




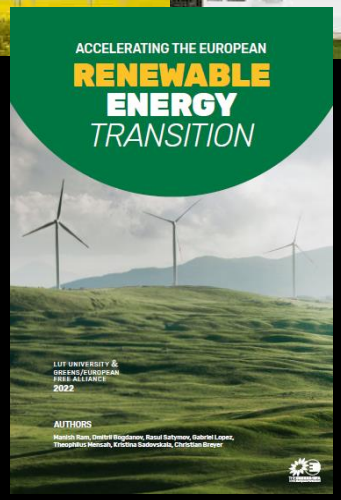

Accelerating the European Renewable Energy Transition

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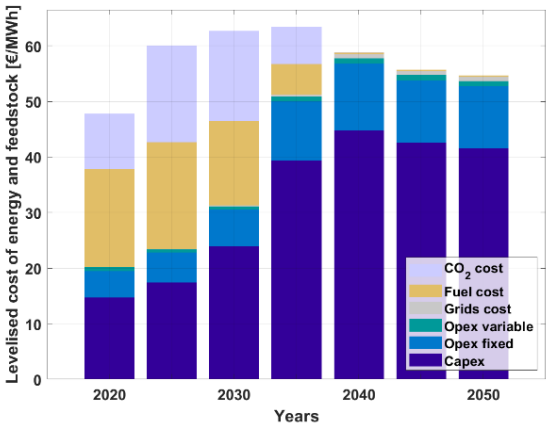
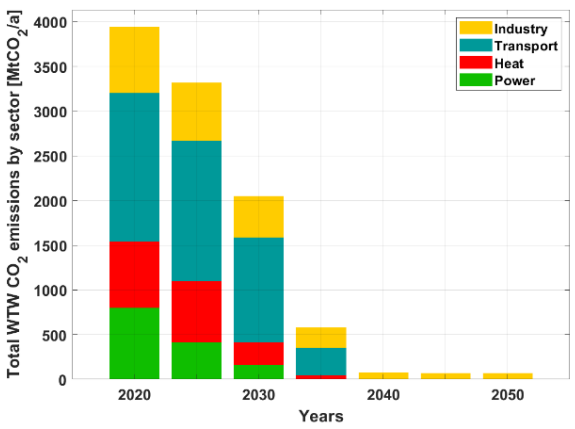
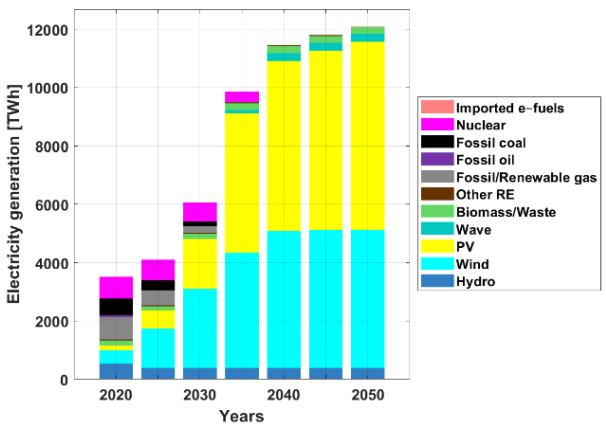
Lappeenranta University of Technology

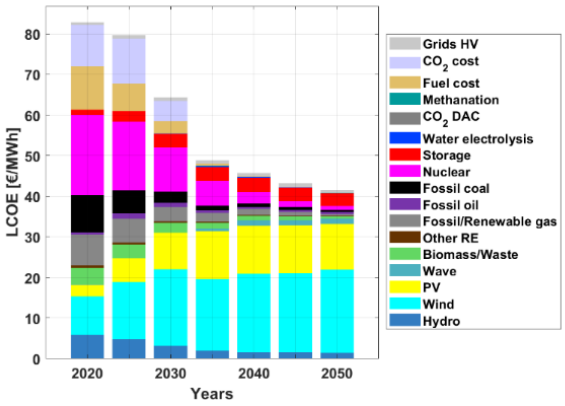
Christian Breyer
Professor for Solar Economy
Europe Calling
webinar, October 11, 2022

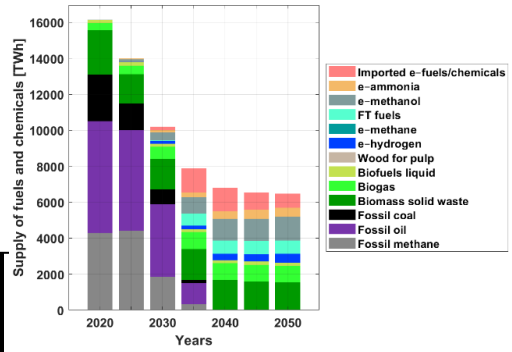
Highly Ambitious Energy-Industry Transition for Europe
Core results for RES-2040 – central summary











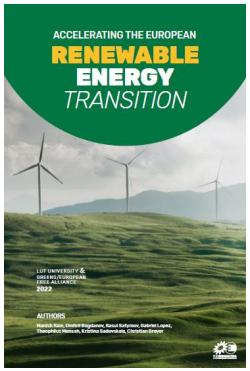
- Methods: LUT-ESTM, 1-h, 20-regions, full sector coupling, cost-optimised
- First energy-industry transition to 100% RE in Europe in 1-h & multi-regions
- Industry: cement, steel, chemicals, aluminium, pulp & paper, other industries
- Energy-industry costs remain roughly stable
- Scenario definition: zero CO_2 emissions in 2040
- Massive expansion of electricity would be required
- e-fuels & e-chemicals ensure stable operation of transport & industry
- Nuclear: by scenario default phased out by 2040; it is NO critical system component; finally countries will decide how to proceed
- What's respected:
  - 1.5 ºC target & biodiversity & cost effectiveness & air pollution phase-out
  - renewal of European energy-industry system & jobs growth
- Why society should not go for such an option?

ergy Transition
i @ChristianOnRE

source: Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022

Overview

Europe – 20 Regions (inclusive of EU-27)



link to report

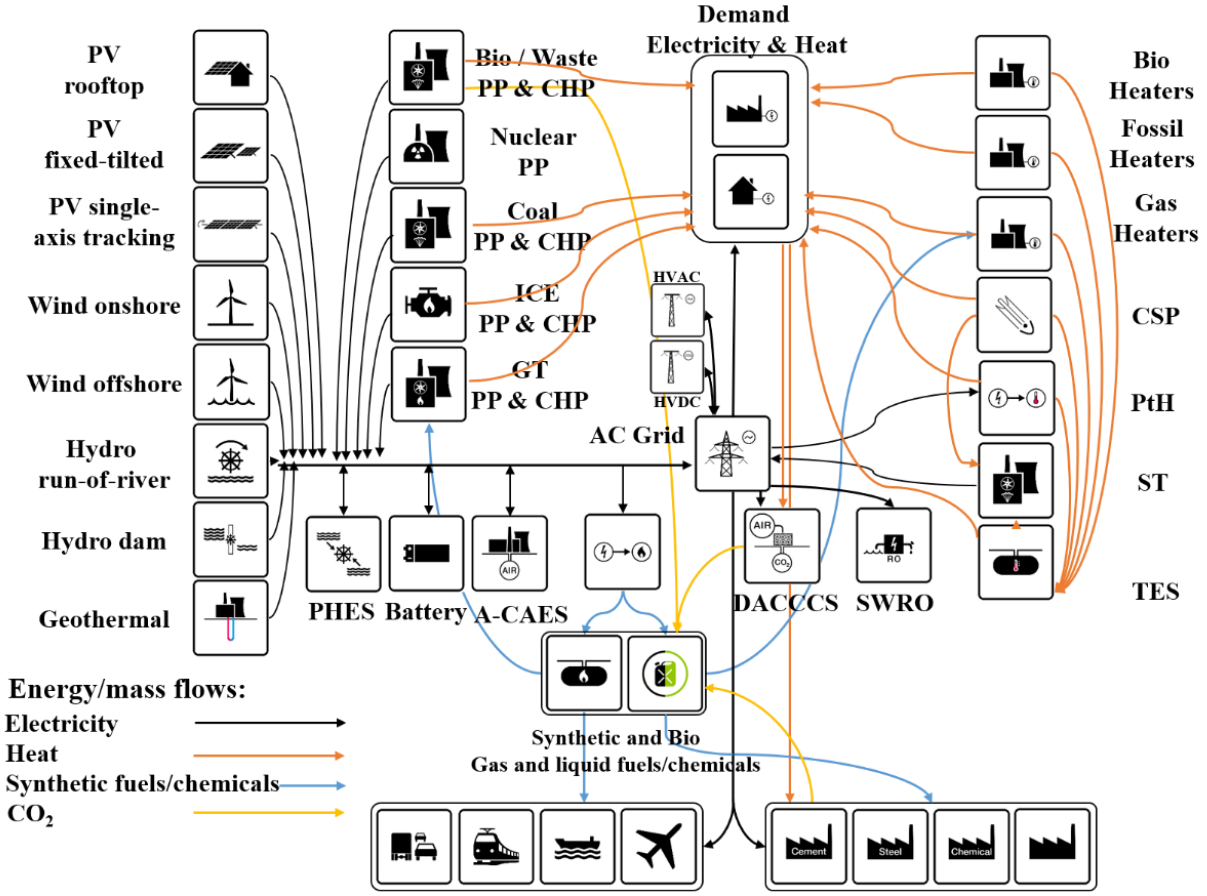
Important information:

- report is for EU-27
- investigation was done for entire Europe (grid integration, overall European perspective)
- results shown in the following are for entire Europe
- there are no structural differences

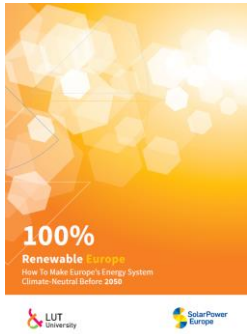
Europe is structured into 20 Regions that includes all 27 EU member states:

- Iceland, Norway, Denmark, Sweden, Finland, BALTIC (Estonia+Latvia+Lithuania),
- Germany, Poland, CRS (Czech Republic+Slovakia), AUH (Austria+Hungary), CH (Switzerland+Liechtenstein)
- IBERIA (Portugal+Spain+Gibraltar), France (France+Monaco+Andorra), Italy (Italy+San Marino+Vatican+Malta)
- BRI (Ireland+United Kingdom), BNL (Belgium+Netherlands+Luxembourg)
- BKN-W (Slovenia+Croatia+Bosnia and Hertzegovina+Kosovo+Serbia+Montenegro+Macedonia+Albania), BKN-E (Romania+Bulgaria+Greece), UA (Ukraine+Moldova), TR (Turkey+Cyprus)

LUT Energy System Transition Model



recent reports



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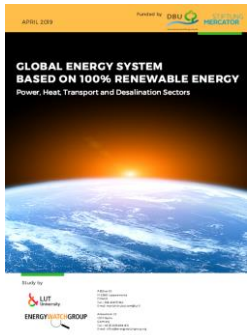

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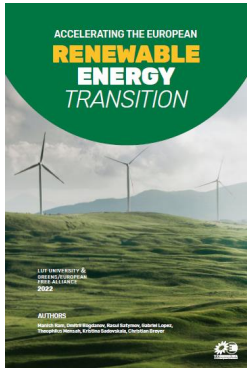

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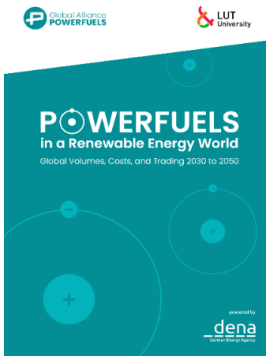

link to report

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)

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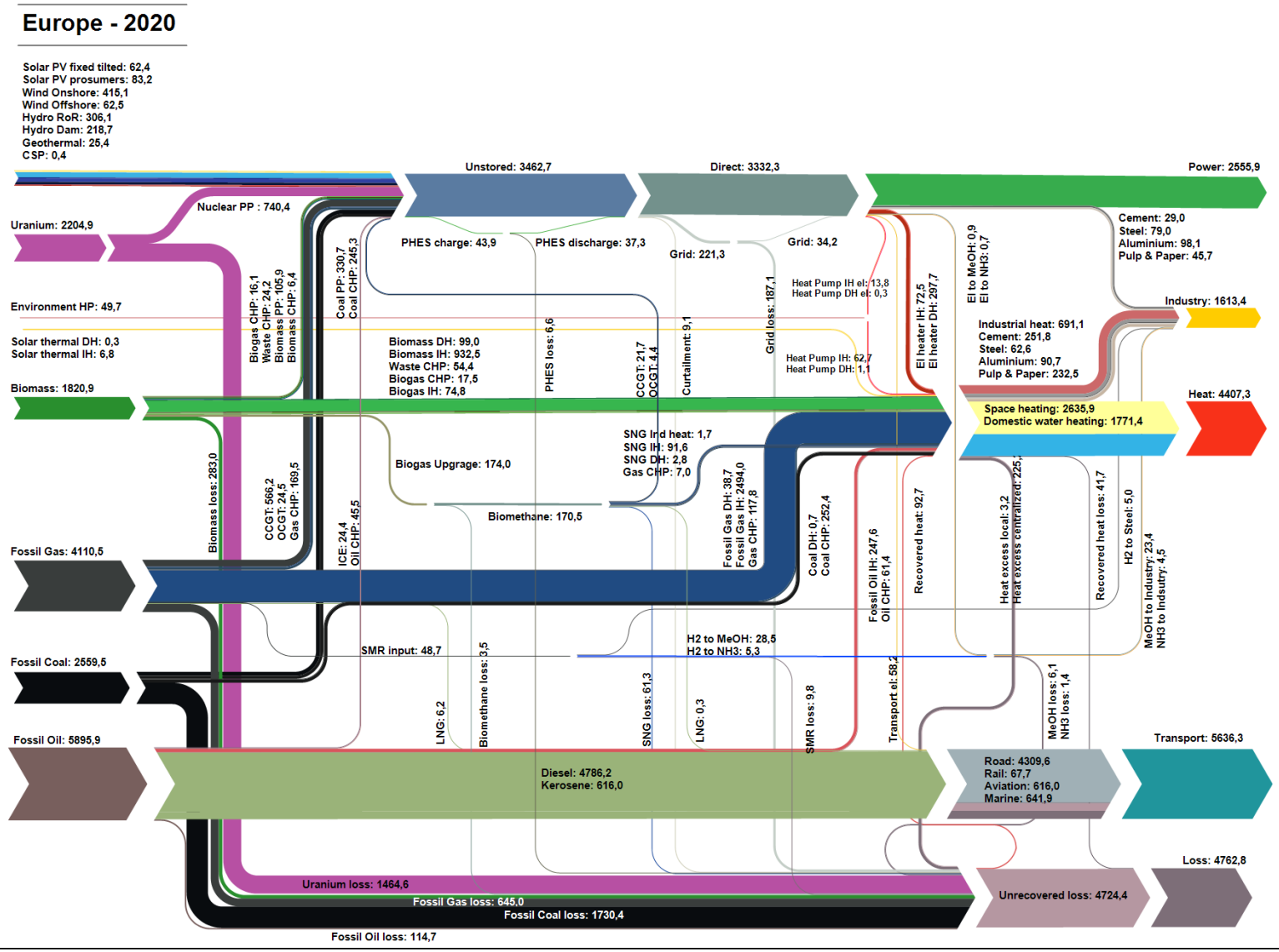
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

source: Bogdanov, Breyer 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

System Outlook – Energy Flows in 2020



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source: [Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022]

European Energy Transition Scenarios

REF, RES-2040 and RES-2035

The European energy system is modelled for 3 distinctive scenarios

- Reference scenario (REF): the energy system across the EU continues with current market trends up to 2030 with renewable energy contributing 40% of the final energy demand across the EU, ramping up efficiency in buildings by doubling current rates and 100% RE by 2050, enabling GHG emissions reduction of 55-65% by 2030, not compatible with the ambitious climate target of limiting temperature rise to below 1.5° C.

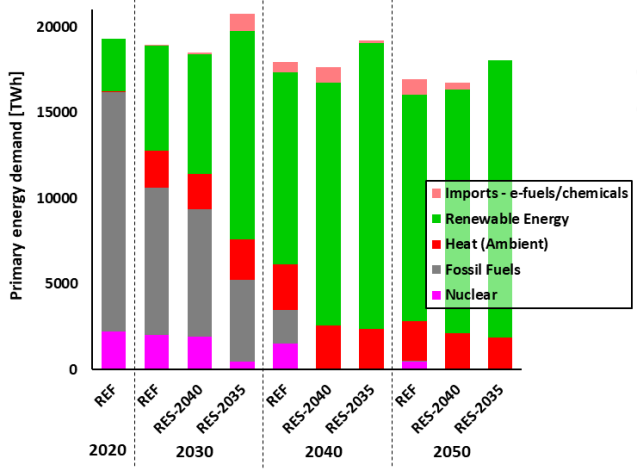
- Renewable Energy System – 2040 scenario (RES-2040): increased efforts are envisioned by all member states to drive the renewable energy share in final energy demand across the EU to 100% by 2040, ramping up efficiency in buildings by tripling current rates and enabling GHG emissions reduction of around 65% by 2030, which is compatible with the ambitious climate target of limiting temperature rise to below 1.5° C with zero emissions in 2040.

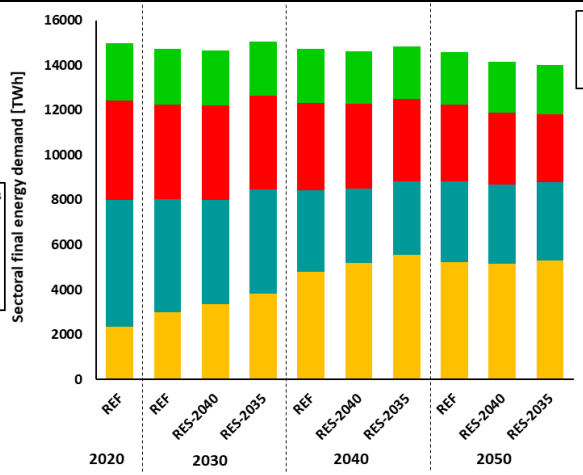
- Renewable Energy System – 2035 scenario (RES-2035): with increased impetus the EU takes a global leadership role in mitigating climate change and drives renewable energy share in final energy demand across the EU to around 60% in 2030 and 100% by 2035, ramping up efficiency in buildings by four times the current rates and enabling GHG emissions reduction of around 65% by 2030 and zero emissions by 2035, which is compatible with the ambitious climate target of limiting temperature rise to well below 1.5° C. 100% renewable energy across the power sector in all EU countries in 2030 and towards 100% renewables by 2035.

