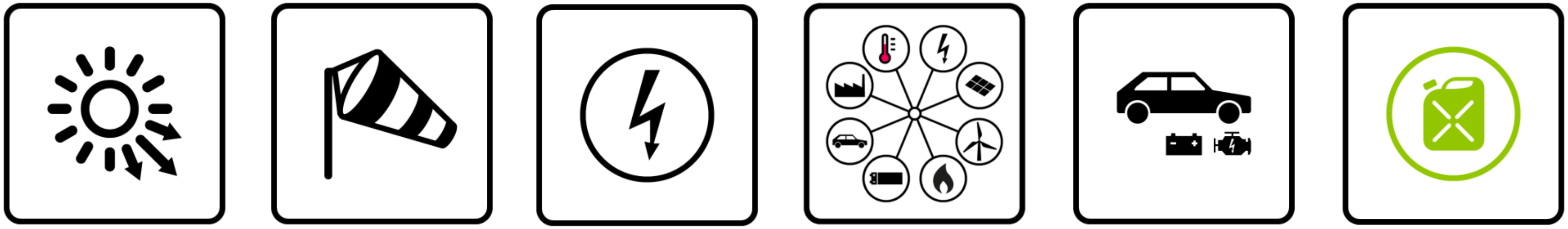
100% Renewable UK

Results - Summary



Christian Breyer, Dmitrii Bogdanov, Philipp Diesing, Rasul Satymov, Michael Child
LUT University, Finland
November 2022

Agenda

- Executive Summary
- Current Status of the Energy System
- LUT Energy System Transition Model
- Input data and key constraints
- Energy Transition Scenario Framing
- Scenario Comparison
- Results - Energy Demand
- Results - Energy Mix
- Results - Energy Storage
- Results - Costs & Investments
- Results – CO_2 Emissions
- Summary
- Extended Results
- Abbreviations

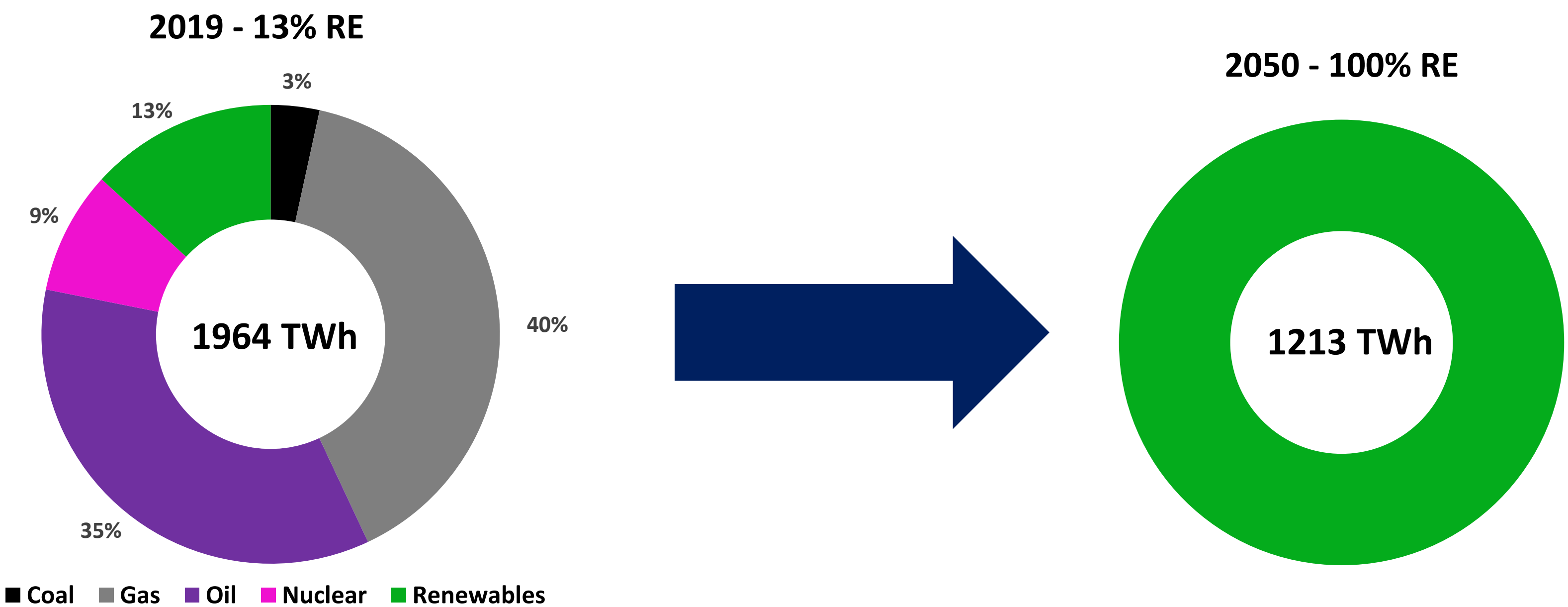
Executive Summary – 100% RE UK

Key parametres	Unit	2020	2030	2040	2050
Primary Energy Demand	TWh	1741.8	1289.2	1234.9	1213
Share of Renewable Electricity	%	46.3	86.7	97.8	100
Offshore wind share	%	19.5	35.7	36.6	43.5
Onshore wind share	%	20.0	26.5	21.6	16.4
Solar PV share	%	4.6	20.7	30.0	25.1
Wave power share	%	0	0	7.3	10.9
LCOE	€/MWh	81.9	64.2	50.6	43.2
Total annual system costs	b€	79.3	83.7	76.6	67.7
CO_2 emissions	$MtCO_2$	486.3	263.1	131.8	0

Results for BPS

Current Status of the Energy System

- Simulating the energy transition with an existing energy system model for the UK
- Goal: Zero greenhouse gas emissions in 2050, supplied by 100% Renewable Energy
- Regional characteristics: industrialised country with high GDP per capita ($44,920) in northern hemisphere, high population density (281/km^2), excellent onshore and offshore wind resources, moderate solar resources

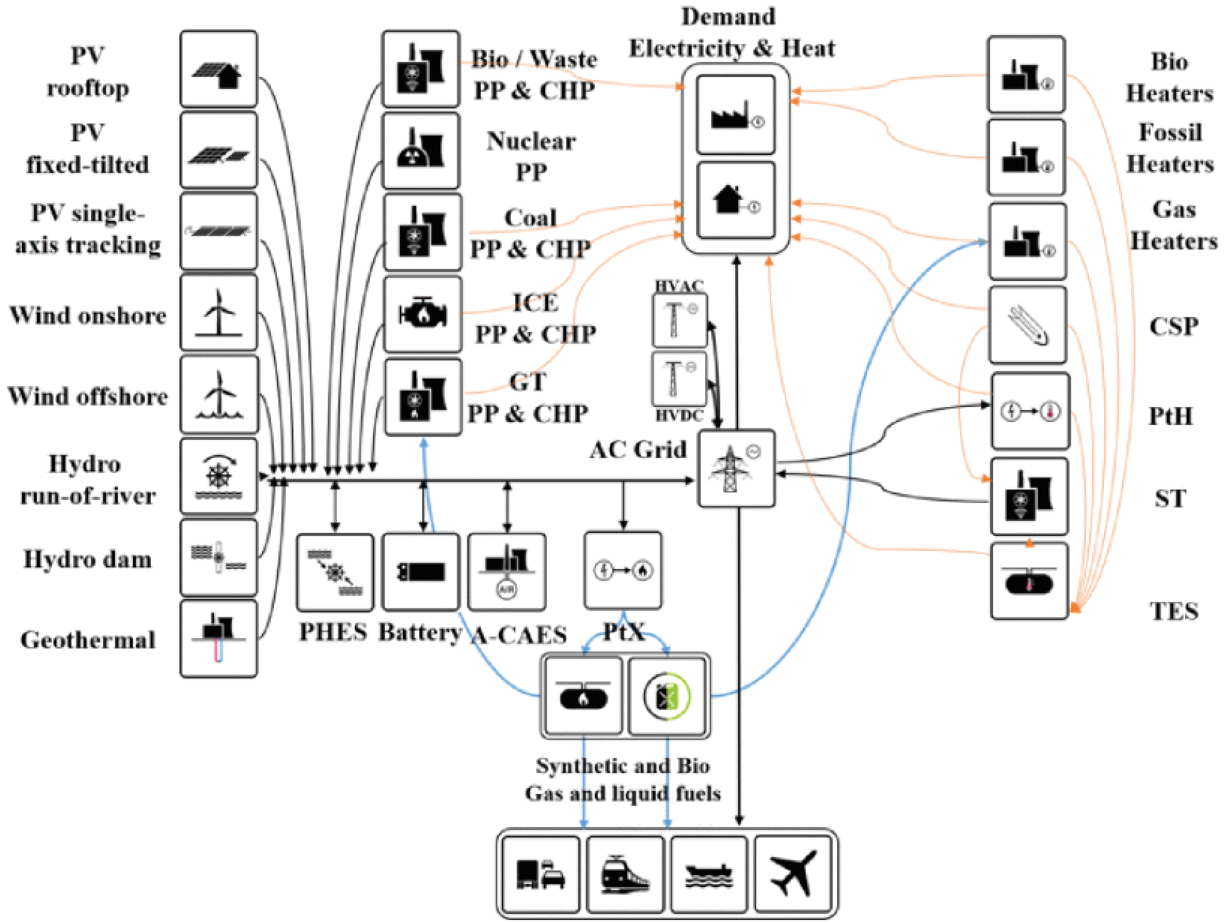


Total primary energy demand by source for United Kingdom in 2019 (IEA Data)

Results for BPS

LUT Energy System Transition Model

Power, Heat and Transport



- 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 across the UK
- The LUT model has been applied across all energy sectors

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

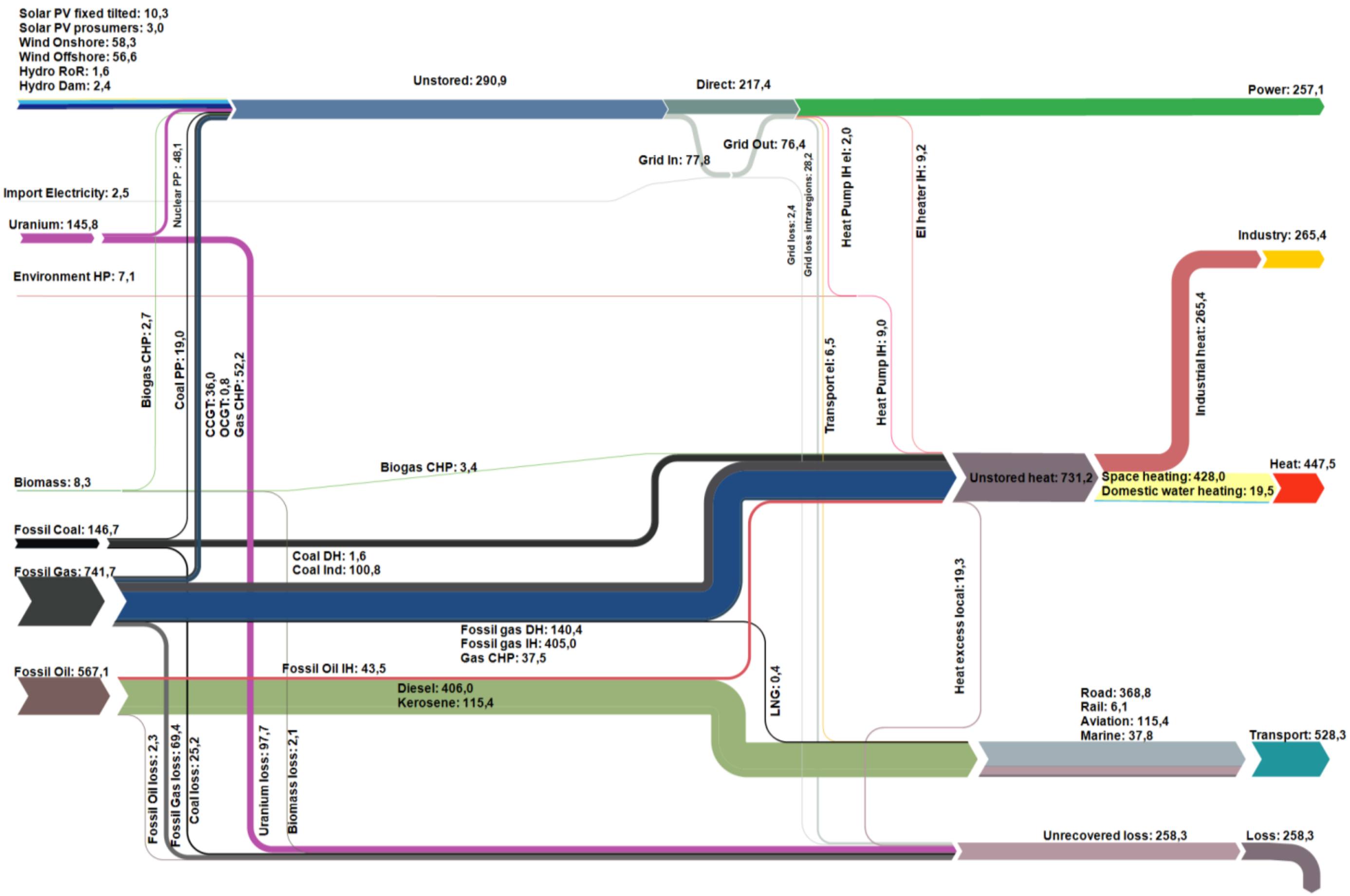
Input Data and Key Constraints

Regional Structuring

- UK and Ireland are divided into ten sub-regions: Southern England, Midlands, North West, North East and Yorkshire, London, East, Scotland, Wales, Northern Ireland and Ireland.
- UK is analysed seperately by limiting the interconnection with Ireland.
- A high number of regions ensure a high accuracy of the modelling and respect local characteristics.
- It enables the energy exchange between regions via HVAC and HVDC transmission lines.
- The interconnection is simulated according to the already existing electricity grid.

Input Data and Key Constraints

Representing the Energy System as of today



- Strong reliance on fossil oil for transportation and natural gas for heating
- Low share of renewables
- Power, Heat, and Transport sectors are barely coupled
- Low level of electrification
- Energy storage is almost non-existent

Results for BPS

more information ► christian.breyer@lut.fi

Input Data and Key Constraints

Power, Heat, and Transport Demand

- High level of electrification is expected until 2050 – large parts of heat and transport sectors will be electrified
- Heat demand grows slightly (space heating demand decreases, due to efficiency gains)
- Transportation demand grows across all sub-categories, but vehicles have higher efficiency
- Transportation demand numbers have been revised based on latest insights
- In 2050, up to 1200 TWh of renewable electricity will be required

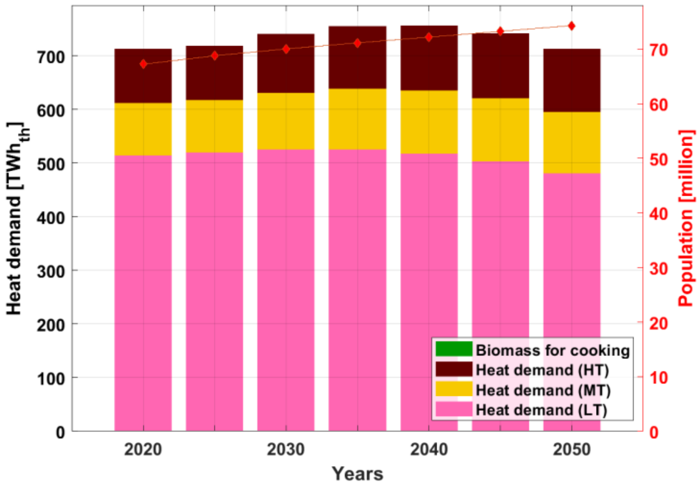
Sector	Unit	Demand	
		2020	2050
Electricity	TWh,el/a	257	333
Heat - space heating	TWh,th/a	428	376
Heat - domestic hot water	TWh,th/a	20	27
Heat - industrial heat	TWh,th/a	265	309

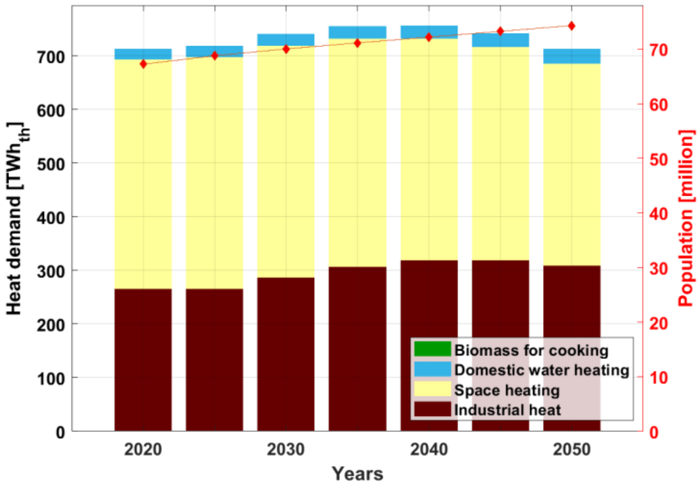
Transport sector	mil p-km		mil t-km	
	2020	2050	2020	2050
Transport - Road	691,293	928,575	162,347	188,876
Transport - Rail	67,836	114,220	15,497	22,543
Transport - Marine	3,131	5,292	850,494	1,195,317
Transport - Aviation	211,715	349,330	5,462	7,677

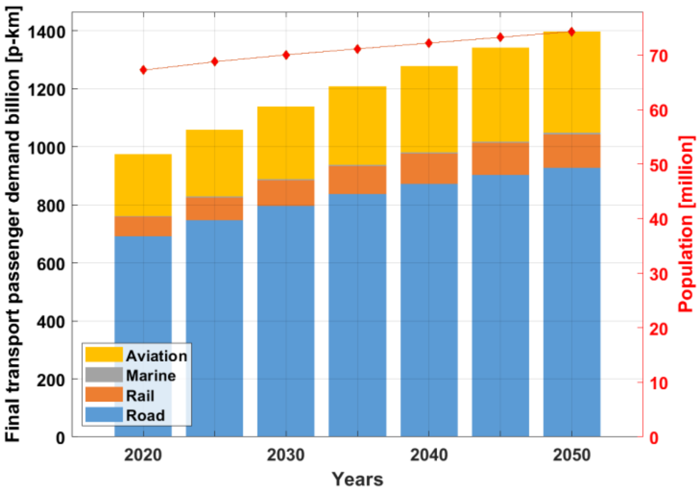
more information ► christian.breyer@lut.fi

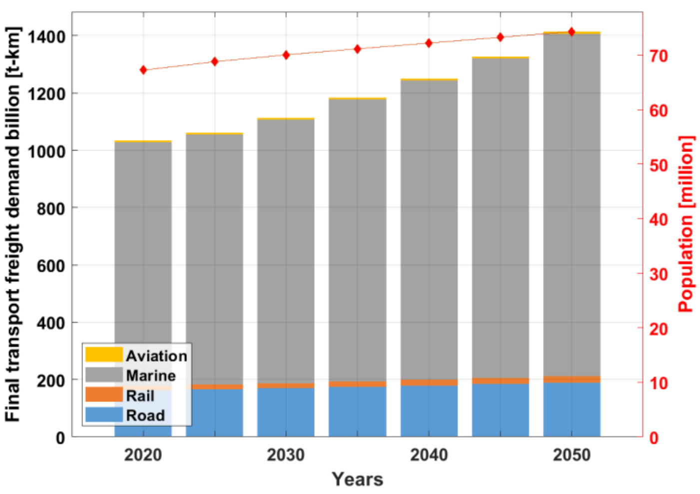
Input Data and Key Constraints

Heat and Transportation Demand



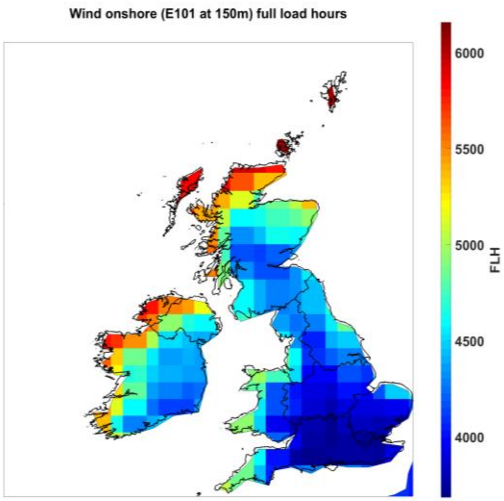


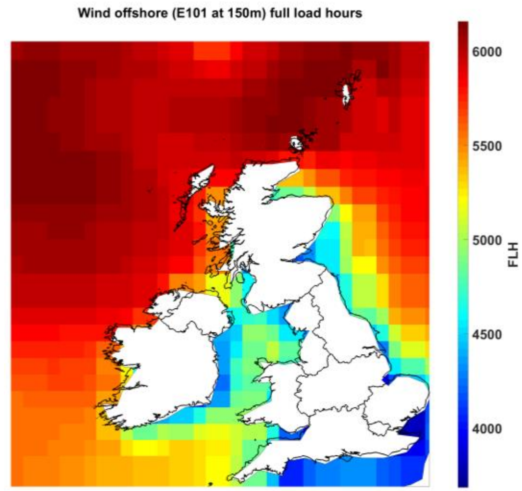




Input Data and Key Constraints

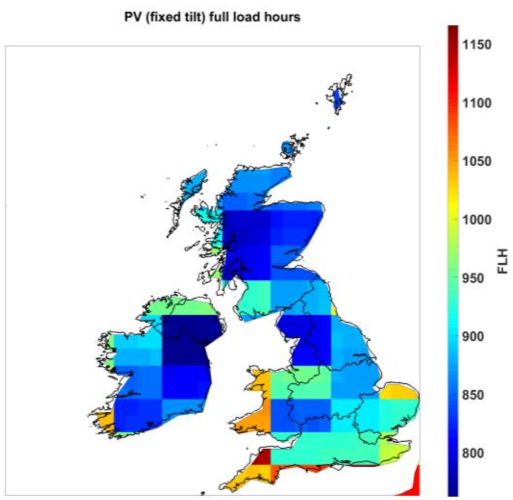
Renewable Resource Potential – Full Load Hours





Key insights:

- Wind resources are the best in Europe
- Vast offshore wind resources can be found, especially in Scotland, Ireland, Northern Ireland
- Solar resources are moderate but still significant: higher irradiation in Southern England, Wales and East of England

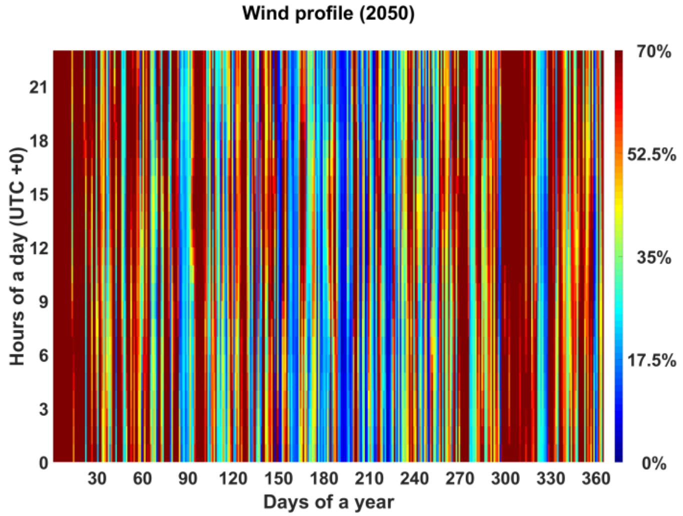


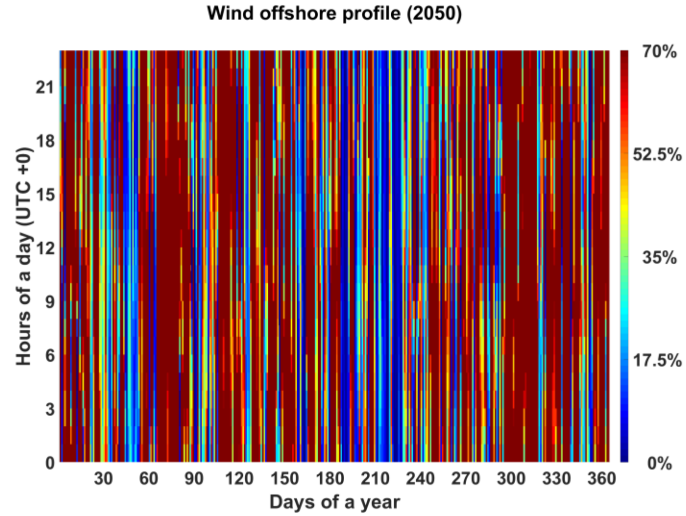
Constraints:

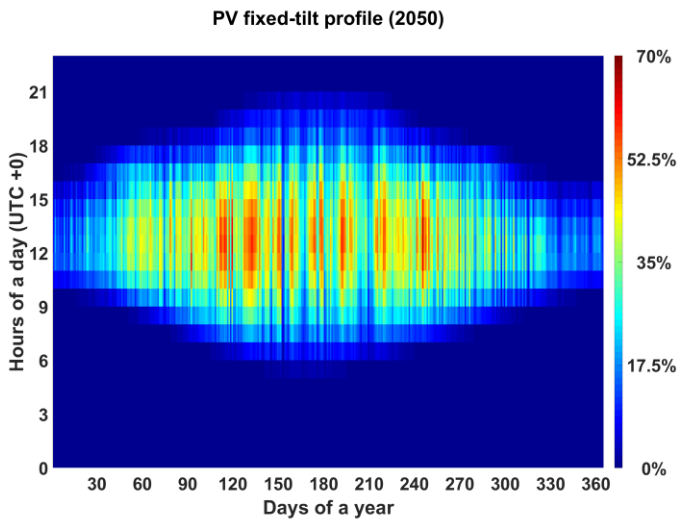
- Given the vast availability of offshore wind resources and societal caveats against onshore wind, the amount of onshore wind installations is limited more strictly than offshore wind
- Onshore wind is limited to 2% of the available land area (2.5% in Scotland, as social acceptance is higher)
- Solar PV is limited to 1% of total land area + rooftop PV for residential, commercial and industrial buildings

Input Data and Key Constraints

Hourly Resolution of Renewable Resources







Key insights:

- Hourly wind profile is distributed rather evenly throughout the year, with higher availability in late autumn and limited availability in summer
- Lack of wind in summer is compensated by solar irradiation during the summer months

Energy Transition Scenarios Framing

Best Policy, Current Policy and Inter-Annual Balancing

The UK government does not clearly pursue an energy system based on 100% renewable energy. Instead, strong expansions in nuclear energy and fossil CCS technologies are planned despite serious sustainability constraints. Therefore, several 100% RE scenarios will be compared to the current policy strategies.

Best Policy Scenario (BPS): The energy system of the UK will be transformed in 5-year time-steps to achieve zero CO_2 emissions and 100% RE in 2050. Using 2020 data as a starting point, fossil and nuclear power plants are to be phased-out according to their technical lifetime, or legally approved lifetime extension. 2 GW/yr of offshore wind is installed until 2026, increasing to 3 GW/yr after that. Onshore wind and solar PV are limited to 2% (Scotland 2.5%) and 1% of available land area, respectively. Biomass is limited to biogas. Imports of e-fuel are allowed.

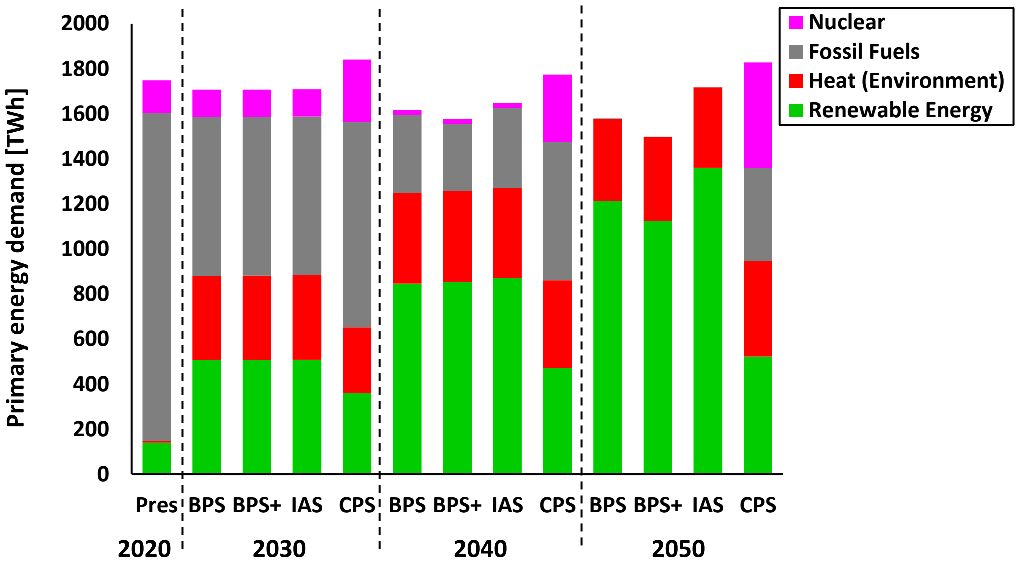
Best Policy Scenario – Inter-Annual Balancing (IAS): Same assumptions as for BPS with lifted upper limit for offshore wind, blocked e-fuel imports and from 2040 an inter-annual storage is introduced to balance inter-annual wind variations. The effect of balancing methods (extra capacity, storage, balancing technologies) is investigated.

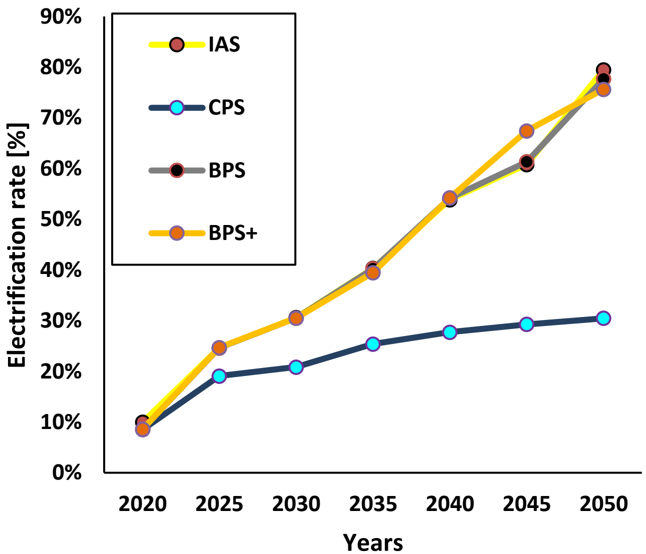
Current Policy Scenario (CPS): According to the Energy White Paper published by the UK government, a scenario is created that orientates on the governmental approach to reduce GHG emissions to net-zero in 2050. Vast deployment of nuclear energy and fossil CCS is to be considered and compared in terms of costs and sustainability constraints with the Best Policy Scenarios.

Best Policy Scenario plus (BPSplus): Same assumptions as for BPS but available land area for onshore wind and solar PV is lifted to 3% (Scotland 4%) and 2%, respectively. Wind offshore with lower limit installation of 1 GW/yr from 2030 onwards, plus existing project reinvestment. More imports of e-fuels are allowed.

