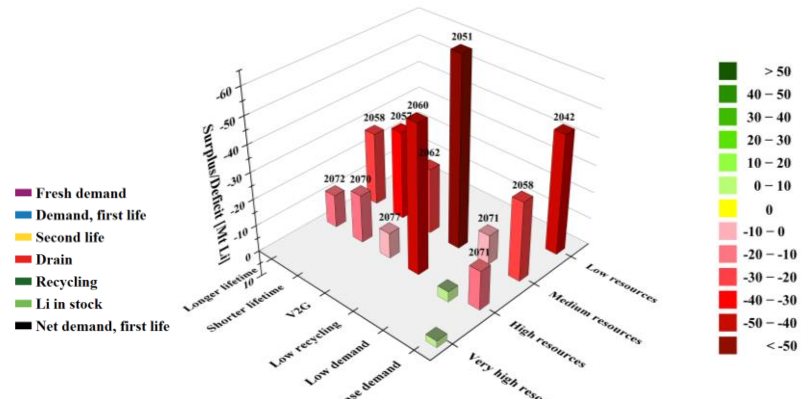


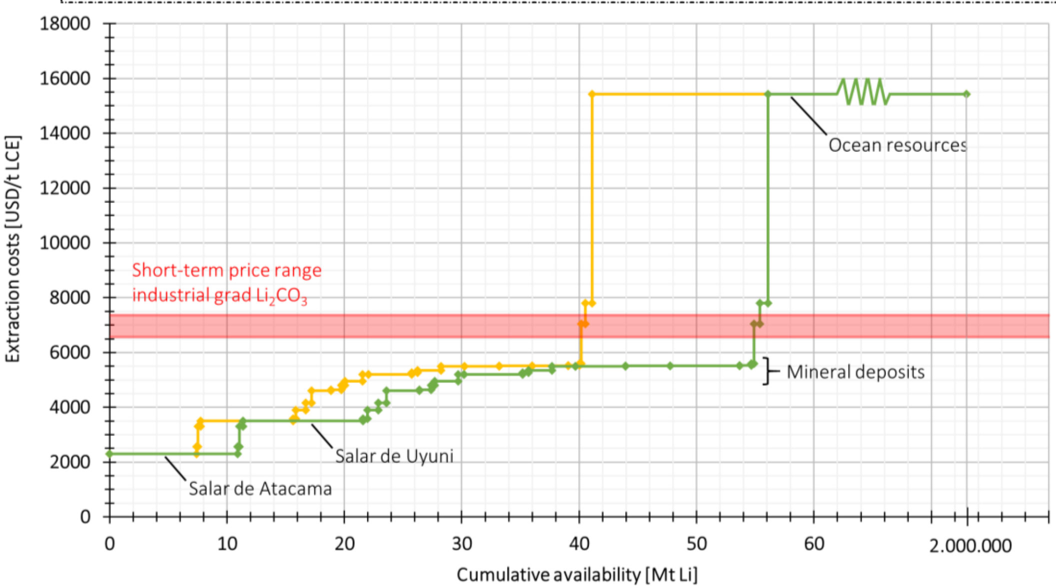
Key insights:

- No consensus on the Lithium availability
- Matching various supply and demand scenarios leads to massive short-term supply deficit
- Lithium is a HUGE asset for Bolivia
- The global demand will be higher than supply, hence excellent position for Bolivia
- advise: fair industrial development, also for high value chain integration (at least Li – to – battery packs)
- Keep control on resources, this may be the most valuable asset of Bolivia

Lithium – a potentially limiting raw material







Key insights:

- No consensus on the Lithium availability
- Matching various supply and demand scenarios almost always leads to supply shortage (total resource in 2060s/2070s, annual supply much earlier)
- Circular economy is a must for Lithium
- Lithium based batteries can carry the energy transition far, but not fully
- Alternative battery concepts needed, such on Aluminium or Magnesium basis
- Advice: use the Lithium richness for full value chain at least Li – to – battery packs
- Be aware of: without the Lithium of the region NO e-mobility revolution will happen

Power-to-X options: Fuels/ Chemicals Sector

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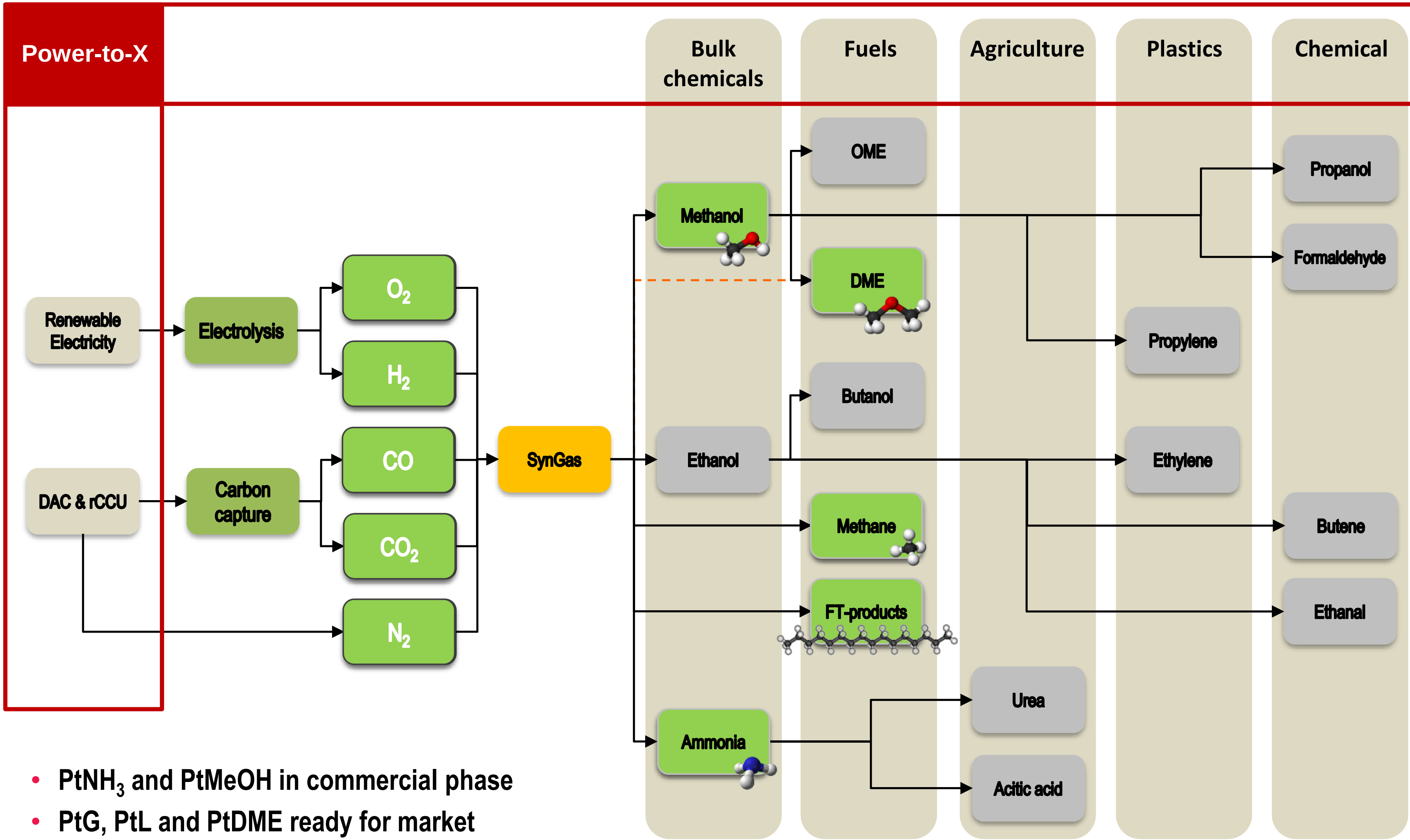