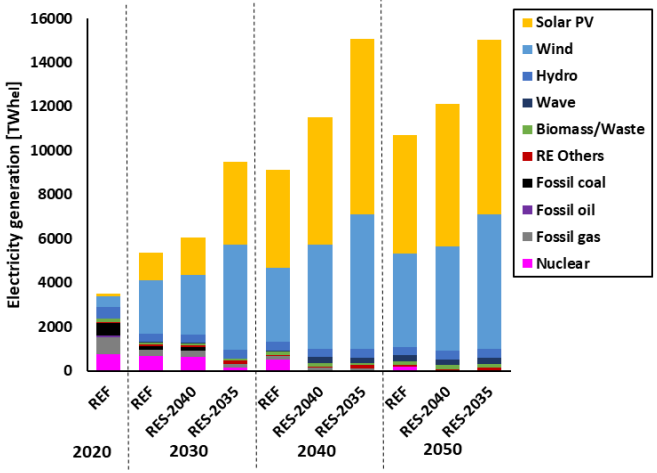
source: Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022

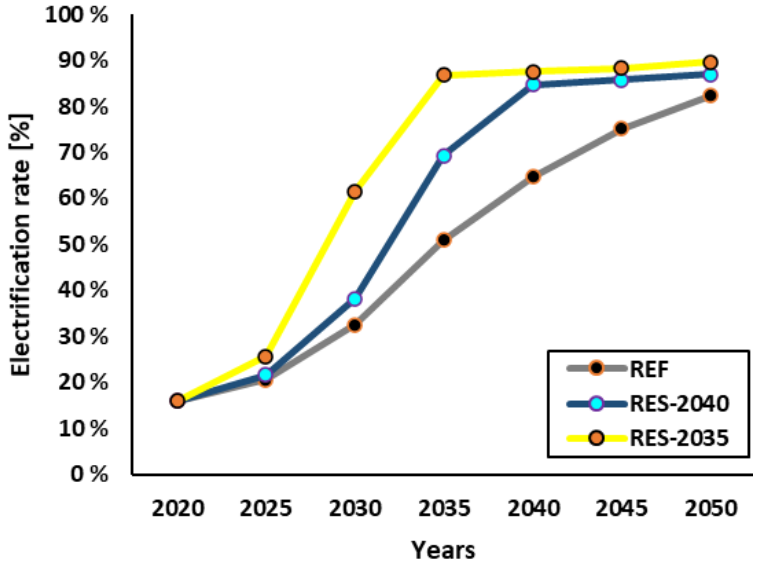
Long-term Demand: Primary, Final, Electricity

Scenario Comparison









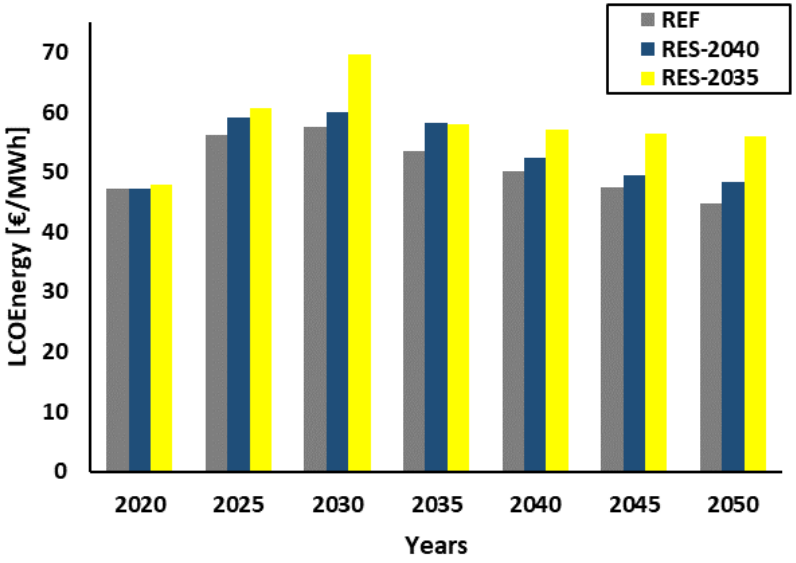
Key insights:

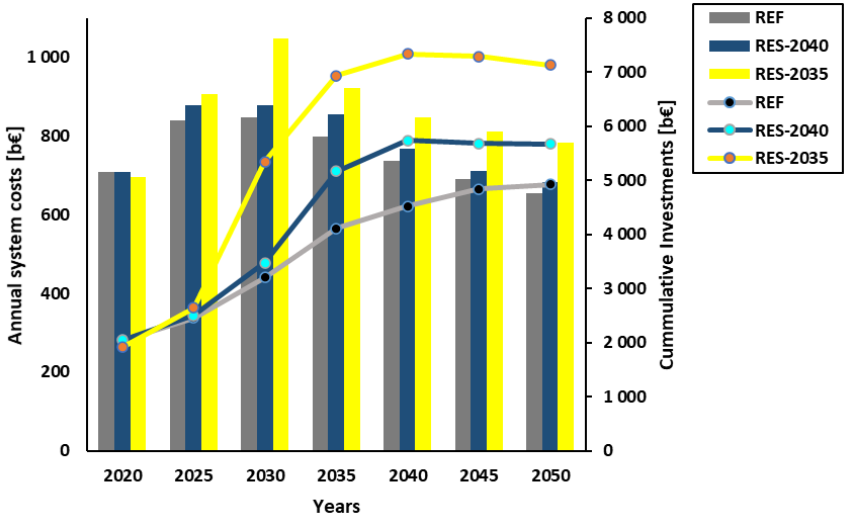
- Energy demand growth in the power, heat, transport and industry sectors is aggregated and linked to powertrain transformation and diffusion of conversion technologies.
- Comprehensive electrification is the underlying theme, which massively increases overall energy efficiency to an even higher growth rate in provided energy services.
- Massive increase in electricity generation required, scaled by PV & wind
- Efficiency gains vary across the scenarios, with all the 3 scenarios gaining around 34-42% in comparison to a low electrification demand with an assumed business-as-usual growth with current levels.
- Increased electrification combined with high shares of renewables is far more efficient than the current fossil fuels dominated energy system.

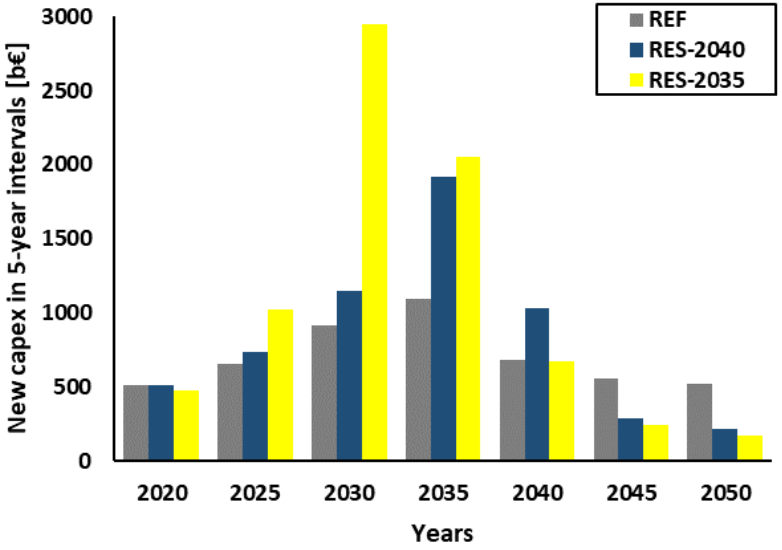
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Costs and Investments

Scenario Comparison



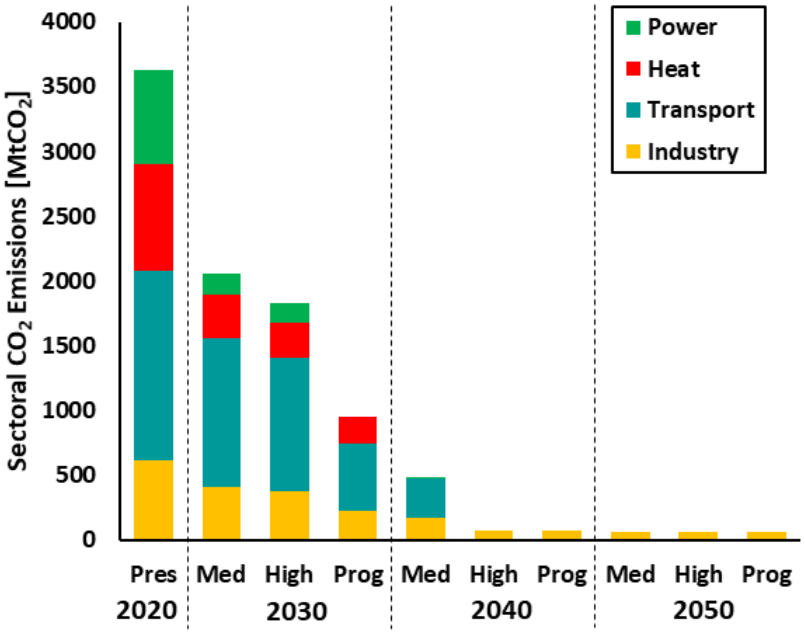


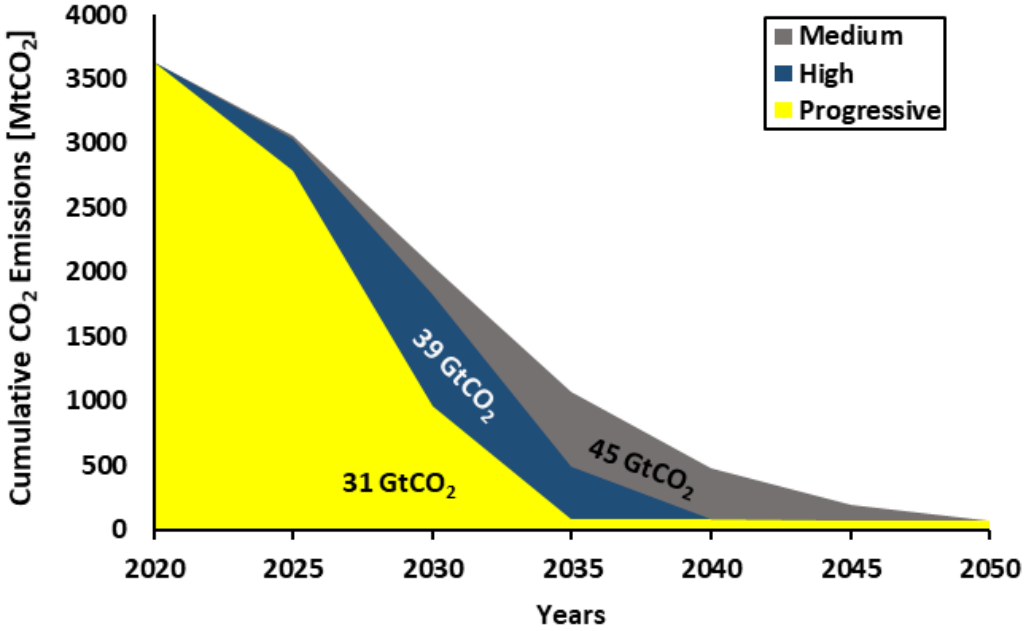


Key insights:

- The total annual system costs are in the range of 600-1000 b€ through the transition period across the 3 scenarios, with the RES-2040 scenario having the least annual system costs in 2050, while the RES-2035 and REF scenarios have higher annual system costs in 2050
- The RES-2035 scenario has a marginally higher LCOEnergy through the transition compared to the RES-2040 and REF scenarios having lower LCOEnergy through the transition, with 15% lower LCOEnergy in 2050
- Annual system costs indicate that pathways towards 100% renewables will not require significant energy system costs, while LCOEnergy remains close to current levels in 2050, expect in RES-2035 scenario with some increase
- Capital expenditures vary drastically across the 3 scenarios, rapid scaling of investments (about 3000 b€) until 2030 in the RES-2035 scenario, while reaching 2000 b€ and 1200 b€ up to 2035 in the RES-2040 and REF scenarios
- Rate of capital diffusion into renewable energy and sustainable technologies will decide the pace of the energy transition across Europe

CO_2 Emissions
Scenario Comparison



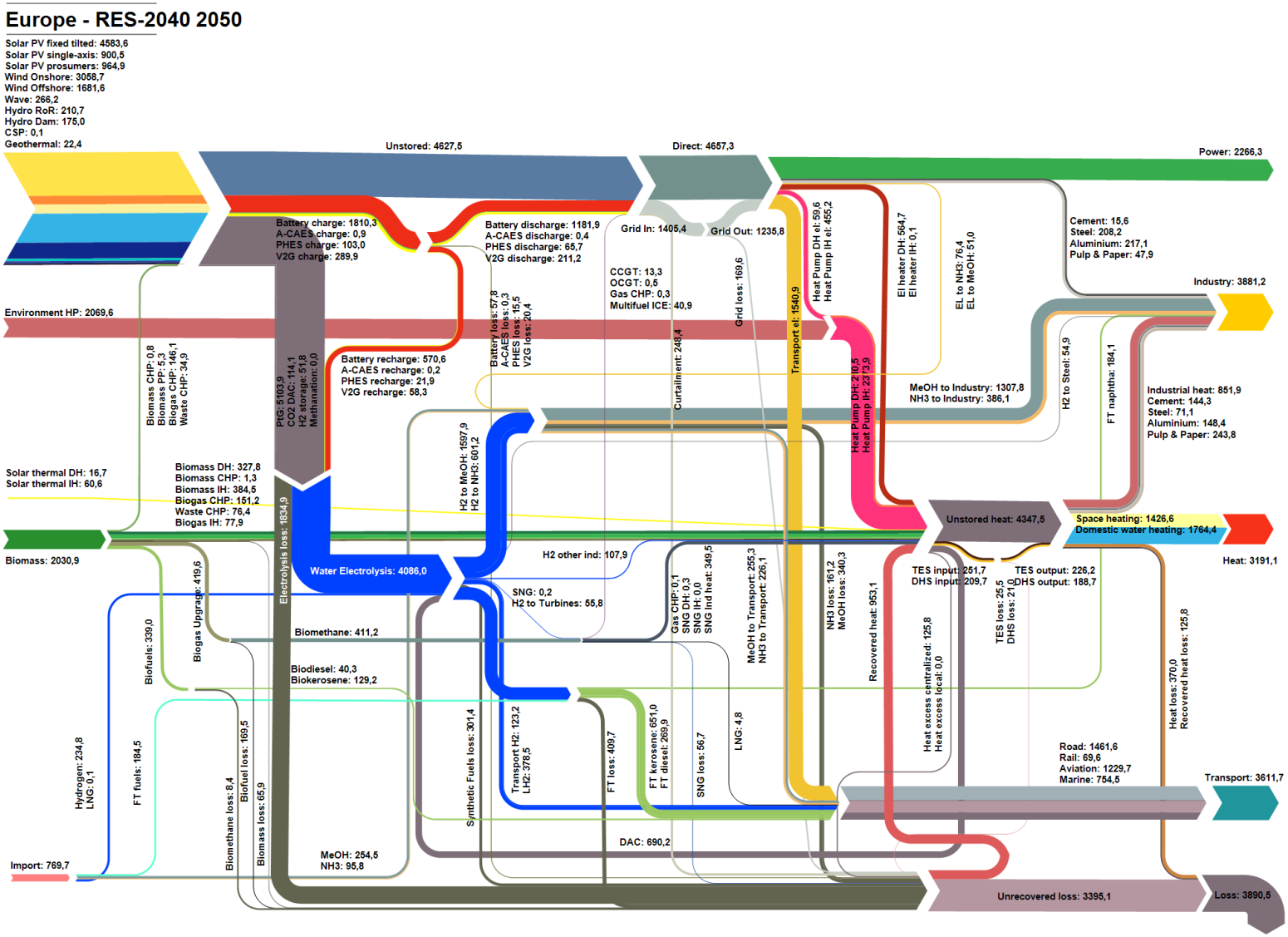


Key insights:

- CO_2 emissions decline in all the 3 scenarios, from over 3500 $MtCO_2$ in 2020 to nearly zero by 2035 in the RES-2035 scenario, nearly zero by 2040 in the RES-2040 scenario and nearly zero by 2050 in the REF scenario (emissions from cement industry persist, can be mitigated with CCS/NCS solutions)
- The remaining cumulative CO_2 emissions comprise around 31 $GtCO_2$ from 2020 to 2035 in the RES-2035 scenario, around 39 $GtCO_2$ from 2020 to 2040 in the RES-2040 scenario and 45 $GtCO_2$ from 2020 to 2050 in the REF scenario
- The presented 100% RE scenarios for the European energy system are compatible with the Paris Agreement, with the RES-2035 scenario highlighting an accelerated pathway for achieving the ambitious target of limiting temperature rise to about 1.5°C, while the RES-2040 scenario shows a less ambitious pathway of achieving 1.5°C - 2°C target and the REF scenario is at the less ambitious end of the Paris Agreement with over 45 $GtCO_2$ of CO_2 emissions until 2050
- A deep defossilisation of the power, heat, transport and industry sectors across Europe is possible by 2035

