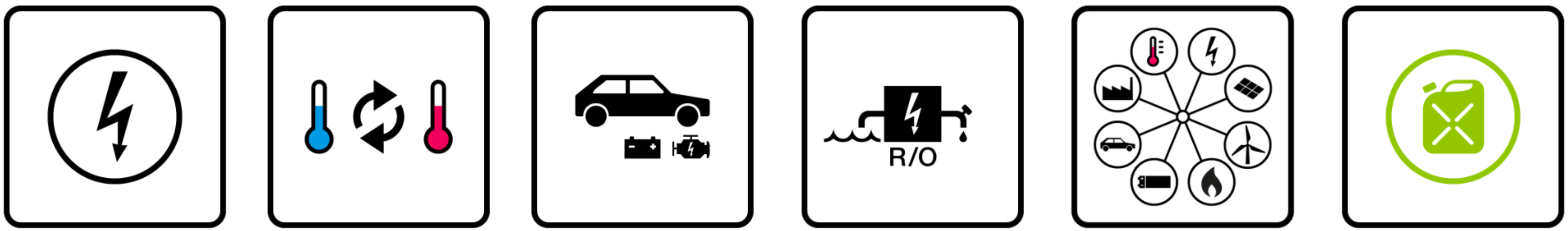
Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors Northeast Asia



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DBU Deutsche Bundesstiftung Umwelt

STIFTUNG MERCATOR

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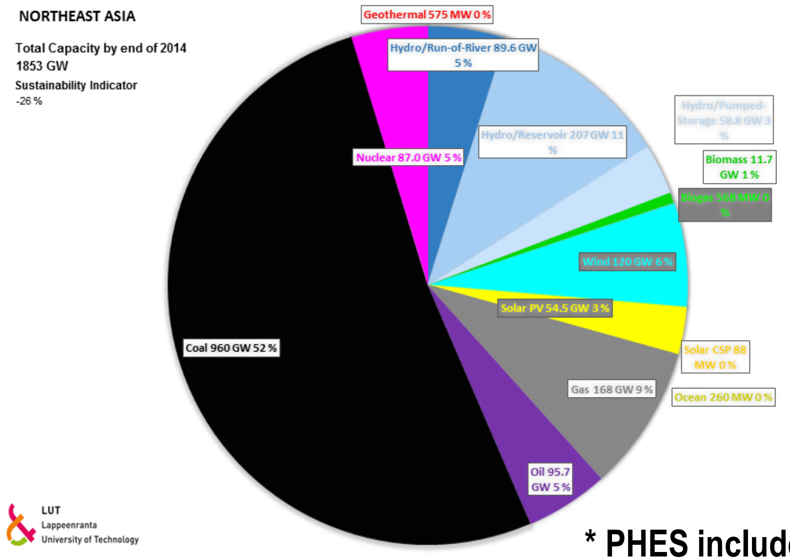
Overview

- Northeast Asia is structured into 13 sub-regions
  - China consists of 8 sub-regions
  - Mongolia
  - Republic of Korea,
  - DPR of Korea
  - Japan (East, West)

Current Status: Power Sector



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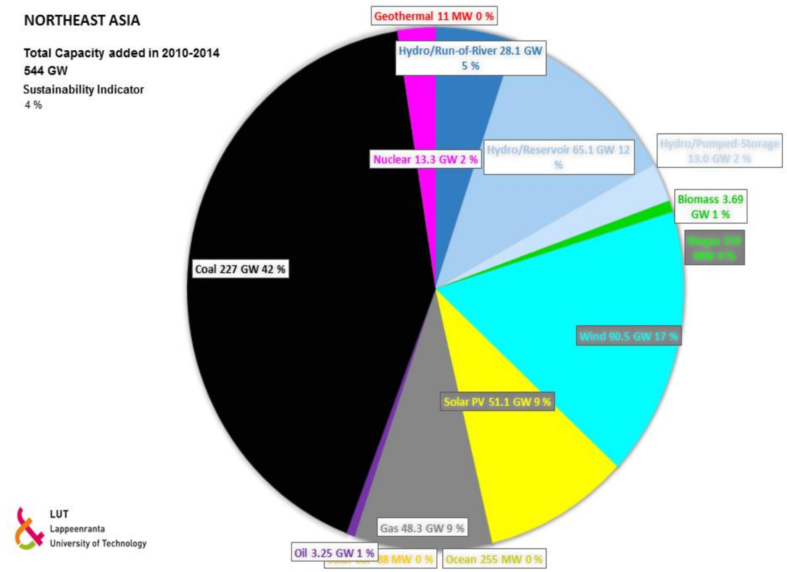
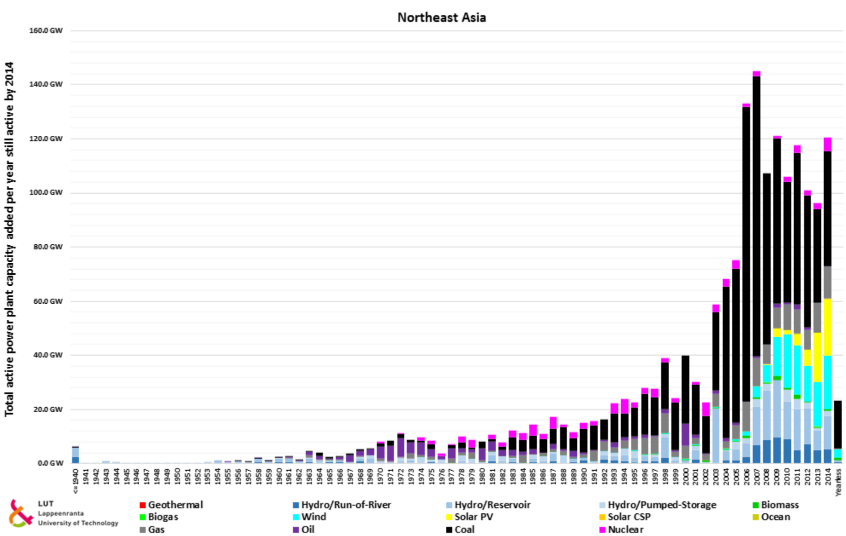




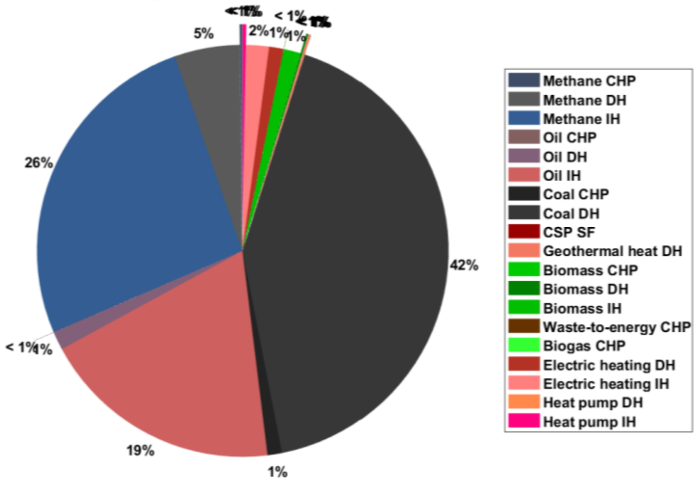
Key insights:

- Historically, a significant share of coal in the generation mix is observed
- In recent times, RE has seen significant growth in the share of installed capacities across Northeast Asia

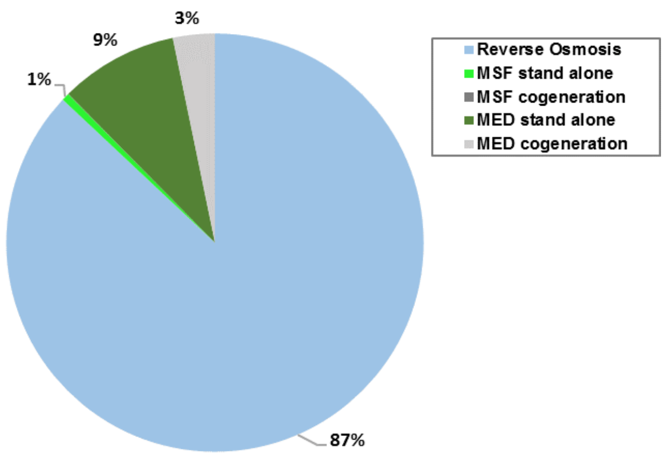
Current Status

Heat, Transport and Desalination Sectors

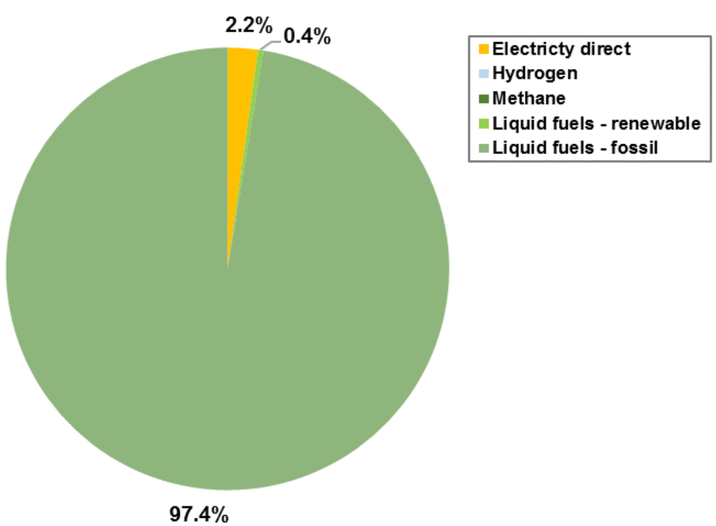
Share of heat generation capacities in 2015



Desalination capacities [m³/day] in 2015



Share of energy sources for transport sector in 2015

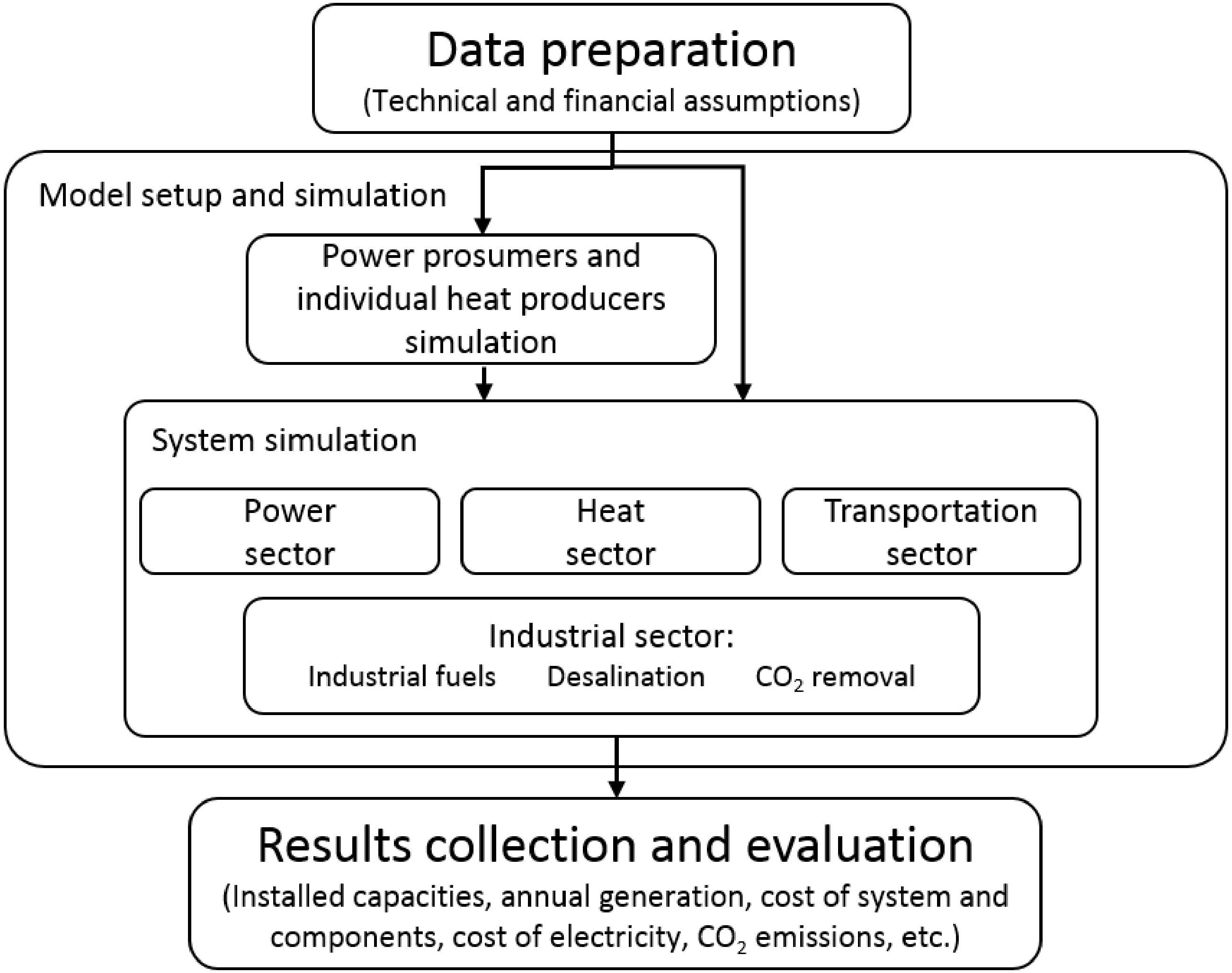


Key insights:

- Historically, a significant share of fossil powered heat generation is present with some shares of bio-based heating
- The transport sector is dominated by fossil liquid fuels with a share of around 97% in 2015
- The desalination sector is predominantly based on demand for reverse osmosis desalination plants, with some shares of MSF and MED in 2015

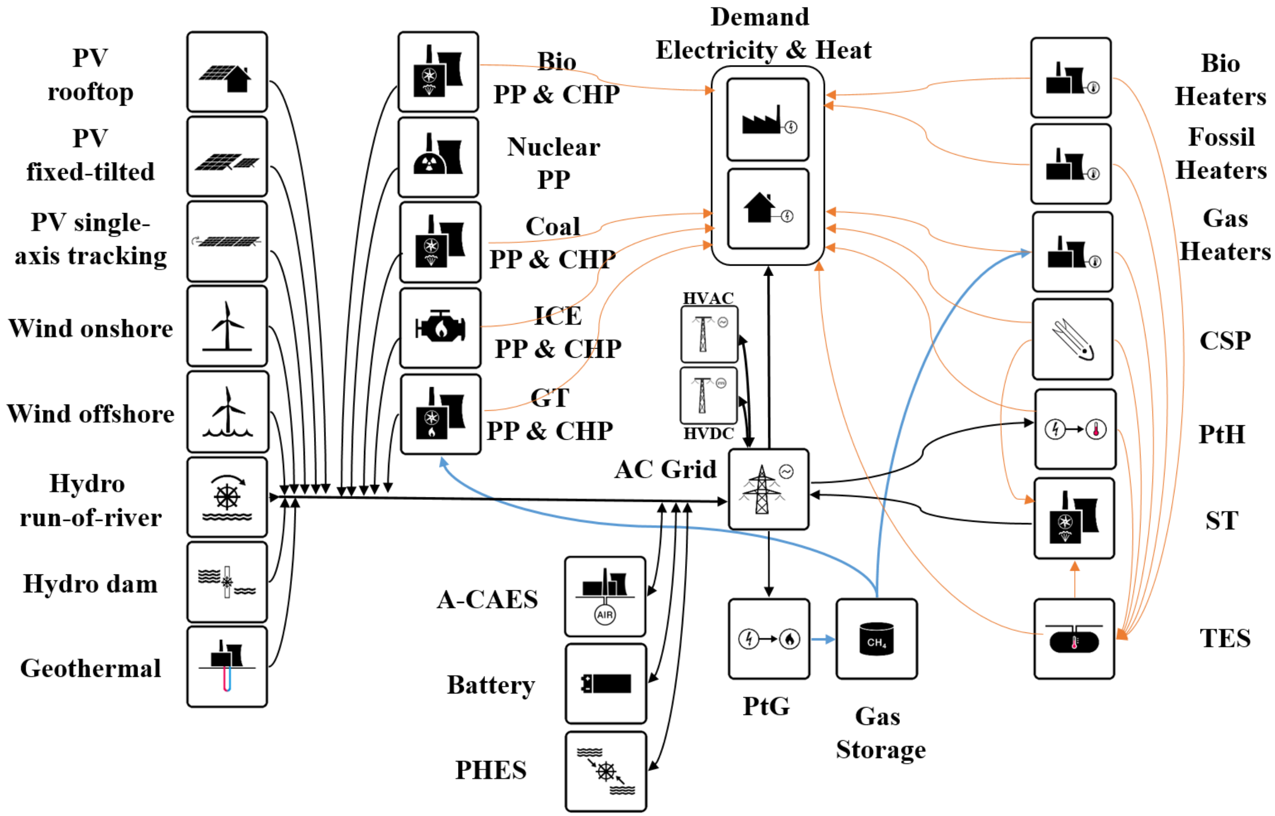
LUT Energy System Transition model

Fundamentals: Data Flow



LUT Energy System Transition model

Power & Heat



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

LUT Energy System Transition model

Transport

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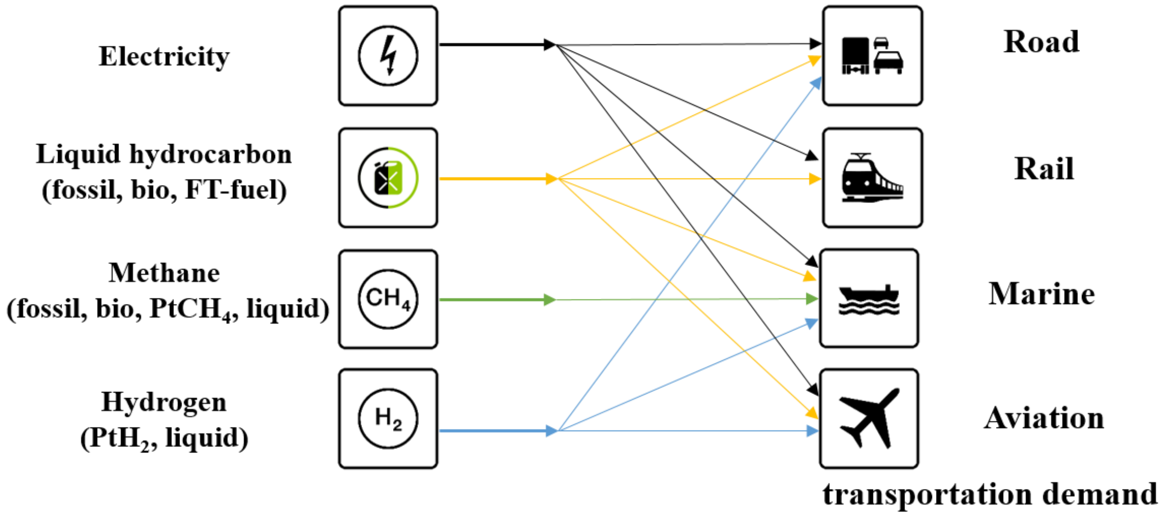
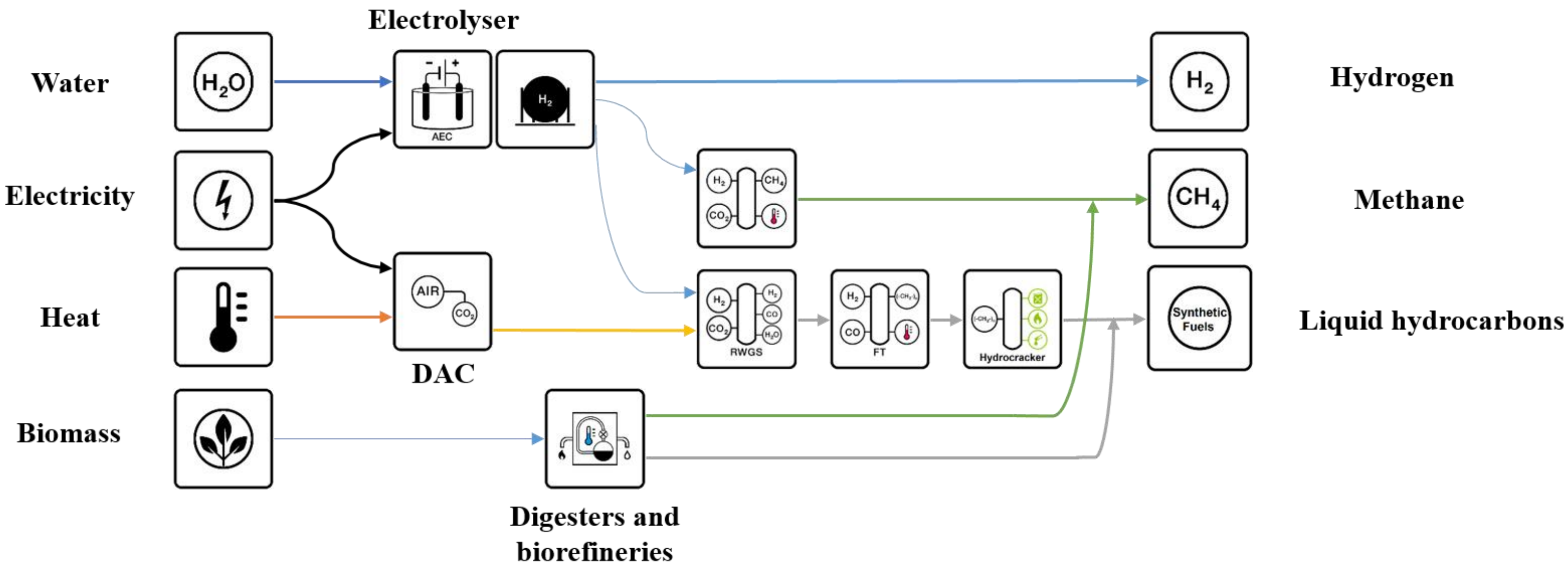