- $PtNH_3$ and PtMeOH in commercial phase
- PtG, PtL and PtDME ready for market

Diagram is based on: Stiessel S., et al., 2017. Techno-economic analysis of various Power2X concepts for the integration of CO_2-based synthesis, IRES, Düsseldorf, March

Methodology

PtG-LNG Value Chain Energy Flow & Mass Balance

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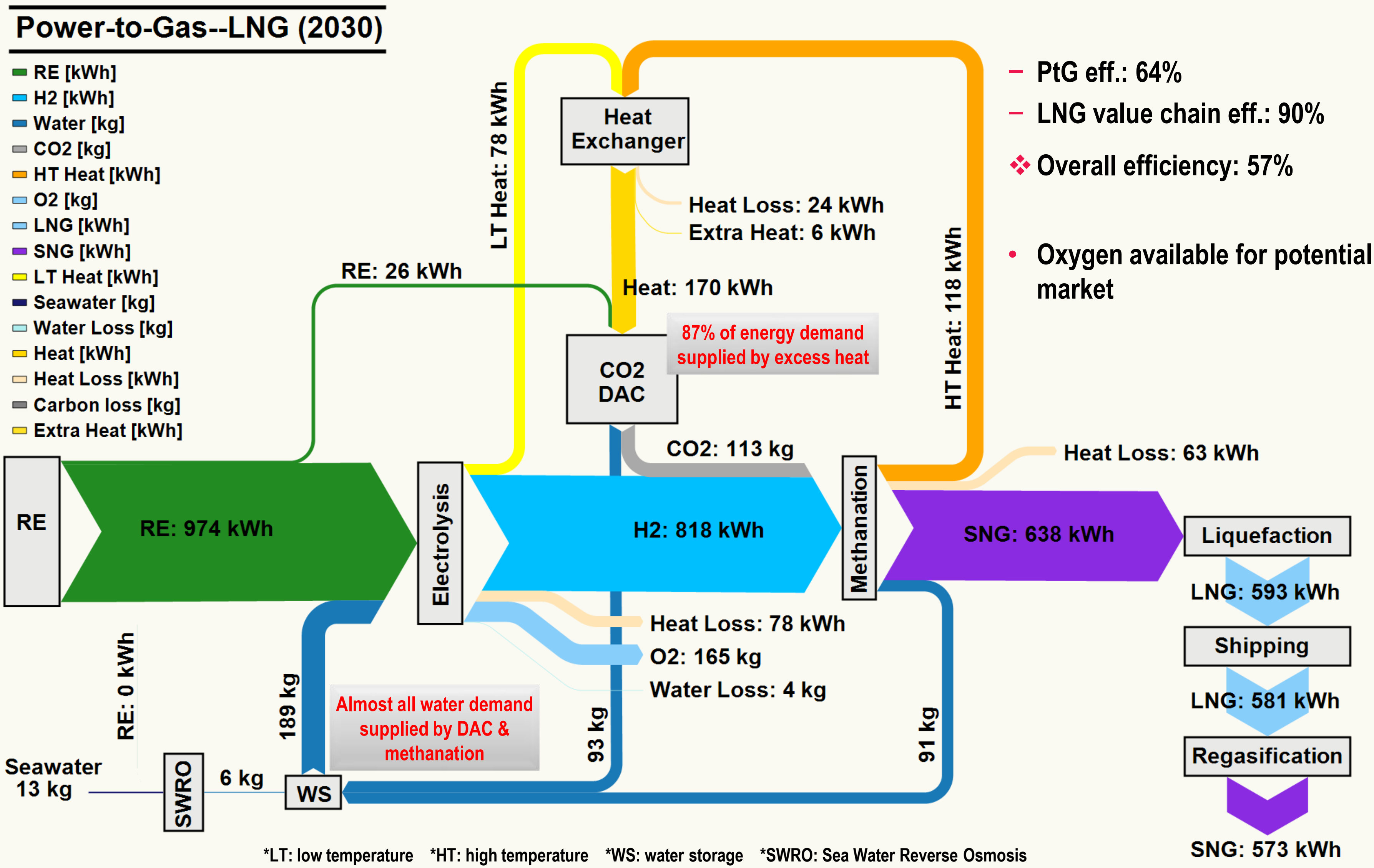
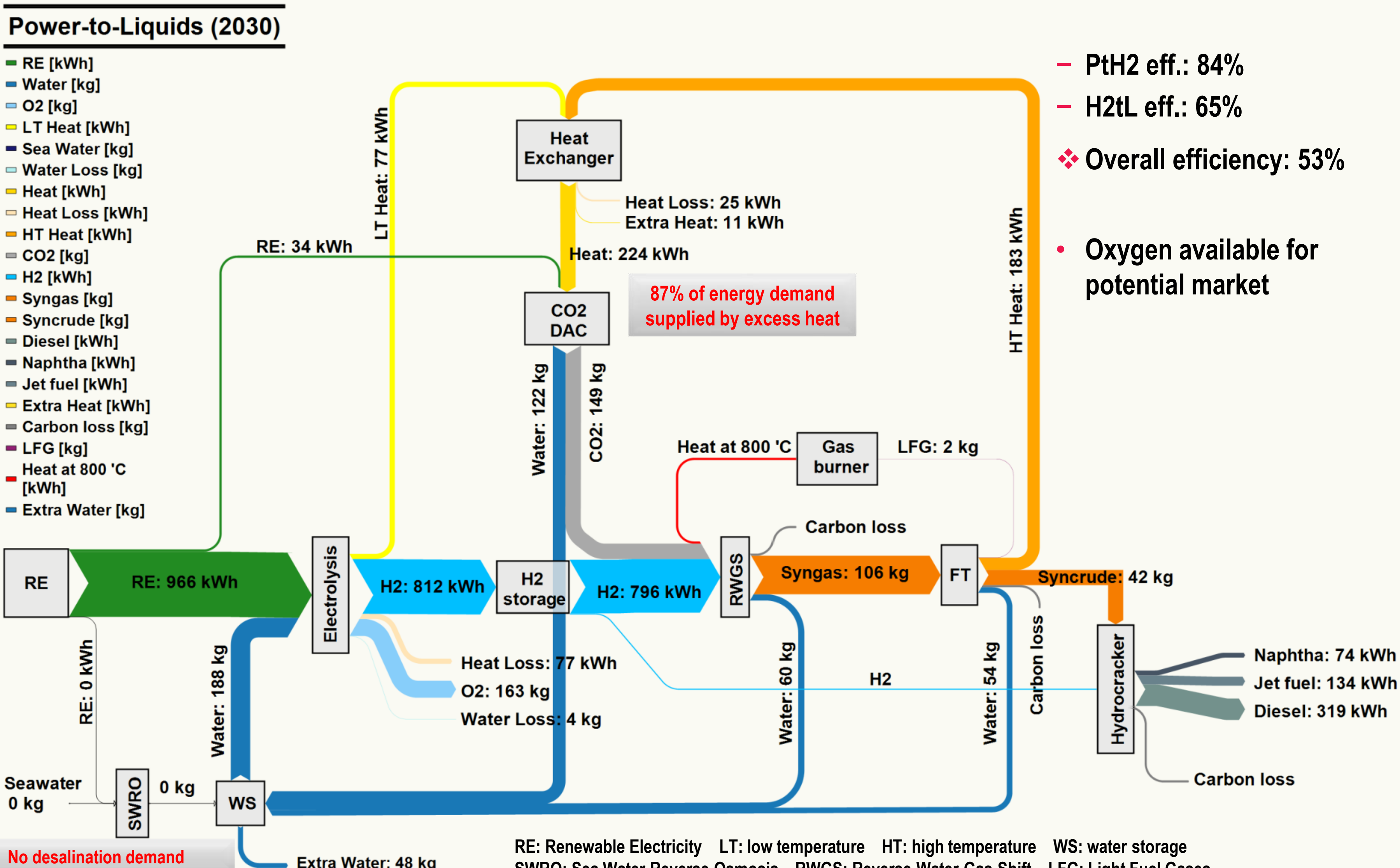