System Outlook – Energy Flows in 2050

RES-2040 Scenario – Power-to-X Economy



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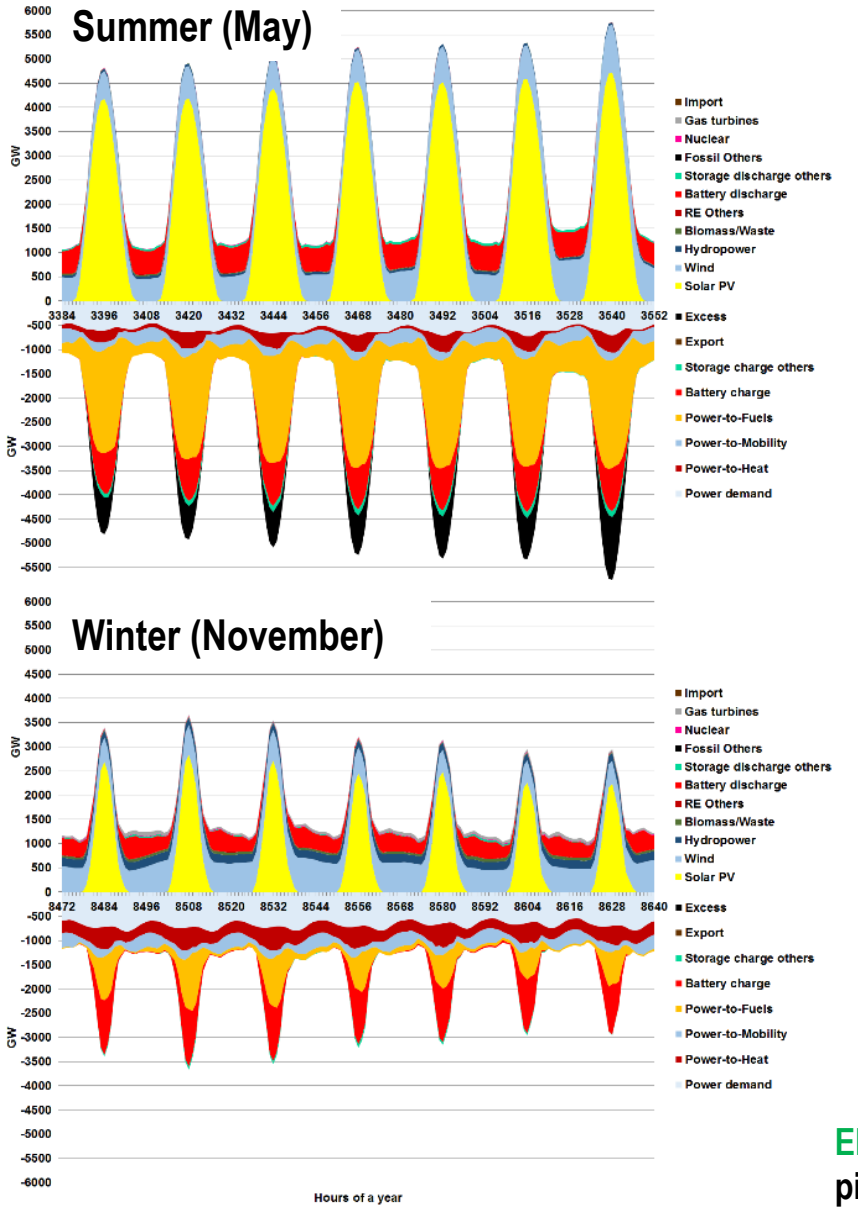
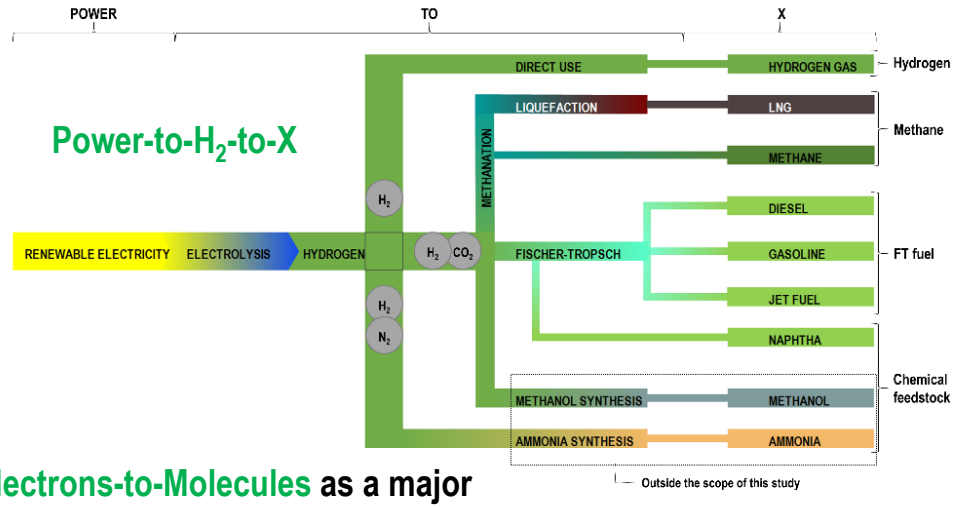
source: [Greens/EFA, Accelerating the European RE transition, Brussels, Sepember, 2022]

Hourly Operation and Balancing



Key insights:

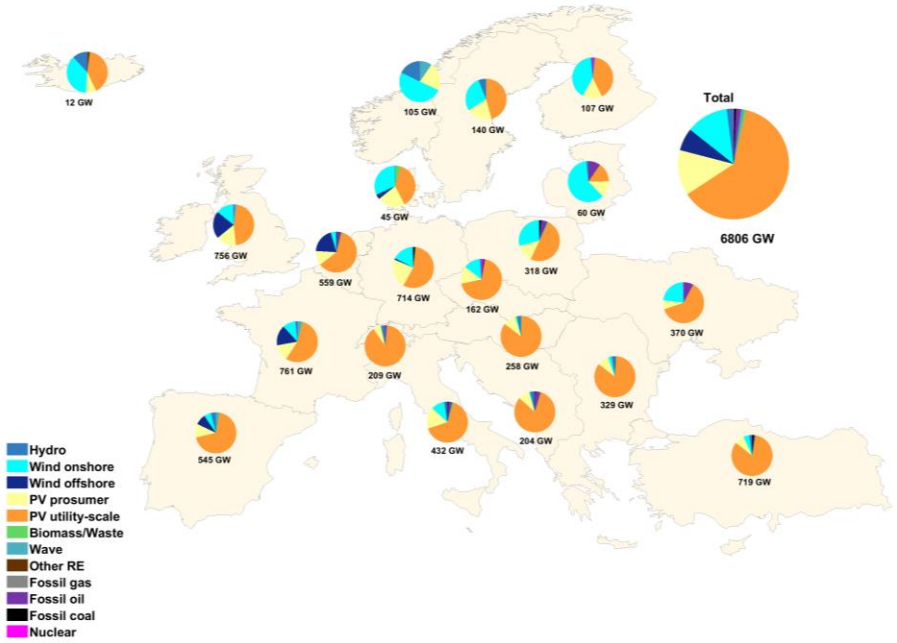
- Week of most renewables supply (spring) and least renewables supply (winter) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the region easily copes with energy demand
- Key balancing components are electrolysers (Power-to-H_2-to-Fuels) that convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability



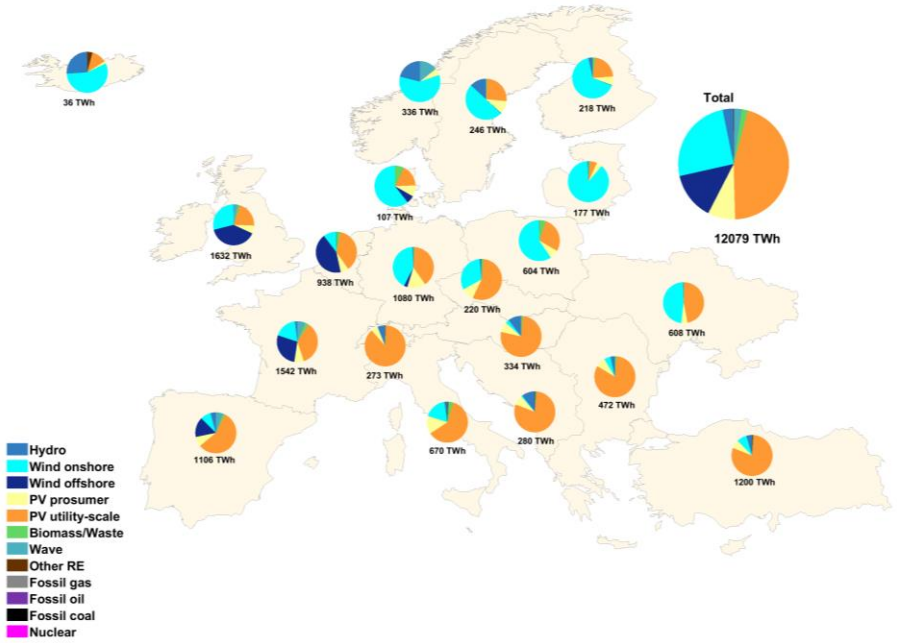
Electrons-to-Molecules as a major piece of **Power-to-X Economy**

Regional Outlook – Electricity capacities and generation in 2050
RES-2040 Scenario

Regional electricity capacities



Regional electricity generation

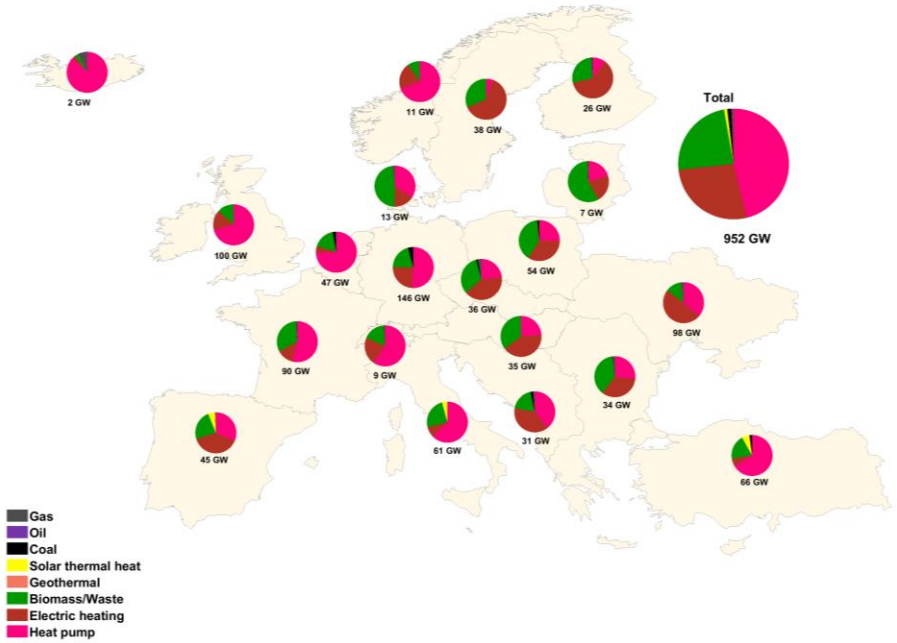


Key insights:

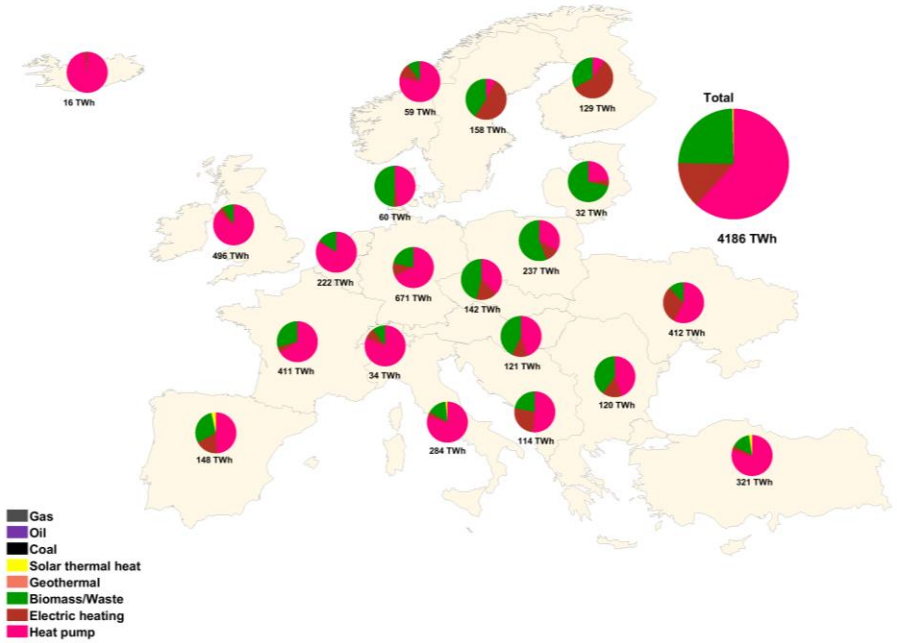
- Electricity generation is comprised of demand for the sectors power, heat, transport and industry
- Solar PV capacities are predominantly in the southern regions of Europe, while wind energy capacities are mainly in the northern regions of Europe with total electricity generation of 12,079 TWh in 2050
- Solar PV generation is higher in the southern region, while wind energy generation is higher in the northern regions with better wind conditions throughout the year complementing different regions
- Overall, solar PV and wind generate most of the electricity needed across Europe by 2050

Regional Outlook – Heat capacities and generation in 2050
RES-2040 Scenario

Regional heat capacities



Regional heat generation



Key insights:

- Heat generation is comprised of demand for domestic hot water, space heating, industrial process heat
- Heat pumps and electric heating capacities are predominantly in the southern regions of Europe, while bioenergy capacities are mainly in the northern regions with total heat generation of 4186 TWh in 2050
- Heating demand across Europe transitions from heavily reliant on imported fossil gas towards heat pumps combined with electric heating and some shares of bio-based heating
- Overall, heat pumps generate most of the heat needed across Europe by 2050 with higher efficiency

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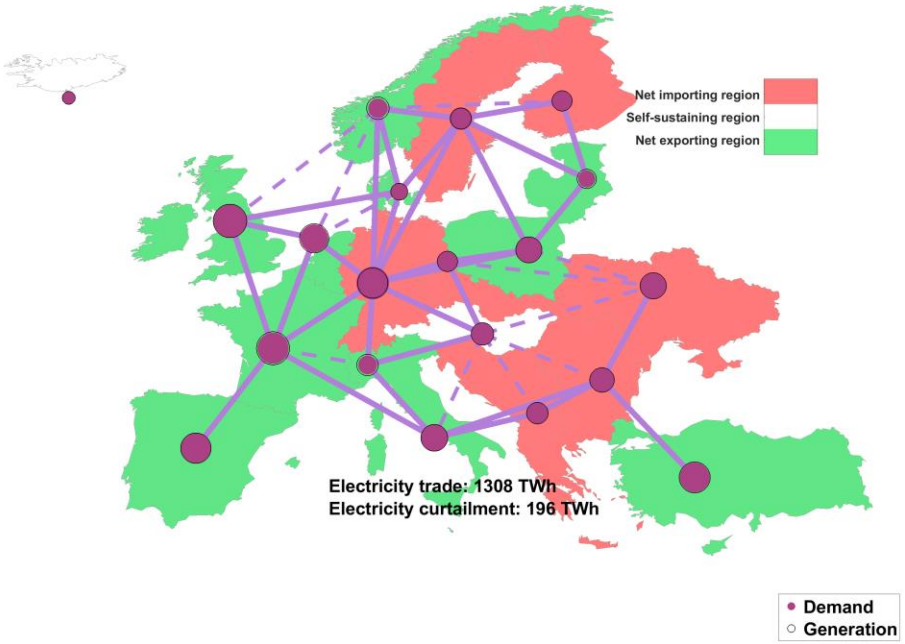
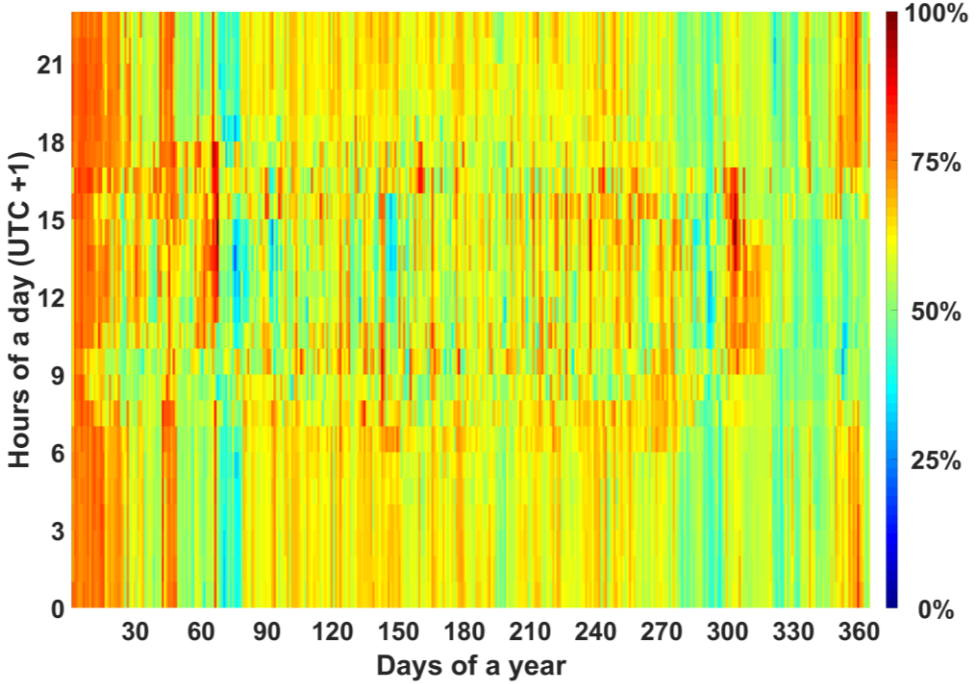
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Regional Outlook – Electricity grids and utilisation in 2050
RES-2040 Scenario

Annual imported and exported electricity



Grid profile (2050)



Key insights:

- **Transmission grids play a vital role in enabling a highly electrified and integrated energy system across Europe in 2050 with 1308 TWh of electricity traded across the different regions**
- **Northern, Central and Eastern regions emerge as net importers, while the Southern and Western regions are net exporters in 2050 for the RES-2040 scenario**
- **Grid utilisation remains high with a range of 50-95% throughout the year and higher utilisation in the winter months across Europe in 2050**

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Concrete numbers for achieving the set target

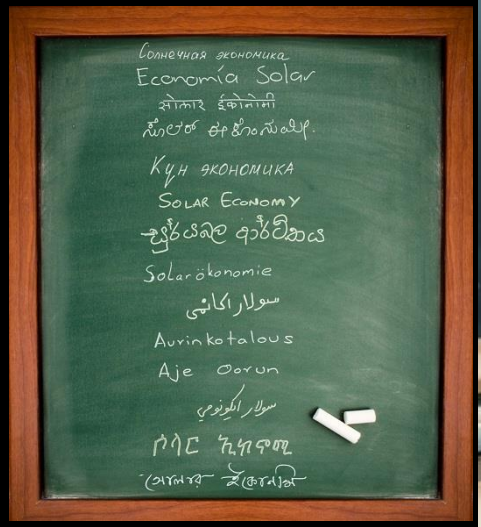
Exemplarily figures for EU-27 for the RES-2040 scenario:

- **solar PV**: annual installation 3x
- **wind onshore**: annual installations 3x
- **wind offshore**: annual installations 15x
- **per year**: 1.3 million **residential roofs** (1% of stock)
- **per year**: 104k **commercial and industrial** systems
- **per year**: 1000 standard 50 MW **PV plants**
- **per year** 5000-6000 **onshore turbines**
- **per year** about 1000 **offshore turbines**
- **in 2040**: **0.4-0.5%** of EU area covered with PV
- **in 2040**: **1.5%** of EU area **gross** covered with wind (**net 0.015%**)

Summary

- European energy transition needs to be accelerated by at least 10 years
  - absolute zero CO_2 emissions by 2035 would be required
  - efforts to achieve zero by 2035 may be beyond the European capabilities
- Electrification is low-cost and highly efficient
- Solar and wind power are central for comprehensive electrification (direct, indirect)
  - Solar PV (about 50% of supply) and wind power (about 40%)
- Hydrogen hype blocks the view on the real solutions
  - direct electrification
  - H_2-to-X for e-fuels and e-chemicals: e-ammonia, e-methanol, e-kerosene jet fuel
- Power-to-X Economy is THE core characteristic of the energy system

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



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NEO CARBON ENERGY

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

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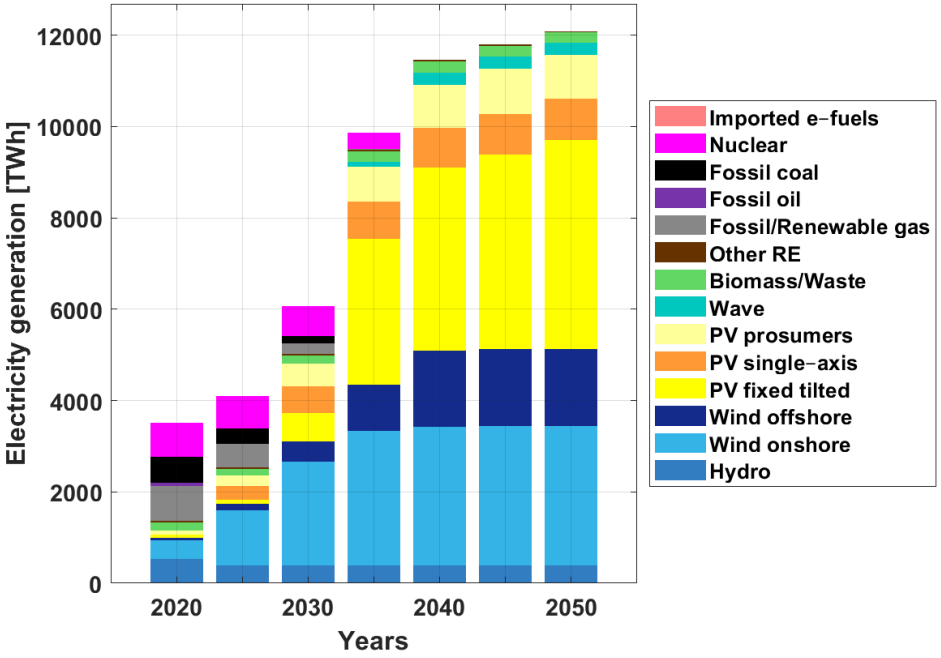
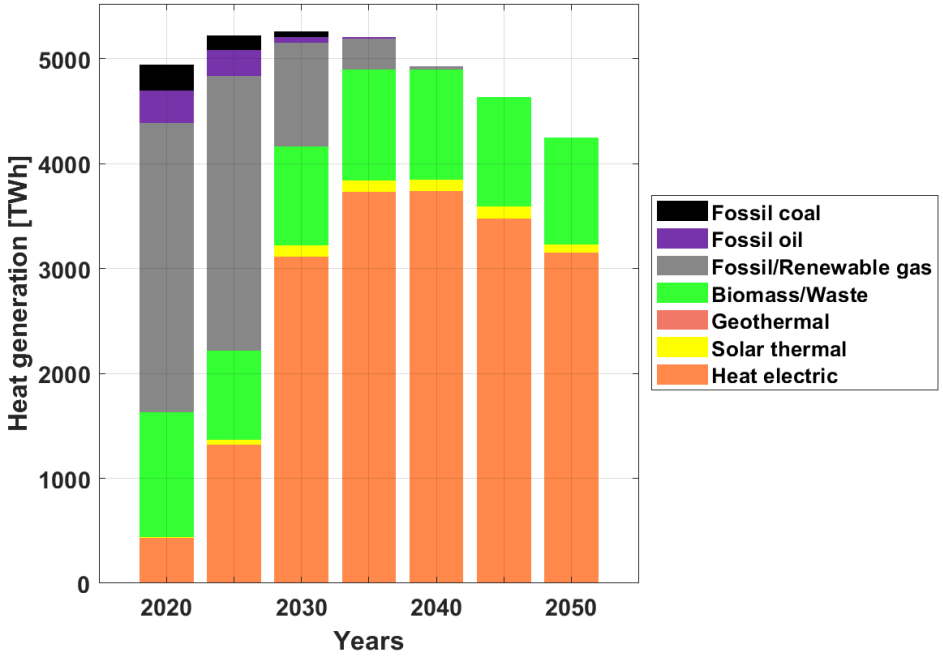
Energy Mix

RES-2040 Scenario



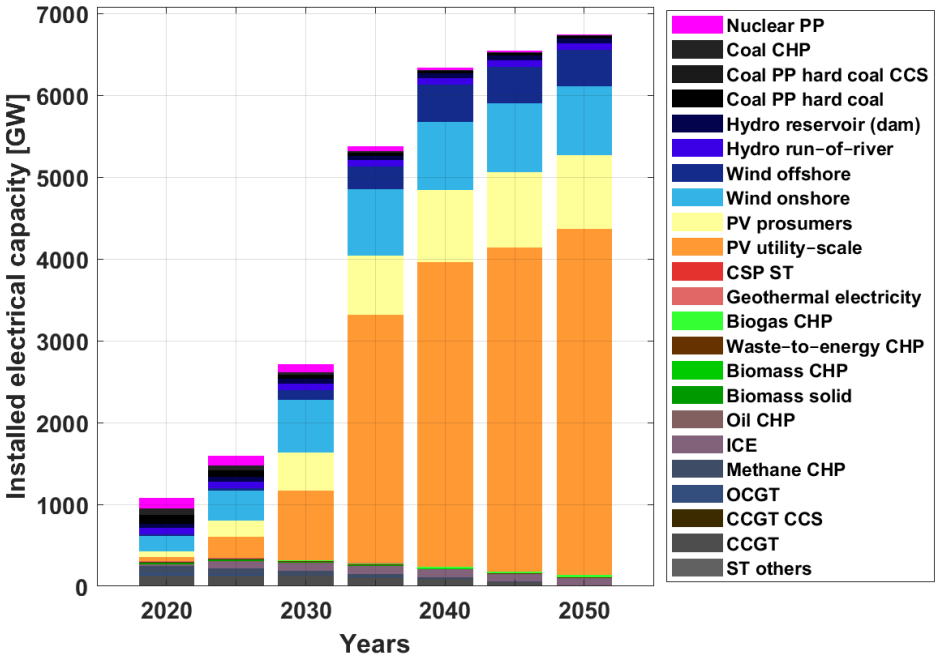


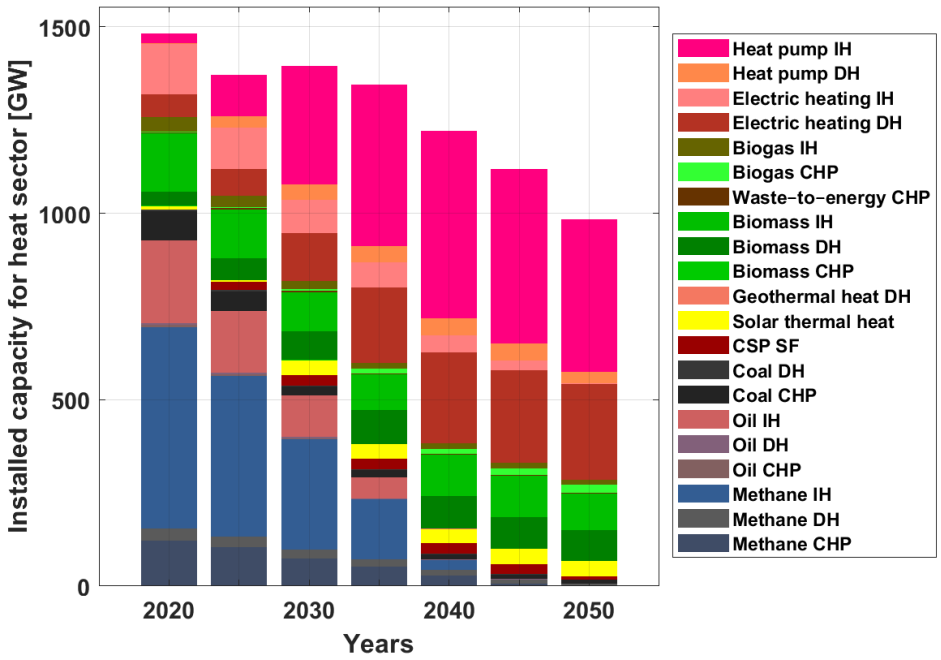
Key insights:

- Electricity generation grows rapidly up to 2040, with high levels of electrification across the different energy sectors, while heat generation declines steadily until 2050 after initial rise
- Solar PV supply increases from about 2000 TWh in 2030 to over 6500 TWh in 2050, becoming the main energy source
- Wind energy increases to around 5000 TWh by 2040 and remains stable up to 2050, complementing solar PV
- Fossil fuels generation declines rapidly and is almost eliminated by 2035 in electricity and by 2040 in heat
- A share of over 3000 TWh of heat generation by 2050 comes from heat pumps and electric heating on district and individual levels with some shares of electric and biomass-based heating, while gas and coal-based heating are drastically reduced
- Heat is utilised for industrial processes, which is dominated by fossil fuels and supplied fully by renewable fuels in 2050

Sectoral Outlook – Power & Heat Installed Capacities

RES-2040 Scenario



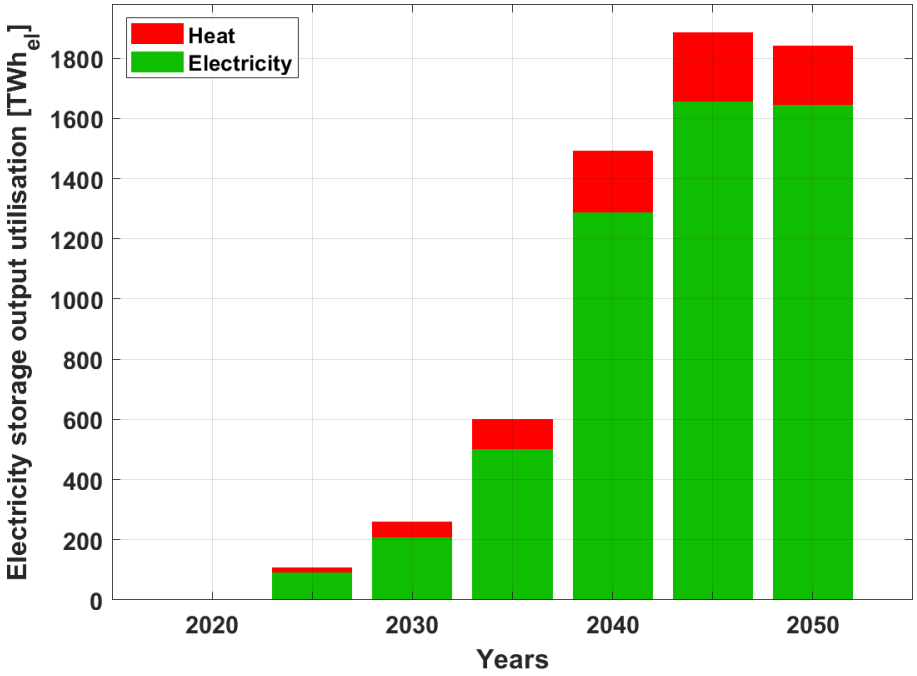


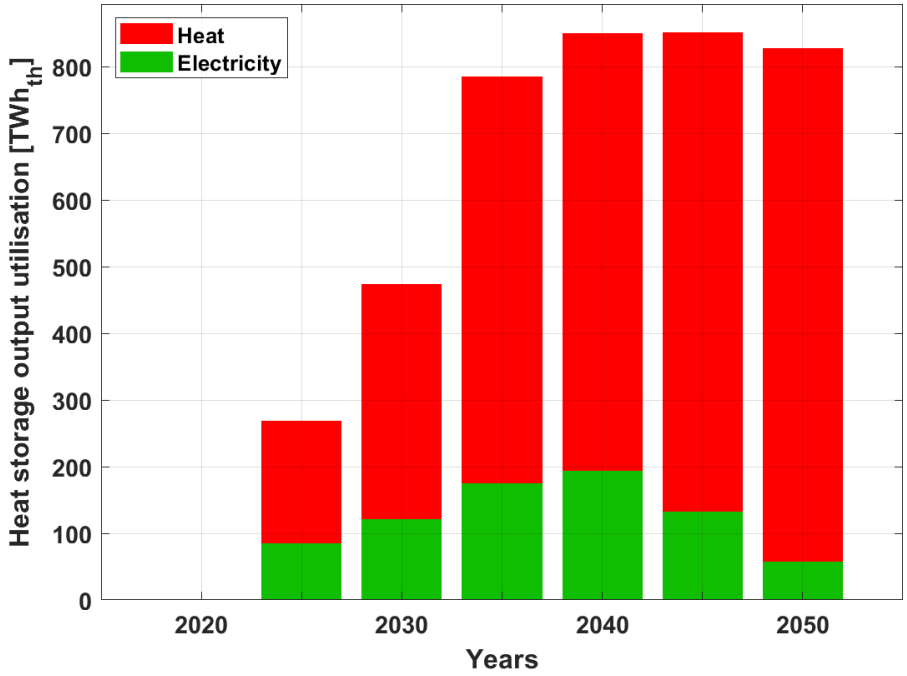
Key insights:

- In the RES-2040 scenario, solar PV with over 5000 GW, wind with over 1000 GW along with 200 GW of hydro and wave energy constitute the majority of installed capacities in 2050, with major ramping in 2035 to enable a rapid transition
- Wind dominates in the initial periods and solar PV takes over as the lowest costing energy sources with massive installations from 2030 onwards, while fossil fuel capacities are redundant and exit the energy system through the transition
- Heat pumps, electric heating, solar thermal and biomass-based heating constitute a majority of the installed capacities during the transition, with a significant decrease in gas, oil and coal-based heating in this period
- From a fossil fuels dominated power & heat sector across Europe in 2020 to a solar PV, wind and heat pumps dominated sector by 2040, with some hydropower and wave-based electricity and bioenergy-based heat enabling the transition

Energy Storage

RES-2040 Scenario





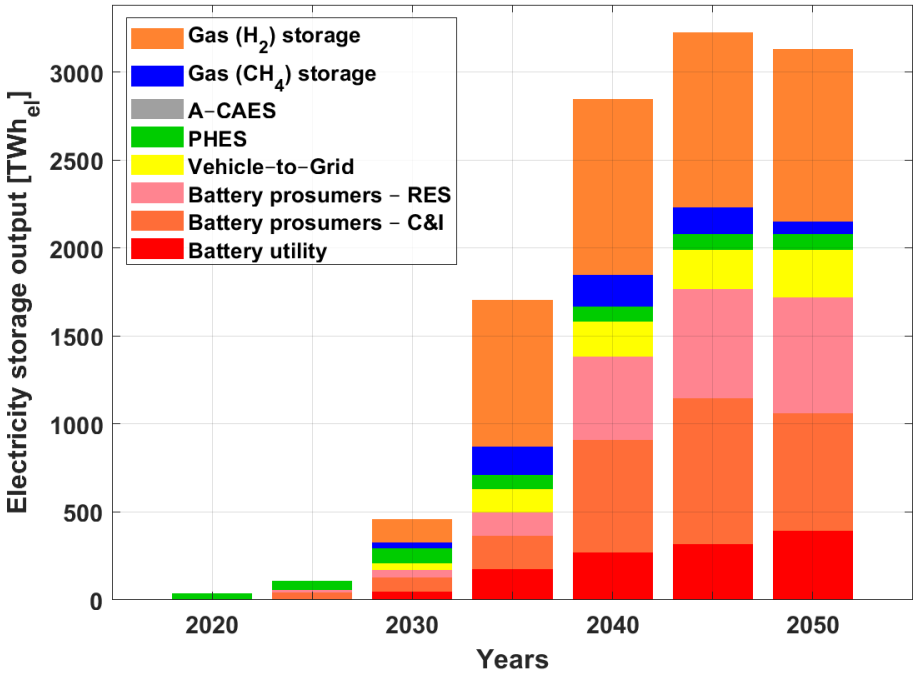
* heat storage includes gas and thermal storage technologies

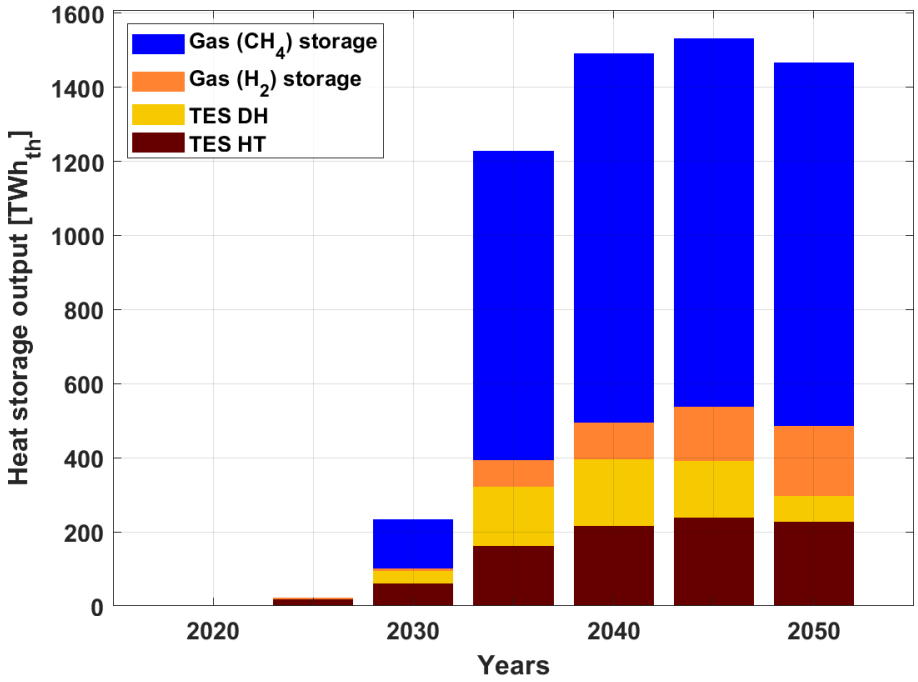
Key insights:

- Electricity and heat storage technologies play a vital role in the RES-2040 scenario, mainly later in the transition beyond 2030, complementing the high shares of renewables
- Electricity storage output grows substantially up to 2045 at around 1850 TWh$_{el}$, with minor shares of heat to electricity through the transition
- Heat storage grows through the transition to over 825 TWh$_{th}$ in 2040 and decline thereafter, electricity to heat contributing minor shares through the transition

Sectoral Outlook – Power & Heat Storage Output

RES-2040 Scenario



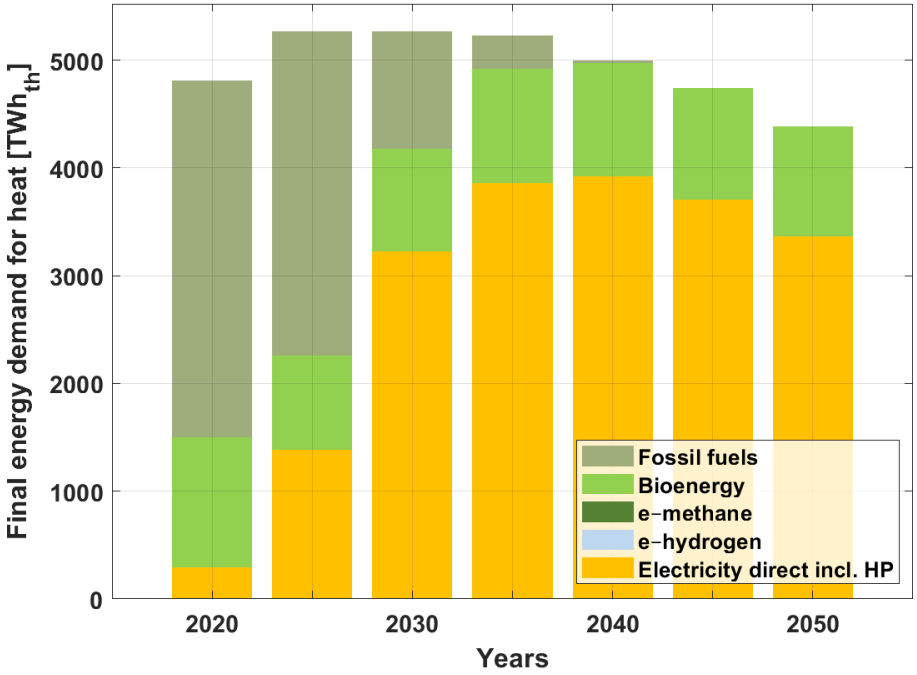


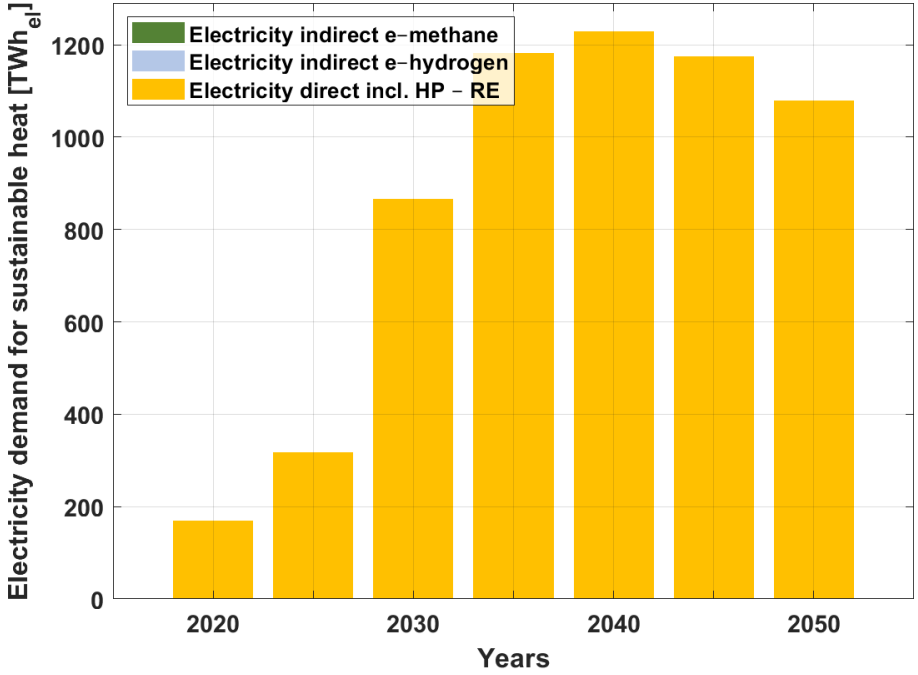
Key insights:

- In the RES-2040 scenario, V2G and prosumer batteries along with stored hydrogen contribute a major share of the electricity storage output with over 3200 TWh_{el} by 2050, major ramping in 2035 to complement the significant growth in renewables and electrification
- Pumped hydro energy storage contributes through the transition with minor shares
- Gas storage contributes nearly 1150 TWh_{th} of the heat storage output in 2045 covering predominantly seasonal demand, which is covered by fossil gas in the initial periods of the transition
- Thermal energy storage provides some shares of the heat storage output from 2030 onward, with around 400 TWh_{th} in 2040 with some shares from hydrogen beyond 2035

Sectoral Outlook – Demand and Electrification of Heat

RES-2040 Scenario

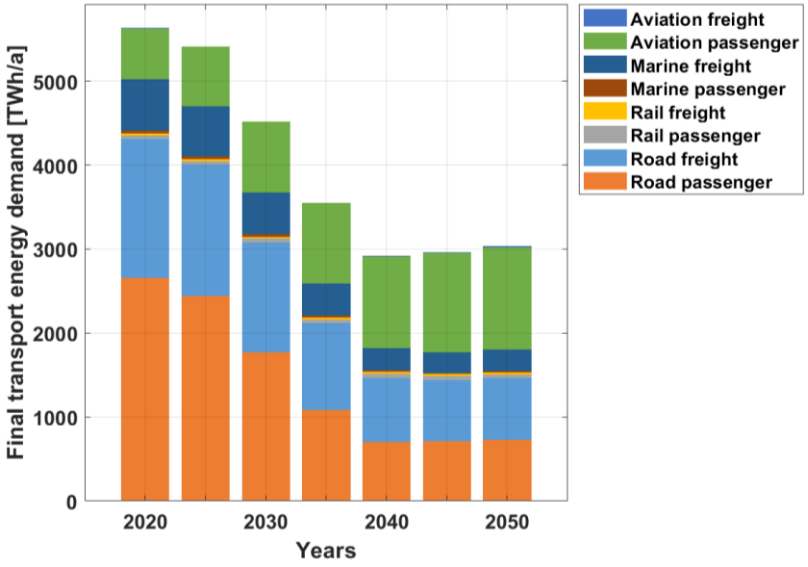


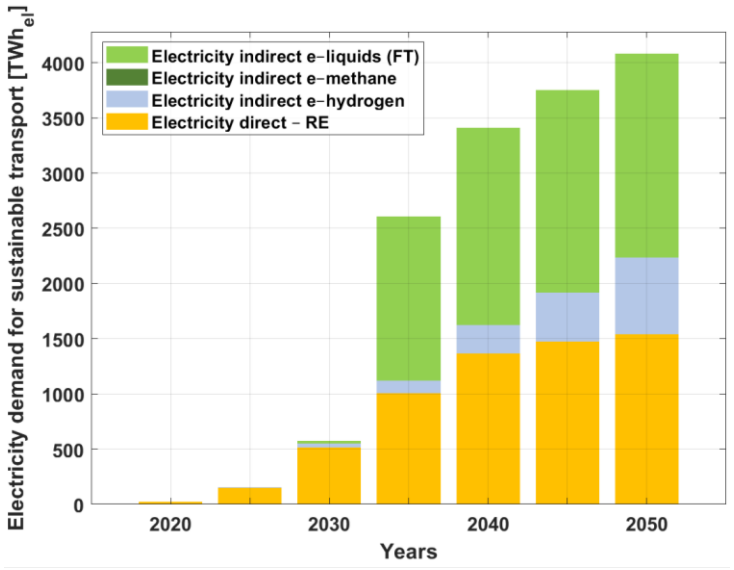


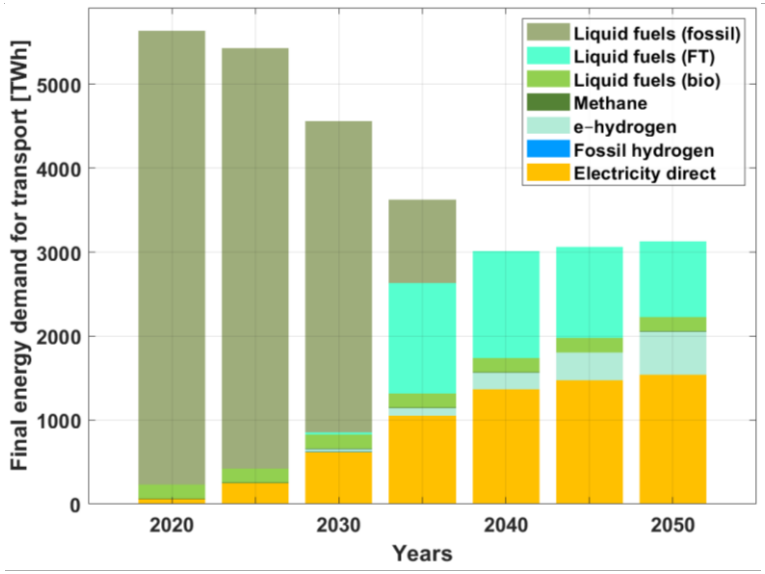
Key insights:

- In the RES-2040 scenario, final heat energy demand declines from around 5100 TWh/a in 2030 to around 4300 TWh/a by 2050, driven by efficiency gains and massive electrification
- Fossil fuel consumption in the heat sector is observed to decline through the transition from over 70% in 2020 to zero by 2040, driven by electricity, electricity-based fuels and sustainable bioenergy
- Fuels produced by renewable electricity and bioenergy contribute some shares of the final energy demand in 2050
- Electrification of the heat sector creates an electricity demand of over 1200 TWh$_{el}$ by 2040, which declines to about 1300 TWh$_{el}$ by 2050 with increasing efficiency levels
- Sustainable bioenergy supplies heat through the transition with nearly 30% in 2050, equivalent to current shares

Sectoral Outlook – Energy Demand and Electrification of Transport
RES-2040 Scenario





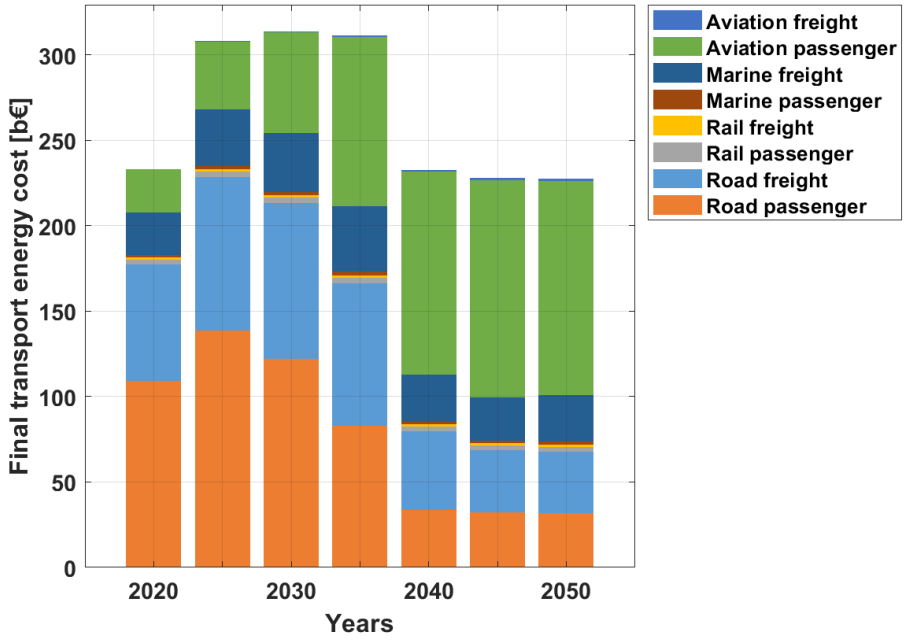


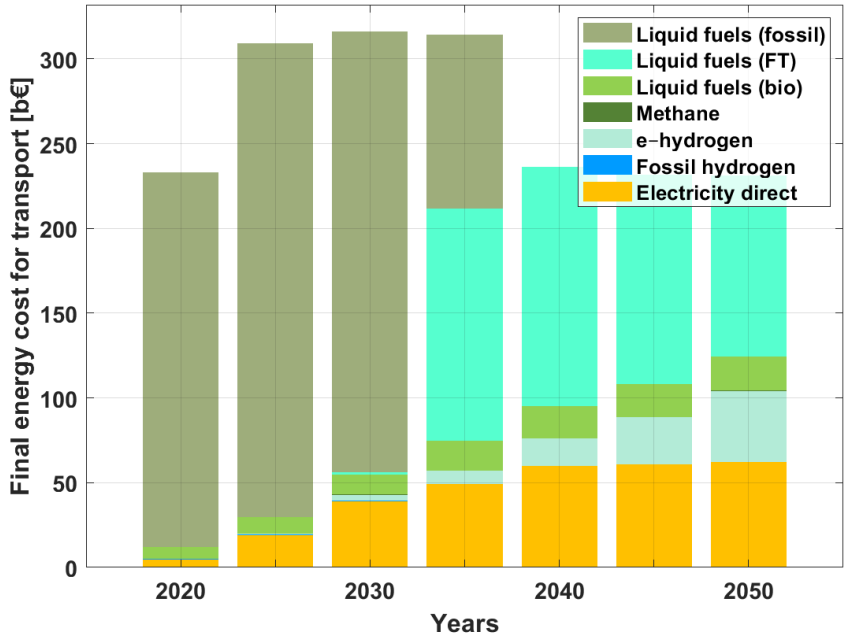
Key insights:

- In the RES-2040 scenario, final transport energy demand decreases from around 5600 TWh/a in 2020 to under 3000 TWh/a by 2050, driven by efficiency gains from electrification, predominantly in road transport
- Fossil fuel consumption in transport is observed to decline through the transition from over 90% in 2020 to zero by 2040
- Liquid fuels produced by renewable electricity contribute more than 30% of the final energy demand in 2050
- Hydrogen constitutes more than 15% of the final energy demand in 2050, with some shares of sustainable biofuels
- Electrification of the transport sector creates an electricity demand of over 4000 TWh_{el} by 2050, massive demand for liquid fuels in 2050

Sectoral Outlook – Transport Final Energy Costs

RES-2040 Scenario



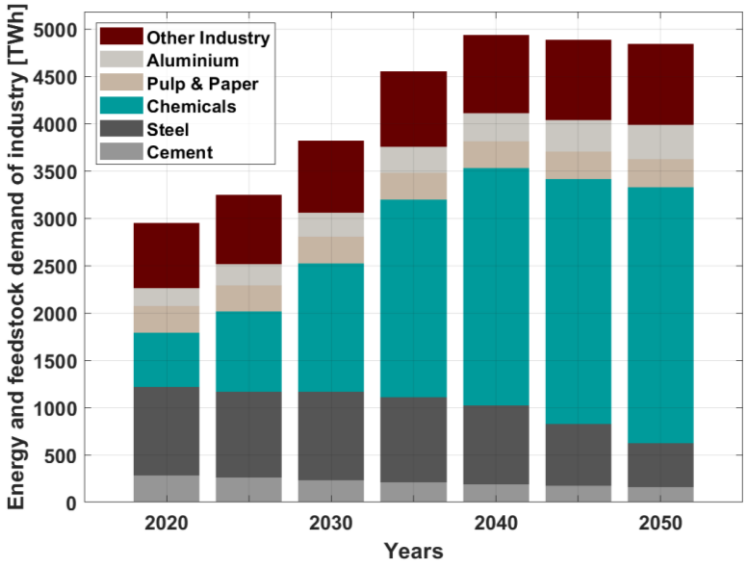


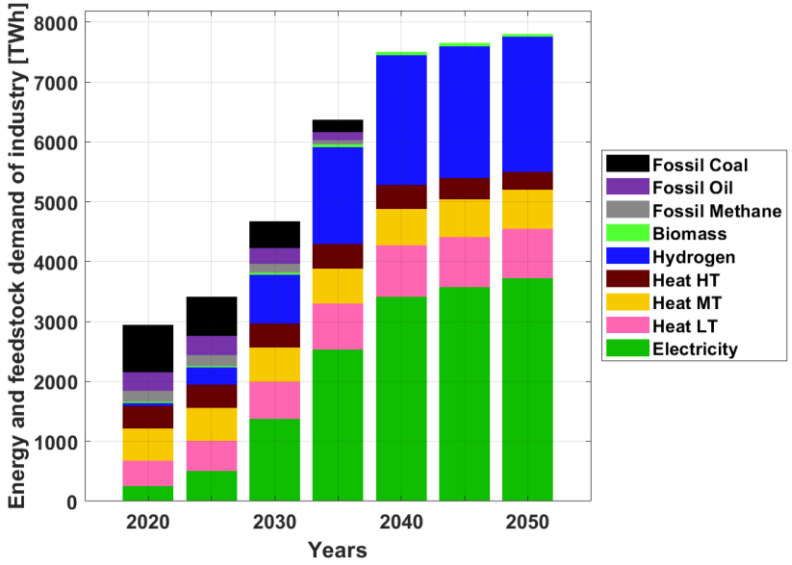
* FT units produce naphtha as by-product, that is included in overall system costs but not in transport cost

Key insights:

- In the RES-2040 scenario, total annual energy costs for transport are in the range of 230-310 b€ through the transition period with a decline from around 310 b€ in 2030 to about 230 b€ by 2050
- Road transport forms a major share of the costs through the transition, beyond 2040 the aviation mode costs increase up to 2050
- The share of rail and marine mode costs remain steady through the transition
- Annual system costs transit from being heavily dominated by fossil fuel costs in 2020 to a more diverse share of costs across various technologies for electricity, e-fuels, e-hydrogen and sustainable biofuel production by 2040