Scenario Comparison

Primary Energy Demand



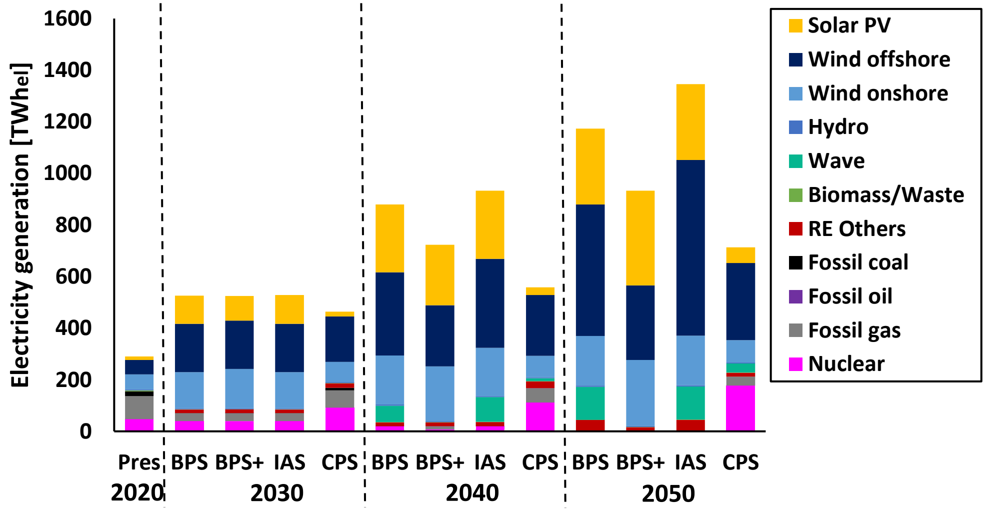


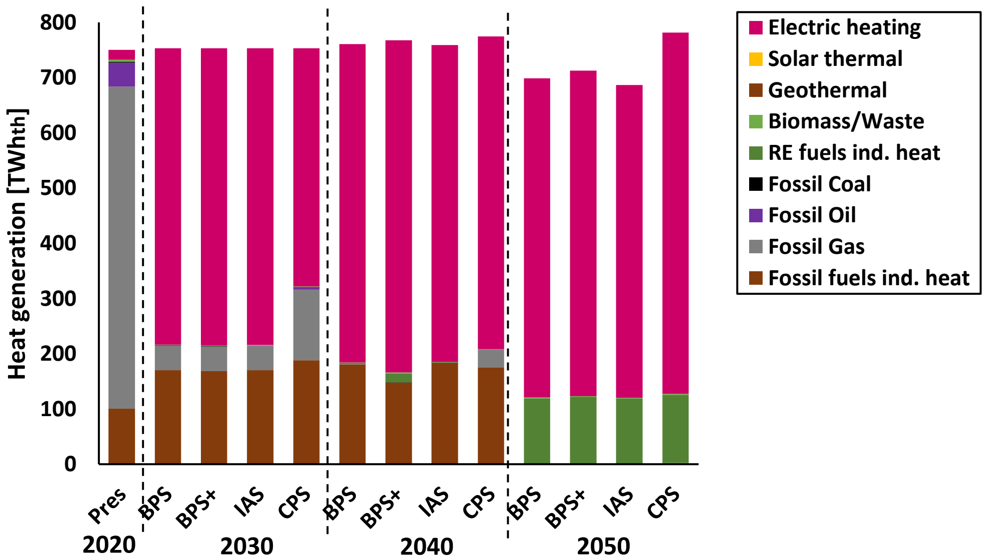
Key insights:

- BPS, BPSplus and IAS have roughly the same level of electrification, which grows steadily, reaching almost 80% in 2050
- IAS has a slightly higher primary energy demand due to the necessity of extra wind generation for inter-annual balancing, BPSplus is slighlty lower due to higher e-fuel import
- CPS has the highest primary energy demand in 2050, due to the smaller level of electrification with 30% and thus lower total system efficiency
- CPS continues nuclear and fossil fuel use to play important roles in the primary energy demand, while the share of renewable energy is recognisable lower

Scenario Comparison

Energy Mix



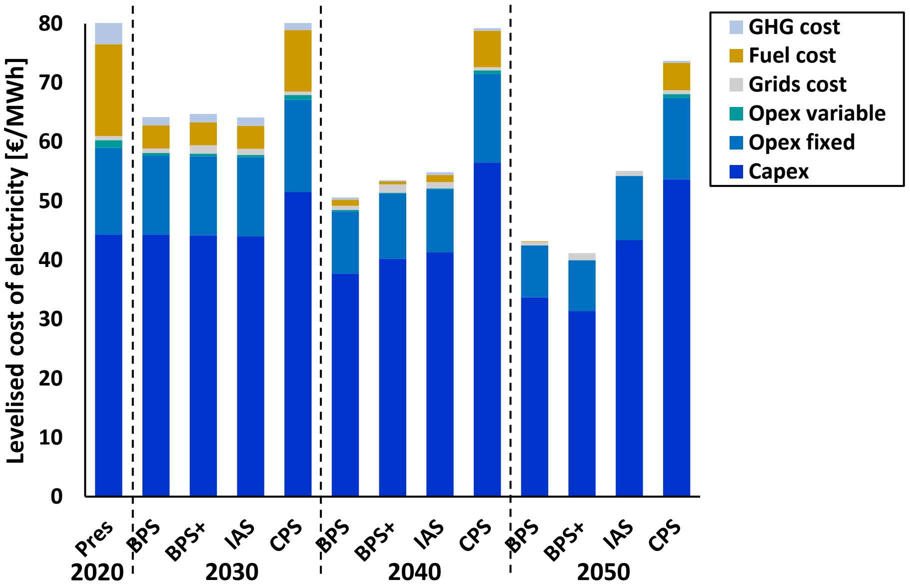


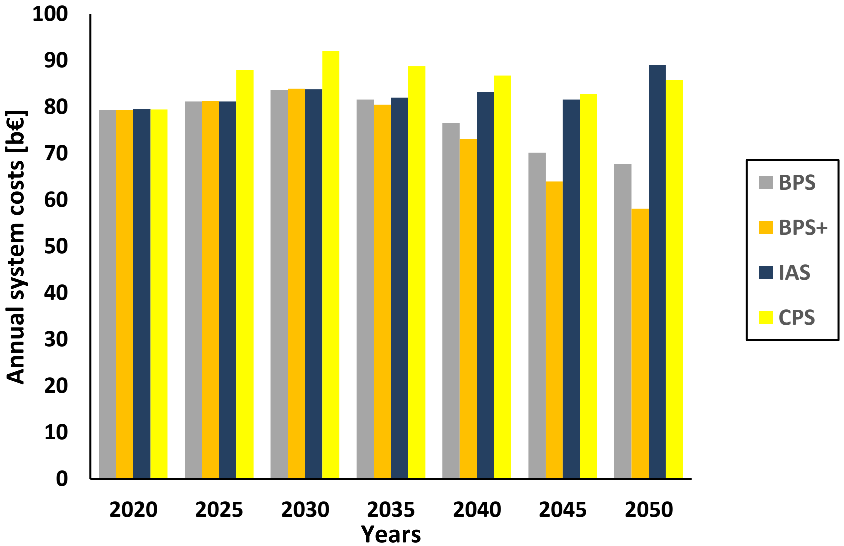
Key insights:

- BPS, BPSplus and IAS have a comparable electricity generation structure, but in the IAS scenario more energy has to be generated to compensate interannual wind variability
- In the CPS, the total electricity generation is significantly lower, as large parts of the heat and transport system are not electrified
- In all scenarios, wind energy, mainly from offshore wind, becomes the most important source of electricity generation (BPSplus: higher share of onshore wind and solar PV)
- In CPS nuclear remains in the system as a key element of energy supply
- Heat demand will be supplied by individual heat pumps for all scenarios for low-temperature heat demand (space heating and domestic hot water)

Scenario Comparison

Costs and Investments



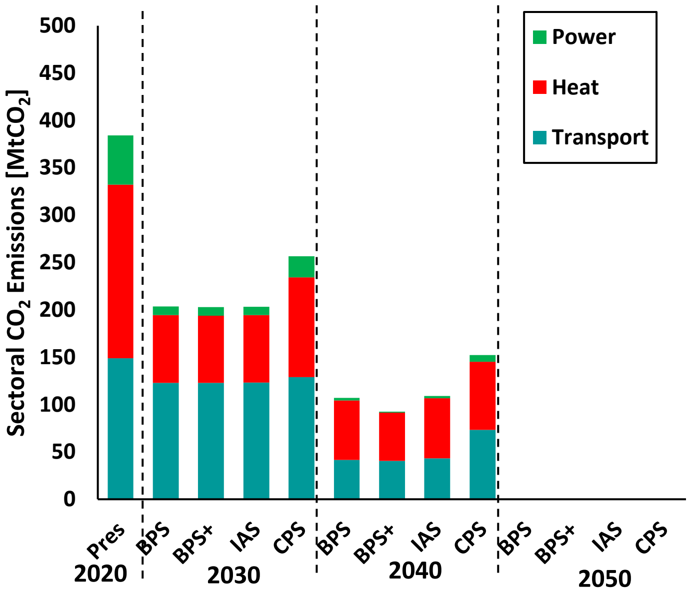


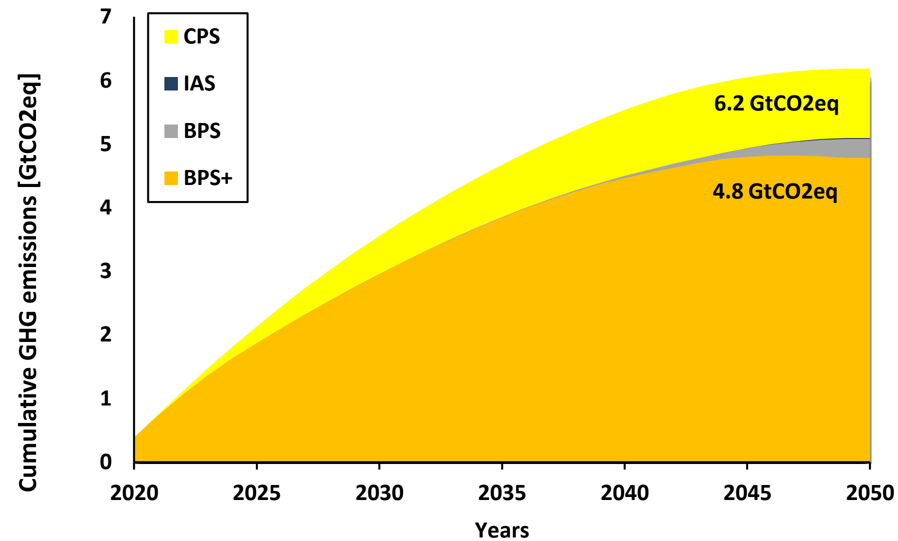
Key insights:

- The lowest LCOE can be found for the BPSplus, the highest for CPS due to remaining fuel costs and higher capex, mainly from nuclear power plants
- IAS shows the highest total annual system costs in 2050, due to the necessity of very large underground storage solutions for methane
- BPS is significantly lower in cost than the CPS: 86 b€ for CPS and 68 b€ for BPS are reached in 2050, indicating that costs will decline for a 100% RE solution
- BPSplus is the most attractive scenario: lowest LCOE with 53 €/MWh and total system costs of 58 b€
- The pathway costs are 2430 b€ (BPS), 2368 b€ (BPSplus), 2546 b€ (IAS), 2675 b€ (CPS) with lower CO_2 pricing in CPS

Scenario Comparison

CO_2 Emissions



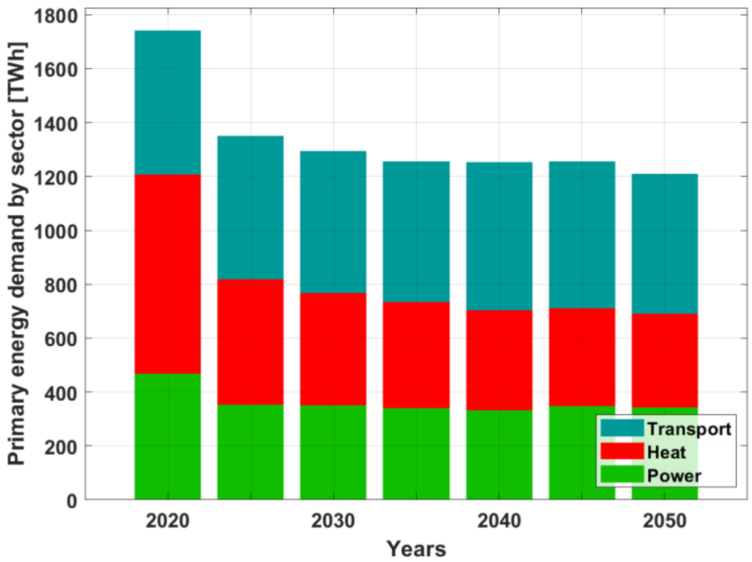


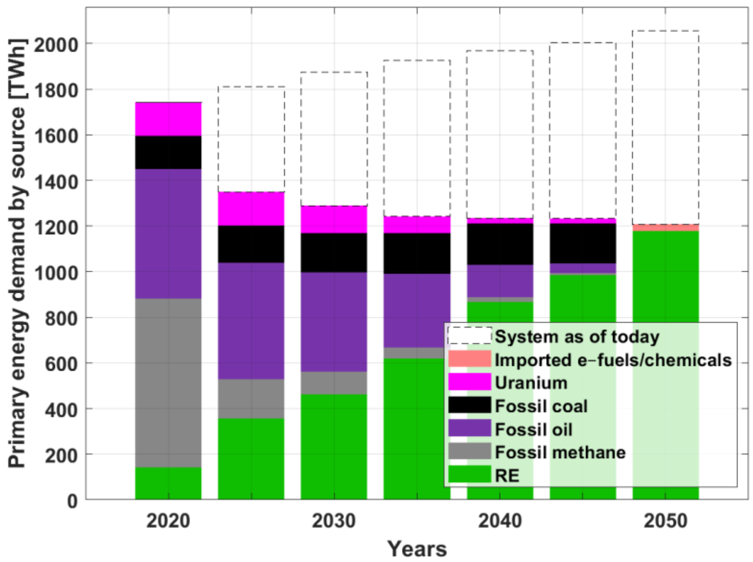
Key insights:

- All scenarios reach zero CO_2 emissions in 2050
- Remaining CO_2 emssions of the CPS are reduced by DACCS
- Due to lower electrification, not all parts of the heat and transport sectors in the CPS are fully decarbonised, thus leading to higher cumulative emissions
- Oil for long-distance transportation and coal for industrial heat stay in the system, even in 2050
- In 2040, fossil fuels in the power sector for BPS and IAS are almost completely phased out
- The production of sustainable e-fuels is the key to achieve a 100% RE-based system for all sectors
- Cumulative emissions for BPS, BPSplus and IAS are lower than for the CPS

Results – Best Policy Scenario

Primary Energy Demand



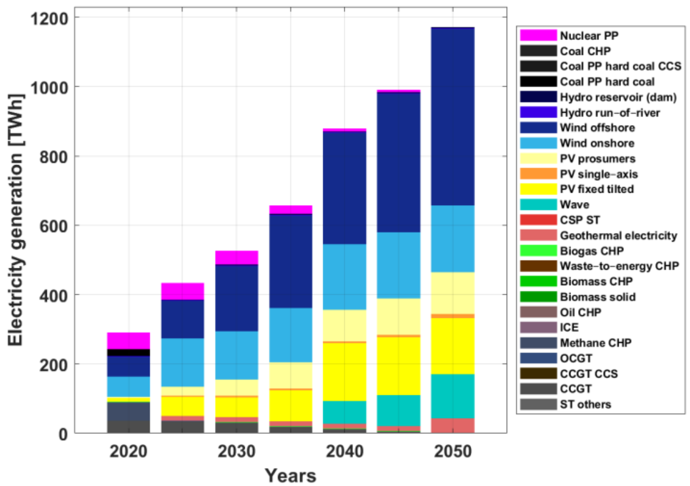


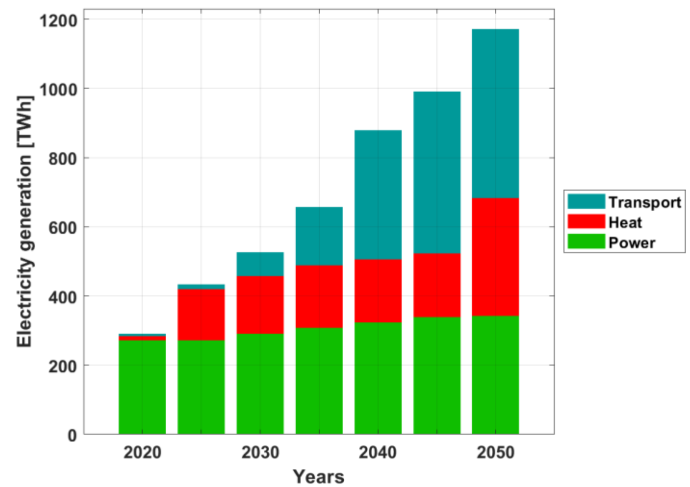
Key insights:

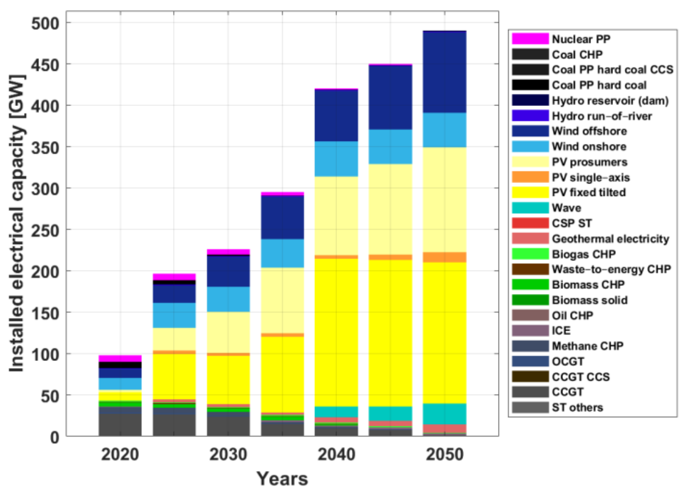
- The primary energy demand decreases during the transition, due to strong electrification across all sectors, leading to an integrated, sector-coupled energy system
- The drop in 2025 occurs due to massive heat pump roll-out with massive efficiency gains
- Fossil fuels and nuclear energy are successively substituted by renewable energy. Oil and coal remain in the system until 2045, for transport and heat, and are finally phased out in 2050
- The combination of renewable energy generation and electrified heating and transportation proves to be more efficient than the current fossil fuel based system

Results – Best Policy Scenario

Electricity Generation Mix







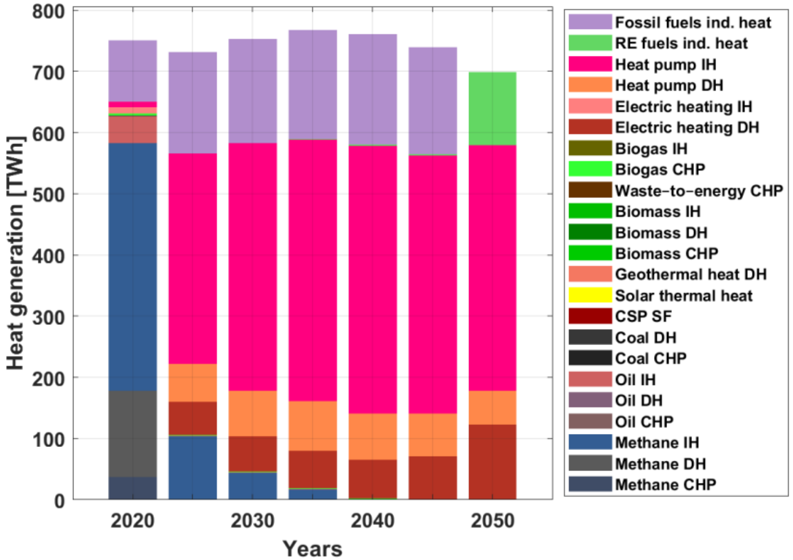
Key insights:

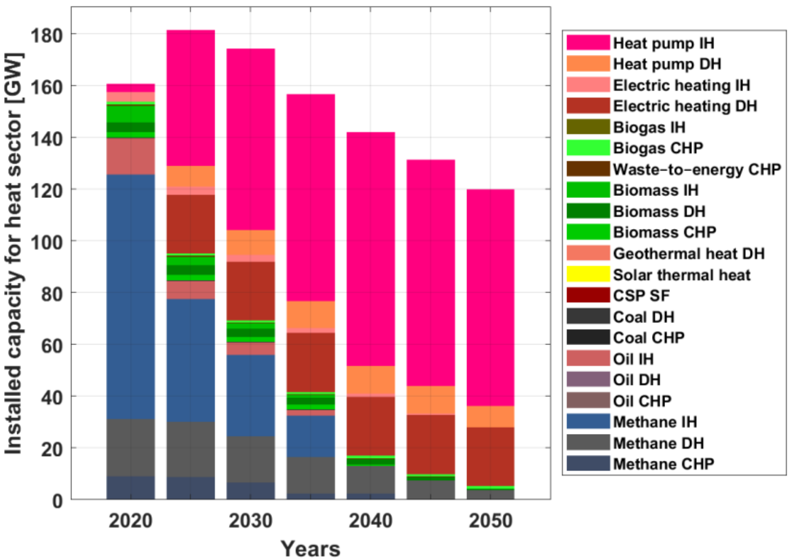
- Electricity generation grows by a factor of 4 and is strongly linked to electrified heat (e.g. heat pumps), electric powertrains (BEV), and e-fuels
- Offshore wind becomes the most important source of electricity generation, contributing a share of 43.5% and 509 TWh of electricity.
- Higher full load hours of wind lead to much lower installed capacity than for solar PV.
- Wave energy contributes a signicant share from 2040 onwards.

more information ► christian.breyer@lut.fi

Results – Best Policy Scenario

Heat Generation Mix



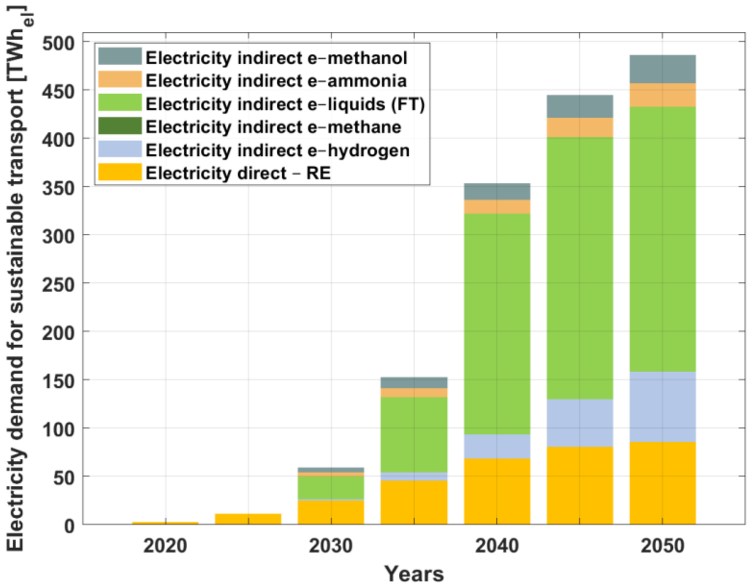


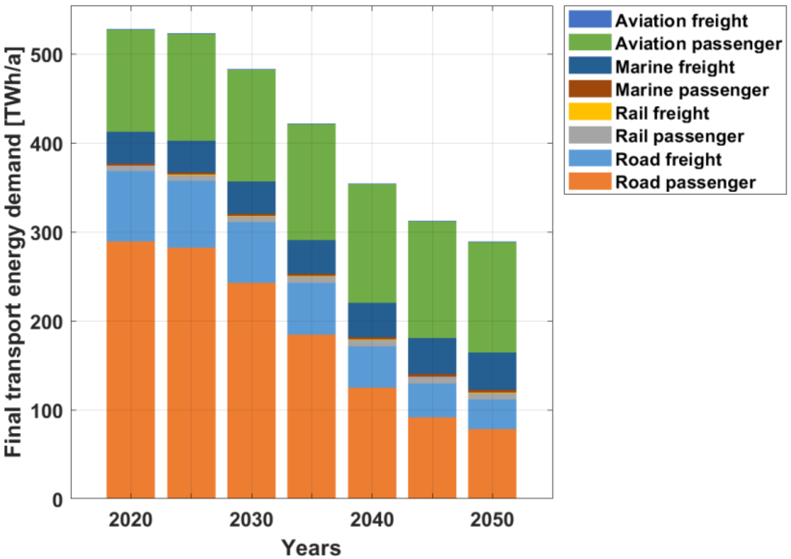
Key insights:

- Heat generation shifts from natural gas boilers to electrified heat pumps with high efficiency
- Massive heat pump roll-out happens already in 2025, substituting a large amount of natural gas
- Heat pumps only supply low-temperature heat, therefore direct electric heating and RE-based solutions need to supply medium and high temperature industrial heat, respectively
- e-fuel production requires substantial renewable capacity and happens at the end of the transition
- Total installed heat capacity declines due to highly efficient heat pumps

Results – Best Policy Scenario

Energy Supply Mix - Transport



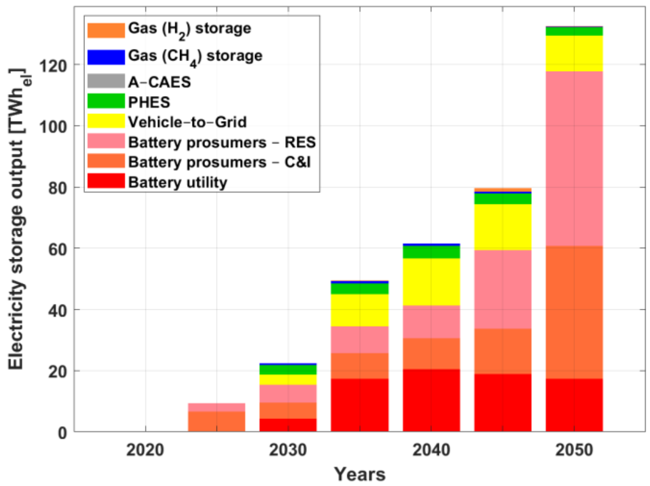


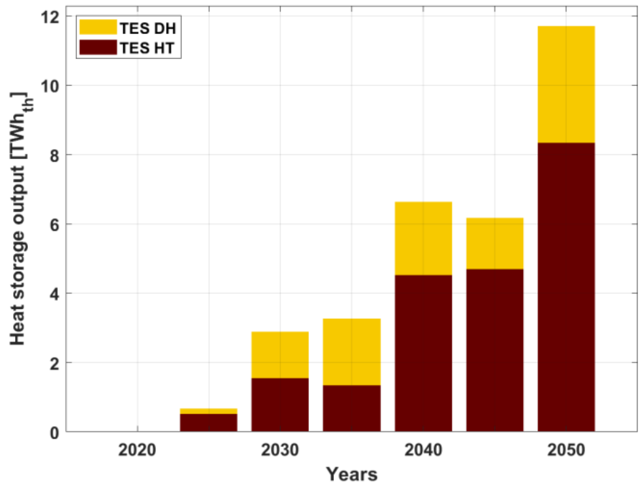
Key insights:

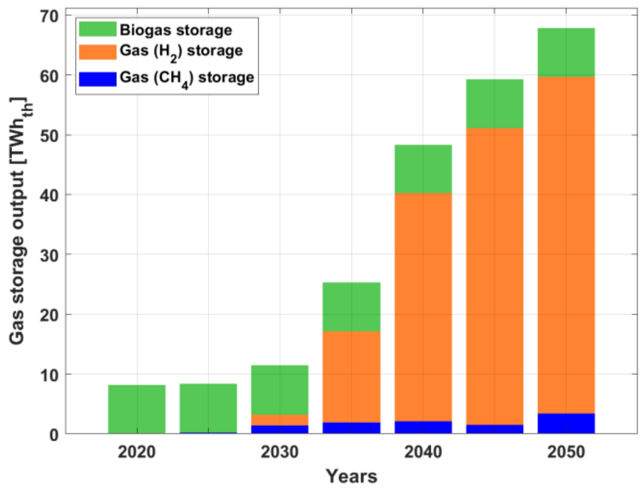
- Transport sector requires signicant amounts of e-fuels such as e-liquids, e-methane, e-hydrogen, e-methanol and e-ammonia
- Total electricity demand rises up to 486 TWh in 2050, thereof 86 TWh for direct electricity
- Highest electricity demand can be assigned to e-liquids with 274 TWh
- Final transport demand substantially decreases from 528 TWh to 290 TWh due to electrification across all modes of transportation but mainly for road transport
- Final energy demand for marine and aviation increases slightly
- e-fuels play a major role for aviation and marine

Results – Best Policy Scenario

Energy Storage





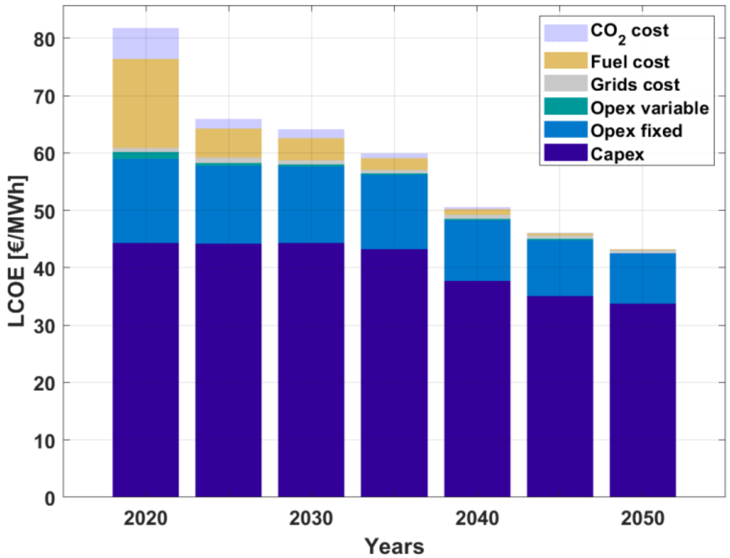


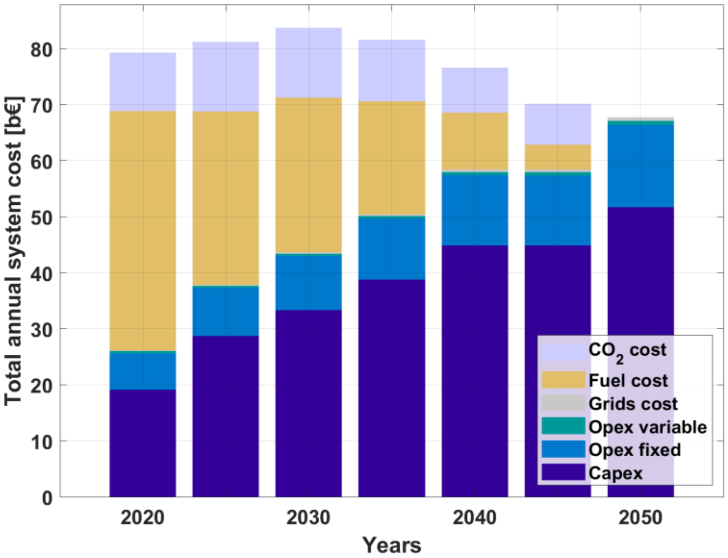
Key insights:

- Along the growing share of variable RE generation, the required storage increases accordingly,
- Electricity storage is dominated by battery prosumers, complemented by stationary batteries and Vehicle-to-Grid
- Major ramps occur in 2040 und in 2050, according to the strong growth in renewable capacity installation

Results – Best Policy Scenario

Costs & Investment



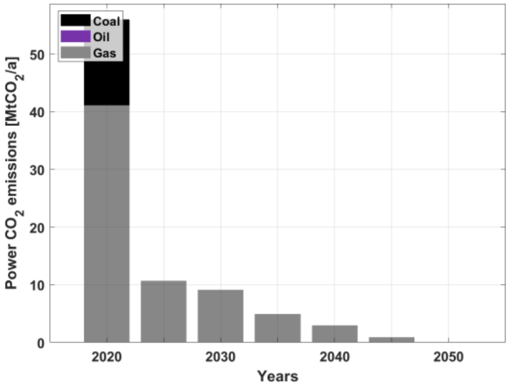


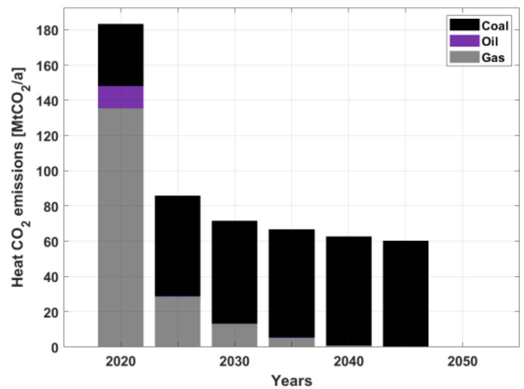
Key insights:

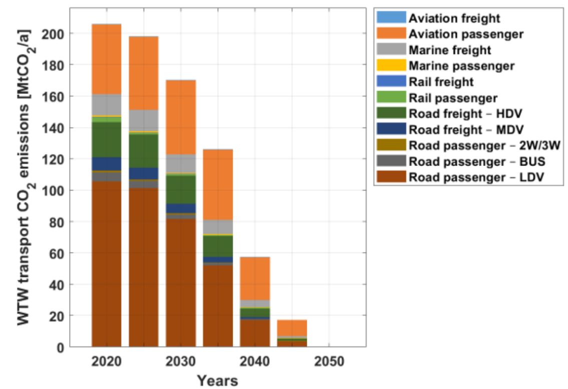
- The Levelised Costs of Electricity drop from 81.9 €/MWh in 2020 to 43.2 €/MWh in 2050
- The total annual system costs decrease during the transition, reaching a maximum of 83.7 b€ in 2030 and declining to 67.7 b€ in 2050
- The highest share of LCOE and total annual costs result from capital expenditures, which are compensated by dispensed fuel costs
- A marginal amount of fuel costs remain in 2050 due to imported e-fuels
- Results show that a 100% RE system for the UK is economically more attractive than the current system
- Main drivers are low-cost renewable electricity supply and efficiency gains from electrification

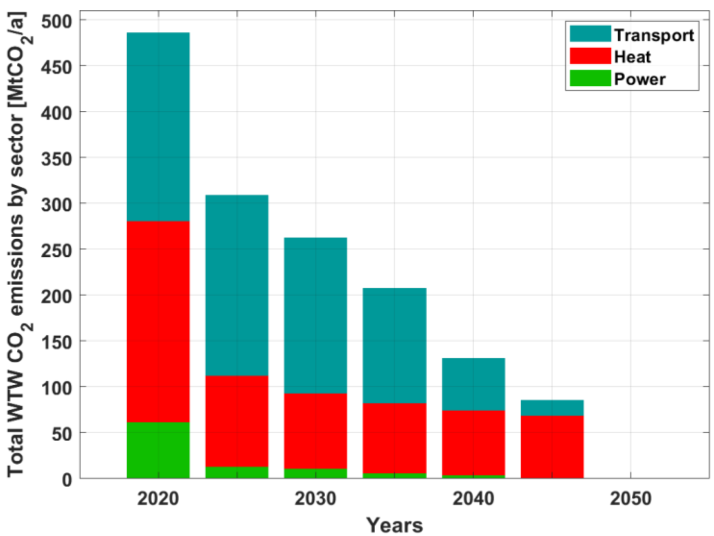
Results – Best Policy Scenario

CO_2 Emissions





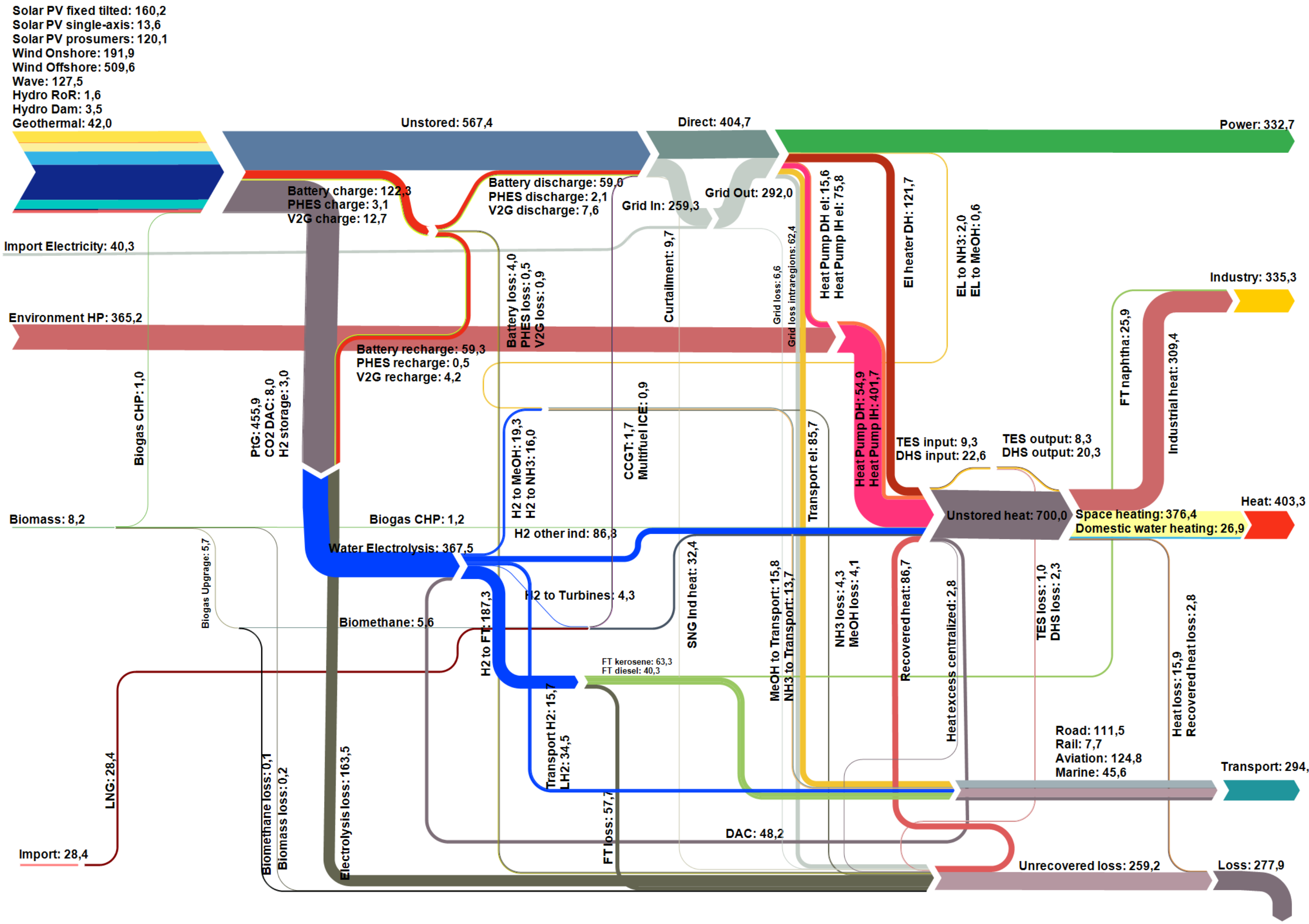




Key insights:

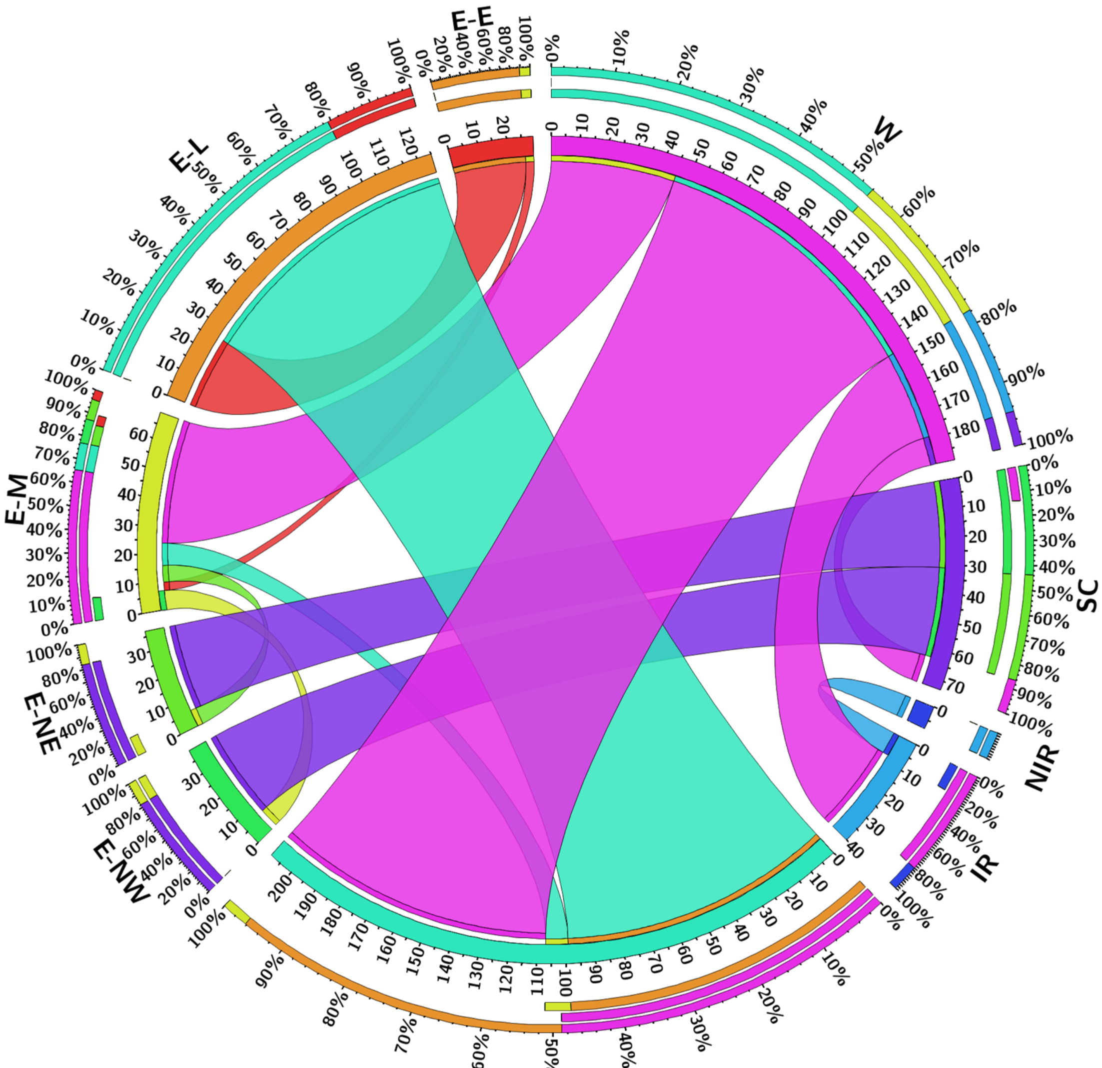
- CO_2 emissions are substantially reduced in 2025, 2040 and 2050, reaching finally zero in 2050
- CO_2 emissions from the power sector are eliminated quickly, while heat and transport emissions require advanced e-fuel production for high-temperature industrial heat and fuels for marine and aviation
- Coal in the power sector is phased out very early, while it remains necessary for industrial heat production until 2045

Summary – UK in 2050



Results for BPS

Summary – Electricity Trade in 2050



Results for BPS

Key insights:

- Electricity exchange becomes highly important with growing RE shares as it increases the system flexibility
- Subregions with surplus energy transfer electricity via the grid to subregions with shortages
- Wales (W) becomes the main exporting region as it connects various subregions and exchanges substantial amounts of electricity
- Strong exchange between London (E-L) and Southern England (E-S), (while E-S works as a transit region) as London is import-dependent due to low regional electricity generation
- Scotland has strong connection to North West (E-NW) and North East England (E-NE), which could be even stronger and Scotland could be a major exporter if the grid interconnection is not limited

Summary

- Defossilisation for the UK to a sustainable 100% RE system is technically feasible and economically viable
- Several benefits are connected to the transition: sustainable energy supply, zero CO_2 emissions, avoidance of nuclear power plant induced risks, avoidance of fossil power plant based air pollution, efficiency increases, improved energy independence and cost reduction
- The presented results demonstrate the case of an offshore wind dominated energy system
- The offshore wind resource availability is the best in Europe and enables very high shares of offshore wind
- Societal caveats against onshore wind, solar PV and bioenergy combustion can have an impact on the overall energy system structure
- One extra scenario (BPSplus) shows significant cost reduction potentials, if onshore wind and solar PV face less restrictions, but also limiting the more costly offshore wind ramping
- Electrification of all sectors is the key element to a sustainable energy system
- Heat pumps will be the dominant heating technology for individual heat, due to high efficiency
- Transport sector will be subject to direct and indirect electrification for all modes of transport while long-distance marine and aviation require large amount of e-fuels
- E-fuels are a key for high-temperature industrial heat generation and sustainable transportation
- Energy storage requirements increase as the renewable generation capacity increases
- Battery storage systems are the main balancing technology for diurnal variations
- CO_2 emissions can be significantly reduced even before 2050
- The UK government should consider a dedicated 100% RE path

LUT University

100% Renewable UK

Extended Assumptions and Results

Christian Breyer, Dmitrii Bogdanov, Philipp Diesing, Michael Child
LUT University, Finland
November 2022

Extended Results

- Detailed Assumptions
- Sectoral Analysis
- Energy Storage
- Electricity Grid & Transmission
- Supply of Fuels, Chemicals and CO_2
- Regional Analysis
- Scenario Variations
- Impacts of Inter-Annual Storage

Detailed Assumptions

Wind Onshore Potentials

100% RE UK: 100 TWh

- Due to limited perceived land availability, the use of onshore wind might be restricted to 1.8% of land area.
- Total area UK = 244,324 km^2
- Total potential
  = 8.4 MW/km^2 * 0.018 * 244,324 km^2
- = 36 GW
- A regionally different capacity factor of 0.32 average leads to an annual generation.
- of 100 TWh

LUT default: 370 TWh

- The default assumption applied for the LUT model is that 8.4 MW per km^2 can be installed. 4% of land area can be used for onshore wind.
- Total area UK = 244,324 km^2
- Total potential
  = 8.4 MW/km^2 * 0.04 * 244,324 km^2
  = 82.1 GW
- A regionally different capacity factor of 0.51 average leads to an annual generation of 370 TWh.