- PtG eff.: 64%
- LNG value chain eff.: 90%
- Overall efficiency: 57%
- Oxygen available for potential market

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

Methodology

PtL Energy Flow & Mass Balance

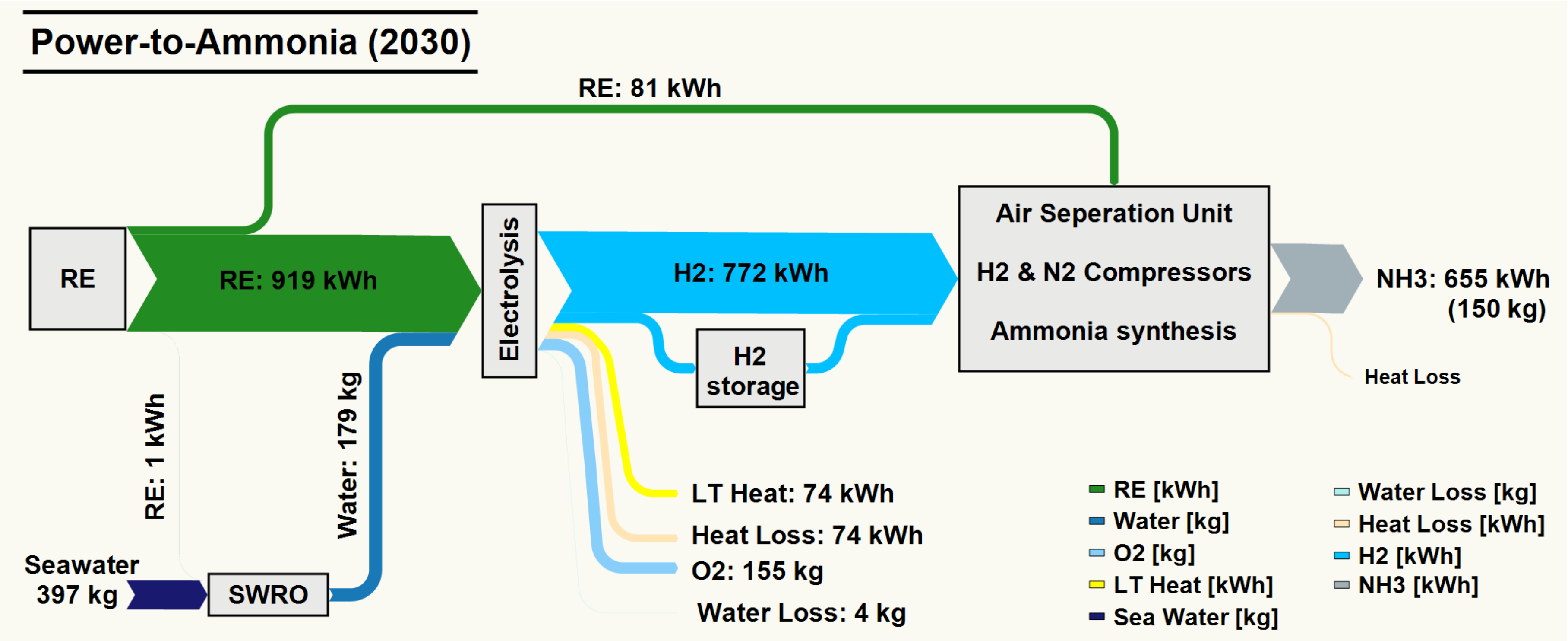


- PtH2 eff.: 84%
- H2tL eff.: 65%
- Overall efficiency: 53%
- Oxygen available for potential market

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

Methodology

PtNH$_3$ Energy Flow & Mass Balance

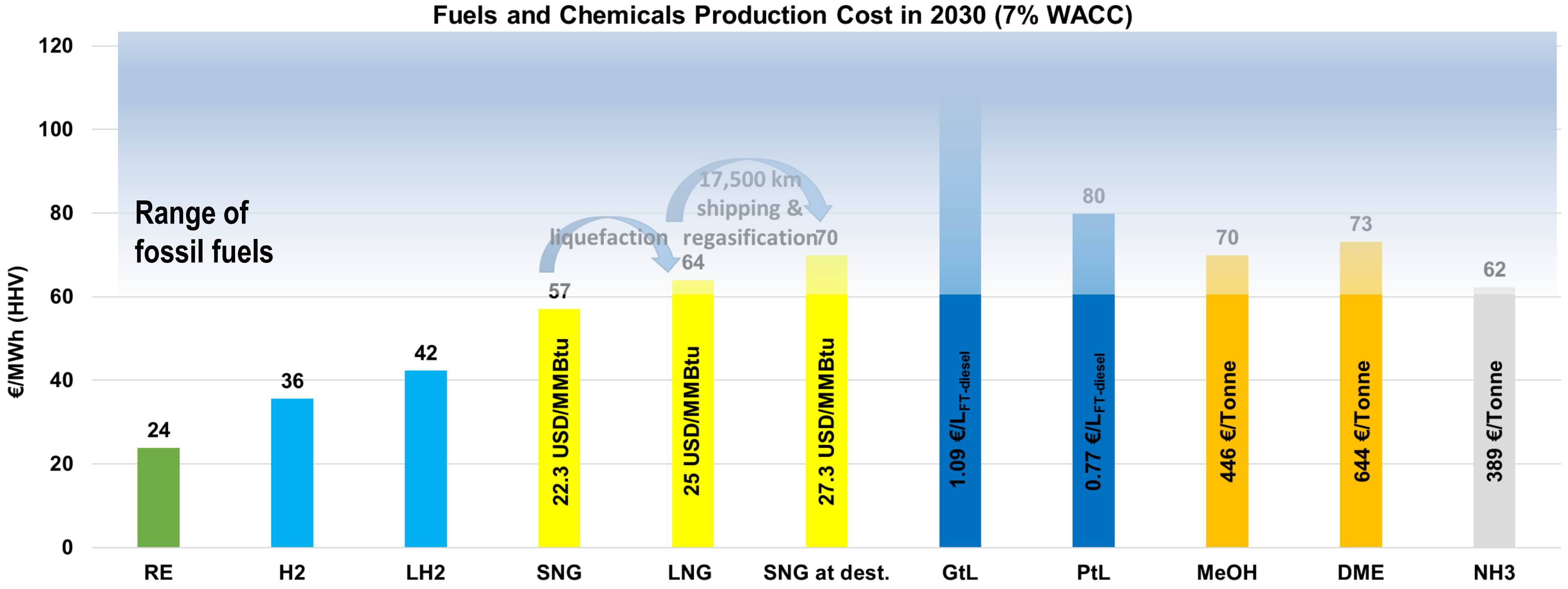


RE: Renewable Electricity LT: low temperature SWRO: Sea Water Reverse Osmosis

- Electrolyser is the main electricity consumer
- PtH$_2$ eff.: 84%
- PtNH$_3$ overall eff.: 65.5%
- 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