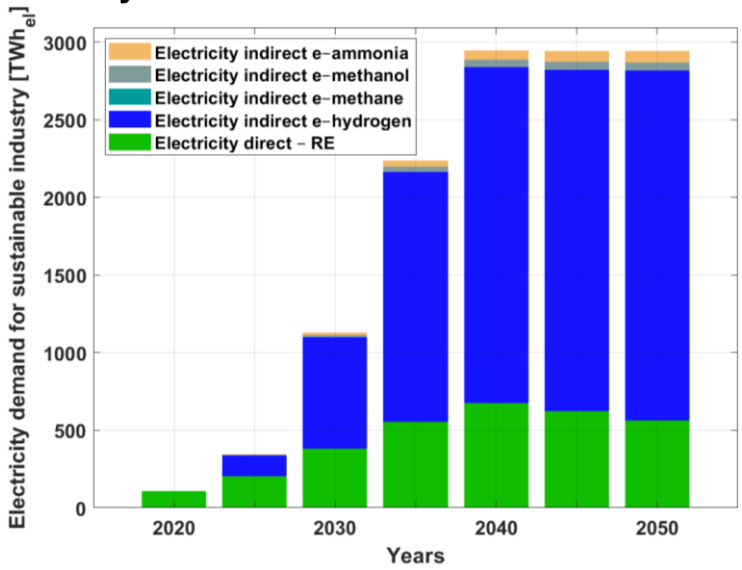
Sectoral Outlook – Energy, Fuels and Electricity Demand of Industry
RES-2040 Scenario





Key insights:

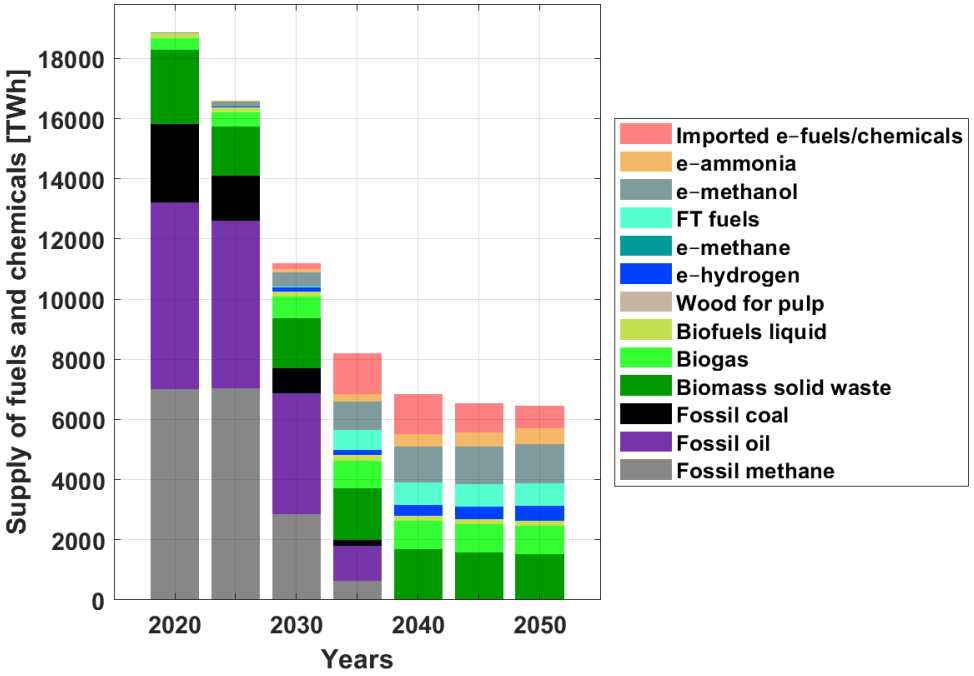
- Chemicals industry requires the most energy input, thereof almost all for e-hydrogen enabling the transition to sustainable chemicals production
- Other industries of Steel, Cement and others have a declining energy demand with electrification of processes
- Electricity evolves to be the main primary energy input, while most electricity is required for hydrogen production, mainly for chemicals, but also for green steel and cement
- In the RES-2040 scenario, a 100% renewables-based industry transition occurs by 2040

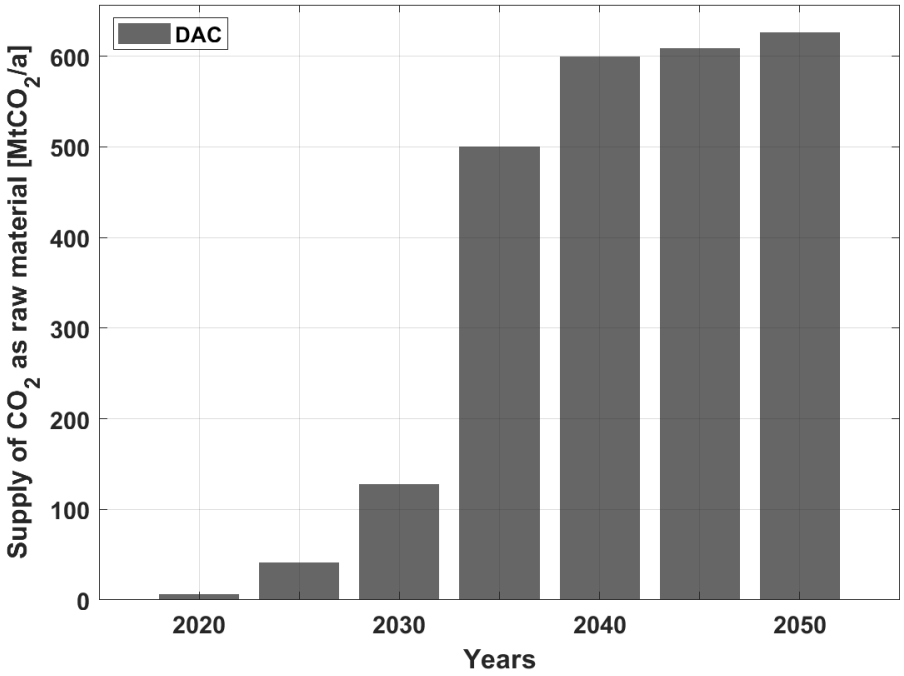


Accelerating the European Renewable Energy Transition
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Supply of Fuels, Chemicals and CO_2

RES-2040 Scenario



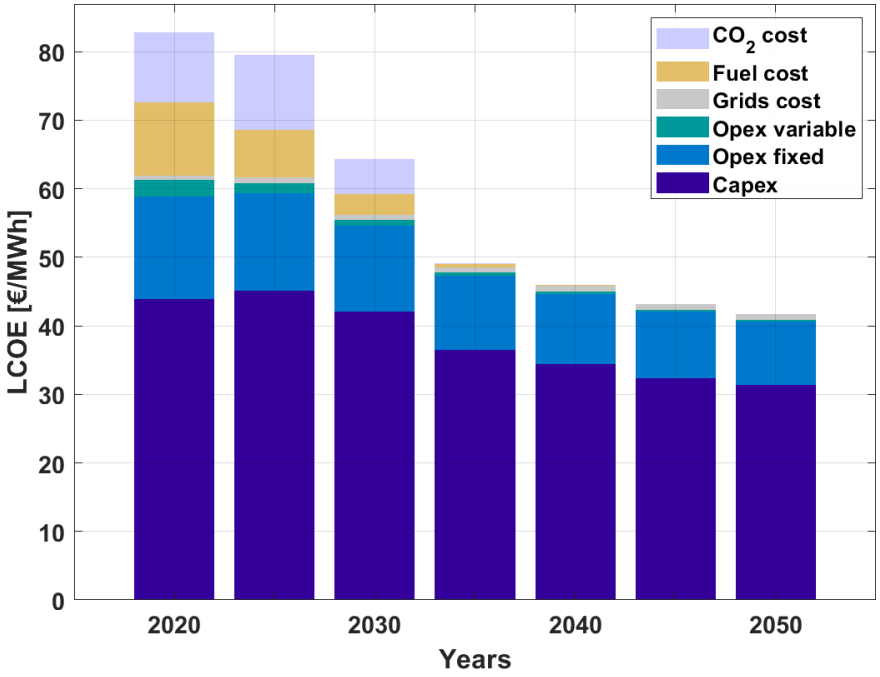


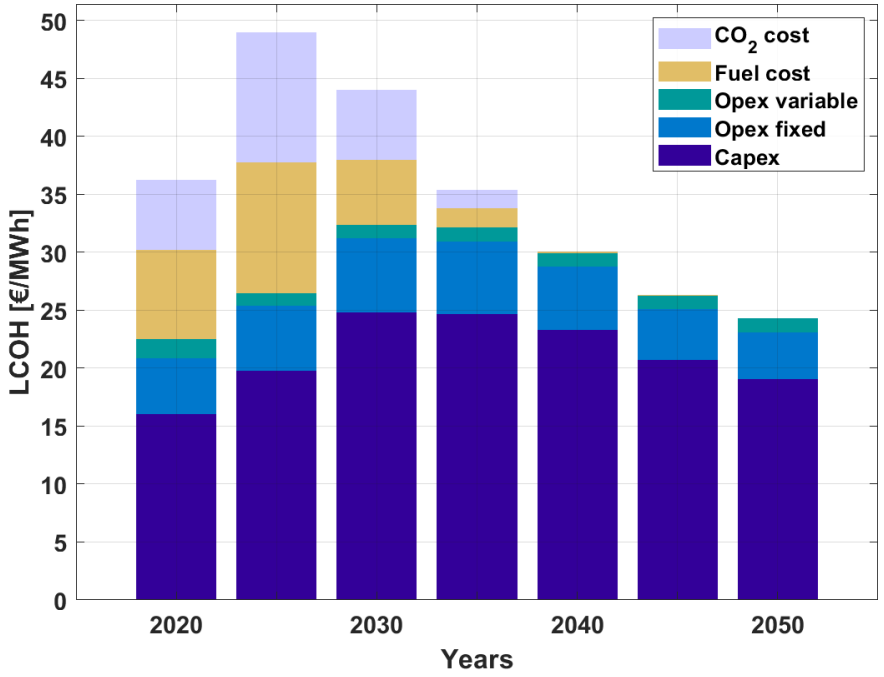
Key insights:

- e-fuel conversion technologies play a significant role in the RES-2040 scenario and the supply shares of e-fuels and e-chemicals increase significantly from 2035 onwards, with major shares of e-Methanol and biomass-based energy along with some shares of e-Ammonia, hydrogen and Fischer-Tropsch fuels supply up to 2050
- Imports of e-fuels kick in beyond 2030, peaking in 2040 and declining by 2050
- On the contrary, supply shares of fossil fuels diminishes significantly through the transition from a majority of the supply in 2020 to reaching zero by 2040, overall increase in electrification drives down the consumption of all fuels
- CO_2 plays a critical role in the production of e-fuels and e-chemicals as a vital ingredient mainly from Direct Air Capture (DAC), however sustainable point sources could have a potential role in the short term until 2030
- CO_2 from DAC increases significantly from 2030 onwards, with more than 600 $MtCO_2$/a by 2040 until 2050

Sectoral Outlook – Power & Heat Costs

RES-2040 Scenario



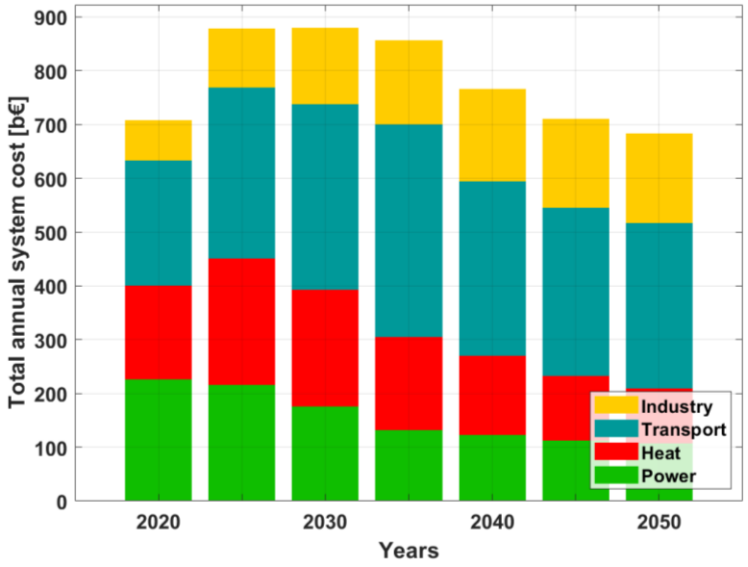


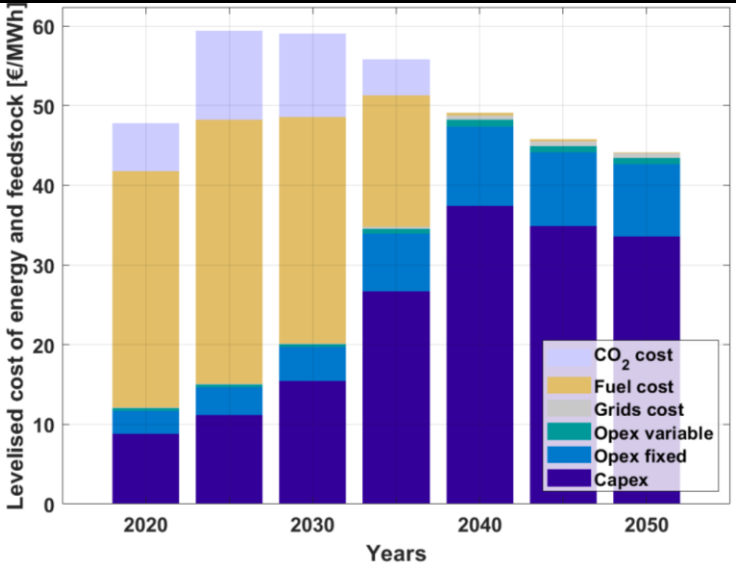
Key insights:

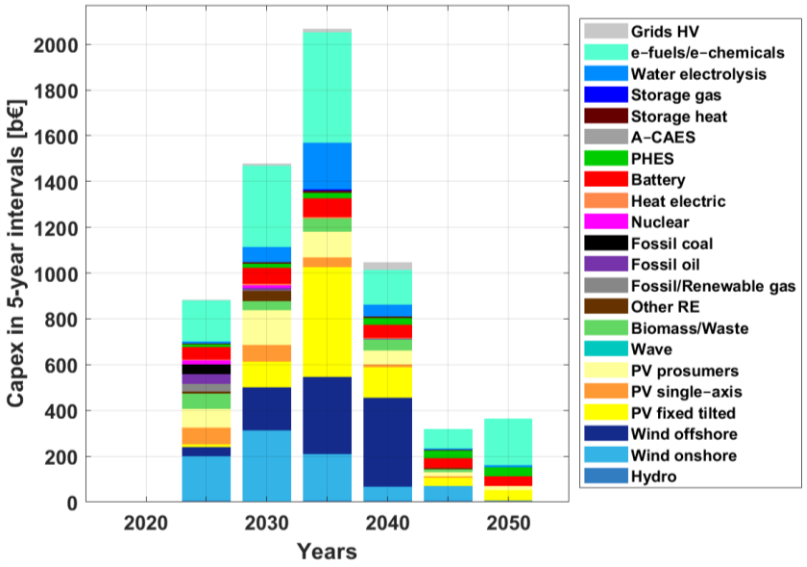
- In the RES-2040 scenario, LCOE of the power sector decreases substantially from around 82 €/MWh in 2020 to around 40 €/MWh by 2050, driven by low-cost renewables mainly solar PV & wind
- LCOE is predominantly comprised of capex, as the share of fuel costs decline through the transition and share of opex remains stable
- LCOH of the heat sector decreases through the transition from over 48 €/MWh in 2025 to about 24 €/MWh by 2050, as fuel costs are replaced by capex and opex
- LCOH is predominantly comprised of capex in 2050 with some shares of opex, driven by heat pumps and electric heating installations and major supply of e-fuels through the transition

Costs and Investments

RES-2040 Scenario



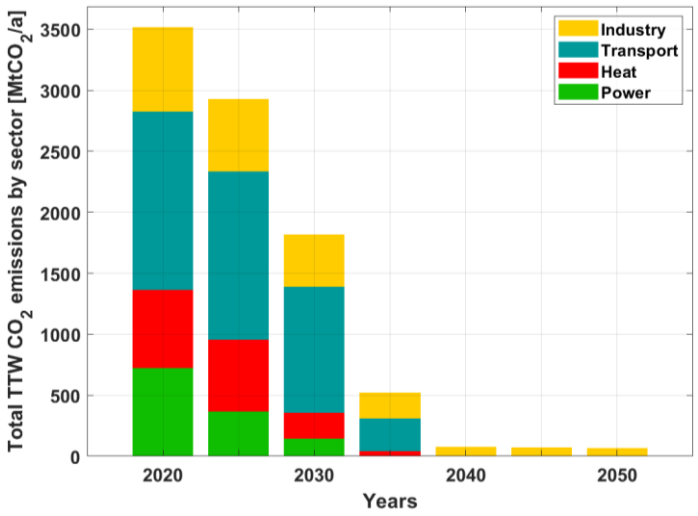


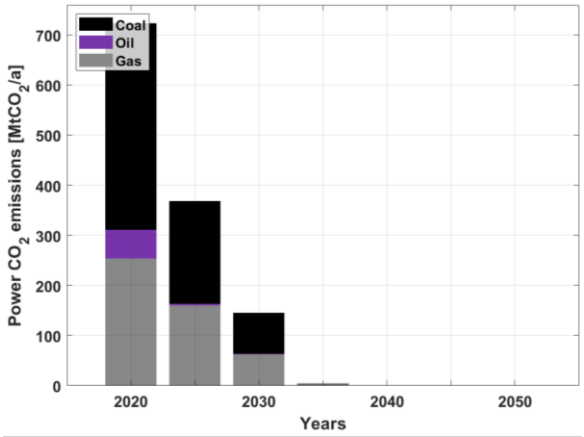


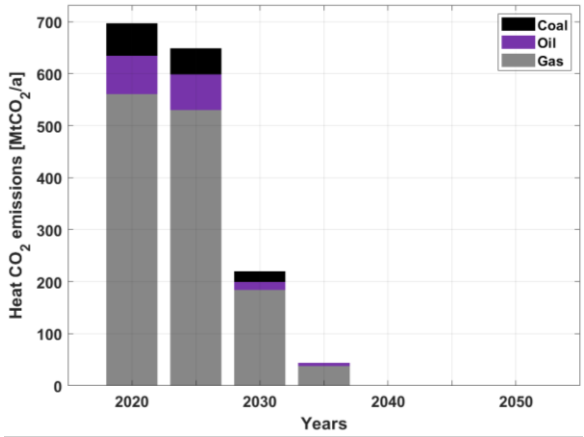
Key insights:

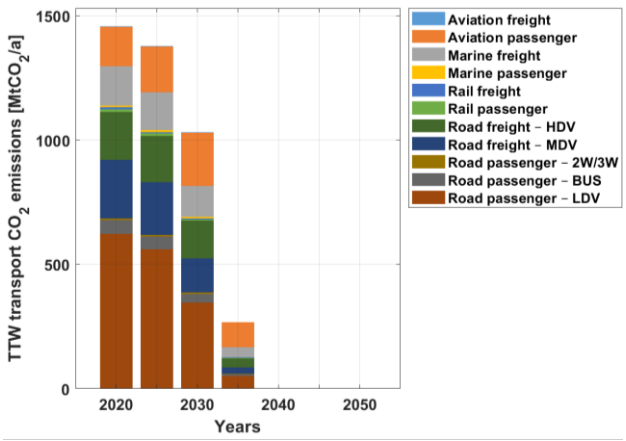
- The total annual system costs decline from around 875 b€ in 2025 through the transition period to under 700 b€ in 2050, and is distributed across the four major sectors of power, heat, transport and industry, with a major share in the transport sector up to more than 40% in 2050
- LCOEnergy declines from nearly 60 €/MWh in 2025 to around 45 €/MWh and is increasingly dominated by capital costs, as fuel costs continue to decline through the transition period
- Investments are well spread across a range of technologies with major investments in wind, PV, heat pumps and electric heating along with e-fuels conversion technologies up to 2050
- The peak investments are in 2035 with over 2050 b€

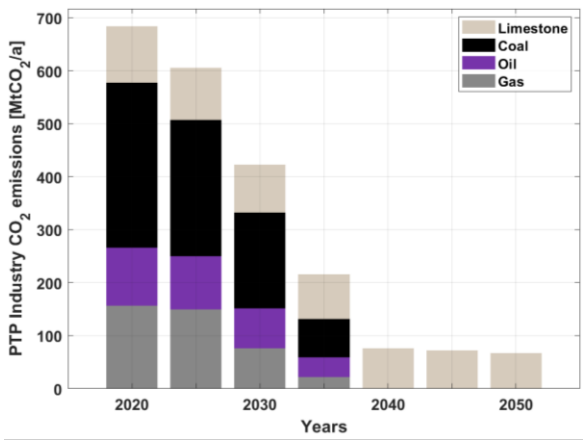
CO_2 Emissions
RES-2040 Scenario







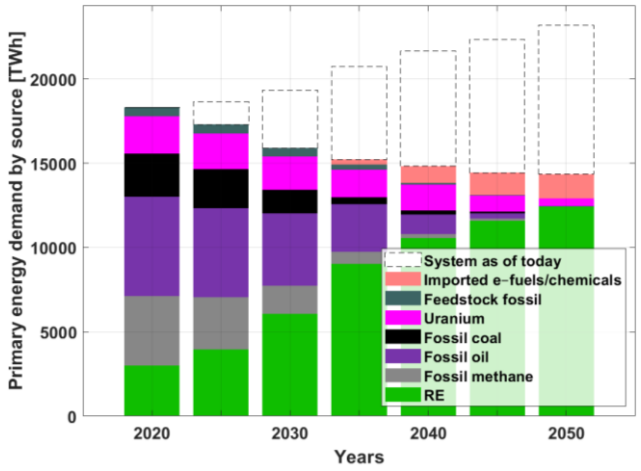




Key insights:

- In the RES-2040 scenario, CO_2 emissions are reduced from over 3500 $MtCO_2$ in 2020 to zero by 2040 across all energy sectors
- Coal and gas in the power and heat sectors emit majority in the 2020s with rapid decline to zero by 2040
- Road and aviation modes contribute around 1300 $MtCO_2$ in 2020 and declines steadily to zero by 2040
- Industry undergoes a significant shift from emitting about 900 $MtCO_2$ towards zero CO_2 emissions by 2040, except some emissions from limestone utilisation prevalent in 2050, which can be offset by natural carbon sinks or storage

Efficiency Gains



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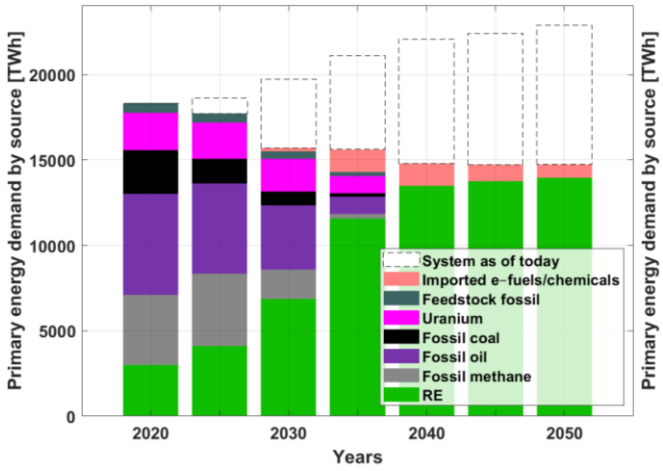
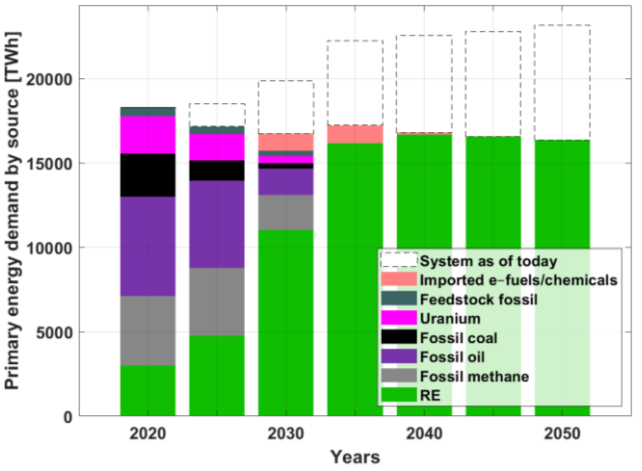


Renewable Energy System - 2040



Renewable Energy System - 2035

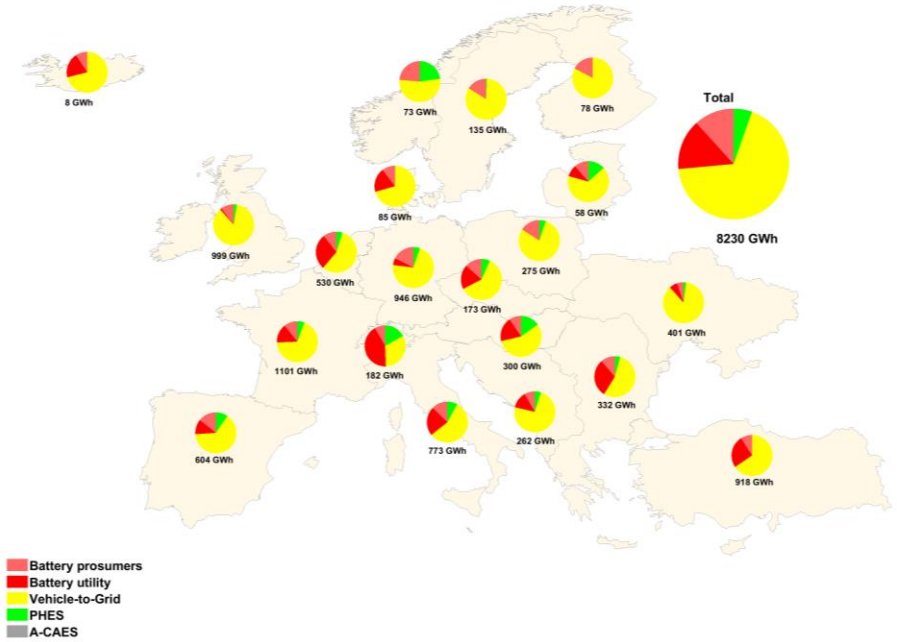
	Unit	EED 2030 compared to 2007 ref scenario		EED 2030 compared to 2020 ref scenario	
		Primary energy	Final energy	Primary energy	Final energy
Reference	TWh	21 946	16 468	13 072	10 048
REF	TWh	11 489	10 587	11 489	10 587
RES-2040	TWh	11 240	10 580	11 240	10 580
RES-2035	TWh	11 854	10 838	11 854	10 838
REF	% of ref.	52%	64%	88%	105%
RES-2040	% of ref.	51%	64%	86%	105%
RES-2035	% of ref.	54%	66%	91%	108%

Key insights:

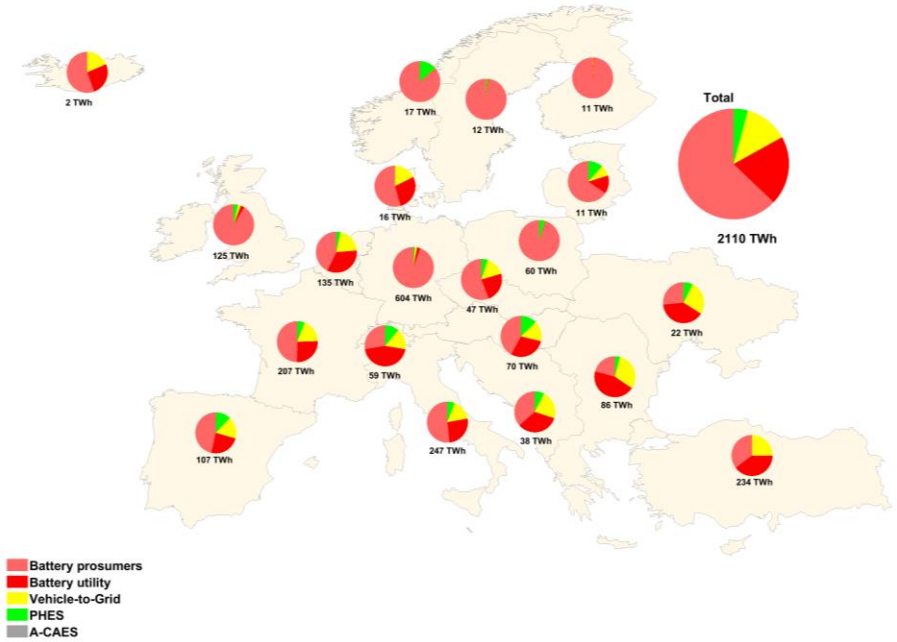
- In all the 3 scenarios, a transition leads to higher efficiency of the system compared to ref scenarios (EED), even though the FED is higher than 2020 scenario estimate, the PED is significantly lower
- Electrification leads to efficiency improvements in some areas and to additional energy demand in others, especially in transport and chemical industry, mainly for the production of e-fuels and e-chemicals resulting in higher FED in RES-2035 scenario
- Efficiency gains are challenging to visualise in terms of PED and FED, but compared to the current energy system assumed to continue until 2050, the efficiency gains are substantial: 34% (RES-2035), 40% (RES-2035) and 42% (REF) in 2050

Regional Outlook – Electricity storage capacities and generation in 2050 RES-2040 Scenario

Regional electricity storage capacities



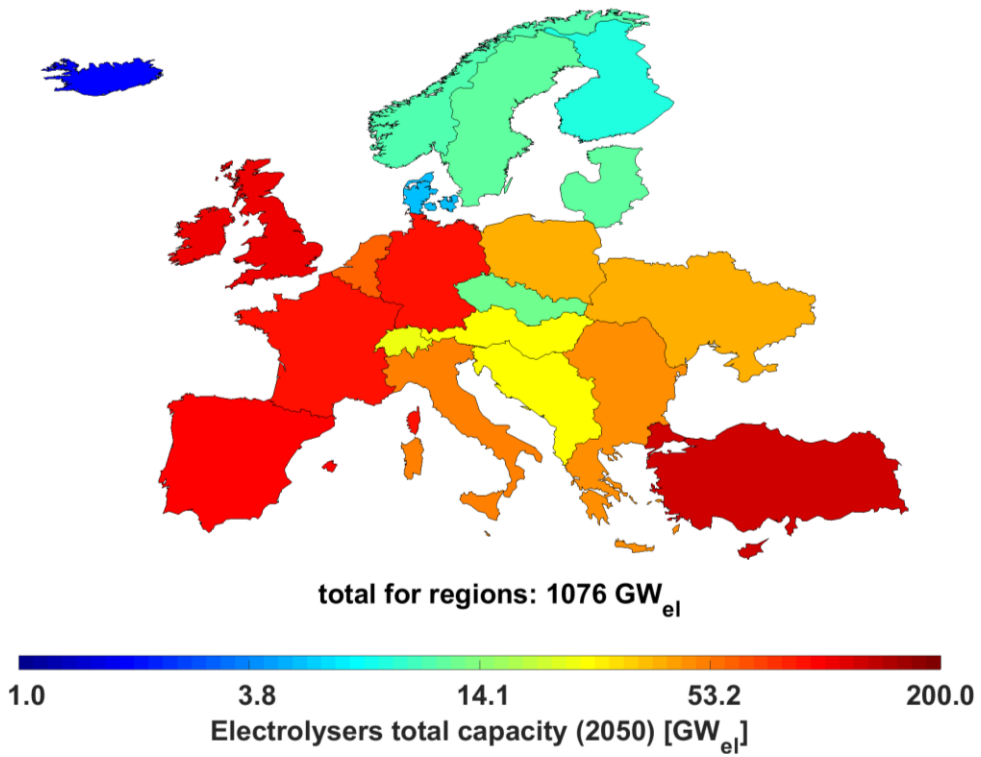
Regional electricity storage annual generation

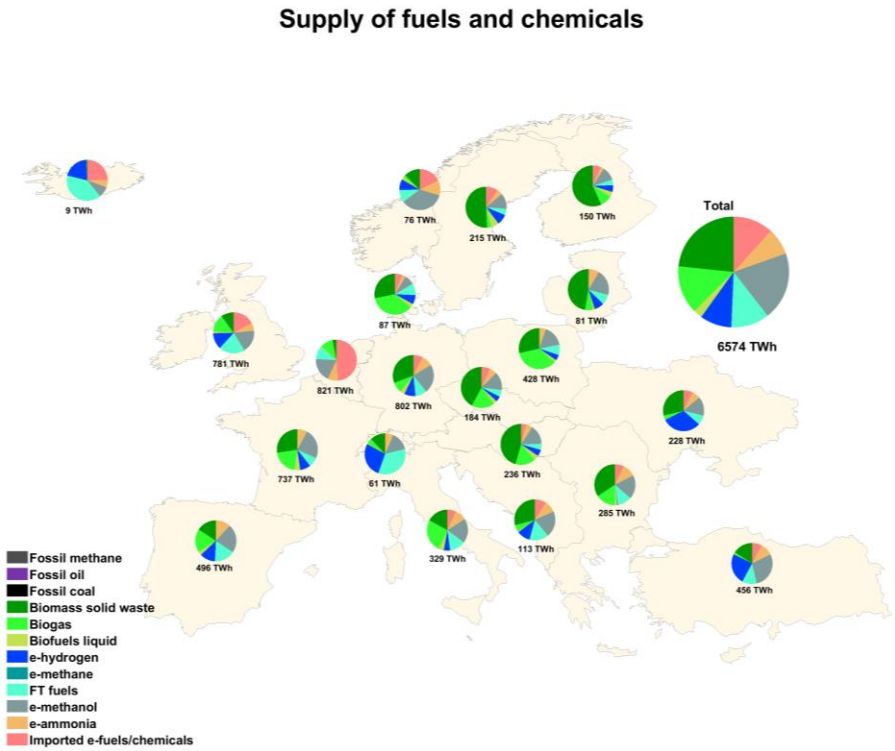


Key insights:

- V2G, utility-scale and prosumer batteries contribute a major share of the electricity storage capacities, with some shares of pumped hydro energy storage and compressed air energy storage by 2050 across Europe with 8230 GWh capacity and output of 2110 TWh in 2050
- Storage capacities are much higher in the southern parts of Europe compared to the northern regions, predominantly complementing solar PV generation
- Batteries, both prosumers and large-scale, deliver the largest shares of output by 2050 across Europe
- V2G and PHES contribute some shares across the regions of Europe

Regional Outlook – Electrolysers, e-fuels, e-chemicals and imports in 2050
RES-2040 Scenario

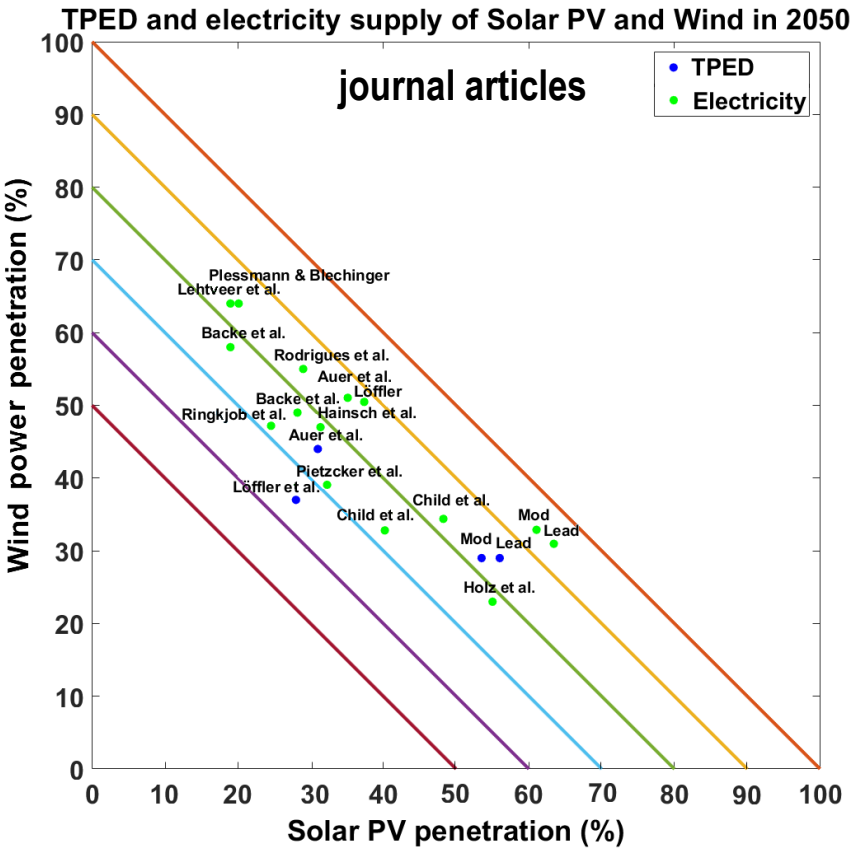




Key insights:

- Electrolysers play a vital role in meeting the hydrogen demand across Europe with major capacities in central and southern regions of Europe in 2050
- The total supply of fuels and chemicals including imports are 6574 TWh in 2050 across Europe
- Central, western and southern regions of Europe emerge as the production hubs of e-fuels and e-chemicals, that play a critical role in the transition particularly in the transport and industry sectors
- Europe can transition from heavily reliant on imported fossil fuels to locally produced green fuels by 2050

Solar PV Share in 100% RE Studies for Europe

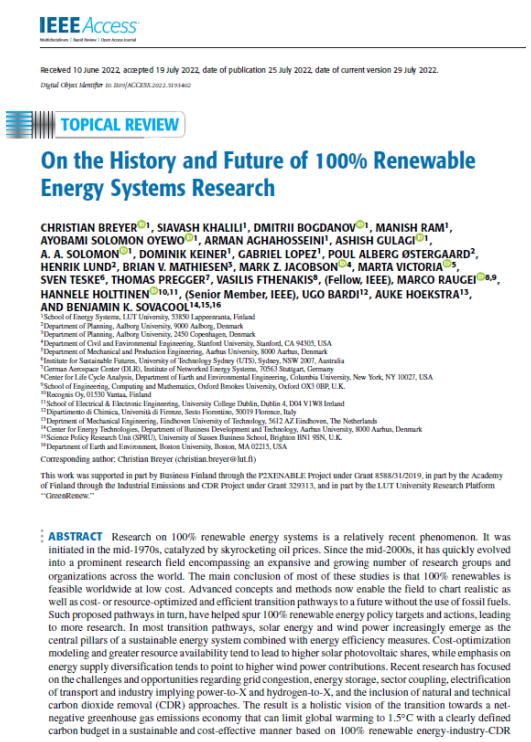


Key insights:

- 2 main groups:
  - high PV & wind: more PV
  - high PV & wind: more wind
- PV & wind electricity share >80% standard
- PV & wind TPED share in 65-85% range
- PV shares around 30-40% by 2050 standard for Europe
- Victoria et al. not in diagram (exact numbers missing), but 50-60% PV share
- This research finds 61-63% PV share
- Reasons for PV shares >50%
  - low-cost of PV & batteries & electrolysers
  - high levels of electrification
  - high levels of PtX: PV benefits strongly from H_2 buffering
- Difference between 50% and 60% PV share
  - PV differentiation: PV prosumers (RES, COM, IND), fixed and 1-axis plants
  - independent optimisation of PV options

- Major reports for public discourse document lack of up-to-date knowledge of consultants
  - McKinsey (20% PV share in 2050), DNV (15%), Navigant (14%); IEA WEO SDS (13%) NZE without regional data
  - lack of ambition: no 100% RE scenario known, much fossil CCS and nuclear, low levels of electrification
  - oversimplified models: low temporal and spatial resolution, no cost optimisation, low levels of PtX and sector coupling
  - cost assumptions used often violate market trends (too high renewables cost, too low CCS & nuclear costs)

100% Renewables Energy Systems Research



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TOPICAL REVIEW

On the History and Future of 100% Renewable Energy Systems Research

CHRISTIAN BREYER[1], SIAVASH KHALILI[1], DMITRII BOGDANOV[1], MANISH RAM[1], AYOBAMI SOLOMON OYEWO[1], ARMAN AGHAHOSSEINI[1], ASHISH GULAGI[1], A. A. SOLOMON[1], DOMINIK KEINER[1], GABRIEL LOPEZ[1], POUL ALBERG ØSTERGAARD[2], HENRIK LUND[2], BRIAN V. MATHIESEN[3], MARK Z. JACOBSON[4], MARTA VICTORIA[5], SVEN TESKE[6], THOMAS PREGGER[7], VASILIS FTHENAKIS[8], (Fellow, IEEE), MARCO RAUGEI[8,9], HANNELE HOLTTINEN[10,11], (Senior Member, IEEE), UGO BARDI[12], AUKE HOEKSTRA[13], AND BENJAMIN K. SOVACOOL[14,15,16]

[1]School of Energy Systems, LUT University, 53850 Lappeenranta, Finland
[2]Department of Planning, Aalborg University, 9000 Aalborg, Denmark
[3]Department of Planning, Aalborg University, 2450 Copenhagen, Denmark
[4]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, USA
[5]Department of Mechanical and Production Engineering, Aarhus University, 8000 Aarhus, Denmark
[6]Institute for Sustainable Futures, University of Technology Sydney (UTS), Sydney, NSW 2007, Australia
[7]German Aerospace Center (DLR), Institute of Networked Energy Systems, 70563 Stuttgart, Germany
[8]Center for Life Cycle Analysis, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA
[9]School of Engineering, Computing and Mathematics, Oxford Brookes University, Oxford OX3 0BP, U.K.
[10]Recognia Oy, 01530 Vantaa, Finland
[11]School of Electrical & Electronic Engineering, University College Dublin, Dublin 4, D04 V1W8 Ireland
[12]Dipartimento di Chimica, Università di Firenze, Sesto Fiorentino, 50019 Florence, Italy
[13]Department of Mechanical Engineering, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands
[14]Center for Energy Technologies, Department of Business Development and Technology, Aarhus University, 8000 Aarhus, Denmark
[15]Science Policy Research Unit (SPRU), University of Sussex Business School, Brighton BN1 9SN, U.K.
[16]Department of Earth and Environment, Boston University, Boston, MA 02215, USA

Corresponding author: Christian Breyer (christian.breyer@lut.fi)

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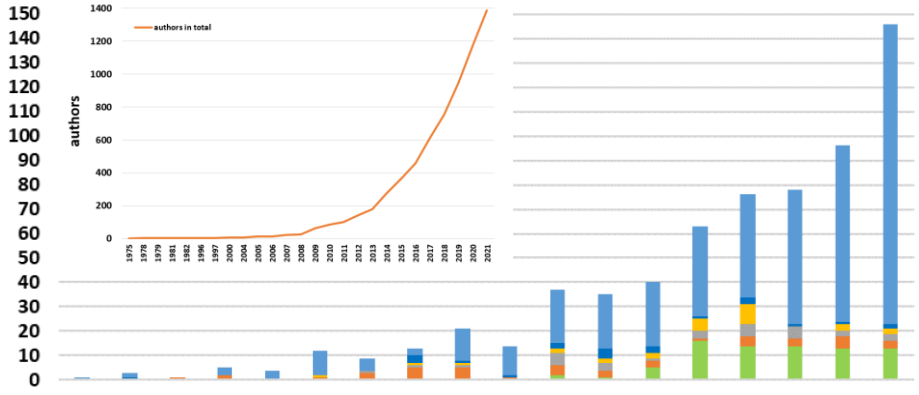
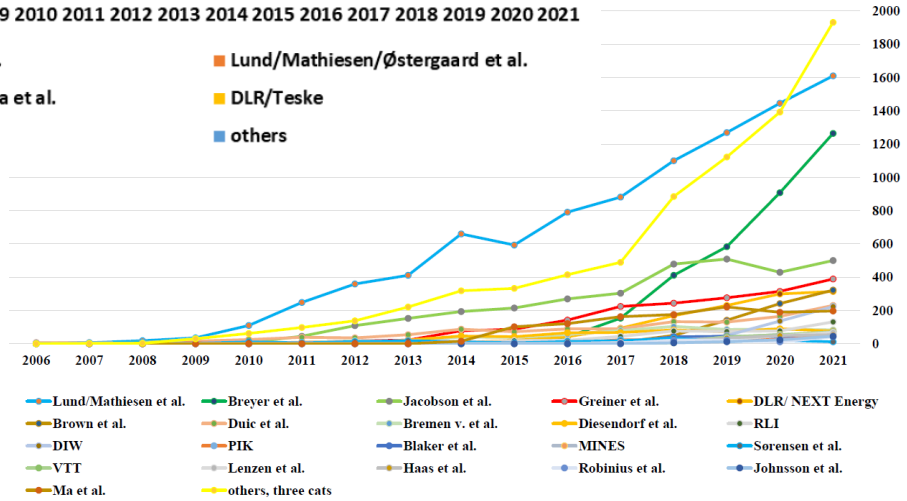
ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and organizations across the world. The main conclusion of most of these studies is that 100% renewables is feasible worldwide at low cost. Advanced concepts and methods now enable the field to chart realistic as well as cost- or resource-optimized and efficient transition pathways to a future without the use of fossil fuels. Such proposed pathways in turn, have helped spur 100% renewable energy policy targets and actions, leading to more research. In most transition pathways, solar energy and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimization modeling and greater resource availability tend to lead to higher solar photovoltaic shares, while emphasis on energy supply diversification tends to point to higher wind power contributions. Recent research has focused on the challenges and opportunities regarding grid congestion, energy storage, sector coupling, electrification of transport and industry implying power-to-X and hydrogen-to-X, and the inclusion of natural and technical carbon dioxide removal (CDR) approaches. The result is a holistic vision of the transition towards a net-negative greenhouse gas emissions economy that can limit global warming to 1.5°C with a clearly defined carbon budget in a sustainable and cost-effective manner based on 100% renewable energy-industry-CDR



From top to bottom: development of
- authors in the field
- articles published
- citations received

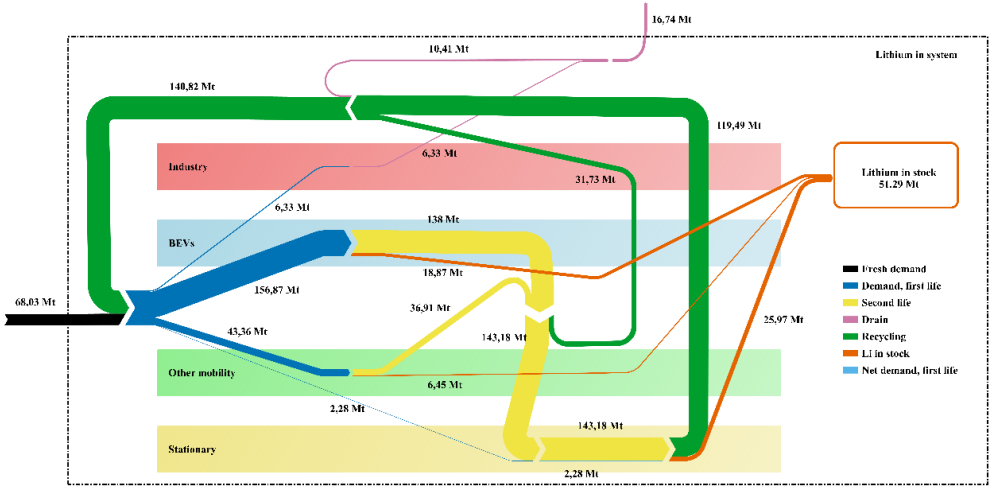


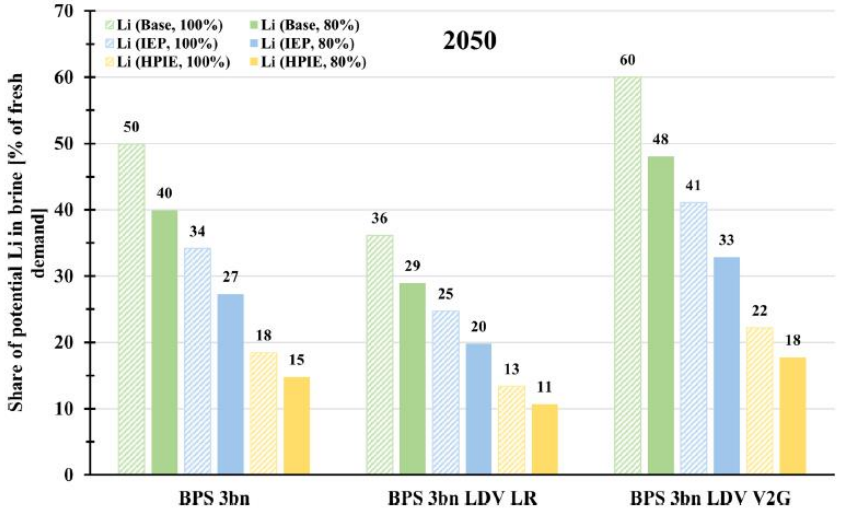
Key insights:

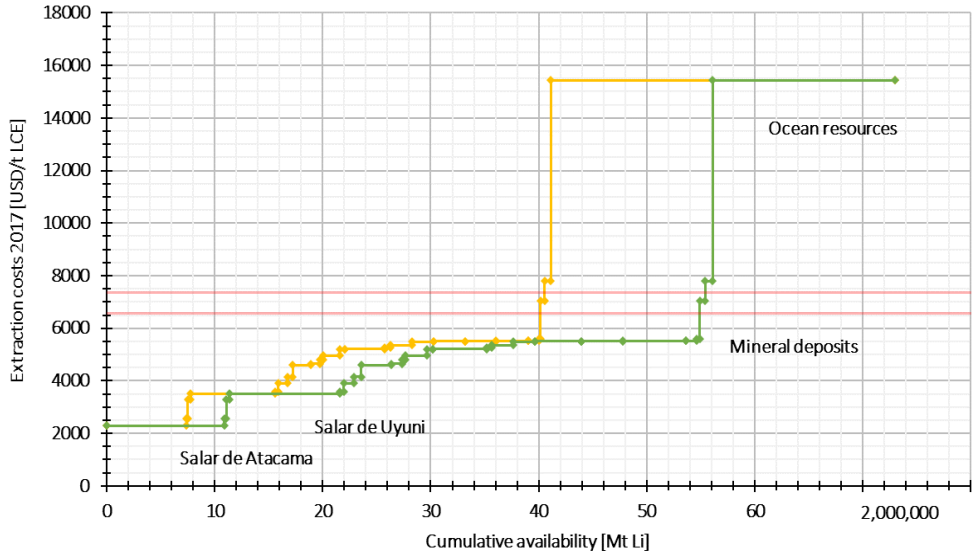
- Research field is growing at high dynamics
- Entirely renewable systems research now established
- Three leading teams: Lund et al. (Aalborg, DK), Breyer et al. (LUT, FI), Jacobson et al. (Stanford, US)
- International organisations are conservative in adoption of new insights, e.g. IPCC, IEA, World Bank, etc.

source: Breyer et al., 2022. IEEE Access 10, 78176-78218

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 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
- Extraction of Lithium from desalination brines may contribute in addition 15-50% of Lithium demand

source: Greim, Solomon, Breyer et al., 2020. Nature Communications, 11, 4570
Lundaev, Solomon, Caldera, Breyer, 2022. Minerals Engineering, 185, 107652

LUT model in Comparison

We have been ranked as one of the more advanced energy models among all available energy models, which is capable of handling long-term energy transitions with high time resolution, high geospatial spread and importantly built-in sector coupling.

Among models used for highly renewable energy systems we are in lead together with EnergyPLAN.

Bottom-up long-term models	*Foresight approach*	*Resolution*				*Transparency*
		In time	*In space*	*In techno-economic detail*	*In sector coupling*	
LEAP [120]	Perfect foresight	Low	Low	Low	High	Medium
MARKAL/TIMES [101,102]	Perfect foresight	Low	Medium	Low	High	Low
OSeMOSYS [104,105]	Perfect foresight	Low	Medium	Low	High	High
Temoa [107,108]	Perfect foresight	Low	Medium	Low	High	High
MESSAGE [110]	Perfect foresight	Low	Medium	Low	High	Low
Balmorel [112]	Perfect foresight	High	High	Medium	Low	High
eMix [121]	Perfect foresight	Medium	Medium	High	Low	Low
EPLANoptTP [119]	Perfect foresight	High	Low	Low	High	Medium
Mahbub et al. [118]	Myopic	High	Low	Low	High	Medium
LUT [114,117]	Myopic	High	High	Medium	High	Medium

source: Prina et al., 2020. Renew Sustain Energy Rev, 129, 109917

Leading Energy System Models ranked by number of published journal articles. Some selected key functionalities of the leading ESMs are displayed, as they are regarded to be key for further progress in the field of 100% RE system analyses. Selection criterion had been more than five articles detected for 100% RE system analyses. Citations comprise the Scopus recordings until early July 2021 for the total and the annual value for 2020.

Model	articles	citations		model used for 100% RE		inter-connected multi-node	Full hourly	multi-sector	Detailed industry	relevant CDR	optimi-sation	simu-lation	transi-tion	over-night
		total	2020	earliest	latest									
EnergyPLAN	73	6670	1081	2006	2021	yes	yes	yes	no	no	no[a]	yes	no	yes
LUT model	63	1983	649	2015	2021	yes	yes	yes	Yes	no	yes	yes	yes	yes
HOMER	22	1044	228	2007	2021	no	yes	no	no	no	yes	yes	no	yes
TIMES	19	601	137	2011	2021	no	no	yes	yes	no	yes	yes	yes	yes
AU model	16	1188	145	2010	2018	yes	yes	no	no	no	yes	yes	no	yes
PyPSA	16	440	169	2017	2021	yes	yes	yes	no	no	yes	no	yes	yes
GENeSYS-MOD	10	141	57	2017	2021	yes	no	yes	no	no	yes	no	yes	no
LOADMATCH	10	925	240	2015	2021	no	yes	yes	no	no	no	yes	yes	no
REMix	10	439	118	2016	2018	yes	yes	yes	no	no	yes	yes	no	yes
ISA model	9	126	43	2016	2020	no	yes	yes	no	no	yes	no	no	yes
NEMO	7	566	82	2012	2017	yes	yes	no	no	no	yes	no	no	yes
H_2RES	6	674	47	2004	2011	no	yes	yes	no	no	no	yes	no	yes
MESAP/PlaNet	6	207	48	2009	2021	no	no	yes	no	no	no	yes	yes	yes
others	292	9204	1694											
total	550	24,600	4800											

[a] EnergyPLAN itself is not able for optimisation, however, the EPLANopt [45] derivative allows optimisations

source: Lopez, Breyer et al., 2022. Renew Sustain Energy Rev, 164, 112452

Accelerating the European Renewable Energy Transition
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE