




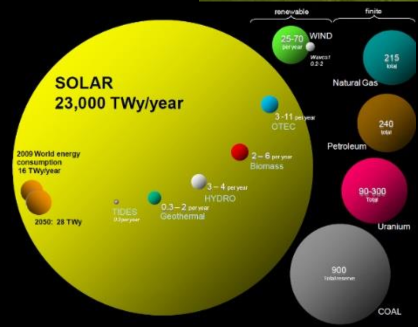

100% Renewable Energy Systems in Europe

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Lappeenranta University of Technology

Christian Breyer
Professor for Solar Economy

100% Renewable UK
Webinar, September 3, 2021

Agenda

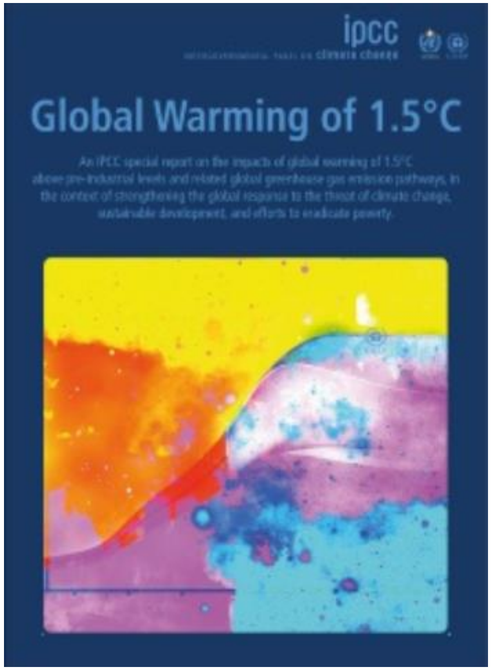
- General Aspects
- European Energy Transition
- Special Aspects
- Summary

Background

European Green Deal

Paris Agreement

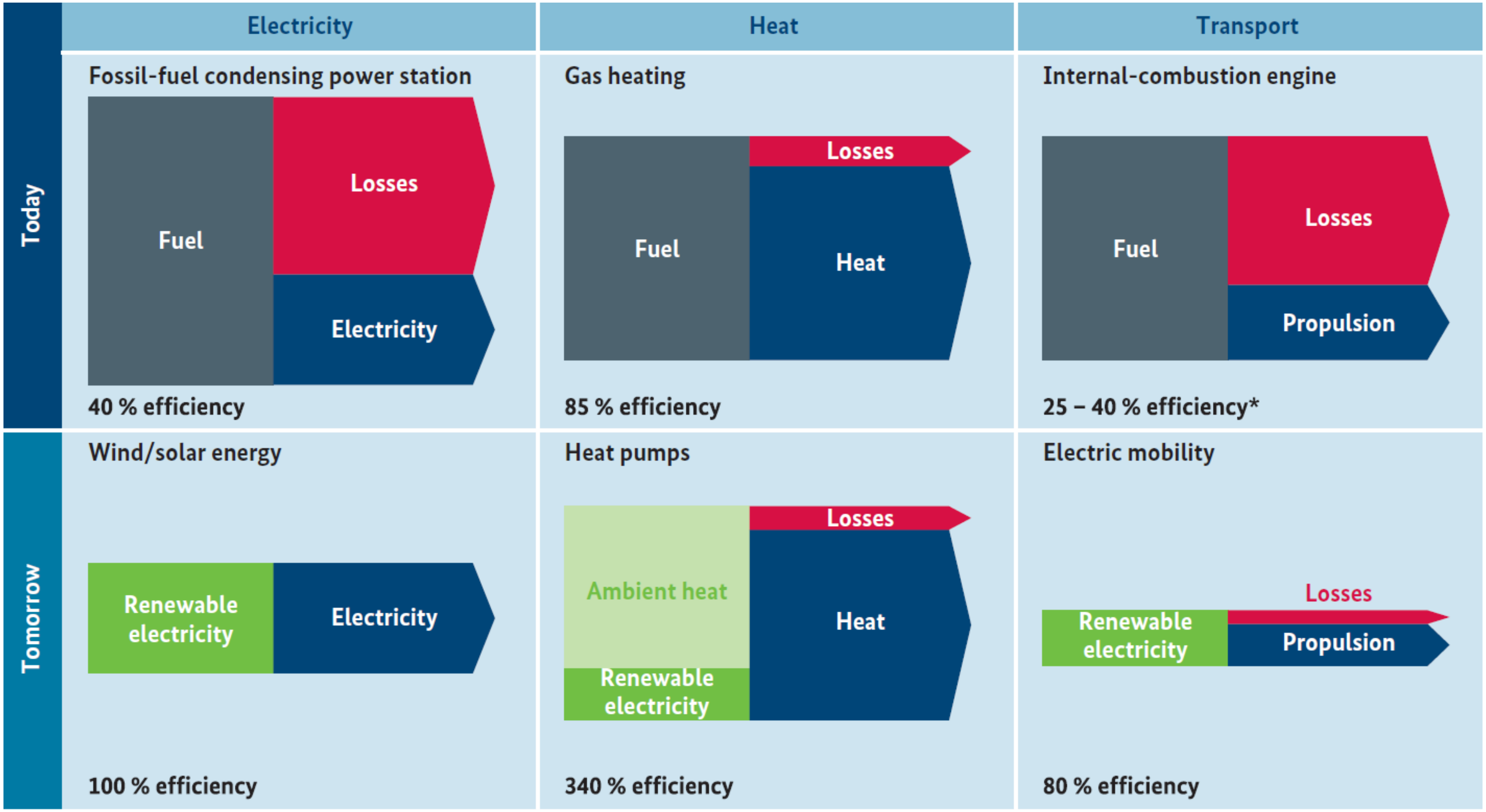
("well below 2°C")



What does it mean?

- (net) zero greenhouse gas (GHG) emissions by 2050 are mandatory
- negative GHG emissions are costly, risky, with unclear responsibilities
- thus zero GHG emissions is the real target for the energy system

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]

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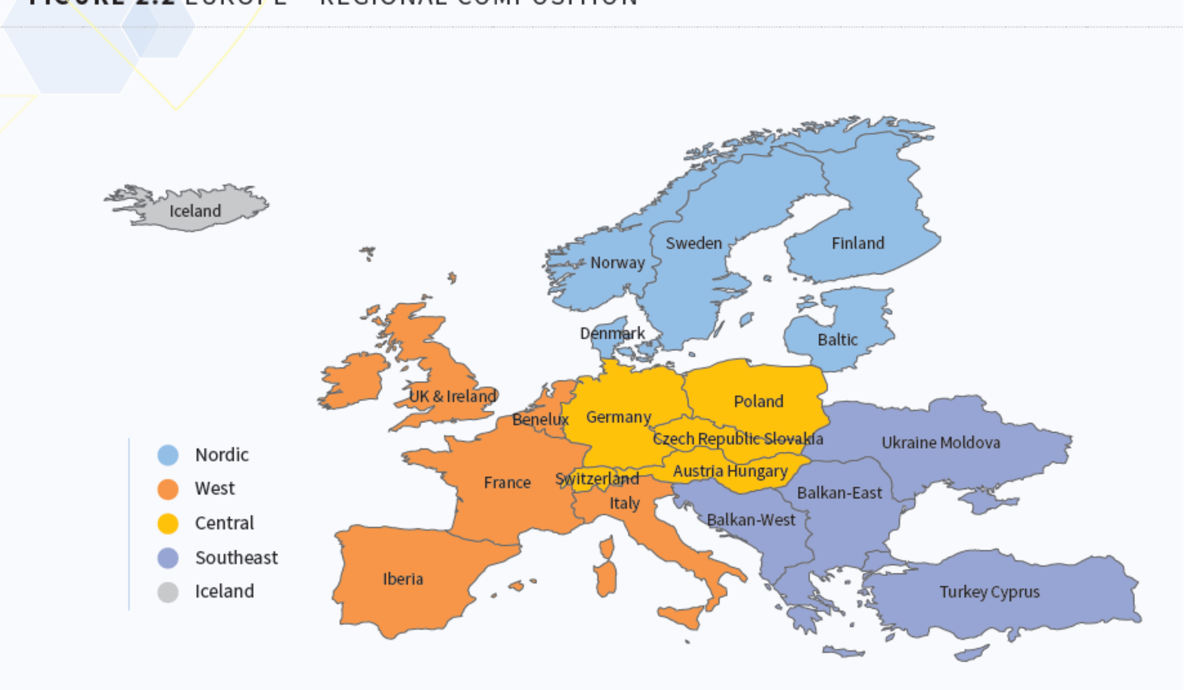
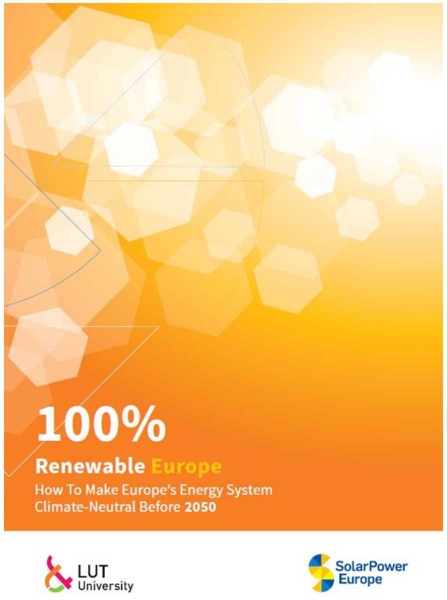
100% Renewables in Europe before 2050

FIGURE 2.2 EUROPE – REGIONAL COMPOSITION





[link to report]

Key insights:

- the following results refer to a recent study of LUT and SolarPower Europe
- Europe in this report refers to EU-27 plus Iceland, UK, Turkey, Ukraine, Switzerland, Norway, all Balkan countries
- the energy system comprises: power, heat, transport, industry; excluding non-energetic fuels demand

Scenario Overview

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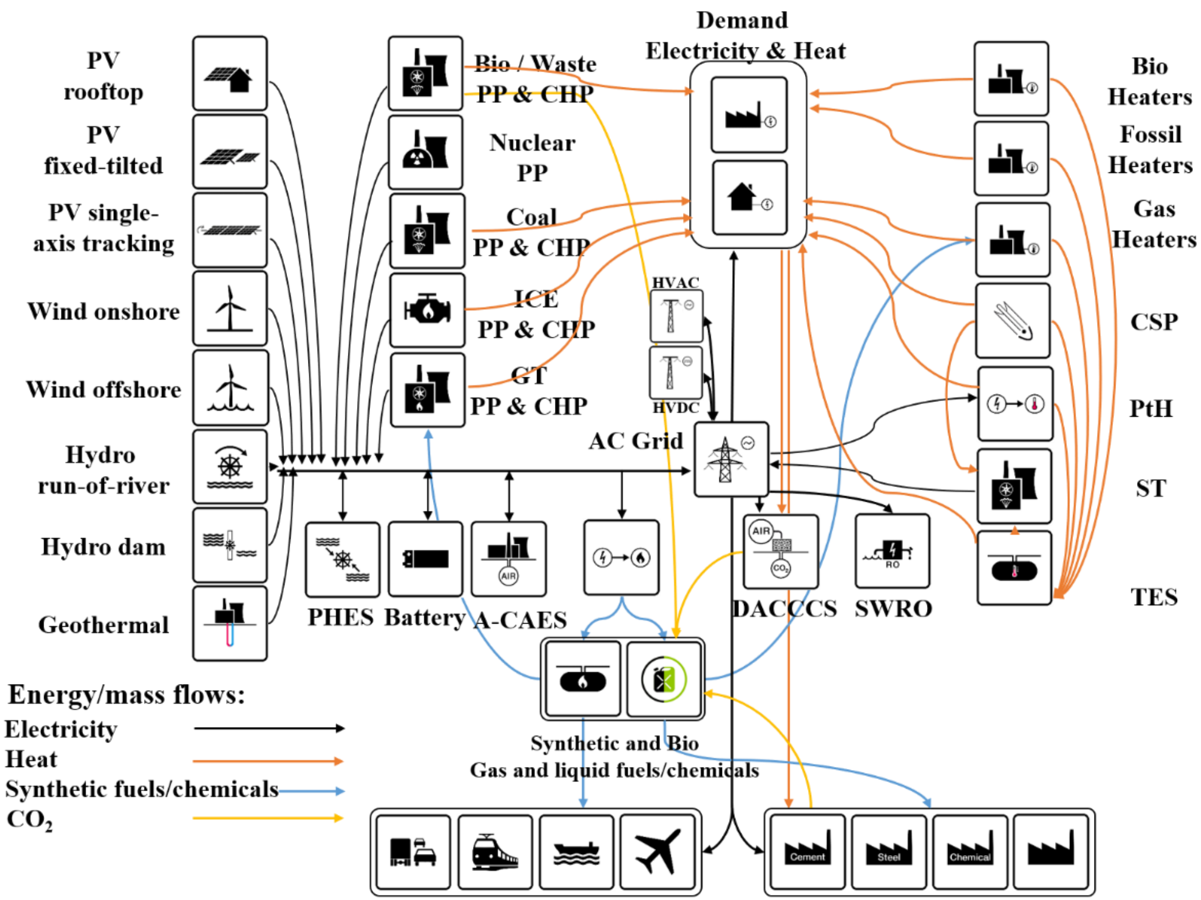
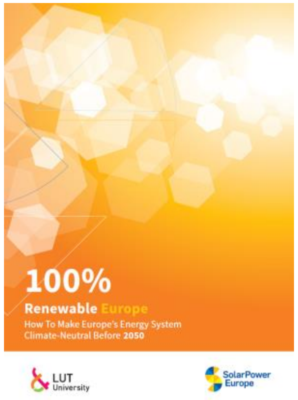
	LAGGARD	MODERATE	LEADERSHIP
RE energy share	62% by 2050	100% by 2050	100% by 2040
Paris Agreement	✕	Achieved 2.0°C	Achieved 1.5°C
GHG emissions in the energy system	-90% in 2050	-100% in 2050	-100% in 2040
Fossil fuels phaseout	✕	Achieved in 2050	Achieved in 2040
Nuclear phaseout	✕	✕	Achieved in 2040

LUT Energy System Transition Model



recent reports



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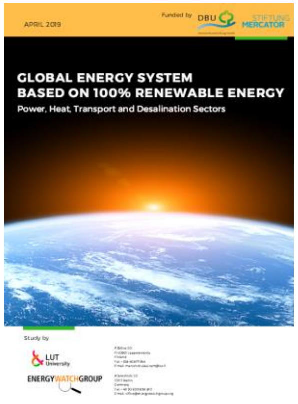

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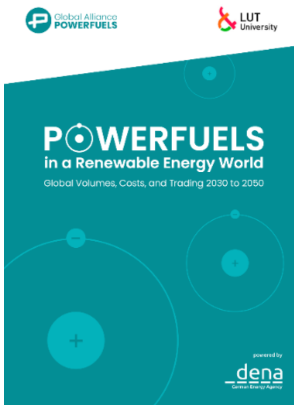


[link to report]

Key features:

- full hourly resolution, applied in global-local studies, comprising about 120 technologies
- used for several major reports, in about 50 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (mobility, heat, fuels, chemicals, desalinated water, CO_2)

source: Bogdanov et al., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, 283, 116273