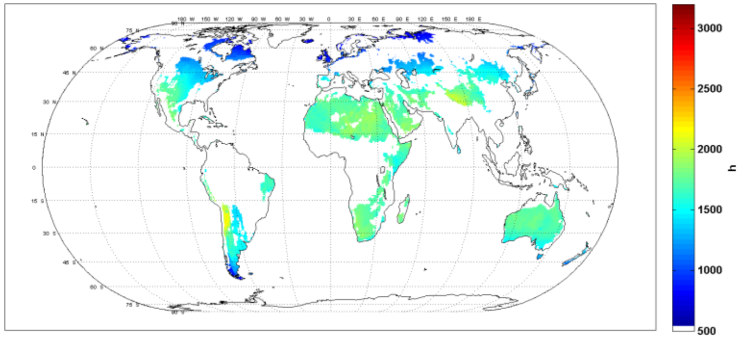


- For conditions in Patagonia
- SNG and PtG-GtL are the cheapest and the most expensive synthetic fuel, respectively.
- the production cost of RE-diesel, RE-methanol and RE-DME are close to each other, however the fuel-parity (cost competitiveness) depends on their respective market price and CO_2 emission 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)

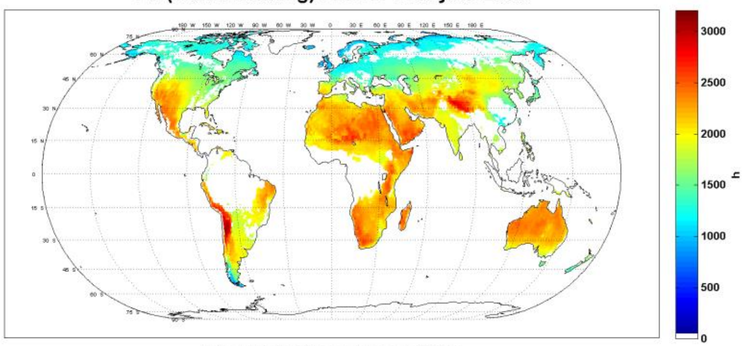
Results

Full load hours

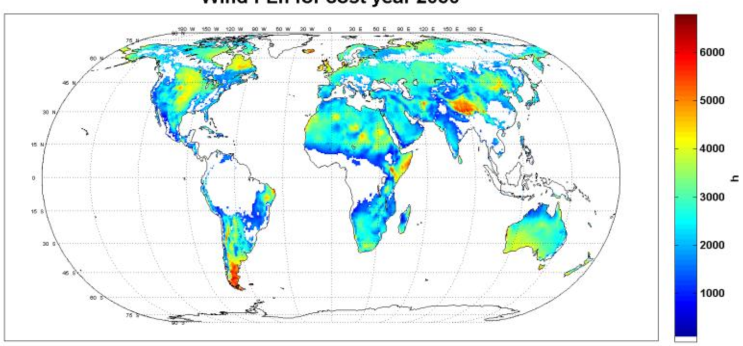
PV (fixed tilted) FLh for cost year 2030



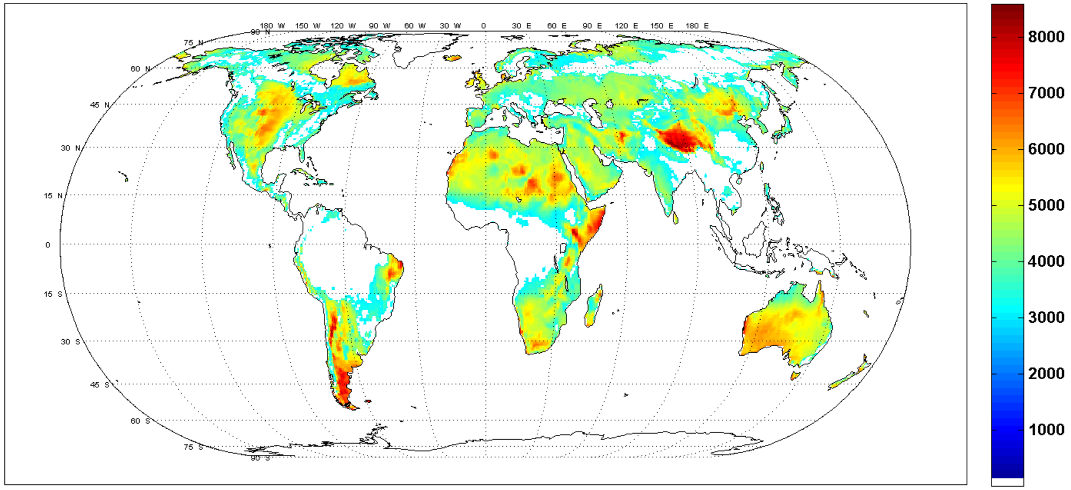
PV (1-axis tracking) FLh for cost year 2030



Wind FLh for cost year 2030



Hybrid PV1-Wind cumulative FLh for cost year 2030



- sites with cumulative FLh higher than 3000 have been taken into account as they have the lowest LCOE
- PV single-axis tracking provides 200-600 higher FLh than PV fixed-tilted
- wind FLh are much higher than PV FLh due to 24h harvesting
- Patagonia, Somalia and Tibet have the highest cumulative FLh globally

Results

Levelised Cost of Electricity (LCOE)

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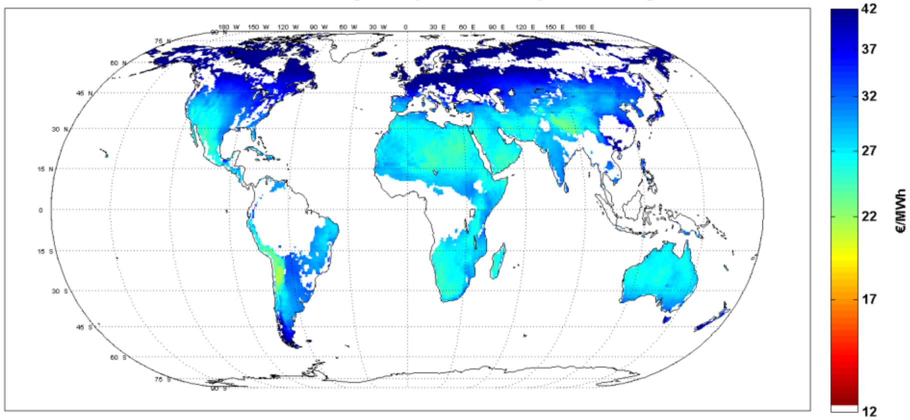
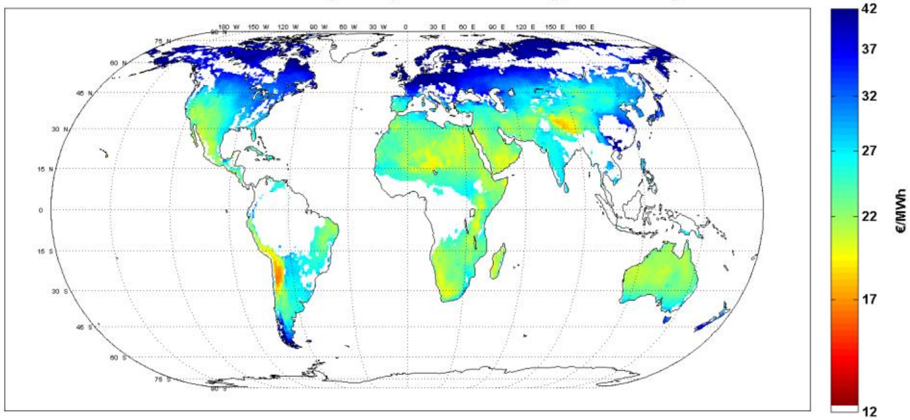
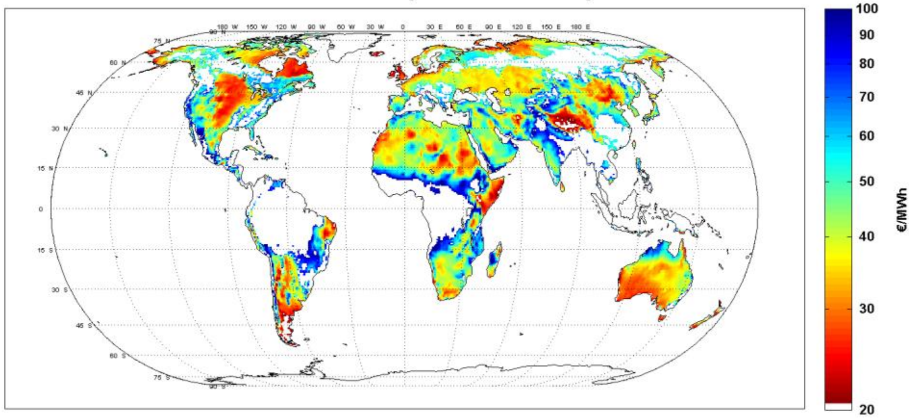