Decision: 2% of land area to be used with a power density of 8.4 MW/km^2. We assume that best sites are used and repowering is done when possible. Therefore, the capacity factor of 0.51 should be applied, based on the capacity installed on 2% of land area, while Scotland can use 2.5% of their total land area due to higher acceptance

Detailed Assumptions

Wind Offshore Potentials

100% RE UK	LUT default	Wind Europe (2017)
250 GW	75 GW	209 – 495 GW
1300 TWh	395 TWh	1100 - 2600 TWh
5200 FLh	5252 FLh	5250 FLh

- **The LUT Model uses a lower default potential of offshore wind, which was adjusted**
- **For the UK, a total economically attractive resource potential of 1100 – 2600 TWh was identified by Wind Europe (2017)**
- **100% RE UK suggested a higher potential of offshore wind – 1300 TWh**
- **UK and Ireland have the highest offshore resource potentials in Europe**
- **Scotland and Ireland have the highest offshore potentials in the region**
- **The overall offshore wind potential would be sufficient to supply the total energy demand**
- **Decision: The offshore wind potential is adjusted according to the potential estimations from Wind Europe. In the Best Policy Scenario, the upper limit of offshore wind is limited to 250 GW while in the variation scenario it is lifted to 400 GW**

Detailed Assumptions

Solar PV potentials: utility-scale and rooftop PV

Rooftop PV:

100% RE UK	LUT default
60 GW	125 GW
61 TWh	119 TWh
1017 FLh	952 FLh

Utility-scale PV:

100% RE UK	LUT default
130 GW	1099 GW
158 TWh	1037 TWh
1215 FLh	943 FLh
0.6% of land area	5.0% of land area

- **PV is assumed to have less area restrictions than onshore wind, thus a higher amount of capacity can be installed on the same area, compared to wind onshore**
- **PV rooftop is zero-impact area; rooftop area should be available, especially in densily populated regions**
- **Decision: Solar PV is limited to 1% of total land area for utility-scale PV, while rooftop PV can be installed acording to LUT default assumptions**
- **Concentrating Solar Power (CSP) is not taken into consideration**

Detailed Assumptions

Renewable resource potential comparison

Renewable Resource	Unit – upper limit	BPS	BPSplus	BPS - IAS	CPS
Wind Onshore	GW (% used)	42 (100%)	68 (80%)	42 (100%)	42 (42%)
Wind Offshore	GW (% used)	250 (39%)	250 (22%)	400 (32%)	250 (23%)
PV utility-scale	GW (% used)	183 (100%)	637 (39%)	183 (100%)	183 (15%)
PV prosumers	GW (% used)	126 (100%)	126 (100%)	126 (100%)	33 (100%)

- The scenarios differ in terms of their upper limit for offshore wind and various constraints set
- For the BPS, a limit of 250 GW of offshore wind is assumed, while e-fuels can be imported
- BPSplus has higher upper limit for onshore wind and PV utility-scale
- BPS – IAS uses the same assumptions as BPS, but with additional requirements for an inter-annual storage and thus lifted upper limit for offshore wind
- The CPS uses the same resource potentials as the BPS, but is subject to more constraints (ramping of nuclear, fossil gas CCS, lower share of solar PV, etc.)

Detailed Assumptions
Financial Assumptions

Capital expenditures [€/kW]:

Technology	2020	2025	2030	2035	2040	2045	2050
Wind onshore	1150	1060	1000	965	940	915	900
Wind offshore	2973	2561	2287	2216	2168	2145	2130
Solar PV (fixed)	475	370	306	237	207	184	166
Wave	5542	4604	3667	3125	2583	2171	1758

Operational expenditures [€/(kW·a)]:

Technology	2020	2025	2030	2035	2040	2045	2050
Wind onshore	23	21	20	19	19	18	18
Wind offshore	85	73	66	64	62	61	61
Solar PV (fixed)	8	7	6	5	4	4	4
Wave	222	184	147	125	103	87	70

Energy Transition Scenarios Framing

Best Policy, Current Policy and Inter-Annual Balancing

The UK government does not clearly pursue an energy system based on 100% renewable energy. Instead, strong expansions in nuclear energy and fossil CCS technologies are planed despite serious sustainability constraints. Therefore, several 100% RE scenarios will be compared to the current policy strategies.

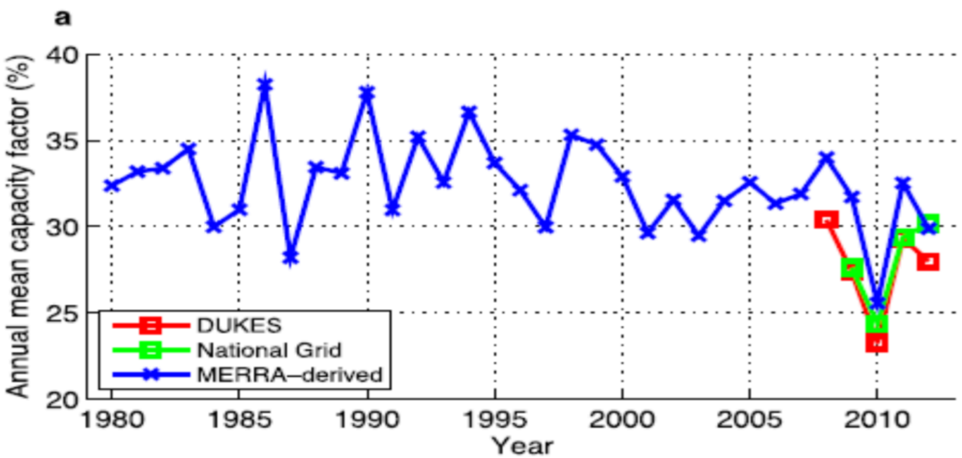
Best Policy Scenario (BPS): The energy system of the UK will be transformed in 5-year time-steps to achieve zero CO_2 emissions and 100% RE in 2050. Using 2020 data as a starting point, fossil and nuclear power plants are to be phased-out according to their technical lifetime, or legally approved lifetime extension. 2 GW/yr of offshore wind is installed until 2026, increasing to 3 GW/yr after that. Onshore wind and solar PV are limited to 2% (Scotland 2.5%) and 1% of available land area, respectively. Biomass is limited to biogas. Imports of e-fuel are allowed.

Best Policy Scenario – Inter-Annual Balancing (IAS): Same assumptions as for BPS with lifted upper limit for offshore wind, blocked e-fuel imports and from 2040 an inter-annual storage is introduced to balance inter-annual wind variations. The effect of balancing methods (extra capacity, storage, balancing technologies) is investigated.

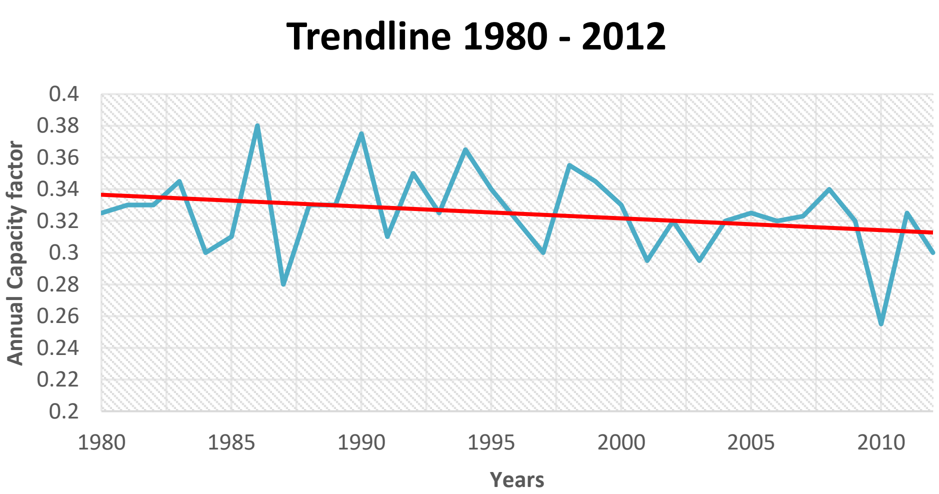
Current Policy Scenario (CPS): According to the Energy White Paper published by the UK government, a scenario is created that orientates on the governmental approach to reduce GHG emissions to net-zero in 2050. Vast deployment of nuclear energy and fossil CCS is to be considered and compared in terms of costs and sustainability constraints with the Best Policy Scenarios.

Best Policy Scenario plus (BPSplus): Same assumptions as for BPS but available land area for onshore wind and solar PV is lifted to 3% (Scotland 4%) and 2%, respectively. Wind offshore with lower limit installation of 1 GW/yr from 2030 onwards, plus existing projects are reinvested. More imports of e-fuels are allowed.

Best Policy Scenario – Inter-Annual Balancing
Approach



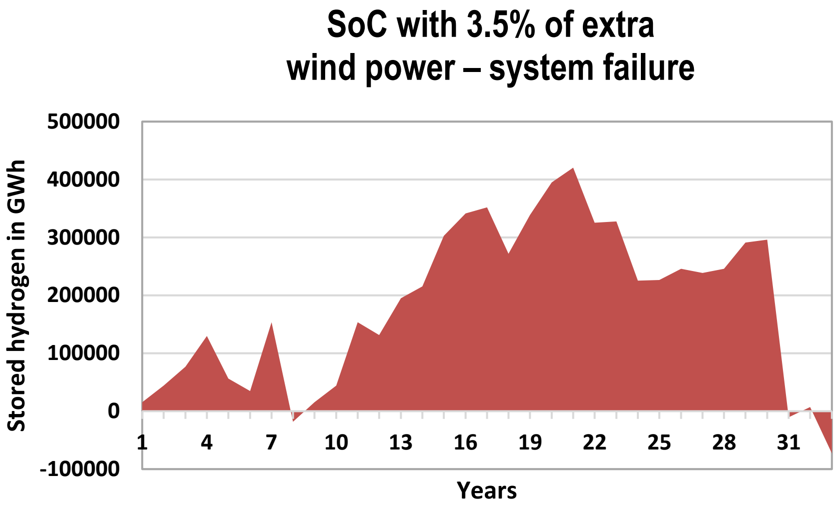
Annual wind resource variability [(Cannon et al. 2015)]

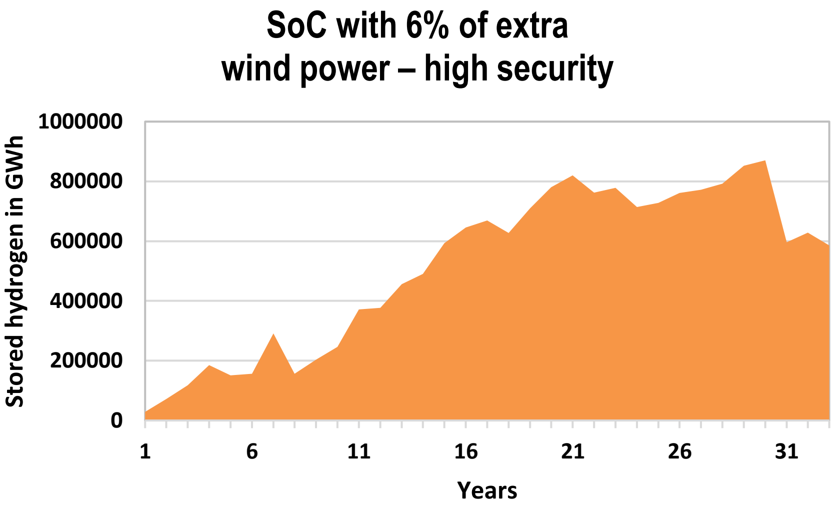


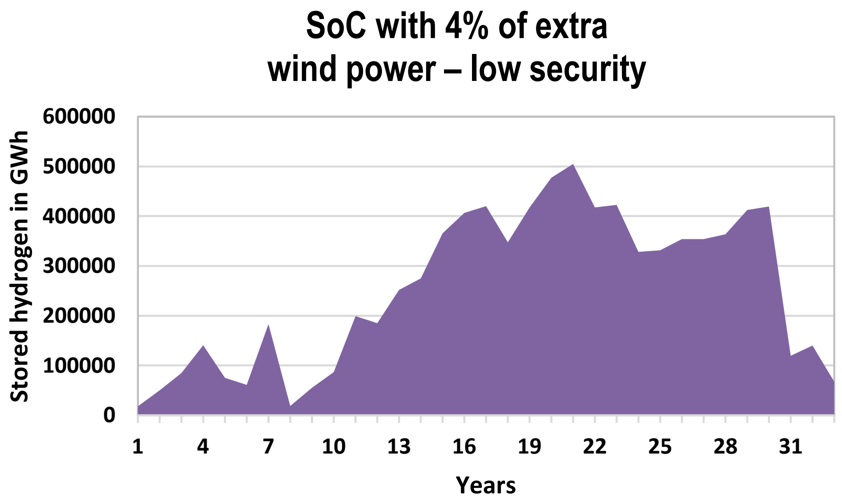
- Annual wind generation varies over a longer period of time
- Observing a 33-year time period (1980 – 2012), it can be seen that there is a tendency for lower wind yields in the near past for the UK
- A deviation between the average year (2005) and lowest wind yield year (2012) of 21.5% can be observed, while the year 2005 represents the average of all years
- Inter-Annual balancing becomes necessary to ensure security of supply
- Key assumption: Gas storage works as an inter-annual storage and is charged in high wind yield years
- 6% of extra wind capacity installed to compensate the lack of resources
- Considering all conversion losses, roughly 4% of annual wind generation goes to the inter-annual storage
- Hydrogen or methane storage?

Best Policy Scenario – Inter-Annual Balancing

Inter-Annual Storage SoC







- Designing the inter-annual storage is a trade-off between securtiy of supply and minimising costs: the bigger the storage, the higher the security and thus the costs
- We assume that security of supply has higher priority than cost minimisation
- Thus for the calculations and the modelling, it was assumed that 6% of extra annual wind capacity is installed from 2040 onwards, producing either hydrogen or methane for the inter-annual storage

Best Policy Scenario – Inter-Annual Balancing

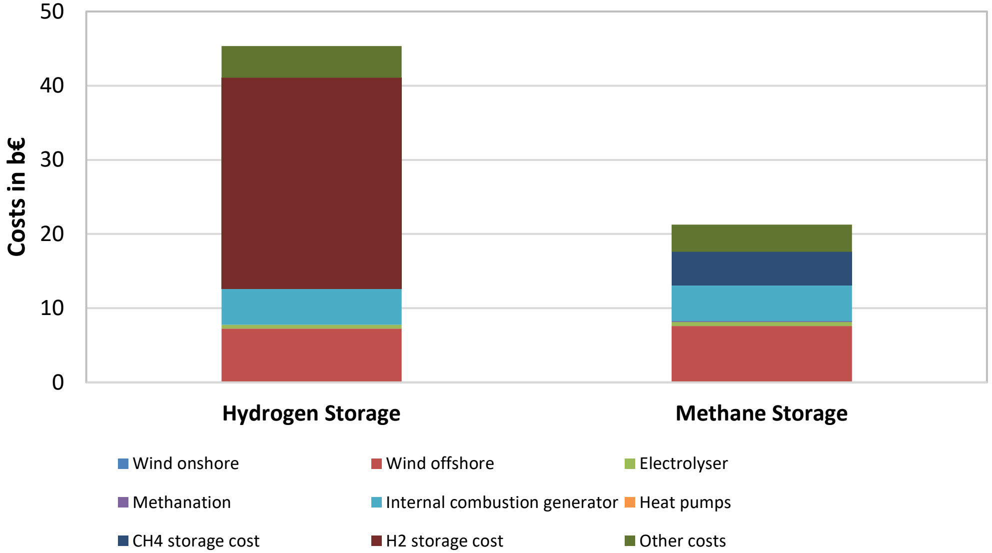
Hydrogen vs Methane Storage

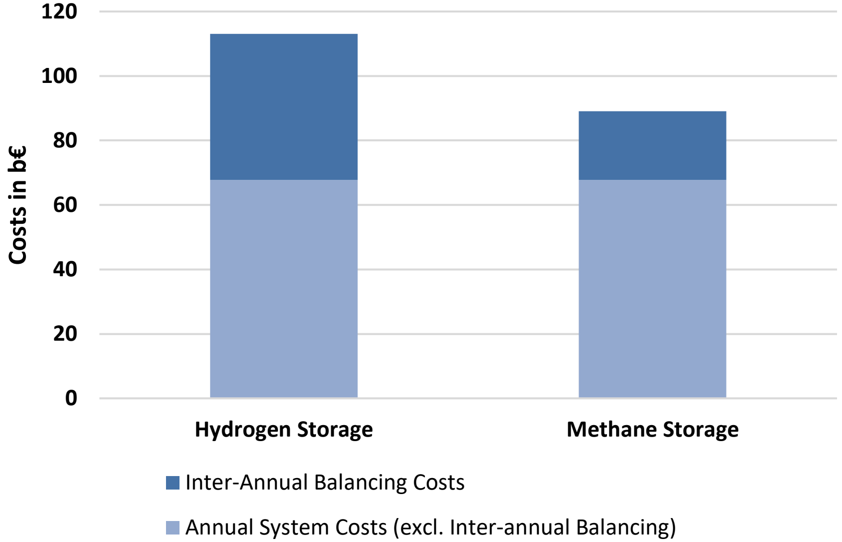
	CAPEX	OPEX	Lifetime	CRF	WACC
	[€/kWh]	[€/(kWh*a)]	years	-	-
CH_4 storage	0.03	0.001	50	0.072	0.07
H_2 storage	0.28	0.0112	50	0.072	0.07
H_2 salt cavern	0.169	0.00676	50	0.072	0.07
H_2 rock cavern	0.586	0.02344	50	0.072	0.07

- Inter-annual storage must be a long-term storage to store energy over months and years
- Two options are available: storing hydrogen or methane in underground caverns
- Additional costs for inter-annual balancing include costs for extra electricity generation capacity, electricity conversion capacity (electrolysers, gas turbines) and costs for gas storage in underground caverns
- If methane is used as a storage, than extra capacity for methanation, CO_2 DAC and heat pumps is required to supply DAC facilities (the latter was not observed in results due to heat recovery)
- However, due to much higher volumetric energy density of methane, less volume for energy storage is needed, reducing the cost of the energy storage: hydrogen – 0.28 €/kWh vs methane – 0.03 €/kWh

Best Policy Scenario – Inter-Annual Balancing

Preliminary Calculations

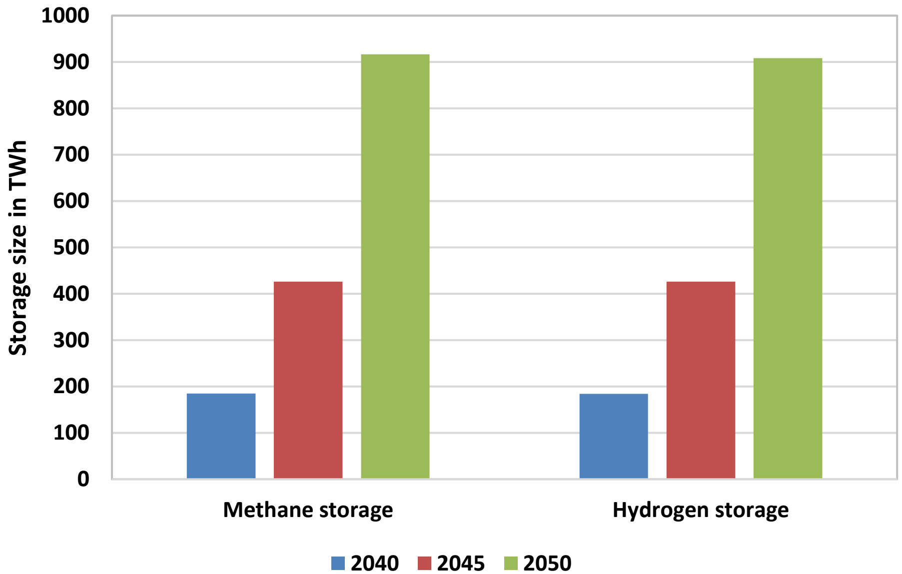


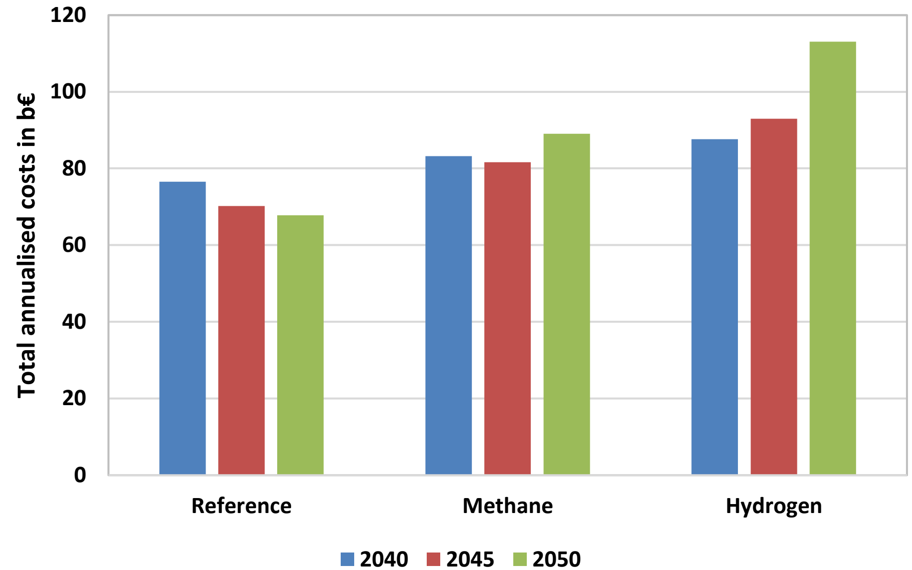


- Both cases add a significant amount of extra costs to the total annual system costs
- Based on the selected technical and fincancial assumptions, methane storage is a cheaper inter-annual balancing option, accounting for 21 b€ per year, while hydrogen storage is significantly more expensive with 45 b€ per year
- The higher hydrogen storage costs exceed the extra requirements for methane production by far
- Methane storage accounts for extra 31% of total annual system costs while hydrogen accounts for 67%

Best Policy Scenario – Inter-Annual Balancing

Modelling Results – Costs and Storage Size

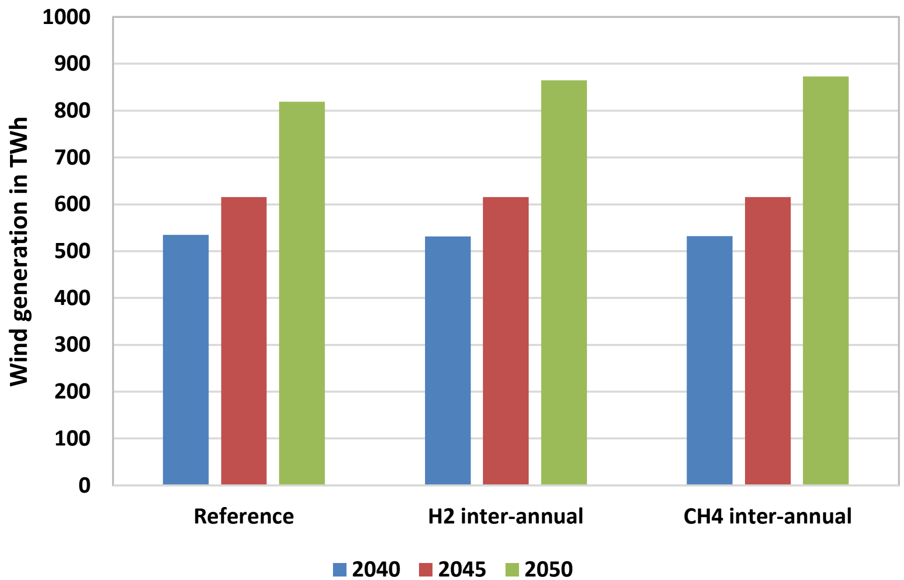


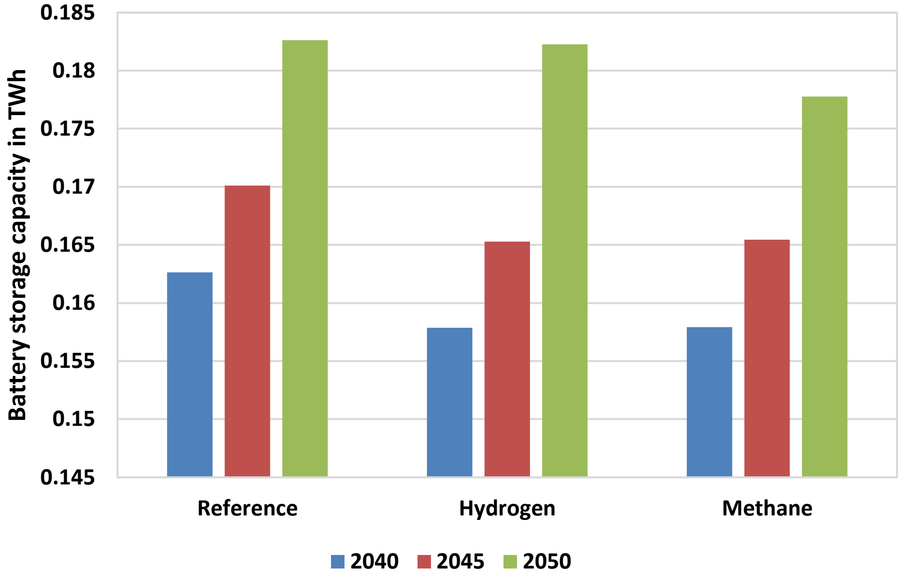


- Both cases indicate the necessity for a massive inter-annual storage, reaching a storage size of roughly 910 TWh in 2050 for the high-security case
- The inter-annual storage size for hydrogen and methane is roughly the same
- The costs for inter-annual hydrogen storage exceed the costs for methane storage by far
- Total annual system costs, reached 113 b€ for hydrogen and 89 b€ for methane, while the reference scenario without inter-annual storage has total costs of 68 b€
- Thus, methane storage is to be prefered compared to hydrogen, due to much lower costs

Best Policy Scenario – Inter-Annual Balancing

Modelling Results – Effects on the Energy System Structure

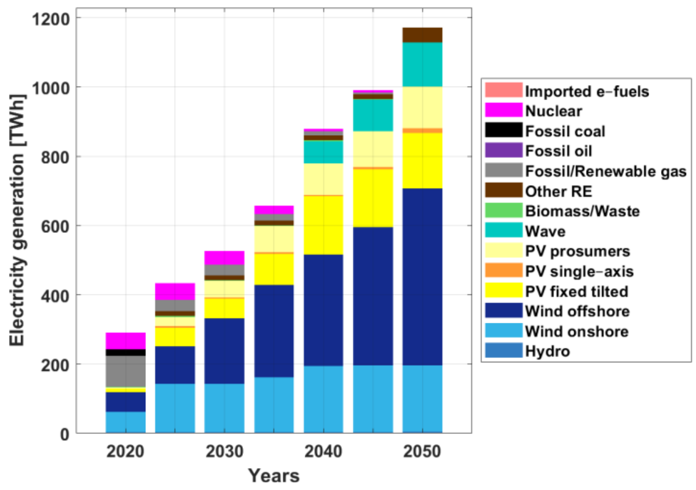


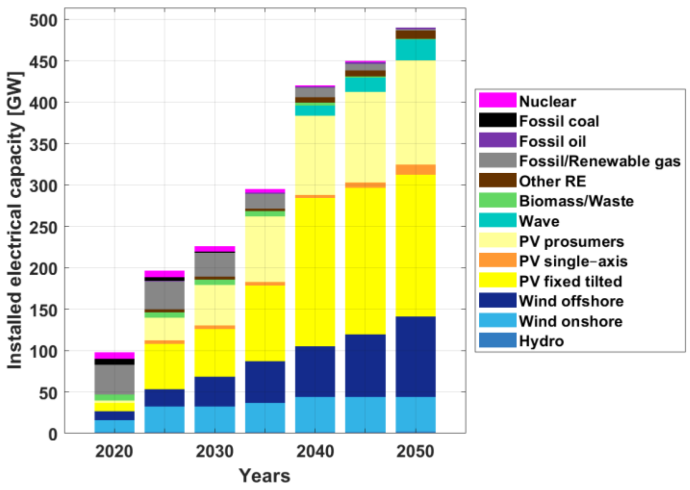


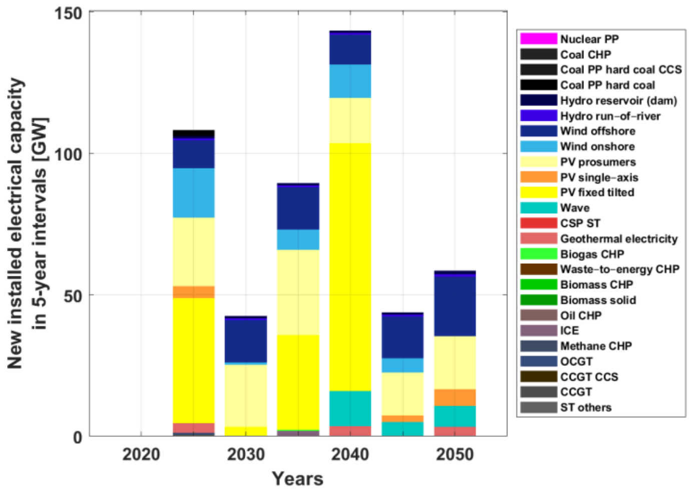
- The implementation of an inter-annual storage effects the structure of the energy system
- More wind needs to be generated for hydrogen and methane production
- Wind generation increases from 819 TWh in the reference scenario to 865 TWh and 873 TWh in 2050 for hydrogen and methane, respectively
- Wind generation is lower for hydrogen, since extra electricity is required for the methanation process
- Battery storage capacity decreases slightly, if methane is used as a storage, but no significant differences can be seen

BPS - Sectoral Analysis

Power Sector



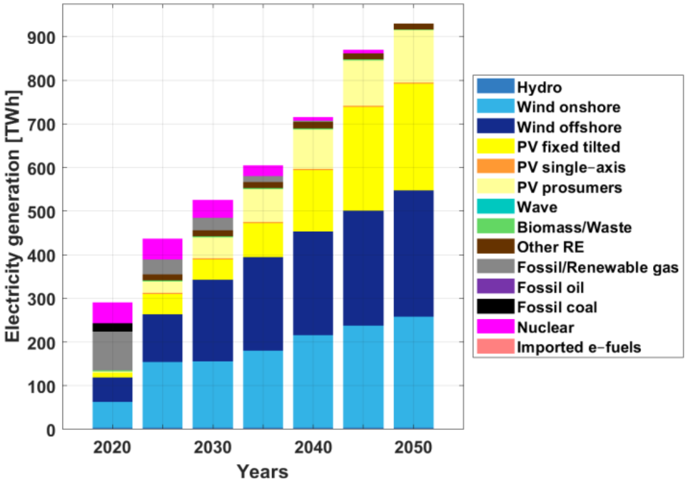


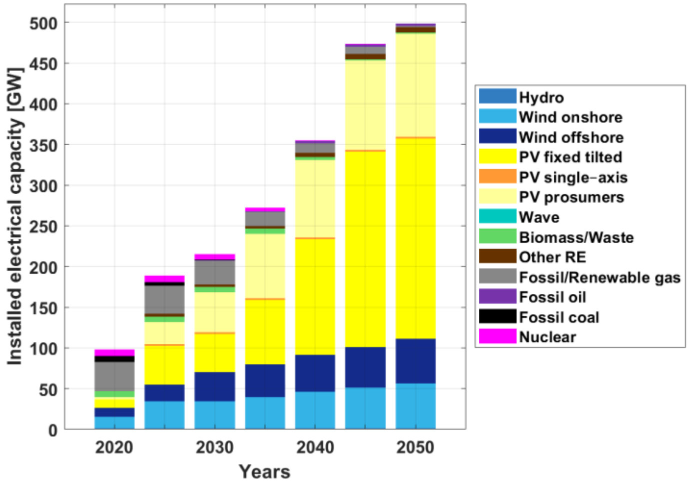


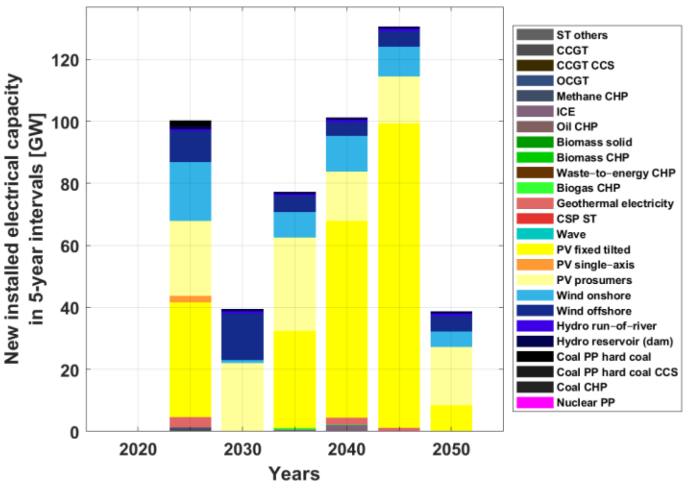
Key insights:

- Electricity grows significantly by a factor of 4
- Wind offshore capacity grows steadily, while the upper limit of wind onshore is reached in 2040
- Massive capacity installation for solar PV occurs in 2040, but also in 2025 and 2035
- Highest share of wind is reached in 2035 with 65% of total generation
- Wave power contributes a significant share from 2040 onwards, reaching 128 TWh in 2050
- Total installed electrical capacity in 2050: 490 GW
- Total electricity generation in 2050: 1171 TWh

BPSplus - Sectoral Analysis
Power Sector





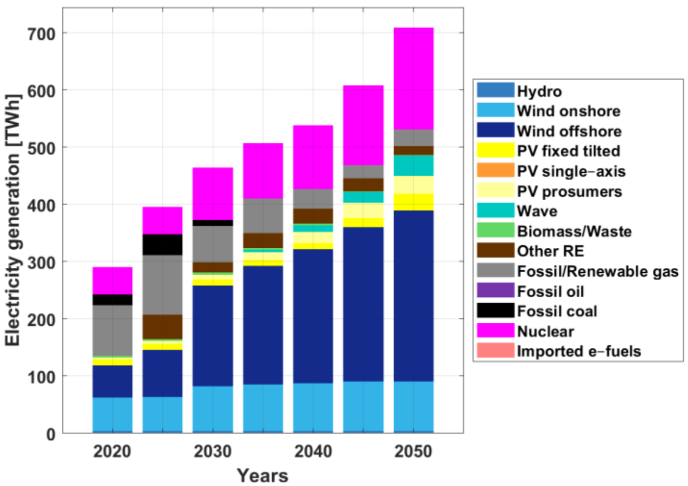


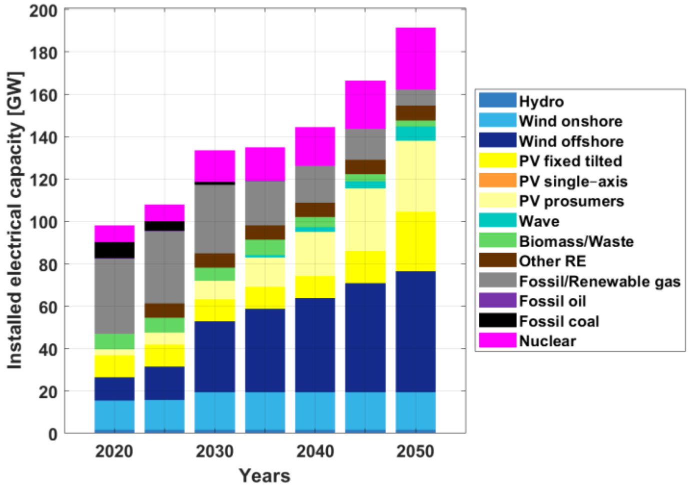
Key insights:

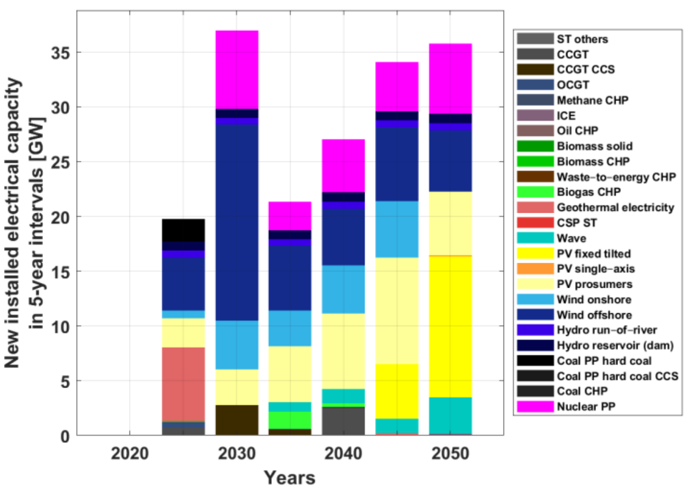
- Less restrictions for onshore wind and solar PV installations enable a more even distribution of the three main generation technologies
- Massive capacity installations for solar PV happen in 2040 and 2045 when PV becomes the least cost source of electricity
- PV prosumers produce 120 TWh of electricity in 2050
- Most new installations happen in 2045, where 131 GW of total new generation capacity is installed
- In 2050, the largest share of electricity generation originates from solar PV (39%), followed by wind onshore (27%) and wind offshore (26%)

CPS - Sectoral Analysis

Power Sector





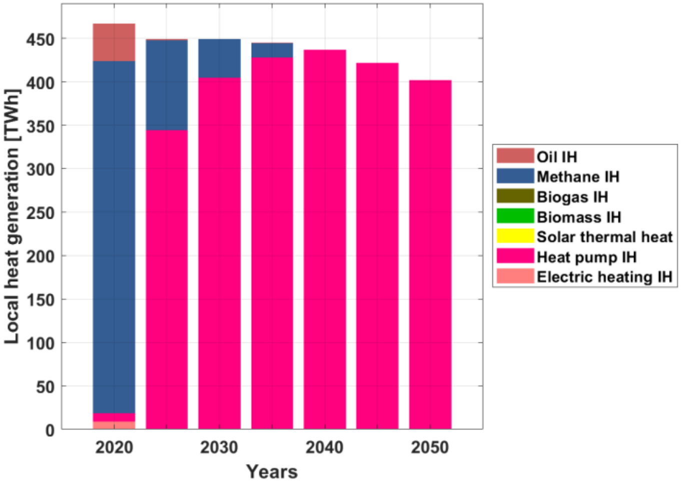


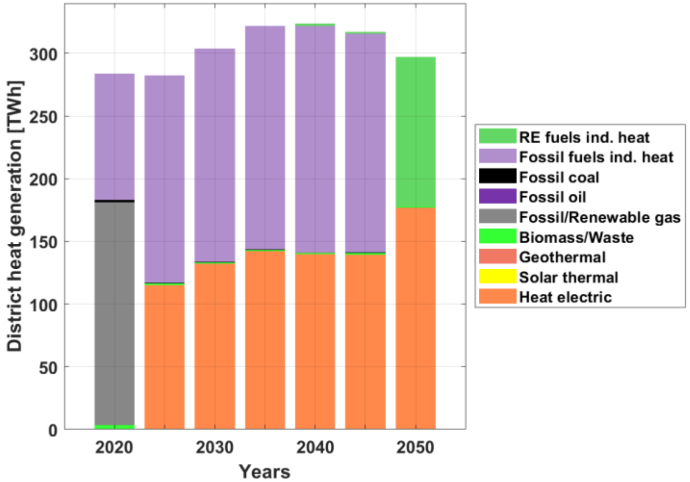
Key insights:

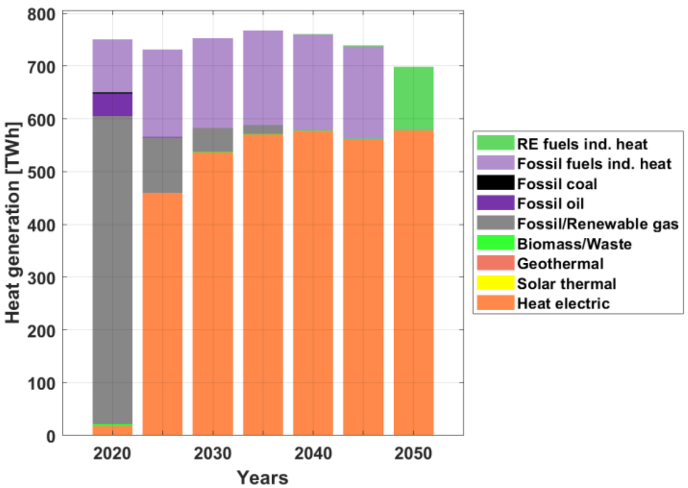
- Electricity grows by a factor of 2-3, indicating an electricifaction trend but not as strong as in the BPS
- Nuclear power contributes a significant share of electricity, reaching 25% in 2050
- Fossil gas remains in the system, combined with CCS
- Offshore wind is the dominant renewable resource used
- Wave power contributes roughly 5% in 2050
- Installed electricial capacity is much lower, due to lower share of solar PV
- Total installed electrical capacity in 2050: 191 GW
- Total electricity generation in 2050: 709 TWh

BPS - Sectoral Analysis

Heat Sector



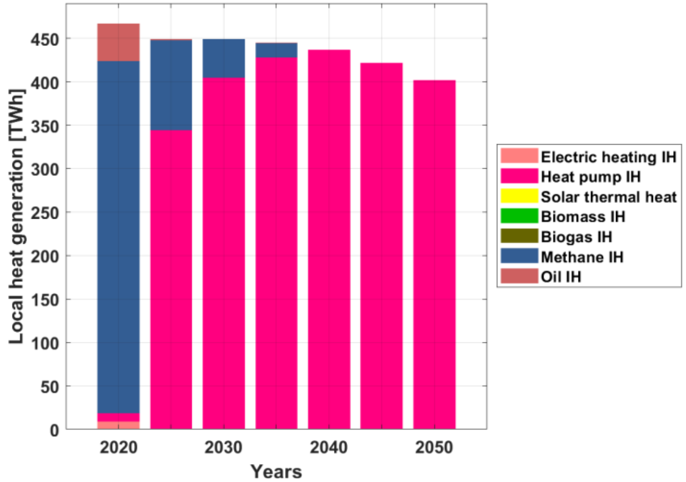


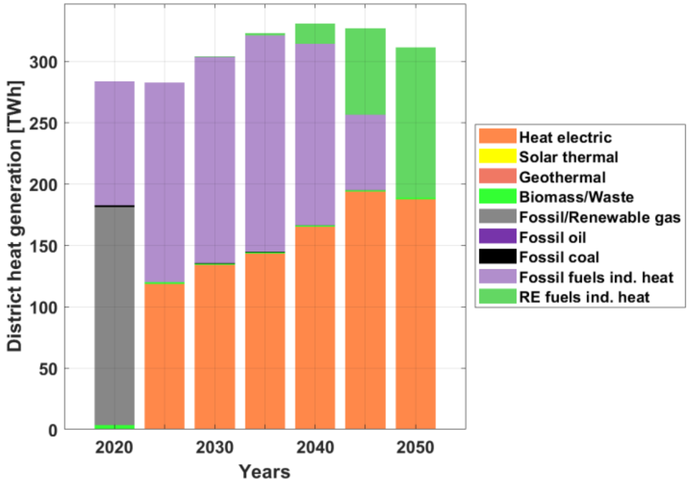


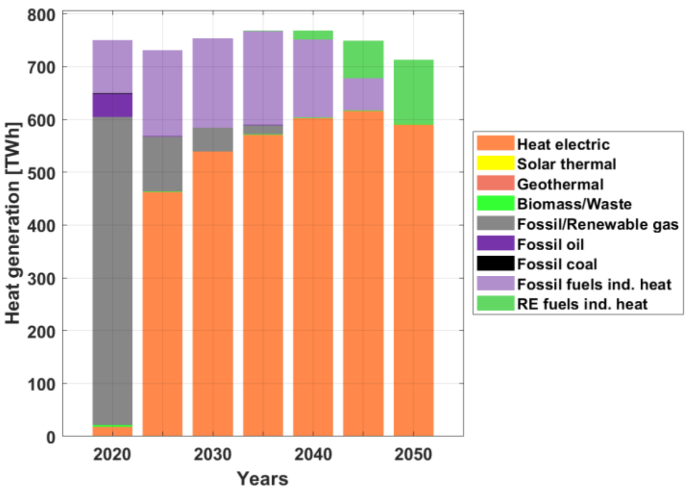
Key insights:

- Local heat generation is fully electrified by heat pumps in 2050, substituting gas boilers already in 2040 completely
- District heat generation includes industrial heat at low and medium temperature levels as well as district heat for space heating and domestic hot water
- For high temperature industrial heat, only fuels can be utilised
- This hard-to-abate sector is transformed at the end of the transition as it faces the most technical challanges
- Low and medium temperature heat demand for industry can be satisfied by electric heating

BPSplus - Sectoral Analysis
Heat Sector





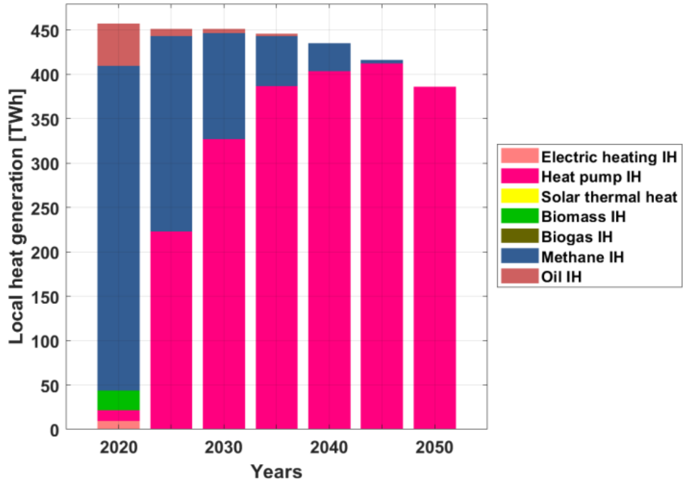


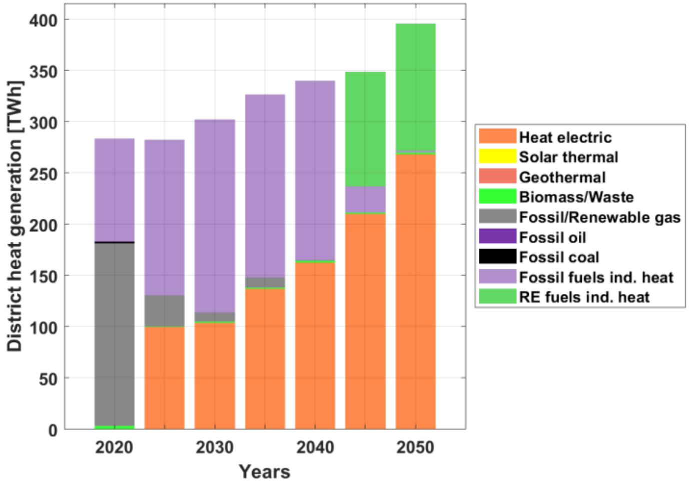
Key insights:

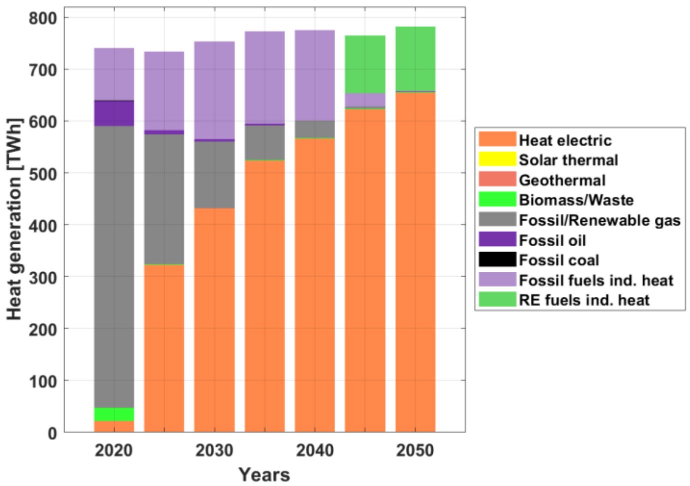
- No significant deviations from BPS
- Sharp phase-in of heat pumps, replacing natural gas boilers
- RE fuels for industrial heat already applied in 2035, growing steadily until 2050, fully replacing fossil fuels

CPS - Sectoral Analysis

Heat Sector





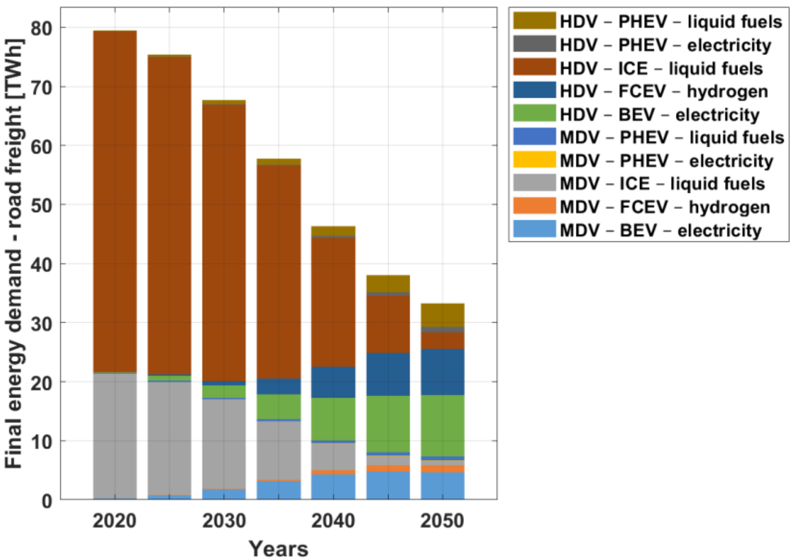


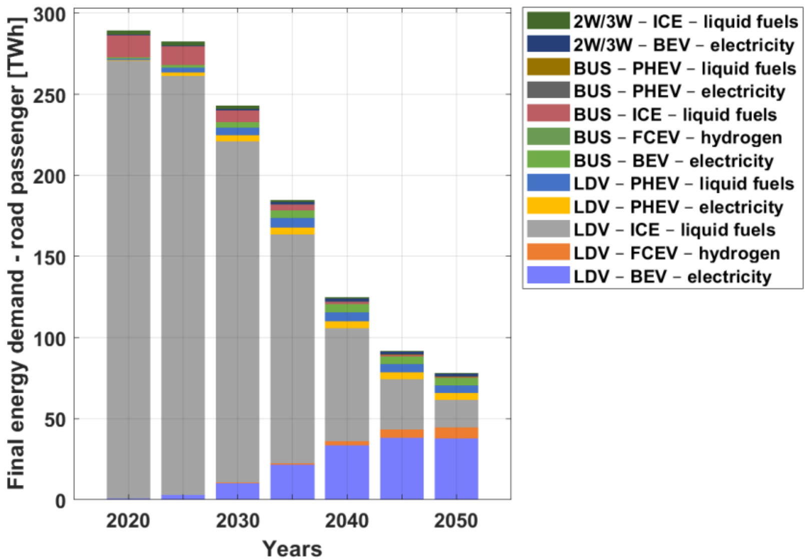
Key insights:

- Electrification trend can be observed, but less than in the BPS
- Transition to individual heat pumps happens slower than in the BPS, but reaches the same result in 2050
- Phase-in of electric heating happens less abruptly
- Slightly different phase-in of RE fuels into industrial heat production, starting a bit earlier, reaching the same amount in 2050

BPS - Sectoral Analysis

Transport Sector - Road



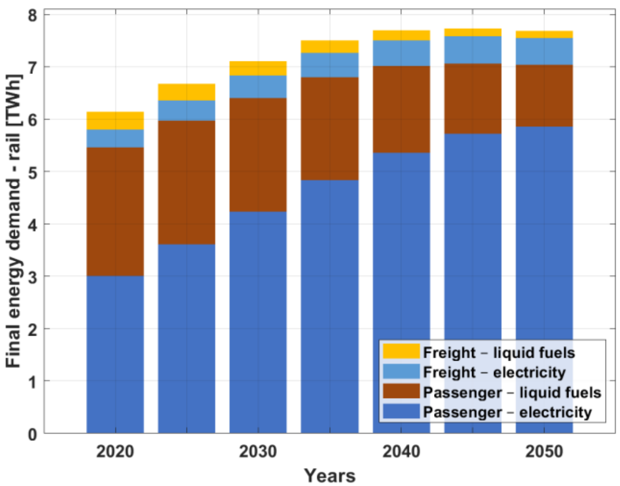


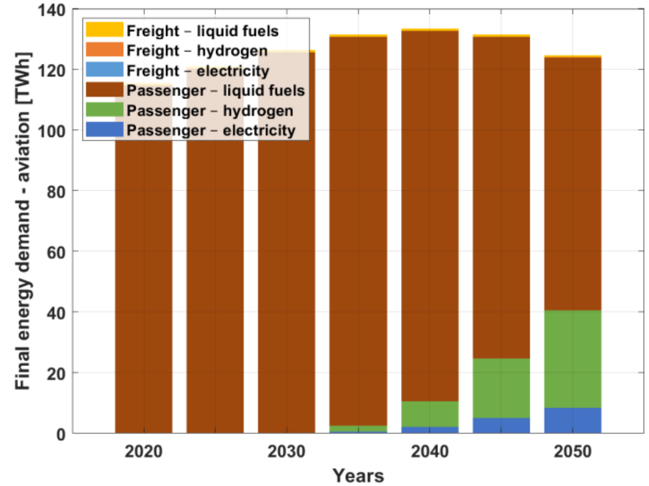
Key insights:

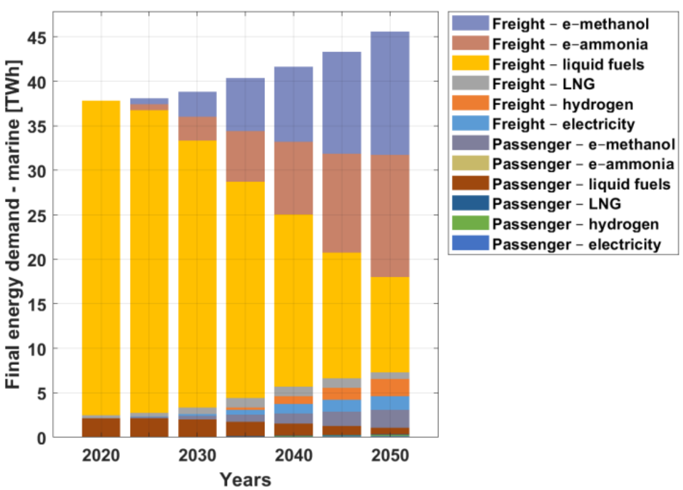
- Final energy demand for road transport drops drastically, as inefficient internal combustion engines (ICE) are successively substituted by electric vehicles with much higher efficiency
- Final energy demand for freight transport decreases from 80 TWh to 33 TWh and for passenger transport decreases from 289 TWh to 78 TWh
- A small share of ICEs remains in the system, but is supplied by sustainable Fischer-Tropsch (FT) fuels
- Hydrogen may play a relevant role for heavy-duty vehicles (HDV)
- Direct and indirect electrification of the transport sector is a key element for the overall energy system transition
- Battery electric vehicles (BEV) are a key technology with high efficiency and are already available at scale

BPS - Sectoral Analysis

Transport Sector – Rail, Marine, Aviation





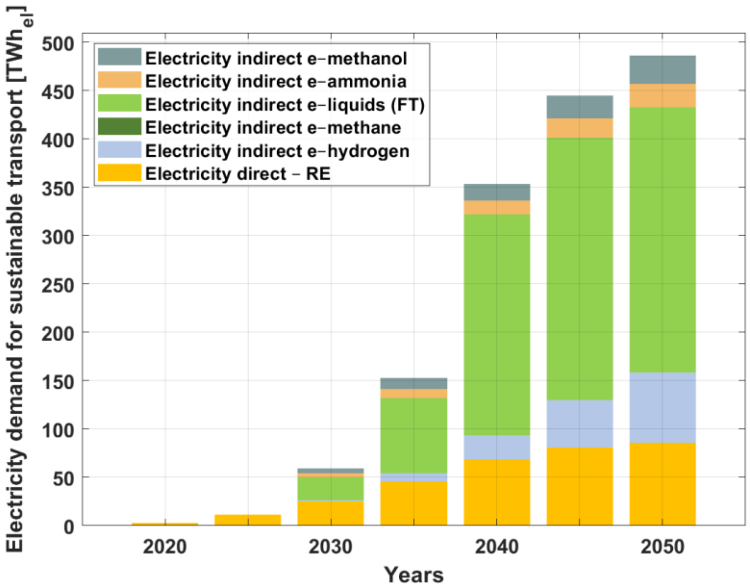


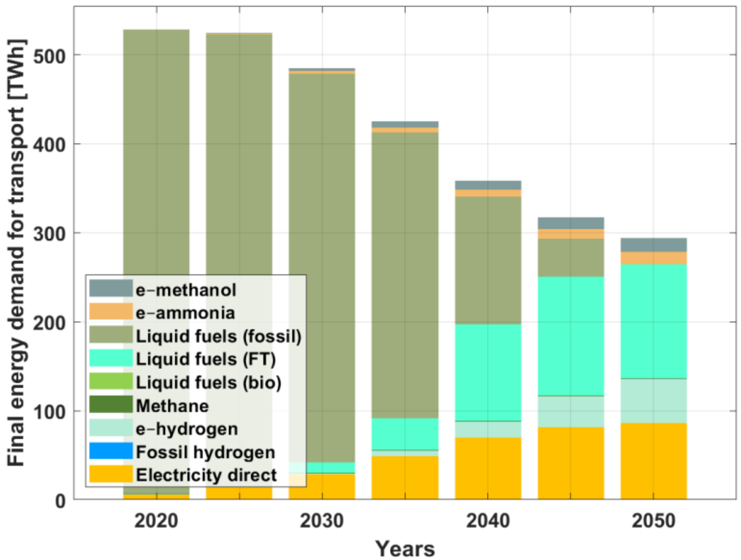
Key insights:

- Final energy demand grows slightly for all modes of transportation
- Growing demand cannot be fully compensated by efficiency gains from direct electrification, since energy intensive e-fuels are necessary for long-distance marine and aviation transport
- e-ammonia and e-methanol become important fuels for marine, being responsible for more than 50% of final energy demand in 2050
- Liquid FT fuels are essential for passenger aviation

BPS - Sectoral Analysis

Transport Sector

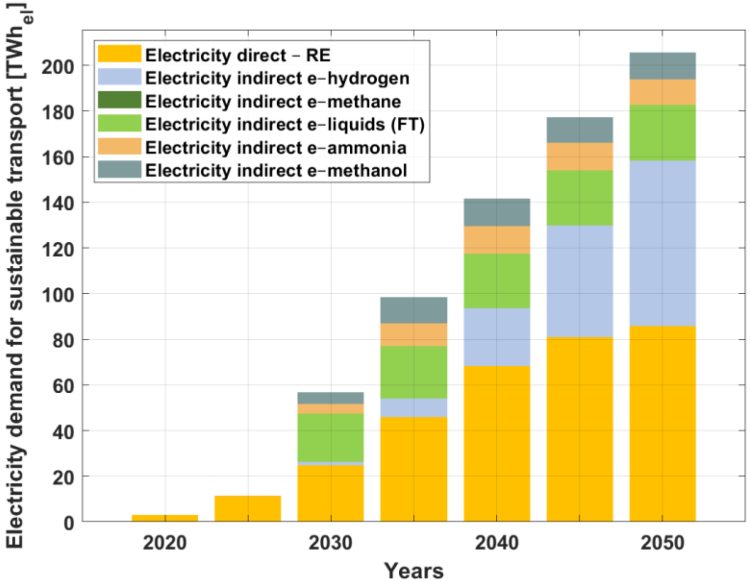


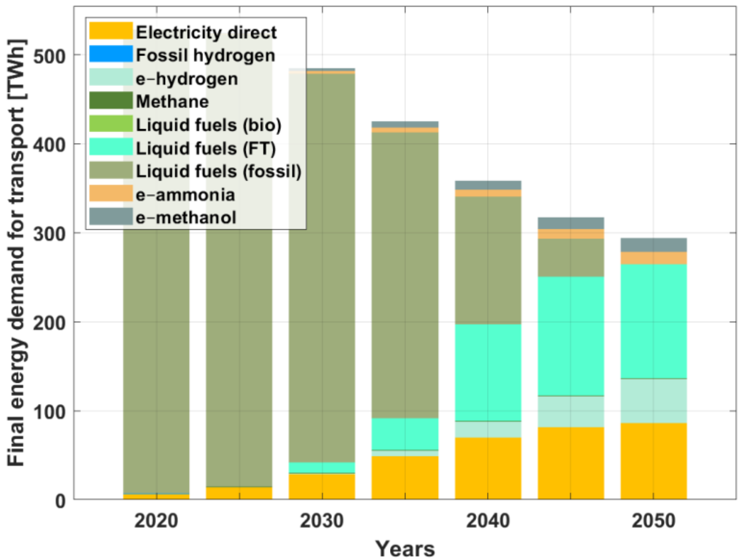


Key insights:

- Transport sector requires signicant amounts of e-fuels such as e-liquids, e-methane, e-hydrogen, e-methanol and e-ammonia
- Total electricity demand rises up to 486 TWh in 2050, thereof 86 TWh for direct electricity
- Highest electricity demand can be assigned to e-liquids with 274 TWh
- Liquid fuels for final energy demand are almost only FT fuels, since fossil fuels are fully phased out and there are not enough biomass resources for biofuel production available
- e-ammonia and e-methanol are important for the marine transport

BPSplus - Sectoral Analysis
Transport Sector



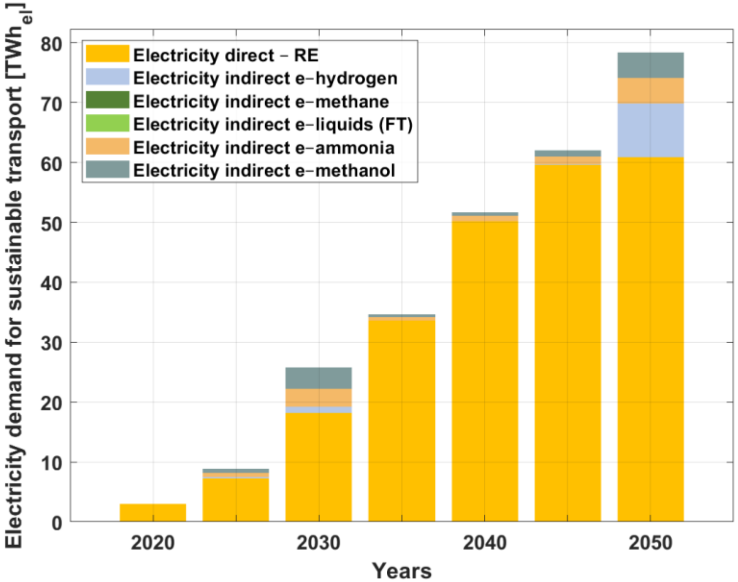


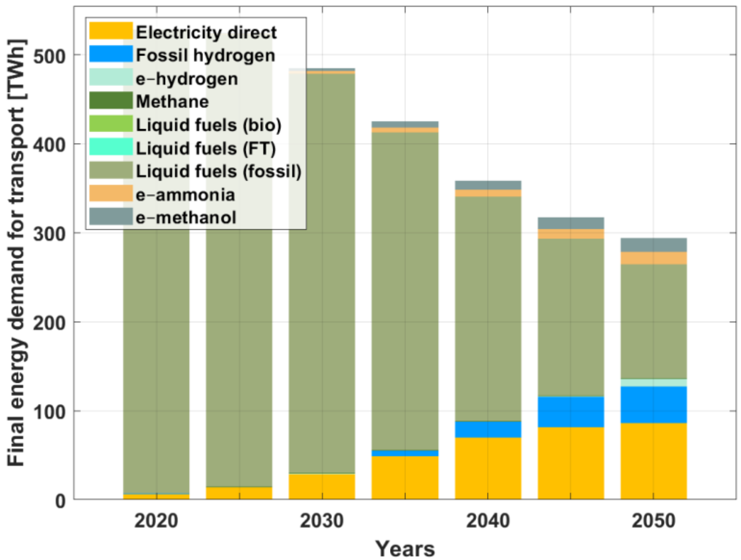
Key insights:

- Electricity demand for sustainable transport is between BPS and CPS, due to higher imports of e-fuels compared to BPS but without utilisation of fossil fuels as in CPS
- Main difference to BPS can be seen in much lower electricity demand for FT fuels (synthetic diesel, kerosene), as those are the ones that are imported (right figure shows, that final energy demand for FT fuels is the same as in BPS)
- Key trend of electrification unchanged to BPS
- Less domestic production of FT fuels indicates the economic benefits of e-fuel imports
- Electricity demand for direct electricity, e-hydrogen, e-ammonia and e-methanol unchanged to BPS

CPS - Sectoral Analysis

Transport Sector



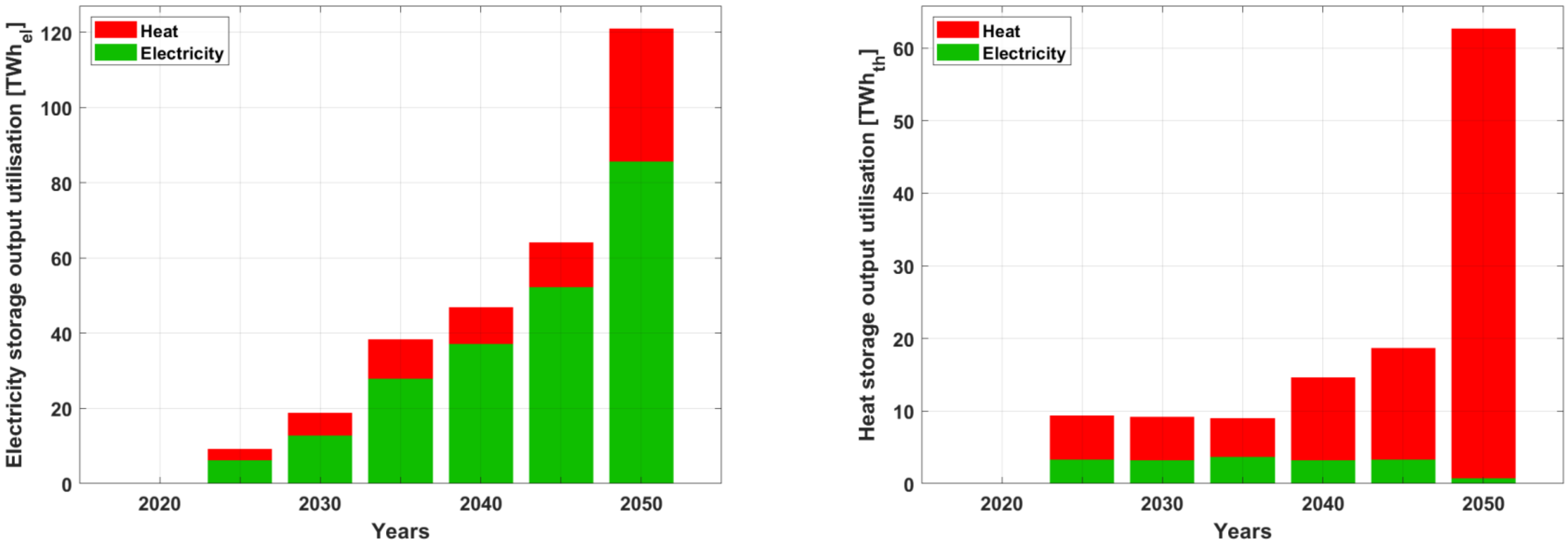


Key insights:

- Since fossil oil is still used in the transport sector, the production of e-fuels for transportation becomes almost unnecessary, thus the electricity demand is lower by a factor of 6 than in the BPS
- Most of the electricity demand for sustainable transport can be allocated to direct electricity use for BEV
- Only a small amount is used for hydrogen (most of the hydrogen is fossil based), e-ammonia and e-methanol production
- Liquid fuels that are used in the transport sector are fossil rather than biofuels or FT fuels
- Electricity demand for e-fuel production is much lower compared to the BPS, since e-liquid production consumes most electricity

BPS - Energy Storage

Energy Storage Utilisation

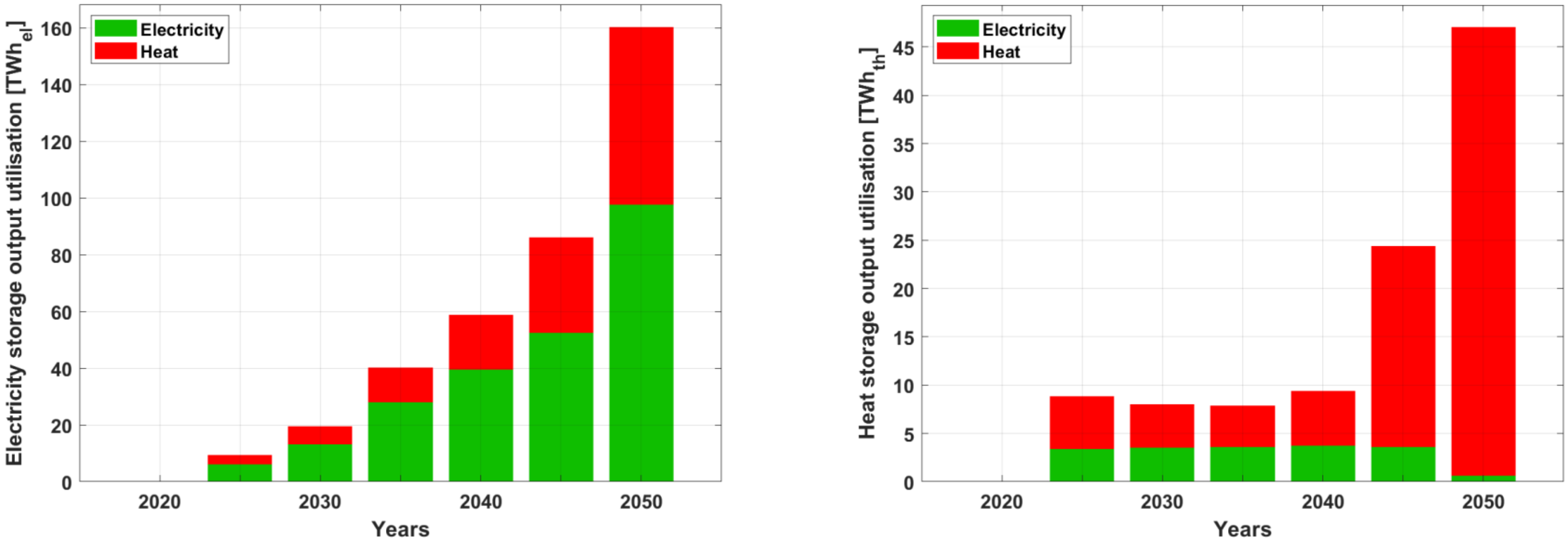


Key insights:

- Energy storage enables a temporal decoupling of energy supply and demand, preventing curtailment
- Electricity storage output increases through the transition, reaching 121 TWh in 2050
- Strong growth happens from 2045 to 2050, when the system finally transforms to a 100% RE system, with high shares of variable renewables
- 86 TWh of electricity storage output is used for electricity and 35 TWh for heat and gas
- Heat and gas storage output reaches 62 TWh in 2050 and is mainly used for heat, due to its application for high-temperature industrial heat
- Different types of energy storage enable a high flexibility, save costs and enable the maximum integration of variable renewable electricity with low curtailment

BPSplus - Energy Storage

Energy Storage Utilisation

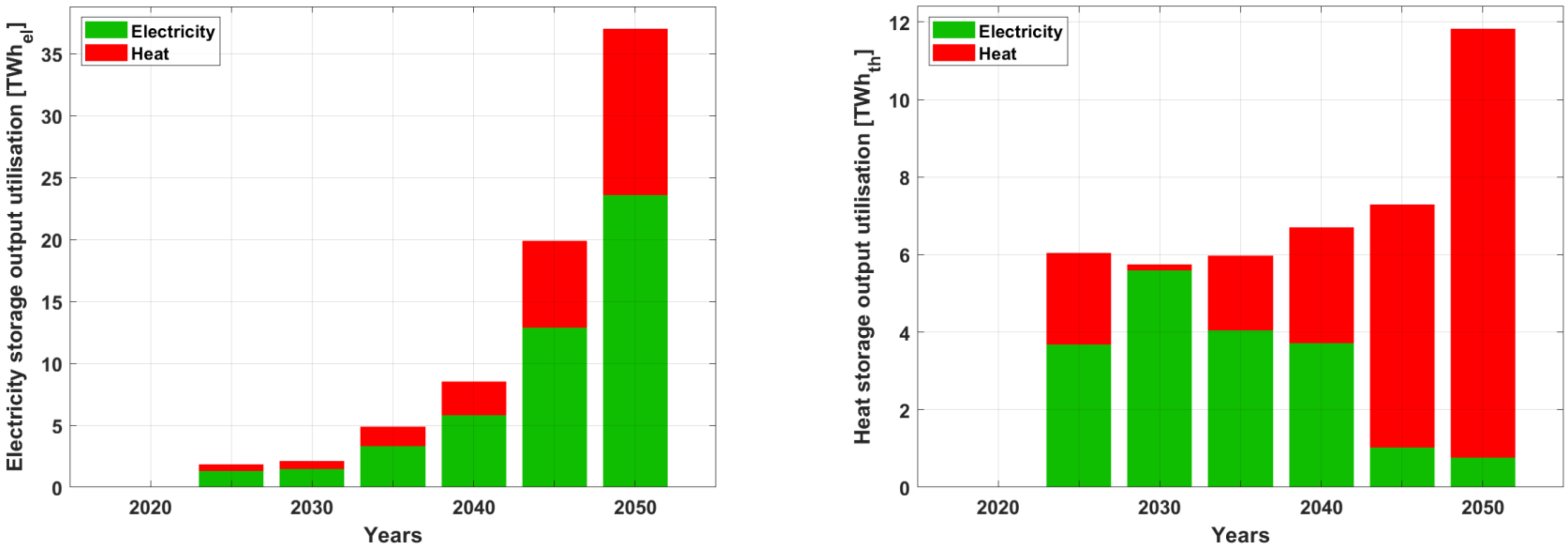


Key insights:

- Electricty storage output utilisation is higher than in BPS and much higher than in CPS, reaching 160 TWh$_{el}$
- More electricity storage output is used for heat than in BPS
- Comapred to BPS, the importance of electricity storage becomes higher, while the importance of heatand gas storage becomes less
- Relevance of storage increases along the transition as in BPS and CPS, with steady growth until 2045 and a strong increase in the last stage of the transition
- Heat and gas storage output utilisation is slightly lower than in BPS, but the utilisation share structure is the same: most of heat storage output is used for heat and only a minor share for electricity
- Heat and gas storage grows in the initial stage of the transition and ramps intensely from 2040 until 2050

CPS - Energy Storage

Energy Storage Utilisation

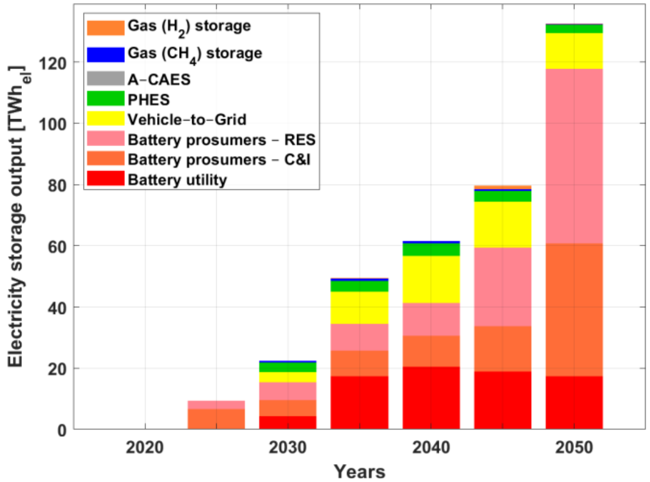


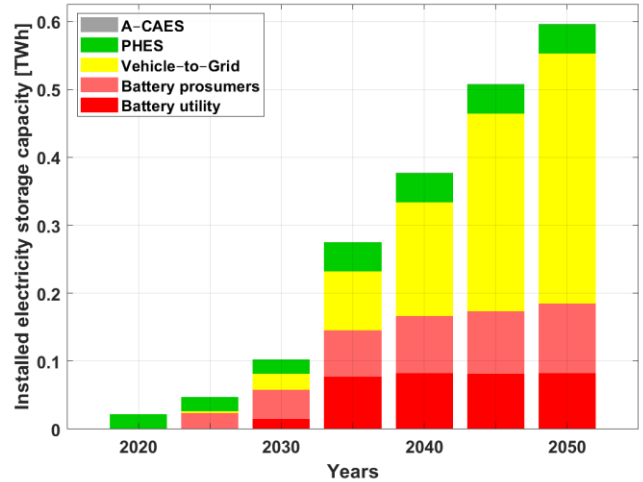
Key insights:

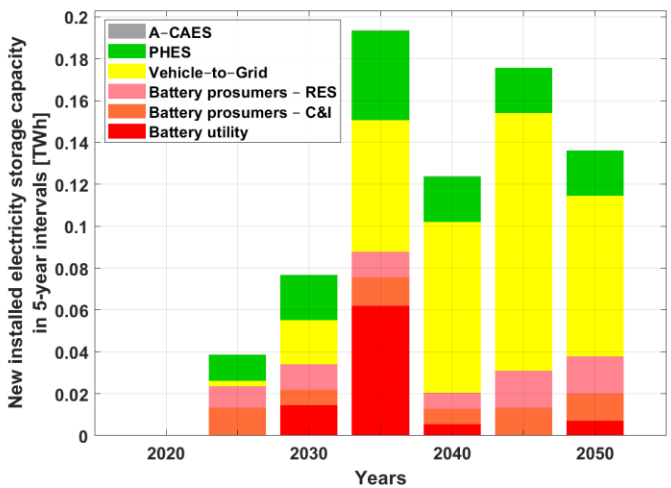
- In general, the storage output utilisation is lower by a factor of 4, compared to the BPS, due to less installed storage capacity
- Electricity storage output is used in the same way as for BPS, some differences can be seen for heat storage output utilisation
- A high share of electricity storage output is used for electricity, while in 2050 roughly 30% is used for heat (heat pumps, direct electric heating)
- In 2050, most of the heat and gas storage output is used for heat, while from 2025 – 2040 a significant share is also used to generate electricity

BPS - Energy Storage

Electricity Storage





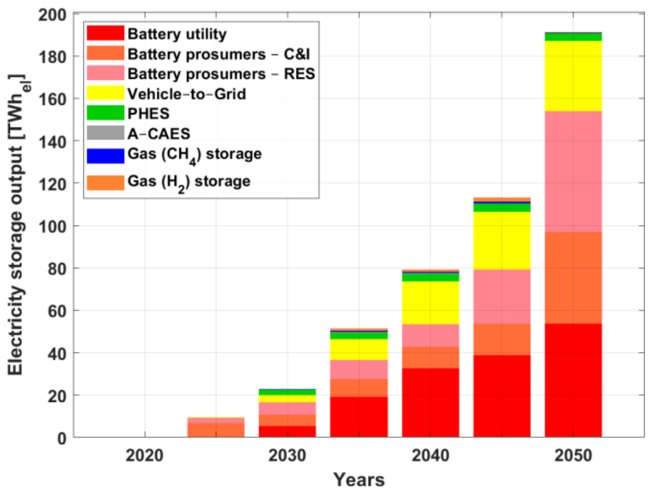


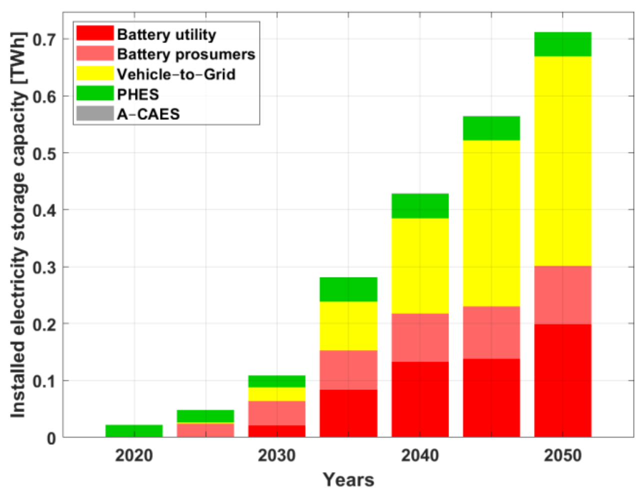
Key insights:

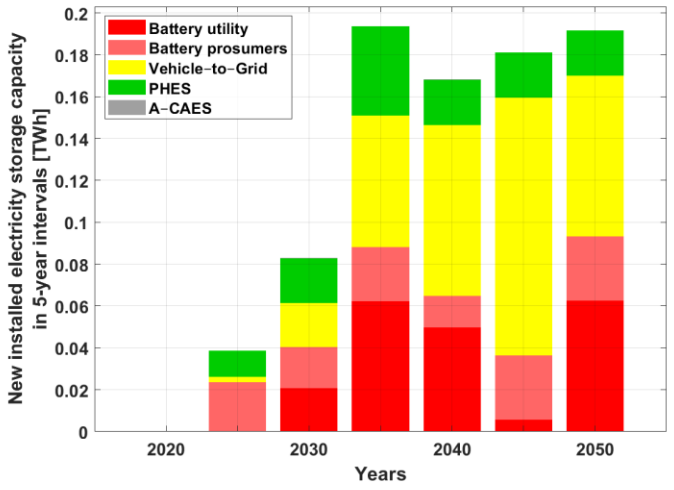
- Different types of battery applications are the key technology for short-term electricity storage
- Battery prosumers (residential, commercial and industrial) become a major element of the future electricity system
- Vehicle-to-Grid storage is an advanced form of electricity storage and is dependent on the willingness of vehicle owners to feed electricity from their vehicle into the grid
- No additional installation costs for Vehicle-to-Grid necessary, since BEV will be a cornerstone of the future energy system

BPSplus - Energy Storage

Electricity Storage





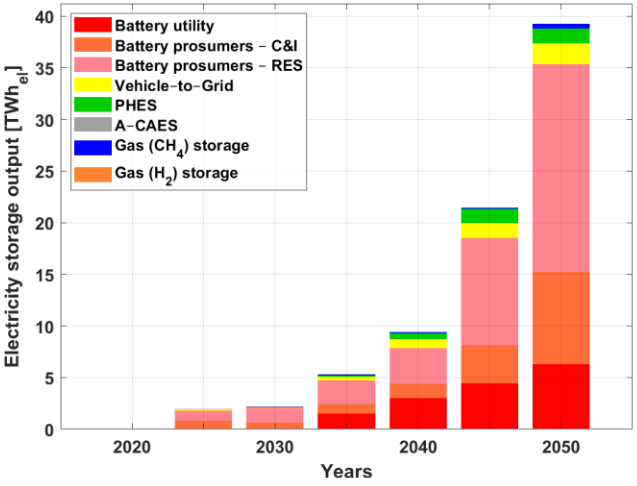


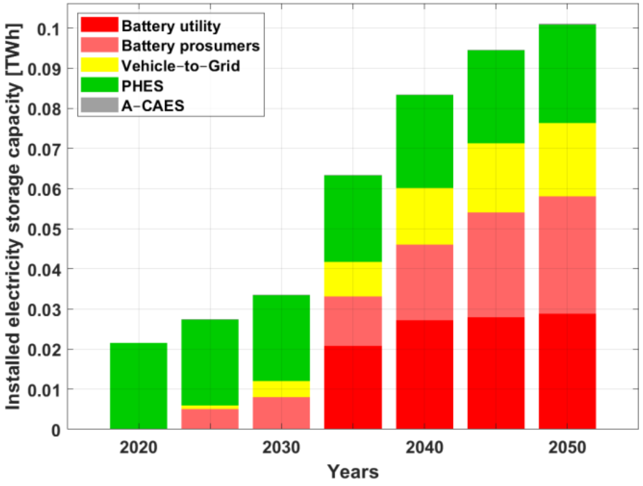
Key insights:

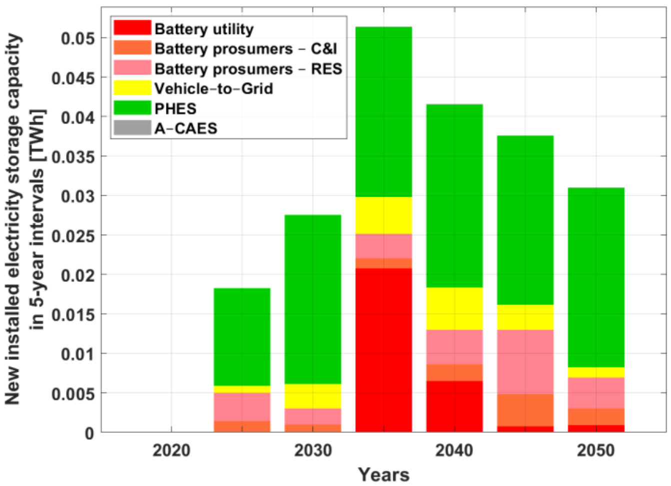
- Electricity storage output is higher than in the BPS and much higher than in the CPS
- Battery utility-scale and Vehicle-to-Grid output increases by a factor of 2-3 compared to BPS
- This strongly affects the new installed Vehicle-to-Grid capacity, which is mainly added from 2035 onwards
- 2035 is the year where the largest amount of new storage technologies are installed

CPS - Energy Storage

Electricity Storage





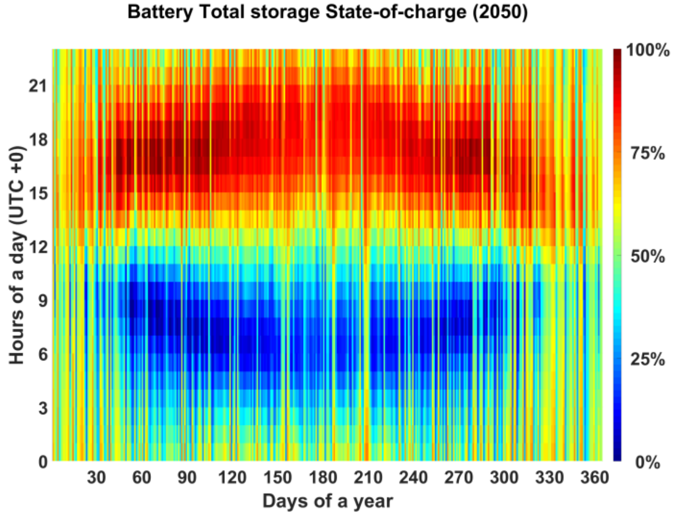


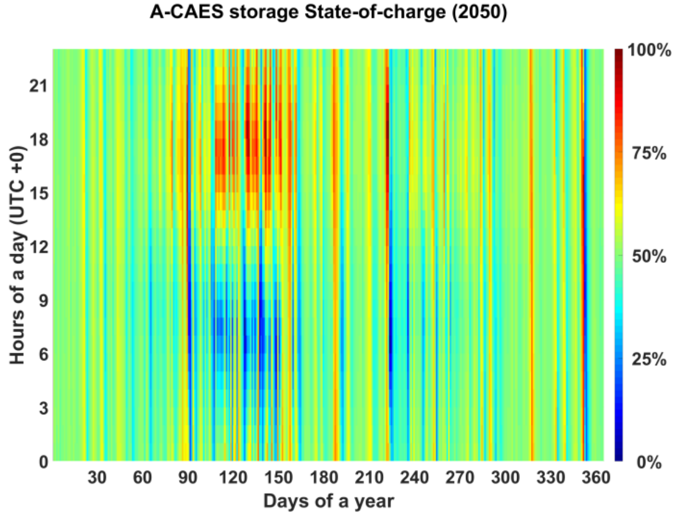
Key insights:

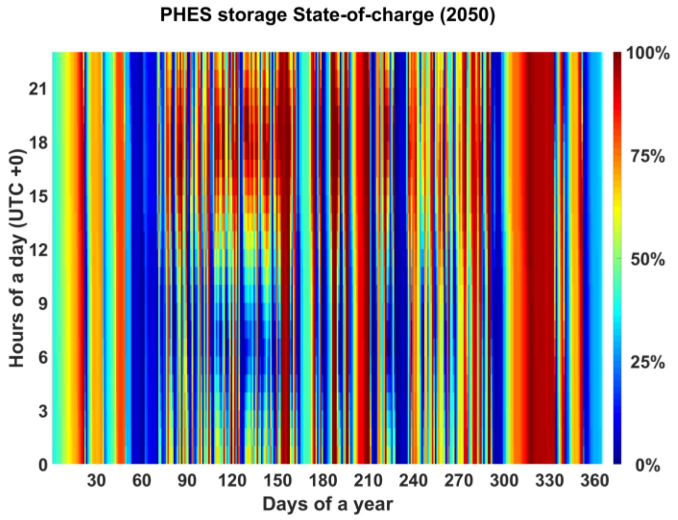
- Electricity storage is lower by a factor of 3, compared to the BPS, reaching a total storage output of 39 TWh
- The lower level of electrification and higher share of fossil fuels and nuclear energy causes less storage needs
- Less vehicle owners enable their vehicle to exchange electricity with the grid
- PHES remains an important component for electricity storage

BPS - Energy Storage

Electricity Storage – Hourly Profiles





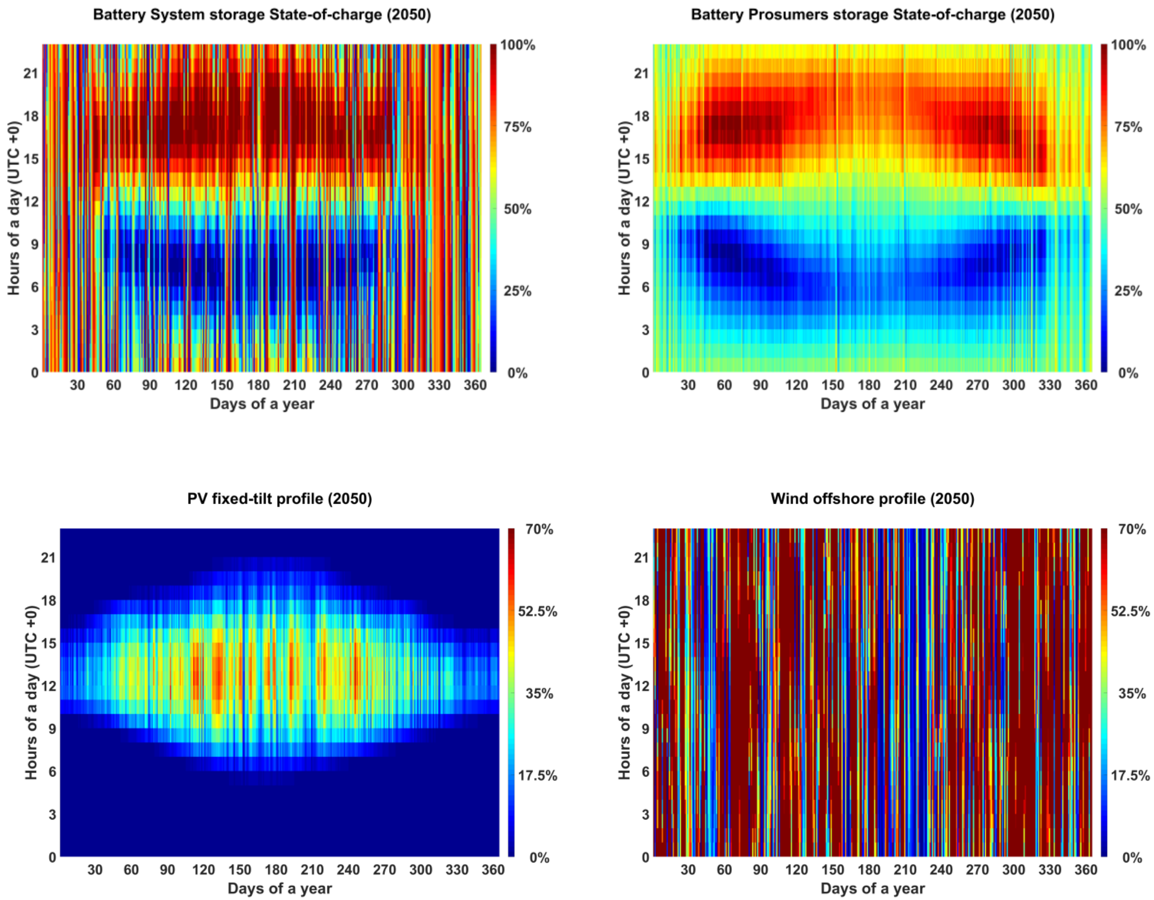


Key insights:

- Battery storage and adiabatic compressed air energy storage (A-CAES) work as short-term balancing solutions
- Batteries cover the day-night variations: fully charged during the day and discharged over night
- A-CAES is utilised during spring, adding flexibility to the existing battery storage
- PHES works as mid-term storage and is utilised all over the year, but can also serve in day-night storage
- A properly balanced energy system is a result of the interaction of different energy storage technologies

BPS - Energy Storage

Battery Storage and RE Complementary

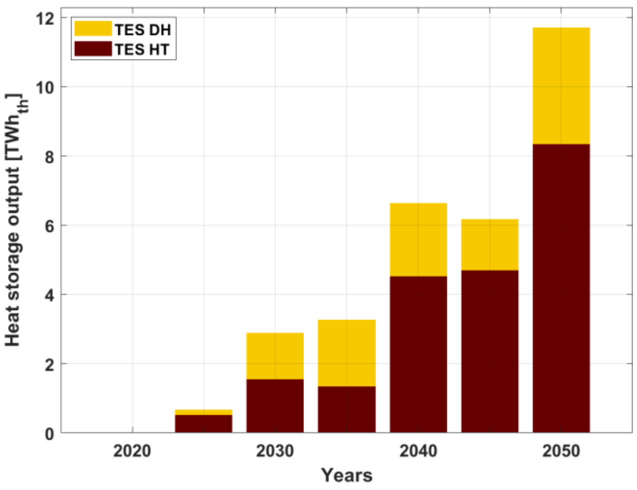


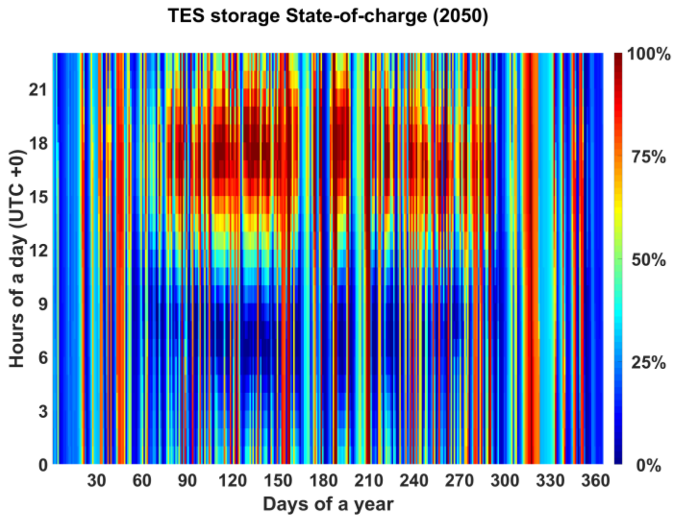
Key insights:

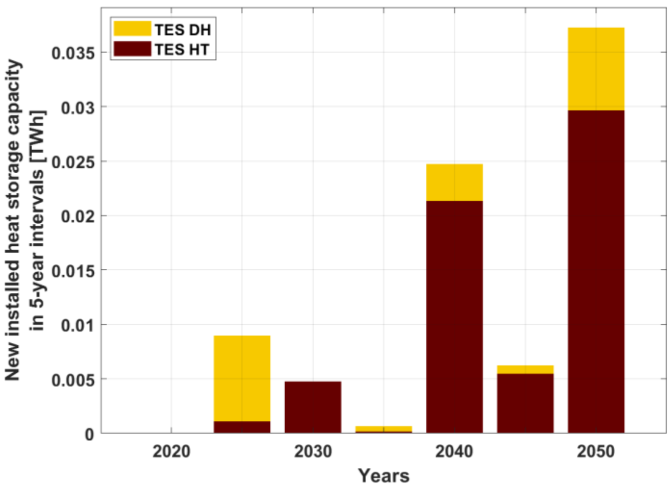
- **Batteries are mainly responsible for balancing hourly variation of RE generation**
- **Battery profile adjusts to the available RE resources, depending on the time of the year**
- **In summer, the battery utilisation profile interacts with the hourly solar PV profile, balancing the day-night variation**
- **In winter, it instead interacts with the wind profile**
- **The battery prosumer profile is even more strongly attached to the solar PV profile, as it directly interacts with PV prosumers**

BPS - Energy Storage

Heat Storage





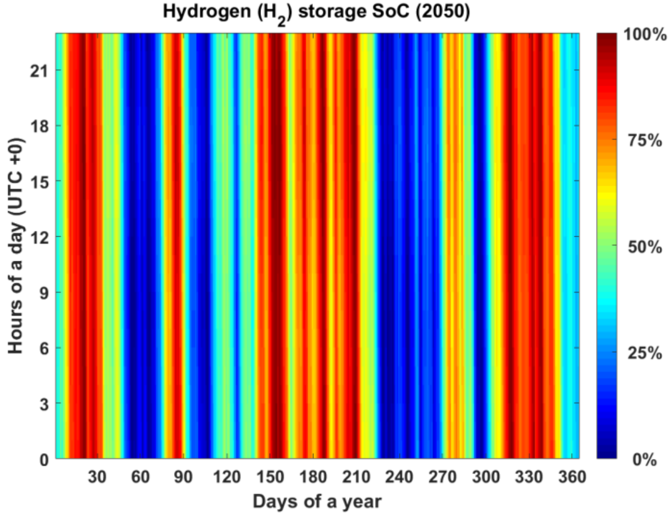


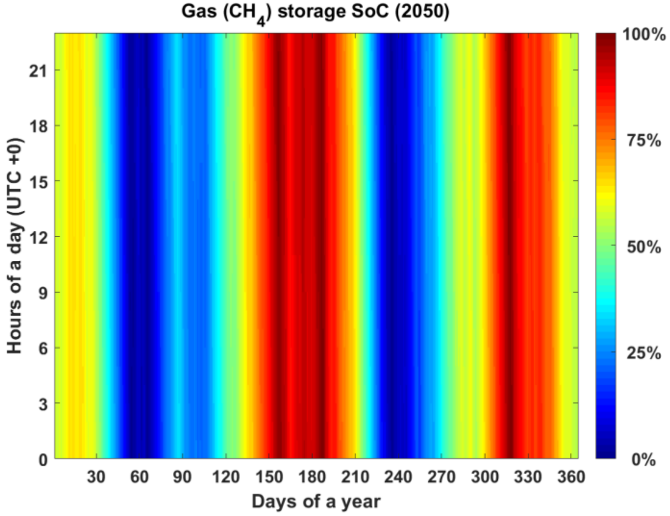
Key insights:

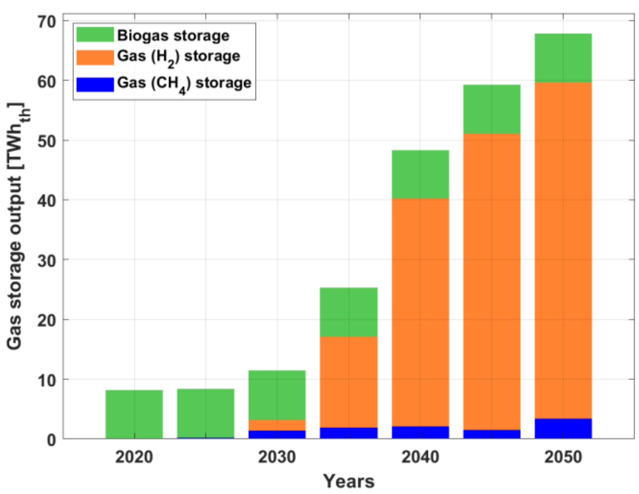
- Thermal energy storage (TES) offers another option for increasing the system flexibility in the heat sector
- District heat (DH) and high-temperature (HT) heat storage enable temporary storage of hot water (sensible heat storage)
- TES is fully charged during the day in spring and summer and discharged over night
- In autumn and winter, the TES is discharged more often and for a longer time as the heat demand is higher

BPS - Energy Storage

Gas Storage & Long-Term Storage



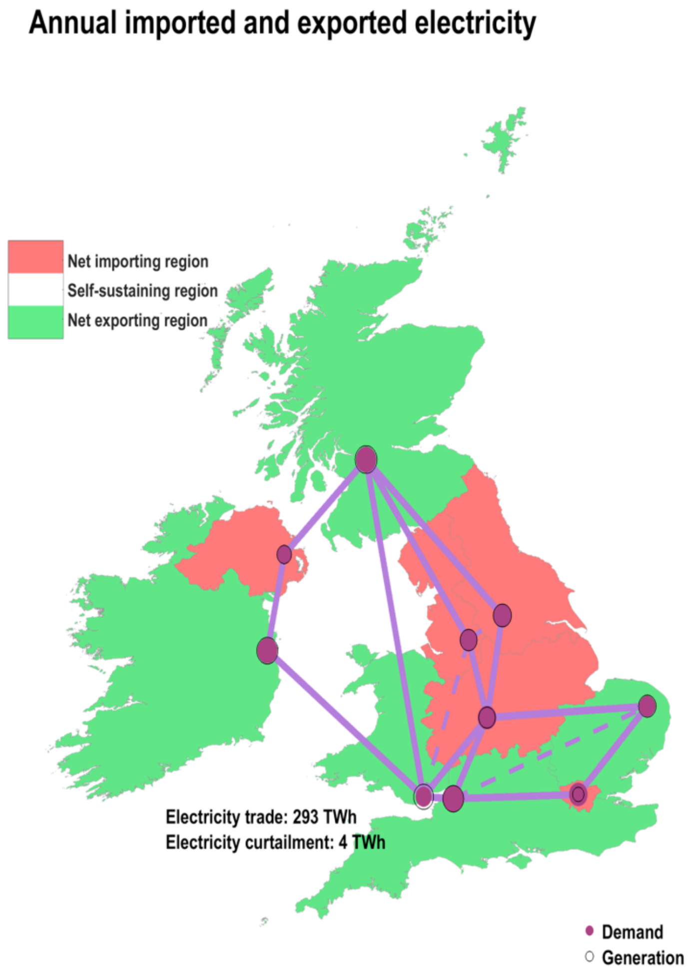


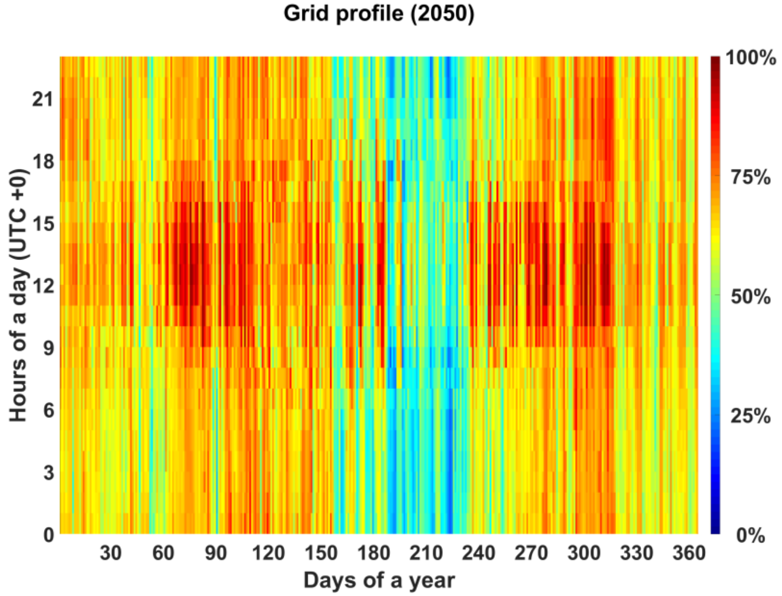


Key insights:

- Gas storage (biogas, H_2, CH_4) works as long-term storage
- Hourly profiles show different periods where the storage facilities are fully charged or discharged
- H_2 is charged and discharged more often than CH_4 storage
- CH_4 storage is fully discharged during winter and gets charged over summer, hence works as a seasonal storage
- However, output from H_2 storage is higher by a factor of 19, resulting in 56 TWh compared to 3 TWh CH_4 in 2050
- Total gas storage output reaches 68 TWh in 2050

BPS - Electricity Grid & Transmission





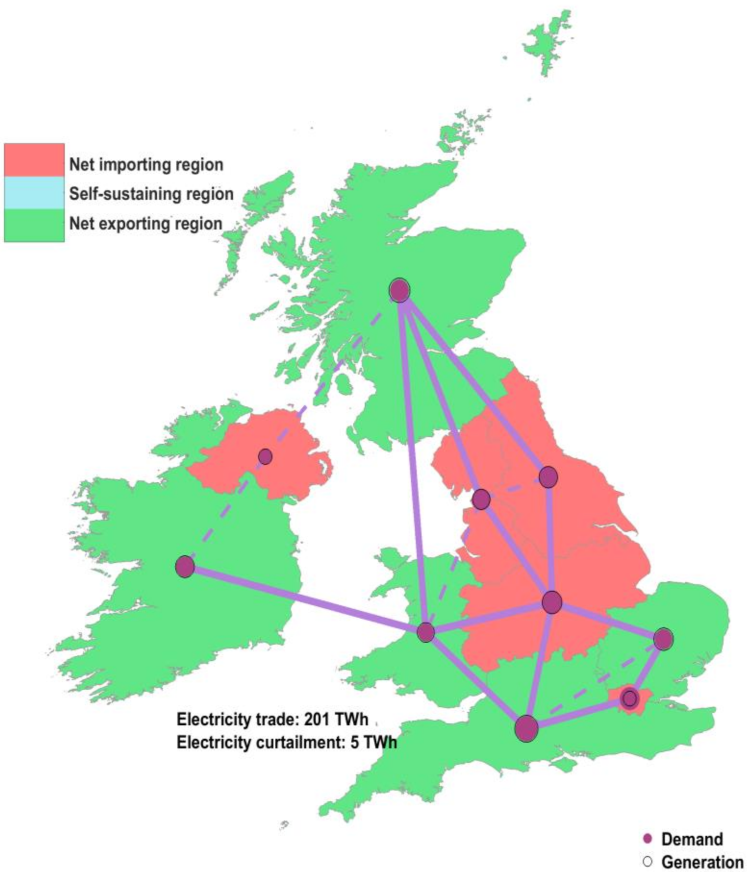
Note: Ireland is part of the integrated modeling, while the energy system numbers presented are only for the UK

Key insights:

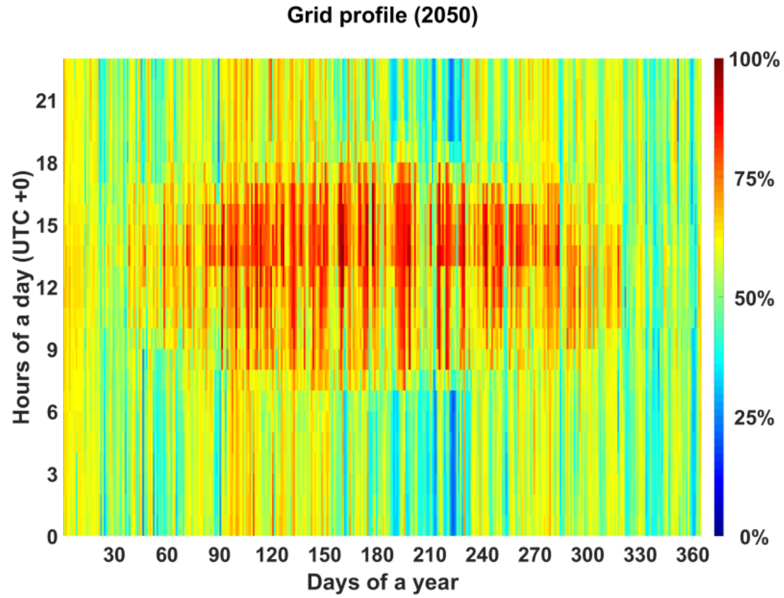
- **Strong interconnection of the subregions increases flexibility of an integrated and sector-coupled energy system**
- **Grid utilisation is highest during the day in spring and autumn**
- **Subregions with high regional production work as exporting regions: Scotland, Ireland, Wales, East of England and Southern England**
- **London is a strong importer with almost no own, regional electricity generation**

BPSplus - Electricity Grid & Transmission

Annual imported and exported electricity



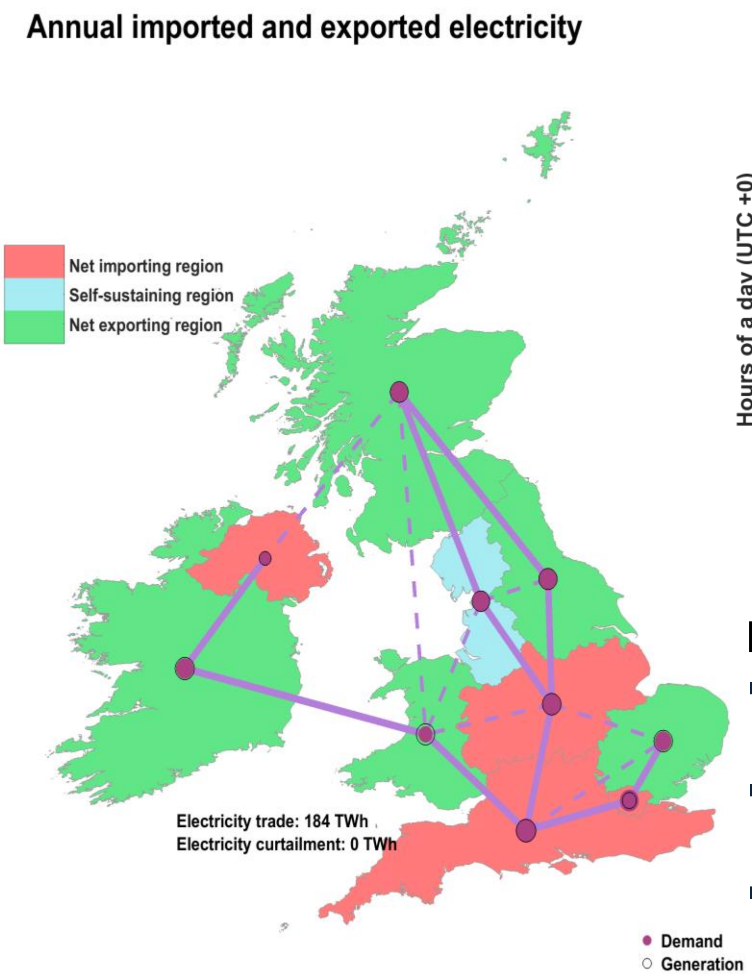
Note: Ireland is part of the integrated modeling, while the energy system numbers presented are only for the UK

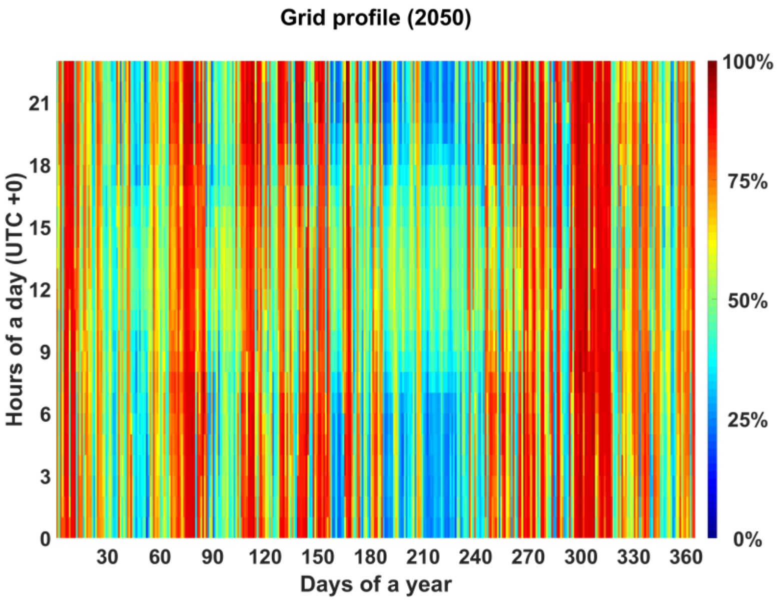


Key insights:

- Grid utilisation interplays with the solar PV generation profile, as higher shares of PV shape the energy system
- Total electricity trade is 31% lower than in BPS, but 9% higher than in CPS
- Structure of importing and exporting regions similar to BPS
- Except for the period of high PV generation, grid utilisation happens rather evenly throughout the year, with low utilisation during night hours in summer

CPS - Electricity Grid & Transmission





Note: Ireland is part of the integrated modeling, while the energy system numbers presented are only for the UK

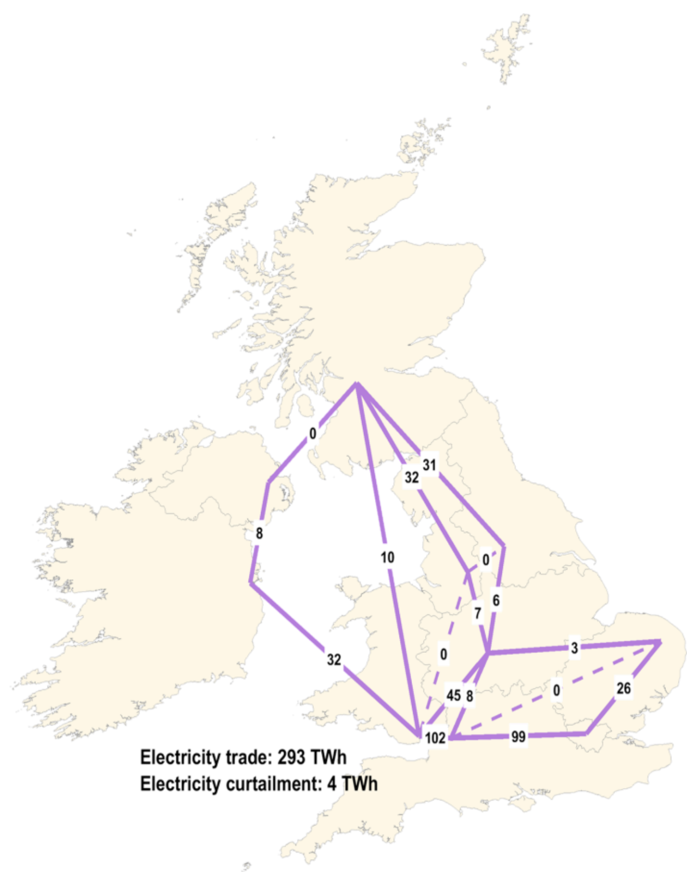
Key insights:

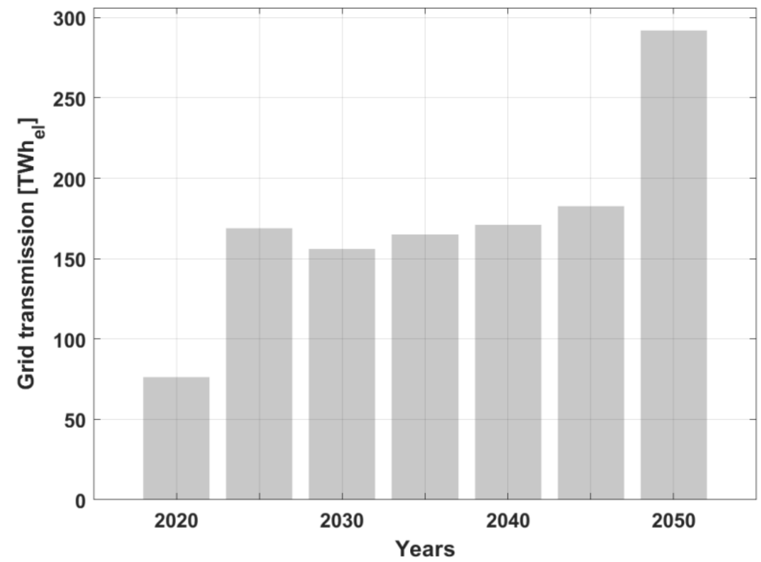
- Grid utilisation happens more selectively throughout the year but then very intensely, while it is better balanced in the BPS
- In the CPS, North East becomes a self-sustaining region while it is a net-importing region in the BPS
- Southern England becomes a net-importing region most likely due to missing PV capacity
- Scotland and Wales remain important exporters

more information ► christian.breyer@lut.fi

BPS - Electricity Grid & Transmission

Annual imported and exported electricity (TWh)

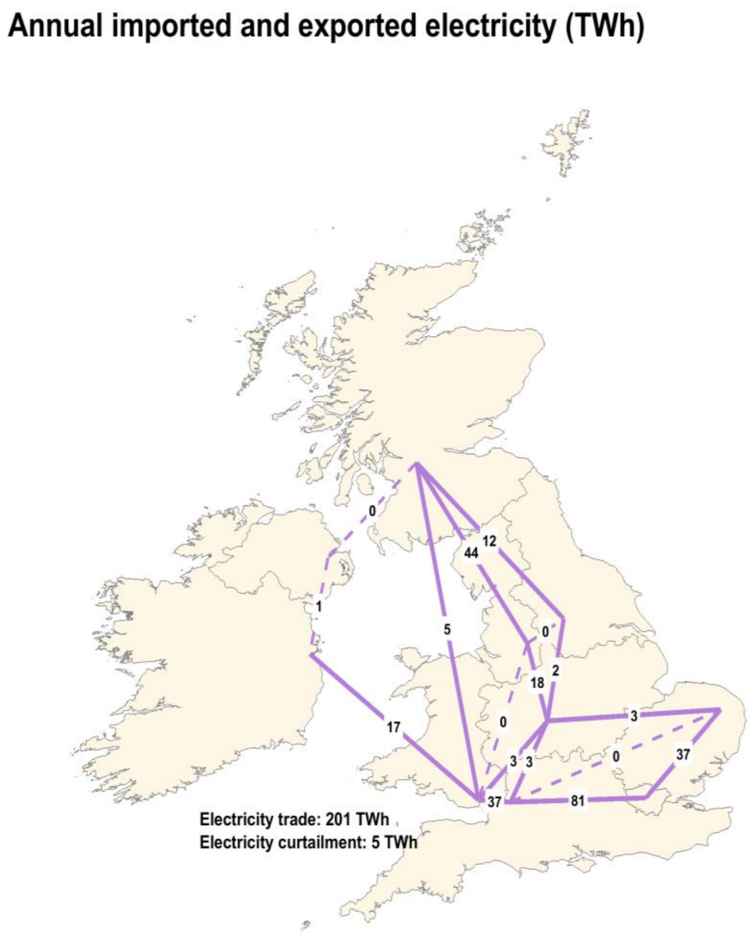


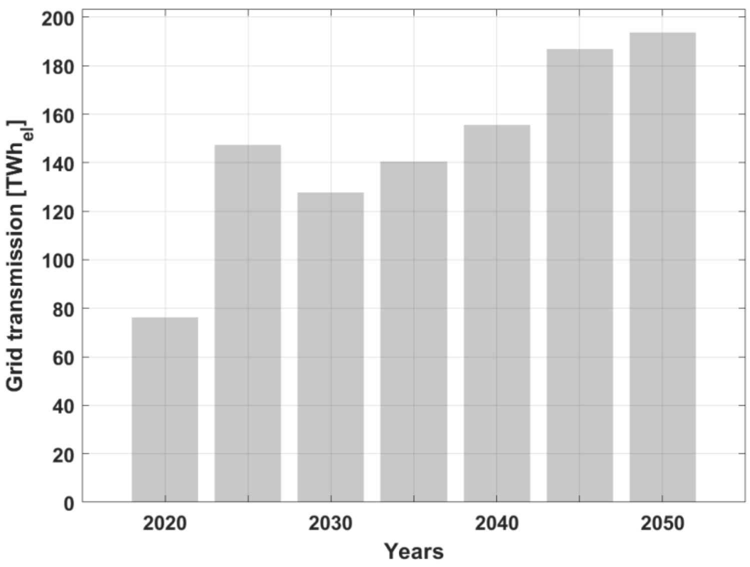


Key insights:

- Total electricity trade in 2050: 293 TWh
- Strong growth in 2025 and in 2050
- Exchange happens to London from surrounding regions and from Scotland to Northern England
- Wales works as a distribution center of electricity, having strong exhange with all neighbouring regions
- High level of sector coulping and system optimisation results in low levels of curtailment: 4 TWh

BPSplus - Electricity Grid & Transmission



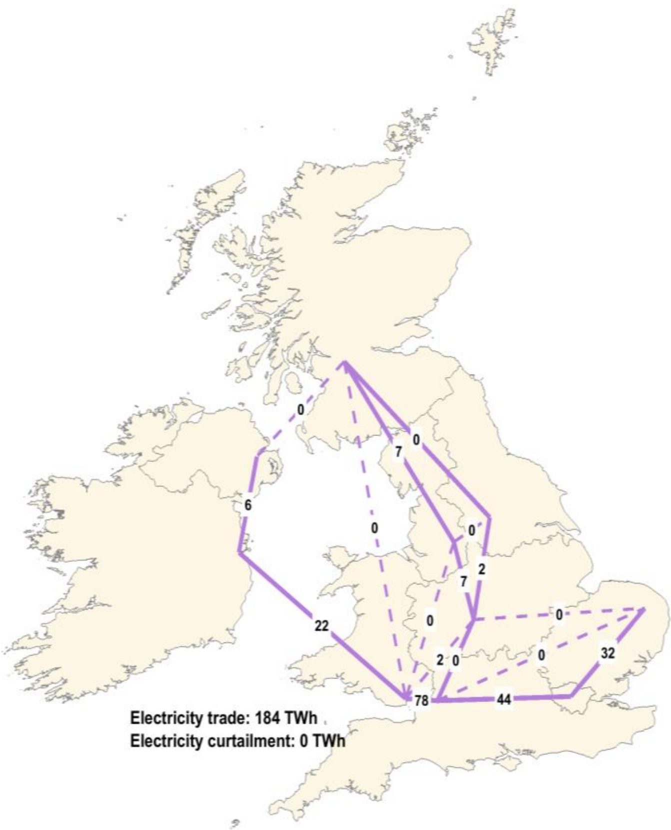


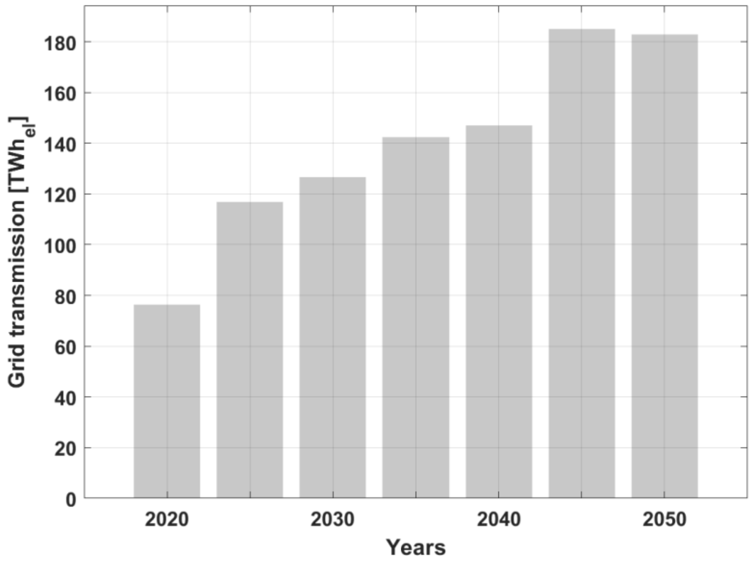
Key insights:

- Total electricity trade in 2050: 201 TWh
- Grid transmission imports rise sharply in the initial transition step, decrease slightly and increase then steadily until 2050
- Export from Scotland to the North West England increases, while export to North East decreases, compared to BPS
- London remains dependent on imports from neighbouring regions

CPS - Electricity Grid & Transmission

Annual imported and exported electricity (TWh)

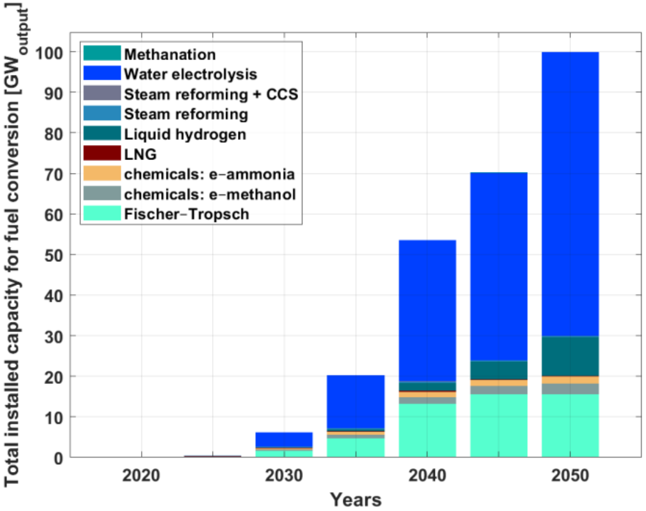


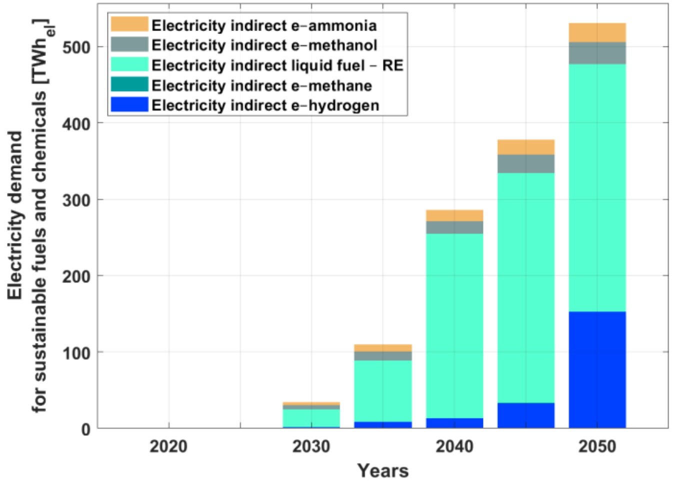


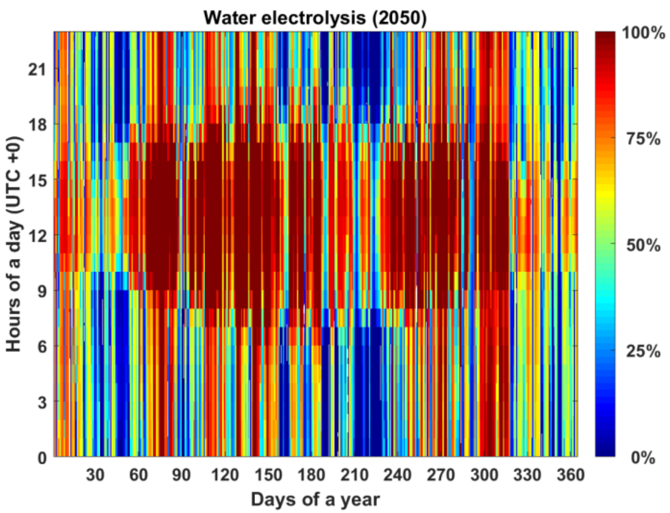
Key insights:

- Total electricity trade in 2050: 184 TWh
- Strong growth in 2025 while it grows evenly until 2045
- Exchange happens to London from surrounding regions
- Wales also works as a distribution center of electricity, having strong exhange with all neighbouring regions
- Southern England receives electricity from Wales, which is than partly supplying London

BPS - Sustainable Fuels and Chemicals



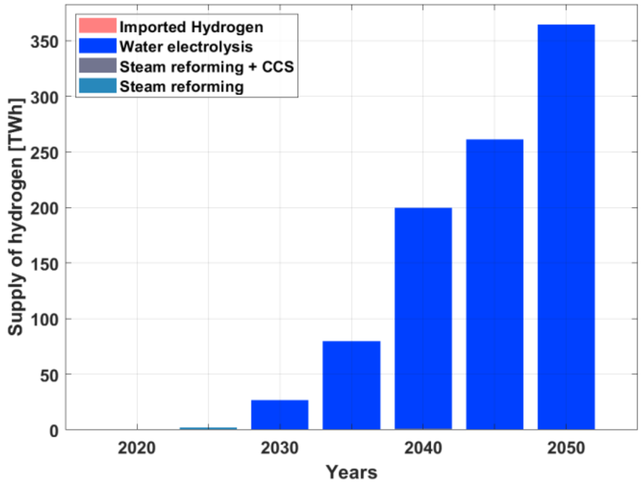


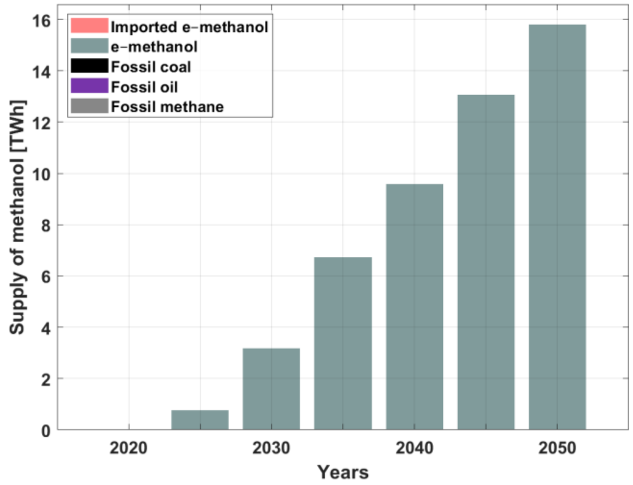


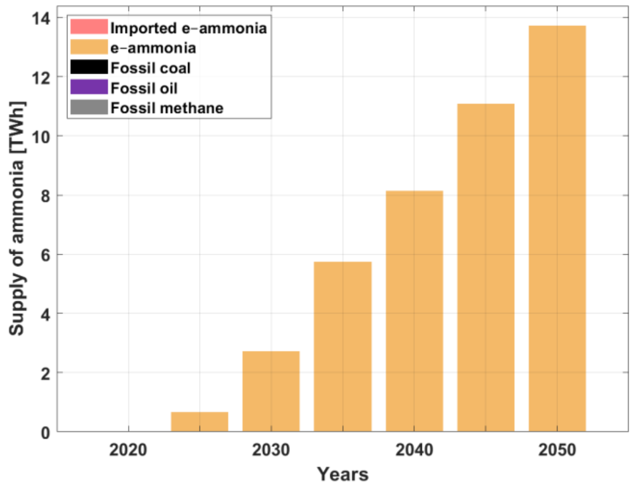
Key insights:

- Total electricity demand for fuel prodution and conversion: 531 TWh
- Sustainable fuels fully replace fossil fuels in sectors where energy services demand cannot be directly electrified
- Water electrolysis emerges as the main fuel production technology, reaching 70 GW_{output} of total 100 GW_{output}
- Water electrolysis contributes to system balancing, using surplus energy from renewables for H_2 production, preventing unnecessary curtailment
- Hydrogen plays a crucial role as a fuel and as chemical feedstock for the production of chemicals and liquid FT fuels
- Liquid fuels require most electricity: 324 TWh

BPS - Sustainable Fuels and Chemicals



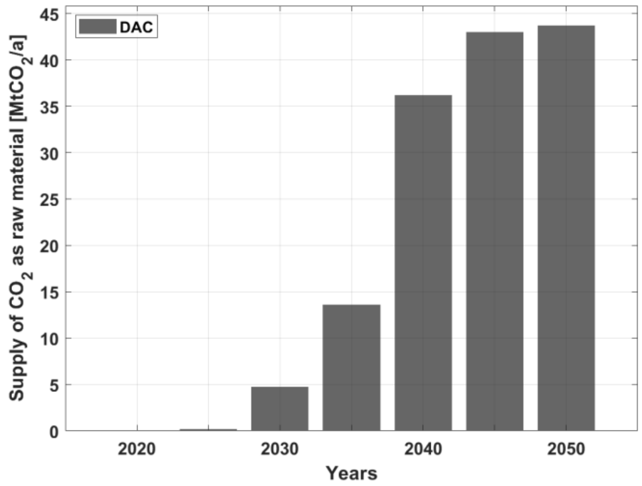


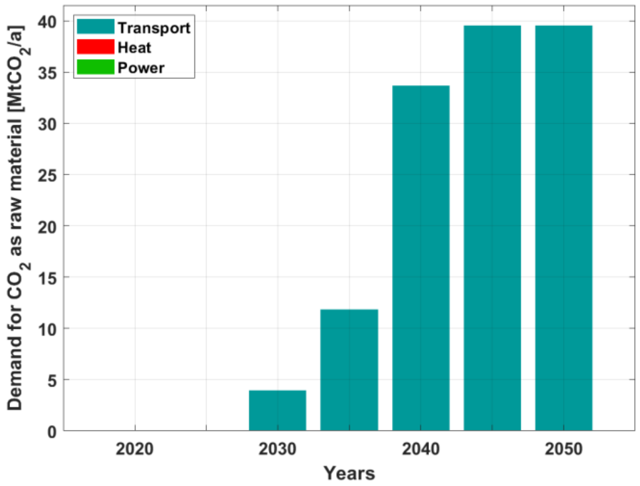


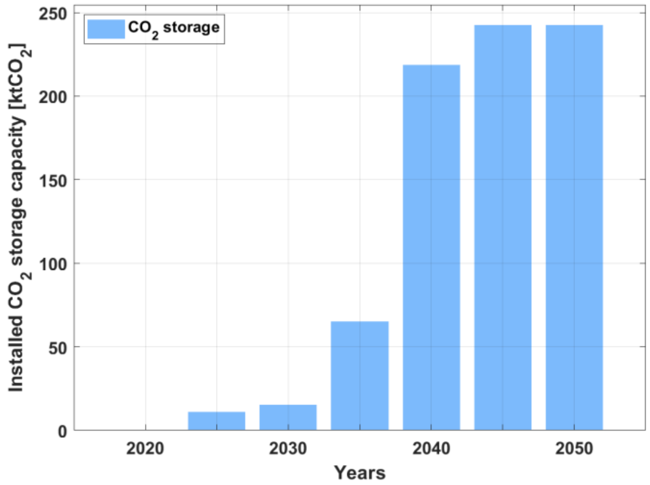
Key insights:

- Hydrogen emerges as the most important component of synthetically produced fuels, reaching 365 TWh
- e-methanol and e-ammonia become important as fuels for long-distance marine shipping, but with lower quantities: 14 TWh for ammonia and 16 TWh for methanol
- Shares of both would be higher if the industry sector is modelled in detail, as both are basic chemicals for the chemical industry (non-energetic use of fuels not part of the model)

BPS - CO_2 Production and CO_2 Storage





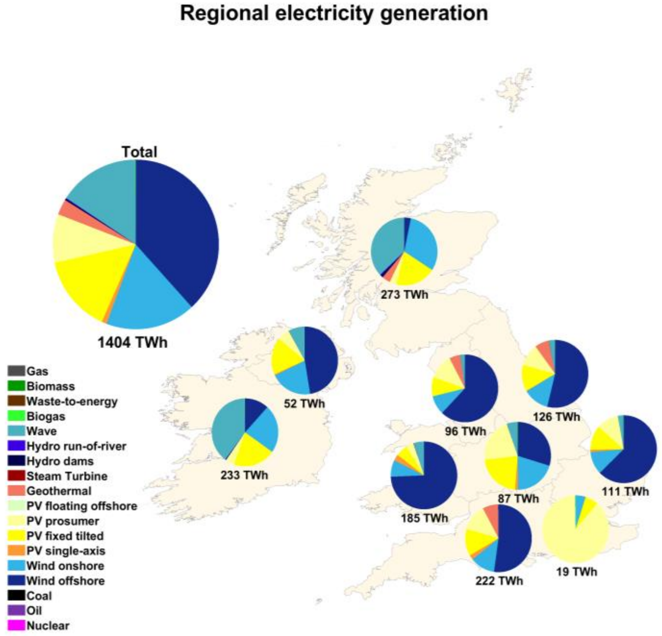


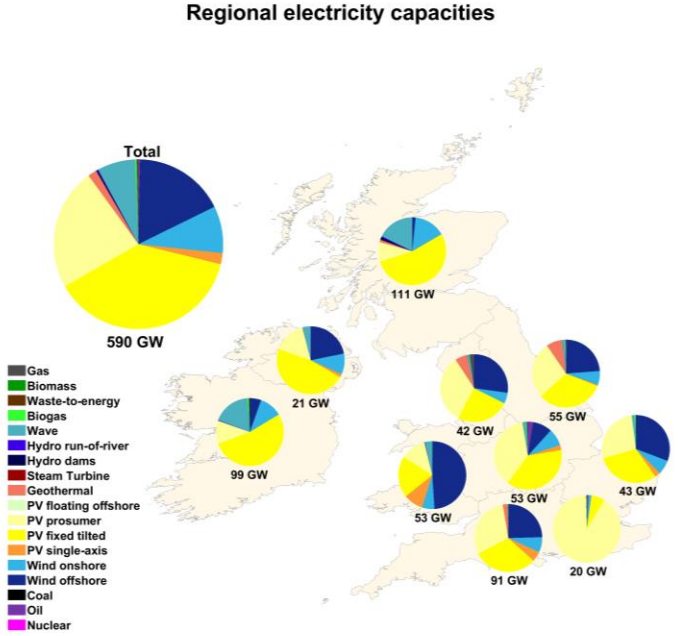
Key insights:

- Demand for CO_2 as a raw material grows significantly through the transition as it is necessary for the production of e-fuels
- CO_2 is captured by Direct Air Capture (DAC) with a strong rise in 2040 to 36 MtCO_2/a and finally to 44 MtCO_2/a
- The utilisation of DAC fully eliminates the necessity of fossil carbon capture and storage (CCS), enabling a 100% RE system
- All CO_2 is used for the transport sector for e-fuel production
- CO_2 storage increases proportional to CO_2 demand

BPS - Regional Analysis

Regional Electricity Generation





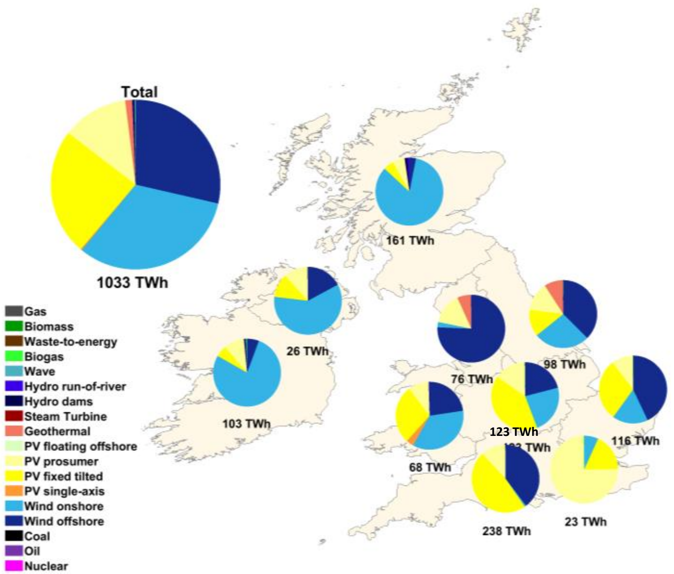
Key insights:

- Scotland generates most of the electricity, while London generates least
- Wave power and onshore wind play a crucial role for Scotland widely replacing offshore wind
- Offshore wind is the dominant resource in most regions: Wales has the highest share of offshore wind, followed by East of England and North West England
- Solar PV contributes a substancial share in all subregions, a large part from PV prosumers
- Signifcant amounts of solar PV capacity have to be installed, due to lower resource availability

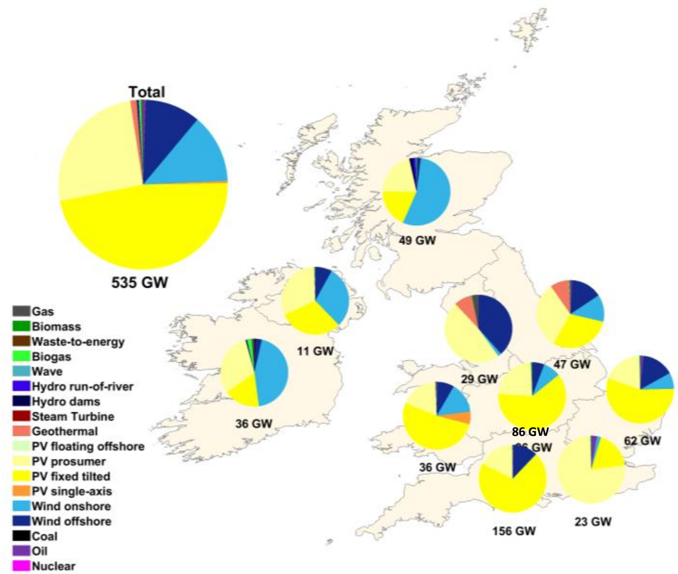
BPSplus - Regional Analysis

Regional Electricity Generation

Regional electricity generation



Regional electricity capacities

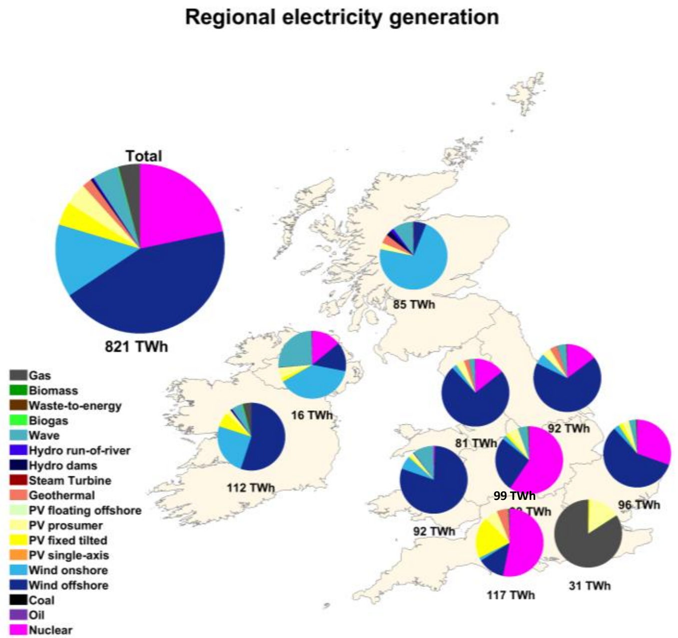


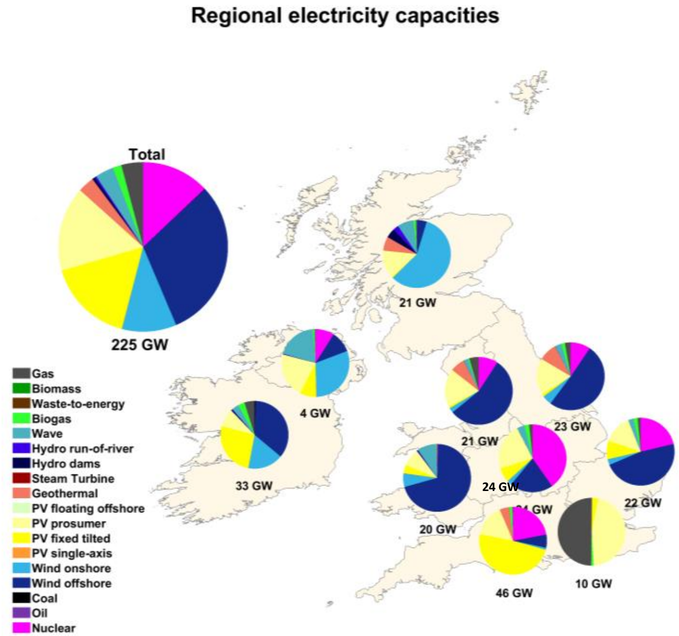
Key insights:

- Southern England generates most of the electricity, thereof more than 50% by solar PV
- Total electricity generation lower than in BPS, due to e-fuel imports
- Total electricity capacities only slightly lower than in BPS, due to significant capacities of solar PV
- Onshore wind as generation technology dominant in Scotland and Northern Ireland
- Offshore wind dominant in North West, and with high shares in East of England and Southern England
- London can only produce electricity from PV prosumers

CPS - Regional Analysis

Regional Electricity Generation



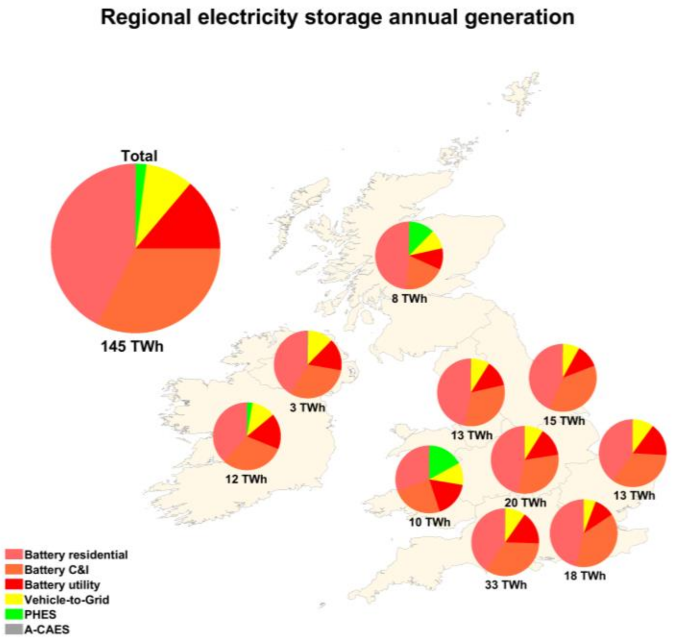


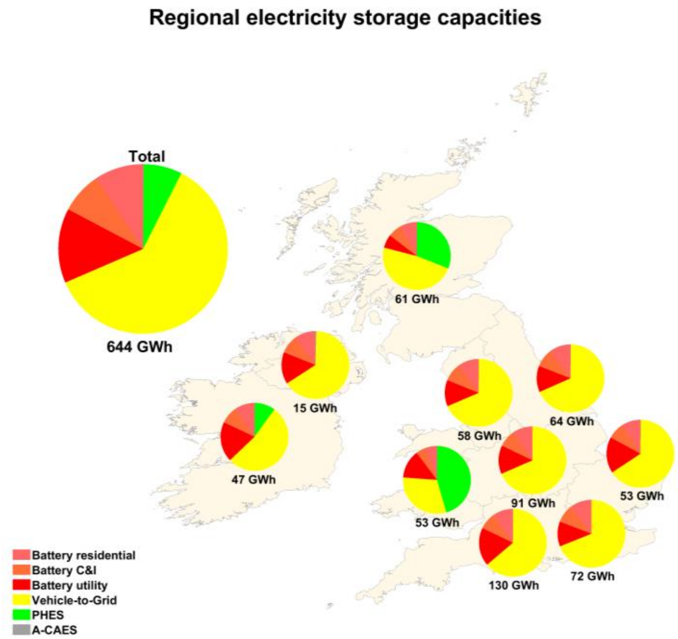
Key insights:

- Southern England generates most of the electricity, thereof more than 50% by nuclear power plants
- Other than in the BPS, the share of wave power is reduced in all regions and replaced by offshore wind and nuclear in most of the regions and by onshore wind in Scotland
- Offshore wind remains the most important source of electricity, reaching close to 50% of total electricity generation
- Southern England and the coast of Midlands become the centers of nuclear power, while Scotland does not rely on it

BPS - Regional Analysis

Regional Electricity Storage



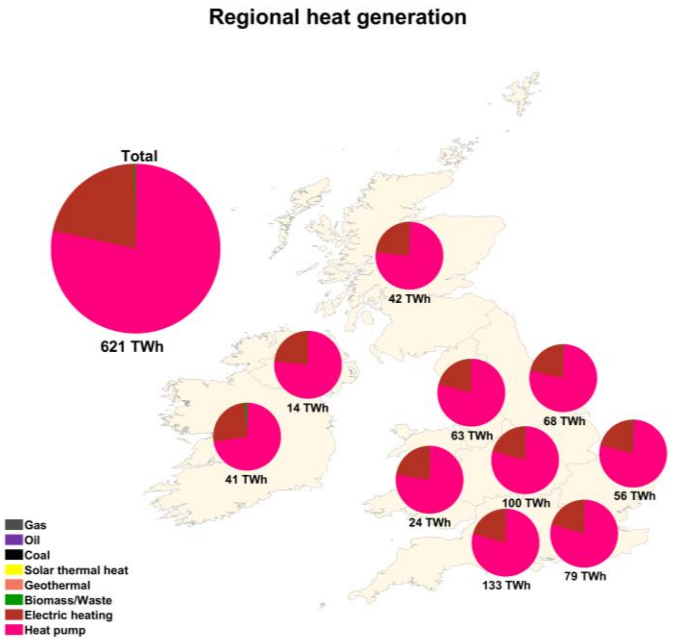


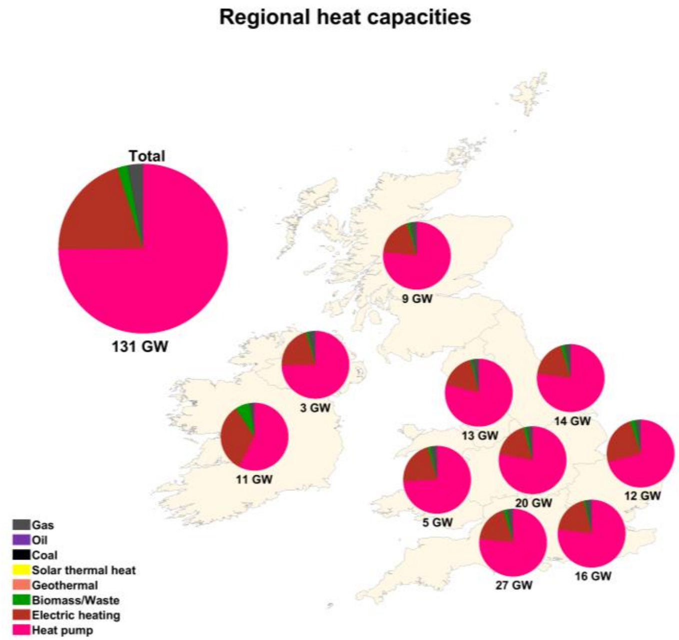
Key insights:

- The total electricity supply from storage is 145 TWh with the largest amount in Southern England
- Battery storage emerges as the key electricity storage technology in every region
- All regions apply significant amounts of battery storage: utility-scale and battery prosumers
- Battery storage and Vehicle-to-Grid are evenly distributed across all regions
- Vehicle-to-grid capacity is very high, but only a small share of electricity interacts with the system
- The regions, where the geographical conditions allow it, use PHES: Scotland and Wales

BPS - Regional Analysis

Regional Heat Generation





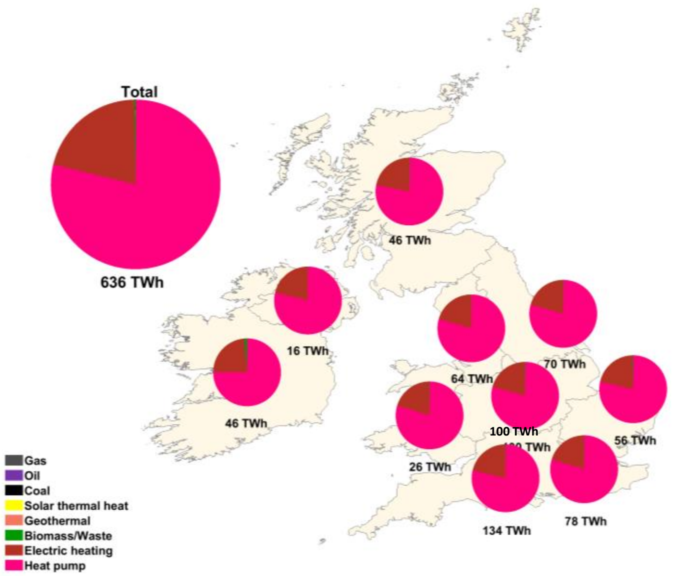
Key insights:

- Heat generation and installed heat capacities do not reveal any significant regional variations
- Heat pumps dominate in every region as they become the key heating technology
- Highest heat demand in Southern England, strongly linked to population
- The share of biomass (biogas) for heating differs slightly, with the highest share in Ireland where more biogas resources are available

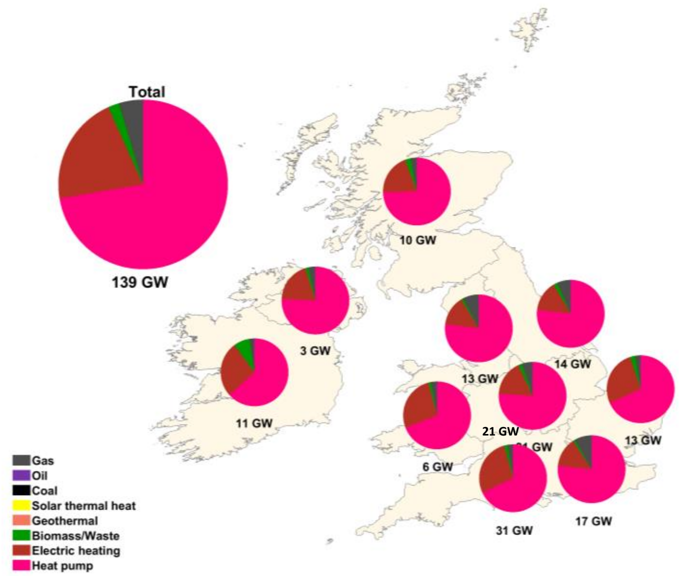
BPSplus - Regional Analysis

Regional Heat Generation

Regional heat generation



Regional heat capacities

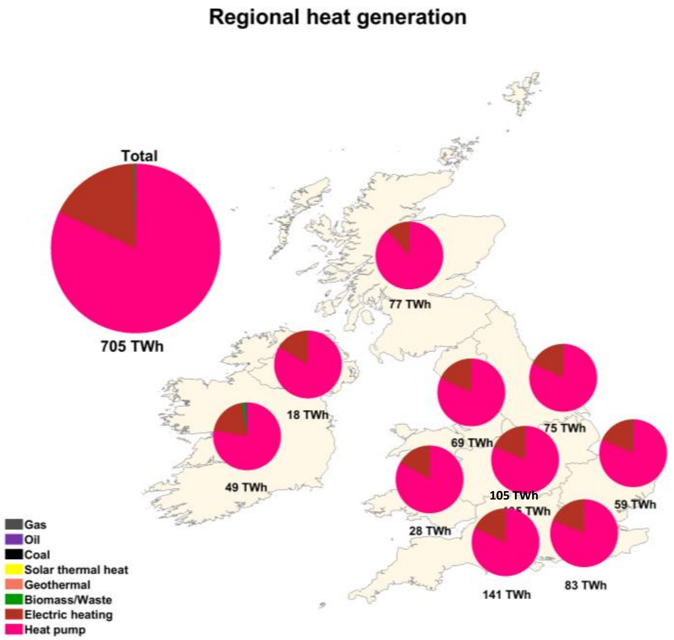


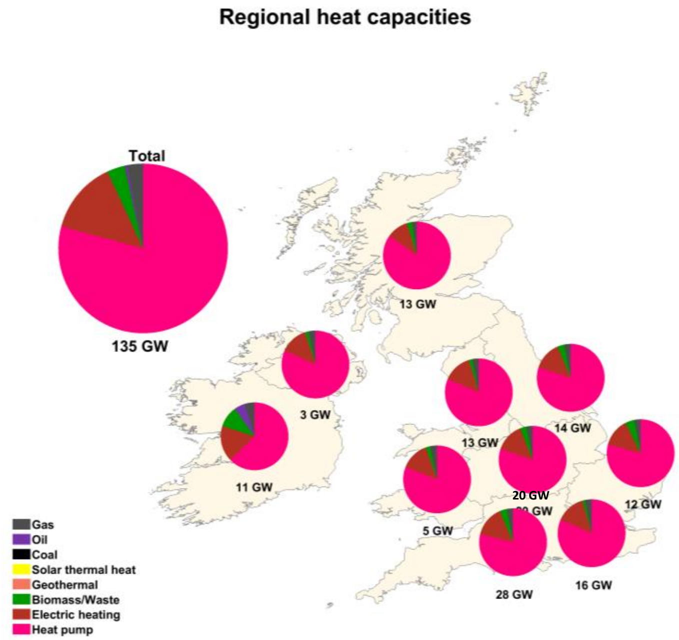
Key insights:

- Heat generation and installed heat capacities do not reveal any significant regional variations
- BPS, BPSplus and CPS results for the regional heat generation do not show significant discrepancies
- Compared to the BPS, a small share of (synthetic) gas is used for regional heat, leading to marginally higher heat capacities
- However, the major share of heat is generated by heat pumps, in all three scenarios

CPS - Regional Analysis

Regional Heat Generation



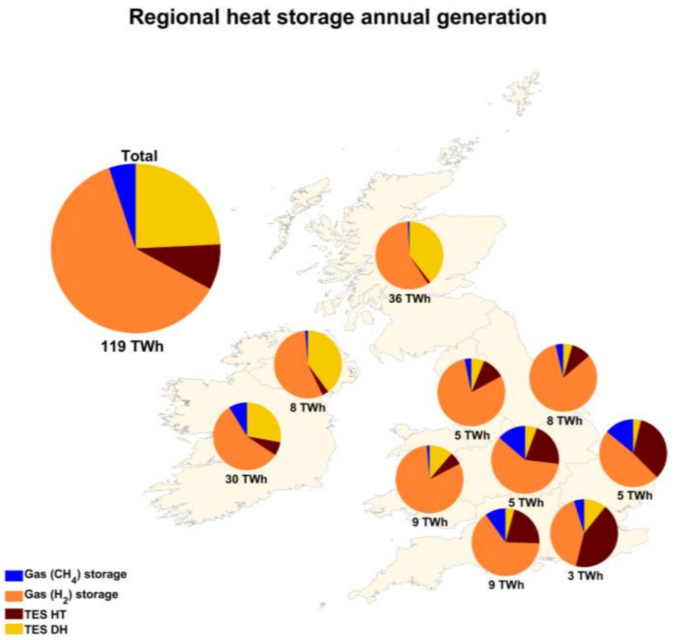


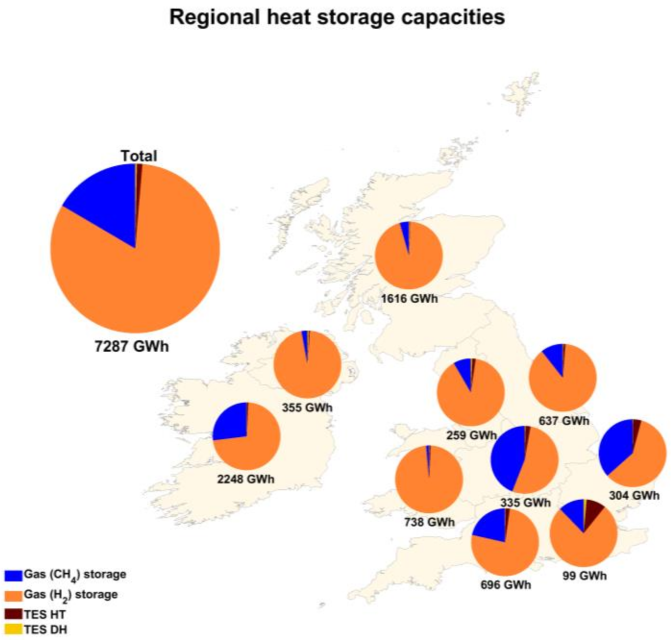
Key insights:

- Heat generation and installed heat capacities do not reveal any significant regional variations
- BPS and CPS results for the regional heat generation do not show significant discrepancies
- Compared to the BPS, a small share of heat generated from natual gas remains in the system
- However, the major share of heat is generated by heat pumps, in both scenarios
- Heat pumps contribute a slightly higher share than in the BPS, while direct electric heating has a slighly lower share

BPS - Regional Analysis

Regional Heat and Gas Storage

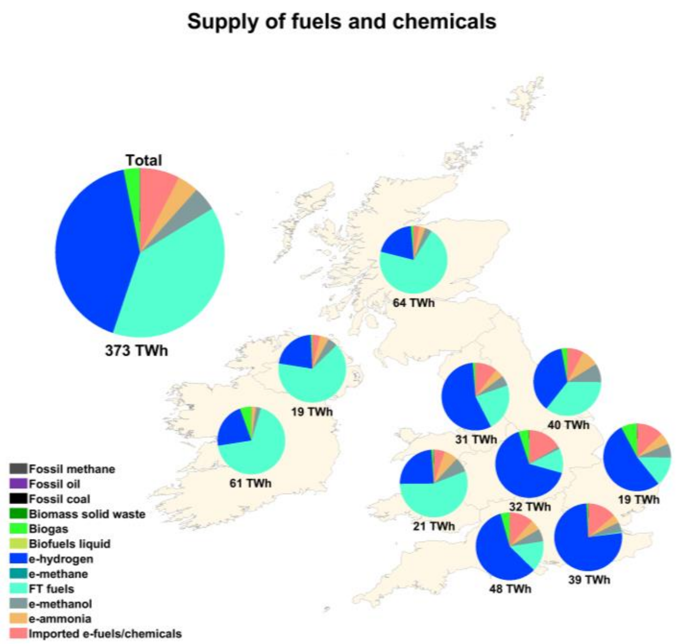


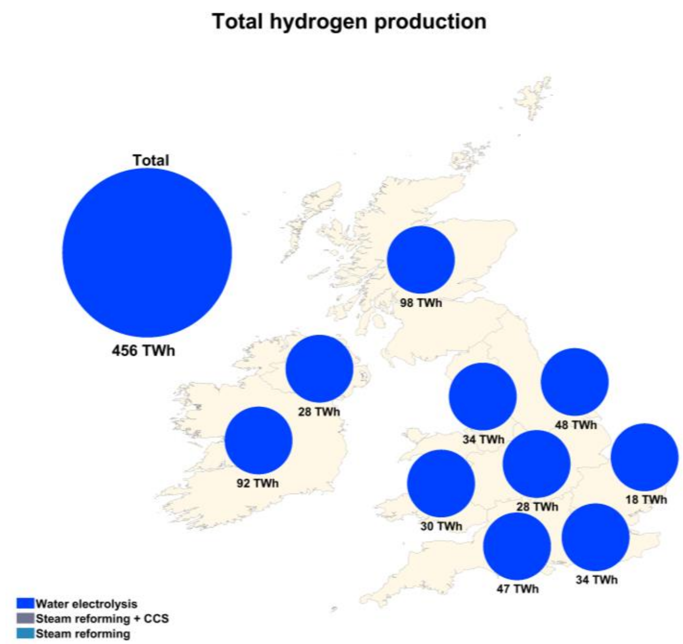


Key insights:

- In all regions, hydrogen contributes the highest share of heat and gas storage generation
- Scotland and Ireland offer the highest amount of heat storage
- In the South of England, including London, HT heat storage is applied due to high population density and therefore higher industrial heat demand
- District heat storage is rather used in Scotland, Northern Ireland and England

BPS - Regional Analysis
Supply of Fuels & Chemicals



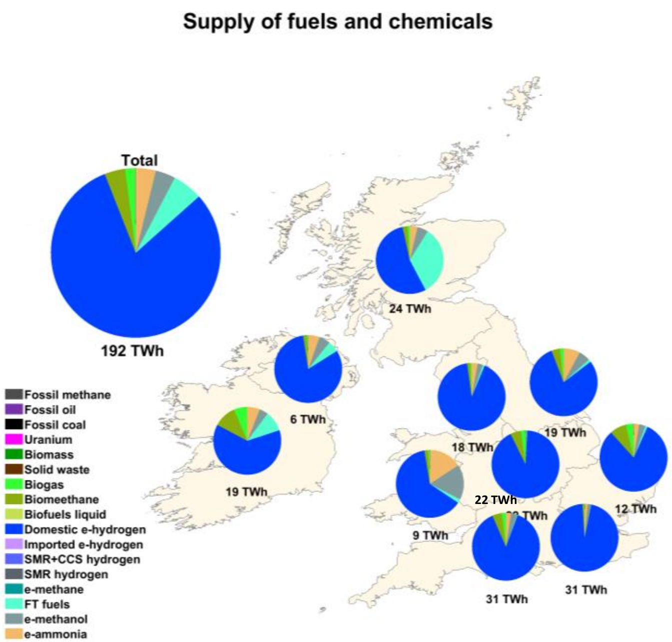


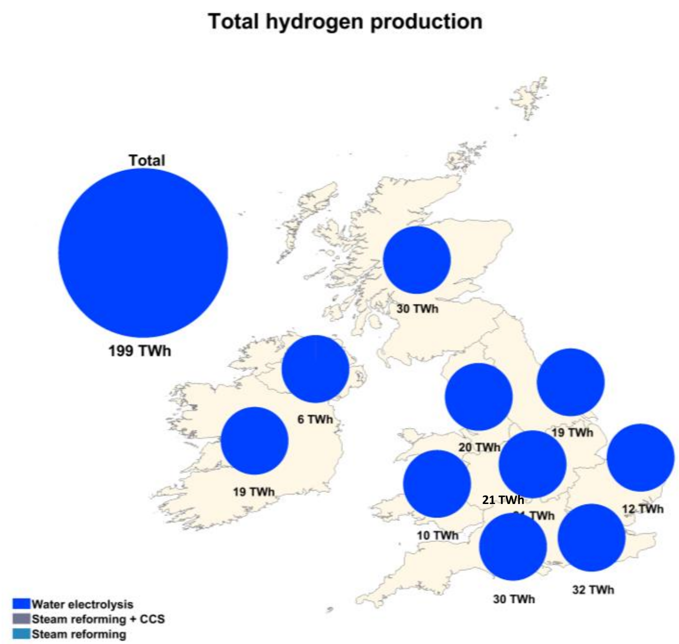
Key insights:

- **Scotland is the main hydrogen production center of the whole system with 98 TWh**
- **In total, hydrogen and FT fuels are the most important fuels**
- **Across all regions, a substantial amount of imported e-fuels can be found with major shares in the South and East of England**
- **Some regions use biogas, depending on resource availability, especially, East of England**

BPSplus - Regional Analysis

Supply of Fuels & Chemicals

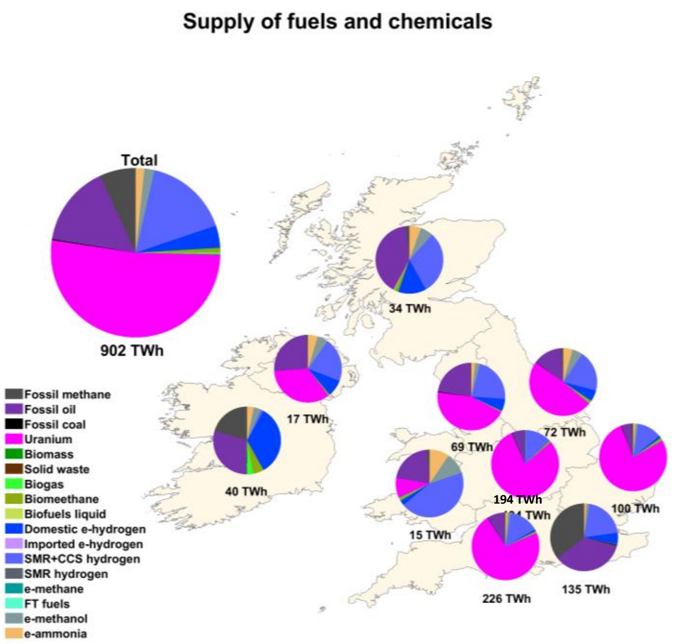


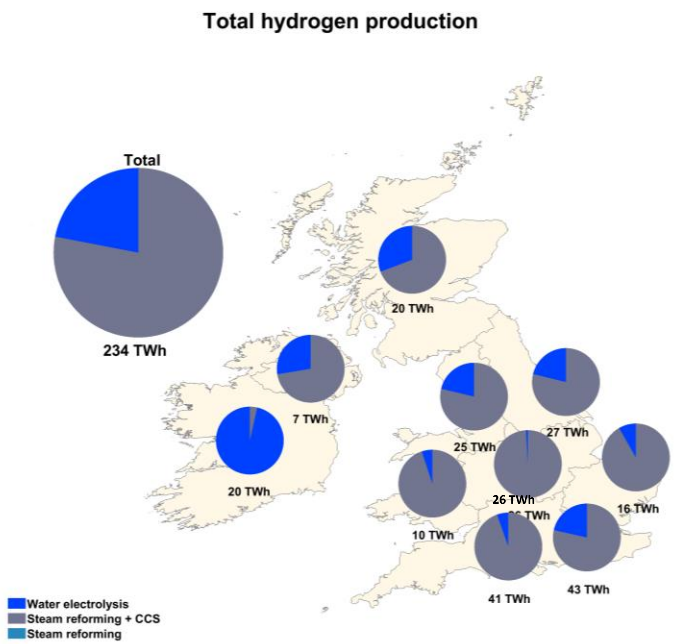


Key insights:

- Domestic e-hydrogen is the most important fuel, having a share of around 80%
- Total hydrogen production is roughly half of what is produced in the BPS and slightly less than in the CPS (where mostly fossil production routes were used)
- However, all hydrogen originates from water electrolysis and avoids utilisation of fossil fuels
- FT fuels are of less importance than in BPS, while the main production happens in Scotland
- Biogas and biomethane utilisation similar to BPS

CPS - Regional Analysis
Supply of Fuels & Chemicals



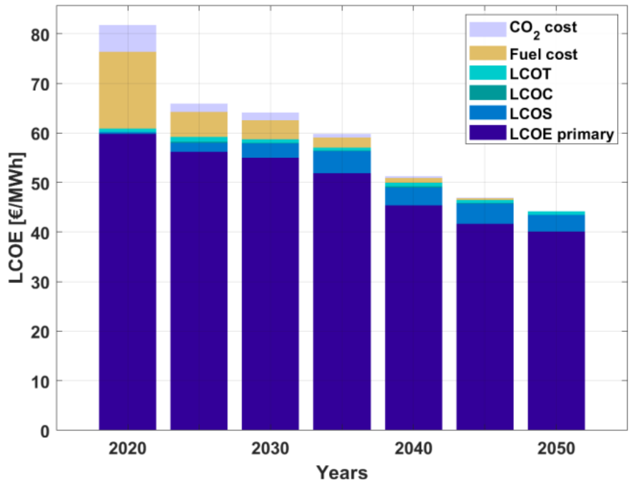


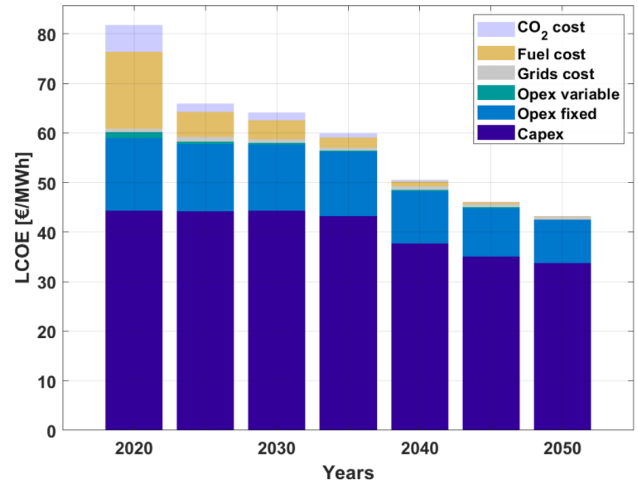
Key insights:

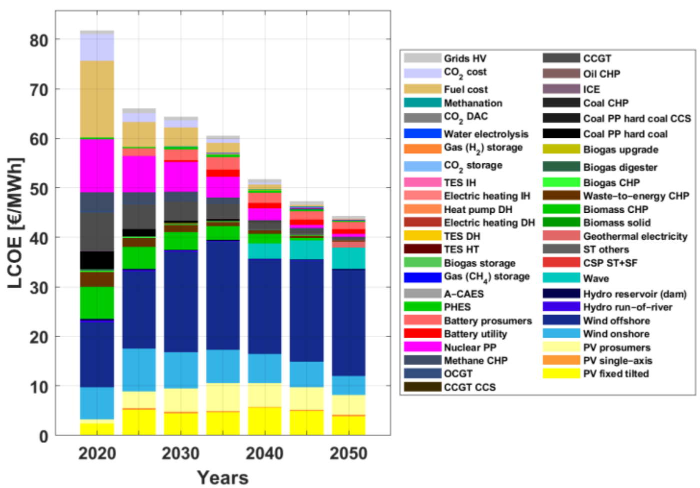
- Fossil gas, oil and coal as well as uranium continue to play an important role for the supply of fuels and chemcials
- Hydrogen, e-methanol and e-ammonia only work as a supplement to fossil fuels
- Total hydrogen production reaches half of what is produced in the BPS: 234 TWh compared to 456 TWh
- Hydrogen is mainly produced by steam methane reforming with CCS, instead of electrolysis
- Hydrogen production and composition of fuel supply does not vary greatly among the regions

BPS - Costs & Investment

Levelised Costs of Electricity





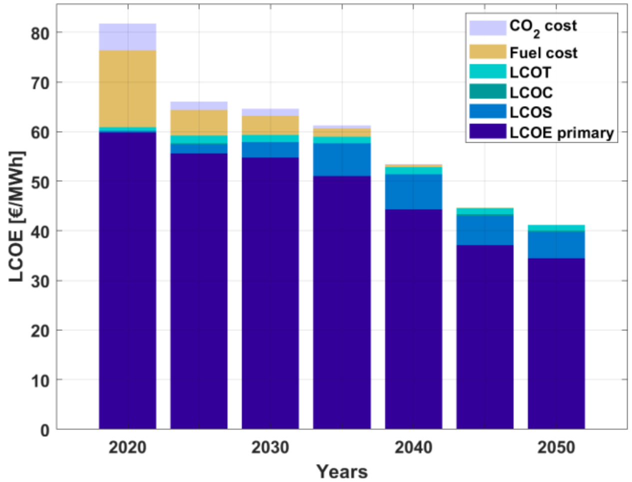


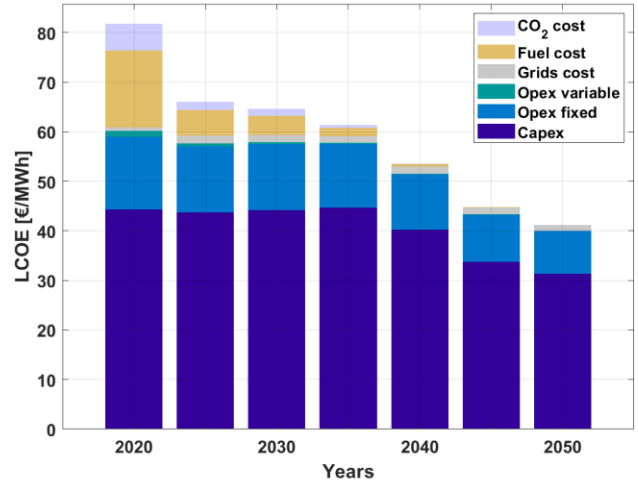
Key insights:

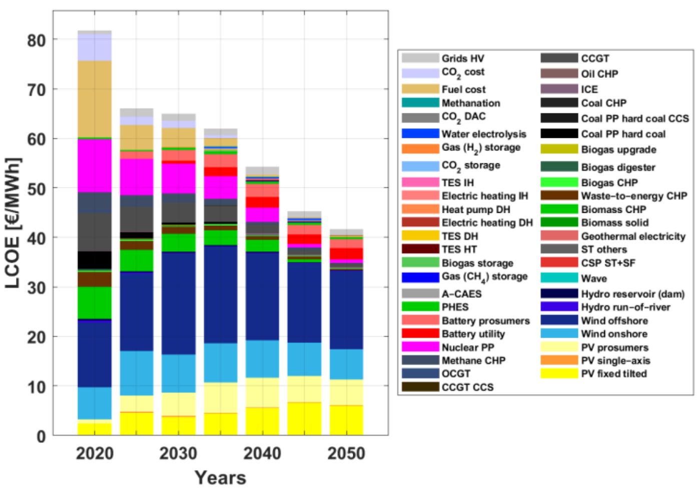
- LCOE decreases through the transition from 82 to 43 €/MWh while fuel costs are almost fully eliminated
- LCOE by type of system component: the by far largest share of LCOE in 2050 is from LCOE primary (40 €/MWh), smaller shares result from storage (LCOS) with 3 €/MWh and transmission (LCOT)
- LCOE by type of cost: largest share results from Capex with 34 €/MWh, followed by Opex fixed with 9 €/MWh
- LCOE by technology: largest share from offshore wind with 21 €/MWh, followed by onshore wind with 4 €/MWh

BPSplus - Costs & Investment

Levelised Costs of Electricity





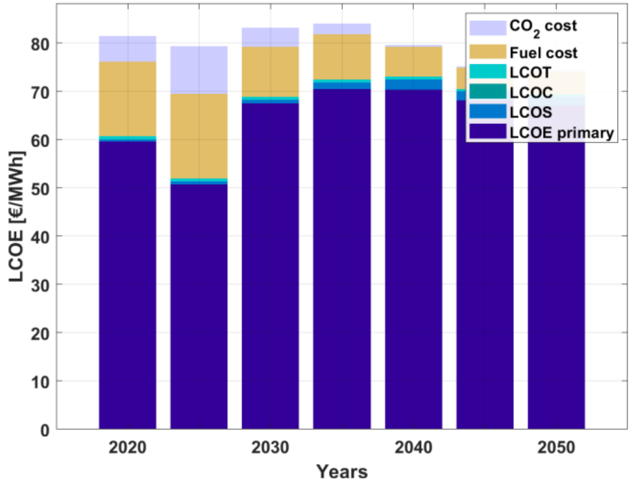


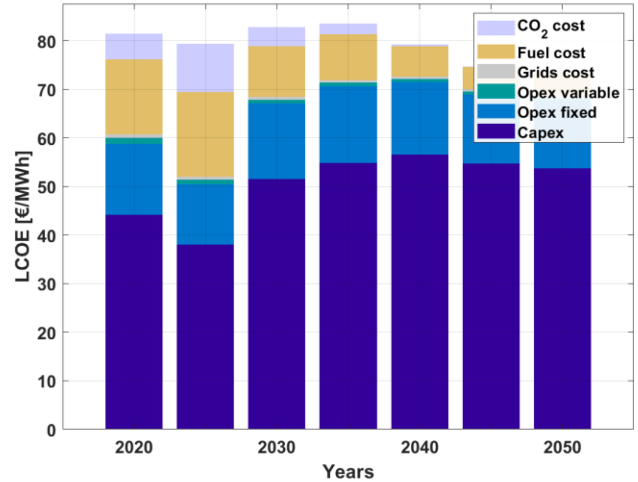
Key insights:

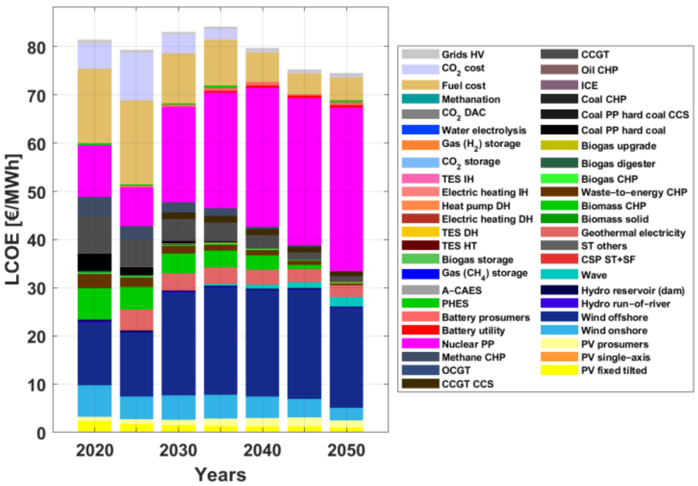
- LCOE shows a strong decline until 2050, reaching 41 €/MWh
- Across all scenarios, this is the least cost level
- Along the transition, the first decline happens in 2025, remains stable until 2035 and than declines steadily until 2050
- Main cost driver for LCOE remains offshore wind, similar to BPS
- Costs of wave power disappear, but are partly replaced by costs for utility-scale batteries

CPS - Costs & Investment

Levelised Costs of Electricity







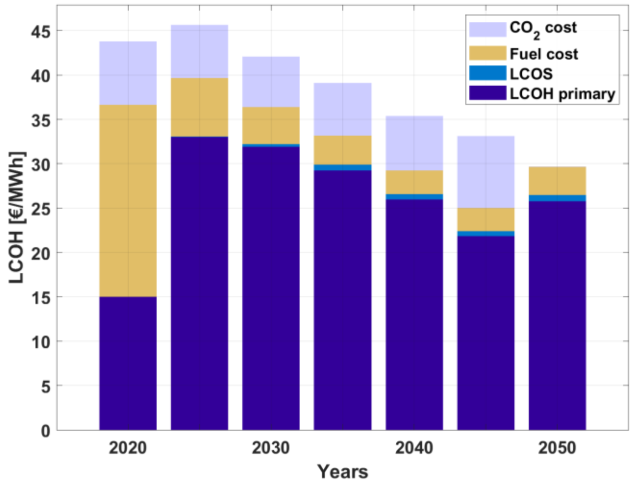
Key insights:

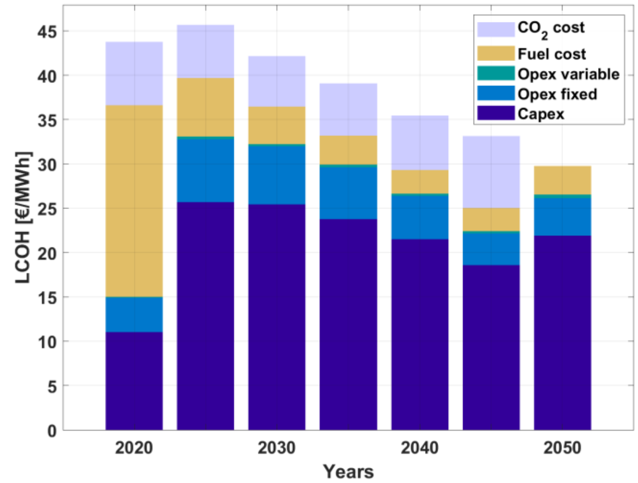
- LCOE decreases through the transition from 81 to 74 €/MWh while fuel costs are almost fully eliminated
- LCOE is shaped by high Capex, mainly from nuclear energy, which does not at all compensate the lower costs for energy storage
- Also, fixed Opex is higher than in the BPS
- Fuel costs for fossil electricity generation remain

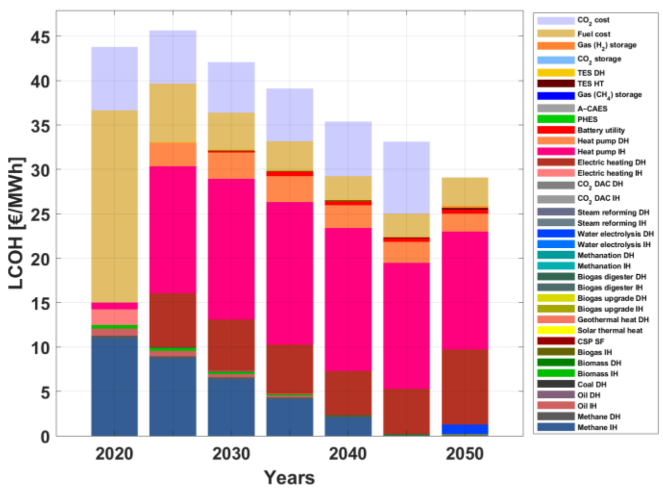
more information ► christian.breyer@lut.fi

BPS - Costs & Investment

Levelised Costs of Heat







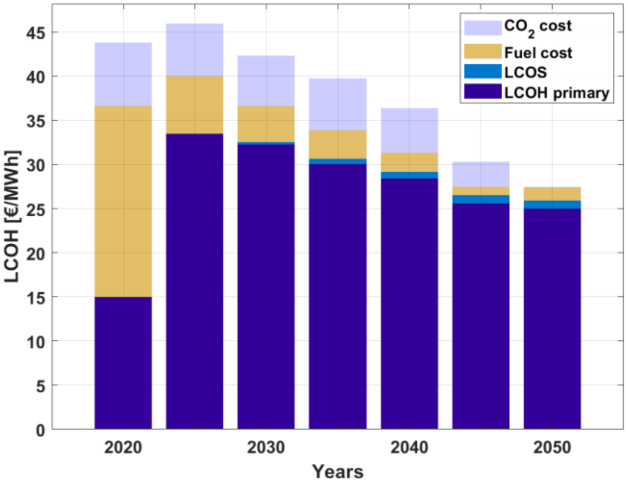
Key insights:

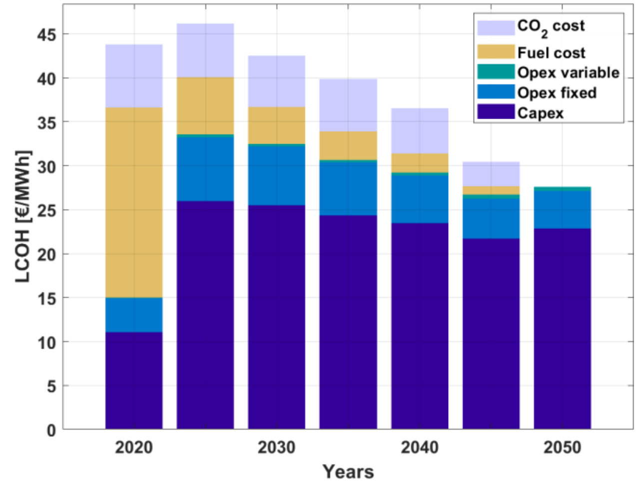
- LCOH decreases from 44 €/MWh to 30 €/MWh in 2050
- LCOH by type of system component: largest share from LCOH primary with 26 €/MWh with some fuel costs for imported fuels and storage costs
- LCOH by type of cost: largest share from Capex with 25 €/MWh, followed by Opex fixed with 4 €/MWh
- LCOH by technology: large shares from individual heat pumps with 16 €/MWh and electric heating with 8 €/MWh

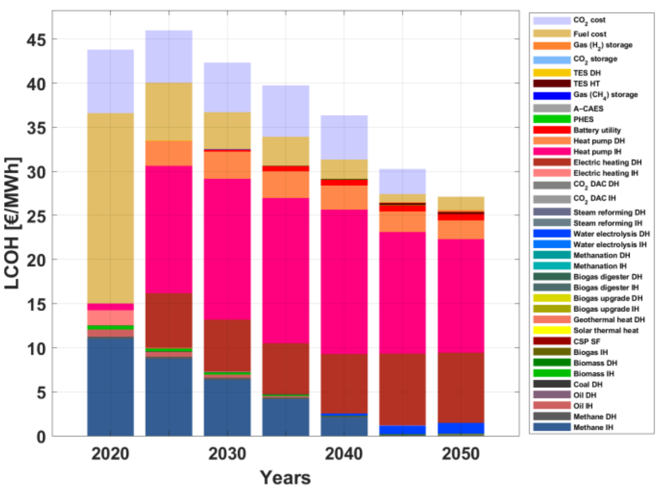
more information ► christian.breyer@lut.fi

BPSplus - Costs & Investment

Levelised Costs of Heat





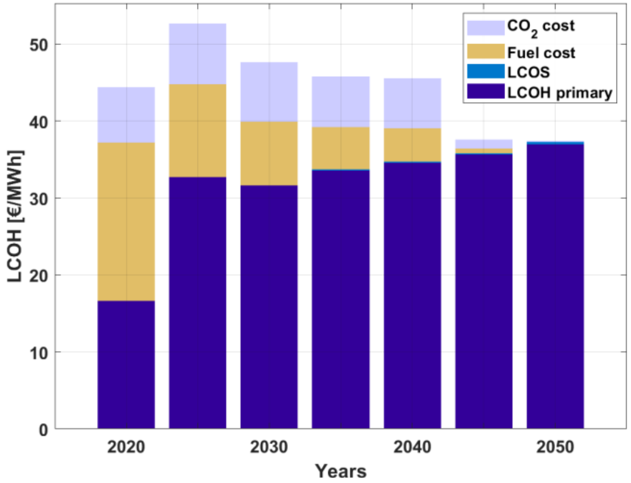


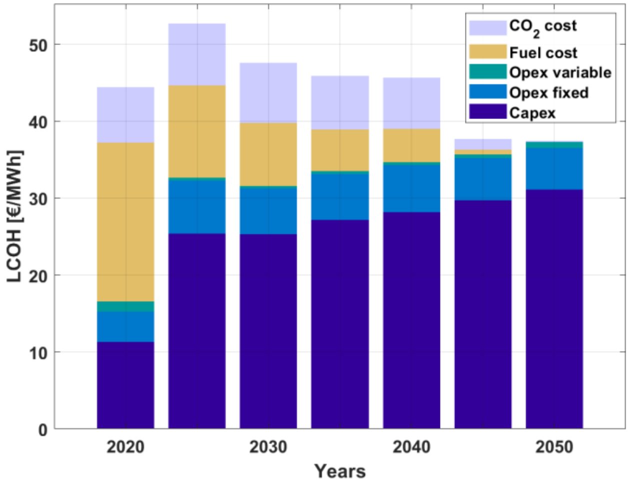
Key insights:

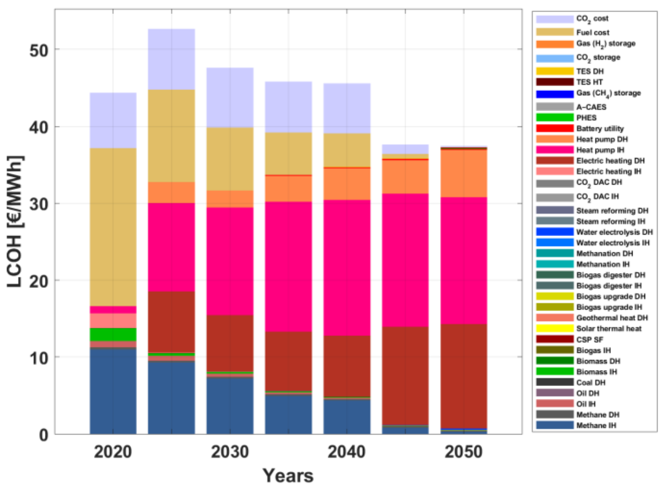
- LCOH decreases from 44 €/MWh in 2020 to 27 €/MWh in 2050
- Fuel costs are replaced by heat pumps and electric heating facilities
- Transition structure is comparable to BPS
- Across all scenarios, LCOH does not show extreme deviations
- LCOH is slightly lower than in BPS

CPS - Costs & Investment

Levelised Costs of Heat





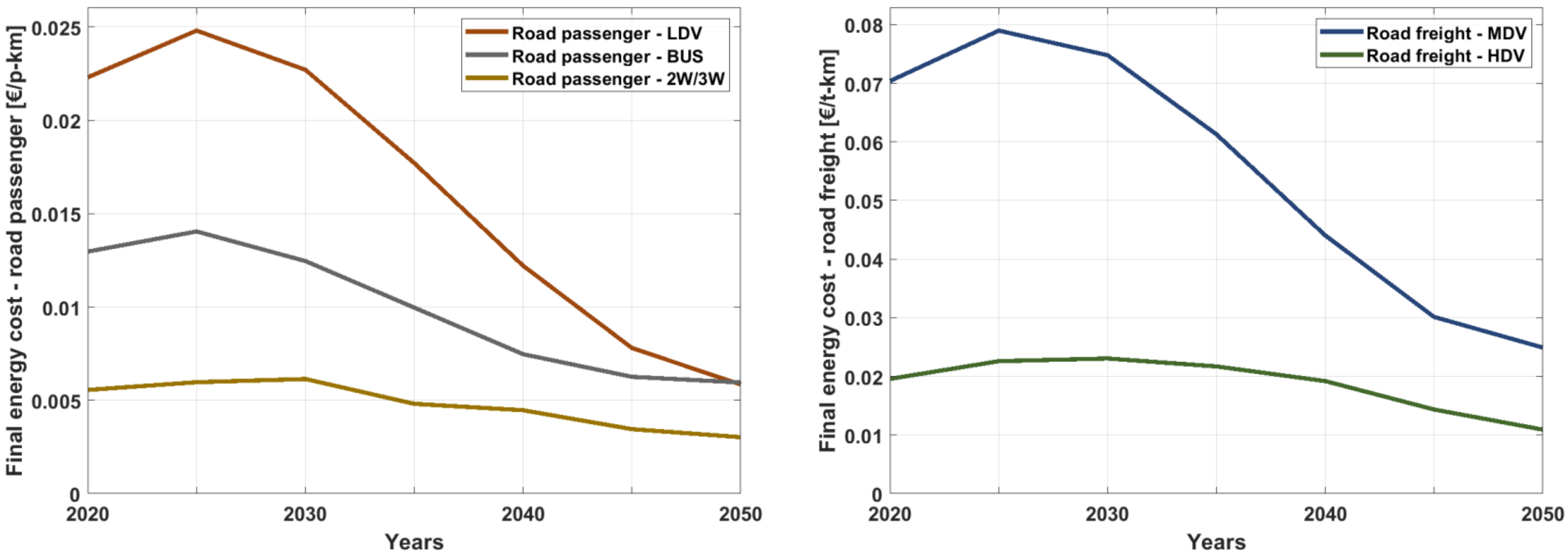


Key insights:

- LCOH decreases slightly from 44 €/MWh in 2020 to 37 €/MWh in 2050
- The LCOH for the CPS is higher than for BPS and BPSplus
- The LCOS is insignificant since not much heat storage capacity is installed in the CPS
- Capex and Opex are significant for the LCOH structure
- LCOH by technology is shaped by heat pumps and electric heating for individual and industrial applications

BPS - Costs & Investment

Transport Costs - Road

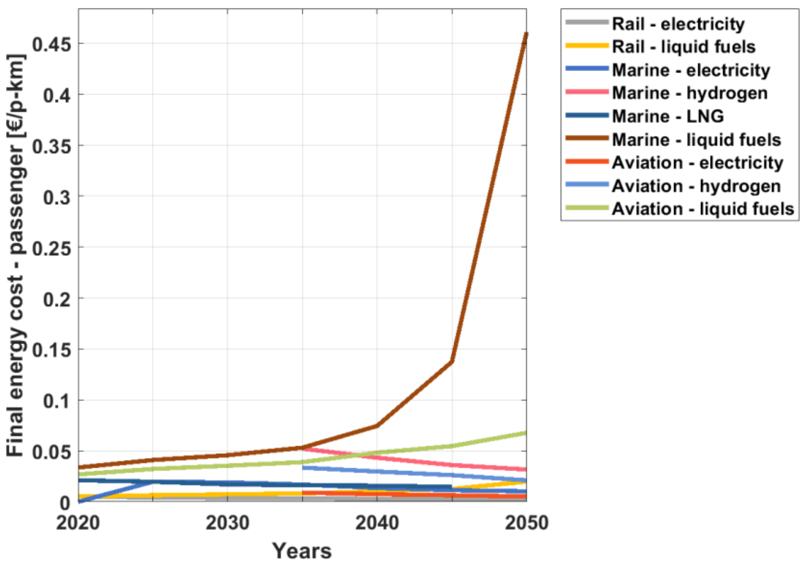


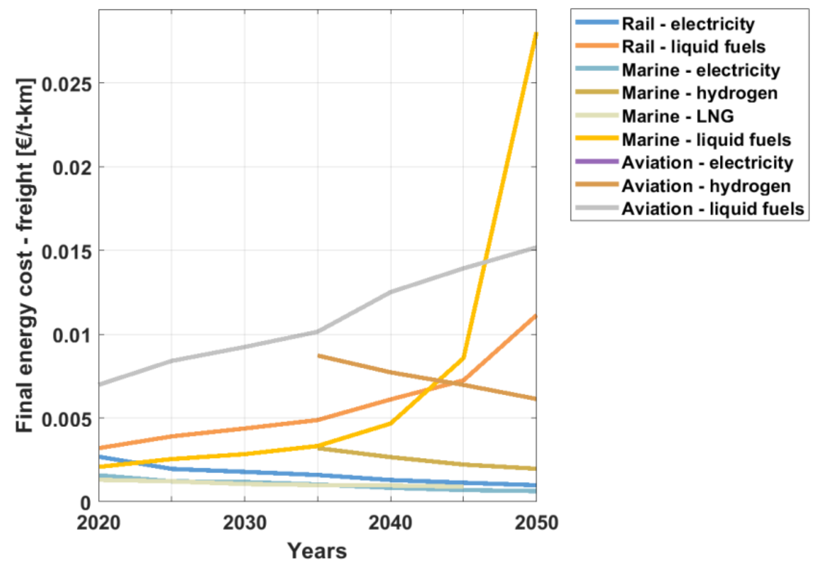
Key insights:

- Final energy costs for road transport decrease for all types of vehicles due to high shares of electrification
- Strongest decrease for light-duty vehicles (LDV), due to highest share of electrification
- Passenger transport: for all vehicles, the costs decrease below 0.01 €/p-km
- Freight transport: medium-duty vehicle (MDV) costs decrease significantly to below 0.03 €/t-km with higher shares of electrification than for heavy-duty vehicles

BPS - Costs & Investment

Transport Costs – Rail, Marine, Aviation



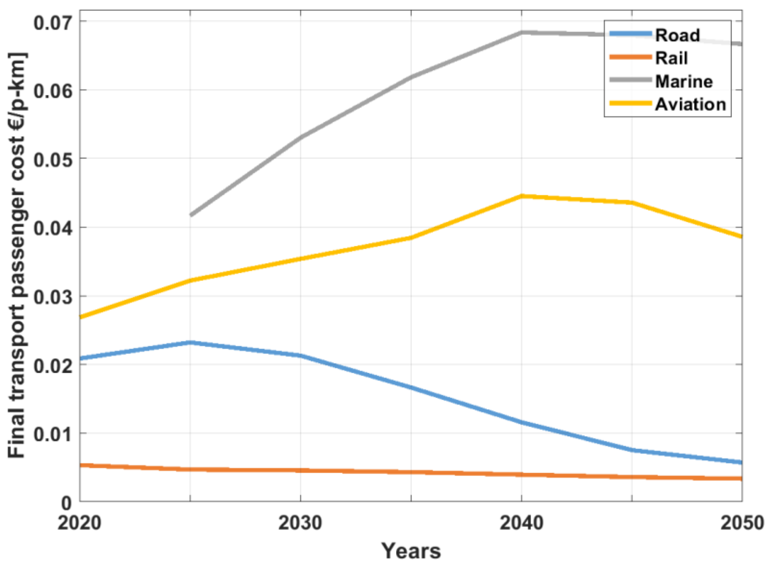


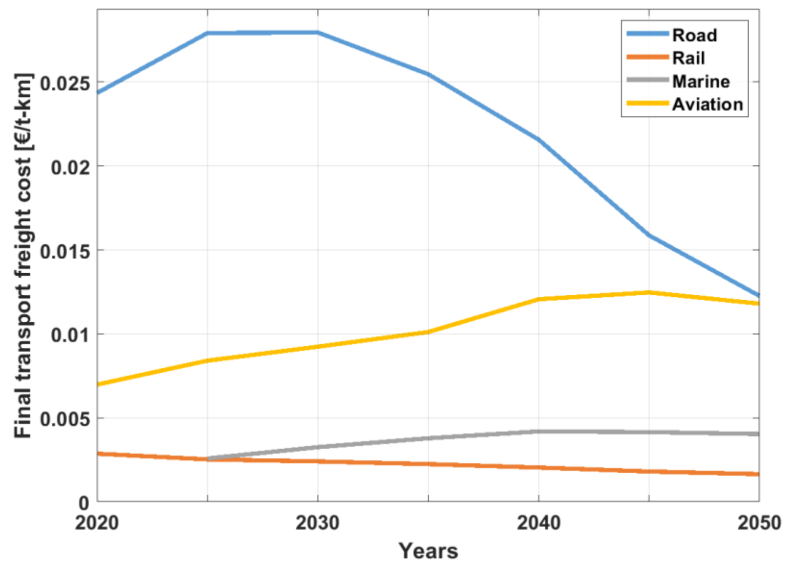
Key insights:

- Final energy costs for almost all modes of transport remain constant, with the exception of vehicles powered by liquid fuels (marine, aviation and rail)
- Liquid fuel production requires a susbstantially large amount of electricity, which increases overall costs
- Direct electrification should therefore be the prefered option, wherever possible, as it significantly reduces costs

BPS - Costs & Investment

Transport Costs

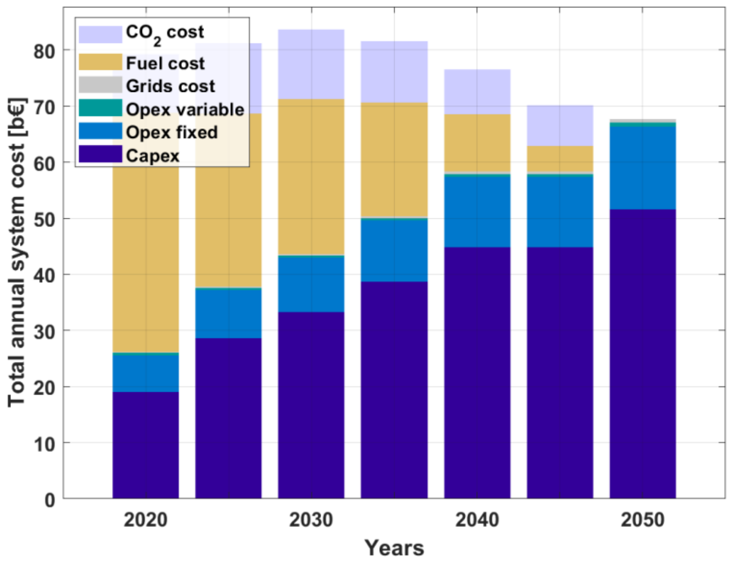


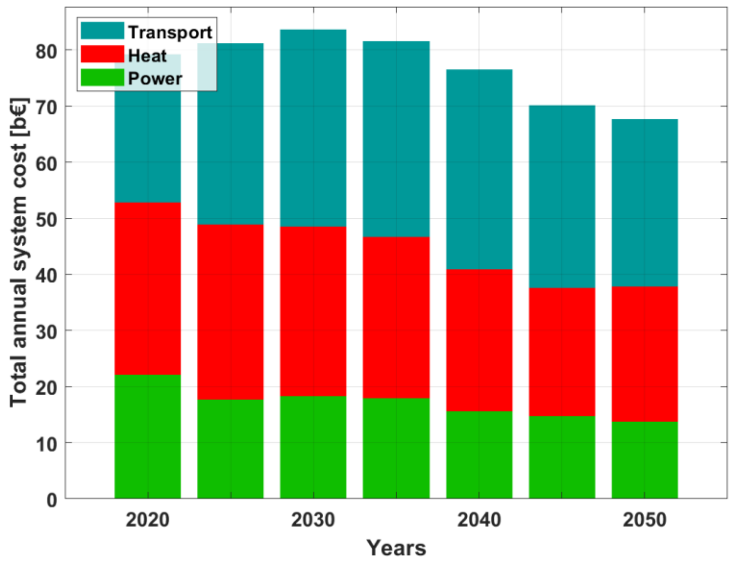


Key insights:

- If all modes of transport are compared to each other, the earlier derived findings can be seen
- Final road transport costs decrease due to highest share of electrification
- Final aviation and marine costs increase due to large utilisation of liquid fuels
- Final rail costs decrease only slightly, as liquid fuel costs are compensated by efficiency increases

BPS - Total Annual System Costs

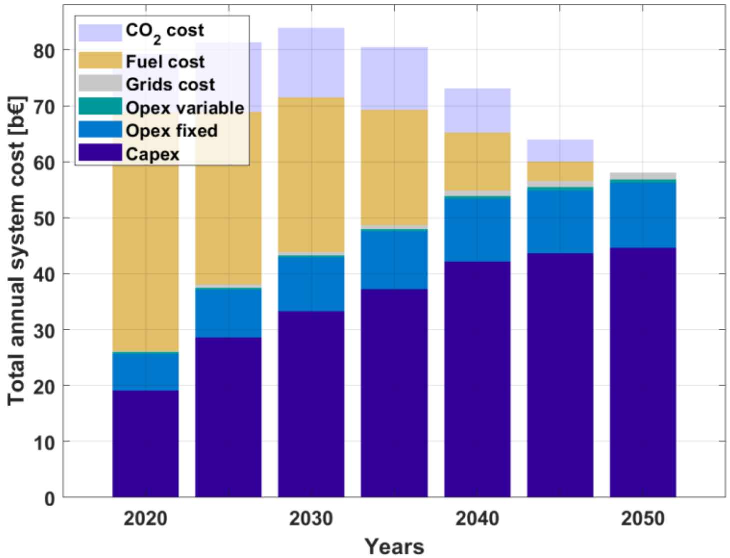


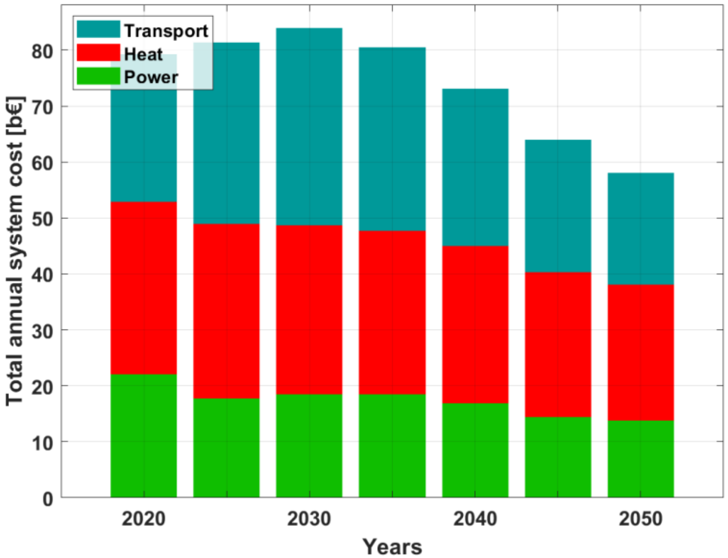


Key insights:

- In the energy system as of today, more than 50% of all costs arise from fossil fuel costs
- Total annual system costs decrease from 79 b€, reaching a maximum in 2030 with 84 b€
- Annualised capital expenditures in 2050: 52 b€, operational expenditures in 2050: 15 b€
- Highest share of costs by type of costs is due to Capex, followed by Opex fixed
- Highest share by sector originates from transport with 44% of total costs, followed by heat with 36% and power with 20% of total costs
- Growing Capex and Opex fixed are compensated by eliminated Fuel and CO_2 costs

BPSplus - Total Annual System Costs

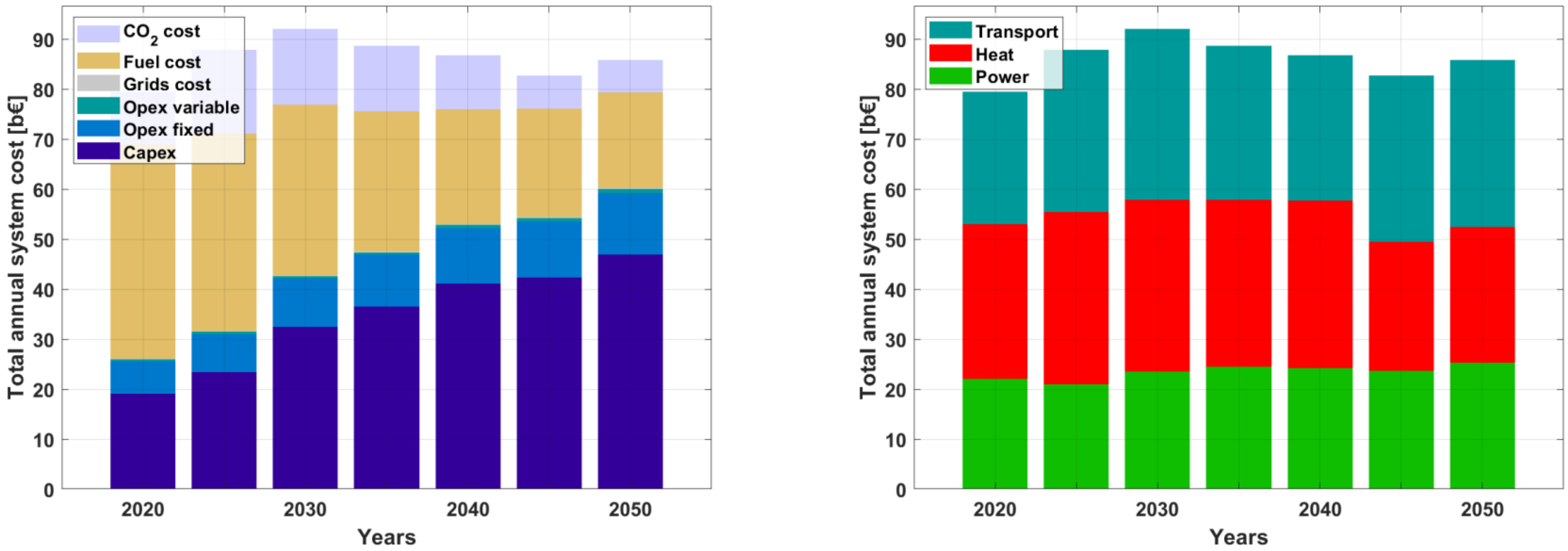




Key insights:

- BPSplus is the scenario with the least total annual costs: total costs are significantly lower in 2050, compared to BPS, reaching 58 b€
- Significant reduction can be observed for annualised capital and operational expenditures: 45 b€ and 12 b€
- The transport sector shows strongest cost change: from 26 b€ in 2020, to 35 b€ in 2030 costs can be reduced to 20 b€
- Costs for power and heat sector decrease as well but without increase in 2030
- Cost reduction happens due to low-cost renewable electricity generation and direct and indirect electrification of heat and transport, complemented by e-fuel imports

CPS - Total Annual System Costs



Key insights:

- Unlike in the BPS, fuel costs and CO_2 costs contribute a significant share of total annual system costs
- Total costs increase slightly to 86 b€, while reaching a maximum of 92 b€ in 2030
- The lower Capex and Opex are compensated by high fuel costs and remaining CO_2 costs
- CPS is significantly more expensive than BPS and BPSplus
- The power, heat and transport sector contribute (roughly) equally to the total annual system costs, with transport costs being highest

Summary

- Four scenarios were carried out with the goal of reaching zero CO_2 emissions in 2050, while all except the CPS aim for 100% renewable energy in 2050
- 100% RE scenarios are cost competitive with the CPS, if not significantly lower in cost
- Most scenarios rely on offshore wind as the most important source of renewable energy, as it was assumed that solar PV and onshore wind will be restricted in terms of available land area
- All scenarios show the vast deployment of energy storage technologies, while the scenarios with 100% renewables require a broad and well developed set of technologies
- One extra scenario (BPSplus) demonstrates that onshore wind and solar PV help to decrease the total costs significantly, as well as limiting the more costly offshore wind ramping
- One scenario was carried out, where the inter-annual wind variabilities were taken into consideration and balanced by inter-annual hydrogen or methane storage
- The CPS represents the governmental strategy that heavily relies on nuclear energy, reaching a share of 25% of total electricity generation in 2050
- The CPS is further not able to eliminate fossil fuels from the heat and transport sector, therefore it needs to rely on carbon dioxide removal options such DACCS but also fossil CCS
- Inter-annual storage together with several balancing mechanisms (extra wind generation, extra e-fuel production capacity, underground storage, reconversion capacity, …) increases the total system costs, but is still competitive with the CPS
- Inter-annual storage requirements should be investigated further, to examine possible cost reduction opportunities such as e-fuel import or a smaller design of the inter-annual storage
- The overall findings substantiate that a 100% renewable energy system brings several advantages to the energy system, being able to reach zero CO_2 emissions

Abbreviations

- 2W/3W – two and three-wheelers
- A-CAES – Adiabatic compressed air energy storage
- BEV – Battery electric vehicle
- BPS – Best Policy Scenario
- b€ - billion Euro
- Capex – Capital expenditures
- CCGT – Combined cycle gas turbine
- CCS – Carbon capture and storage
- CHP – Combined heat and power
- CPS – Current Policy Scenario
- CSP – Concentrating Solar Thermal Power
- C&I – Commercial & Industrial
- DACCS – Direct air carbon capture and storage
- DH – District heating
- e-Fuel – Electricity-based fuel
- FCEV – Fuel cell electric vehicle
- FLh – Full load hours
- FT – Fischer-Tropsch
- GDP – Gross domestic product
- GHG – Greenhouse gas
- GW - Gigawatt
- GT – Gas turbines
- $GtCO_{2eq}$ – Gigatonne CO_2 equivalent
- HDV – Heavy duty vehicle
- HT – High temperature
- HVAC – High voltage alternating current
- HVDC – High voltage direct current
- IAS – Inter-Annual Storage
- ICE – Internal combustion engine
- IEA – International Energy Agency
- IH – Individual heating
- Ind – Industry
- LDV – Light duty vehicle
- LCOS – Levelised Cost of Storage
- LCOE – Levelised Cost of Electricity
- LCOH – Levelised Cost of Heat
- LCOT – Levelised Cost of Transmission
- LNG – Liquified natural gas
- LT – Low temperature
- MDV – Medium duty vehicle
- Mil p-km – Million passenger kilometres
- Mil t-km – Million tonne-kilometres
- MT – medium temperature
- $MtCO_2$ – Megatonne CO_2
- MWh – Megawatt-hours
- Opex – Operational expenditures
- RE – Renewable Energy
- RoR – Run-of-river
- OCGT – Open cycle gas turbine
- PHES – Pumped Hydro Energy Storage
- PHEV – Plugin hybrid electric vehicle
- PP – Power plant
- PtH – Power-to-Heat
- PtX – Power-to-X
- PV – Photovoltaics
- RES – residential
- SoC – State-of-charge
- ST – Steam Turbines
- TES – Thermal energy storage
- TWh – Terrawatt-hours
- UK – United Kingdom
- UTC – Coordinated universal time
- V2G – Vehicle-to-Grid