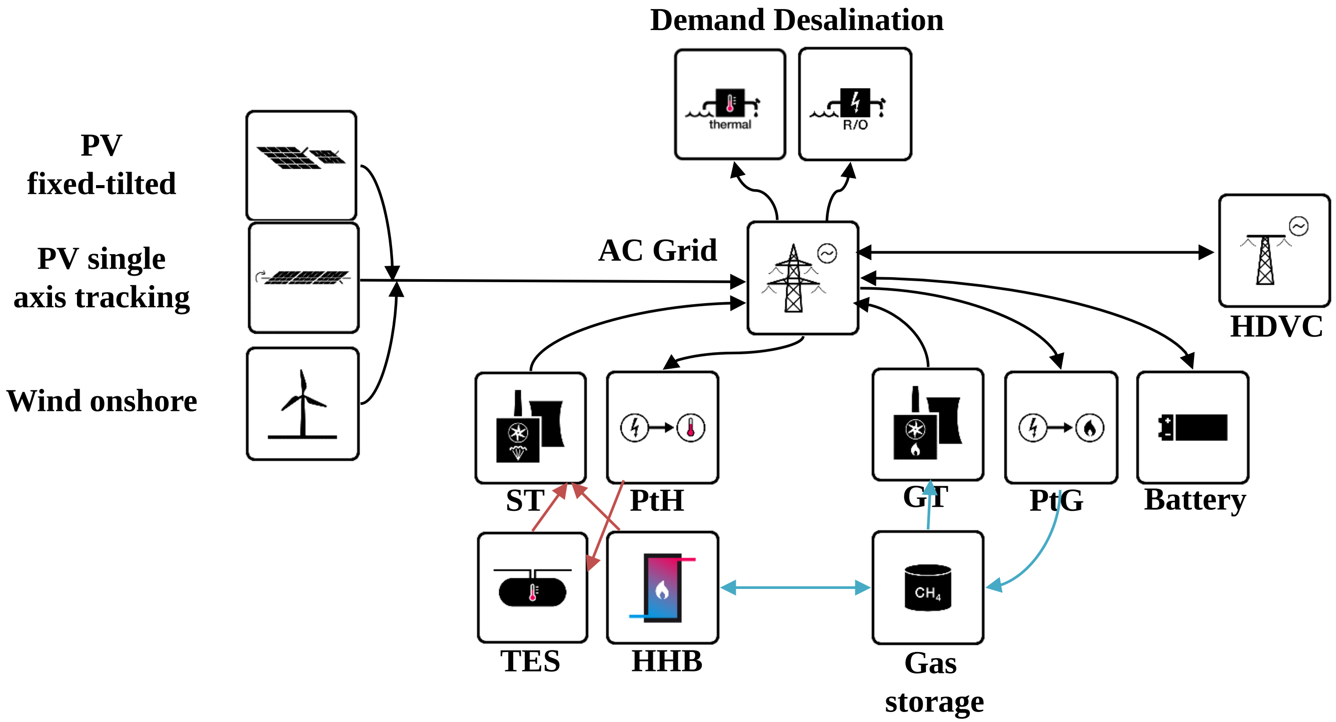
Key insights:

- All forms of transportation categorised into Road, Rail, Marine and Aviation
- Majority of demand to be covered by electricity directly and indirectly by liquid hydrocarbon (including biofuels), methane and hydrogen



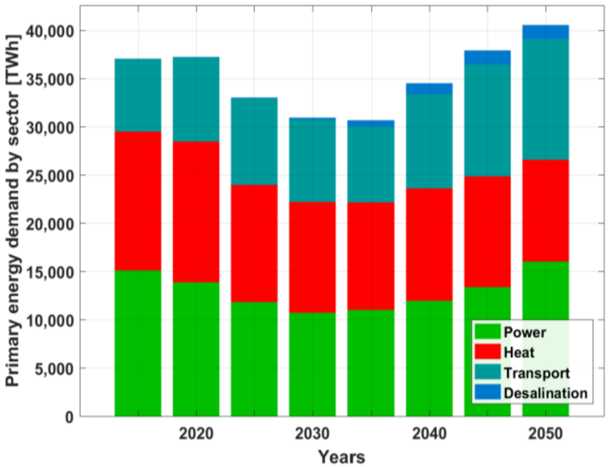
LUT Energy System Transition model

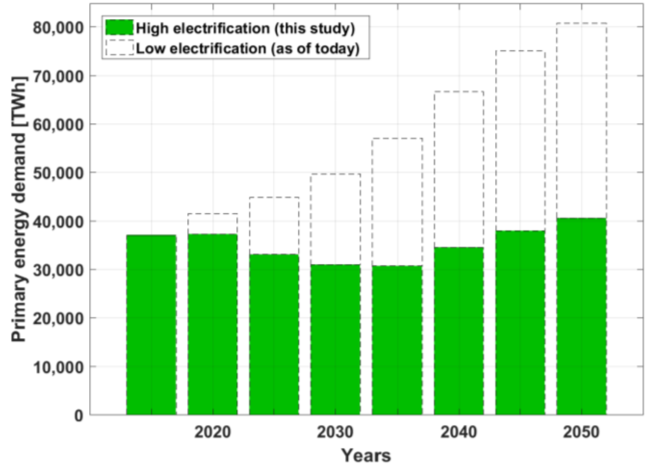
Desalination

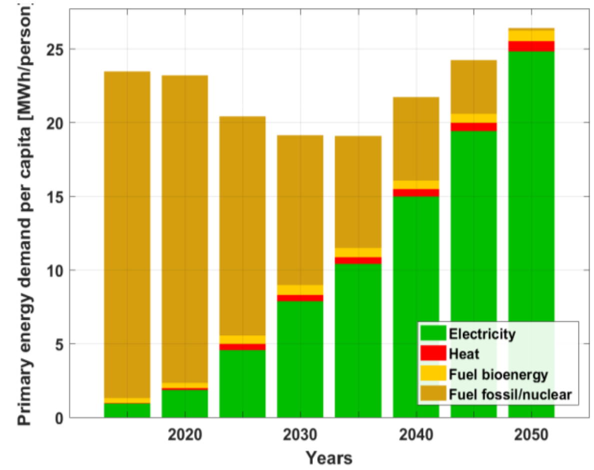


- The LUT model applied to the desalination sector
- The desalination demand is from reverse osmosis and MED

Long-term Energy Demand







Key insights:

- A regional cumulative average annual growth rate of about 1.5% in final energy demand drives the transition. This is aggregated by final energy demand growth for power and heat, desalinated water demand and transportation demand linked to powertrain assumptions. This leads to a comprehensive electrification, which massively increases overall energy efficiency, to an even higher growth rate in provided energy services.
- Resulting in an average annual growth rate of about 0.4% in total primary energy demand (TPED).
- The population is expected to shrink slightly from 1581 to 1537 million, while the average per capita PED decreases from around 24 MWh/person in 2015 to 19 MWh/person by 2035 and increases up to 27 MWh/person by 2050.
- TPED decreases from around 36,000 TWh in 2015 to around 30,000 TWh by 2035 and increases up to 40,000 TWh by 2050 in this study (which assumes high electrification).
- In comparison, current practices (low electrification) would result in a TPED of over 80,000 TWh by 2050.
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 92% in 2050, saving nearly 40,000 TWh compared to the continuation of current practices (low electrification).

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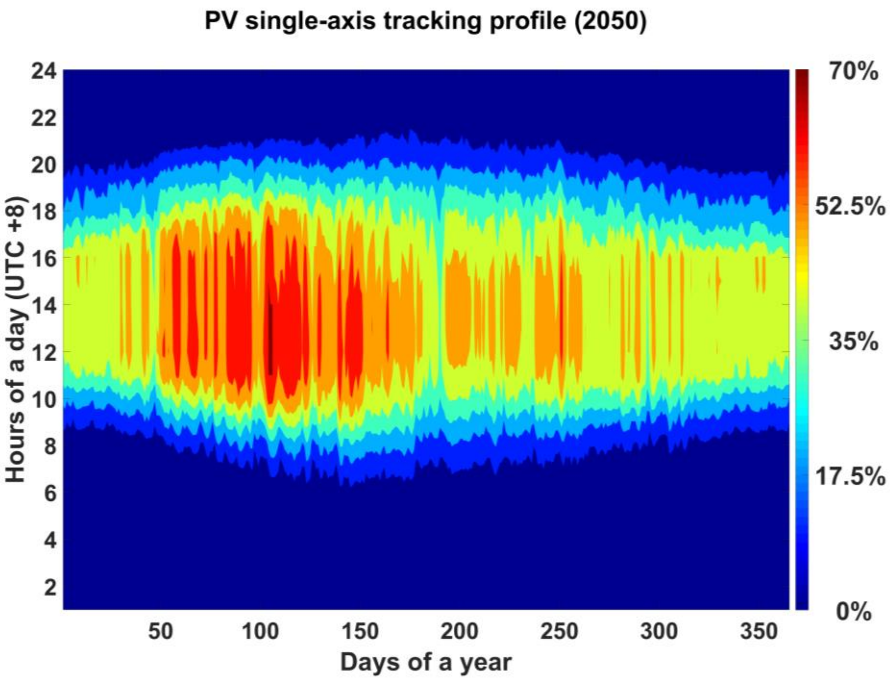
Energy Resources (Solar, Wind)

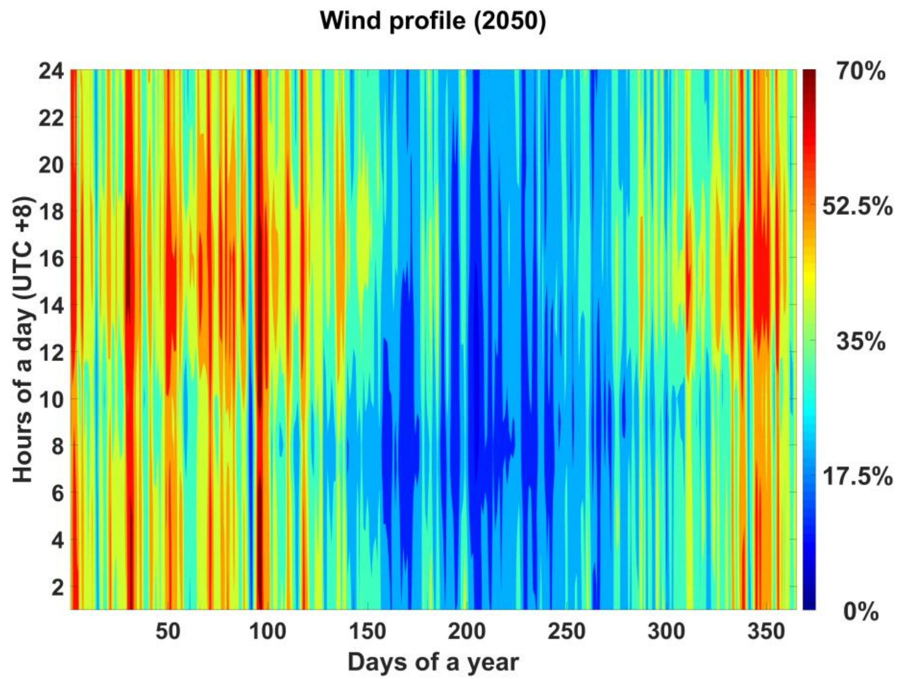
Solar PV generation profile

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



Wind generation profile

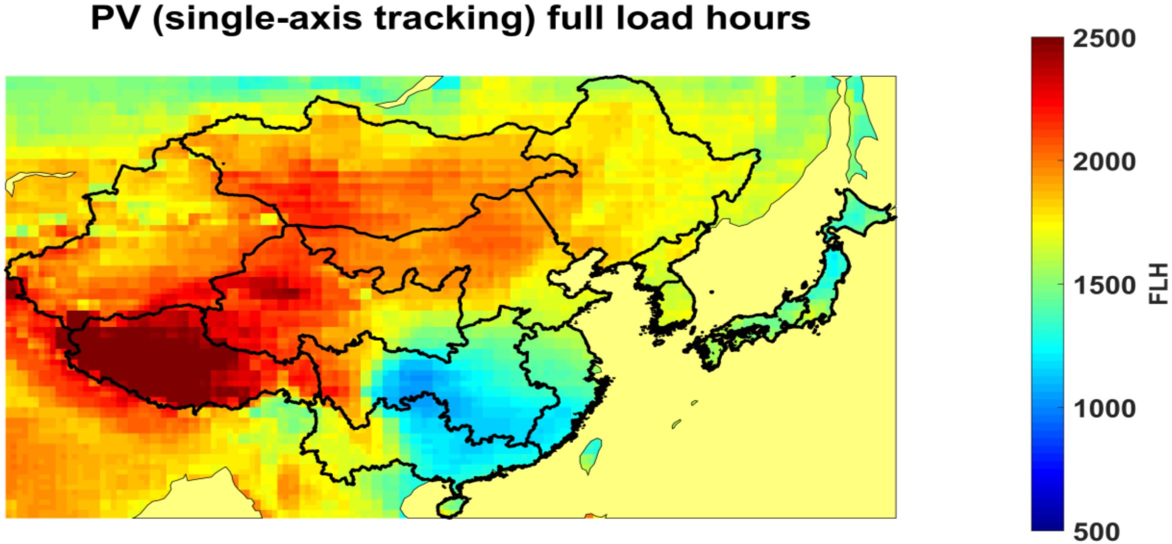
Regional aggregated wind feed-in profile computed using the weighed average rule



Key insights:

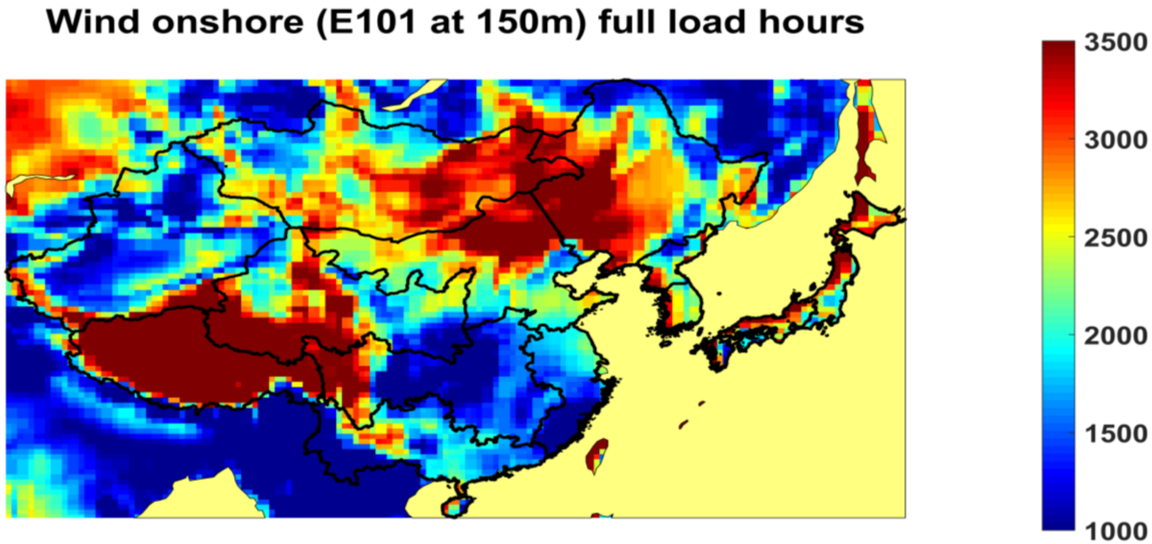
- Wind: Rather stable wind generation over the year with lack of generation during the summer
- Solar PV: More evenly distributed throughout the year and lower generation during the winter period

Full Load Hours

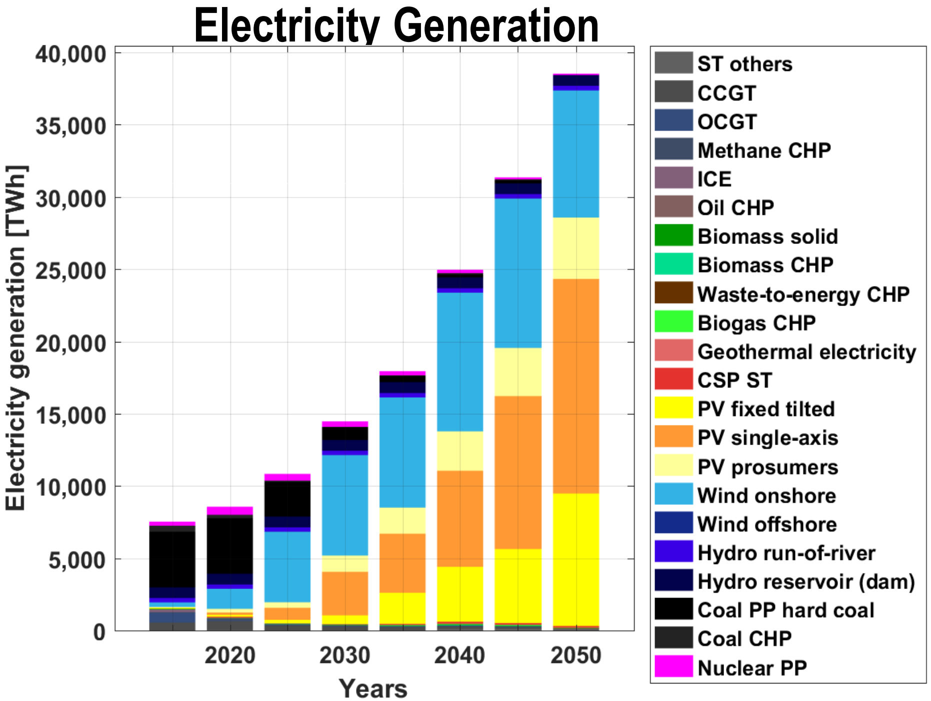


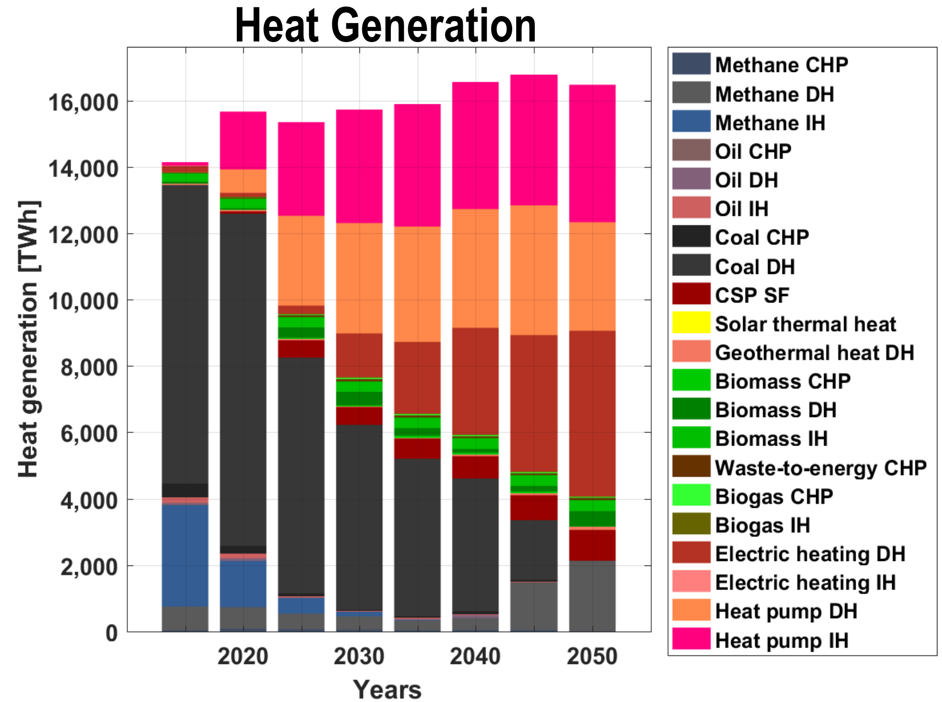
Key insights for solar PV:
- Excellent PV potential in North-West regions and Tibet
- Moderate solar potential in the major demand centers: Japan, South and East China

Key insights for wind:
- Perfect wind conditions in Tibet and Inner Mongolian regions of China
- Good wind conditions in Japan and Mongolia
- Not so good wind potential in South and East China



Energy Supply



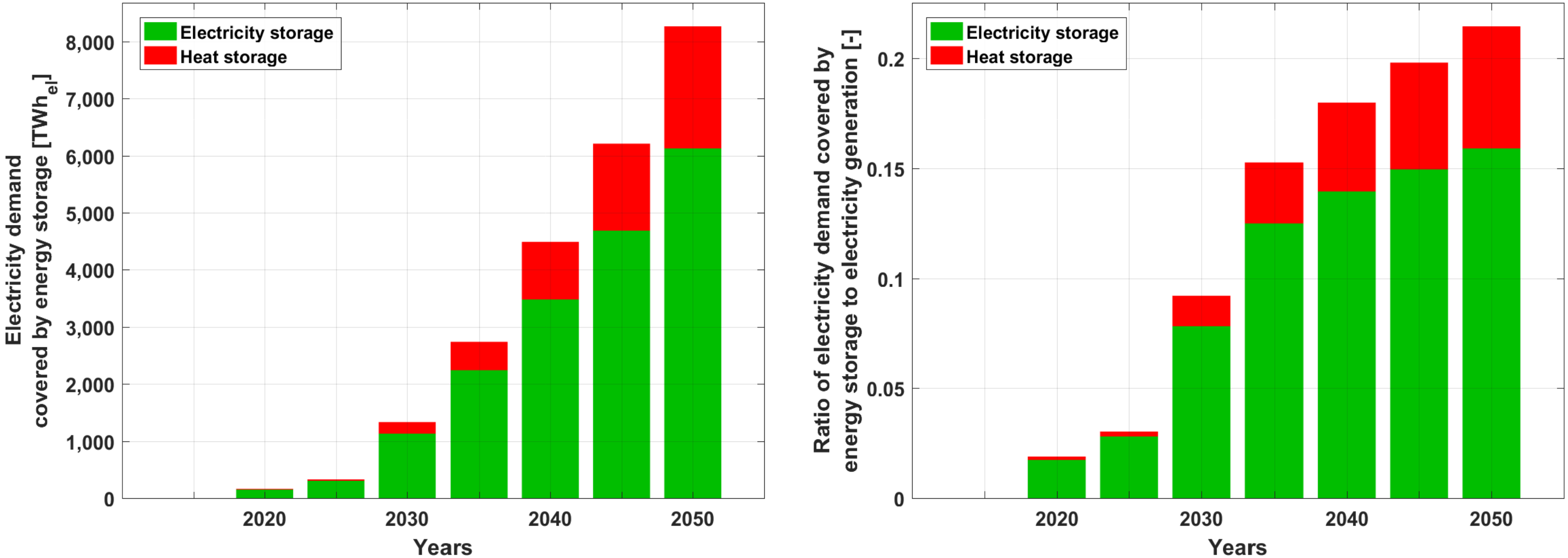


Key insights:

- Electricity generation is comprised of demand form all energy sectors (power, heat, transport, desalination)
- Solar PV supply increases from 29% in 2030 to about 72% in 2050 becoming the main energy source
- Wind energy increases to 49% by 2030 and steadily declines to 22% by 2050
- Heat pumps play a significant role in the heat sector with a share of nearly 44% of heat generation by 2050 coming from heat pumps on district and individual levels
- Coal based heating decreases through the transition from around 64% in 2015 to zero by 2050