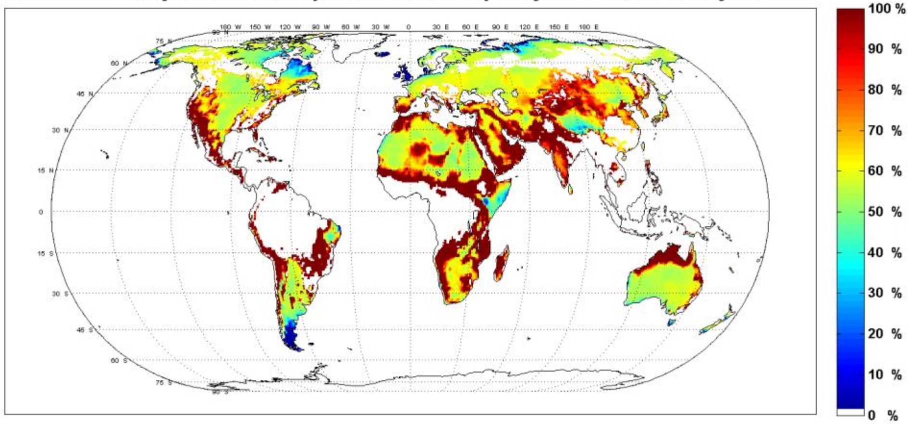
- sites of high FLh of PV or Wind plants have the lowest LCOE
- LCOE of PV single-axis tracking is about 4-5 €/MWh cheaper than LCOE of PV fixed tilted, and even more relevant more FLh (20-30%) on a least cost basis
- Atacama Desert reaches PV LCOE of close to 15-17 €/MWh
- Patagonia reaches wind LCOE of close to 19-20 €/MWh



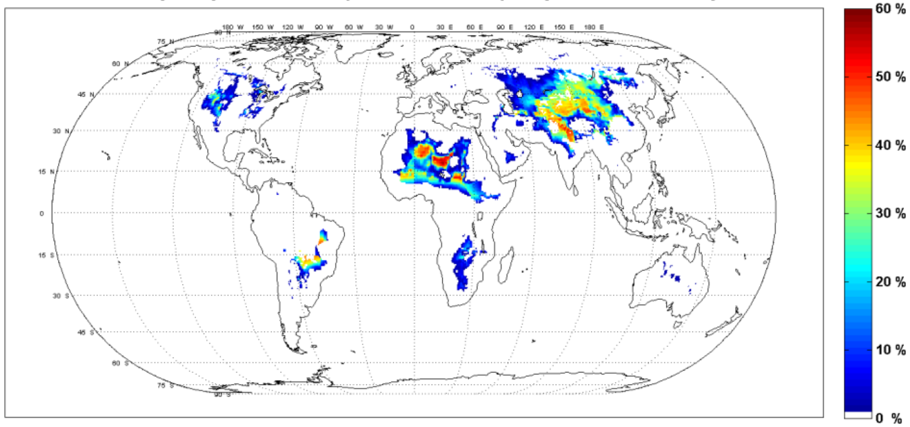
Results

The share of PV and batteries from 2030 to 2040

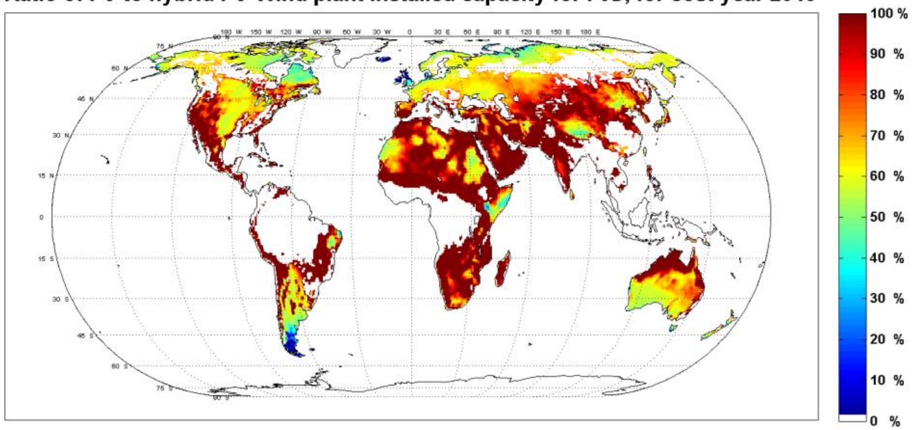
Ratio of PV to hybrid PV-Wind plant installed capacity for PtG, for cost year 2030



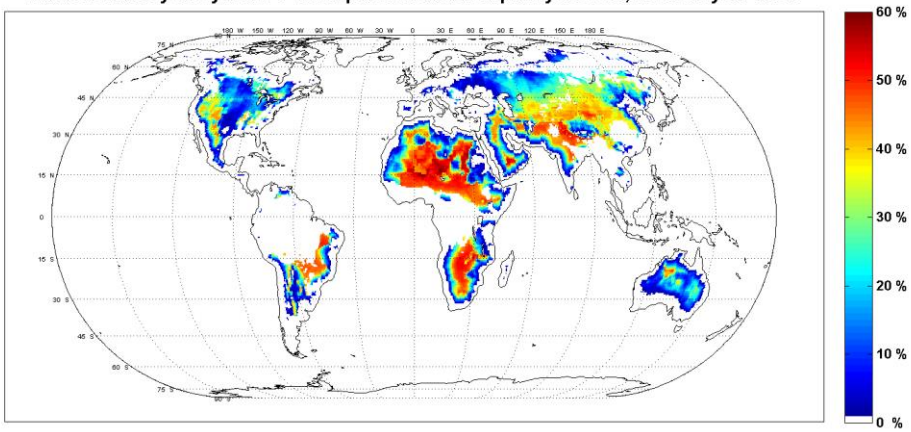
Ratio of battery to hybrid PV-Wind plant installed capacity for PtG, for cost year 2030