Primary Energy Demand: Fuel Use

FIGURE 3.7 PRIMARY ENERGY SUPPLY - FUEL USE

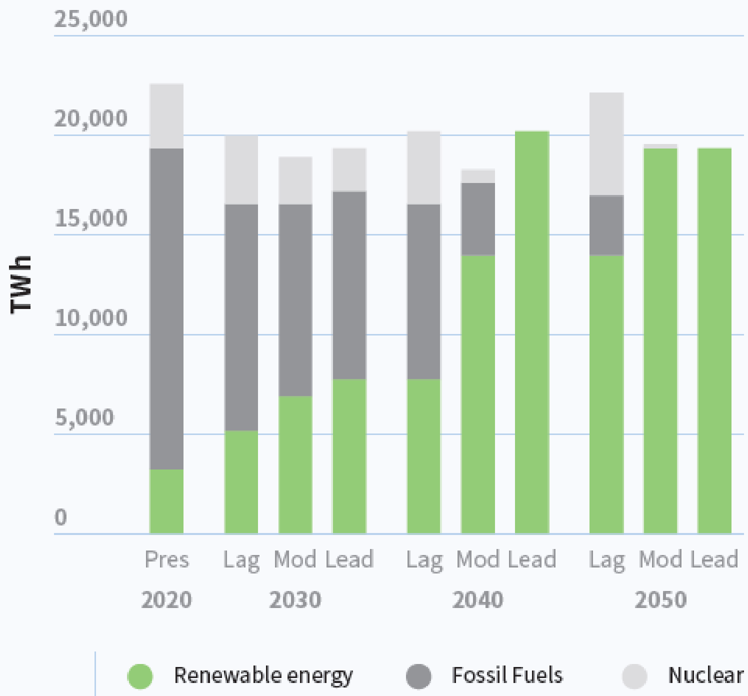
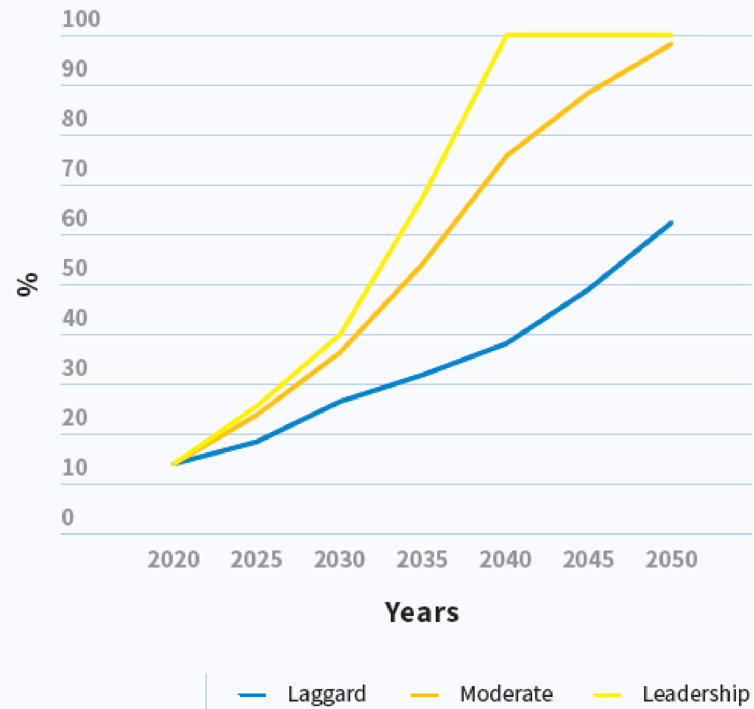


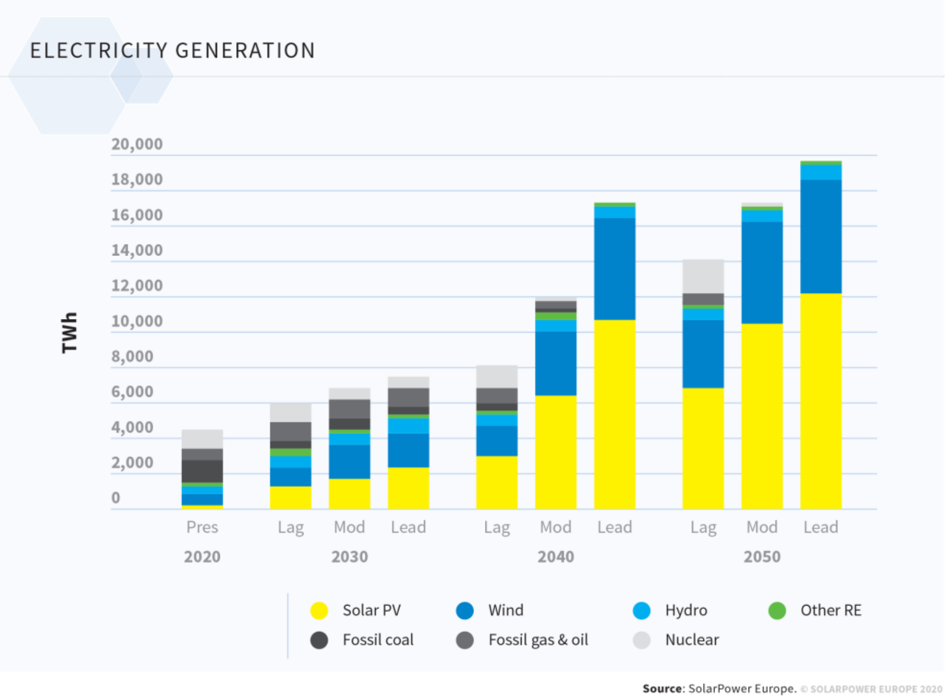
FIGURE 3.8 RENEWABLE ENERGY SHARE OF PRIMARY ENERGY SUPPLY



Key insights:

- High rate of electrification is essential to achieving a 100% renewable and integrated energy system
- Combustion processes are a burden for an efficient energy system, well documented by Laggard

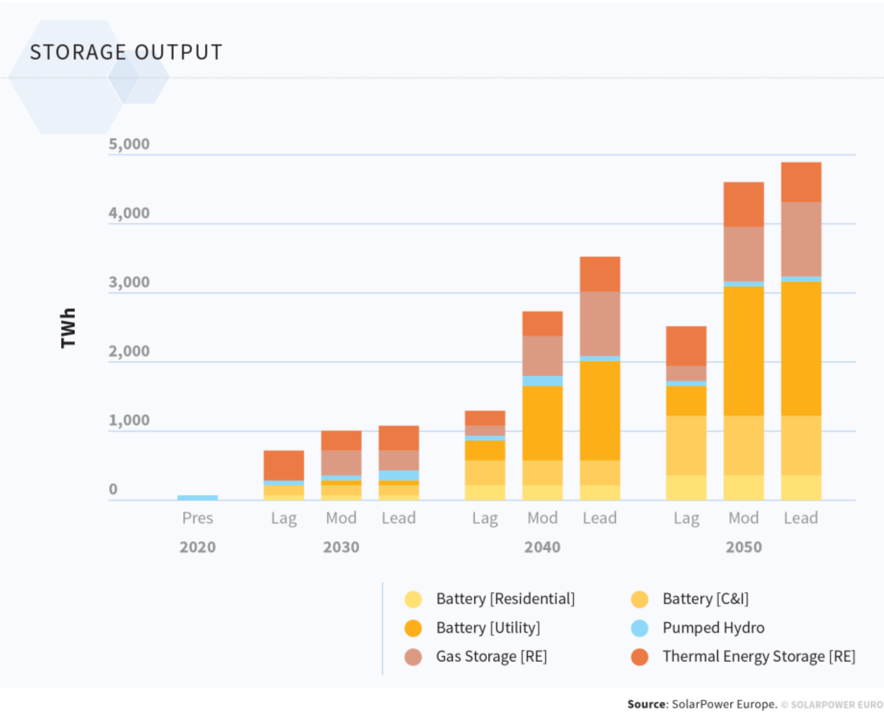
Electricity Generation and Heat Supply

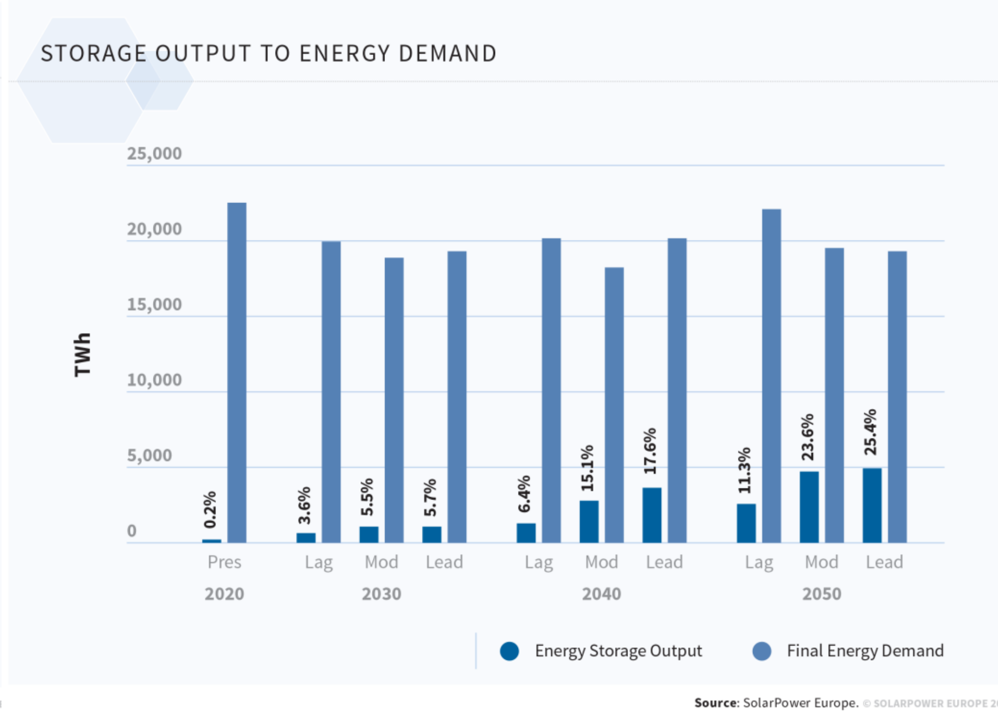


Key insights:

- As of 2040, solar PV will become the dominant source of electricity generation across the three scenarios, and by 2050 it will reach at least 48% in the Laggard scenario and up to 63% in the Leadership scenario
- Solar PV economics perform excellently, while benefiting from low-cost storage and Power-to-X flexibility
- Heat pumps emerge as core part of a 100% renewable system, with over 60% share of heat generation by 2050

Storage Output and Energy Demand



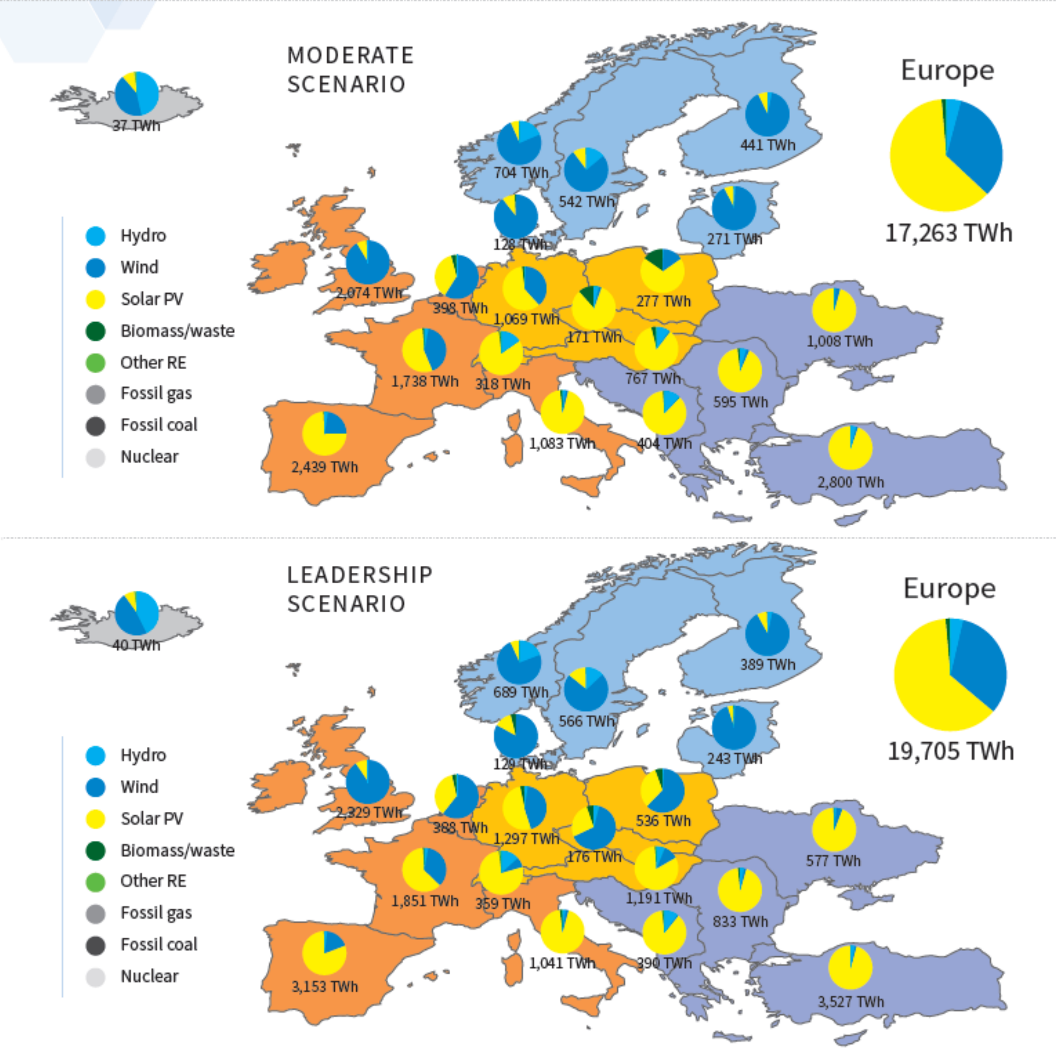


Key insights:

- Batteries provide the bulk of energy storage in a 100% renewable energy system
- Only little seasonal storage is needed in a 100% renewable system, due to vast flexibility in sector coupling and broad electrification
- Full sector coupling and high electrification rates keep the growth of storage output up to 25% of final energy demand in 2050

Regional Electricity Capacities in 2050

FIGURE 4.2 REGIONAL ELECTRICITY GENERATION IN 2050 ACROSS EUROPE

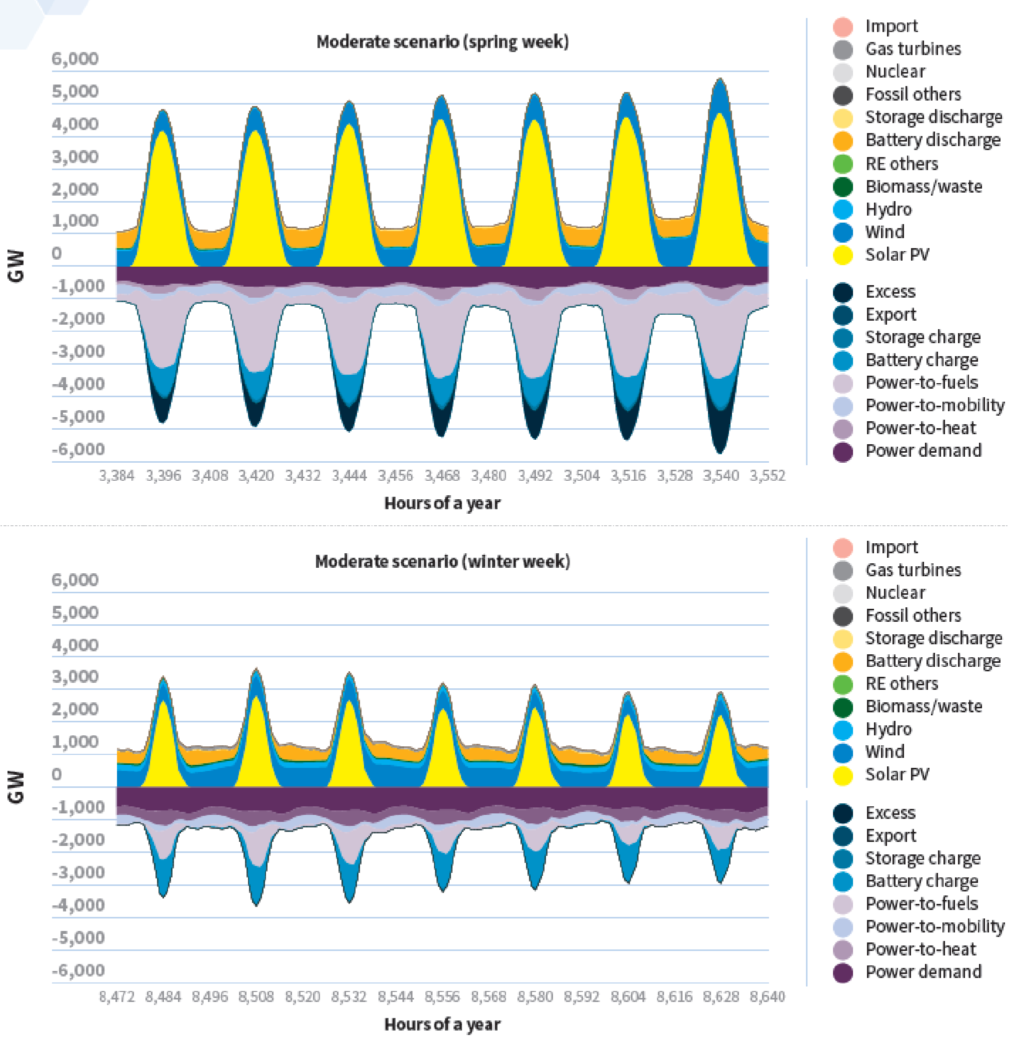


Key insights:

- Full sector coupling provides energy security for Europe, with PV capacities predominantly located in the southern regions, while wind energy systems are mainly installed in the northern and western regions of Europe
- Leadership requires more electricity than Moderate, since more combustion processes have to be covered by 2040 due to failed investments in 2010s and 2020s
- Export of synthetic fuels in 2040s may lead to net-negative GHG emissions in Europe
- Faster transition requires more wind, slightly delayed transition leads to more solar PV, see for instance Germany
- Curtailment is 4-5%, while 15% cross-border trade

Hourly Operation of the Energy System

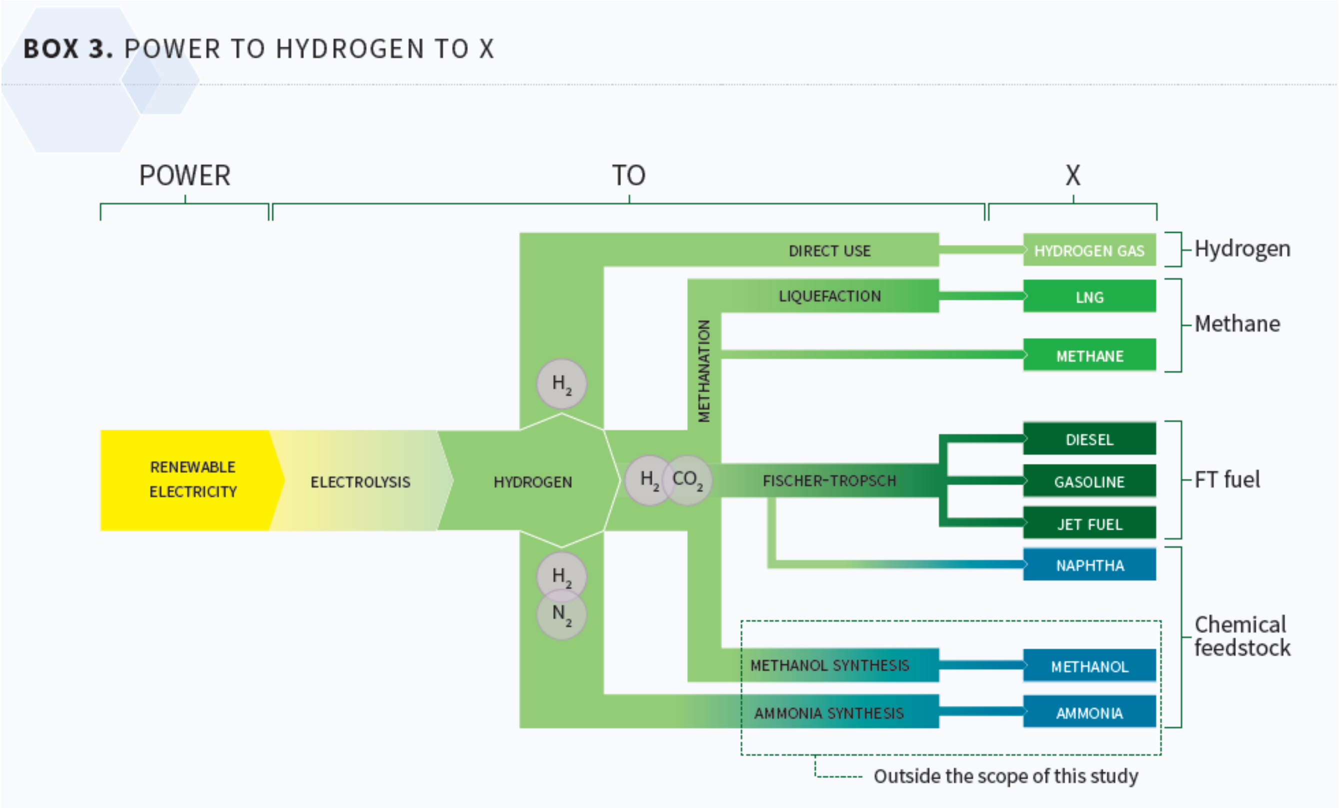
FIGURE 4.8 HOURLY OPERATION OF THE EUROPEAN ENERGY SYSTEM



Key insights:

- Week of least renewables supply (winter) and most renewables supply (spring) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the country easily copes with energy demand
- Key balancing component are electrolysers (Power-to-fuels) which convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability
- Massive ramp rates in the energy system have to be managed, as well as forecasting errors require balancing

Power-to-X: the Core of Sector Coupling



Key insights:

- **Power-to-X comprises: Mobility, Fuels, Chemicals, Heat, Steel, Desalinated Water**
- **Hydrogen is ONLY required, where direct electrification fails, e.g. chemicals, fuels for aviation/ marine**

100% Renewable Energy Systems
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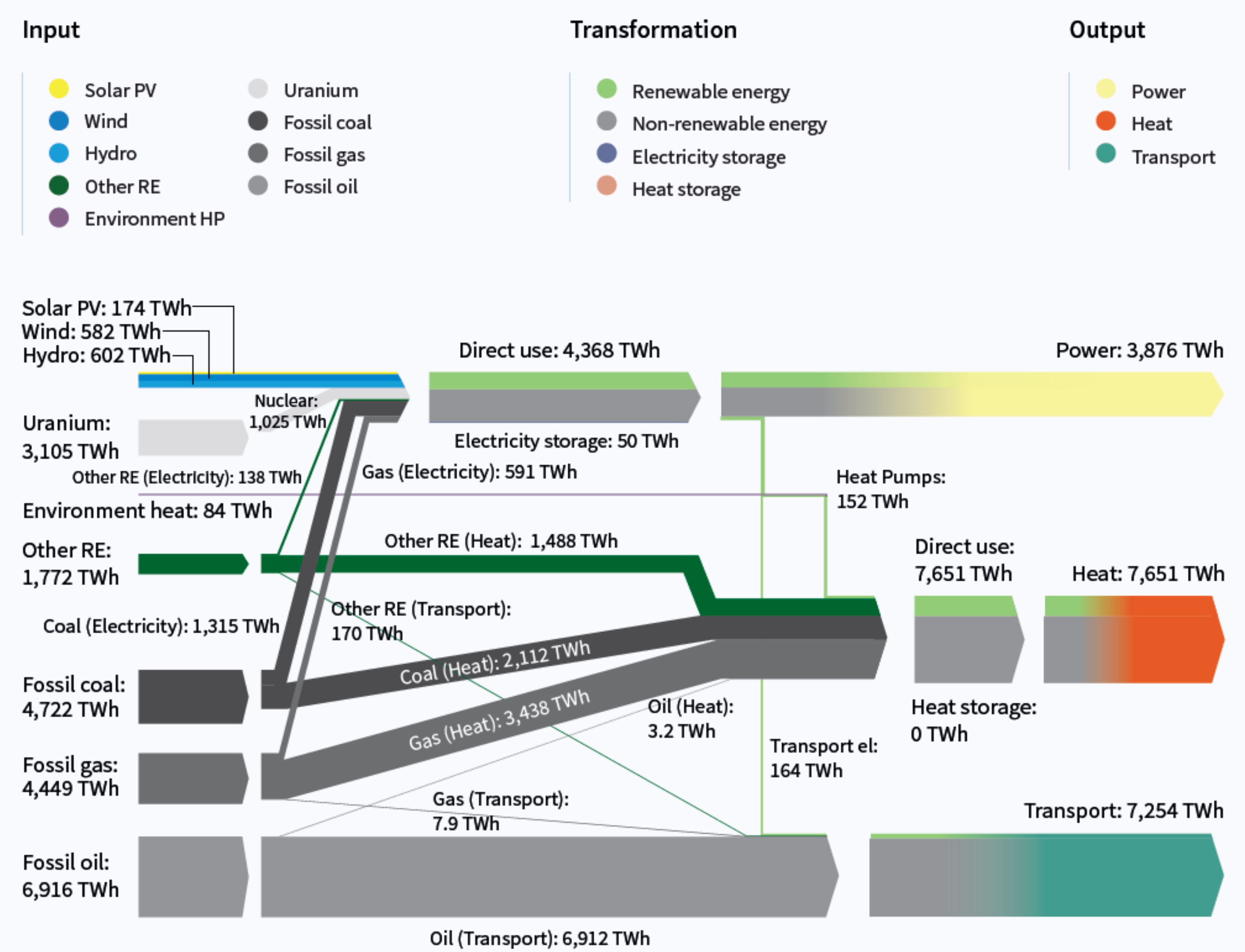
Energy System Structure: present

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020

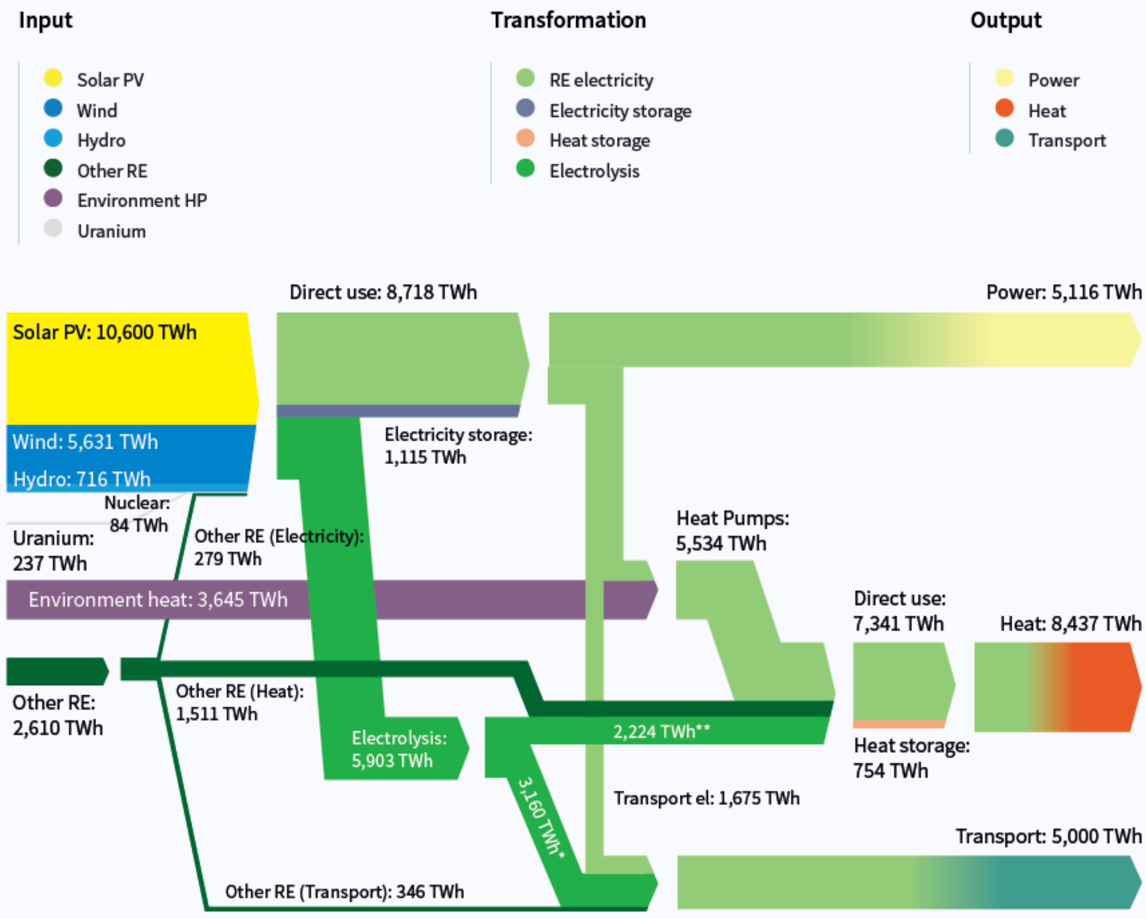


Key insights:

- Energy sectors (power, heat, transport) practically separated
- Dominating role of fossil fuels
- Transport sector has practically not yet started the transition

Energy System Structure: future

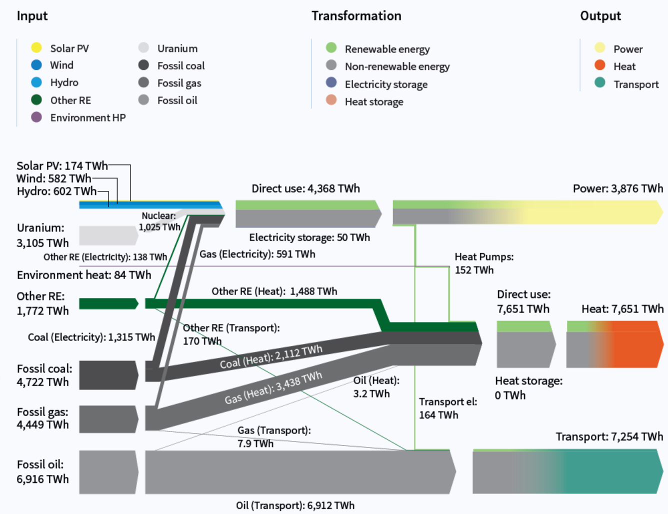
FIGURE 3.25 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN THE MODERATE SCENARIO IN 2050



*RE synthetic fuels for transport.

**RE synthetic fuels for heat, recovered heat.

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020



Key insights:

- 100% renewables will lead to strongly coupled energy system
- Most important energy carrier is electricity, while second most important is green hydrogen
- Fossil and nuclear fuels are not part of a sustainable and least cost energy system

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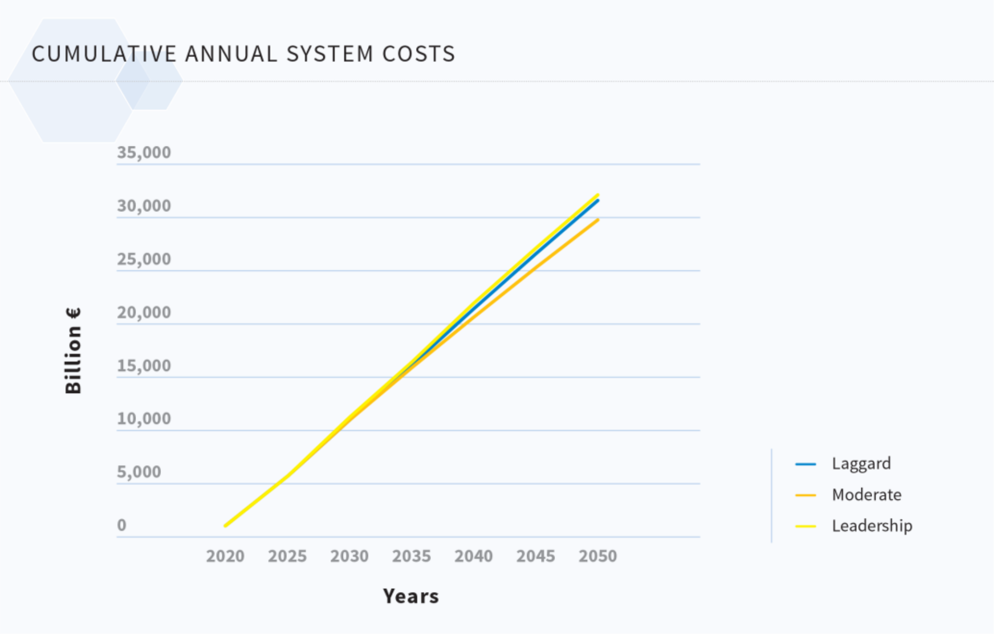
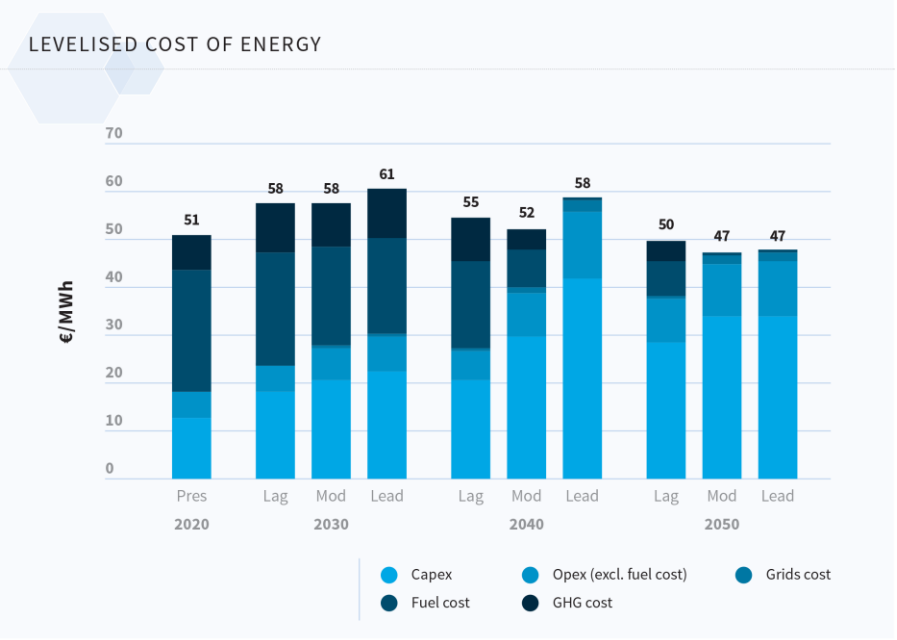
Cumulative Energy System Cost



Source: SolarPower Europe. © SOLARPOWER EUROPE 2020

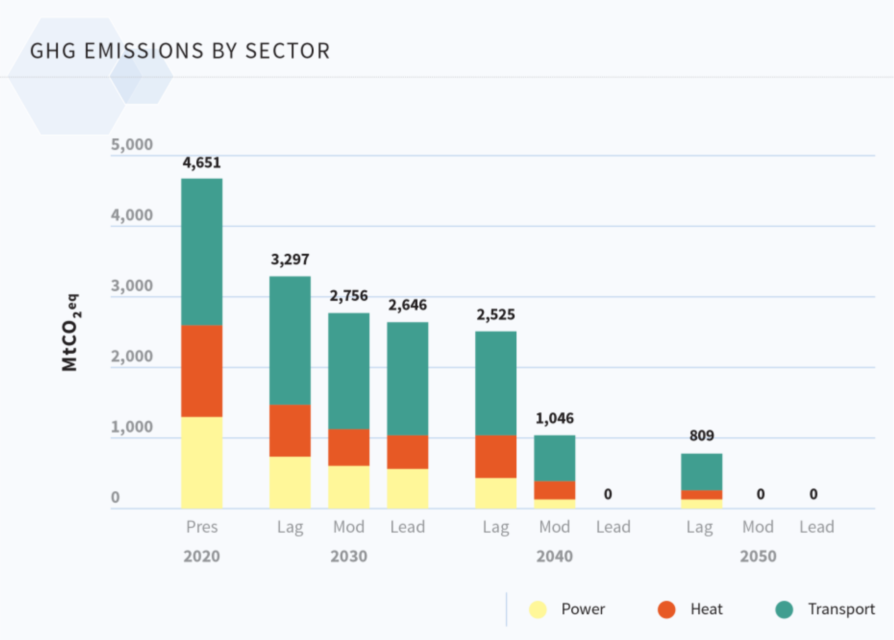


Source: SolarPower Europe. © SOLARPOWER EUROPE 2020

Key insights:

- A 100% renewable energy system is the most cost-efficient way to become climate neutral by 2050: cumulative costs of achieving 100% renewable energy by 2050 in the Moderate scenario are 6% lower than the cost of the less ambitious Laggard scenario
- The Leadership scenario achieves zero GHG emissions by 2040, for slightly higher cost than for a zero GHG emission system by 2050, while it costs practically the same as a delayed transition
- In 2050, the levelised costs of energy in the 100% renewable scenarios are 5–6% lower than costs in a less ambitious scenario, and at the same time 7% more competitive than today's costs

GHG Emissions: per Sector, cumulative



Source: SolarPower Europe.

Source: SolarPower Europe. © SOLARPOWER EUROPE 2020

Key insights:

- A 100% renewable transition triggers the sharpest decline in GHG emissions, decline by over 60% by 2030, and will be down to zero in 2050, or even 2040 in the Leadership scenario. By contrast, Laggard scenario still emits around 800 million tonnes of CO_{2eq} per year by 2050
- The Leadership Scenario has the most positive impact on the climate, resulting in remaining cumulative GHG emissions of only 53 $GtCO_{2eq}$ and down to zero over the next 20 years. Leadership scenario emits 41% and 28% less GHG emissions compared to Laggard and Moderate, respectively

Insights for Europe's ET: Power Sector

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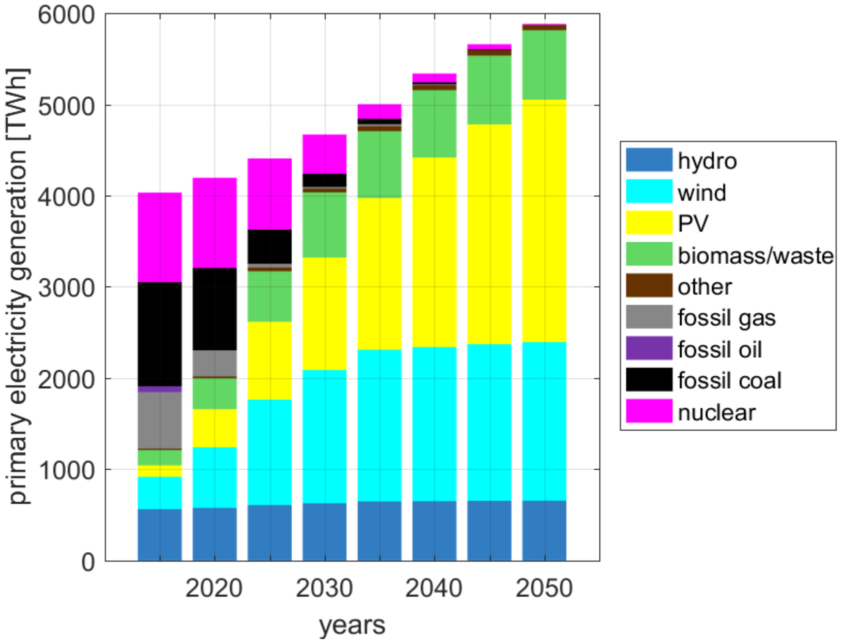

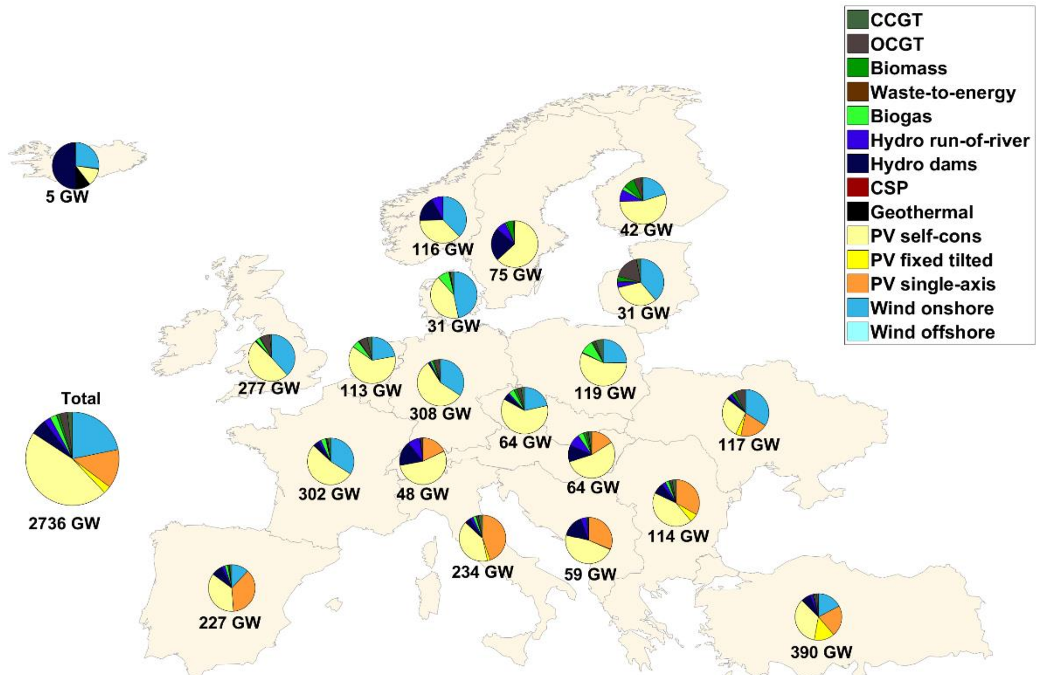

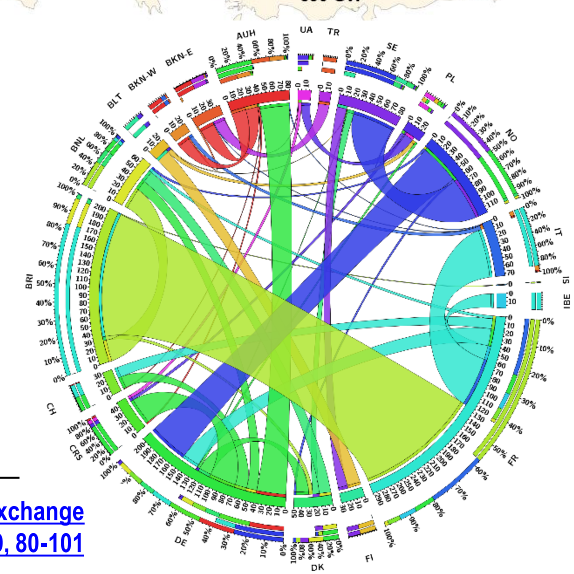

- Two transition pathways for 100% RE are simulated for Europe
- Flexible generation, grid exchange and storage are supportive
- Higher levels of grid interconnection result in lower system cost
- PV prosumers with battery storage reduce need for grids
- Policy and technological development should proceed in a Super Smart Energy System manner

source: Child, Kemfert, Bogdanov, Breyer, 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% RE in Europe, Renewable Energy, 139, 80-101

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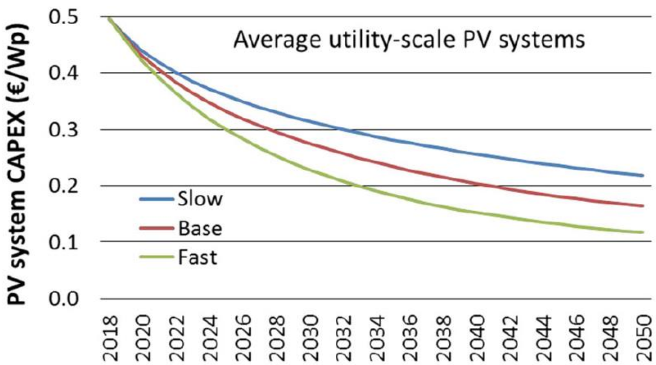
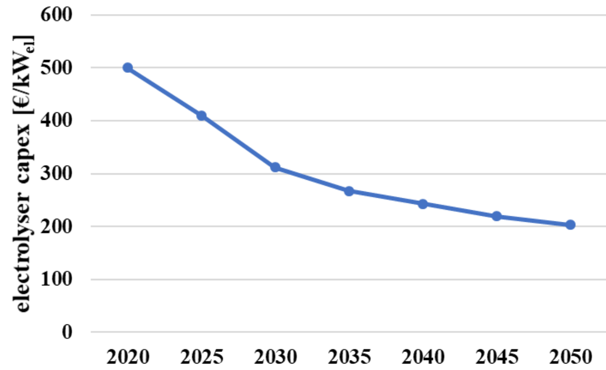
Role of Sector Coupling and Flexibility

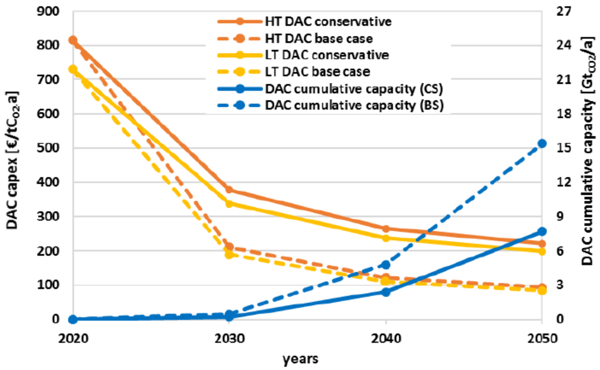
Key insights:

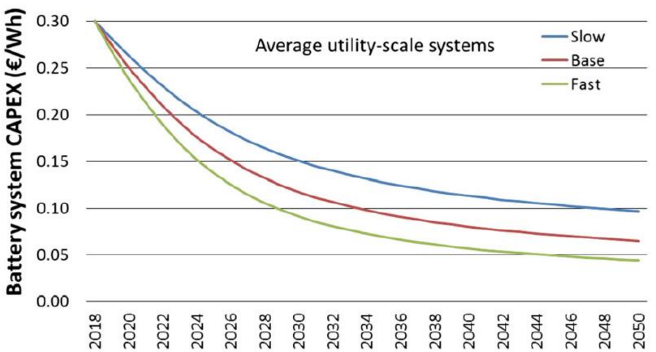
- Power-to-X is the central element of a future energy system, since electricity is the universal platform
- Electricity-based hydrogen emerges to the 2nd relevant energy carrier (for fuels, chemicals)
- **Flexibility in the energy system is key:**
  - **Supply response (hydro dams, bioenergy) for indirect 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

Key diagrams why there will be massive change

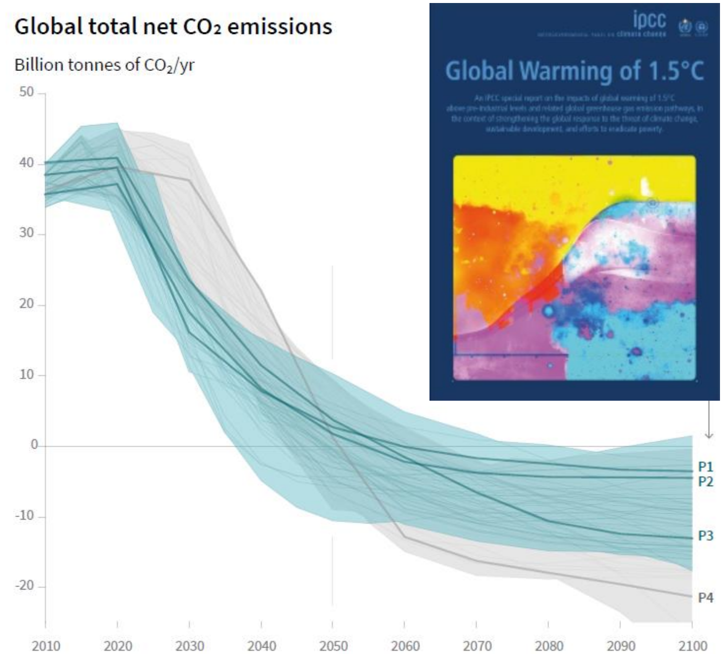








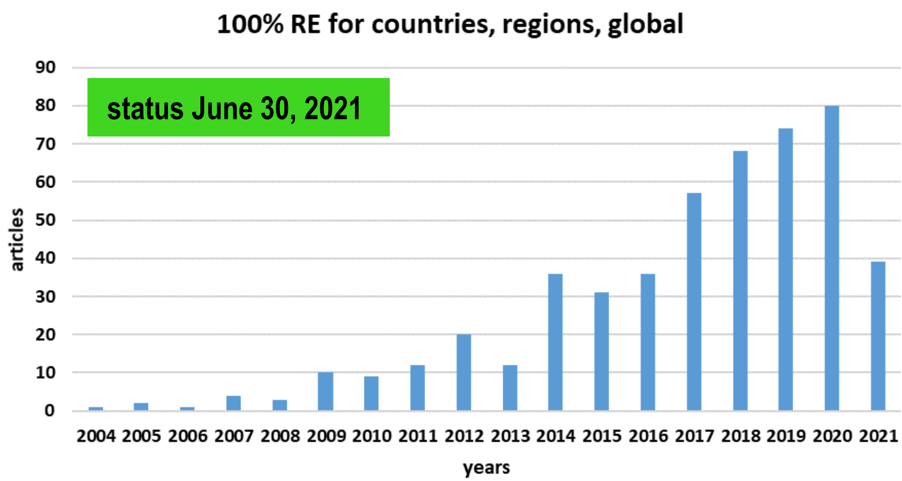
References:
PV, battery: [Vartiainen et al., Progress in PV]
Electrolyser: [LUT model assumptio, Nature]
CO_2 DAC: [Fasihi et al., J of Cleaner Prod]
CO_{2eq} decline: IPCC SR1.5

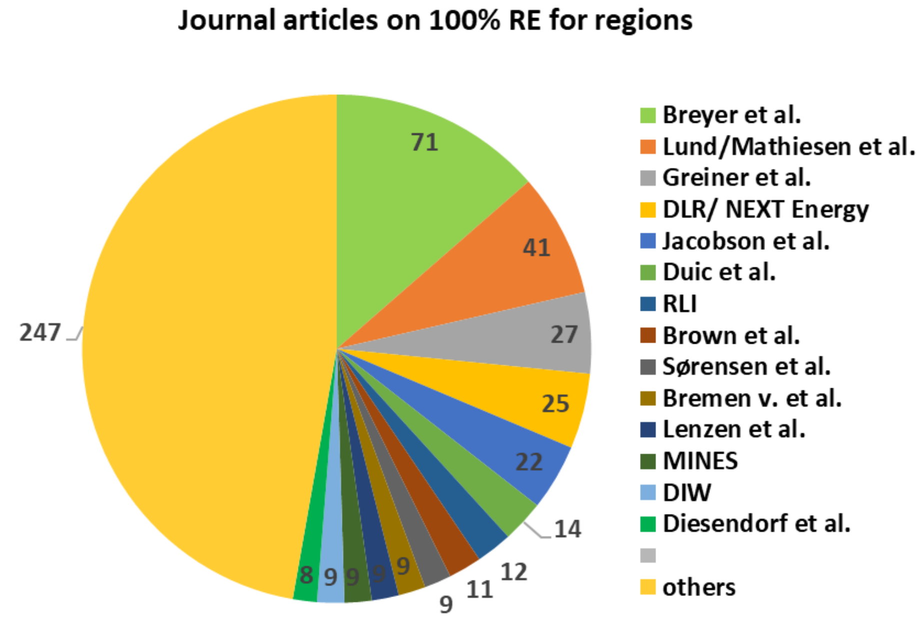


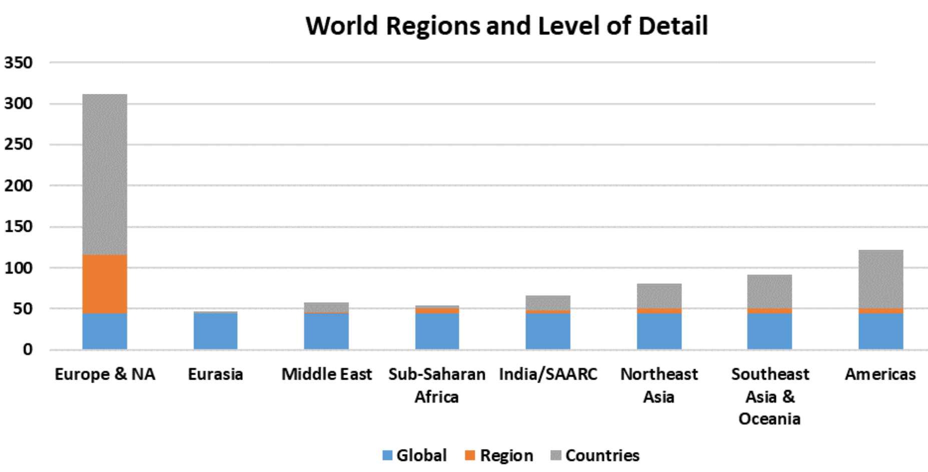
Key insights:

- 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 articles in recent years







Key insights:

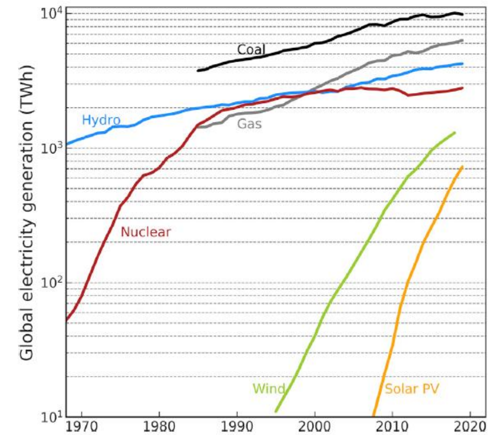
- Research field exists since about 10 years
- Most publications are in hourly resolution
- More multisector publications
- Europe (FI, DK, DE) is hot spot of 100% RE research
- Gaps are in regional coverage and sectoral coverage (industry, NETs), temporal range (21st century)
- Community starts to get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

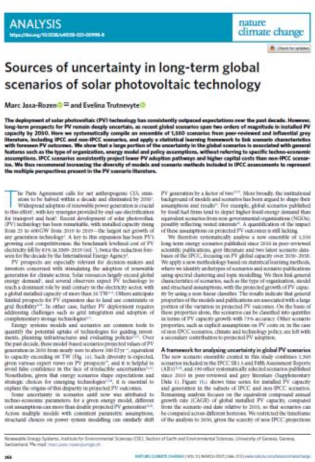
source: Hansen, Breyer, Lund H., 2019. Energy, 175, 471-480

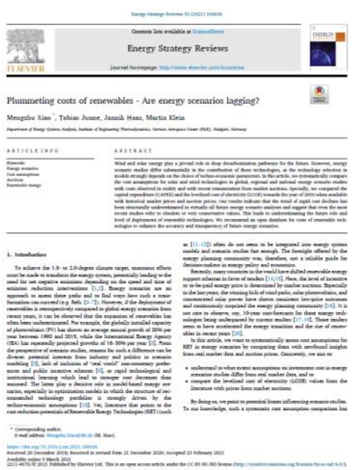
Special Note on solar PV

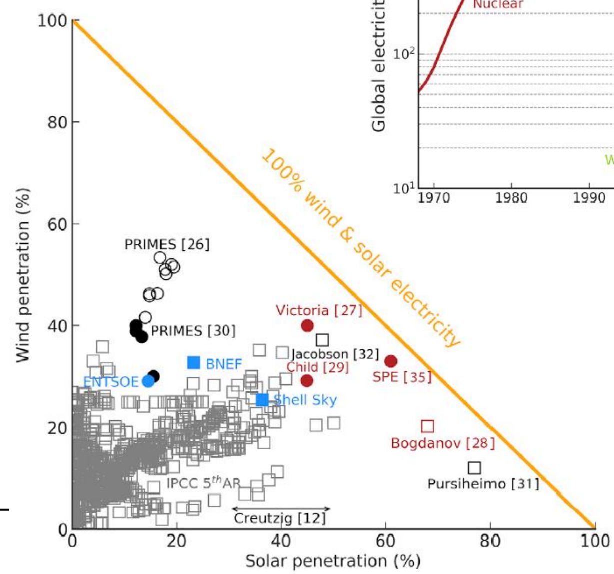
Key insights:

- The severely outdated solar PV costs in energy scenarios, in particular in IPCC (based on IAMs), have been now excellently document in various independent research
- finding 1: IPCC scenarios use highly outdated cost data, worse than non-IPCC scenarios
- finding 2: cost as of today are lower than projected in IPCC/IAMs by 2050
- finding 3: PtX routes are not much used in IPCC/IAMs, due to limited methods and wrong PV costs
- What does it mean?
  - Renewal of IPCC/IAMs for PV & PtX, more diversified scenarios
  - High risk of distorted policies based on IPCC/IAMs results









articles discussing the PV cost issue
[Jaxa-Rozen and Trutnevyte, 2021. Nature Climate Change, 11, 266-273]
[Xiao et al., 2021. Energy Strategy Reviews, 35, 100636]
[Victoria et al., 2021. Joule, in press]

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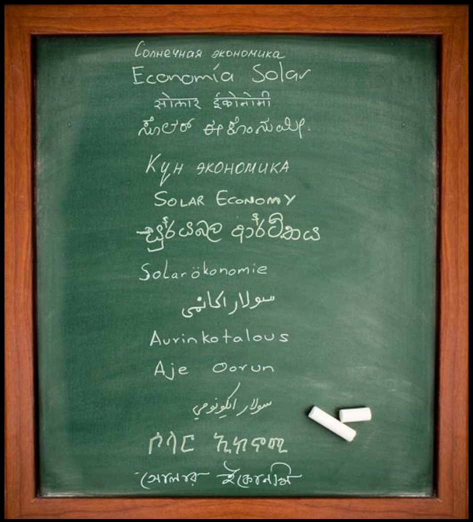
Summary

- Low ambition pathway in Europe is a burden for society, from both a climate change and economic perspective.
- The Moderate scenario modelling zero GHG emissions by 2050 appears to be the most economic pathway.
- A highly ambitious climate change mitigation pathway is possible, which would result in more investments, but with the benefit of lower per unit energy costs as of 2050
- Power-to-X is the central element of a future energy system, while solar PV is the prime source of energy, complemented by wind energy, supported by hydro/bio
- UK energy transition comparable to Europe but with higher wind shares
- 100% renewable energy is a fast growing research field serving societal needs

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



all publications at: www.scopus.com/authid/detail.uri?authorId=39761029000
new publications also announced via Twitter: @ChristianOnRE

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Major milestones on 100% RE research

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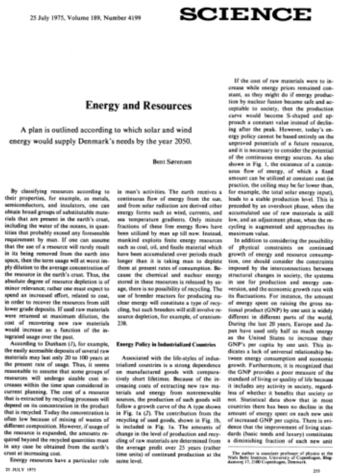
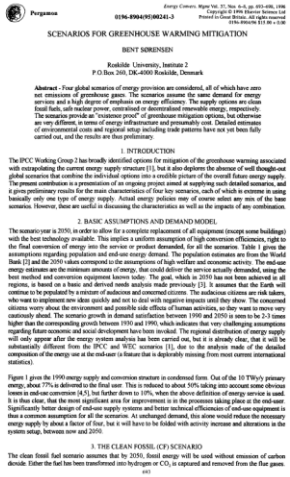
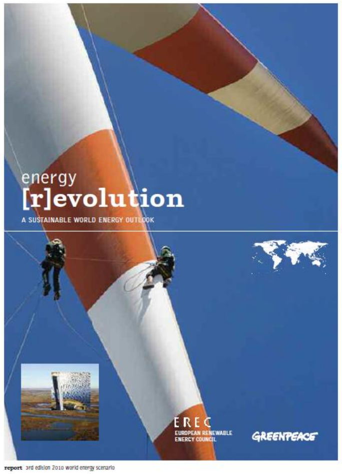
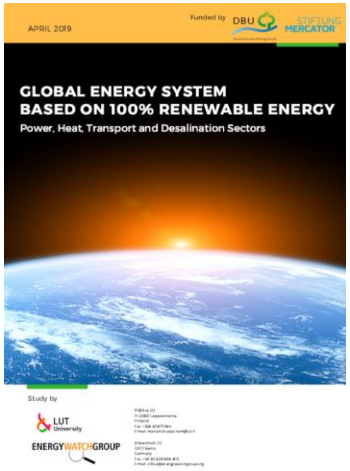


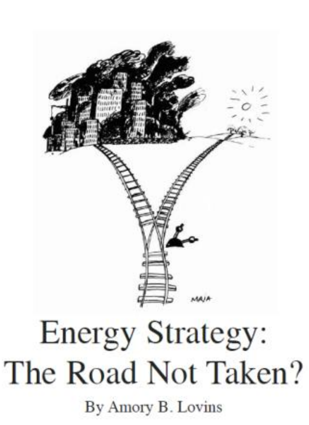


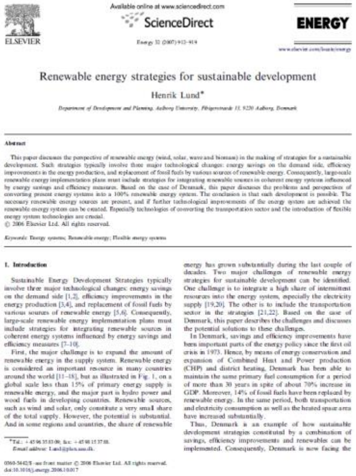


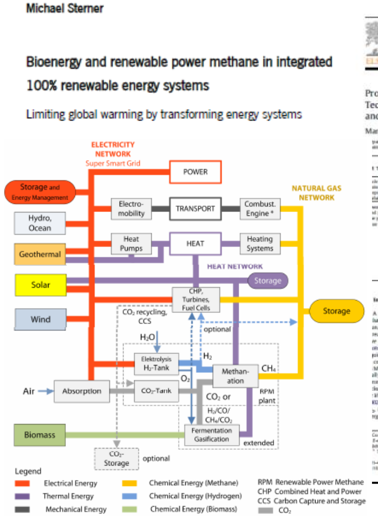


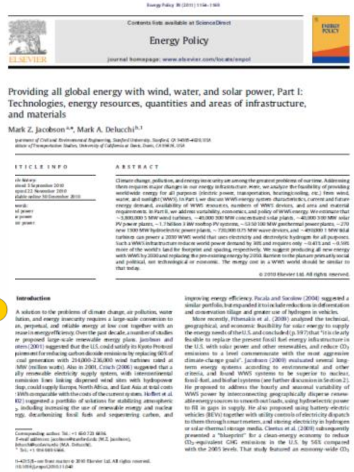
[Sorensen, 1975](#) [Sorensen, 1996](#) [Czisch, 2005](#) [Greenpeace, 2010](#) [LUT/EWG, 2019](#)

[Lovins, 1976](#) [Lund, 2007](#) [Sterner, 2009](#) [Jacobson, 2011](#) [Bogdanov et al. 2019](#)





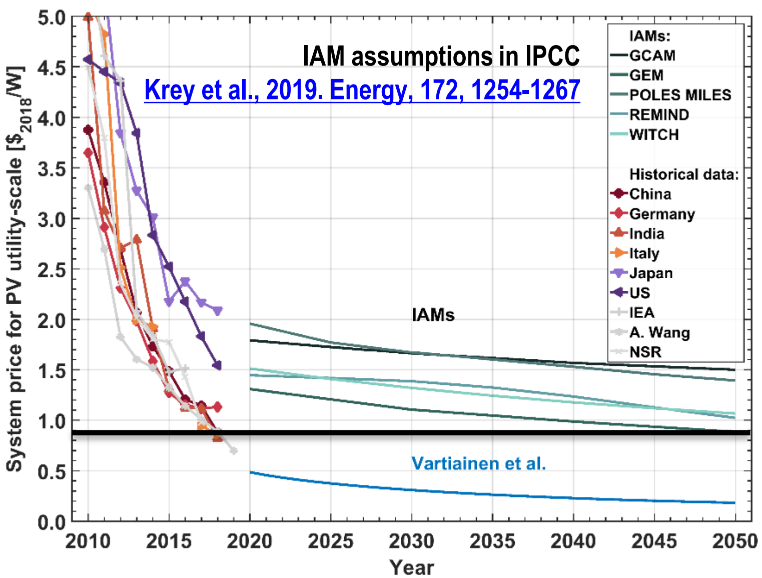




Special Note on solar PV

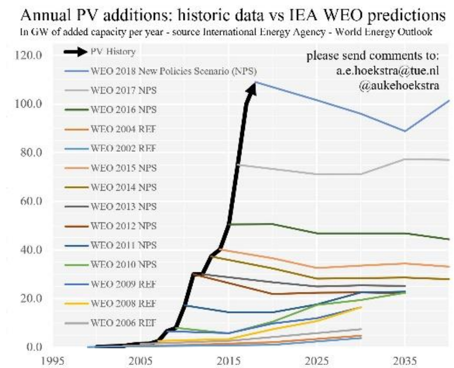
Key insights:

- **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

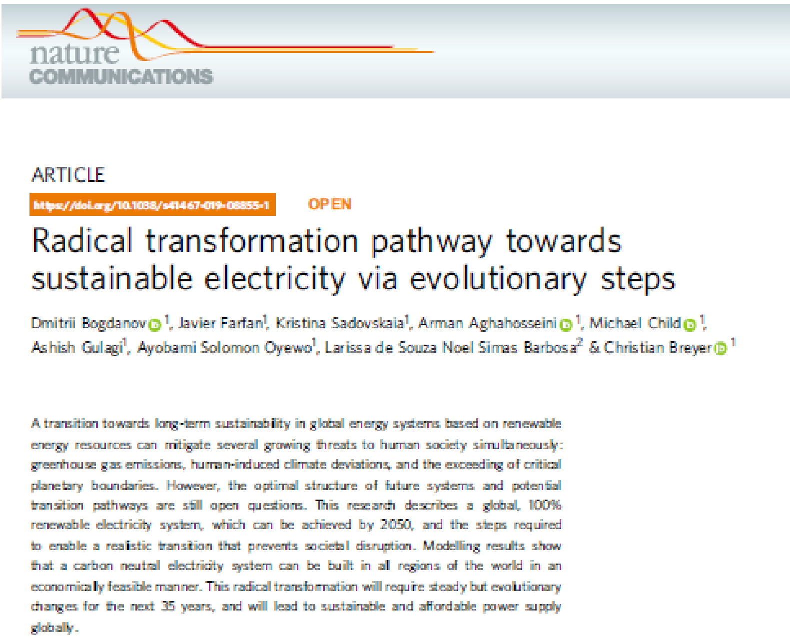


articles based on real PV cost

[Heagel et al. 2019. Science, 364(6443), 836-838]
[Vartiainen et al., 2020. PIP, 28, 439-453]
[Breyer et al., 2018. PIP, 26, 505-523]
[Breyer et al., 2017. PIP, 25, 727-745]



100% RE for Power Sector


nature COMMUNICATIONS

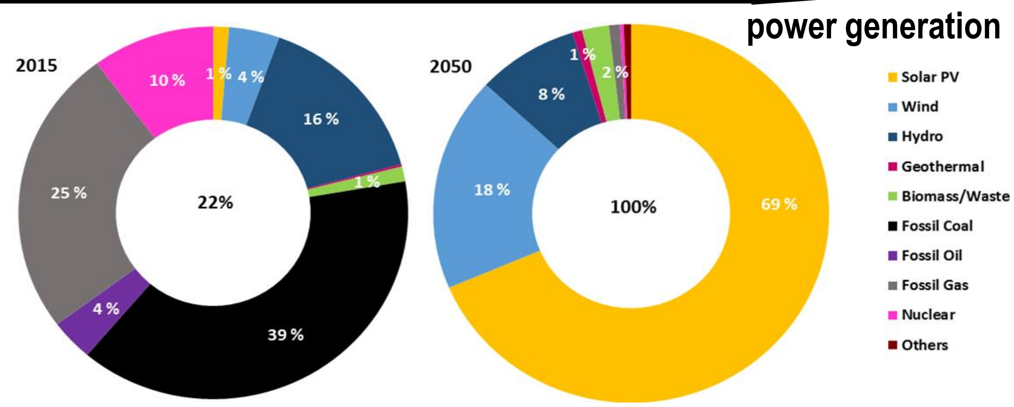
ARTICLE

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

Radical transformation pathway towards sustainable electricity via evolutionary steps

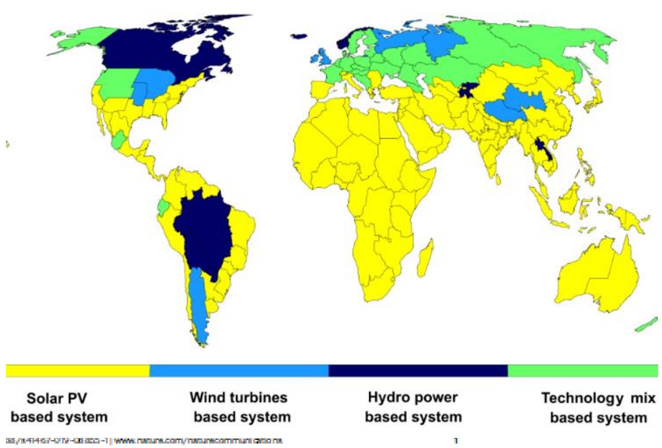
Dmitrii Bogdanov[1], Javier Farfan[1], Kristina Sadovskaia[1], Arman Aghahosseini[1], Michael Child[1], Ashish Gulagi[1], Ayobami Solomon Oyewo[1], Larissa de Souza Noel Simas Barbosa[2] & Christian Breyer[1]

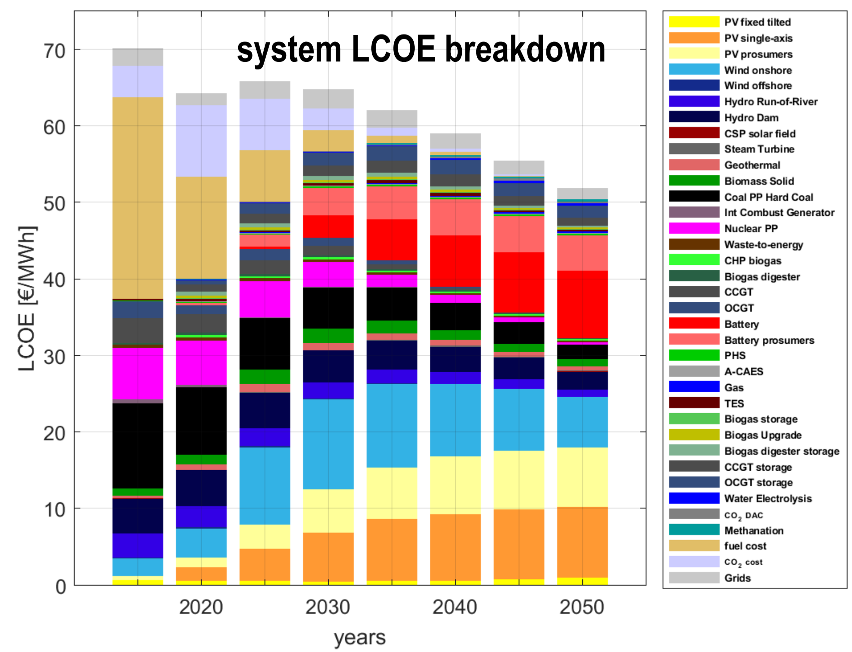
A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: greenhouse gas emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the 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.



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**





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

Overview on transport sector transition

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Source	Publication year	Unit	2015	2020	2025	2030	2035	2040	2045	2050	TFED share in 2050 * fossils	biofuels	synfuels	electricity
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 %

source: Khalili et al., 2019. Energies, 12, 3870

- synthetic fuels is still very often only hydrogen
- LUT has the highest synthetic fuel share among all groups in the world
- 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
- 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

Lithium – a potentially limiting raw material

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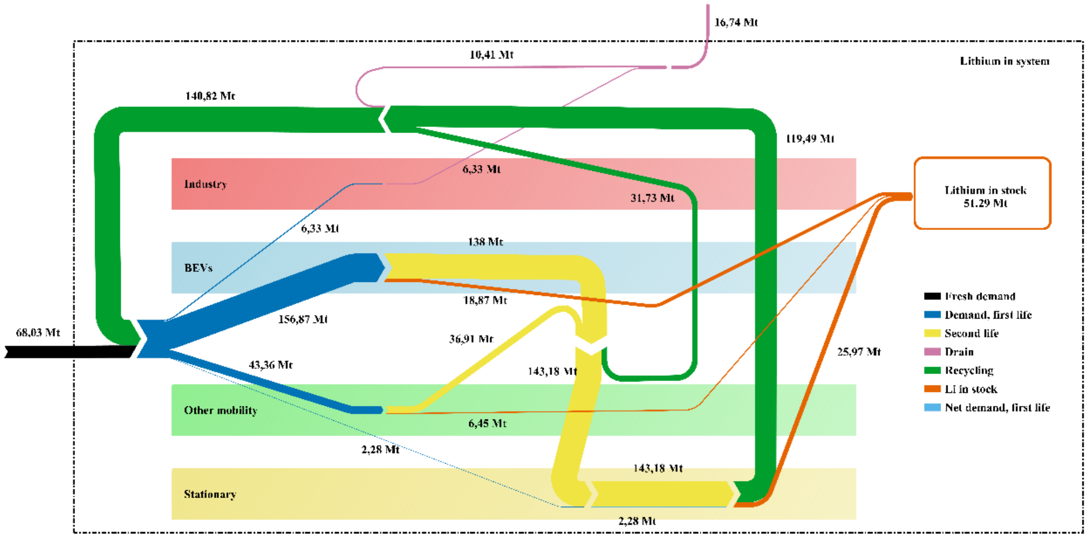
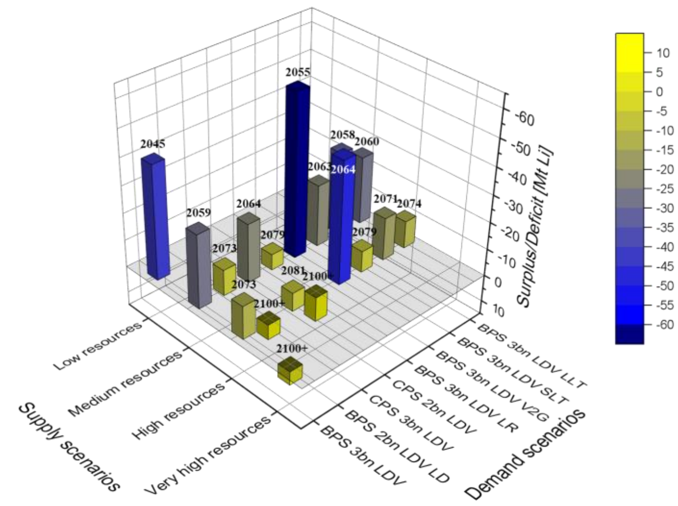
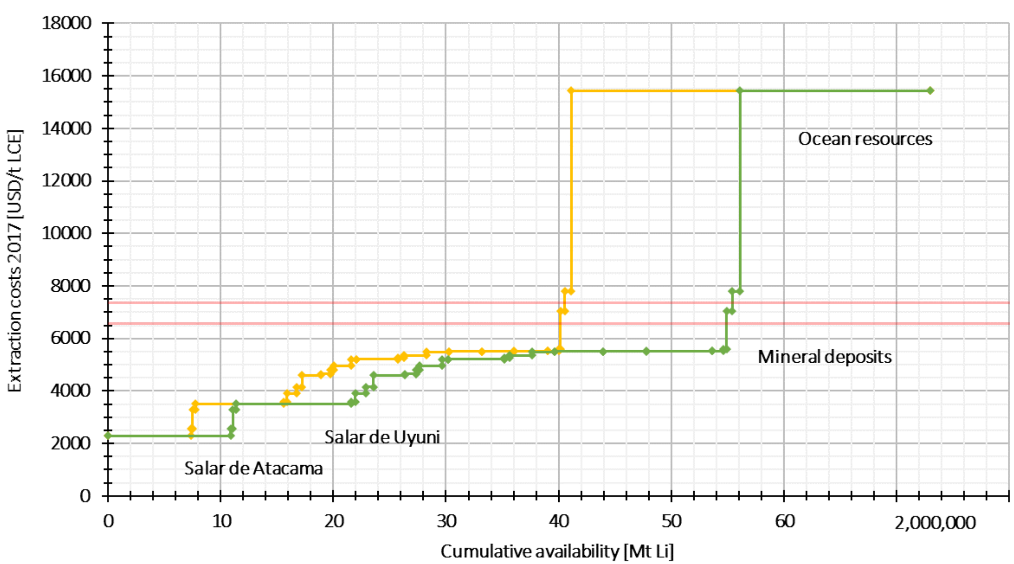




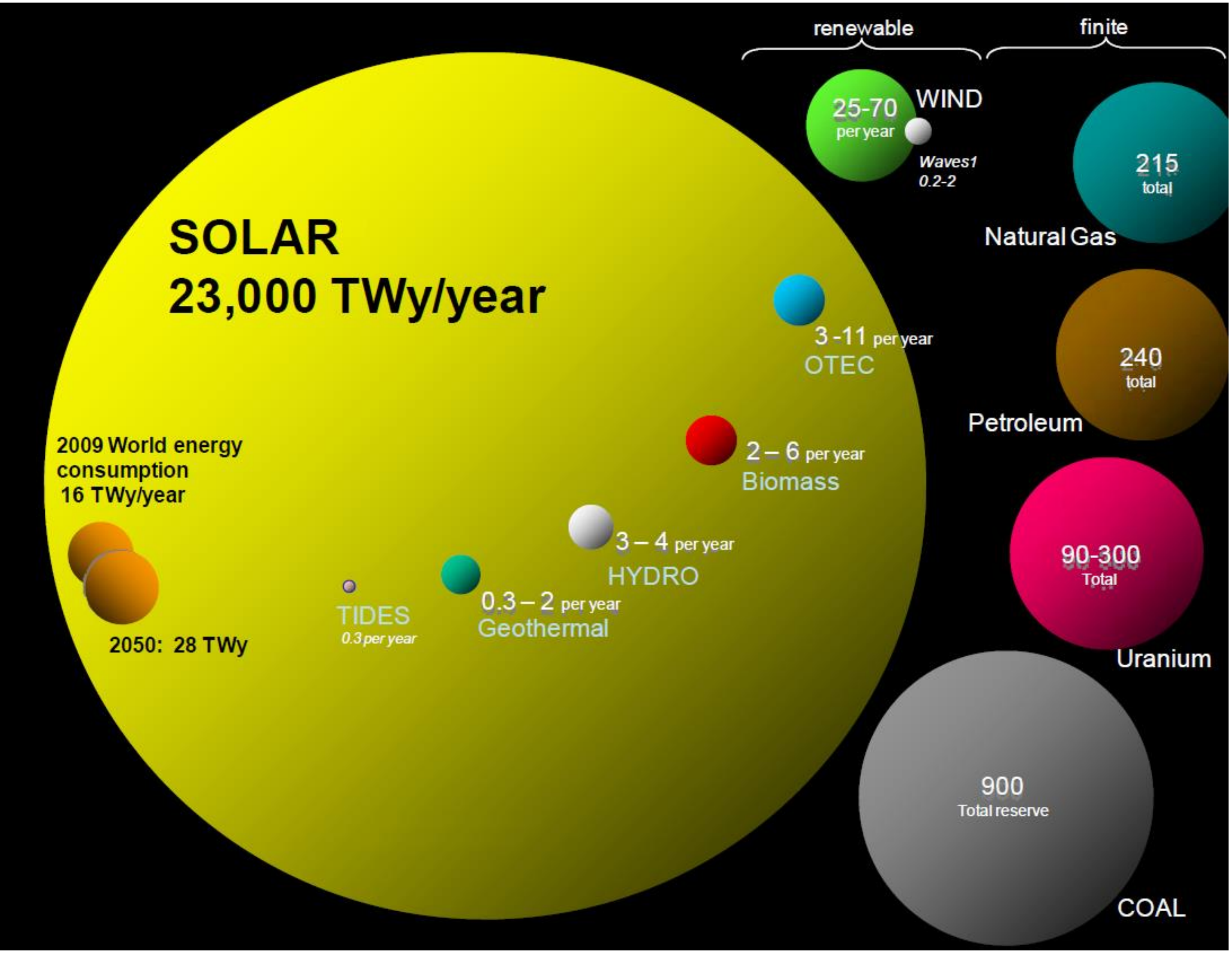


Key insights:

- 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

source: Greim et al., 2020. Nature Communications, 11, 4570

Resources and Energy Demand



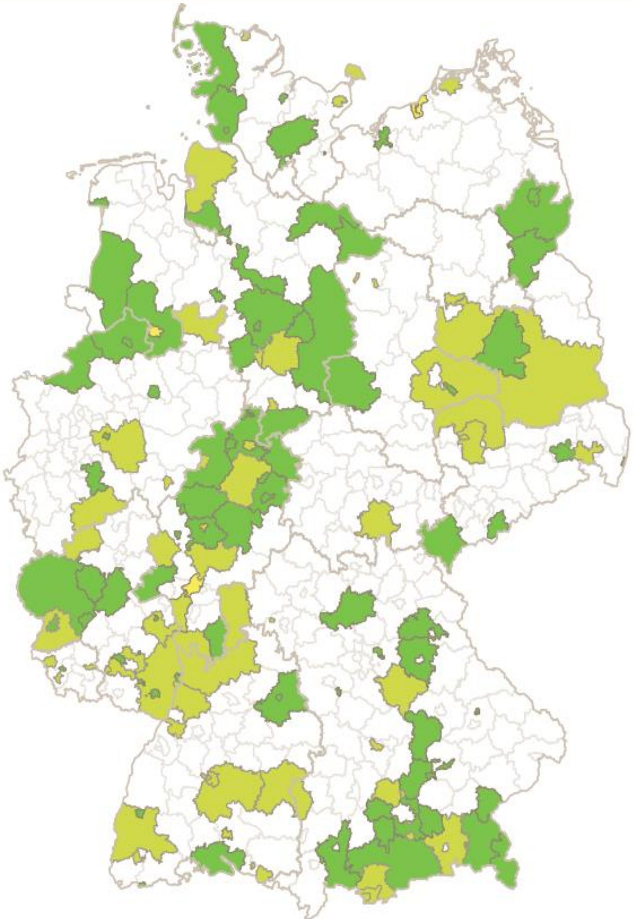
Key insights:
- no lack of energy resouces
- limited conventional resources
- solar and wind resources need to be the major pillars of a sustainable energy supply

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

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, Tokelau, …

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, …

Role of Sector Coupling and Flexibility

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 dams, 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

Electricity exchange across Europe

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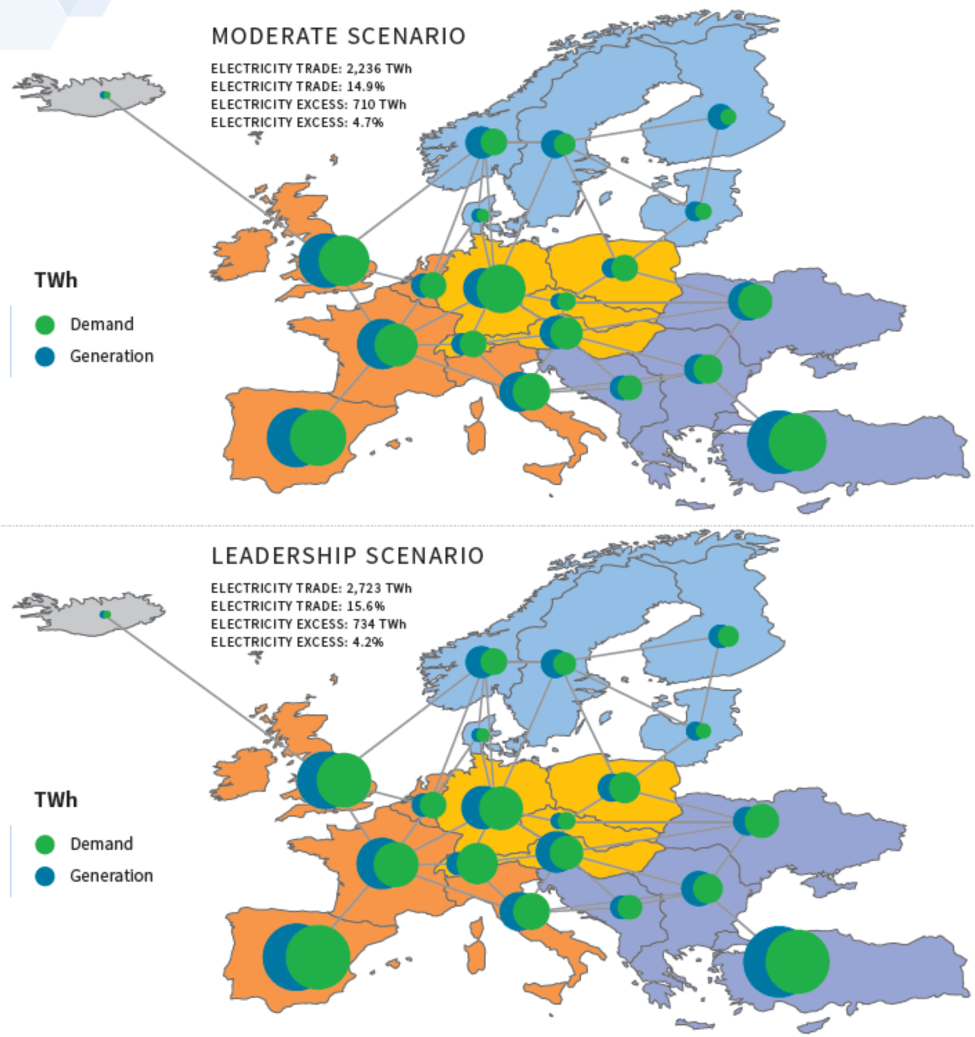
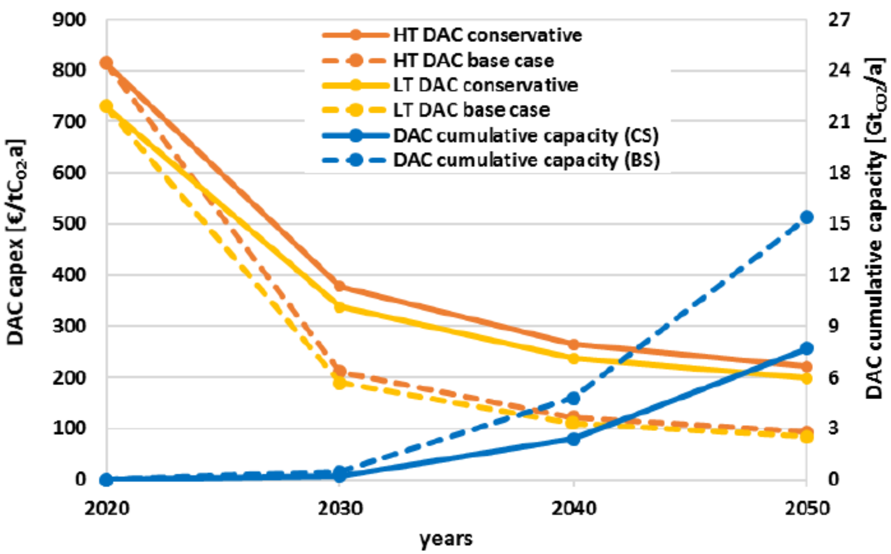
FIGURE 4.7 ELECTRICITY DEMAND, GENERATION AND TRADE IN 2050 ACROSS EUROPE



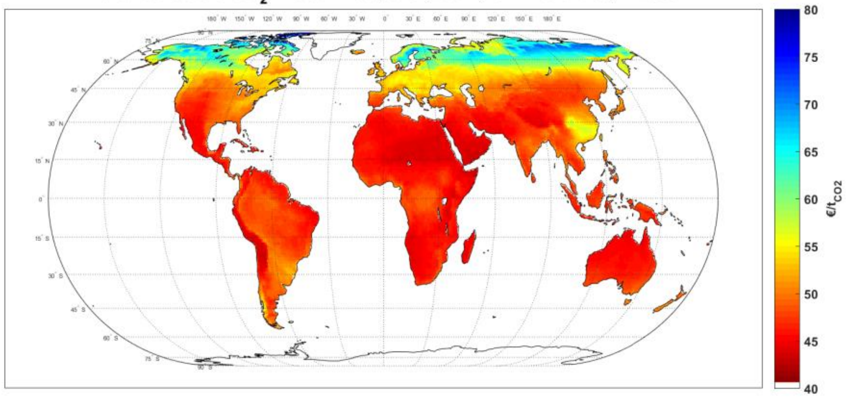
Key insights:

- **Exchange of electricity across borders at around 15%, thus it is a highly decentralised energy system**
- **Curtailment of electricity is around 4-5%, which is result of a least cost energy system**
- **Good news: European cooperation leads to lower overall cost; in case of lack of cooperation the transition can be still organised nationally**

CO_2 Direct Air Capture



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

Nordic region: Power sector first (only power sector

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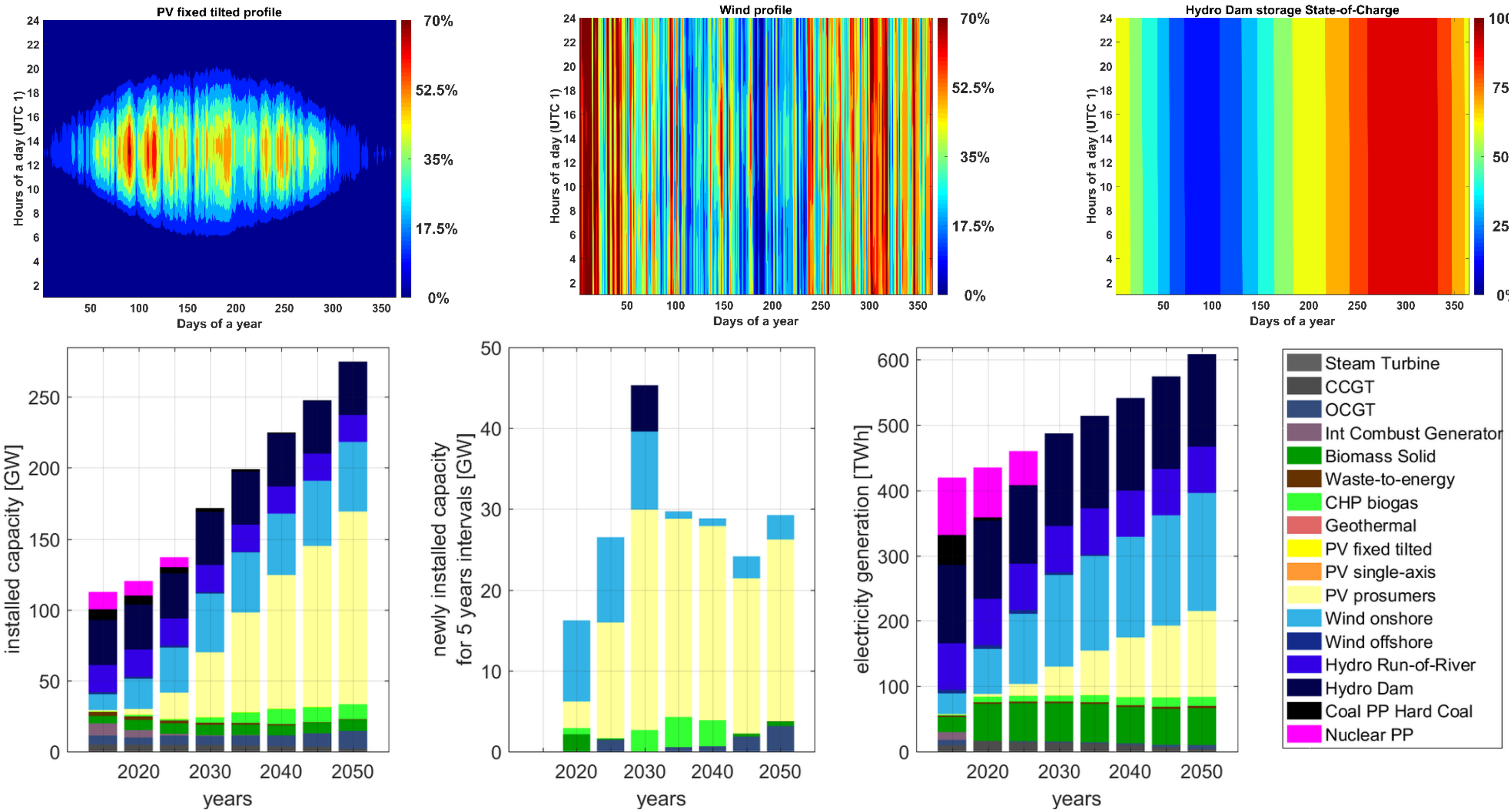
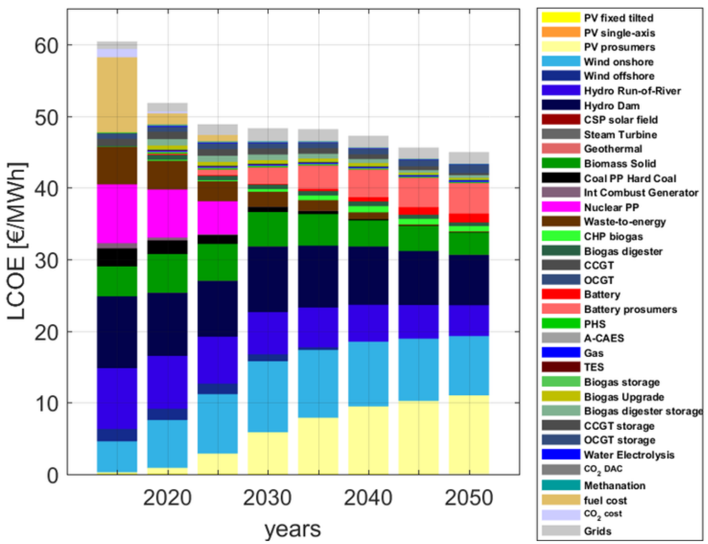


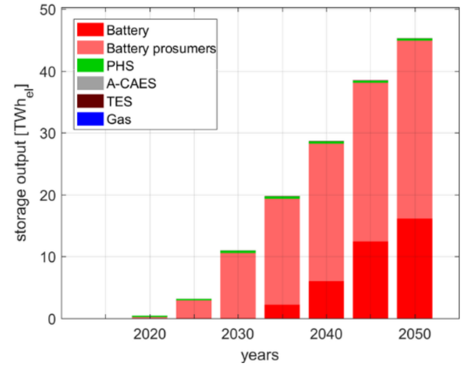
Key insights:

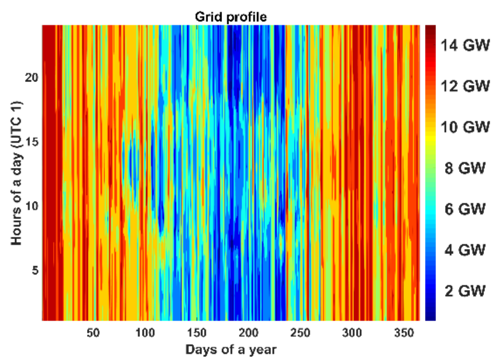
- Excellent resources in the Nordic/ Baltic Sea Region enable a fast track transition towards 100% renewables
- Most relevant new capacities are wind energy and distributed solar PV
- Most polluting capacities are oil shales in Estonia, while nuclear violates sustainability criteria and is not affordable

source: Child et al., 2018. The Baltic Sea Region: Storage, grid exchange and flexible electricity generation for 100% renewable energy, Energy Procedia, 155, 390-402

What does this mean for the Nordic?

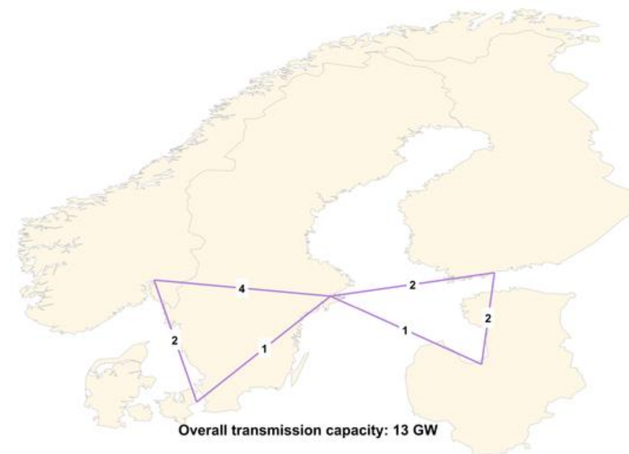






2050

Transmission capacities (GW)

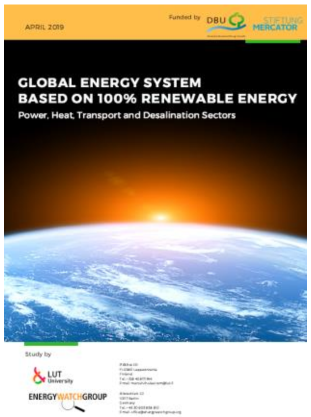


Key insights:

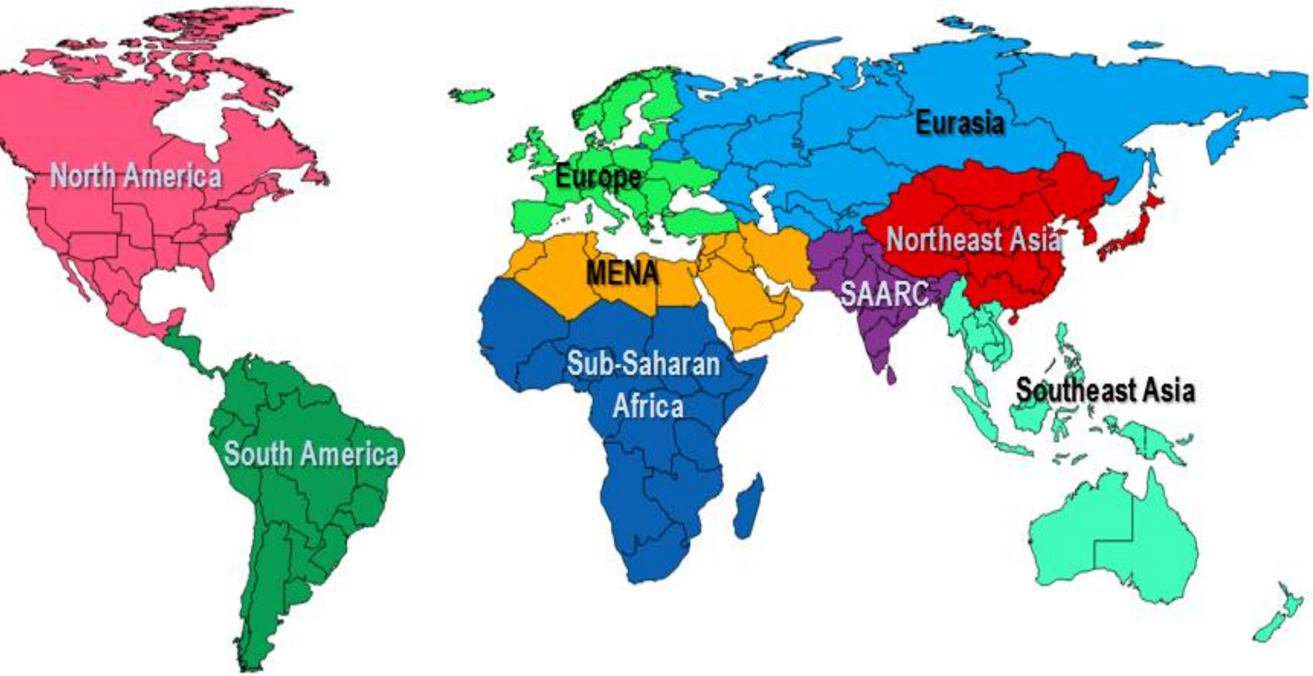
- Be aware of these results are only for the power sector, without considerations for heat, transport, industry
- Decreasing levelised cost of electricity, driven by phase-out of oil shales and nuclear, and low-cost renewables
- Storage becomes increasingly relevant as source of flexibility
- Current interconnections amount to approximately 12 GW
- Simulation results do not show significant need for expansion (+1 GW between Finland and Estonia)
- 15% of total generation of 587 TWh is traded to other Baltic regions and not consumed in the region of origin

source: Child et al., 2018. The Baltic Sea Region: Storage, grid exchange and flexible electricity generation for 100% renewable energy, Energy Procedia, 155, 390-402

Global Overview



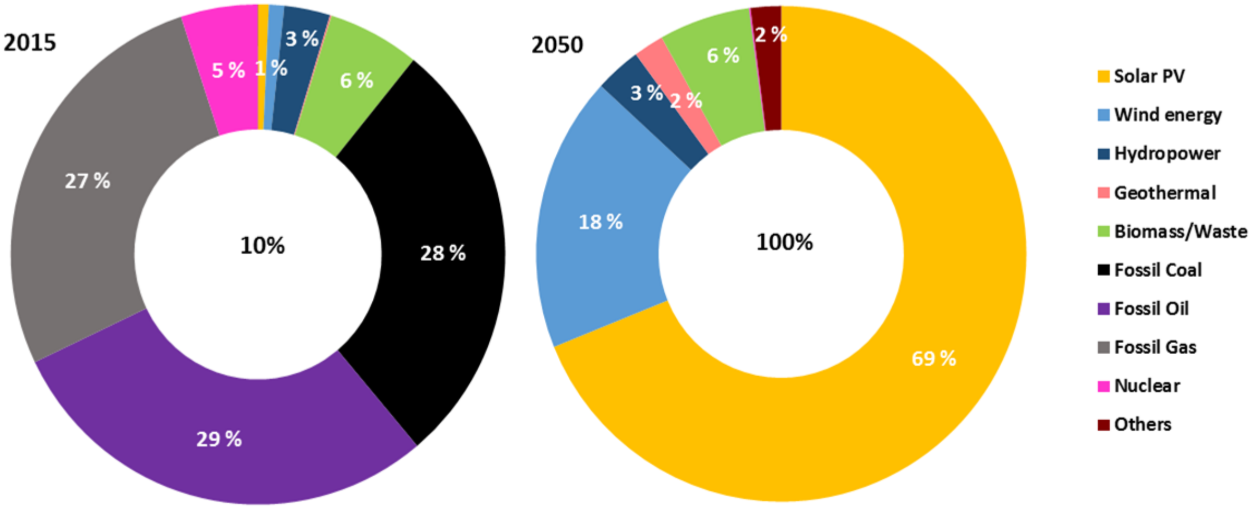
link to report

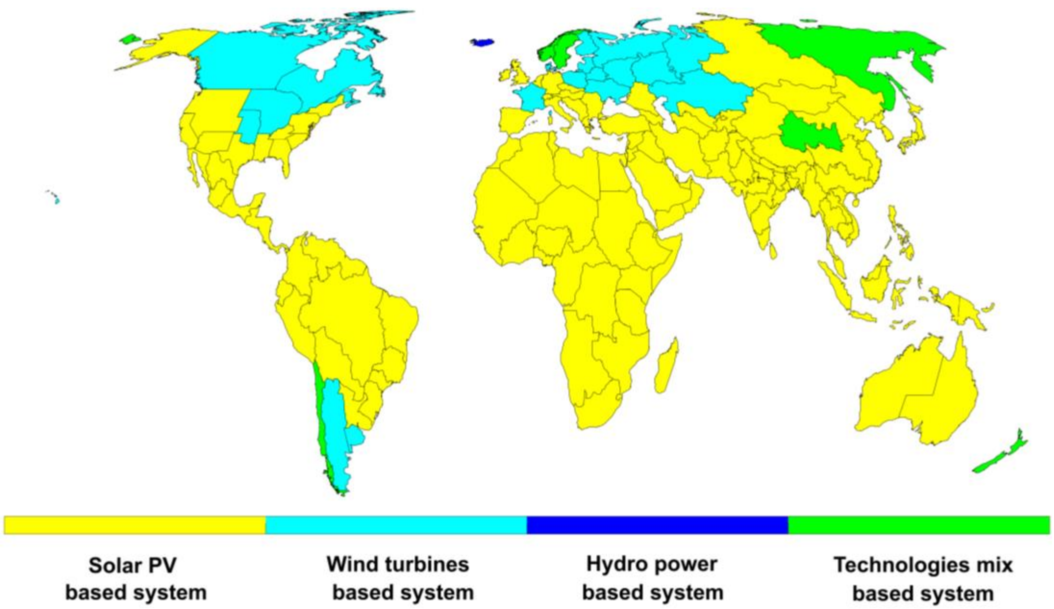


- The world is structured into 9 major regions, which are further divided to 145 sub-regions
- Some sub-regions represent more than one country, others parts of a larger country
- The sub-regions are interconnected by power lines within the same country
- The results shown are for the Power, Heat, Transport,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

source: EWG/LUT, 2019. Global Energy System based on 100% RE ; Bogdanov et al., 2021. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, Energy, in press

Renewables for ALL energy demand (TPED)



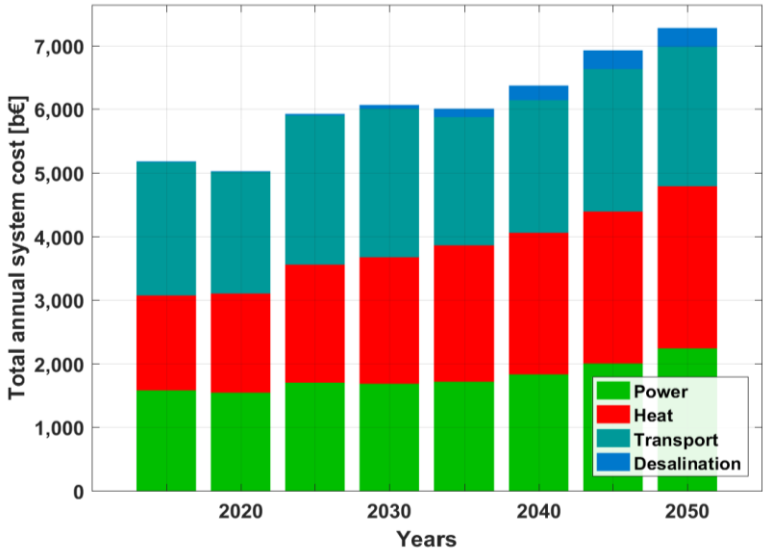


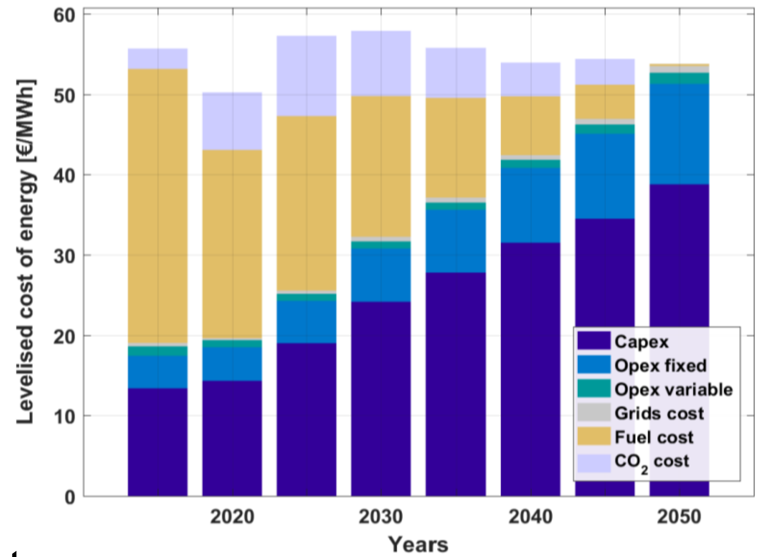
Key insights:

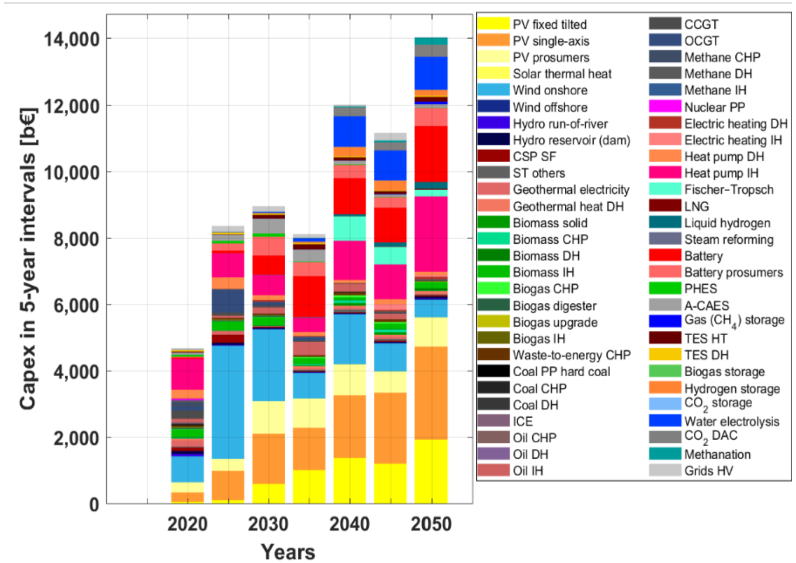
- TPED shifts from being dominated by coal, oil and gas in 2015 towards solar PV and wind energy by 2050
- Renewable sources of energy contribute less than 20% of TPED in 2015, while in 2050 they supply 100% of TPED
- Solar PV drastically shifts from less than 1% in 2015 to around 69% of primary energy supply by 2050, as it becomes the least cost energy supply source across the world
- Solar PV capacity demand
  - 63 TW energy system
  - 13 TW chemical industry

source: EWG/LUT, 2019. Global Energy System based on 100% RE ; Bogdanov et al., 2021. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, Energy, in press

Global: 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 system
- Cost of energy remains around 50-57 €/MWh and is increasingly dominated by capital costs as fuel costs lose importance through the transition period
- 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€
- This is the only known cost-neutral 1.5C compliant pathway without negative CO_2 emission technologies and significantly growing energy services demand

source: EWG/LUT, 2019. Global Energy System based on 100% RE ; Bogdanov et al., 2021. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, Energy, in press