Energy Storage

Electricity

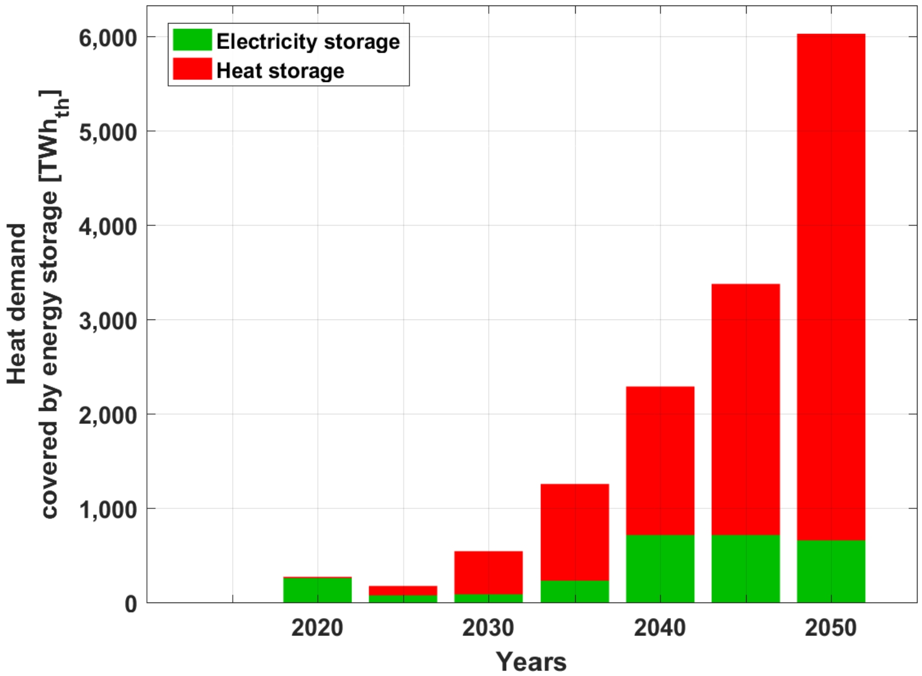


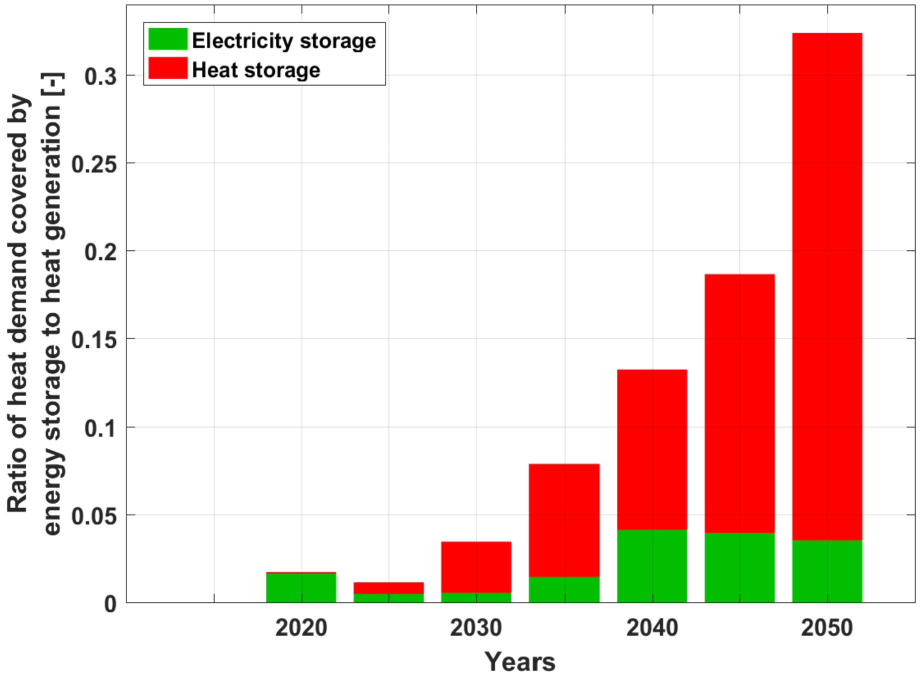
* heat storage includes gas and thermal storage technologies

Key insights:

- Electricity demand covered by storage increases through the transition period from about 2800 TWh$_{el}$ by 2035 and further significantly increases to over 8000 TWh$_{el}$ in 2050
- The ratio of electricity demand covered by energy storage to electricity generation increases significantly to around 15% by 2035 to about 26% by 2050
- Batteries emerge as the most relevant electricity storage technology contributing about 91% of the total electricity storage output by 2050 (more details on slide 19)

Energy Storage
Heat

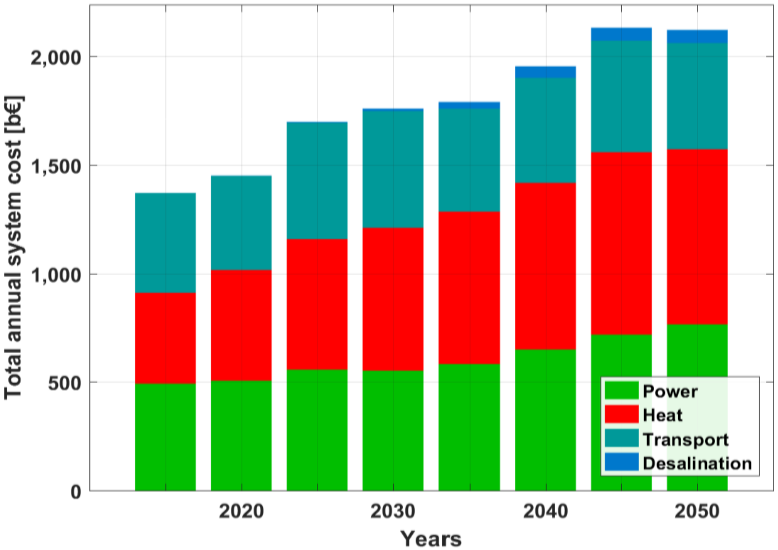


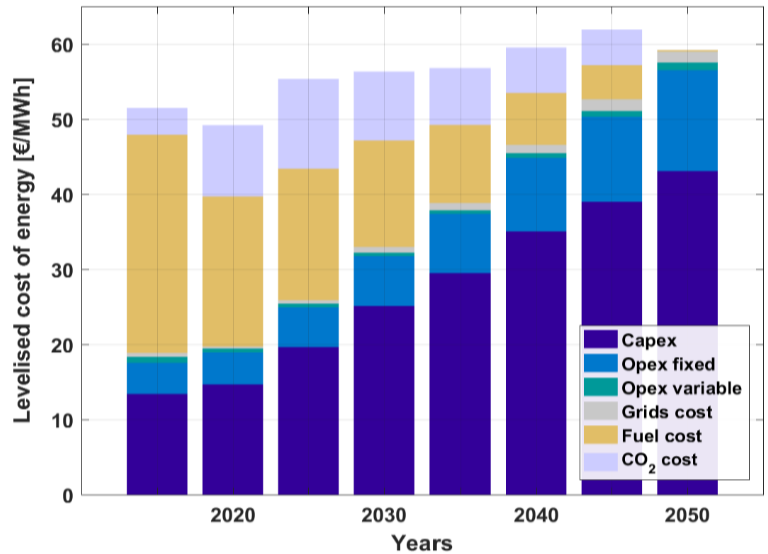


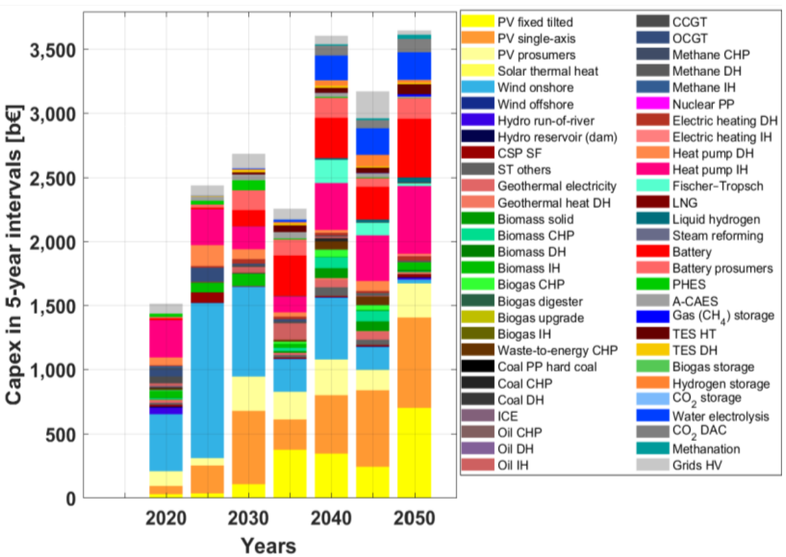
Key insights:

- Storage output covers more than 30% of the total heat demand in 2050 and heat storage technologies play a vital role
- The ratio of heat demand covered by energy storage to heat generation increases substantially to almost 28% by 2050
- Thermal energy storage emerges as the most relevant heat storage technology with about 64% of heat storage output by 2050 (more details on slide 19)
- Power-to-Gas contributes around 37% of the heat storage output in 2050

Energy System Cost



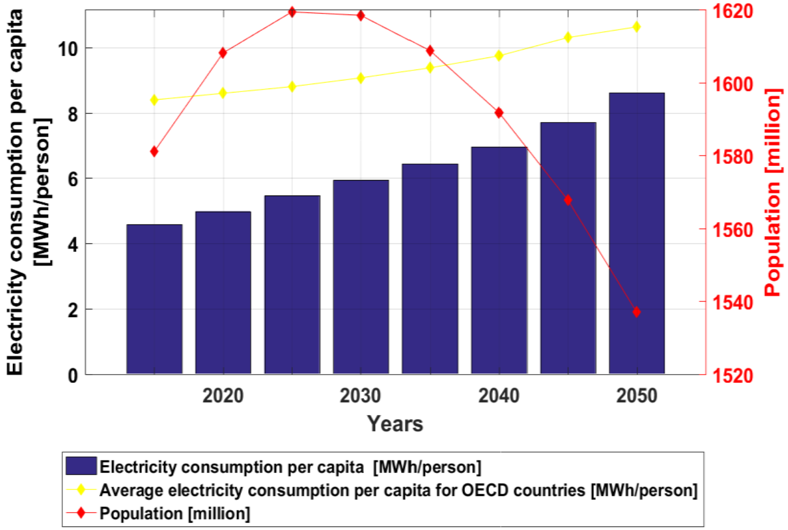




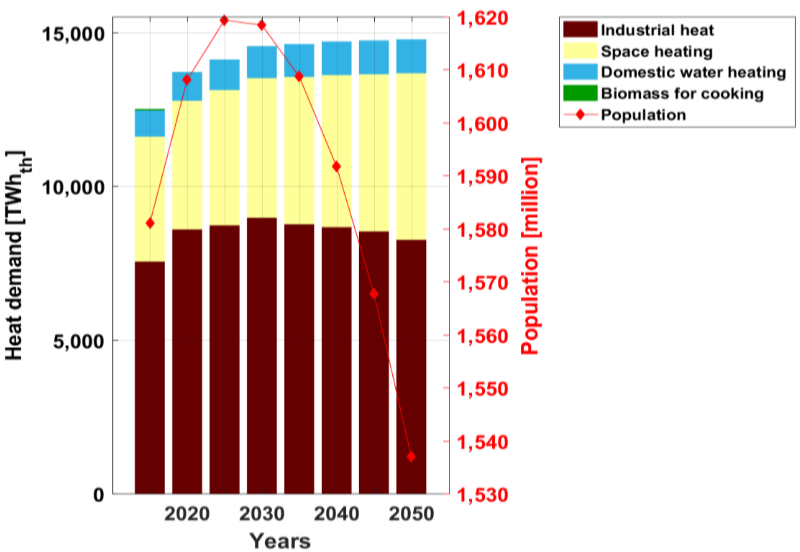
Key insights:

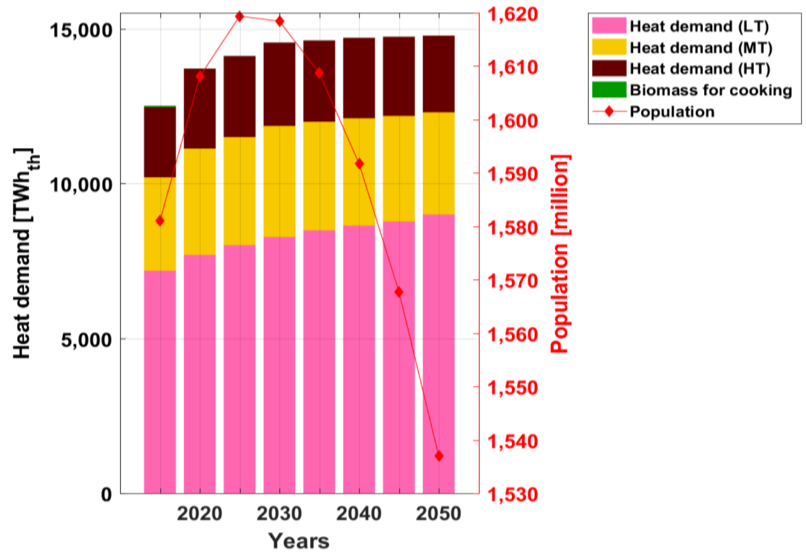
- The total annual costs are in the range of 1400-2100 b€ through the transition period and well distributed across the 3 major sectors of Power, Heat and Transport
- LCOE remains around 50-61 €/MWh and is increasingly dominated by capital costs, as fuel costs continue to decline through the transition period, which could mean increased energy self reliance for Northeast Asia by 2050
- Costs are well spread across a range of technologies with major investments for PV, wind, batteries, heat pumps and synthetic fuel conversion technologies up to 2050
- The cumulative investments are about 19,200 b€

Sectoral Outlook
Power & Heat - Demand



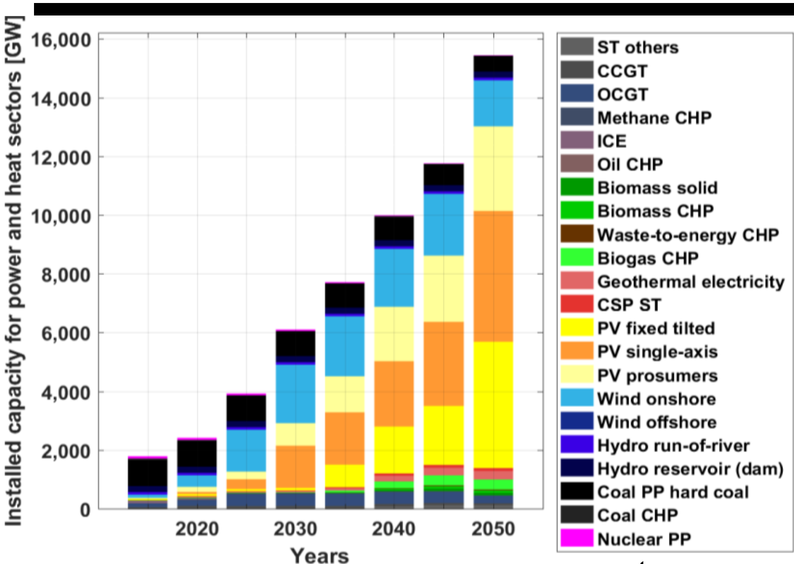
Key insights:
- Electricity consumption per capita increases from over 4 MWh/person in 2015 to over 8 MWh/person by 2050
- Total heat demand increases steadily from around 13,000 TWh_{th} in 2015 to nearly 15,000 TWh_{th} by 2050, mainly driven by higher demand for industrial process heat, but also growing building space per person reducing the gains from building efficiency standards
- Space heating and Industrial heat contribute the major share of demand which is mainly low temperature (LT)

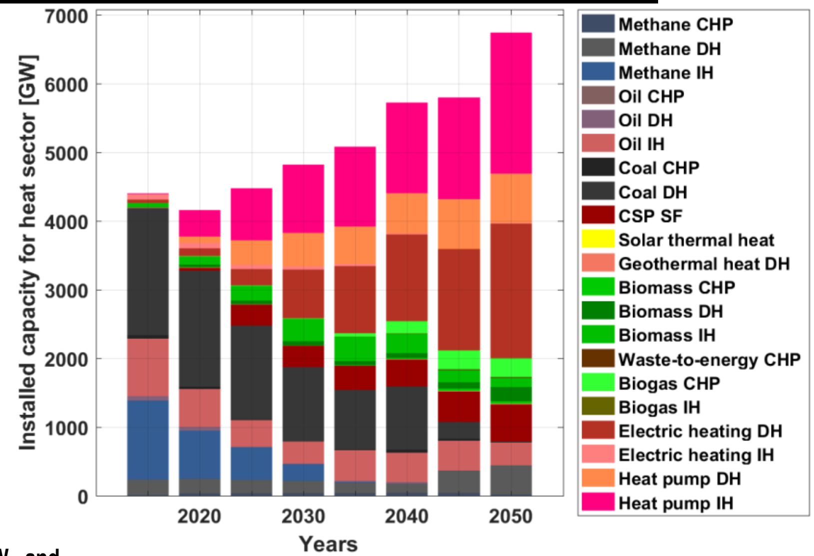




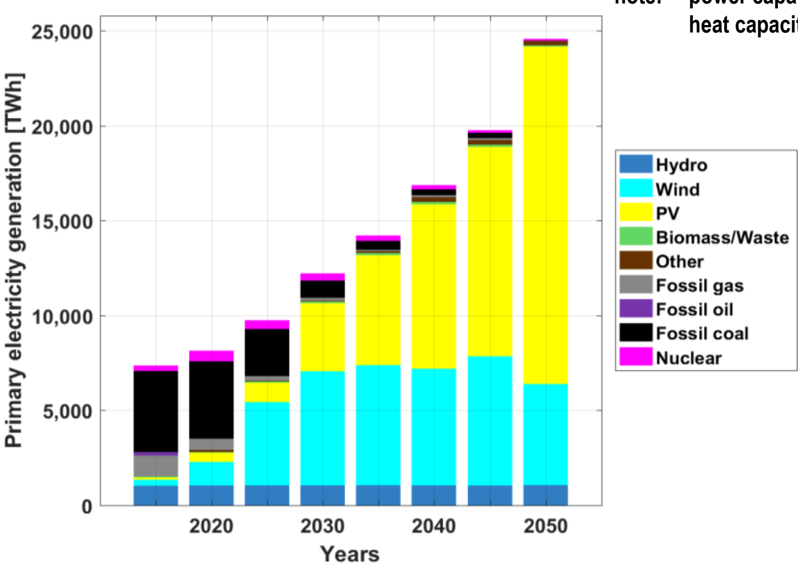
Sectoral Outlook

Power & Heat – Installed Capacities and Generation





note: power capacities are in GW_{el} and heat capacity in GW_{th}



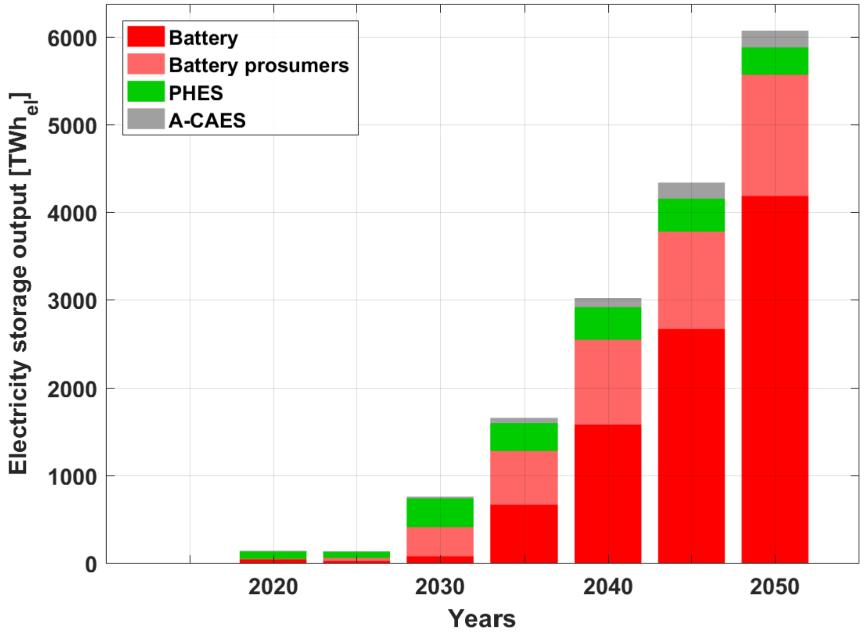
Key insights:

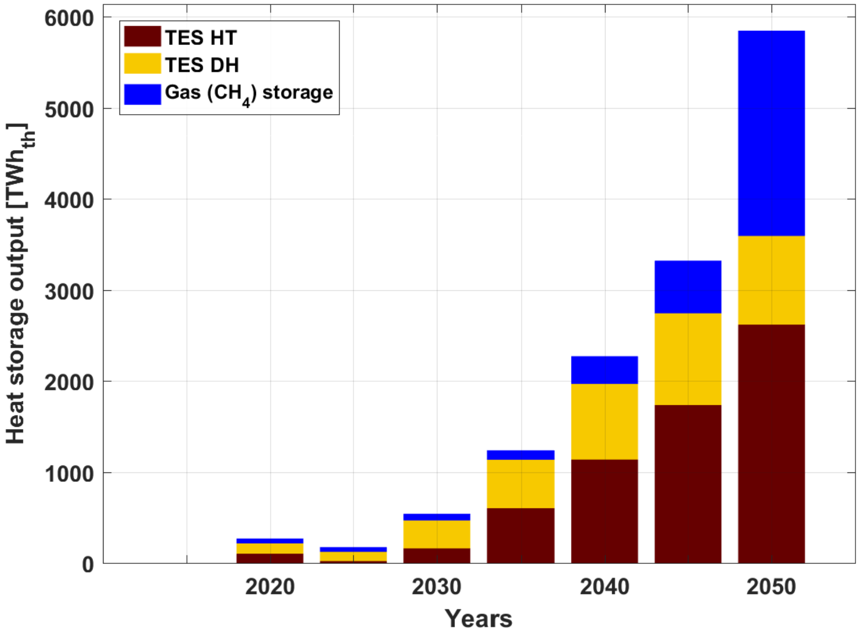
- Solar PV with 11,638 GW and wind with 1566 GW constitute a majority of the installed capacities by 2050
- Heat pumps, electric heating and biomass based heating constitute a majority of the installed capacities during the transition, with a significant increase in 2050 due to the absence of fossil fuels in the system in this period
- From a fossil dominated power & heat sector in 2015 to a solar PV and wind dominated sector by 2050

more information ► office@energywatchgroup.org, manish.ram@lut.fi

Sectoral Outlook

Power & Heat – Storage Output



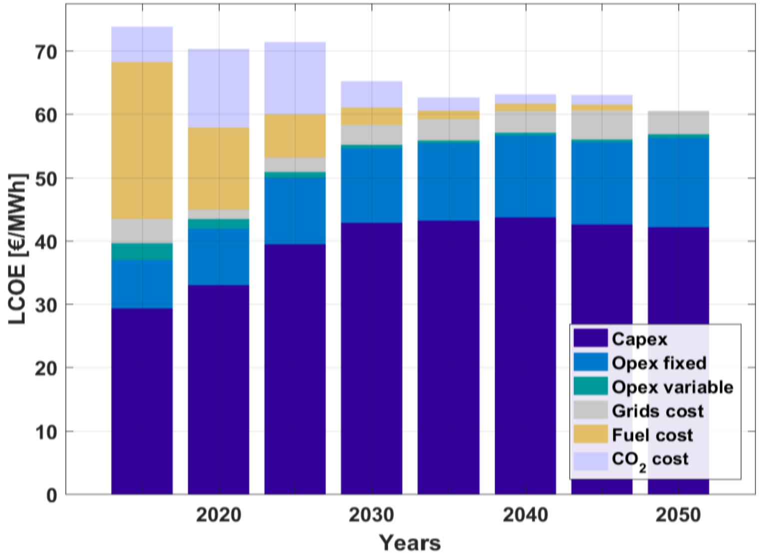


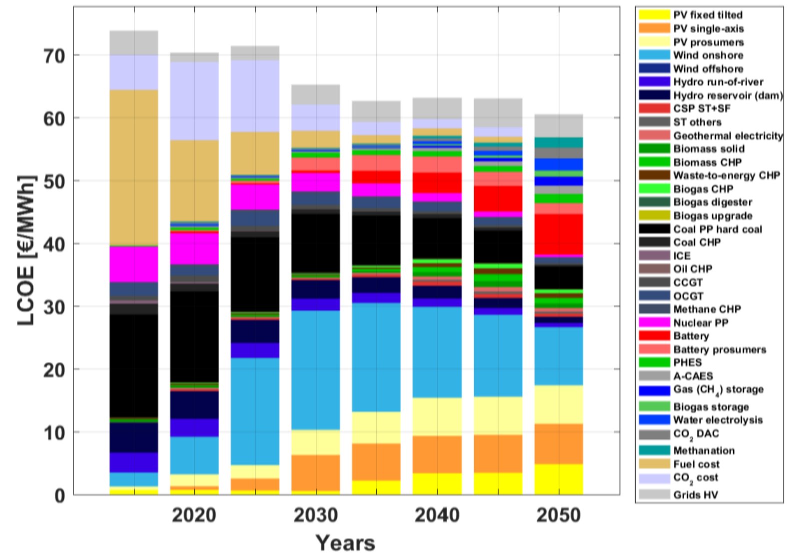
Key insights:

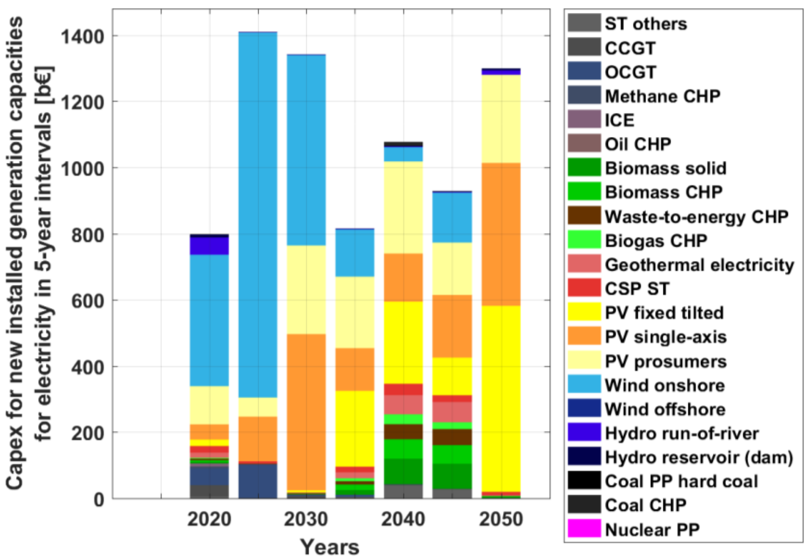
- Utility-scale and prosumer batteries contribute a major share of the electricity storage output with nearly 91% by 2050
- Pumped hydro energy storage and compressed air energy storage contribute through the transition
- Thermal energy storage emerges as the most relevant heat storage technology with about 64% of heat storage output from 2030 until 2050
- Gas storage contributes around 37% of the heat storage output in 2050 covering predominantly seasonal demand, which was covered by fossil gas before 2050

Sectoral Outlook

Power – Costs and Investments







Key insights:

- LCOE of the power sector decreases substantially from around 74 €/MWh in 2015 to around 61 €/MWh by 2050
- LCOE is predominantly comprised of capex as fuel costs decline through the transition
- Investments are well spread across a range of technologies with major share in solar PV, wind and batteries up to 2050

Sectoral Outlook

Heat – Costs and Investments

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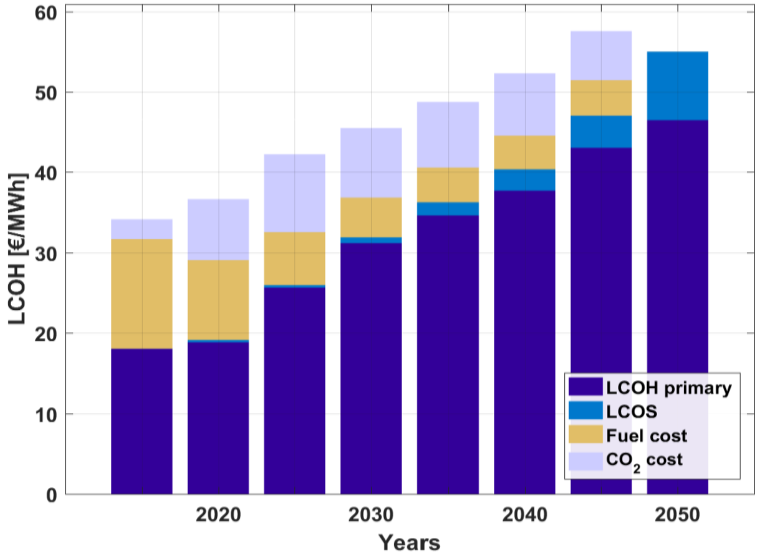
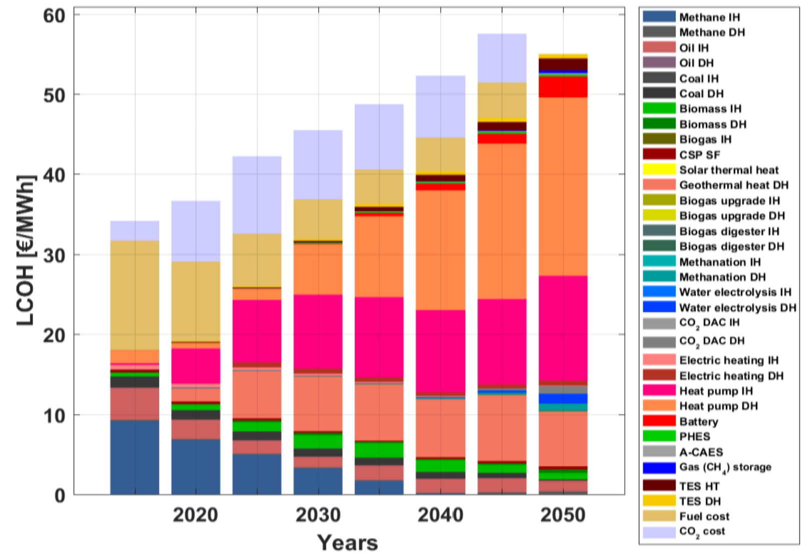
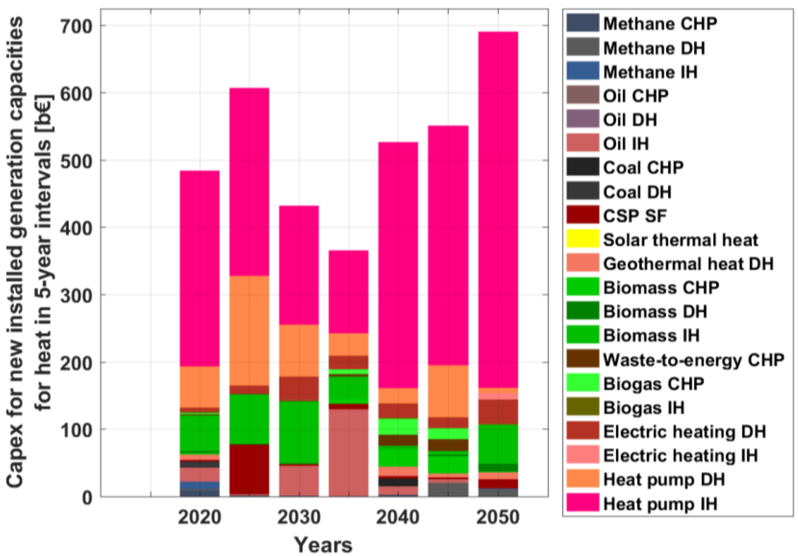




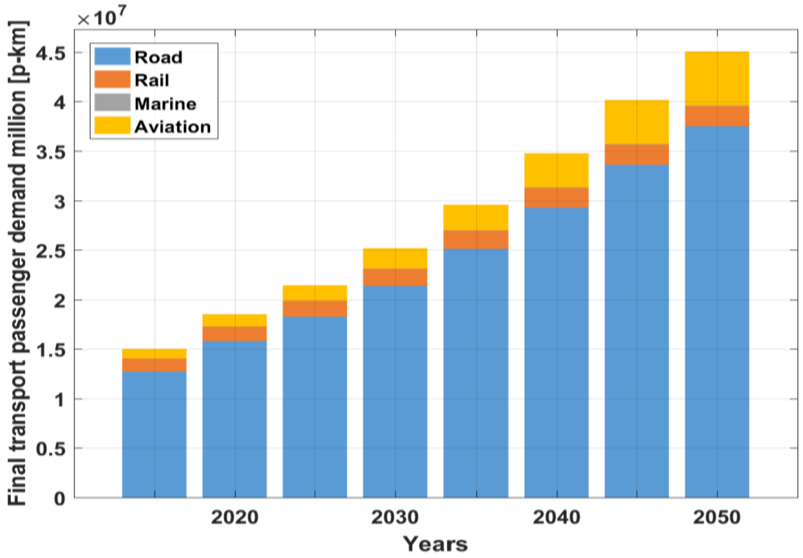


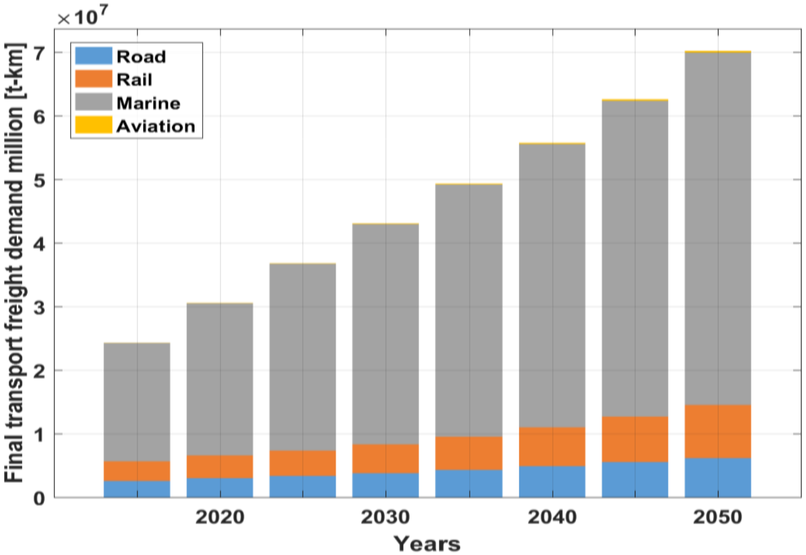
Key insights:

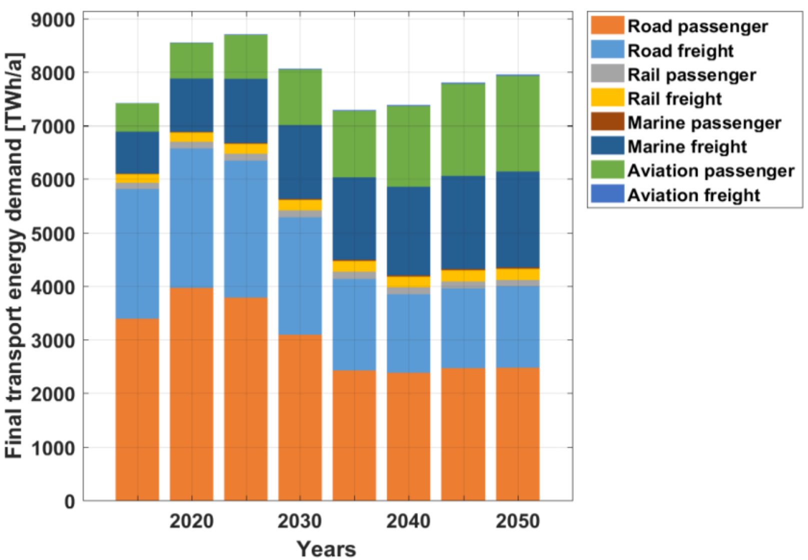
- LCOH of the heat sector increases from around 34 €/MWh in 2015 to around 55 €/MWh by 2050
- LCOH is predominantly comprised of capex as fuel costs decline through the transition
- Investments are mainly in heat pumps along with some shares in biomass heating up to 2050 and a steep increase in heat pump investments in 2050, replacing the remaining fossil-based heating systems

Sectoral Outlook

Transport – Demand





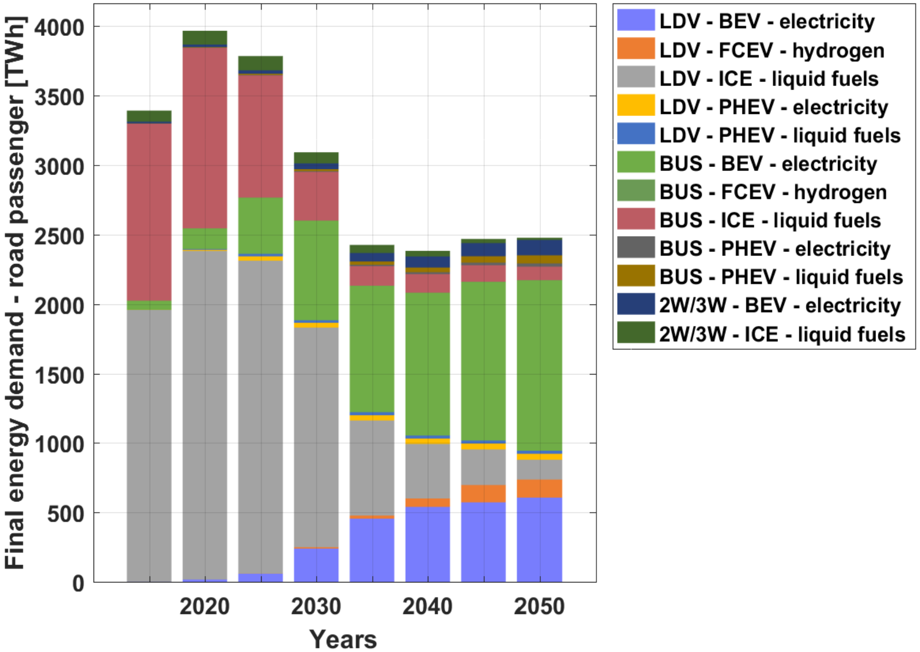


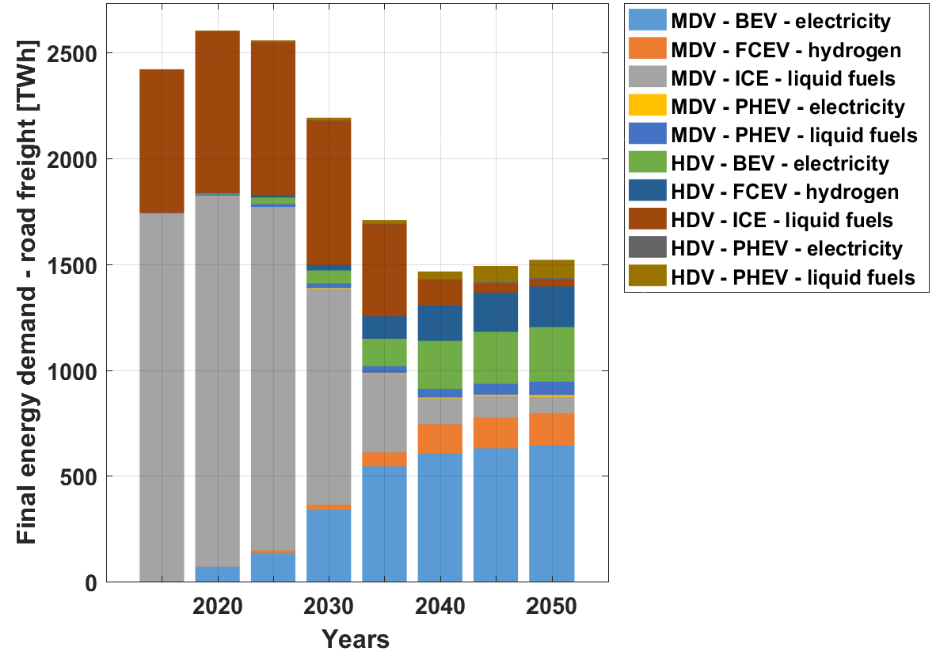
Key insights:

- The final transport passenger demand increases from around 15 million p-km to around 45 million p-km, with rapid growth in Northeast Asia
- The final transport freight demand also increases from around 24 million t-km to around 70 million t-km
- Whereas, the final energy demand for overall transport increases just from 7400 TWh/a in 2015 to 8000 TWh/a by 2050, enabled by high efficiency of electric vehicles
- Marine freight is aligned to the scenario with a drastic decline in fuels transportation during the transition

Sectoral Outlook

Transport – Road Demand



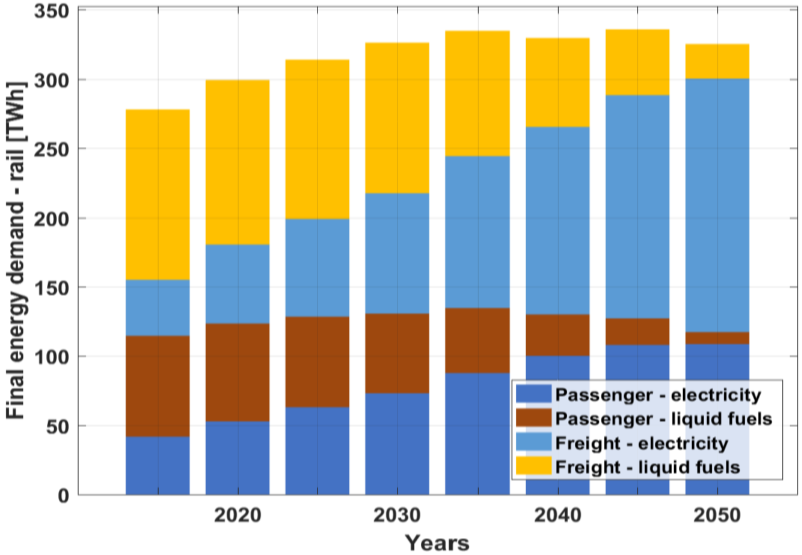


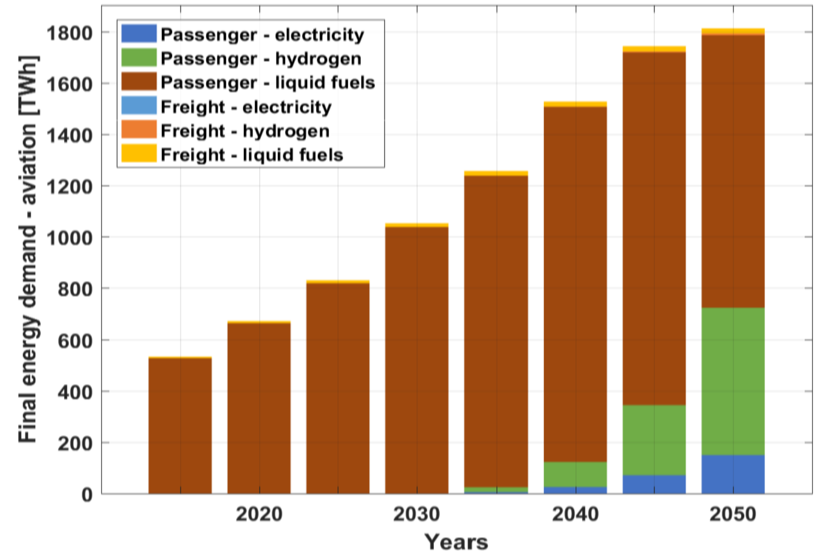
Key insights:

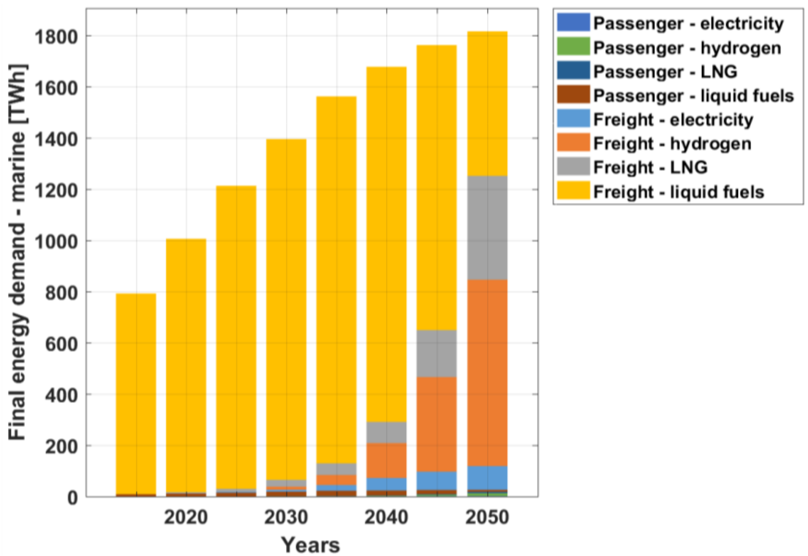
- The final energy demand for road passengers decreases significantly from around 3400 TWh in 2015 to 2500 TWh by 2050
- The final energy demand for road freight decreases substantially from around 2400 TWh in 2015 to around 1500 TWh by 2050
- The significant decrease in final energy demand for overall road transport is primarily driven by the massive electrification

Sectoral Outlook

Transport – Rail, Marine and Aviation Demand





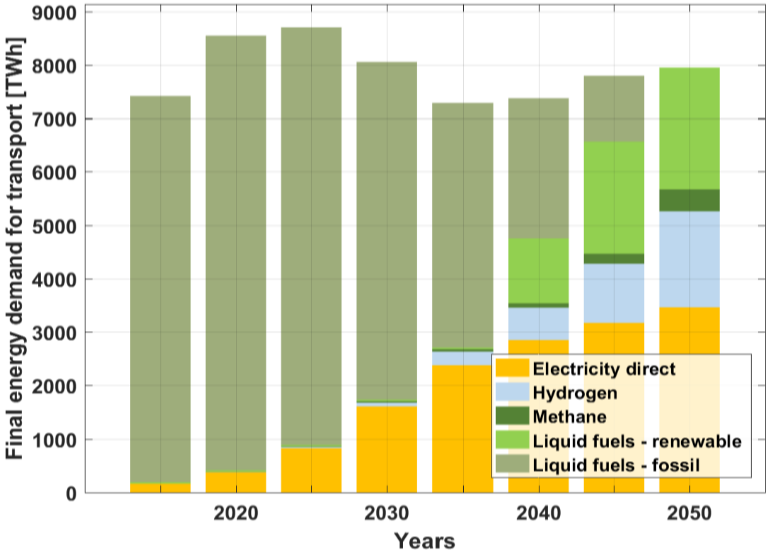


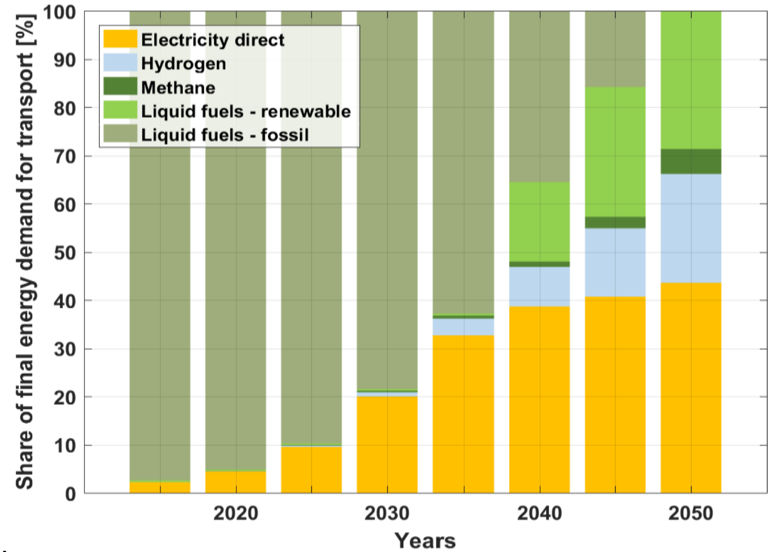
Key insights:

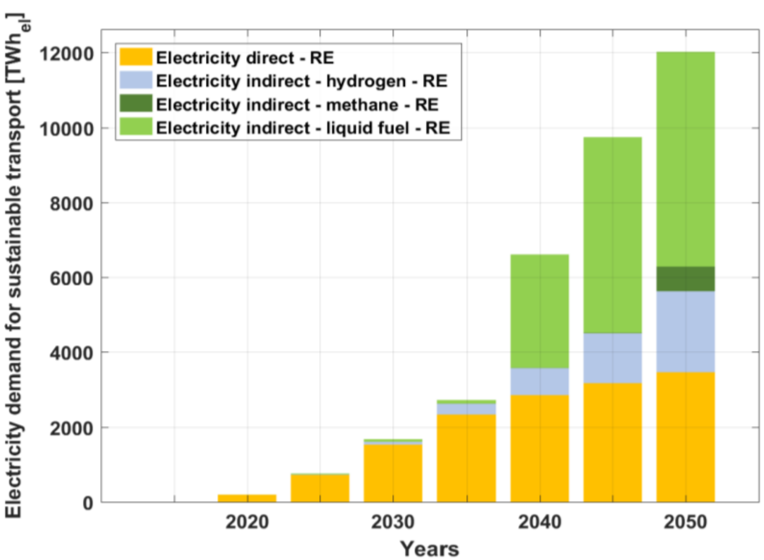
- The final energy demand for rail transport increased from around 270 TWh in 2015 to about 320 TWh by 2050
- The final energy demand for marine transport increases steadily from around 800 TWh in 2015 to around 1800 TWh by 2050
- The final energy demand for aviation transport increases significantly from nearly 570 TWh in 2015 to around 1800 TWh by 2050

Sectoral Outlook

Transport – Defossilisation and Electrification



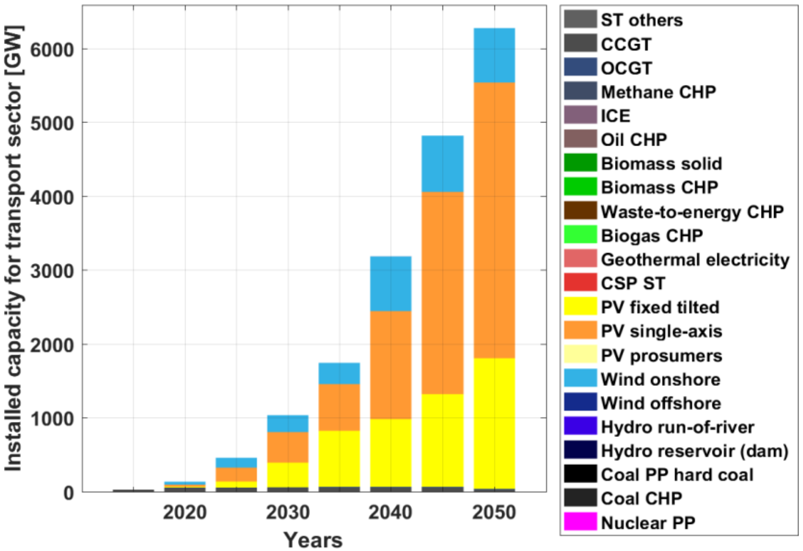


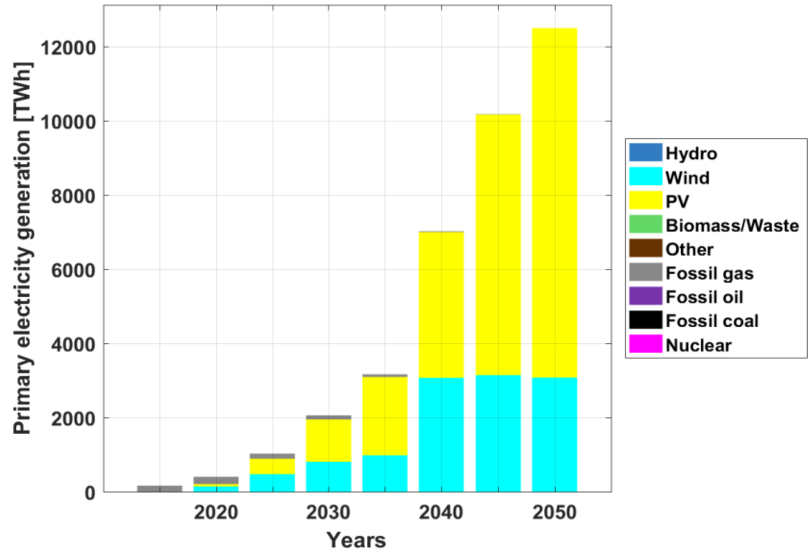


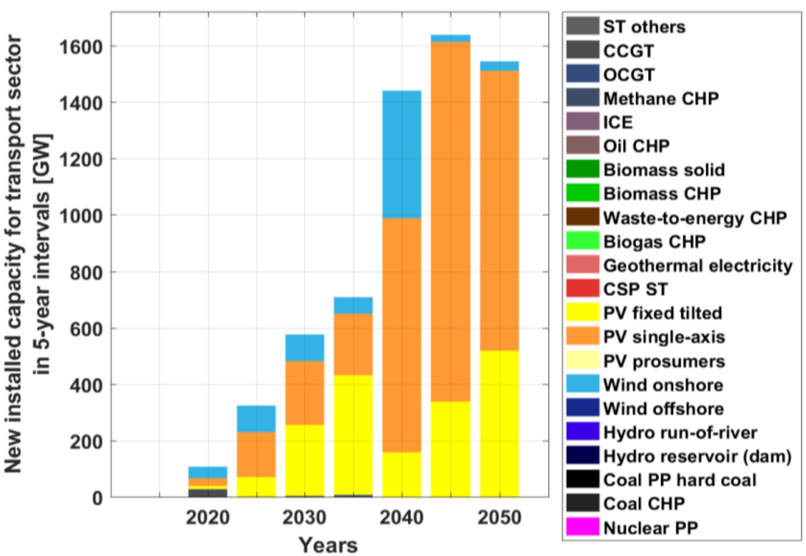
Key insights:

- Fossil fuel consumption in transport is observed to decline through the transition from about 97% in 2015 to zero by 2050
- Liquid fuels produced by renewable electricity contribute around 30% of the final energy demand in 2050
- Hydrogen constitutes about 22% of final energy demand in 2050
- Electrification of the transport sector creates an electricity demand of around 12,000 TWh$_{el}$ by 2050
- Massive demand for liquid fuels kicks in from 2040 onwards up to 2050

Sectoral Outlook
Transport – Power Capacities and Generation





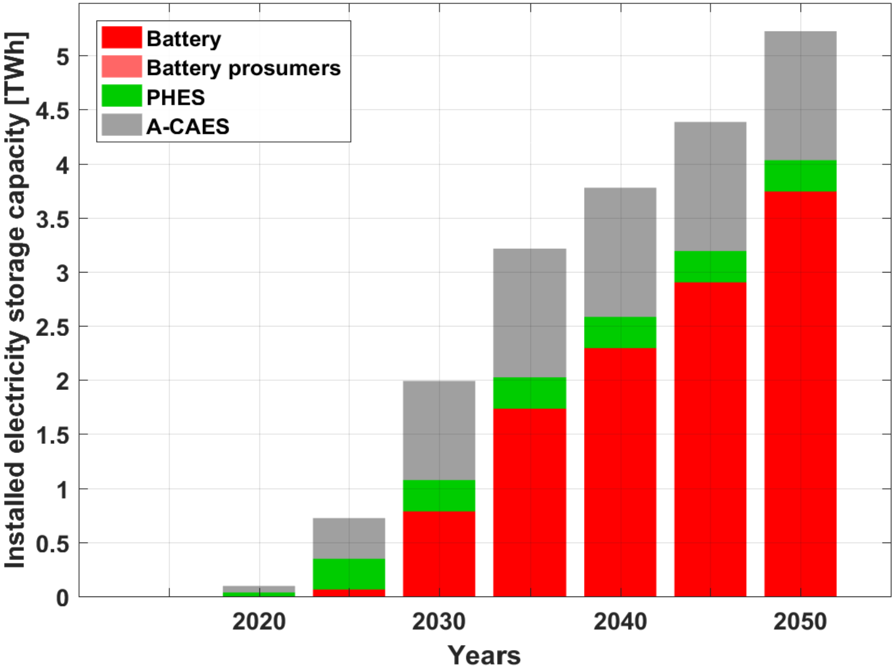


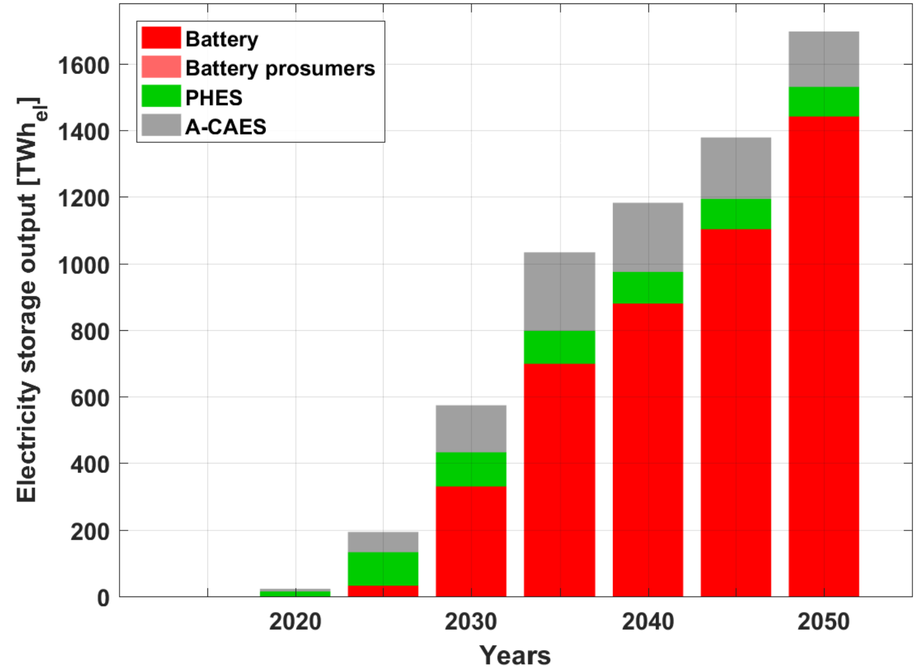
Key insights:

- Solar PV with around 5400 GW and wind with around 737 GW constitute majority of the installed capacities by 2050
- Solar PV and wind generate all of the electricity in 2050 of nearly 12,500 TWh
- Most of the capacity addition is 2035 onwards, with a rapid change in the transport sector towards increased electrification beyond 2030 across Northeast Asia

Sectoral Outlook

Transport – Storage Capacities and Output



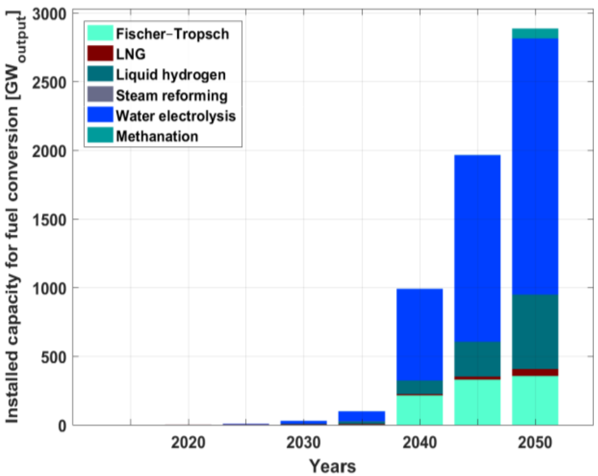


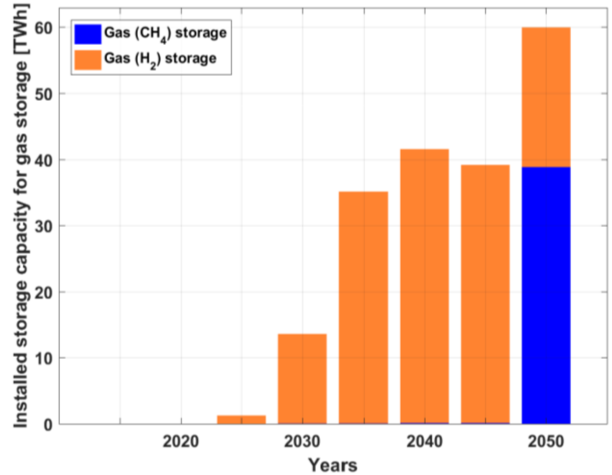
Key insights:

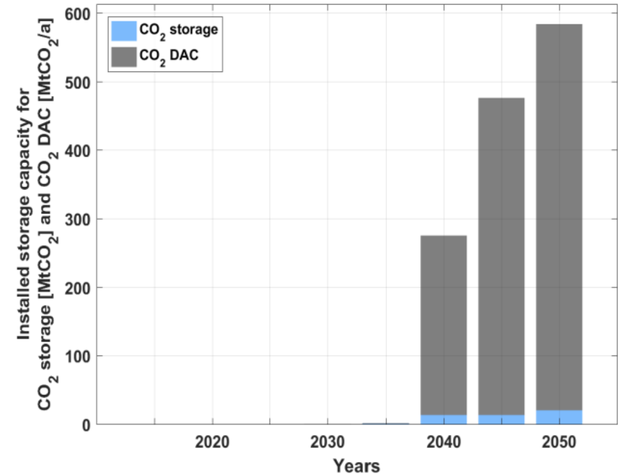
- Utility-scale batteries and A-CAES installed storage capacities increase up to 2050, with some share of PHES through the transition
- Storage capacities increase beyond 2030 as electricity demand for transport increases
- Utility-scale batteries contribute the major share of storage output in 2050 with over 1400 TWh$_{el}$
- Conservative charging of vehicles is assumed, which excludes smart charging and vehicle-to-grid functionalities. Both would reduce storage demand. Some storage is needed for synthetic fuels production.

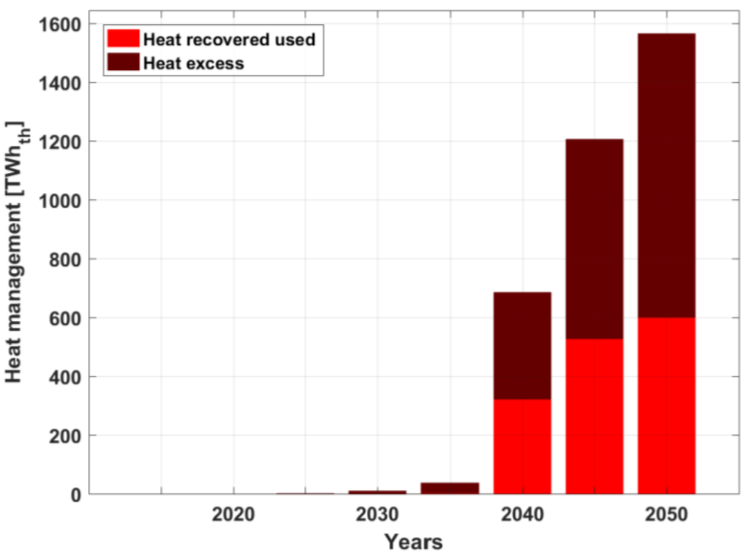
Sectoral Outlook

Transport – Fuel Conversion, Storage Capacities and Heat Management







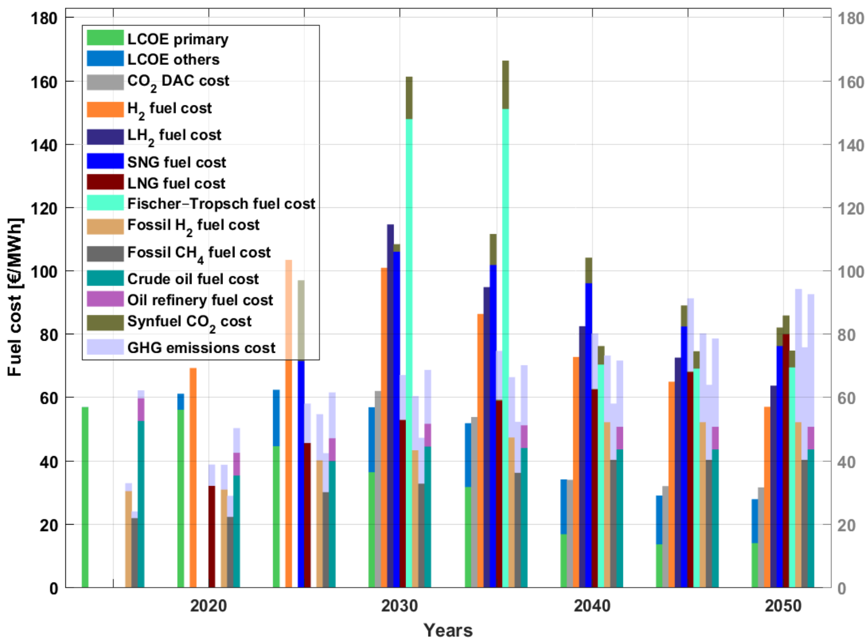


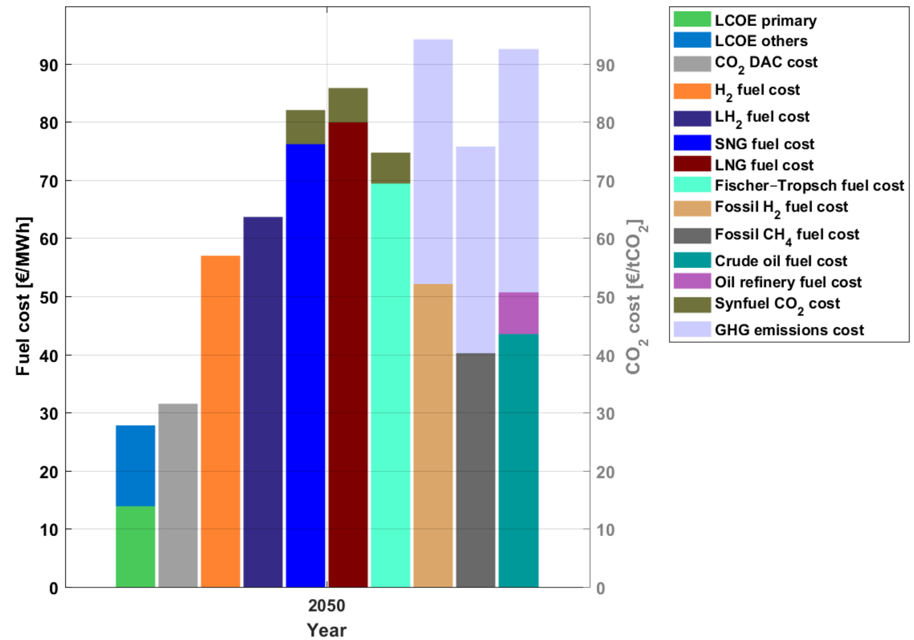
Key insights:

- Installed capacities of fuel conversion technologies increase significantly beyond 2040, with a major share of water electrolysis and some shares of Fischer-Tropsch and hydrogen up to 2050
- Installed capacity of gas storage comprised of hydrogen and methane reaches up to 60 TWh by 2050, with major share of hydrogen storage
- Installed CO_2 storage and CO_2 DAC increase significantly from 2040 onwards, with major share of CO_2 DAC
- Heat for fuel conversion process is managed with excess heat and utilisation of recovered heat

Sectoral Outlook

Transport – Fuel Costs



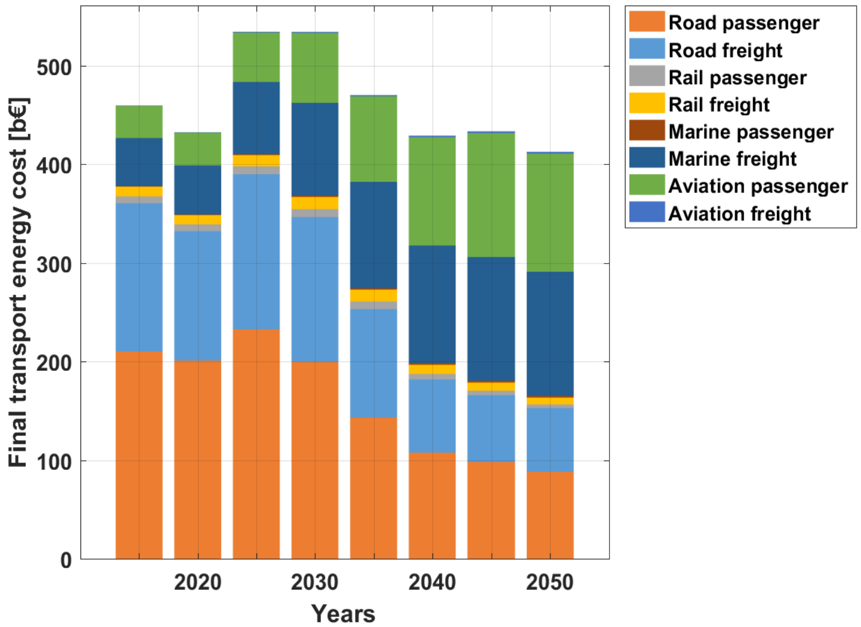


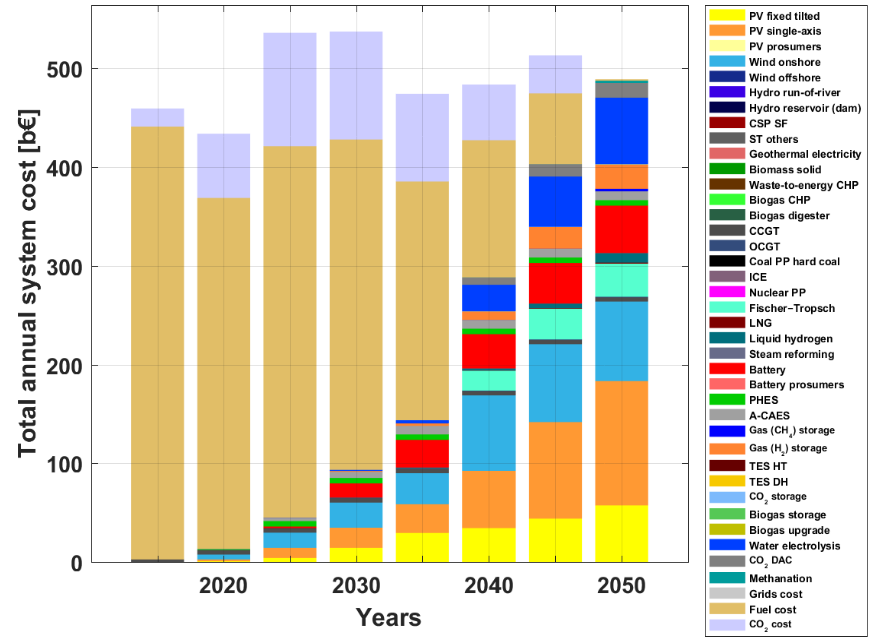
Key insights:

- Fischer-Tropsch (FT) and Synthetic Natural Gas (SNG) fuel costs decline through the transition up to 2050
- FT fuels are in the range of costs of fossil liquid fuels with GHG emissions costs, on a level of about 90 €/MWh
- Electricity emerges as the most cost effective option with LCOE primary around 13 €/MWh and along with complementary costs of storage and other system components, total LCOE is around 28 €/MWh in 2050
- Hydrogen (H_2) fuel costs decline to be more cost competitive than fossil fuels, in the range of 57 €/MWh in 2050, while liquid H_2 is in the range of 61 €/MWh
- CO_2 from DAC is a critical component for synthetic fuels at around 31 €/tCO_{2eq} in 2050, using waste heat

Sectoral Outlook

Transport – Annual Energy Costs



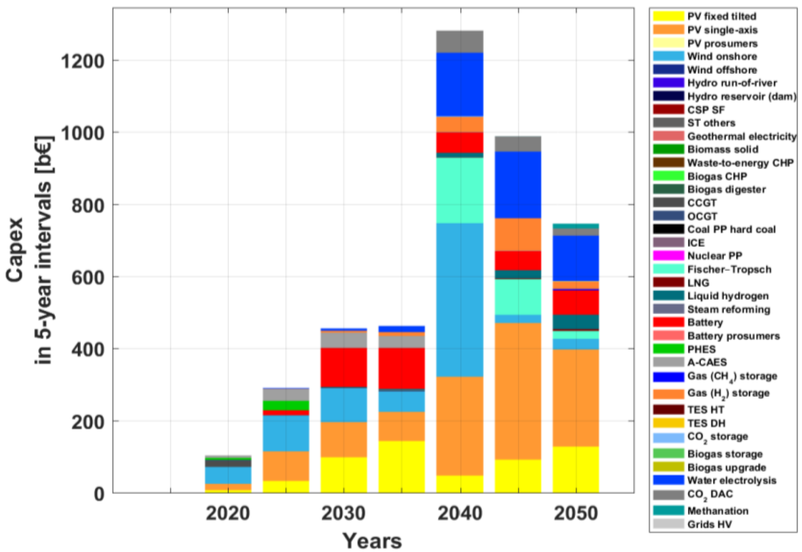


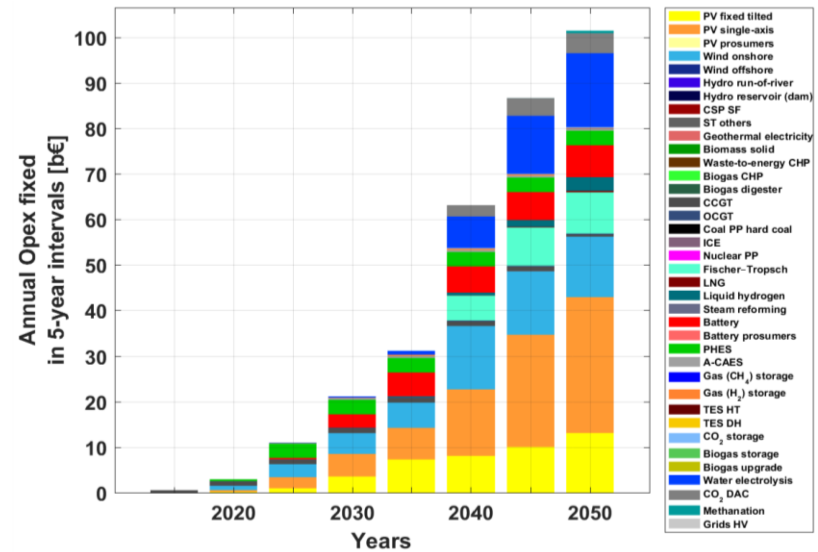
Key insights:

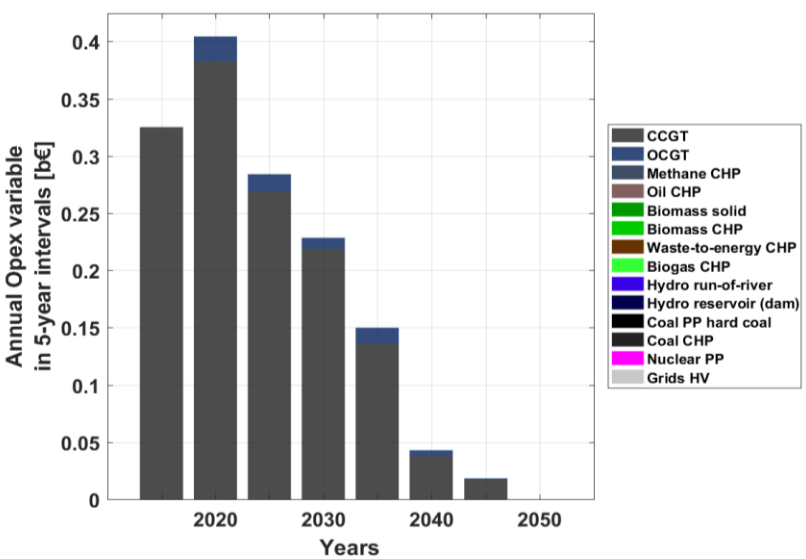
- The total annual energy costs for transport are in the range of 400-570 b€ through the transition period with a decline from around 470 b€ in 2015 to about 410 b€ by 2050
- Road transport form a major share of the costs in the initial years up to 2030, beyond which the aviation sector dominates the share of costs as cost in the road sector declines through the transition up to 2050
- Rail and marine sector costs remain more steady through the transition
- Annual system costs transit from being heavily dominated by fuel costs in 2015 to a very diverse share of costs across various technologies for electricity, synthetic fuels and sustainable biofuel production by 2050
- FT units produce naphtha as by-product, which is included in overall system costs, but not in transport costs

Sectoral Outlook

Transport – Capex and Opex





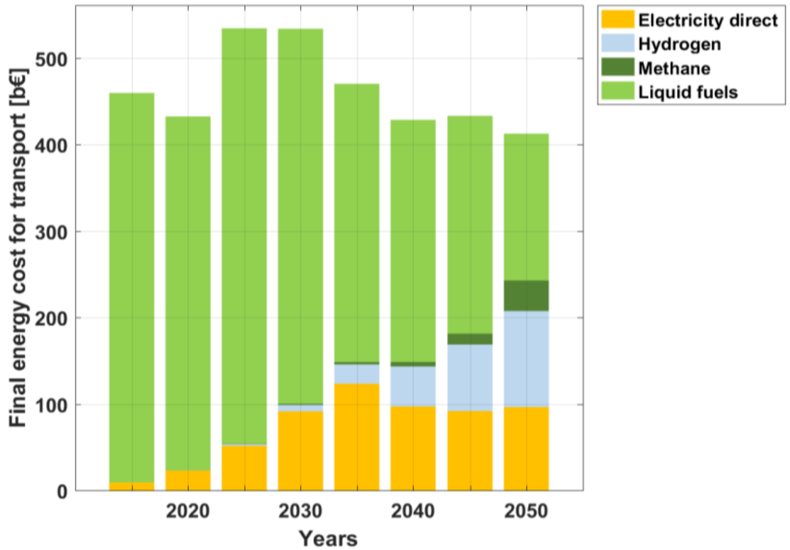


Key insights:

- Investments are predominantly in solar PV and wind up to 2030, beyond with significant investments are in fuel conversion technologies such as Fischer-Tropsch, water electrolysis and others
- A significant increase in annual fixed operational costs is observed beyond 2030, with more fuel conversion technologies up to 2050
- Whereas, the annual variable operational costs decrease beyond 2035 to very low amounts by 2050

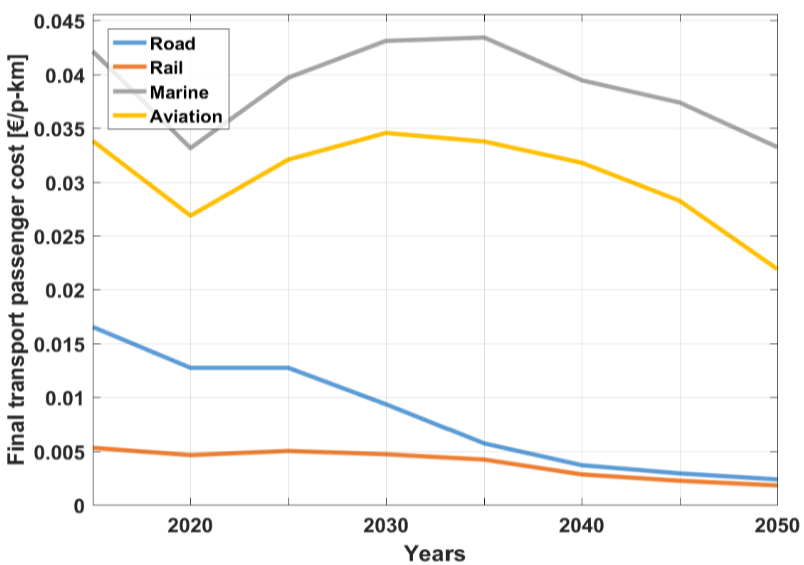
Sectoral Outlook

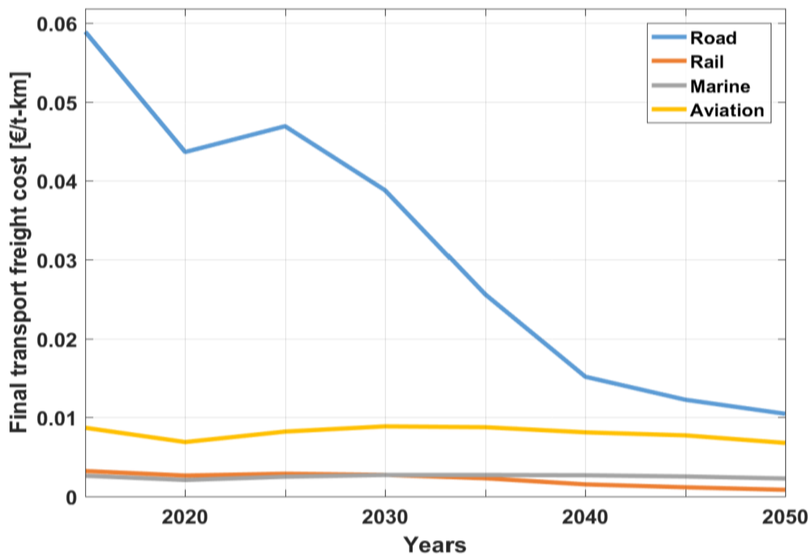
Transport – Passenger and Freight Costs



Key insights:

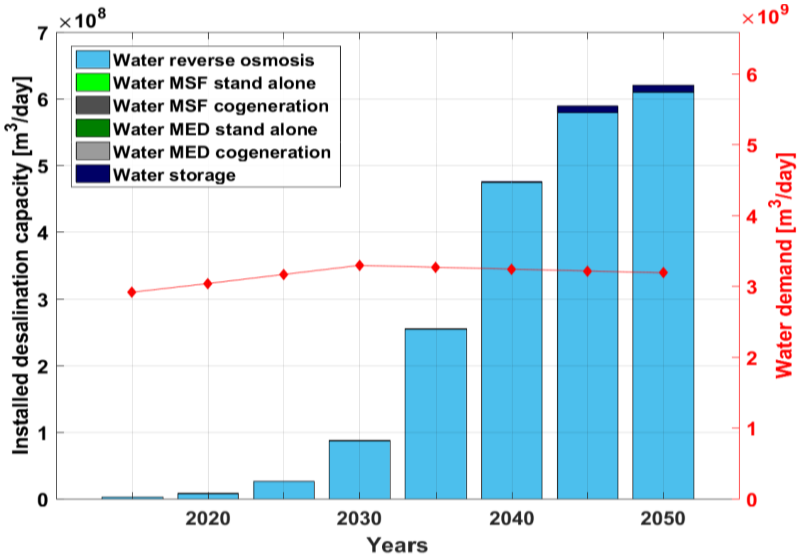
- The total annual costs for transport are in the range of 410-570 b€ through the transition period with a decline from around 470 b€ in 2015 to about 410 b€ by 2050
- Final transport passenger costs decline for road transport through the transition, whereas for marine and aviation there is a marginal decrease
- Similarly, final transport freight costs decline in the case of road and decrease slightly for rail and remains stable for aviation and marine

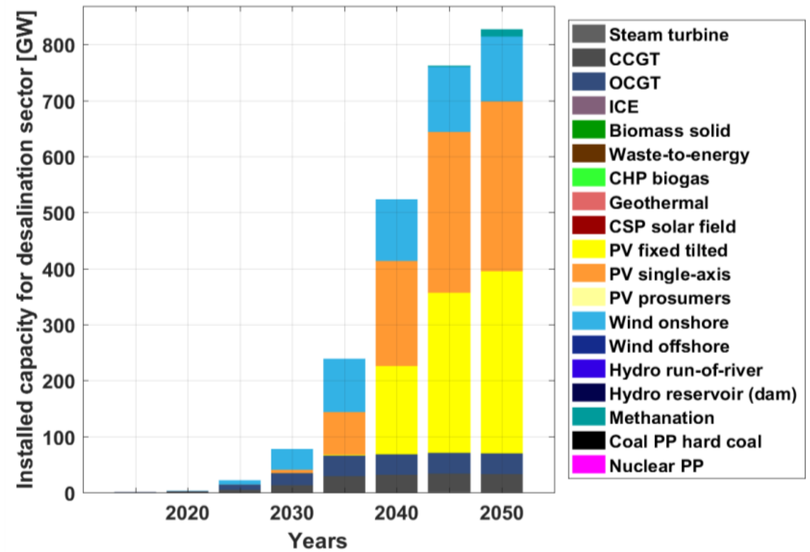


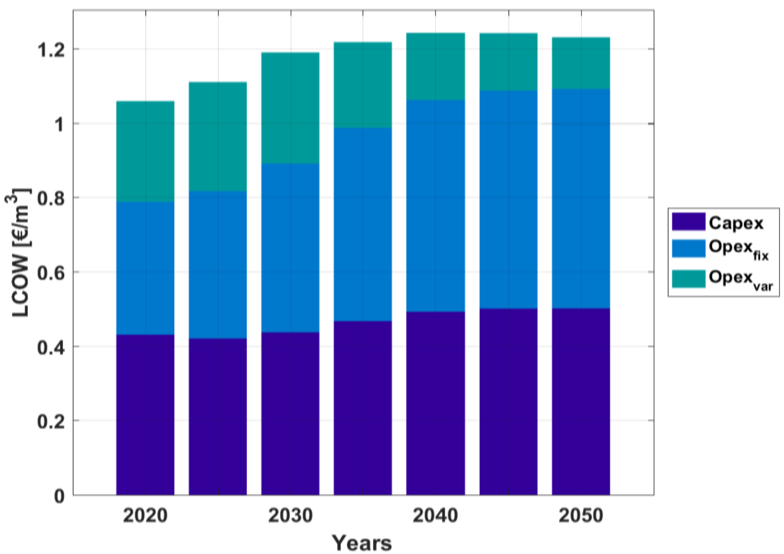


Sectoral Outlook

Desalination







Key insights:

- The steady rise in water demand across Northeast Asia leads to increased desalination capacities and some water storage by 2050
- Installed capacity of power generation for the desalination sector increases through the transition to around 28 GW by 2050, which is mainly renewables
- The LCOW for desalination increases through the transition from nearly 1.1 €/m³ in 2015 to around 1.2 €/m³ by 2050

GHG Emissions Reduction

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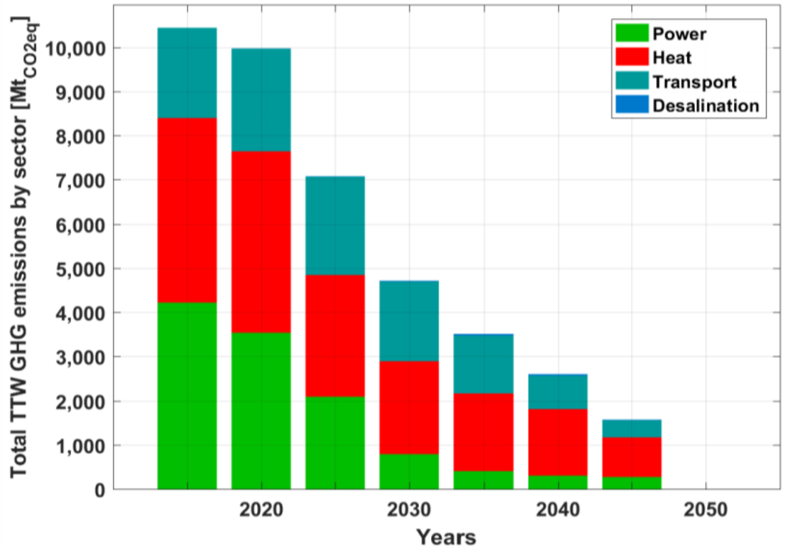
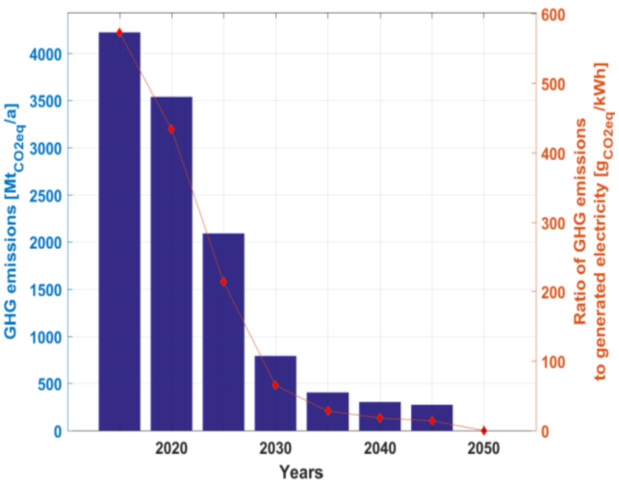
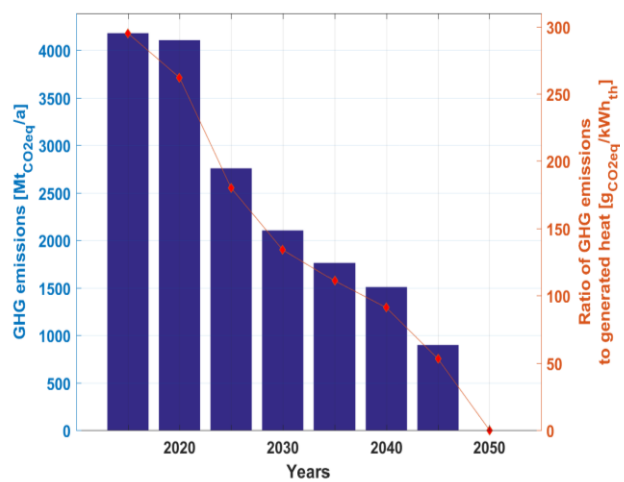
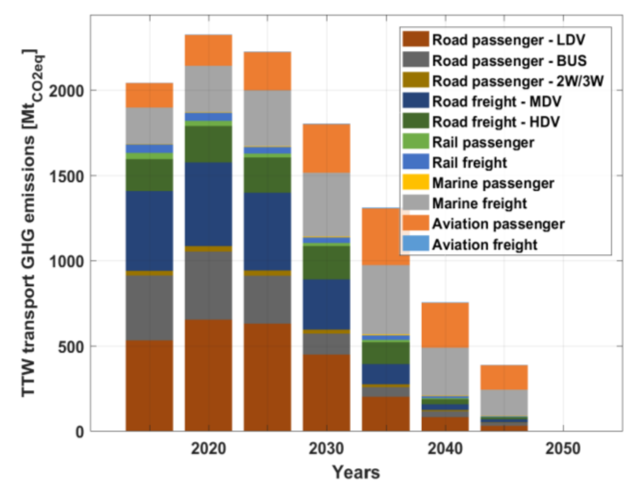


Key insights:

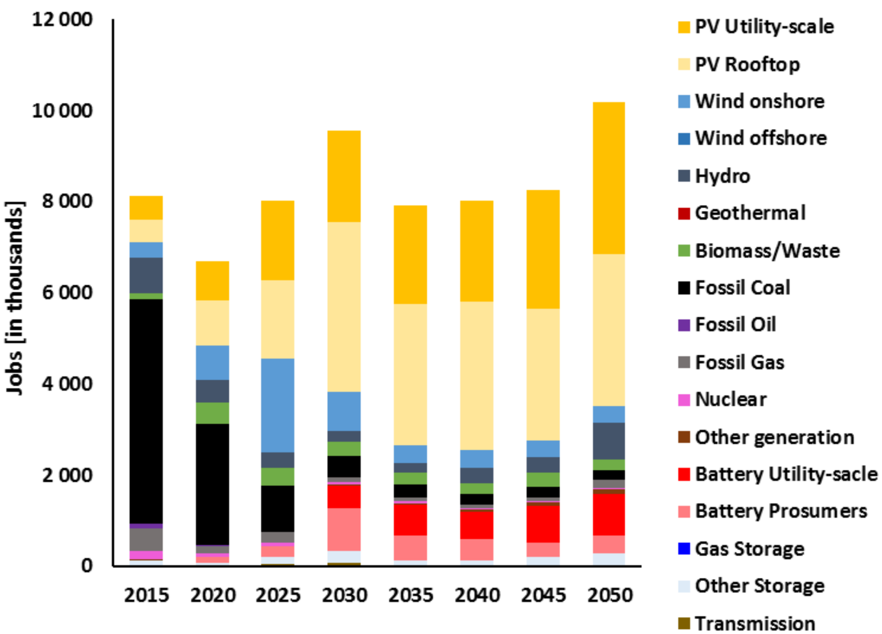
- GHG emissions can be reduced from over 10,000 $MtCO_{2eq}$ in 2015 to zero by 2050 across all energy sectors
- The remaining cumulative GHG emissions comprise around 147 $GtCO_{2eq}$ from 2018 to 2050.
- The presented 100% RE scenario for the energy sector across Northeast Asia is compatible with the Paris Agreement
- Deep defossilisation of the power and heat sectors is possible by 2030, while the transport sector is lagging and a steady decline of emissions is possible beyond 2030 up to 2050

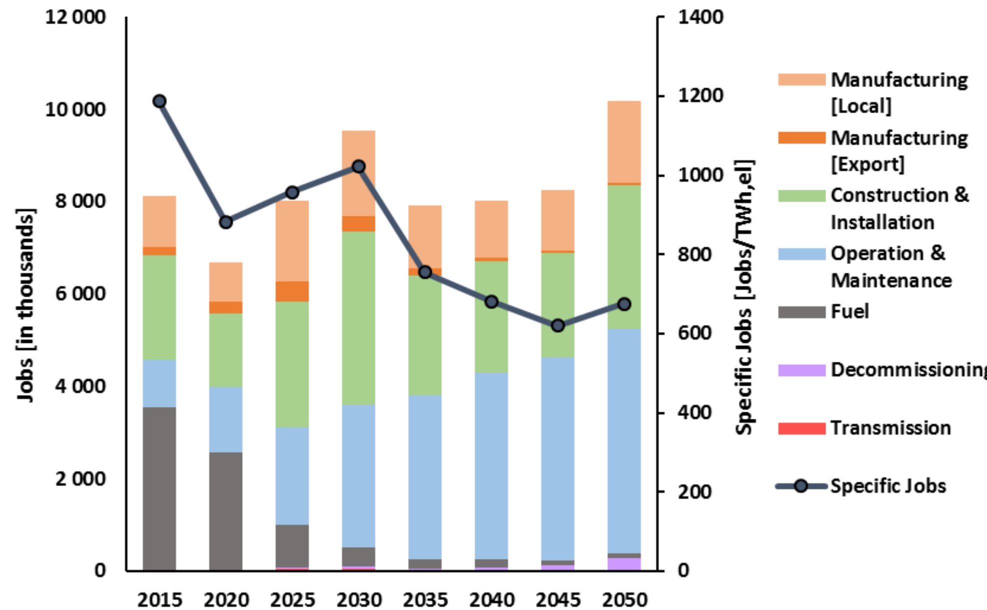






Job Prospects – Power Sector



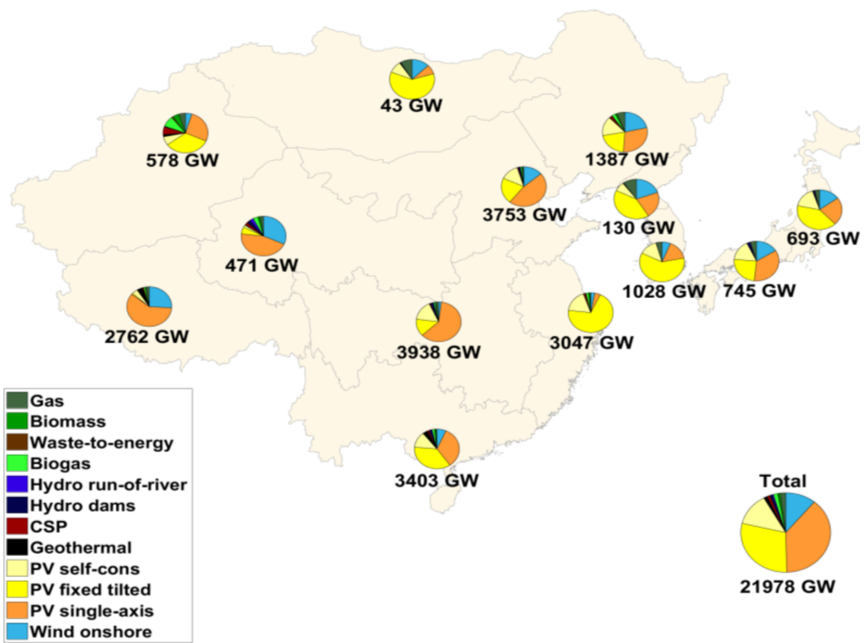


Key insights:

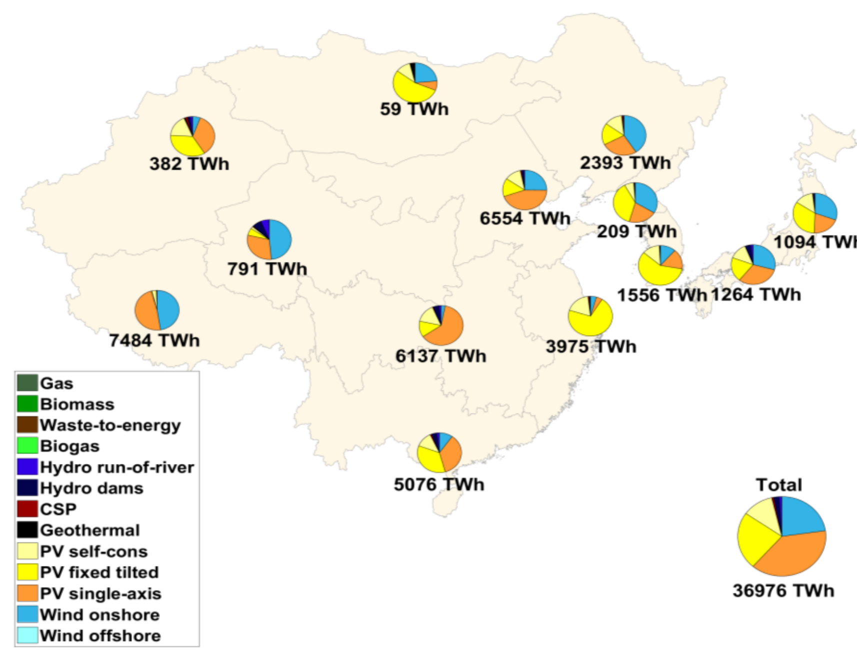
- Total direct energy jobs are seen to increase from around 8 million in 2015 to 9.5 million by 2030 and after a decline, number of jobs rise back to around 10 million by 2050, primarily with the replacements of power plants beginning to increase in the period from 2045 to 2050
- Solar PV emerges as the prime job creator in the region up to 2050 with about 6.7 million jobs
- Storage technologies led by batteries are observed to create a fair share of jobs from 2030 onwards and continue unto 2050 with 1.3 million jobs in the battery sector.
- The share of operation and maintenance jobs grows through the transition period from 13% of total jobs in 2015 to 48% of total jobs in 2050, as fuel jobs decline rapidly

Electricity generation and capacities

Regional electricity capacities



Regional electricity generation

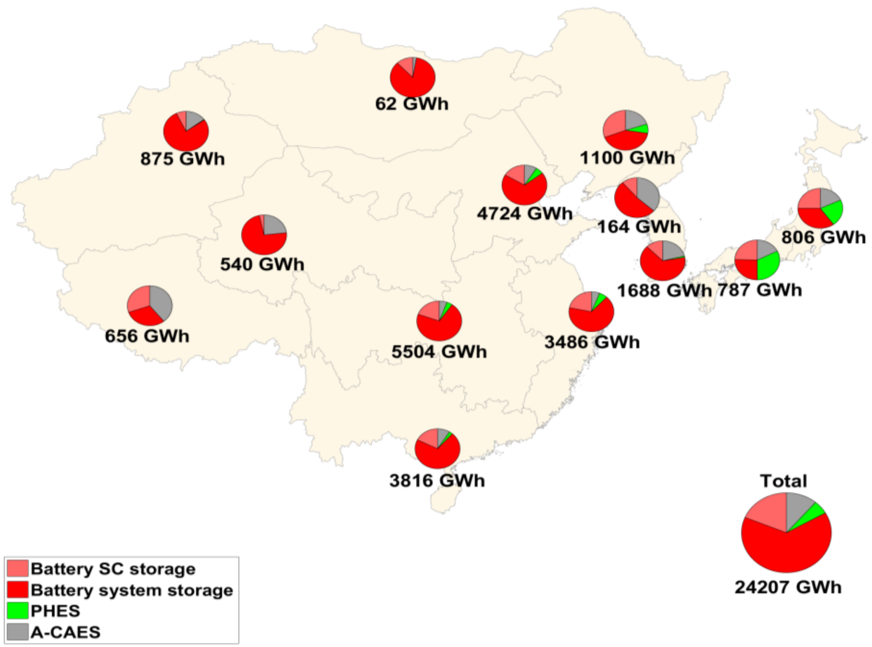


Key insights:

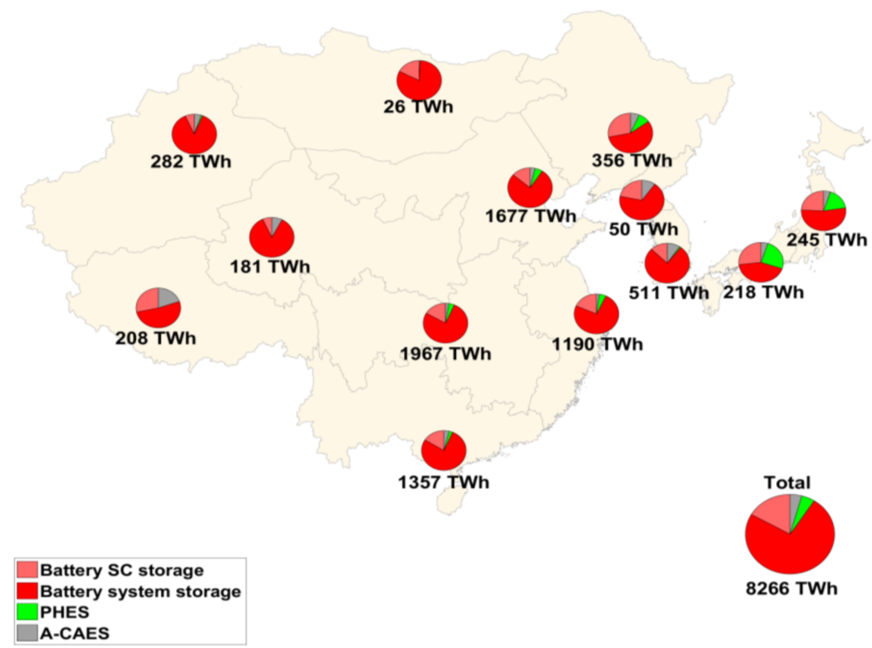
- Electricity generation is comprised of demand for the sectors power, heat, transport and desalination
- Solar PV capacities are predominantly in China, while most wind capacities is found in China (Tibet) and China (North), as well as in China Northeast and China South
- Solar PV generation dominates in terms of generation followed by wind in China (Tibet) and China North
- Overall, solar PV and wind generate most of the electricity needed across Northeast Asia by 2050
- Installed capacities and electricity generation are considered for all energy sectors

Storage capacities and throughput
Electricity

Regional electricity storage capacities



Regional electricity storage annual generation



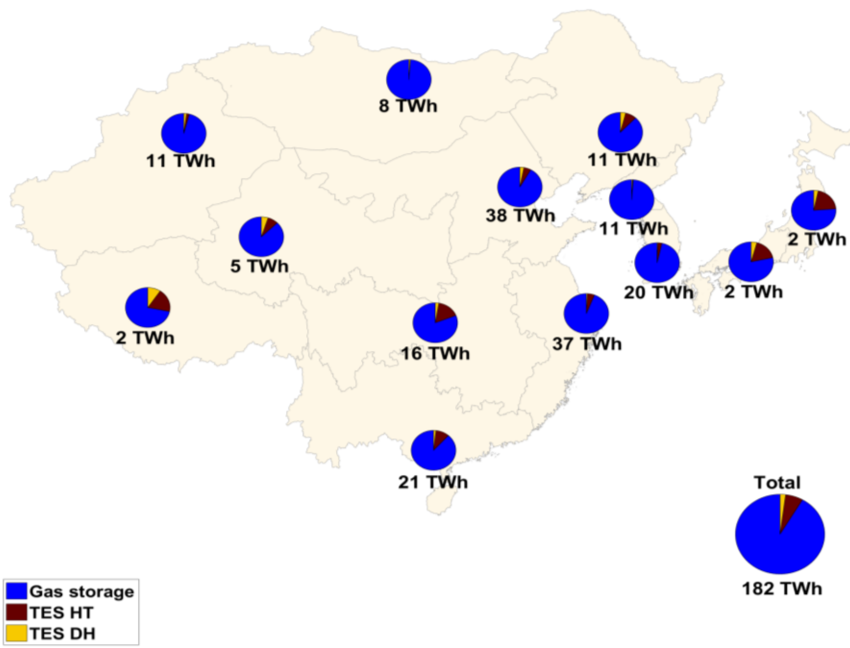
Key insights:

- Utility-scale and prosumer batteries contribute a major share of the electricity storage capacities, with some shares of compressed air energy storage and pump hydro energy storage by 2050
- Storage capacities are much higher in China North and China Central
- Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050
- Compressed air energy storage and pump hydro energy storage contribute through the transition
- Storage capacities and output are considered for all energy sectors across Northeast Asia

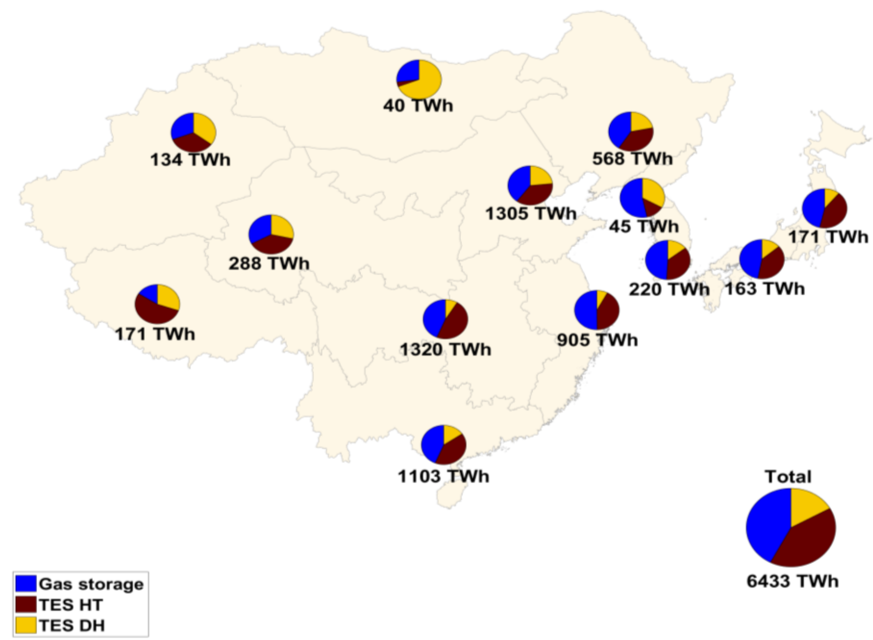
Storage capacities and throughput

Heat

Regional heat storage capacities



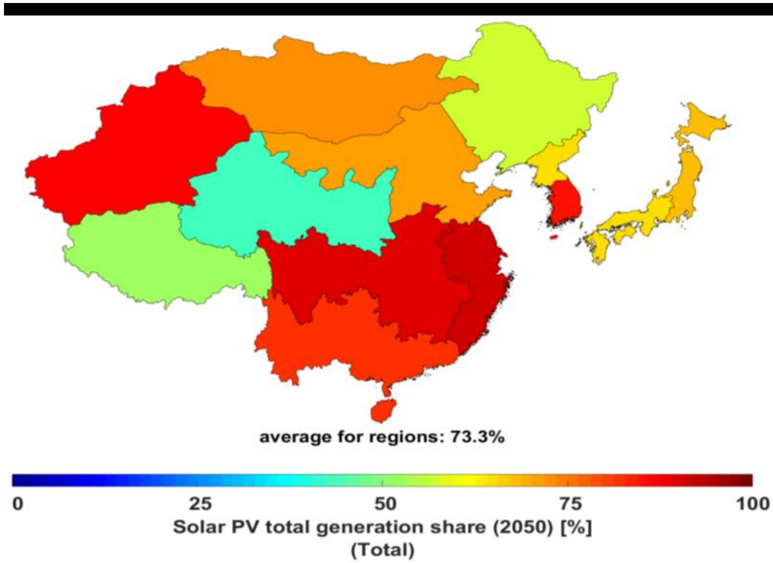
Regional heat storage annual generation

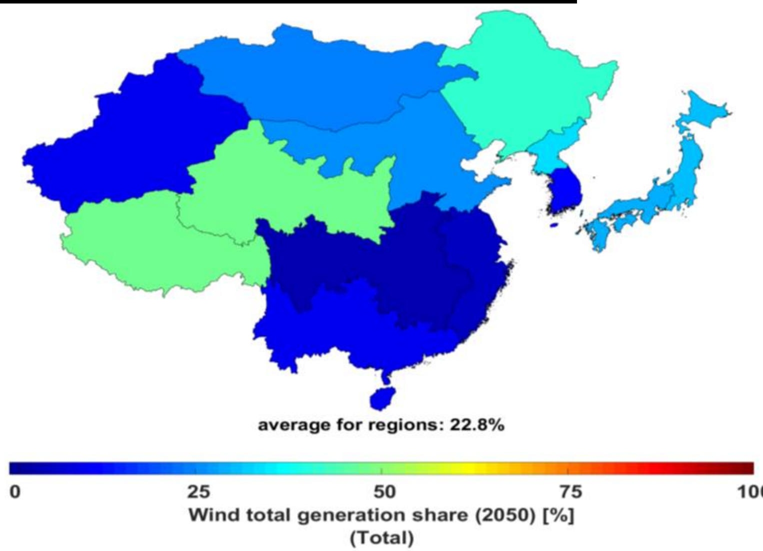


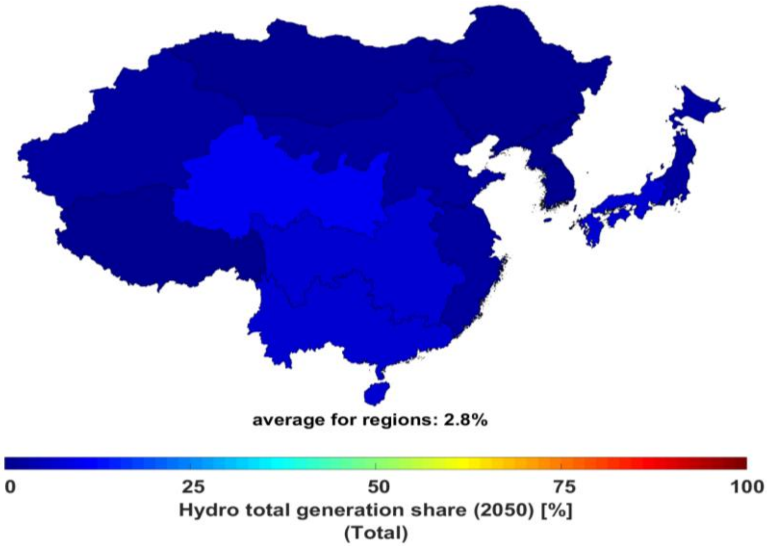
Key insights:

- Gas storage contributes the most for heat storage capacities in 2050 covering predominantly seasonal demand, covered by fossil gas before 2050
- Gas storage output is much higher in most regions in the north and east of China
- Thermal energy storage emerges as the most relevant heat storage technology in terms of heat storage output across Northeast Asia in 2050

Major RE Supply Shares in 2050



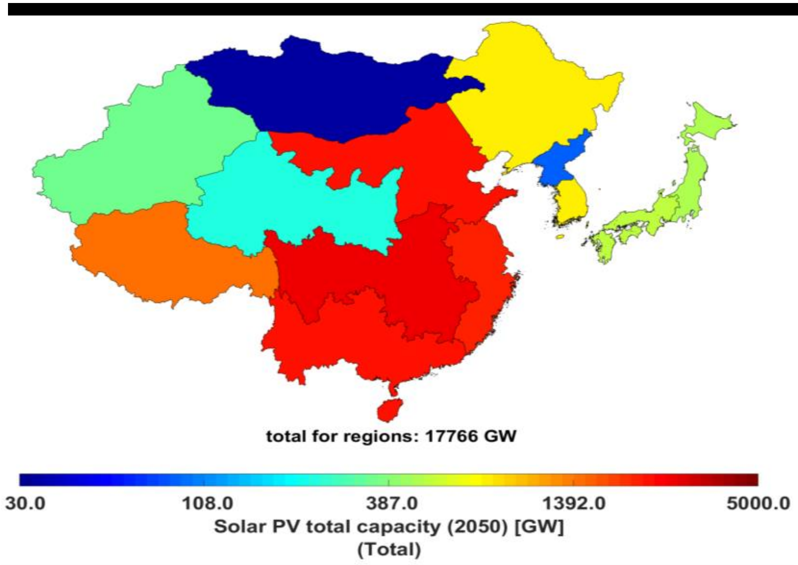


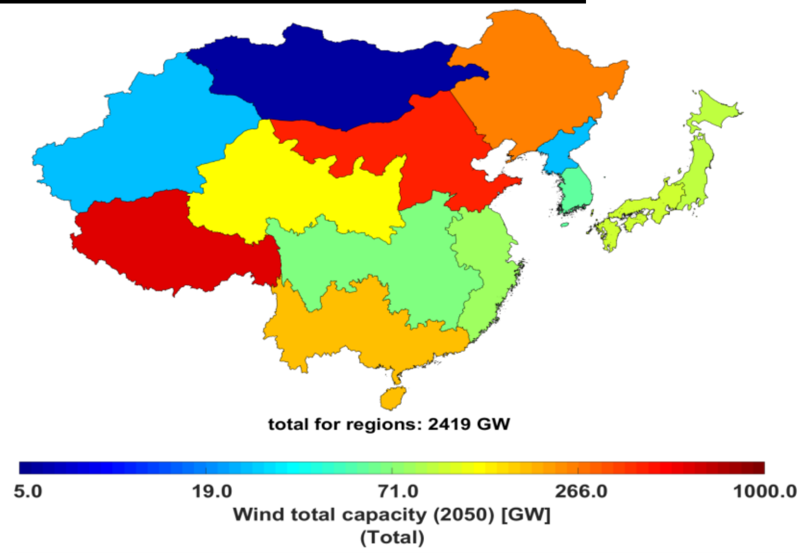


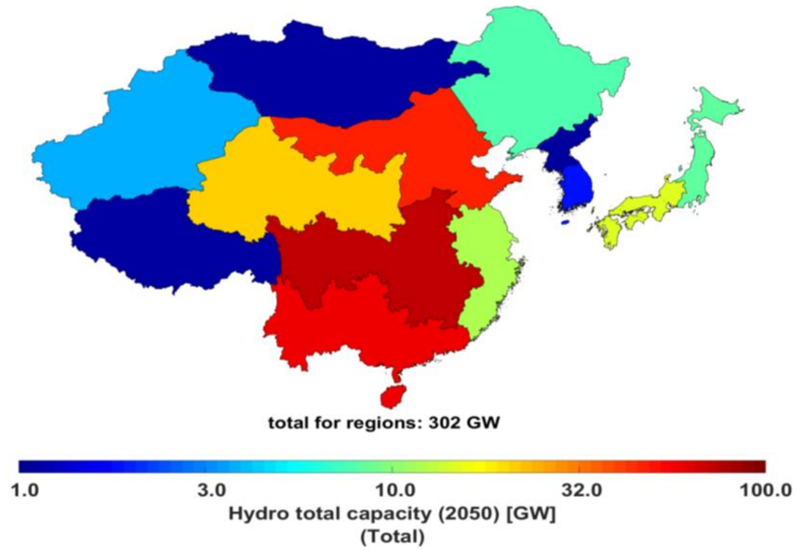
Key insights:

- Solar PV dominates the total electricity generation supply shares in 2050
- Electricity generation shares in Northeast Asia for all energy sectors are
  - Solar PV at about 73.3%
  - Wind energy at about 22.8%
  - Hydropower at about 2.8%

Major RE Capacities in 2050



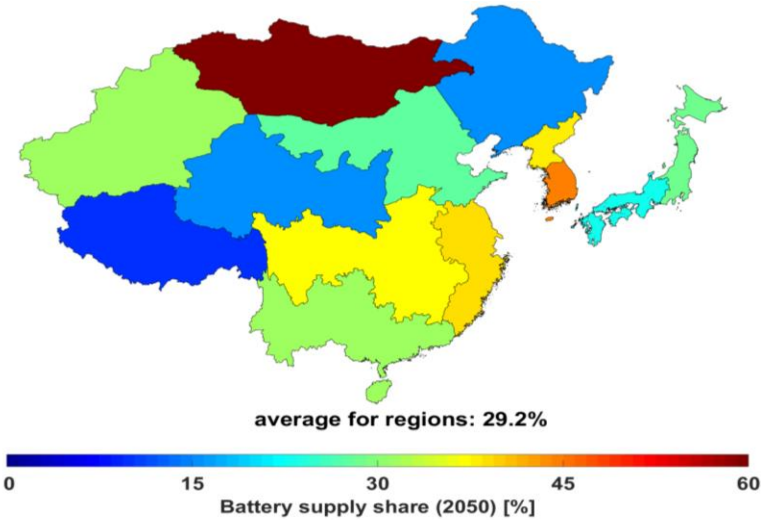


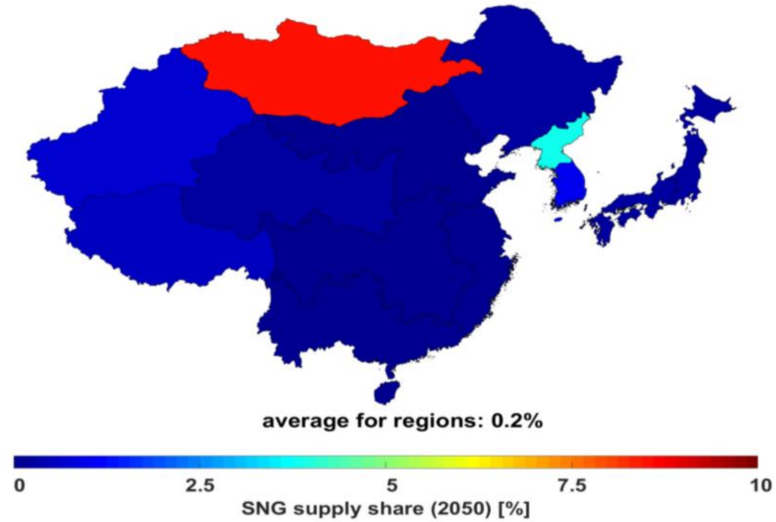


Key insights:

- Solar PV dominates the total electricity generation capacity across Northeast Asia in 2050
- Installed capacities in 2050 across Northeast Asia for all energy sectors are about
  - Solar PV: 17,770 GW
  - Wind energy: 2420 GW
  - Hydropower: 300 GW

Storage Supply Shares in 2050

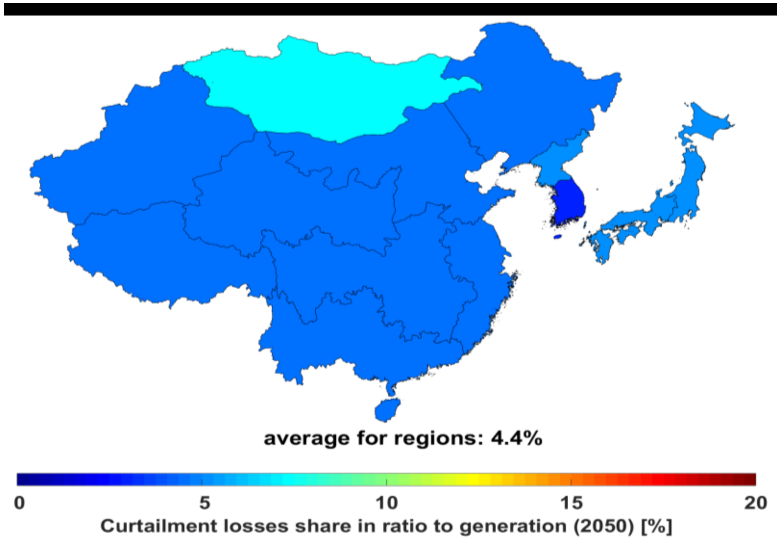


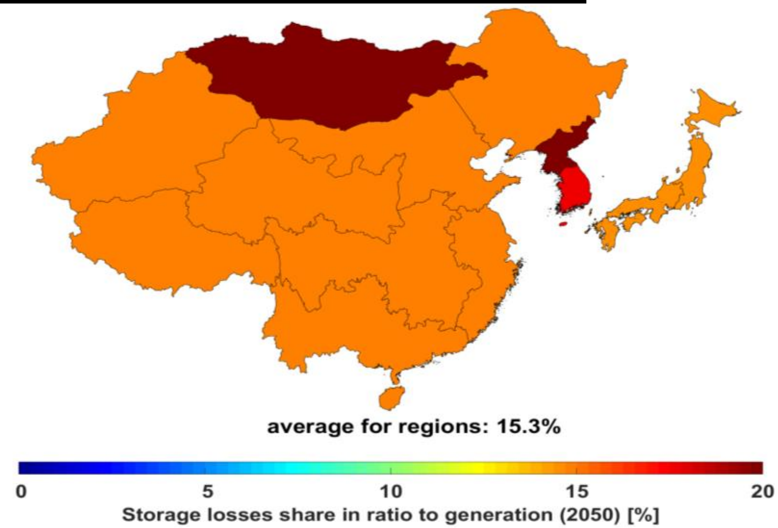


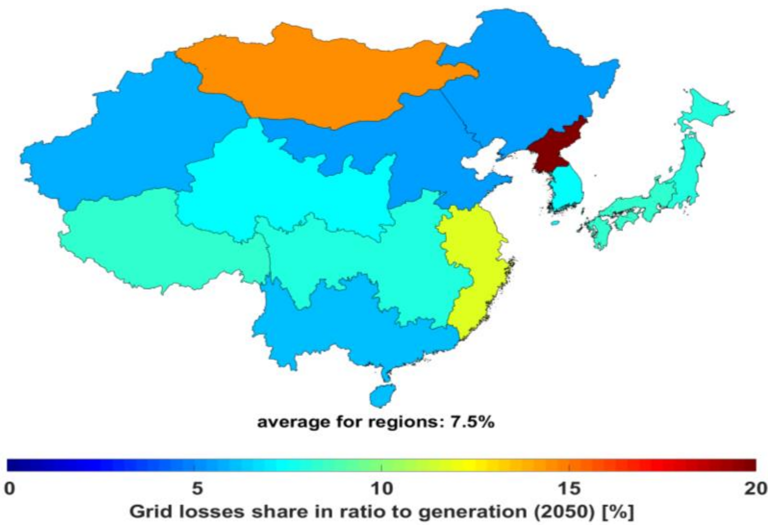
Key insights:

- Battery storage mainly plays a role in providing diurnal storage with around 29% of the total supply
- SNG via PtG plays a role in providing seasonal storage with just 0.2% of the total supply for the power sector. The other sectors are not considered here, however, sector coupling of the power and heat sectors indirectly leads to a lower SNG demand for the power sector due to more flexibility
- Prosumers play a significant role and hence a large portion of batteries can be observed in 2050, also with low costs of solar PV and batteries
- Storage supply shares are considered just for the power and heat sectors

Losses (Curtailment, Storage, Grids) in 2050



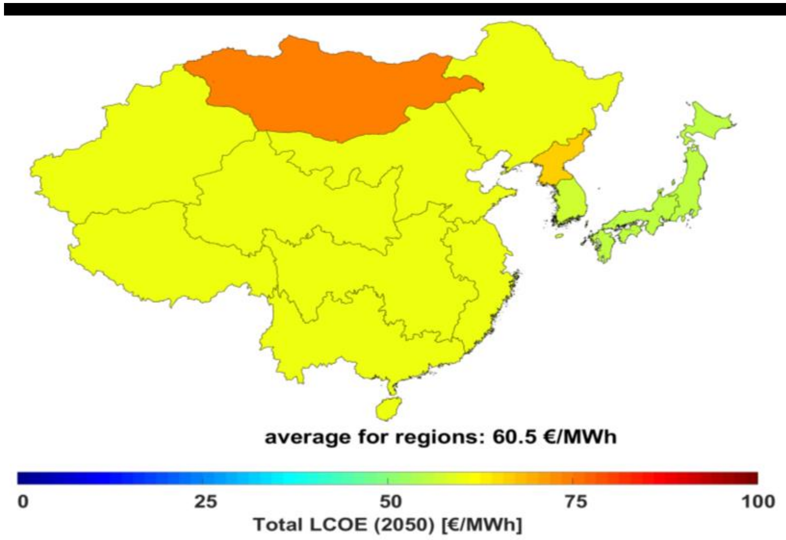


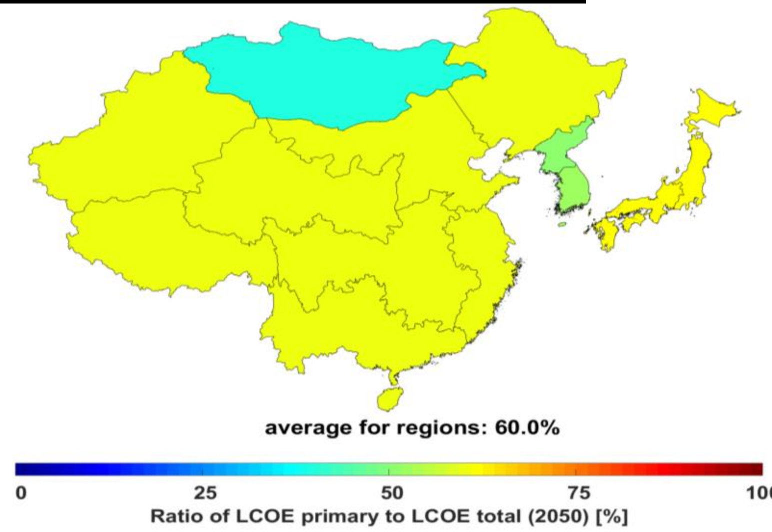


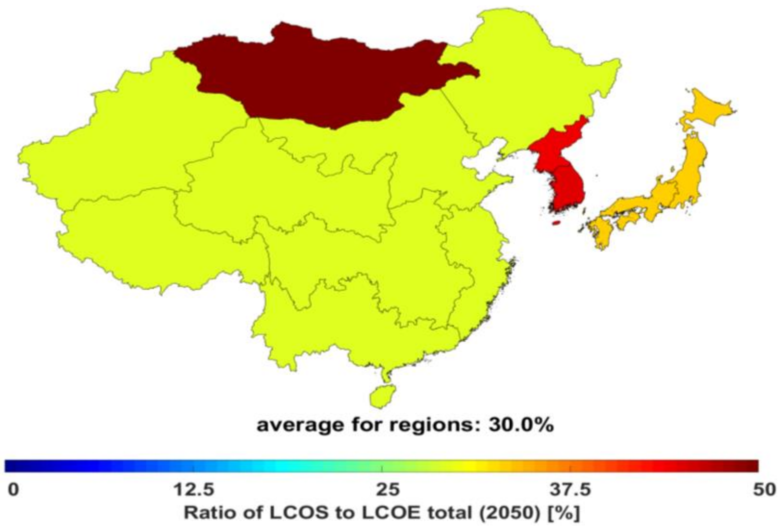
Key insights:

- The total losses in a 100% RE-based electricity system in 2050 are just around 27% of the total generation
- Curtailment has a share of 4.4%, storage contributes 15.3% and grid losses amount to 7.5%
- RE-based electricity system is significantly more efficient in comparison to the current system based predominantly on fossil fuels and nuclear
- Losses are considered for the sectors of power and heat

Total Cost and Share of Primary Generation







Key insights:

- Total LCOE by 2050 is around 60.5 €/MWh (including generation, storage, curtailment and some grid costs), the range for 75% of regional power demand is 43.1 – 70.2 €/MWh
- A 58% ratio of the primary generation cost to the total LCOE can be observed, in a range of 40% - 64% for 75% of regional power demand
- Cost of storage contributes substantially to the total energy system LCOE, with ratios ranging from 27% - 50% for 75% of regional power demand
- Costs are considered for just the power and heat sectors

Summary – Power & Heat

- Electricity consumption per capita increases from over 4 MWh/person in 2015 to over 8 MWh/person by 2050, while total heat demand increases steadily from around 12,500 TWh_{th} in 2015 to about 14,770 TWh_{th} by 2050
- Solar PV with 11,638 GW and wind with 1566 GW constitute a majority of the installed power capacities by 2050, while heat pumps, electric heating and biomass based heating constitute a majority of the installed heat capacities by 2050
- Utility-scale and prosumer batteries contribute a major share of the electricity storage output, while thermal energy storage emerges as the most relevant heat storage technology in the transition
- LCOE of the power sector decreases substantially from around 74 €/MWh in 2015 to around 61 €/MWh by 2050, while LCOH of the heat sector increases from around 34 €/MWh in 2015 to around 55 €/MWh by 2050
- Deep defossilisation of the power and heat sectors is possible from around 8400 $MtCO_{2eq}$ in 2015 to around 2892 $MtCO_{2eq}$ in 2030 and further to zero by 2050

Summary – Transport

- The modes of transportation are: Road, Rail, Marine and Aviation
- The main forms of energy supply are direct and indirect electricity, the latter with liquid hydrocarbons, methane, hydrogen and some biofuels
- The final energy demand for road freight decreases substantially from around 2400 TWh in 2015 to around 1500 TWh by 2050, mainly driven by the massive electrification of road transport
- Fuel utilisation reduces drastically through the transition as fossil fuels are completely replaced by electricity and synthetic fuels along with some sustainable biofuels
- The final energy costs for transport remain around 430-540 b€ through the transition period, with massive reduction for road, while an increase for marine and aviation by 2050
- GHG emissions can be reduced from about 2000 $MtCO_{2eq}$ in 2015 to zero across the transport sector by 2050

Summary – Desalination

- The water desalination demand is mainly covered by reverse osmosis
- The steady rise in water demand and water stress leads to increased desalination capacities and some water storage by 2050
- Installed capacity of power generation for the desalination sector increases through the transition period to around 800 GW by 2050
- Utility-scale solar PV and onshore wind comprise around 90% of the installed capacity by 2050
- Installed storage capacities are dominated by gas storage, while storage output is mainly from utility-scale batteries
- The LCOW for desalination remains quite stable through the transition and increases slightly from 1.1 €/m^3 in 2015 to 1.2 €/m^3 by 2050
- GHG emissions can be reduced from about 4 $MtCO_{2eq}$ in 2015 to zero across the desalination sector by 2050

Summary – Energy Transition

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- Northeast Asia can reach 100% RE and zero GHG emissions by 2050
- The LCOE obtained for a fully sustainable energy system for the region ranged from 50-61 €/MWh by 2050
- The annual energy costs are in the range of 1400-2100 b€ through the transition, with cumulative investment costs of about 19,200 b€ up to 2050
- Solar PV emerges as the most prominent electricity supply source with around 72% of the total electricity supply by 2050
- Heat pumps play a significant role in the heat sector with a share of nearly 37% of heat generation by 2050 coming from heat pumps on district and individual levels
- Batteries emerge as the key storage technology with 91% of total storage output
- GHG emissions can be reduced from about 10,000 $MtCO_{2eq}$ in 2015 to zero by 2050, with remaining cumulative GHG emissions of around 147 $GtCO_{2eq}$ from 2018 to 2050
- Around 10 million direct jobs are created annually in 2050 across the power sector
- A 100% RE system is more efficient and cost competitive than a fossil based option and is compatible with the Paris Agreement

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Acronyms 1

BECCS	Bioenergy Carbon Capture and Storage	HVAC	High Voltage Alternating Current
BEV	Battery Electric Vehicle	HVDC	High Voltage Direct Current
CAES	Compressed Air Energy Storage	ICE	Internal Combustion Engine
CAPEX	Capital Expenditures	IEA	International Energy Agency
CCS	Carbon Capture and Storage	IH	Individual Heating
CCGT	Combined Cycle Gas Turbine	LCOC	Levelised Cost of Curtailment
CHP	Combined Heat and Power	LCOE	Levelised Cost of Electricity
CSP	Concentrated Solar Thermal Power	LCOH	Levelised Cost of Heat
DAC	CO_2 Direct Air Capture	LCOS	Levelised Cost of Storage
DACCS	Direct Air Carbon Capture and Storage	LCOT	Levelised Cost of Transmission
DH	District Heating	LCOW	Levelised Cost of Water
DME	Dimethyl Ether	LDV	Light Duty Vehicle
FCEV	Fuel Cell Electric Vehicle	LNG	Liquefied Natural Gas
FLH	Full Load Hours	LT	Low Temperature
FT	Fischer-Tropsch	MDV	Medium Duty Vehicle
GHG	Greenhouse Gases	MED	Multiple-Effect Distillation
GT	Gas Turbine	MSF	Multi-Stage Flash
GW	Gigawatt	MT	Medium Temperature
HDV	Heavy Duty Vehicle	MW	Megawatt
HHB	Hot Heat Burner	OCGT	Open Cycle Gas Turbine
HT	High Temperature	OPEX	Operational Expenditures

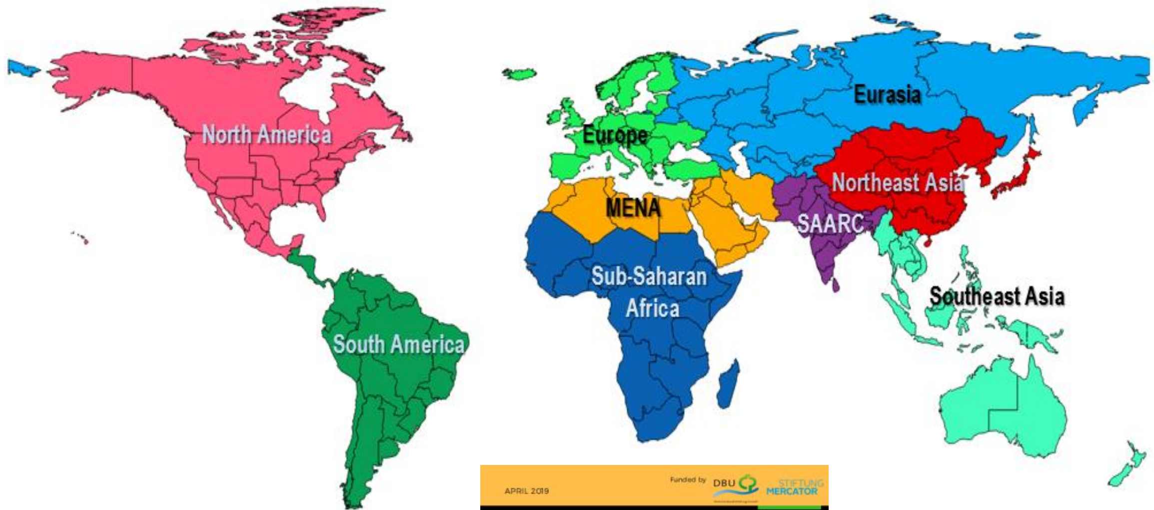
Acronyms 2

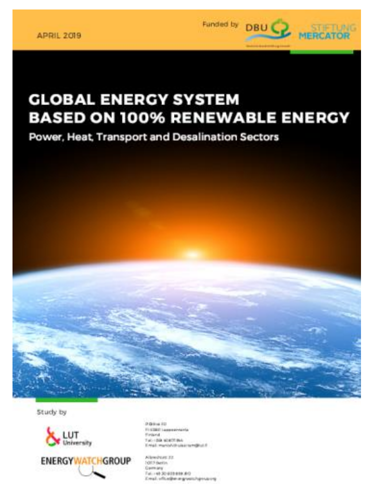
PHEV	Plug-in Hybrid Electric Vehicle
PHES	Pumped Hydro Energy Storage
PP	power plant
PtG	Power-to-Gas
PtH	Power-to-Heat
PtL	Power-to-Liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy
R/O	(Seawater) Reverse Osmosis
SNG	Synthetic Natural Gas
ST	Steam Turbine
TES	Thermal Energy Storage
TPED	Total Primary Energy Demand
TW	Terawatt
TTW	Tank to Wheel

Further Findings

Results for an overview on global aspects and all other major regions are available:

- Global results — link
  - Europe — link
  - Eurasia — link
  - MENA — link
  - Sub-Saharan Africa — link
  - SAARC — link
  - Northeast Asia — link
  - Southeast Asia/ Pacific — link
  - North America — link
  - South America — link
- Supplementary Data — link
- Report — link





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Further information and all publications at:
www.energywatchgroup.org
www.researchgate.net/profile/Christian_Breyer

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