Ratio of PV to hybrid PV-Wind plant installed capacity for PtG, for cost year 2040



Ratio of battery to hybrid PV-Wind plant installed capacity for PtG, for cost year 2040

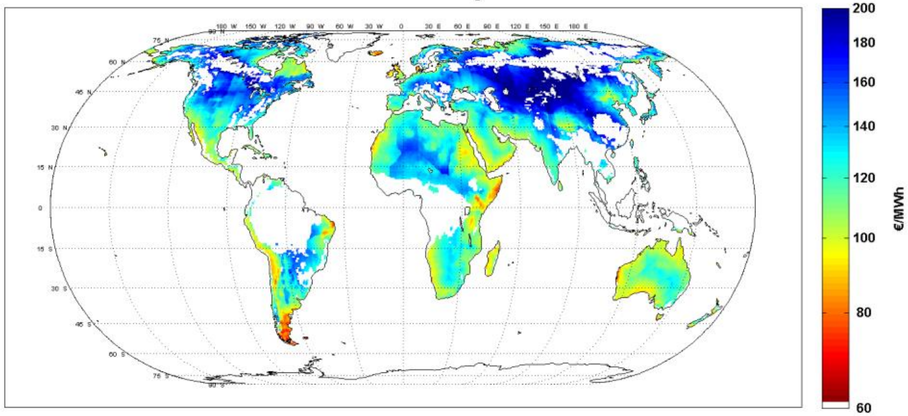


- in Africa, the installed capacity of batteries would be up to 60% of installed capacity of hybrid PV-wind plant by 2040.
- strong increasing relevance of battery technology from 2030 to 2040

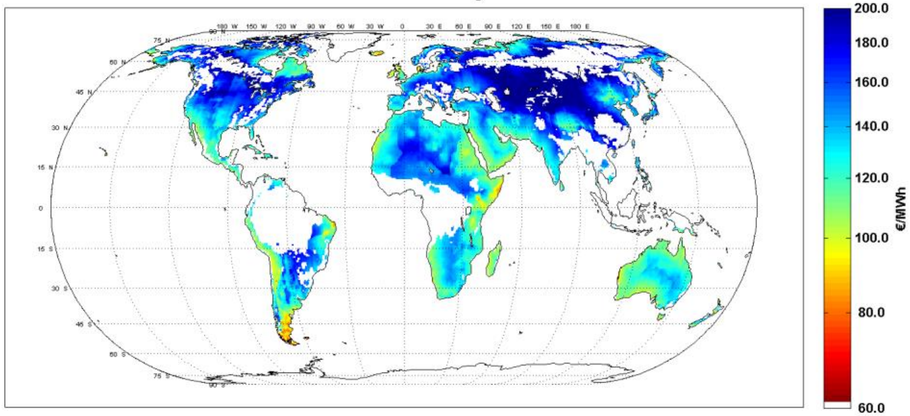
Results

Levelised Cost of Fuels (LCOF)

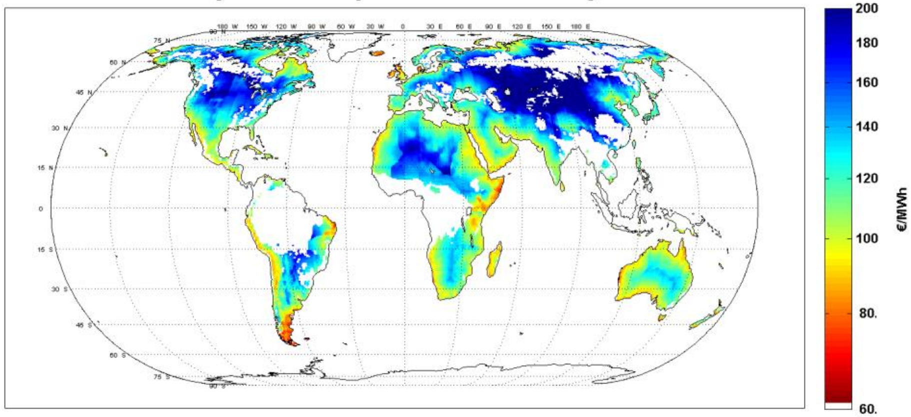
Cost of SNG for cost year 2030



Cost of LNG for cost year 2030



Cost of Synthetic Liquid Fuels for cost year 2030

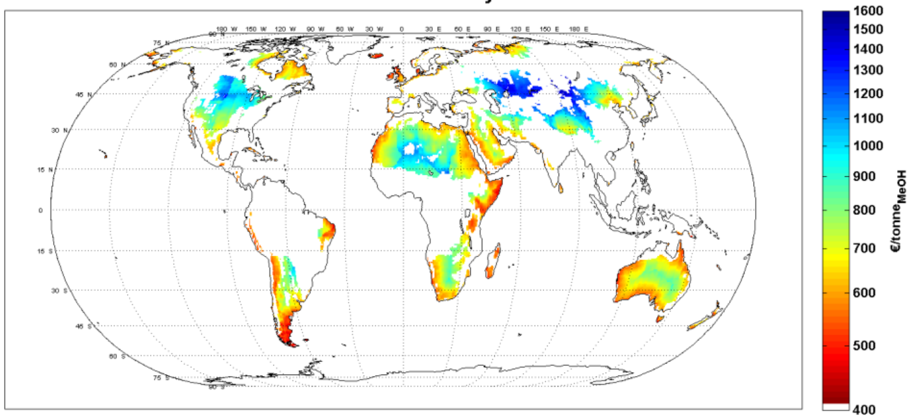


- LCOF as a function of LCOE and FLh of plants' components
- in 2030, top sites in the world reach LCOF of 70 – 80 €/MWh (0.68 - 0.77 €/l for diesel and 27.4 - 31.3 USD/MMBtu for SNG)
- LNG value chain adds 15-20 €/MWh to delivered SNG cost
- regions not so far from coast are generally a better place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

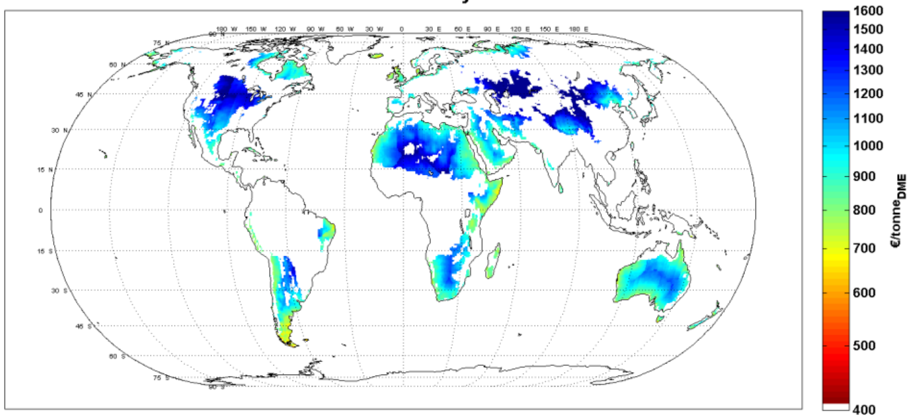
Results

Levelised Cost of Fuels (LCOF)

Cost of Methanol for cost year 2030

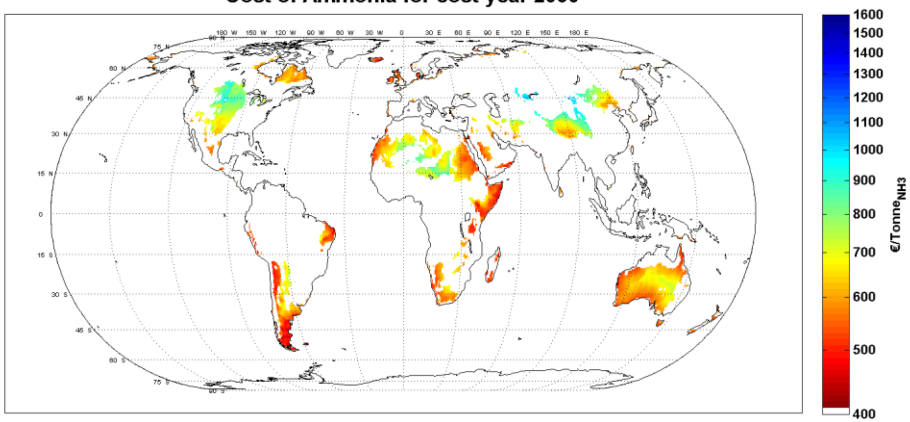


Cost of DME for cost year 2030



- 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

Cost of Ammonia for cost year 2030



Methodology
RE-PtCO_2 Value Chain

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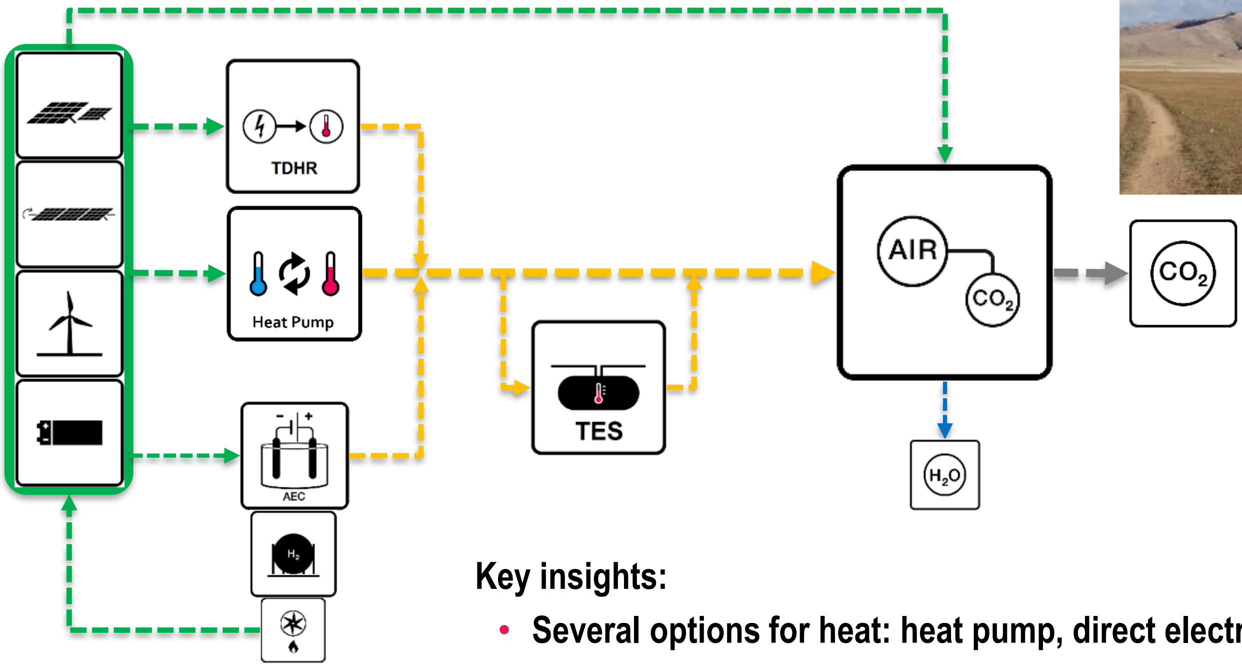


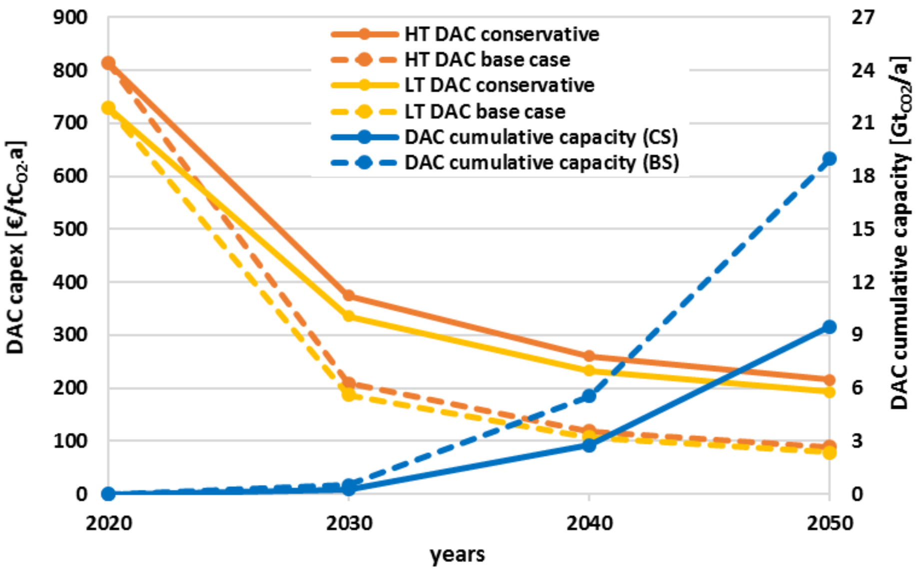
Key insights:

- Several options for heat: heat pump, direct electric heating or waste heat
- PtH_2-H_2tP as a second option for balancing electricity generation and consumption

- Dashed lines represent fluctuating flows
- Continuous lines represent steady flows

LUT Energy System Model

Financial Assumptions: CO_2 DAC



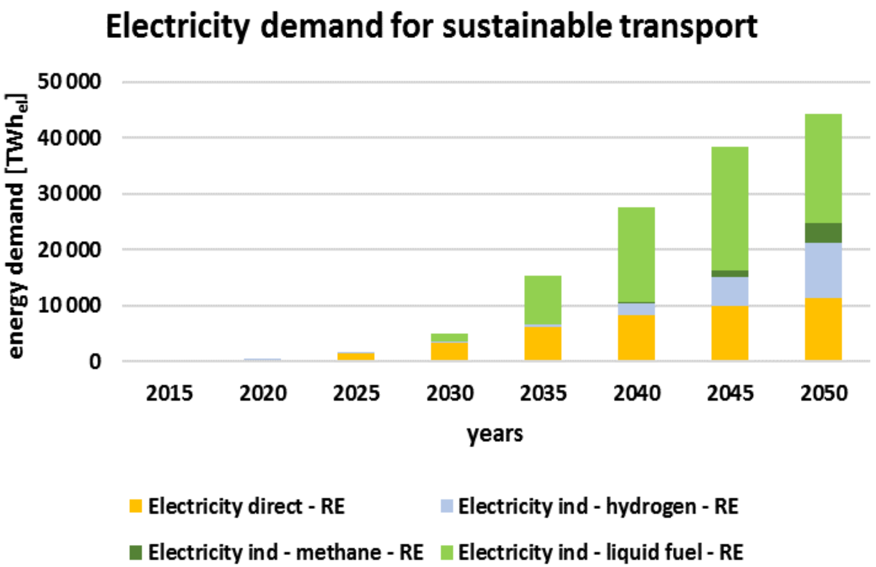
Sector		unit	2020	2030	2040	2050
power	power-to-gas	Mt_{CO_2}/a	3	7	142	363
	waste-to-energy	Mt_{CO_2}/a	0	-17	-99	-165
	sewage plant	Mt_{CO_2}/a	0	n/a	n/a	n/a
transport	road (cars/bus/trucks)	Mt_{CO_2}/a	0	242	1714	844
	rail	Mt_{CO_2}/a	0	6	67	75
	marine	Mt_{CO_2}/a	0	58	1137	3568
	aviation	Mt_{CO_2}/a	0	54	1120	3490
industry	chemical industry	Mt_{CO_2}/a	0	220	1054	2753
	pulp and paper	Mt_{CO_2}/a	0	-8	-52	-95
	cement mills (limestone)	Mt_{CO_2}/a	0	-69	-425	-607
	others	Mt_{CO_2}/a	0	n/a	n/a	n/a
CO_2 DAC, energy system		Mt_{CO_2}/a	**3.0**	**494**	**4658**	**10227**
CO_2 removal		$Mt_{CO_2,captured}/a$	0	0	1000	10000
other Negative Emission Technologies		$Mt_{CO_2,captured}/a$	0	0	200	2000
CO_2 DAC, CO_2 removal		Mt_{CO_2}/a	**0**	**0**	**876**	**8760**
CO_2 DAC, total		Mt_{CO_2}/a	**3**	**494**	**5534**	**18987**

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., 2018. Techno-economic assessment of CO_2 direct air capture plants, submitted

Business Opportunities



Key insights:

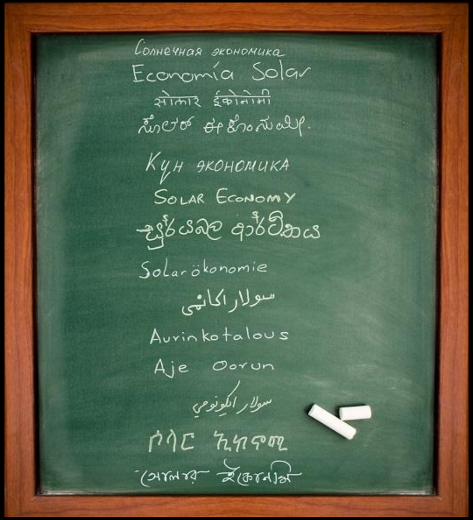
- Electricity direct: this only works with Lithium batteries and best Lithium resources are in Latin America
- Electricity indirect for liquid fuels (marine/ aviation) is most competitive for least cost of electricity, which is Patagonia (wind) and Atacama (solar), again globally
- Synthetic fuels can be globally traded as a commodity product
- All forms of indirect electricity use in transport sector are hydrogen based, hence a global liquefied hydrogen trade would enable Latin America to establish a HUGE global export business

- Not to forget:
- Hydrogen will be also needed for defossilisation of the global iron & steel and chemical industry
- The markets are outstanding HUGE for least cost electricity, if transformed to the products needed

Key takeaways

- Climate Change forces a drastic and fast change of the energy system
- 100% renewable energy is technically feasible and economically viable
- Full hourly resolved modeling ensures energy supply throughout the year
- Key energy system components are solar PV, wind energy, batteries, PtX (incl. CCU)
- PV will emerge to the dominating source of energy in this century
- Energy transition to 100% RE eliminates GHG emissions, reduces cost and creates jobs
- Electricity demand will drastically rise due to broad electrification of the energy system
- Latin America owns the best resources in the world for solar, wind, hydro and lithium!!
- Energy-intensive products have the least cost globally in Latin America in 21st century!!
- Almost no one understood so far what 10 USD/MWh electricity cost really means
- Enormous economic rise is possible, if good governance allows harvesting of benefit
- Substantially more studies are needed to better understand the comparative competitiveness

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



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

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100% RE Scenarios: Country to Global

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Breyer et al., 100% RE articles in journals

Plessmann et al.	2014	J	Global, ON
Moeller et al.	2014	J	Berlin-Brandenburg, ON
Bogdanov & Breyer	2015	J	Northeast Asia, ON
Bogdanov & Breyer	2016	J	Northeast Asia, improved, ON
Child & Breyer	2016	J	Finland, ON
Barbosa et al.	2016	J	Brazil, ON
Gulagi et al.	2017	J	Southeast Asia, ON
Barbosa et al.	2017	J	South America, ON
Breyer et al.	2017	J	Global, ON
Gulagi et al.	2017	J	East Asia, ON
Aghahosseini et al.	2017	J	North America, ON
Gulagi et al.	2017	J	India/ SAARC, ON
Caldera et al.	2017	J	Saudi Arabia, ET
Ghorbani et al.	2017	J	Iran, ET
Child et al.	2017	J	Ukraine, ET
Gulagi et al.	2017	J	India, ET
Child et al.	2017	J	Åland, ON
Gulagi et al.	2017	J	India, monsoon, ET
Caldera et al.	2018	J	Saudi Arabia, water, ET
Kilickaplan et al.	2017	J	Turkey, ET
Breyer et al.	2017	J	Global, ET
Barasa et al.	2018	J	Sub-Saharan Africa, ON
Aghahosseini et al.	2018	J	Iran, ON
Sadiqa et al.	2018	J	Pakistan, ET
Meschede et al.	2018	J	La Gomera, ON
Caldera & Breyer	2018	J	Saudi Arabia, desalination, ET
Bogdanov et al.	2018	J	Northeast Asia, ET, accepted
Oyewo et al.	2018	J	Sub-Saharan Africa, Grand Inga, ON
Solomon et al.	2018	J	Israel, ET
Child et al.	2018	J	Åland, ET – V2G
Oyewo et al.	2018	J	Nigeria, ET

Breyer et al., related topics, articles in journals

Blechinger et al.	2014	J	Islands
Breyer et al.	2015	J	PtX: PtG value chains
Breyer et al.	2015	J	CO_2 reduction benefits
Cader et al.	2016	J	off-grid: PV-battery-diesel
Caldera et al.	2016	J	PtX: RE-based desalination
Görig & Breyer	2016	J	Energetic learning curves of PV
Blechinger et al.	2016	J	Islands
Koskinen & Breyer	2016	J	Storage in global scenarios
Fasihi et al.	2016	J	PtX: power-to-liquids
Afanasyeva et al.	2016	J	Battery and hybrid PV plants
Breyer et al.	2017	J	Rebalancing within limits of Earth
Farfan & Breyer	2017	J	Global power plant databasis
Raugei et al.	2017	J	EROI of PV systems
Fasihi et al.	2017	J	PtX: Hydrocarbons from Maghreb
Child & Breyer	2017	J	Transition and Transformation
Breyer et al.	2017	J	CSP vs hybrid PV-battery plants
Solomon et al.	2017	J	Storage demand
Bertheau et al.	2017	J	Electrification in Sub-Saharan Africa
Caldera & Breyer	2017	J	PtX: RO desalination learning curve
Horvath et al.	2018	J	Defossiliated marine sector
Azzuni & Breyer	2018	J	Energy security
Child et al.	2018	J	Sustainability guardrails in scenarios
Brown et al.	2018	J	Review on feasibility of 100% RE
Aghahosseini et al.	2018	J	CAES resource potential
Ram et al.	2018	J	Comparing RE to fossil-nuclear in G20
Afanasyeva et al.	2018	J	Relevance of tracking PV for ET scenarios

Abbreviations: OverNight scenario (ON), Energy Transition scenario (ET), peer-reviewed journal publication (J)