Decarbonisation Speedways

Final report
June 20, 2023

Preface by Kristian

The introduction of the 'Fit for 55' package has significantly raised the decarbonisation ambition for Europe, and with that, the need for faster progress in decarbonising end use and the power system. Eurelectric and its members aim to be firmly positioned in Brussels policy circles as respected and critical partner in Europe's decarbonisation agenda. A sound and up-to-date scenario study on accelerated decarbonisation pathways is critical to achieve this.

In this study, we aim to provide insight into applying the accelerated decarbonisation ambition of the economy and power sector to the current reality of the power sector. Alternative scenarios towards full decarbonisation are provided, with key milestones in 2030, 2040 and 2050, accounting for high electrification expectations and growing focus on sector integration, as well as the uncertainty resulting from ongoing geopolitical tensions and supply pressures.

This study relies on the collaboration with dedicated industry professionals in the European power sector. Many experts contributed actively by providing input and reviews of both the report and the underlying demand framework.

We hope that this report will contribute to the decision making in a rapidly changing environment.

Kristian Ruby

Secretary General
Eurelectric

Overview

The Decarbonisation Speedways study focuses on decarbonisation pathways for the European energy sector. The study primarily concentrates on achieving decarbonisation through direct electrification. By examining the potential of electrification across three main sectors and 10 corresponding subsectors, the study's analysis aims to identify effective paths for realizing full energy sector decarbonisation in the EU27 countries and the United Kingdom by 2050.

The data analysis process comprised two distinct phases. In the first phase, we meticulously assessed the demand side, utilizing the existing Ten-Year Network Development Plan (TYNDP) scenario as our basis. We further refined this scenario by incorporating industry experts' input, conducting extensive literature research, and integrating the EU Fit for 55 and REPowerEU policy packages. This approach allowed us to create a robust, comprehensive framework for analysing the energy requirements of the different sectors represented in the study, including industry, built environment and mobility.

Building on the insights gained from the demand-side analysis, the second phase involved modelling the generation side using the Maon (Model for Assessing and Optimizing the National Power System) model. This advanced modelling tool enabled us to simulate the electricity generation and integration based on the demand patterns identified in the first phase. This way, the feasibility and implications of different generation options for each scenario were assessed, ultimately leading to the most viable paths for achieving full decarbonisation.

The combined findings from our demand-side analysis and the Maon modelling provide valuable insights into the potential strategies and challenges involved in the transition to a decarbonised energy system in Europe.

Role of Accenture

In support of the Decarbonisation Speedways study, Accenture was the knowledge partner and performed the data analysis and modelling efforts in collaboration with Maon. On the basis of Accenture's expertise and data-driven insights, Eurelectric and its experts provided a political dimension to this analysis, transforming the research findings into a solid foundation for informed decision-making processes in the pursuit of decarbonisation objectives. Any policy references or recommendations included in this study are those of Eurelectric and do not reflect the opinions or views of Accenture.

Executive summary

A decarbonised energy system in Europe in 2050 is possible if we act now:

- With the **FF55-inspired** and **REPowerEU-inspired** scenarios achieving net zero emissions in 2050, and **Radical Action** scenario even in 2040.
- Taking **clean direct electrification** as the main driver for efficient and effective decarbonisation, almost eliminating fossil fuels in buildings, transport and industry
- **Using hydrogen** where it is most effective, under certain ramifications only
- **Acknowledging** that different countries have different starting points in the transition, requiring tailored transition pathways
- Fostering **adoption** of the key technologies per sector: heat pumps in buildings, electric engines in transport and e-boilers and industrial heat pumps in industries
- Offering **flexibility** to the power system to provide security of supply and resilience via demand side response and storage options
- **Investing** in the strengthening and digitisation of distribution & transmission power grid and in new clean generation capacities
- **Collaborating** on market design fit for purpose, improved financing frameworks, grid reinforcements & digitisation, faster permitting & spatial planning, focus on skills & training and a cohesive industrial policy
- Keeping in mind that the benefits of a decarbonised energy system **outweigh the associated costs,** taking into account the long-term effects of climate change

58% - 71%

Share of electricity in final energy demand in 2050 in the defined scenarios

66% - 93%

Growth of final electricity demand in 2050 compared to 2015

75% – 82%

Share of electricity generation by renewable energy sources* in 2050

38% - 41%

Increase in energy efficiency in 2050 compared to 2015

531 TWh - 782 TWh

Generated total flexibility via demand side response and storage options

~5-7 times more GW

Of **installed RES capacity** in 2050 compared to 2020 (71 GW – 98 GW per year)

Note: ranges reflect the values in 2050 for the FF55-inspired and Radical Action scenario
*RES includes solar PV, onshore wind, offshore wind, hydro power and other RES

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Recent developments require an update for the European pathways to decarbonisation: Decarbonisation Speedways

New policy developments

REPowerEU policy package with increased ambitions compared to FF55

Geopolitical tensions

Higher uncertainty due to conflict in Ukraine

New technological developments

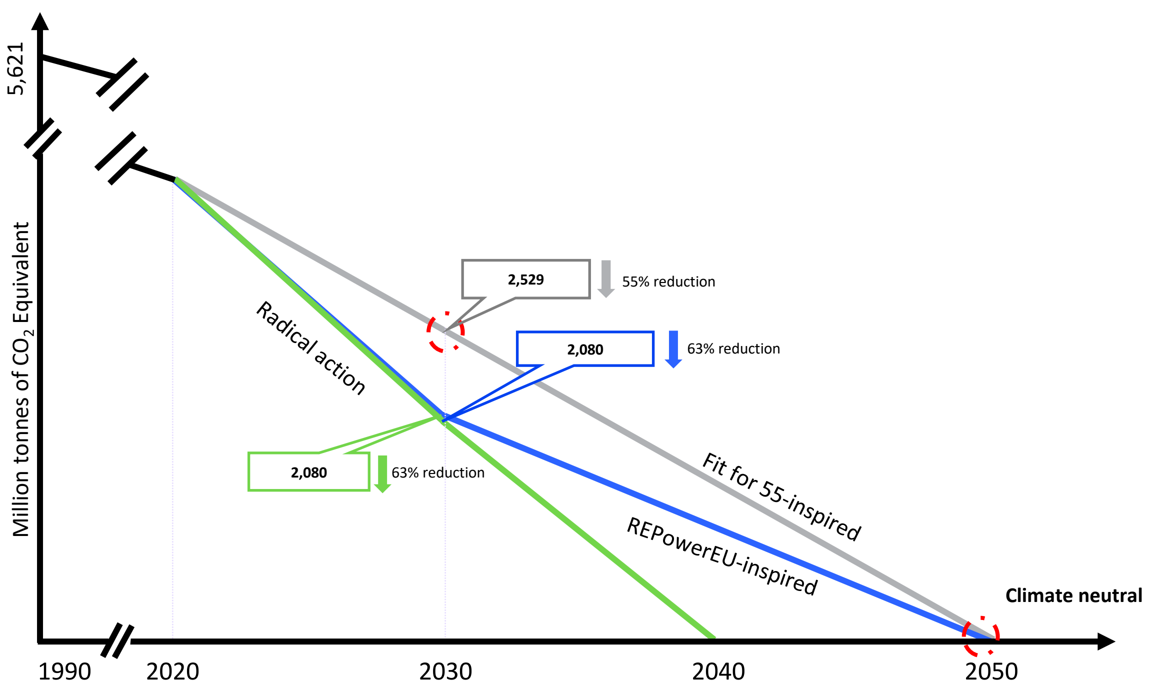
i.e. Hydrogen, E-Mobility, Batteries, DSR, Heat pumps and more

Three Decarbonisation speedways for 2030, 2040 and 2050 in EU27+UK

The scenarios reflect ambitious decarbonisation trajectories, more ambitious than many of the scenarios published before the energy crisis in 2022.

Three decarbonisation speedways are defined: Fit for 55-inspired, REPowerEU-inspired and Radical Action

Net annual emissions EU27 + UK (Mton CO_2 eq.)



Note: the double lines indicate a break in the axis or trend line. This indicates that the space of the graph is not to scale to the numbers. Scope: Including international transport

Introducing the three scenarios

Decarbonisation speedways presents three scenarios that illustrate a future where serious and immediate climate responsibility is taken by the EU and its member states. However, it is not a prediction of the future. Decarbonisation Speedways is the successor of Eurelectric's 2018 study, 'Decarbonisation Pathways'. Based on the most recent political and market trends, the scenarios show speedways of achieving climate neutrality in or before 2050 and achieving already very ambitious targets in 2030. The main sectors in scope are buildings, transport and industries. Agriculture and other are modified more simply and not always reported as the energy demand here is small. The scenarios are inspired on two policy packages, but not necessarily aligned in specific numbers with public scenarios.

The insights resulting from these scenarios provide a roadmap to further detail what constraints limit the pathways towards carbon neutrality and provides guidance on how these bottlenecks can be eliminated.

Description of the three scenarios

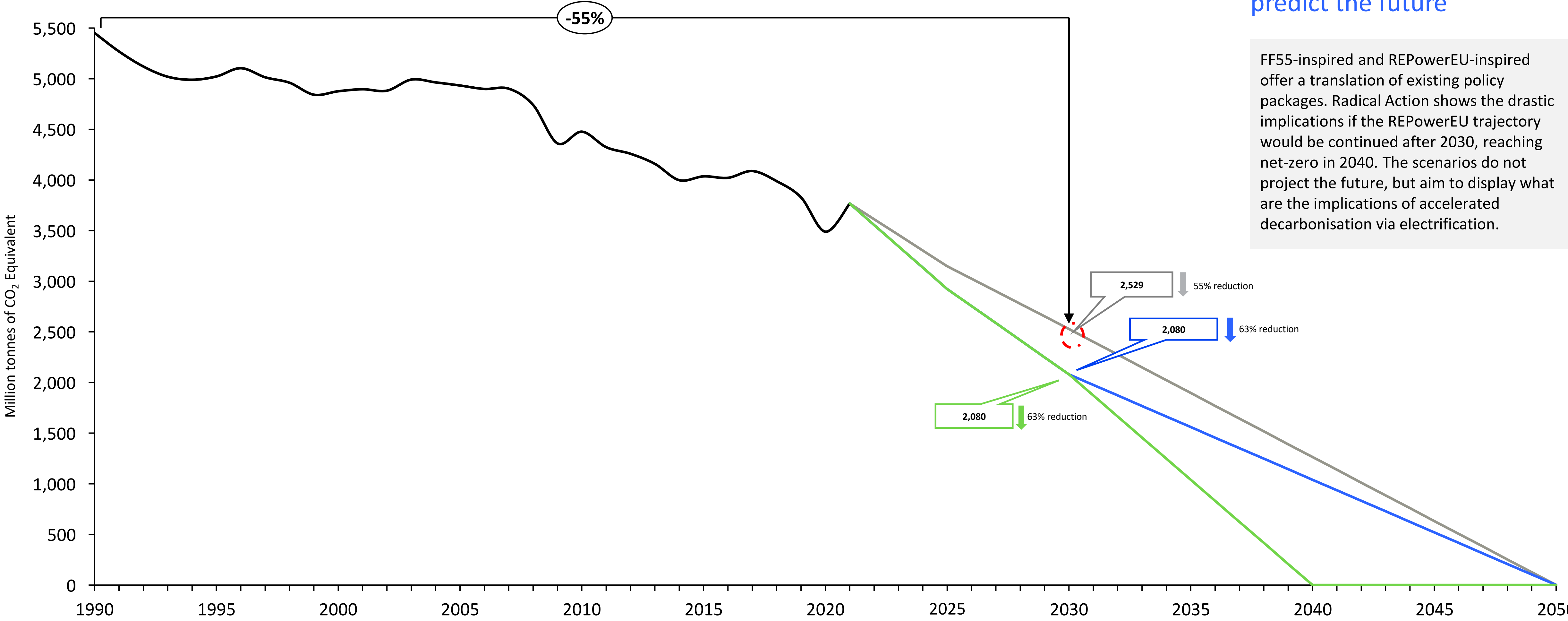
1. The **FF55-**inspired is based on TYNDP Distributed Energy (DE) 2022 dataset, modified based on literature research and expert judgement. FF55-inspired is in line with the European Commissions ambitious targets in the Fit For 55 package, achieving carbon neutrality in 2050.
2. **REPowerEU-**inspired is closely aligned to REPowerEU policy plan and the latest targets to accelerate both European independence from Russian energy and transition to decarbonised energy sources. This results in higher electrification and decarbonisation in 2030 and a partial relaxation of the decarbonisation pace between 2030 and 2050, reaching net zero in 2050.
3. The **Radical Action** scenario reflects an accelerated path towards net zero in 2040. Although clearly demanding, it aims to describe where accelerated decarbonisation in line the REPowerEU ambition would lead to after 2030. Until 2030, the scenario is in line with REPowerEU. After 2030 however, Radical Action continues the trend from REPowerEU-inspired to achieve net zero in 2040. It can be seen as a stress test scenario, showing the implications of accelerated action and what is needed for system if the pace of REPowerEU-inspired is continued.

Sources: 1. 1990 emissions: EEA (n.d.) 2. Emissions for scenarios estimated based on gross inland consumption: EC (2022)

Note: see appendix section for more background on scenarios (LINK)

European emissions need to decrease faster in order to comply with the latest political goals to reach at least 55% reduction in 2030 compared to 1990

Total aggregated annual greenhouse gas emissions including LULUCF for EU27 + UK (Mt CO_2 equivalent)



Sources: UNFCC- Greenhouse Gas Inventory Data - Detailed data by Party (2022)
IEA CO2 emissions 2021 – for relative increase in 2021 (2022)

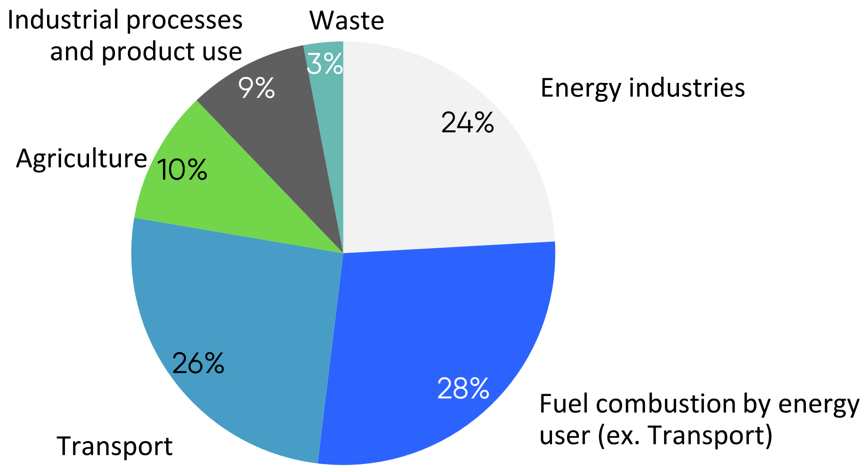
Scenarios not aim to predict the future

FF55-inspired and REPowerEU-inspired offer a translation of existing policy packages. Radical Action shows the drastic implications if the REPowerEU trajectory would be continued after 2030, reaching net-zero in 2040. The scenarios do not project the future, but aim to display what are the implications of accelerated decarbonisation via electrification.

Legend: Historic FitFor55 REPowerEU Radical Action

~70% of the final energy demand in transport, buildings and industry relies on fossil fuels. This is the main target for decarbonisation

Share of European emissions by source[1] – (2020)

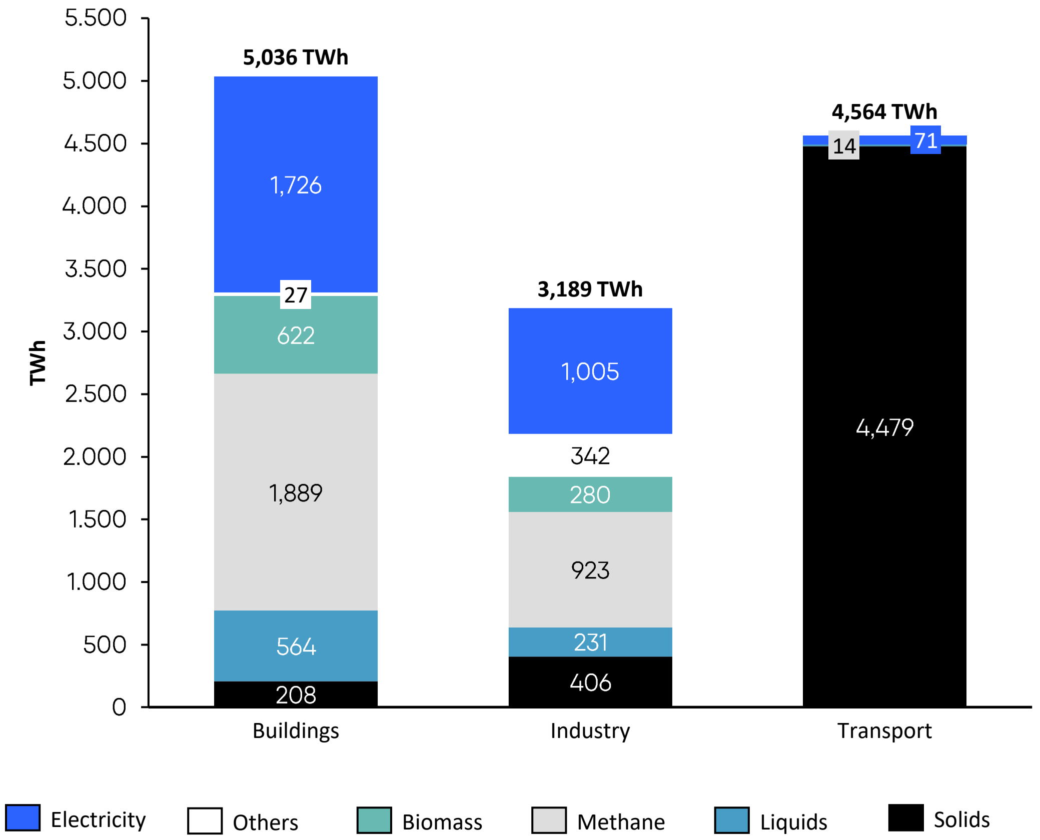


Description of emission categories[1]

- Energy industries: Emissions from fuel combustion and to a certain extent fugitive emissions from energy industries, for example in public electricity, heat production and petroleum refining.
- Fuel combustion by users (excl. transport): Emissions from fuel combustion by manufacturing industries and construction and small scale fuel combustion, for example, space heating and hot water production for households, commercial buildings, agriculture and forestry.
- Transport: Emissions from fuel combustion of domestic and international aviation, road transport, railways and domestic navigation.
- Agriculture: This includes among others emissions from livestock-enteric fermentation – greenhouse gases that are produced when animals digest their food, emissions from manure management and emissions from agricultural soils.
- Industrial processes: Emissions occurring from chemical reactions during the production of e.g. cement, glass, etc

Sources 1. Eurostat & EEA - Greenhouse gas emissions by source (2023)

Overview of energy consumption by energy carrier per sector in EU27+UK in TWh – (2015)



Note: energy usage is from the demand framework from the TYNDP dataset, used as base for the final energy demand for the scenario development. 2015 Is used to remain close to the dataset of the study.

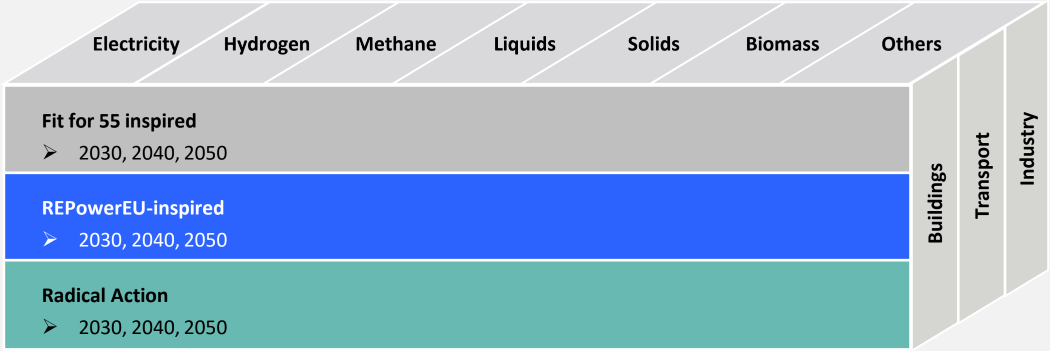
During the first phase the final energy per sector was defined. In phase 2 the electricity wholesale market is simulated for the three scenarios

Phase 1

Focus: on final energy demand

- Developed **three scenarios** including the finale energy demand of the **seven energy carriers** for **three largest sectors** in the target years.
- Starting point was the **TYNDP 2022 dataset** - Distributed Energy scenario. Modifications were made based on **literature studies**, **policy packages** and **expert interviews**.

Visualization of the final energy demand framework



Phase 2

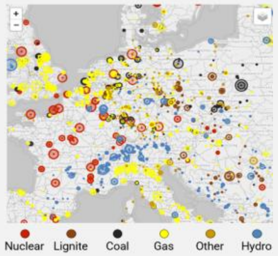
Focus: on power sector, the generation mix for all scenarios via modelling the European electricity wholesale market:

Model input

Non-exhaustive overview of variables

- The electricity demand (from phase 1)
- The emission constraints (from phase 1)
- Generation capacities (RES & conventional)
- Flexibility capacities
- Hourly load profiles per bidding zones
- Net Transfer capacities between bidding zones

Capacities per technology

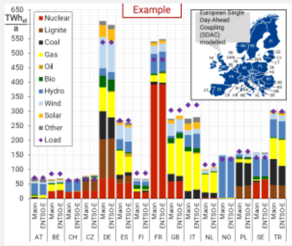


Model output

Non-exhaustive overview of variables

- Dispatch per technology
- Emissions
- Flexibility activated
- NTC saturations
- Energy not served
- Energy curtailed
- Fuel consumption
- Average costs for electricity generation

Dispatch per technology



Note: see the appendix section and the methodology report for more extensive overview of the methods used for the scenarios and the modelling.

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Three driving forces will play a key role in decarbonisation, direct electrification, energy efficiency and decarbonised energy sources

Three main driving forces of decarbonisation in this study

1. Direct Electrification

Direct electrification of all sectors is the most important enabler of decarbonisation in this study, due to its potential as a **carbon-free energy source**, and the large **energy efficiency gains**. When processes are electrified, more efficiency gains are realized compared to liquid, solid or gaseous energy sources.[1] The development of heat pumps, storage- and electric transport **technologies** are crucial in the coming decades for increase electronification.

2. Energy efficiency

Energy efficiency is driven by fuel switching, energy management services and behaviour[4]. New technologies and innovations enable increased efficiencies in all areas. Regarding **fuel switching**, electrification is one of the major contributors since The quantified efficiency gains in the scenarios largely result from additional electrification on top of the TYNDP dataset. **Active Energy Management** and related services help to save energy by making smarter choices driven by data collection and integration[5]. **Behaviour** helps to decrease energy demand. Current **energy prices**, increasing **climate awareness** and **regulation** drive consumers and companies to use energy more consciously.

3. Alternative decarbonised energy sources

Bioenergy, clean hydrogen and waste heat are included as decarbonised energy carriers. **Bioenergy** provides carbon neutral energy as the emitted GHGs are cancelled out by the carbon sequestration through the process of photosynthesis. While being aware of the evolving regulatory environment for bioenergy[2,3], it contributes to net zero goals . **Clean hydrogen and its derivatives** can play a crucial role in hard-to-abate sectors, (heavy transport and heavy industry). Finally, **geothermal**, **solar thermal energy** and **ambient heat** can provide clean and efficient source of energy within buildings and industries. Since the electronification ambition increases with each of the speedways, we expect less decarbonised energy carriers in Radical Action compared to the other two speedways.

Intensity of driving forces per scenario	Percentage of direct electrification in mix of final energy demand		Percentage final energy demand reduction due to energy efficiency (compared to 2015)	Percentage of alternative decarbonised energy sources in final energy demand	
	2015	2050	2050	2015	2050
1. FF55 -inspired	22%	58%	-38%	16%	38%
2. REPowerEU -inspired	22%	61%	-39%	16%	34%
3. Radical Action	22%	71%	-41%	16%	27%

Decarbonised energy share decreases with increased electrification ambition

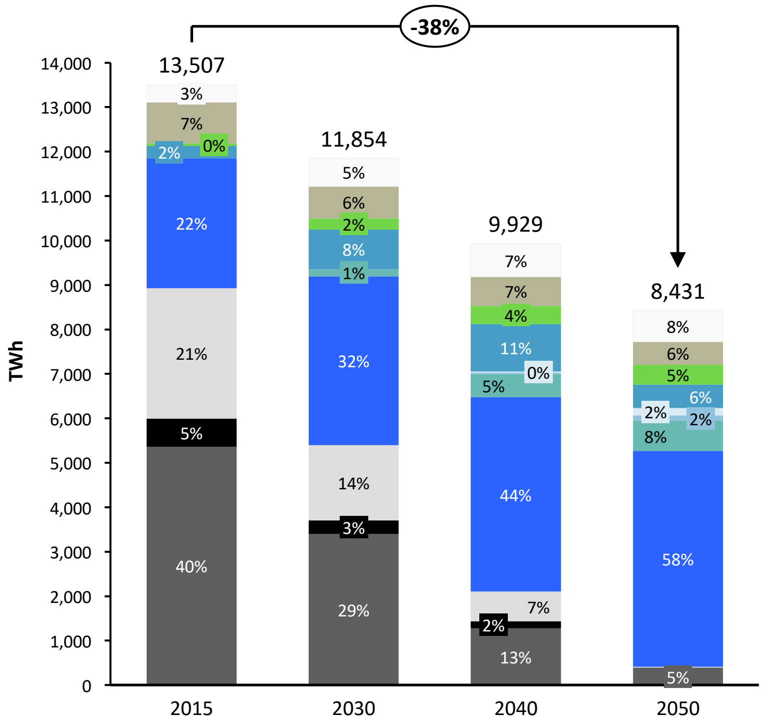
Sources: 1. ACEEE (2019)
2. UNFCCC (2021)
3. European energy directive (2021)
4. IEA (2022)
5. Schneider Electric (2022)

Note: Regarding final energy demand in 2050: Direct electrification + bioenergy, hydrogen, heat + CCUS (fossils) =100% of energy mix. Exception: REPowerEU-inspired sums up to 101% due to rounding at whole percentages.

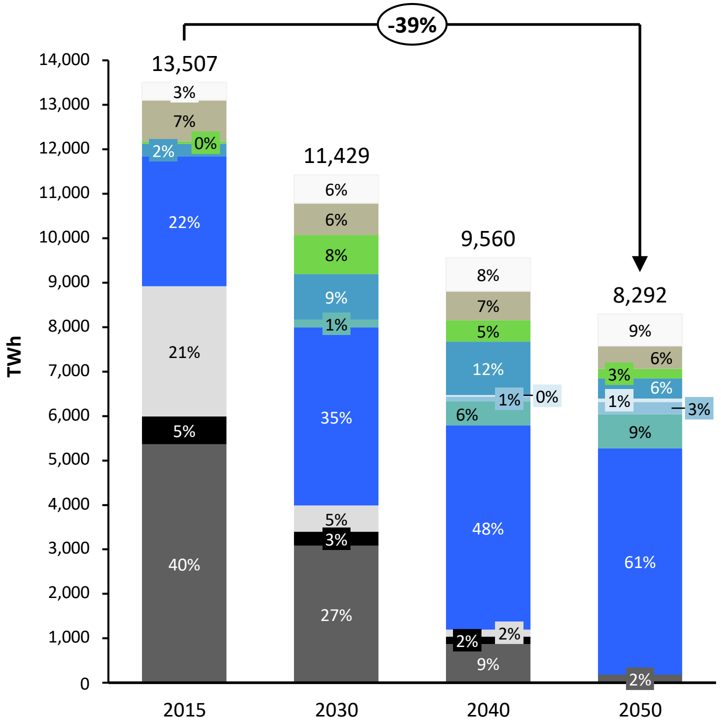
All three scenarios outline electrification strategies enabling further efficiency gains to replace carbon intensive carriers

- To achieve the decarbonisation goals for each scenario, all sectors must be largely electrified, and low-carbon hydrogen or bio-based energy carriers must replace fossil fuels where direct electrification is not an option.
- Direct electrification is considered the main route for decarbonisation. Furthermore, efficiency gains via electrification lead to a reduction of total energy needed.
- Indirect electrification is only favored for hard to abate sectors, such as heavy industries and heavy transport.

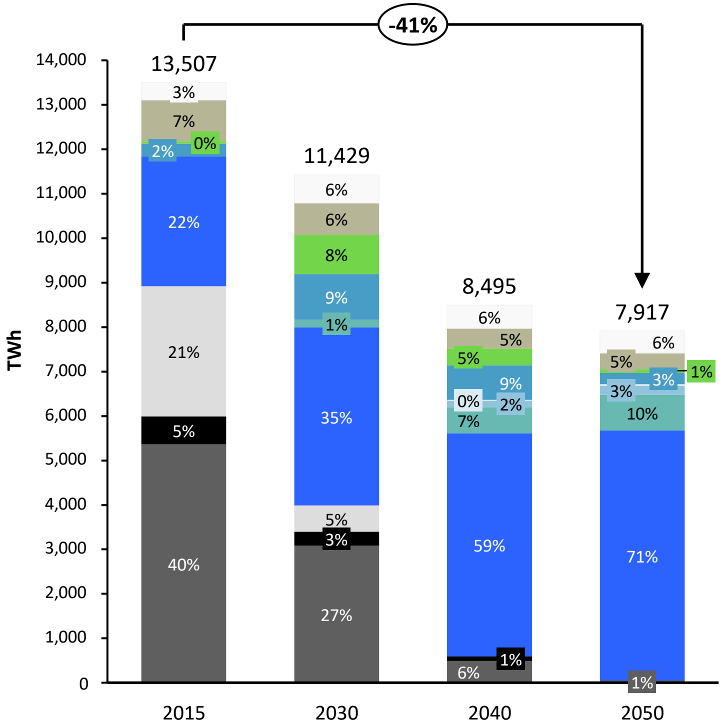
Final energy demand – FF55-inspired (TWh)

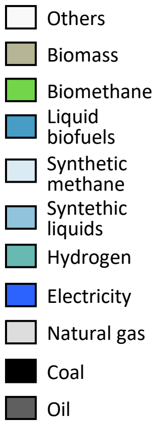


Final energy demand – REPowerEU-inspired (TWh)



Final energy demand – Radical Action (TWh)





1. Agriculture and other sectors are included in the scenarios but not extensively researched and modified
2. Does not include feedstock and non-energy use. Includes domestic and international transport.
3. Others include heat for example solar thermal energy
4. Assumption: 2% of methane is biomethane in 2015 (excl. electricity generation) calculated via: Scarlat et al (2018)
5. Assumption: 5% of liquids are biofuels in 2015: Transport and environment (2021)

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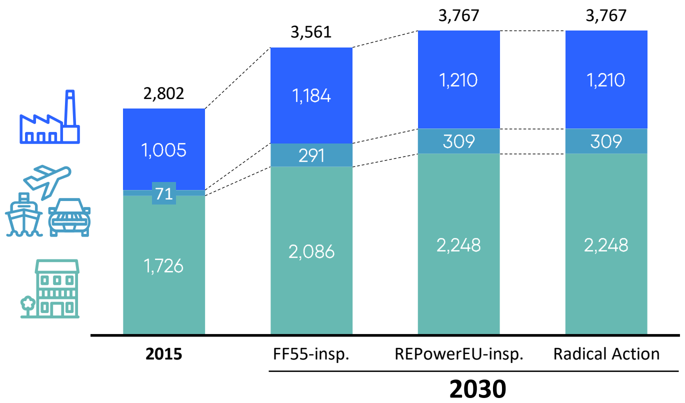
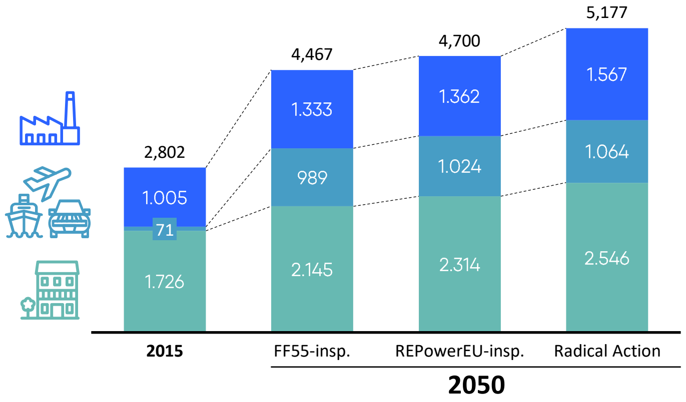
Buildings sees the largest absolute electricity demand, relative growth is the highest in transport. Hydrogen mainly in heavy industries and heavy transport

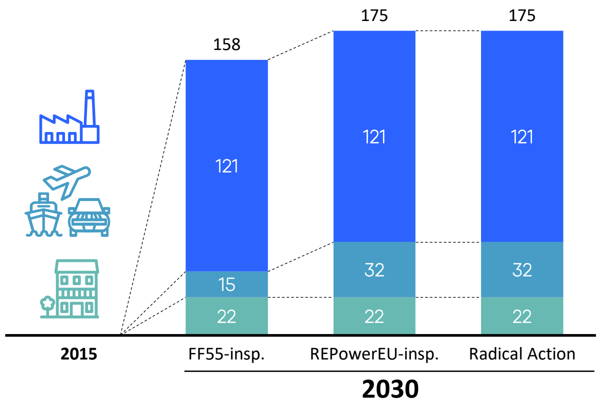
Final electricity demand 2030 and 2050 - TWh

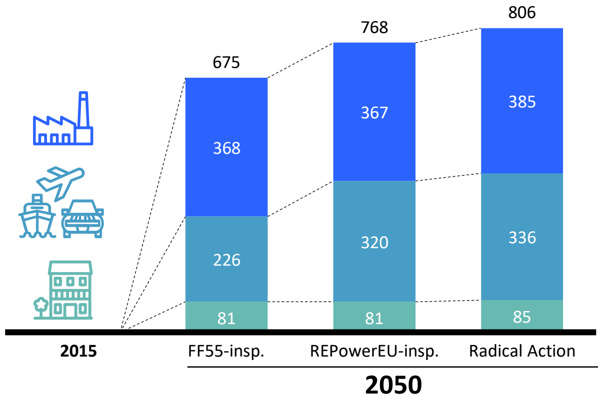
Note that Y-axis scales differ per graph



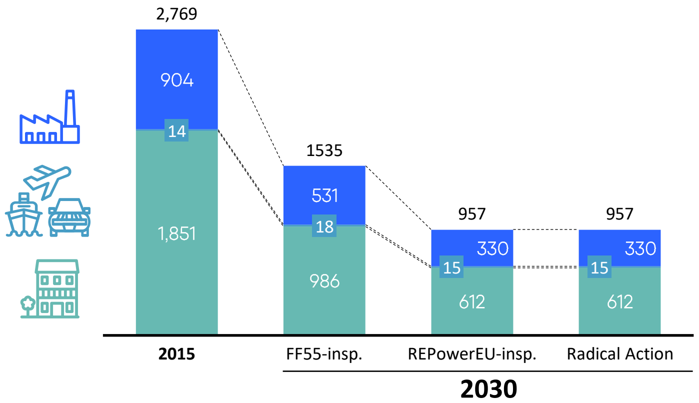


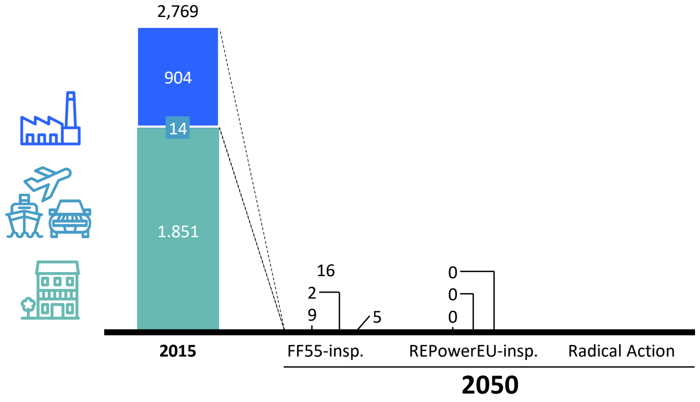
Final hydrogen demand 2030 and 2050 - TWh





Final natural gas demand 2030 and 2050 - TWh





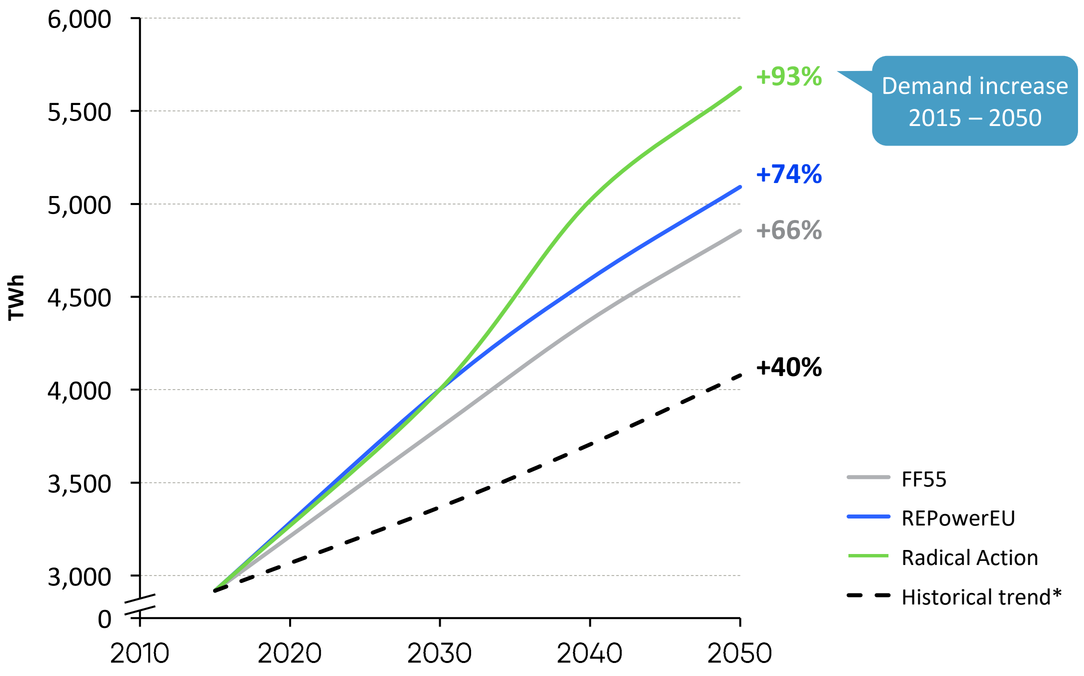
Note: Hydrogen is mainly used for heavy transport and hard to abate industries. Hydrogen values in buildings are lowered compared to TYNDP dataset. However, not removed completely, since it is considered an option for buildings were electrification is less efficient due to lack of insulation. Some countries already started projects to heat buildings with (blended) hydrogen. See also IEA hydrogen outlook (2021)

All speedways rely heavily on electrification of demand as main route for decarbonisation

All speedways rely heavily on electrification of demand

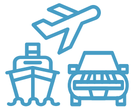
All speedways rely heavily on massive electrification of the demand sectors buildings, transport and industry.

Growth in final electricity demand of sectors in 2015-2050 EU27+UK (TWh)

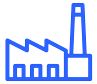


Main technologies driving increase electrification in demand

- **Heat pumps** drive electric heating of homes, instead of natural gas fired boilers. Depending on the scenario in 2050 between 231 million (FF55-inspired) and 276 million (Radical Action) heat pumps will be installed throughout EU27+UK. For an overview of the abated emissions of heat pumps, see appendix section on abatement.



- **Electric engines** replace internal combustion engines fueled by gasoline in road transport, realizing higher efficiencies. In 2050, it is assumed that, depending on the penetration rate, there will be between 220 million (FF55-inspired) and 250 million (Radical Action) electrically powered light vehicles.



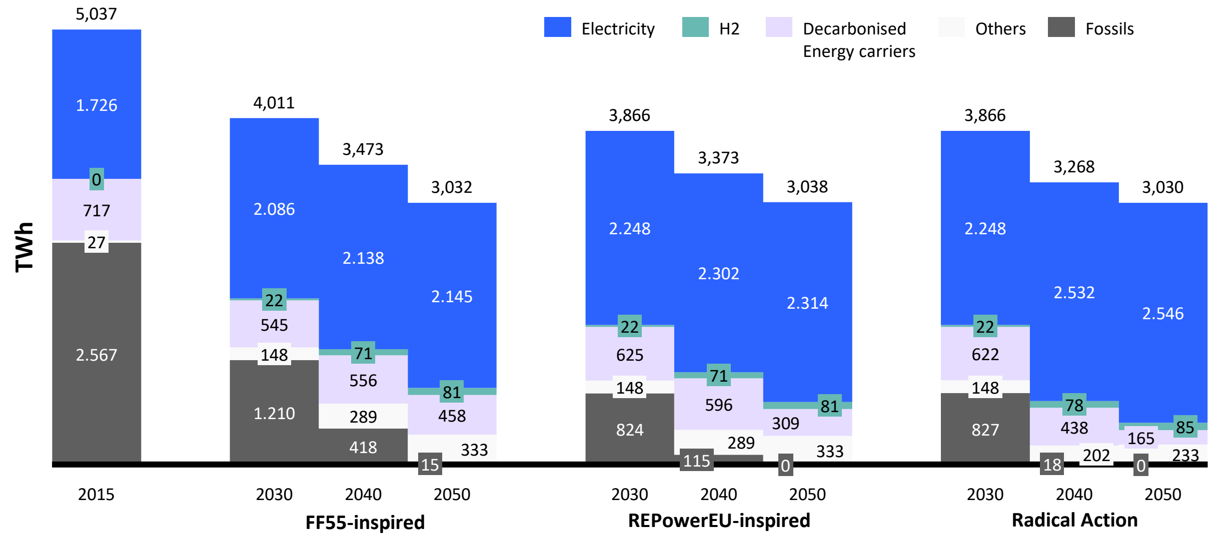
- **Electric boilers, engines and industrial heat pumps** replace fossil fuels in industrial processes. High industry heat is more difficult to abate but technological developments are bringing this closer.

*If historical YoY growth rate of electricity demand is continued (calculated using Eurostat data, extrapolated using the average annual growth rate between 2000 and 2015. However, it should be noted that the growth stagnates from 2010 onwards.

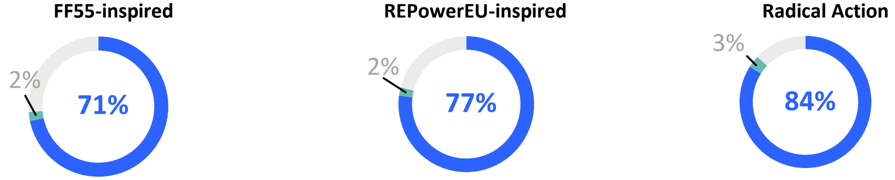
Decarbonisation in the buildings sector is driven by electrification in all three scenarios, hydrogen has a minor role

The buildings sector accounts for 36% of the GHG emissions in Europe[3]. Heating is the largest contributor to residential GHG-emissions, followed by cooking and water heating[4]. Currently buildings are primarily heated using fossil energy sources, such as natural gas which accounted for 37% of the energy demand in buildings in 2015. Below an overview of the buildings sector is depicted with the distribution of the most important categories of energy carriers over time, for the three scenarios.

Final energy demand in buildings for all scenarios (TWh)



Share direct electrification and hydrogen in final energy demand buildings – all scenarios (2050)



Sources: 1. Accenture (2021) 2. Accenture expert interview (2022) 3. European climate foundation (2022) 4. Statista (2018) 5. Decerna (2019)

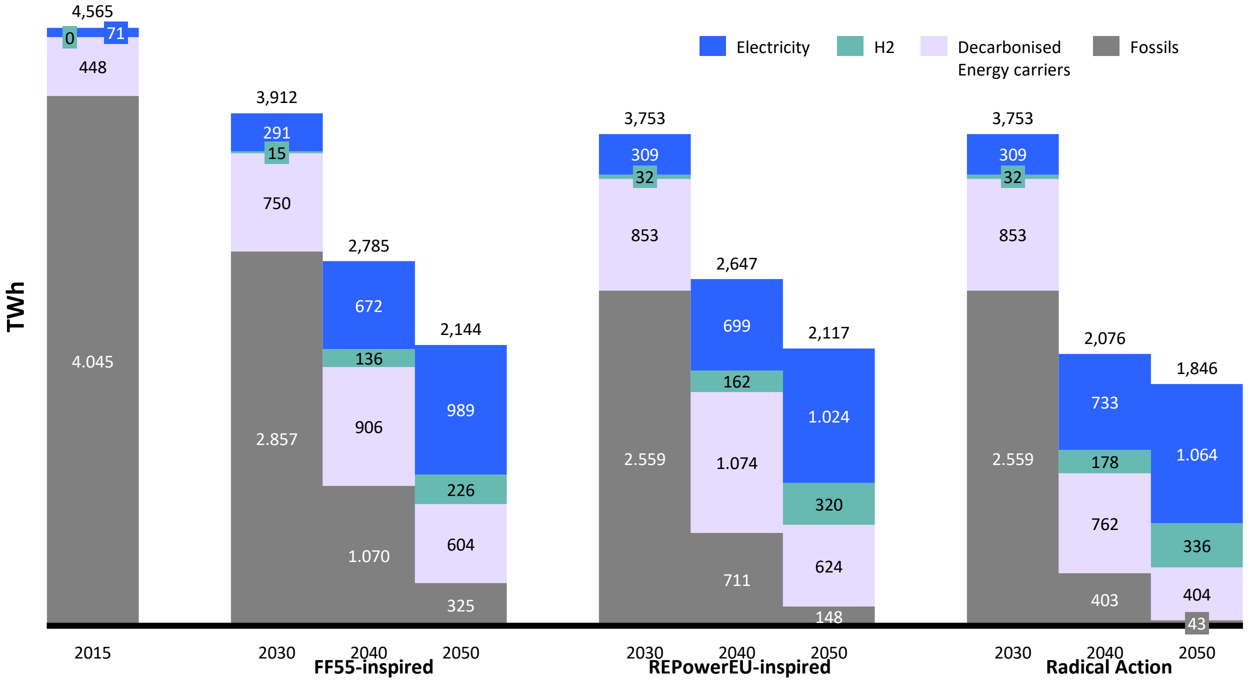
Key insights & main drivers

- The energy demand in buildings declines as we electrify by utilizing heat pumps and increase energy efficiency through smart implementation of technology and insulation of buildings
  - Heat pumps achieve an efficiency of about 2.9 times the efficiency of a traditional boiler running on natural gas[1,2]
- Currently, most energy in buildings is supplied by methane, expected to rapidly decrease looking forward to 2030 and 2040 and will be completely phased out in 2050
  - New technologies will foster direct electrification substituting demand for methane
  - Electrification of buildings via heat pumps, combined with district heating networks, account for large share of the methane reduction in 2050
- District heating and/or cooling will play an increasing role for buildings. Sources differ per country, where some countries still rely on coal, other countries will increasingly use sources as solar thermal, geothermal and aqua thermal to heat or cool the water in the system. This can be used in combination with seasonal thermal storage, residual heat from industrial processes and / or heat pumps. District cooling will become increasingly important as an alternative for air conditioning, due the expected temperature increase as result of climate change. The energy sources used for district heating are included in the final energy demand of the respective energy carriers.

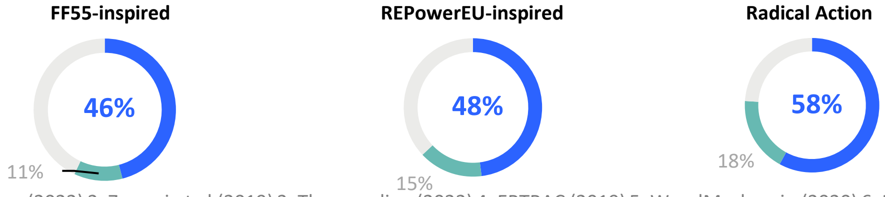
Notes: Electricity for hydrogen production is not included. 'Others' includes heat (i.e. solar thermal). Decarbonised energy carriers include bio-methane, bio-fuels, synthetic methane, synthetic fuels and biomass.
Efficiency heat pump: 1 kwh electricity to 2.6 kwh heat (Seasonal Performance Factor 2.6)[1,5]
Efficiency gas boiler: 1 kwh natural gas to 0.9 kwh heat

Electric transport displaces fossil liquids by both an increased tank-to-wheel efficiency and the usage of electricity

Final energy demand in transport for different energy carriers (TWh)



Share direct electrification and hydrogen in final energy demand transport – all scenarios (2050)



Sources: 1. EDF Energy (2022) 2. Zuccari et al (2019) 3. The guardian (2022) 4. ERTRAC (2019) 5. WoodMackenzie (2020) 6. EEA (2021)

Key insights, main drivers and challenges

Comparing the different sectors for end use, the largest energy efficiency gains are achieved in the transport sector, with at least a 53% reduction of final energy demand in 2050 compared to 2015. Efficiency gains are mainly driven by the transition from an internal combustion engine to an electrically powered motor, as the energy efficiency for an electric road vehicle is over 3 times as efficient compared to an ICE vehicle[1,2].

Road transport has the biggest potential to electrify, with 79% in 2050 for the FF55-inspired scenario. Road transport includes motorcycles, passenger vehicles, light- and heavy trucks and buses. While passenger cars and city buses are most likely to become largely electric, challenges remain to electrify heavy trucks that transport cargo over long distances. Currently ~80% of freight transport travel long haul (>150 km)[4]. Electric trucks manufacturers currently claim ranges of 250-350 km[5]. Technological developments indicate ranges of 500 km will be feasible in the future with a 700-KWh battery capacity. This would be sufficient for the majority of the operations when combined with a dense network of fast charging infrastructure, meaning most of the road transport can be electrified in the long run[6].

For aviation and marine shipping, there are two main challenges: (1) these large vessels and aircrafts have an economic lifetime of several decades and therefore it is unlikely a very large proportion of the fleet will be replaced by electric alternatives once the technology is there (2) to electrify these sectors engineering challenges remain[3].

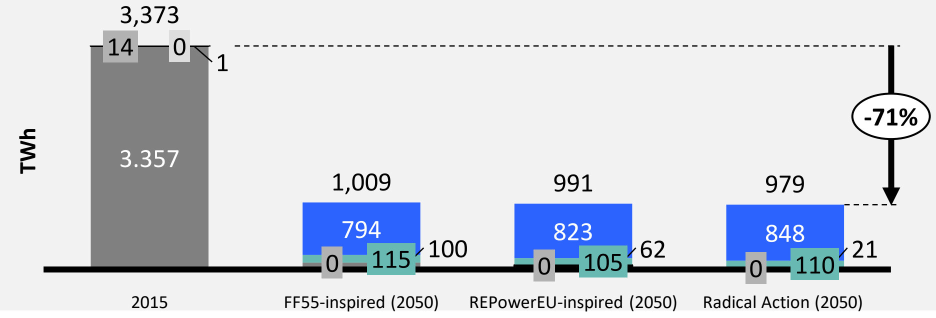
Rail transport is already largely electrified and could partially replace other modes of transportation for passengers and cargo. However, geographical and socio-economic challenges hamper the expansion of the current railway network in Europe.

Notes: Electricity for hydrogen production is not included. 'Others' includes heat (i.e. solar thermal). Decarbonised energy carriers include bio-methane, bio-fuels, synthetic methane, synthetic fuels and biomass.

Within transport, road and rail transport largely electrify towards 2050, in marine and aviation hydrogen is introduced as an alternative

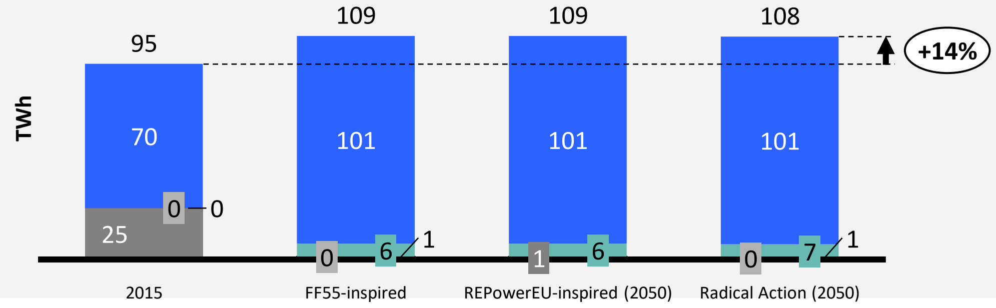
Road – 2015 to 2050 in three scenarios

Within road transport, high efficiency gains are expected resulting from the superior efficiency of electrical engines. For the FF55-inspired speedway, 220 million electric passenger vehicles are expected on the European roads by 2050. The agreement of the EU from 2022 to ensure that all new cars and vans registered in the EU will be zero-emission vehicles by 2035, is an important step forward[4].



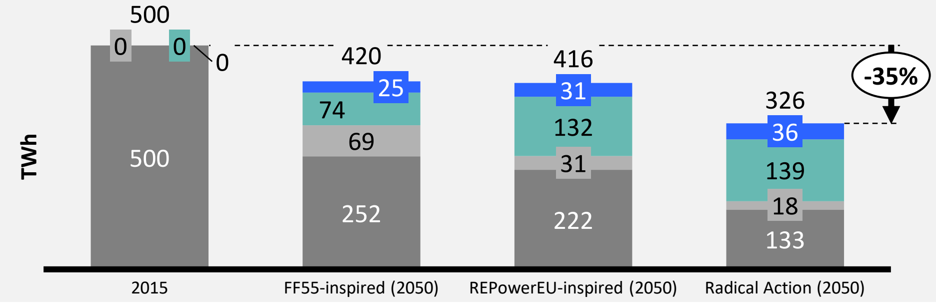
Rail – 2015 to 2050 in three scenarios

The sector is expected to grow as more railways are built and travelers choose a railway option more often, resulting in additional demand for energy and hence, for electricity. Railway transport is already largely electrified and is expected to almost completely electrify by 2050.



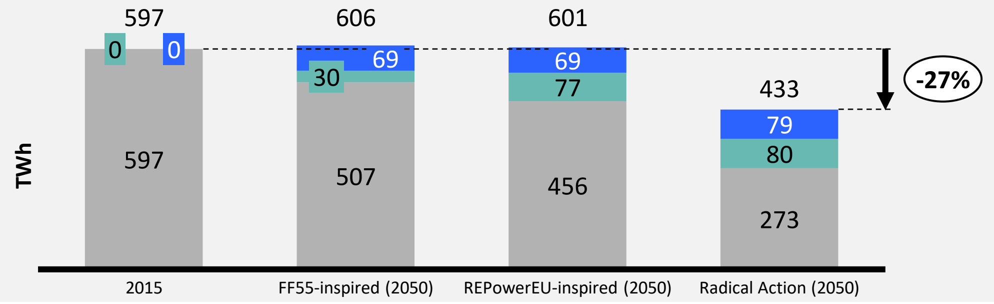
Marine – 2015 to 2050 in three scenarios

Hydrogen plays an important role via indirect electrification. Lower demand for energy is expected due to a reduction of fossil fuel shipment needed as result of the energy transition. Currently, 40% of all products transported by global shipping are fossil fuels (coal, oil, gas)[1]. Policies for sustainable aviation fuels will need to be further developed[2].



Aviation – 2015 to 2050 in three scenarios

Aviation can be partially electrified, but mainly for short distances. Hydrogen is an option, but synthetic- or bio-fuels could offer more possibilities with higher energy density. Policies for sustainable aviation fuels will need to be further developed[3].



Source: 1. UNCTAD (2021) 2. European Commission (2021)

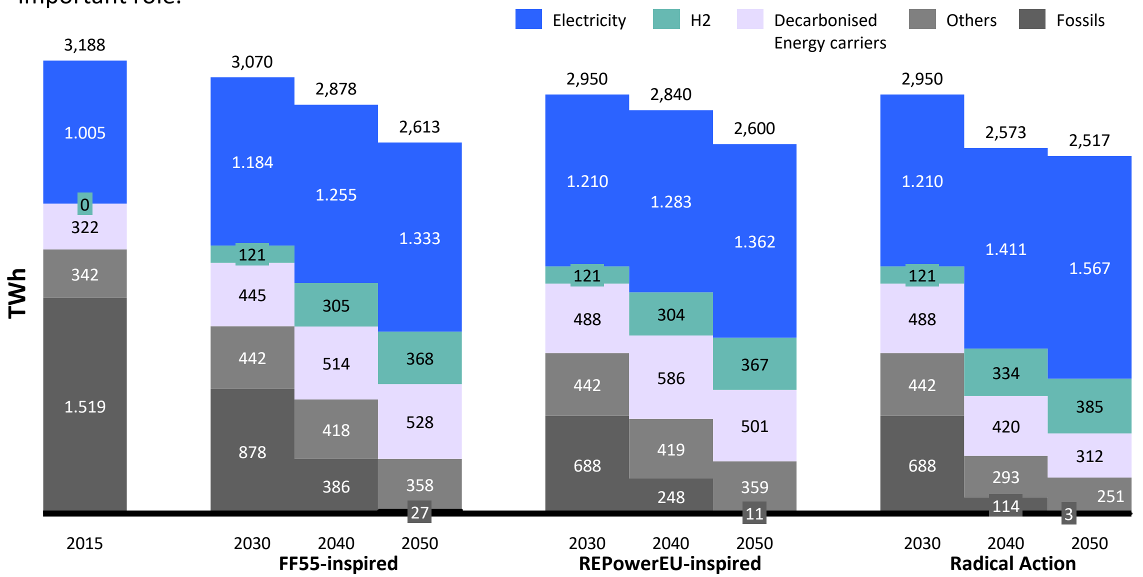
Source: 3. European commission (2021) 4. European Commission (2022)

Electricity | Hydrogen | Methane | Liquids

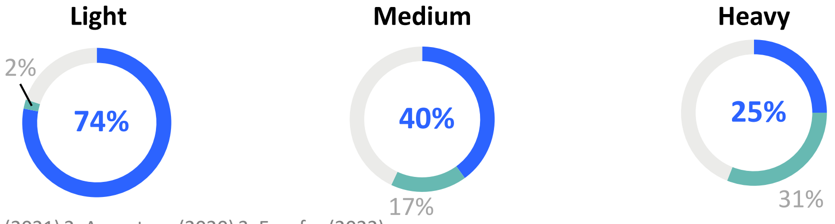
Light industries reach electrification rates of 74%. Heavy industries are the hard-to-abate sectors, with 31% hydrogen in 2050

Results scenarios for industry in the three scenarios over time (in TWh)

The industries sees a decline in all scenarios of total energy demand. Electricity is expected to contribute mainly to decarbonisation in the light industries. For the heavier industries, hydrogen plays a more important role.



Direct electrification and hydrogen for sub-industries in 2050 – FF55 inspired



Sources: 1. WEF (2021) 2. Accenture (2020) 3. Eurofer (2022)

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Examples of direct and indirect electrification in the industry

Steel production via Electric Arc Furnaces

In steel two main production processes can be distinguished: 1. Electric Arc Furnaces (EAF) driven by electricity and using usually scrap steel as raw material. 2. Blast Furnace-Basic Oxygen Furnace (BF-BOF), using coal as to bring liquid iron up to ~1,500 degrees Celsius. iron ore is used as base raw material. In Europe in 2019, ~55% of the steel produced is still via BF-BOF. However, EAF requires approximately 20% of the energy compared to BF-BOF and allows for the usage of scrap steel as input material, instead of iron ore as raw material[3]. When combined with low-carbon electricity, this can provide significant emission reductions for the steel sector. This can be done via for example specific Power Purchasing Agreements (PPA) with wind or solar park operators.

Humber industrial cluster, United Kingdom

The Humber area around Yorkshire is the largest industrial area in the United Kingdom with energy intensive industries and hard to abate emissions, like steel, refining and manufacturing. In total, this industrial cluster emits 10 million tonnes of CO_2 per year, which is more than 2% of the total GHG emission from the UK.

Collaboration projects in Humber area[1]*

1. **Zero Carbon Humber**: 12 partners working together to produce low and zero carbon hydrogen, the development of CCS network, and creating a shared hydrogen infrastructure. The goal is to be the first net zero cluster in 2040.
2. **Gigastack**: to advance economically viable zero carbon hydrogen production with a cross sectoral coalition of Orsted, Phillips 66 and ITM power. A 100 MW electrolyser is planned to supply 30% of the refinery's existing hydrogen demand. The consortium will also develop a blueprint for deploying scalable electrolysers in the rest of the country.
3. **Humber zero**: 1 km of the coast of the Humber river, the main partners Phillips 66, Uniper and Vitol's VPI Immingham power plant will collaborate to create a network of hydrogen and CO_2 pipelines, to connect the energy, housing and industry locations. The infrastructure is expected to be operational around 2026.

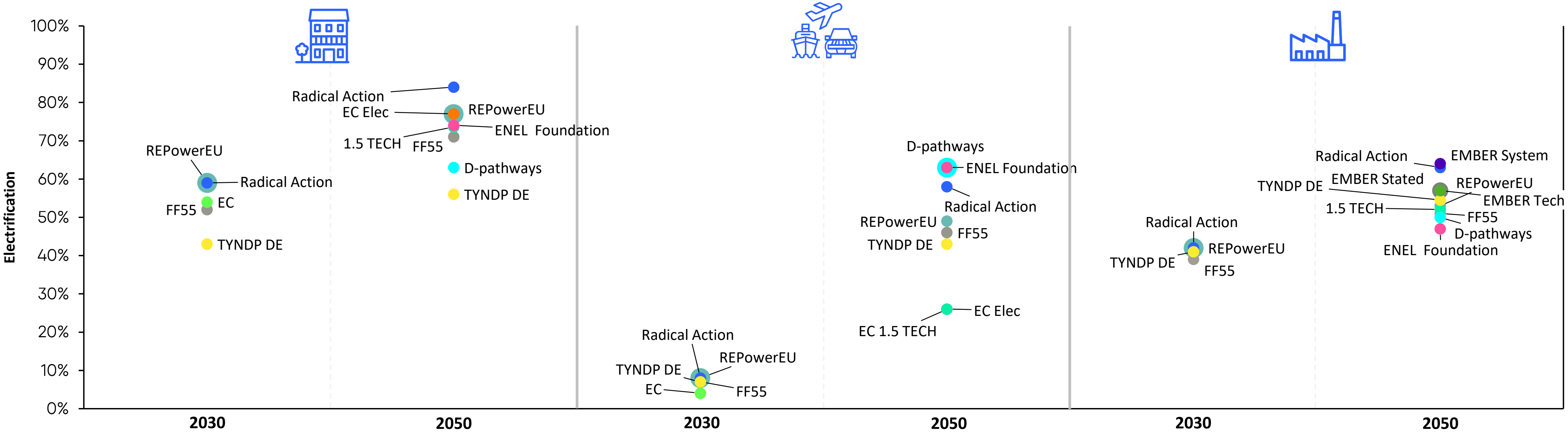
*Non exhaustive

Notes: Electricity for hydrogen production is not included. 'Others' includes heat (i.e. solar thermal). Decarbonised energy carriers include bio-methane, bio-fuels, synthetic methane, synthetic fuels and biomass.

Our study sets ambitious electrification targets, comparable to scenarios from the European Commission and other studies

Benchmarking of scenarios on electrification rate in Buildings, Transport and Industry – 2030 & 2050

Decarbonisation Speedways aims for high electrification, comparable to similar studies that were conducted in the previous years. The graph below displays the electrification rates of our three scenarios for three main sectors compared to scenarios from relevant studies. Three scenarios from the European Commission's study 'A Clean Planet for all' were used along with the TYNDP DE scenario, the ENEL Foundations CL decarbonisation scenario, EMBER studies on European Clean Power Pathways and the previous Eurelectric study, Decarbonisation Pathways. For buildings, TYNDP DE deviates most from our scenarios due to increased electrification rates after expert interviews. The transport sector has different interpretations in the various subsectors in scope, resulting in less equal comparisons. EC scenarios in transport have lower electrification rates, due to the higher total energy demand.



Report	Scenario	Year published
ENEL foundations	CL decarbonisation scenario	2020
European commission - A clean planet for all	ELEC, 1.5 TECH, Baseline	2018
TYNDP 2022	Distributed energy	2022
Decarbonisation pathways	Scenario 3	2018
EMBER New Generation - Technical Report	all	2022

Decarbonisation Speedways scenarios
- Radical Action
- REPowerEU
- Fit for 55

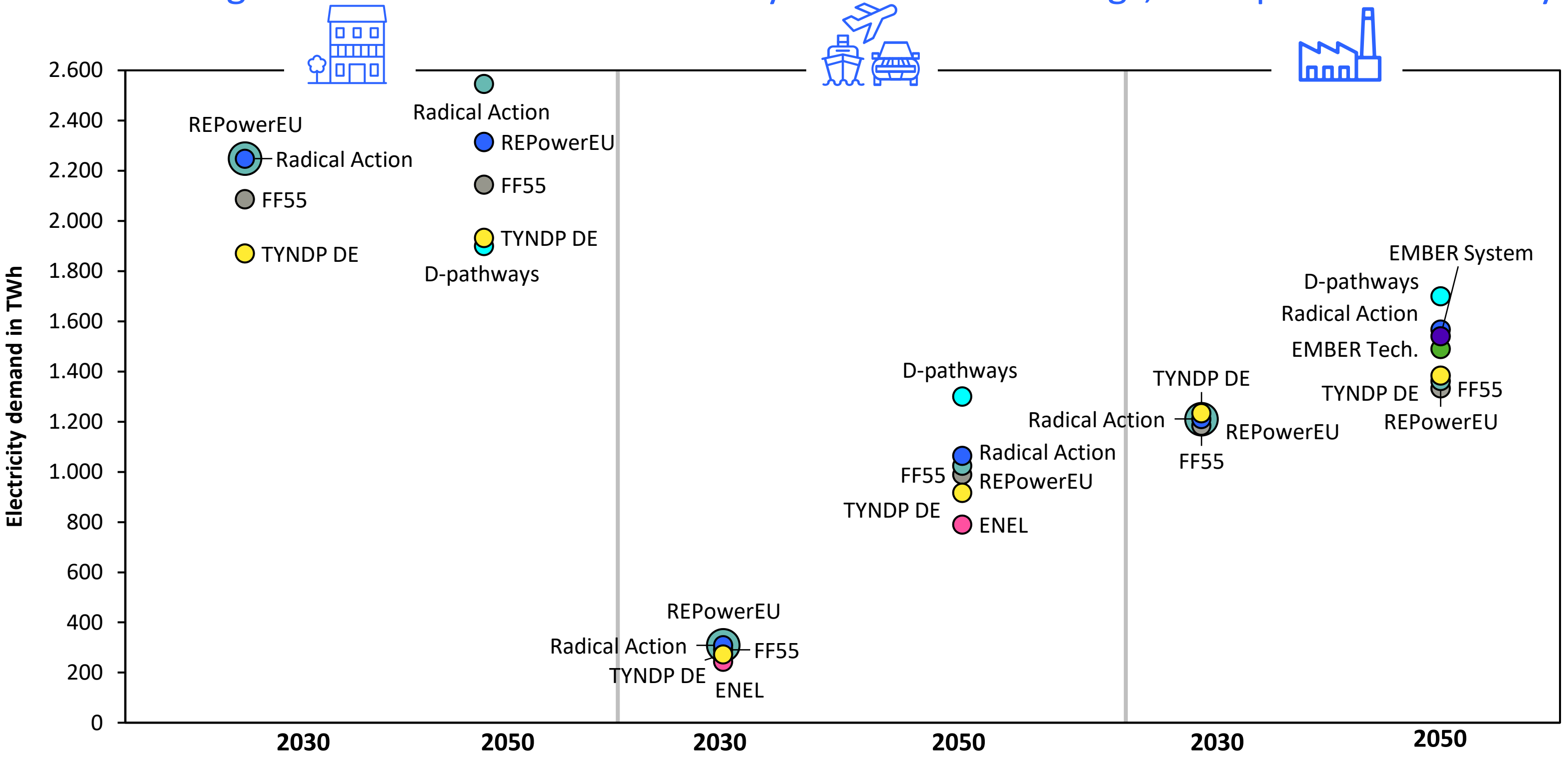
Benchmark scenarios
- EC Baseline
- EC 1.5 TECH
- EC ELEC
- TYNDP Distributed Energy
- Decarbonisation Pathways
- EMBER Technology Driven
- ENEL CL decarbonisation
- EMBER System Change
- EMBER Stated Policy

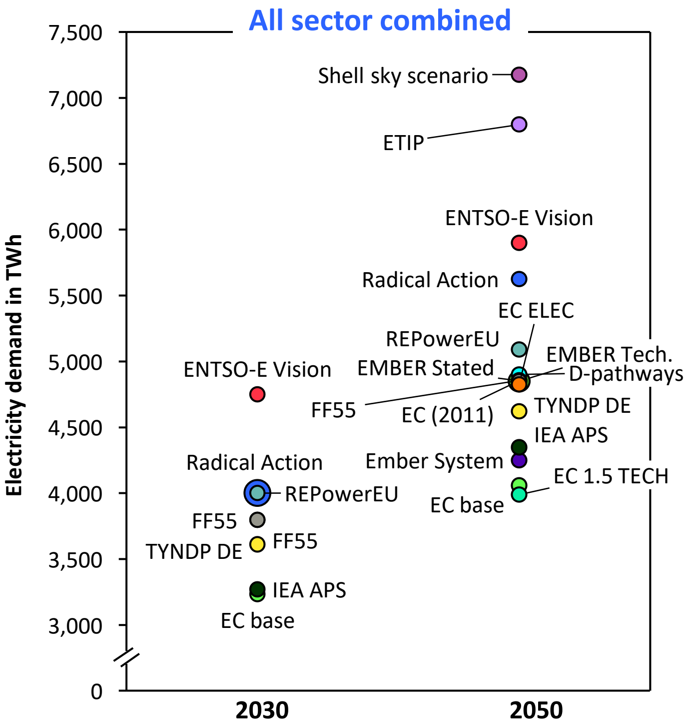
Note: not every study published a value on each section, therefore not every study is shown in all sections

Sources: 1. European Commission (2018) 2. ENEL (2020) 3. Eurelectric (2018) 4. EMBER (2022)

Absolute TWh of final electricity demand per sector are significant, but within the range of other studies

Benchmarking of scenarios on final electricity demand in Buildings, Transport and Industry – 2030 & 2050 (TWh)





Report	Scenario	Year published
ENEL Foundation	CL decarbonisation scenario	2020
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TYNDP 2022	Distributed energy	2022
Eurelectric Decarbonisation pathways	Scenario 3	2018
EMBER New Generation - Technical Report	Technology Driven, System Change, Stated Policy	2022
IEA World Energy Outlook 2022	APS	2022
ENTSO-E Vision	-	2022
Shell Scenarios Sky	-	2018
ETIP Getting fit for 55 and set for 2050	-	2021

Decarbonisation Speedways scenarios

- Radical Action
- REPowerEU
- Fit for 55

Benchmark scenarios

- EC Baseline
- EC 1.5 TECH
- EC ELEC
- ENEL CL decarbonisation
- Decarbonisation Pathways
- ENTSO-E Vision
- Shell sky scenario
- ETIP (based on FF55 package, excl. UK)
- European Commission (2011)–scenario 6
- TYNDP Distributed Energy
- EMBER Technology Driven
- EMBER System Change
- EMBER Stated Policy
- IEA APS

Sources: 1. European Commission (2018) 2. ENEL (2020) 3. Eurelectric (2018) 4. ETIP (2021) 5. European Commission (2020) 6. European Commission (2011) 7. ENTSO-E Vision (2022): estimated from figure 8. Shell Sky scenario refers to whole Europe. 9. IEA (2022) refers to European Union 10. EMBER (2022)

Note: definitions of electricity demand differ per study. Ember uses electricity demand as total TWh final demand. EC: Share of energy carriers in final energy consumption. Hence differences in the benchmark are present due to variation in exact demarcation of scope.

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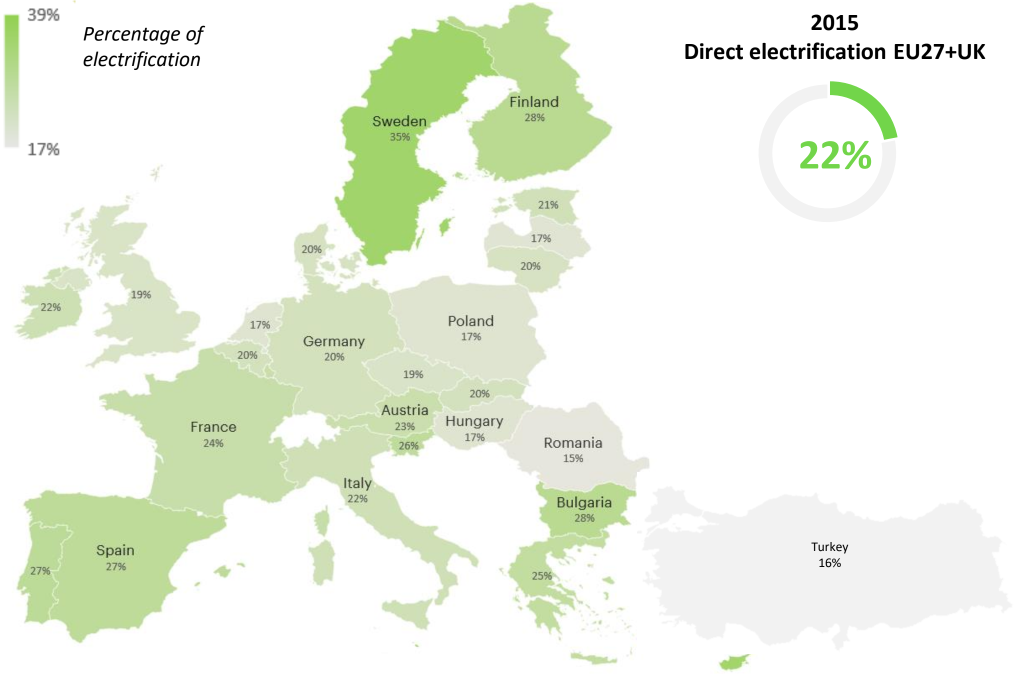
The impact of direct electrification to drive decarbonisation in the complete energy system, is impacted by the regional differences among countries

Regional differences apply and define future trajectories

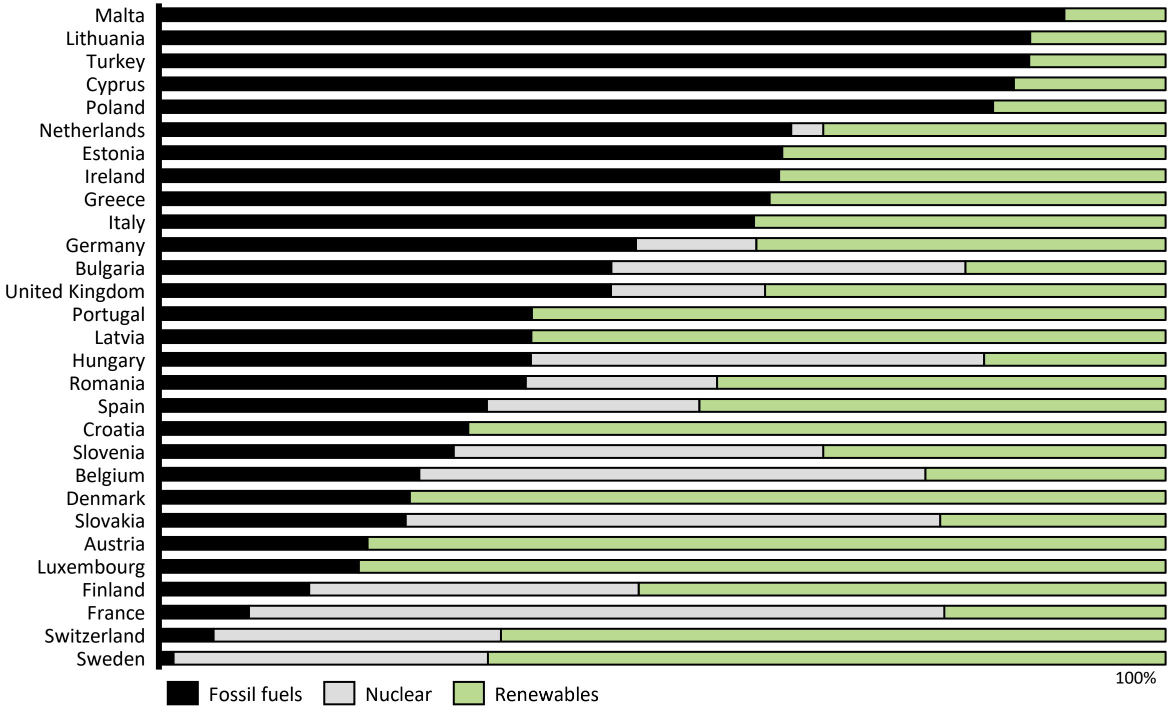
The Decarbonisation Speedways put emphasis on electrification of all demand sectors and their subsectors. By driving as much processes within these sectors as possible on electricity, no direct GHGs are emitted which is needed to achieve the EU's decarbonisation targets. However, to achieve a net-zero economy in 2050 or before, the generation of this carbon-free energy carrier cannot emit any GHGs either. Therefore, many countries in scope require need to fundamentally change their electricity generation mix so that climate neutrality can be reached. While Sweden has already phased out almost all fossils in its electricity generation mix, other countries such as Lithuania, Poland and the Netherlands have some work to do between now and 2050. Note that countries cannot be compared one-on-one due to factors such as share of (heavy) industry, geographical (dis)advantages for electricity production and economic differences.

Direct electrification rate per country in EU27+UK[1] (2015)



Source: 1. TYNDP Distributed energy scenario - (2022). Note: this source is taken since it was starting point of the study.

Electricity production by source per country[2] (2021)

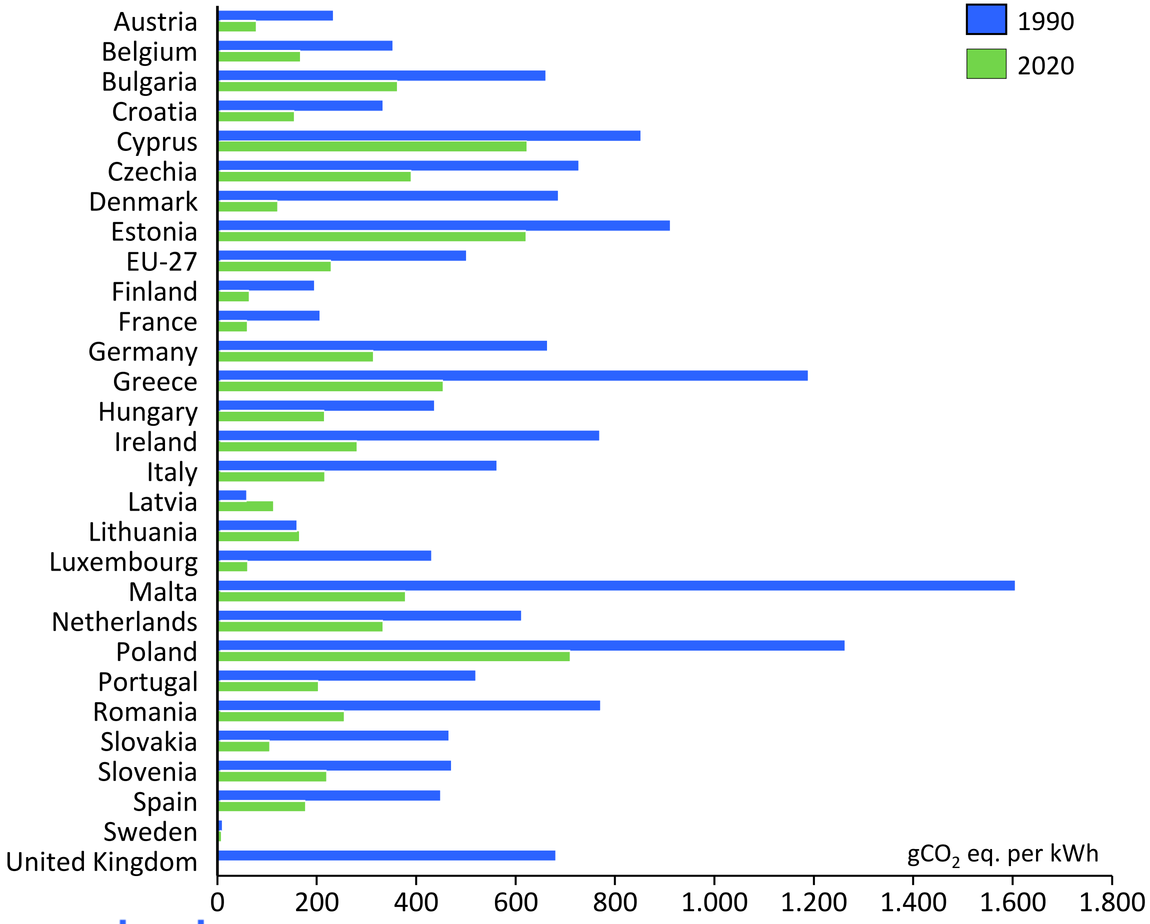


Source: 2. Our world in data (2021)

The carbon intensity of power needs to drop further in order to realize the decarbonisation goals in Europe via electrification

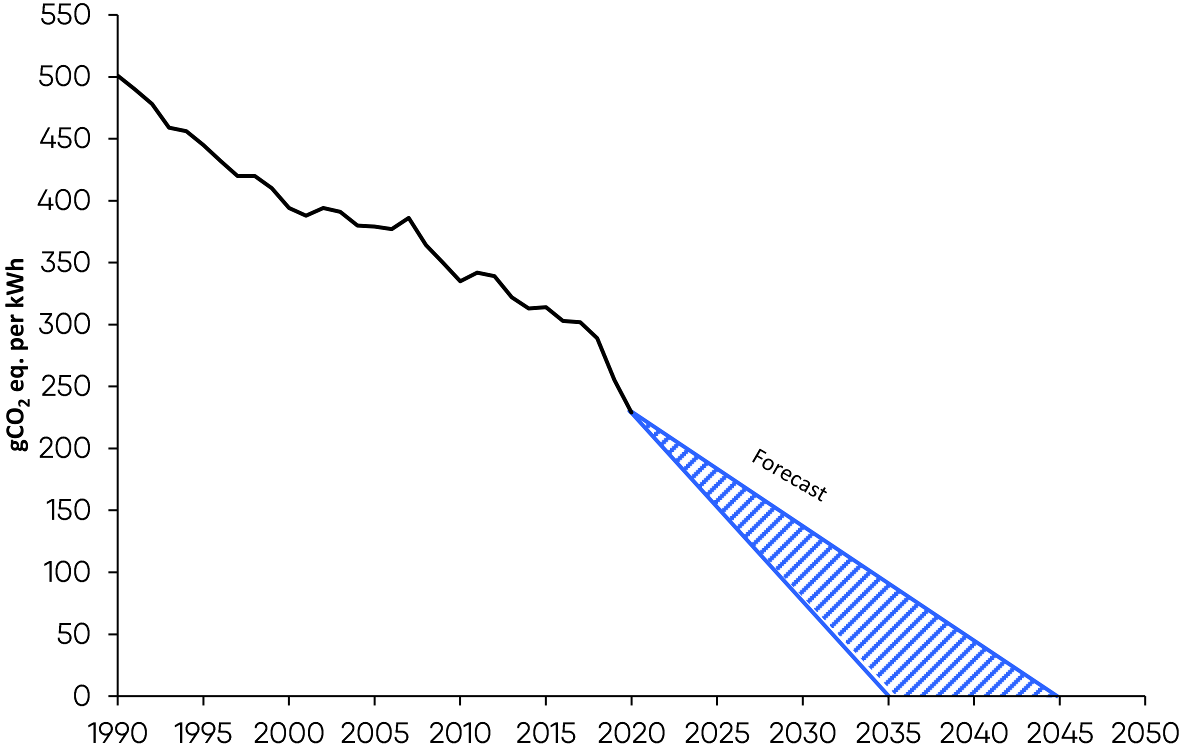
Carbon intensity of electricity generation per country ($g\ CO_2$ eq. / kWh)

Strong reductions in emission intensity have already been realized within the EU, achieving a reduction of 54% between 1990 and 2020. However, further decrease is required to achieve decarbonisation of the complete energy system via electrification.



Decrease of carbon intensity over time in EU27+UK (gCO_2 eq. /kWh)

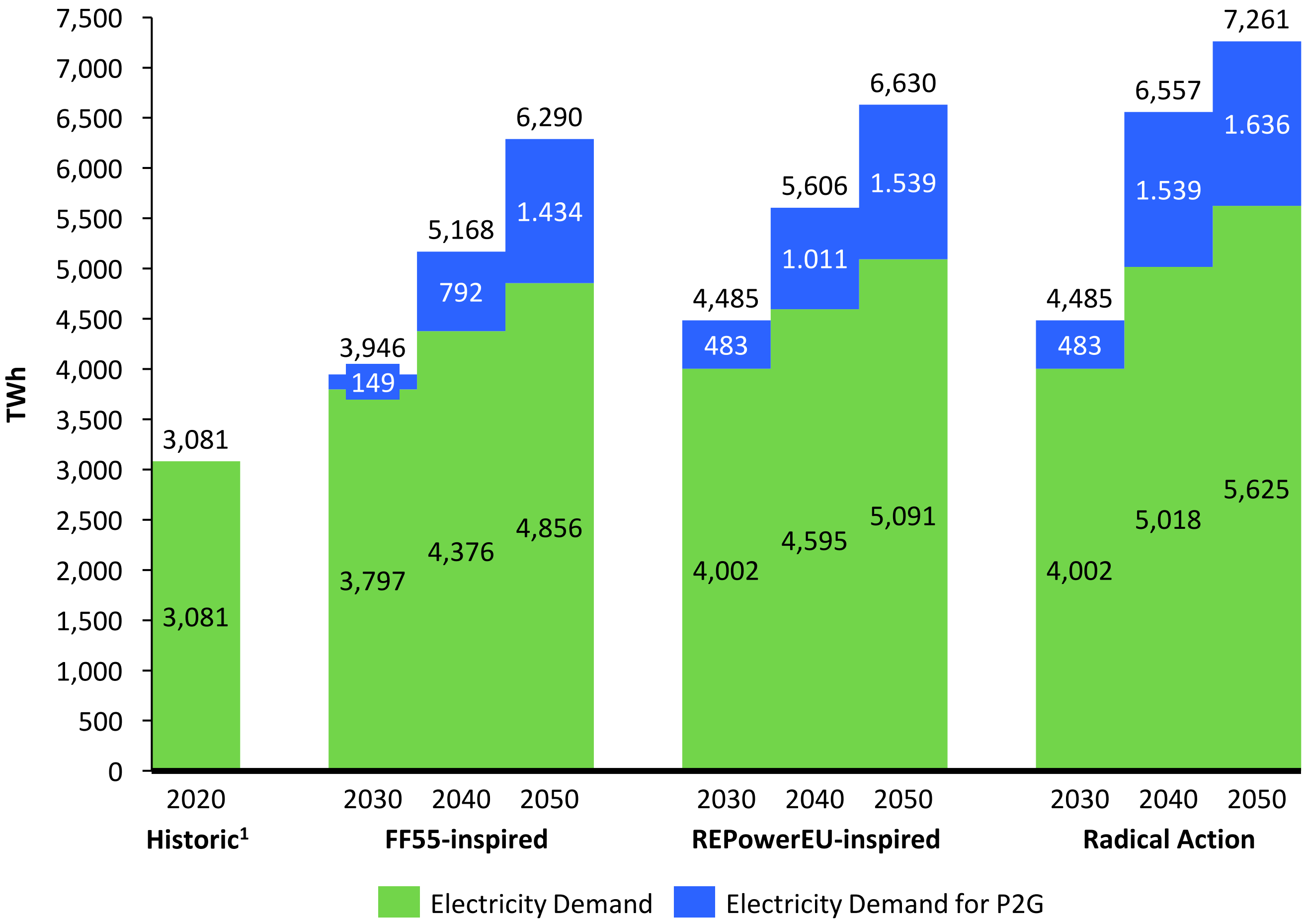
- Average carbon intensity of EU27+UK already decreased substantially. Between 2000 and 2021 a reduction of 39% was realized in gram per kWh of electricity generated.
- FF55-inspired and REPowerEU-inspired reach a net-zero power sector around 2040.
- In case of earlier desired decarbonisation, CCUS can be applied to eliminate the last remaining emissions in an earlier stage (See appendix section). However, the feasibility of CCUS remains questionable.



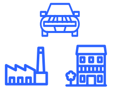
Source: European Environment Agency – GHG emission intenstity of electricity generation in Europe (2022)

The power sector enables both the direct electrification and the indirect electrification of final energy demand for various sectors

Final & Power-2-Gas Electricity Demand for all Scenarios and target years in EU27+UK – (TWh/year)



Sources: 1. EMBER (2023)



The direct electrification of sectors such as heat and transport will lead to a significant increase in the final electricity demand.

However, there are also sectors that cannot be decarbonised through direct electrification and will rely on the supply of synthetic gases and fuels. Accordingly, the power sector will also need to assist in the **indirect electrification** of individual sectors.

Hydrogen

- The most dominant P2G energy carrier for indirect electrification in this study is hydrogen.
- Clenar hydrogen is in this report defined as hydrogen produced without emissions.
- Electricity Demand for P2G is based on the assumption that of the overall hydrogen demand approximately 50 % will be imported.
- The electrolyser efficiency will increase from 69% in 2030 to 74 % in 2050.
- Further details can be found in the hydrogen appendix section and the methodology report.

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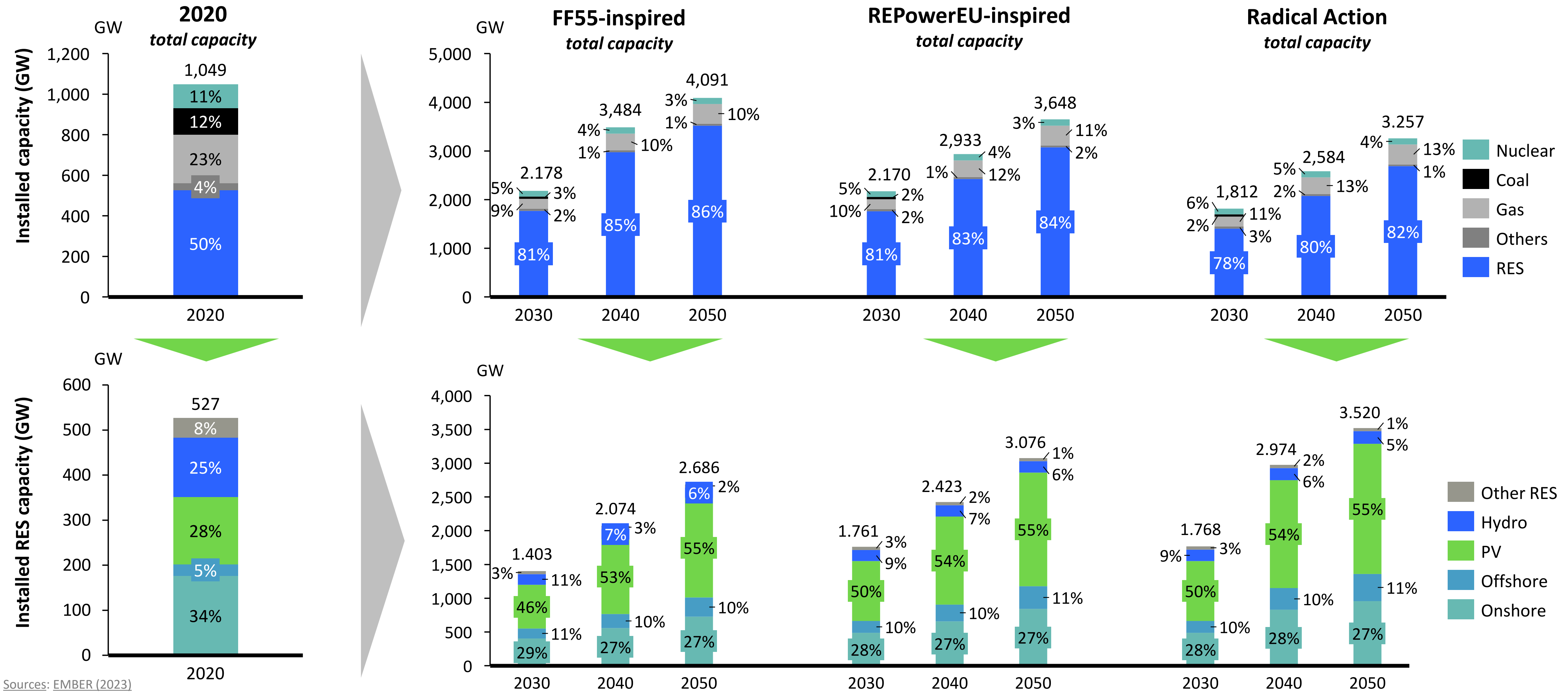
To generate the needed electricity while at the same time decarbonising the power system, all scenarios call for a strong increase in RES capacities



Sources: EMBER (2023)

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Others include oil and small-scale CHP; Other RES include geothermal, maritime, biomass etc.
Note: gas capacities indicated in light grey include turbines for natural gas, hydrogen and biomethane. Natural gas is phased out in the power sector after 2040.

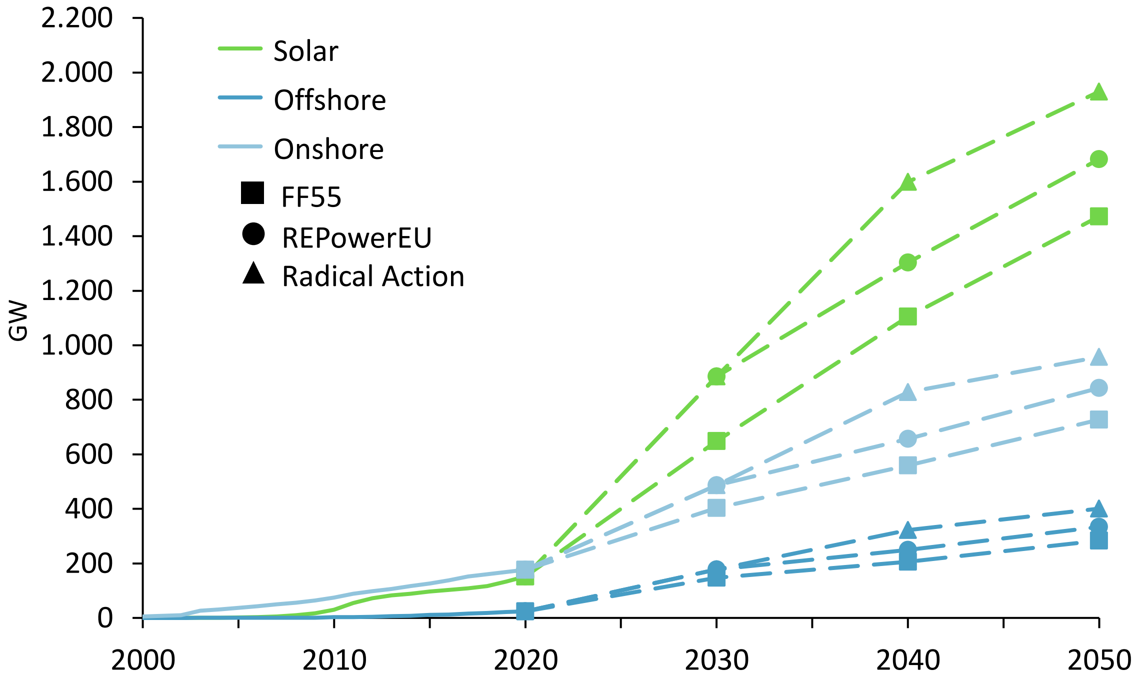
Faster RES rollout will be essential to meet the capacity demand. Especially solar PV, onshore wind and offshore wind will drive the growth

In all scenarios, it is recognisable that a functioning, decarbonised electricity system requires a massive magnitude of PV and Wind capacities. The total necessary aggregated wind and PV capacity grows from 2,485 GW in FF55-inspired to 3,287 GW in Radical Action in 2050.

To reach these renewable capacity targets, the expansion of solar, onshore and offshore needs to be accelerated significantly compared to historical growth rates.

	2020 (Growth per year[3] 1990 – 2020)	2050 (Growth per year[2] 2020 – 2050)		
	Historic	FF55-inspired	REPowerEU-inspired	Radical Action
Solar PV	150 GW (7.6 GW/a)	1,473 GW (44.1 GW/a)	1,683 GW (51.1 GW/a)	1,930 GW (59.3 GW/a)
Wind offshore	25 GW (1.2 GW/a)	284 GW (8.6 GW/a)	334 GW (10.3 GW/a)	400 GW (12.5 GW/a)
Wind onshore	177 GW (8.9 GW/a)	728 GW (18.4 GW/a)	843 GW (22.2 GW/a)	957 GW (26.0 GW/a)

Growth rates for top three RES capacities EU27+UK over scenarios (GW)



Sources for historic values:1. EMBER (2023)
Note: 2020 year is used to match complete scope for all countries and technologies.

[2] Note: Calculation of growth rates per year is based on difference between 2020-2050. Furthermore, scenarios focus on long-term and hence, it needs to be noted that the targeted growth rates of the underlying scenarios have not been reached in 2021 and 2022.

[3] Note: for historical growth rates the values between 2000 - 2020 are taken, since installed RES capacities in 2000 had limited scale: solar PV: 0.18 GW, wind on-shore: 5.84 GW wind off-shore 0.05 GW (Eurostat 2022).

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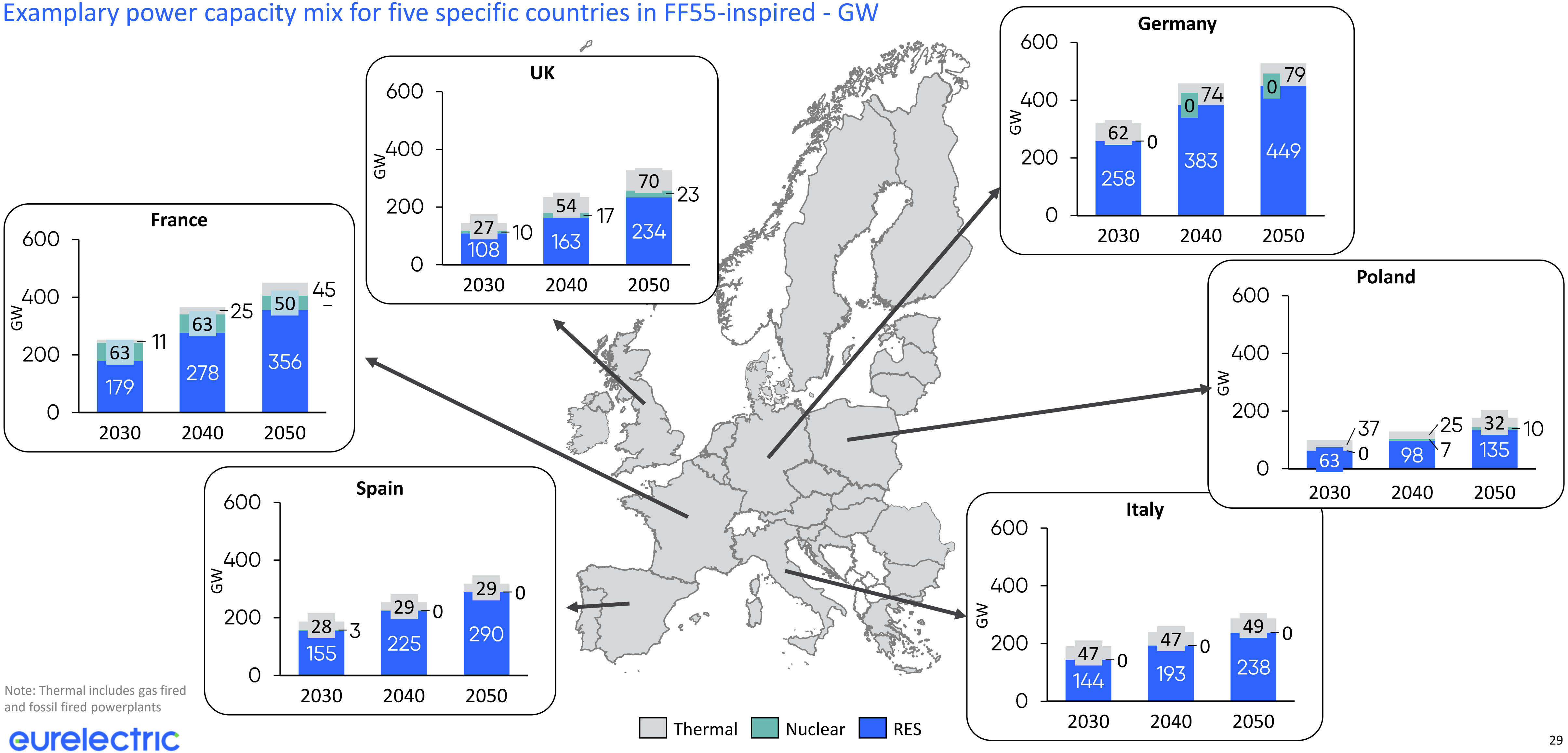
The development of power capacity mix in Europe shows a significant shift towards RES capacities – Nuclear stays relevant in several bidding zones

Examplary power capacity mix for five specific countries in FF55-inspired - GW



Note: Thermal includes gas fired and fossil fired powerplants

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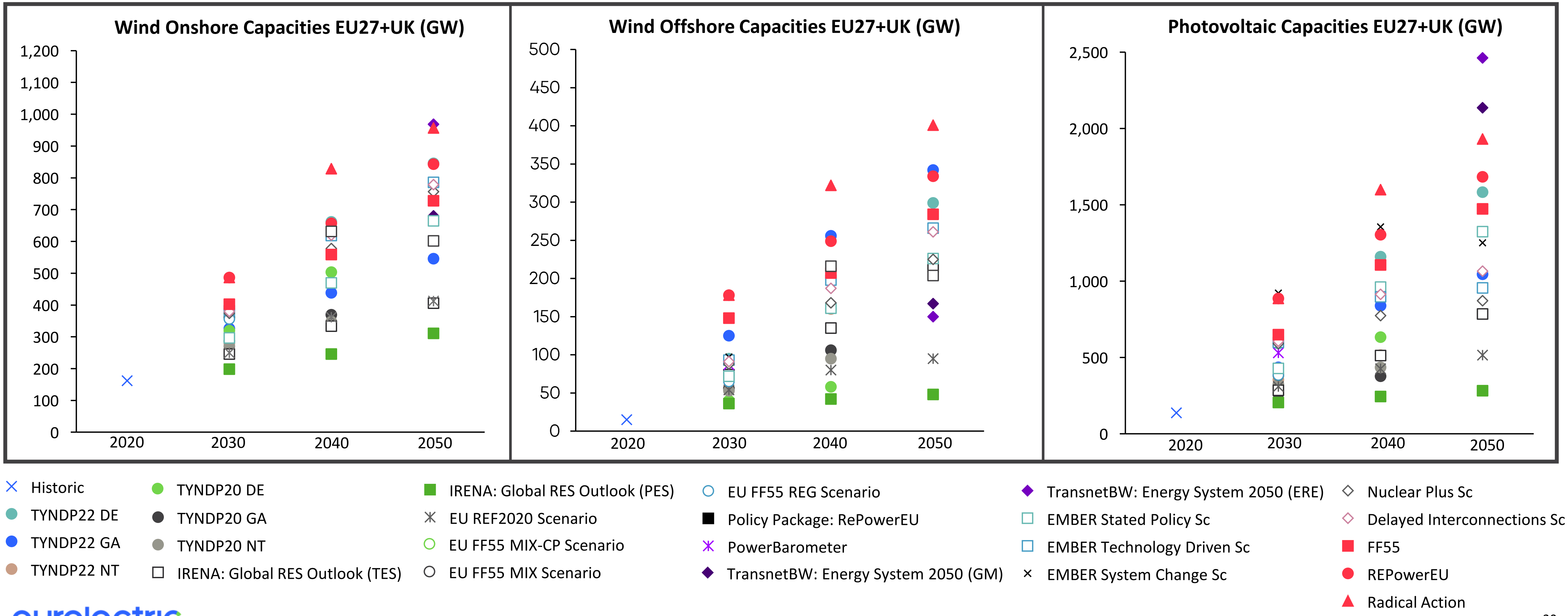
The FF55-inspired and REPowerEU-inspired RES capacities are in line with EU-wide recognised decarbonisation studies. Radical Action are upper end

The FF55-inspired scenario maps a potential development towards a decarbonised energy system. A carried out meta-analysis indicates that the scenario created is ambitious, especially with a view to 2030. However, the installed capacity is within the range of the other studies. It is striking that the EU's lead scenarios show a significantly lower installed capacity in all target years, as the demand for electricity in particular is significantly lower than expected today.



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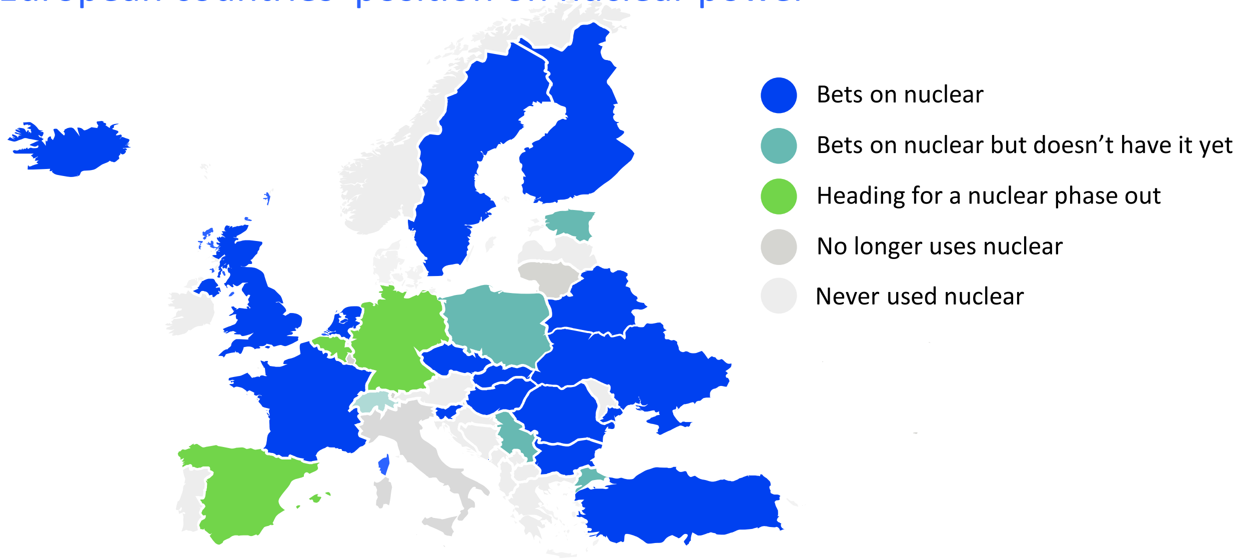
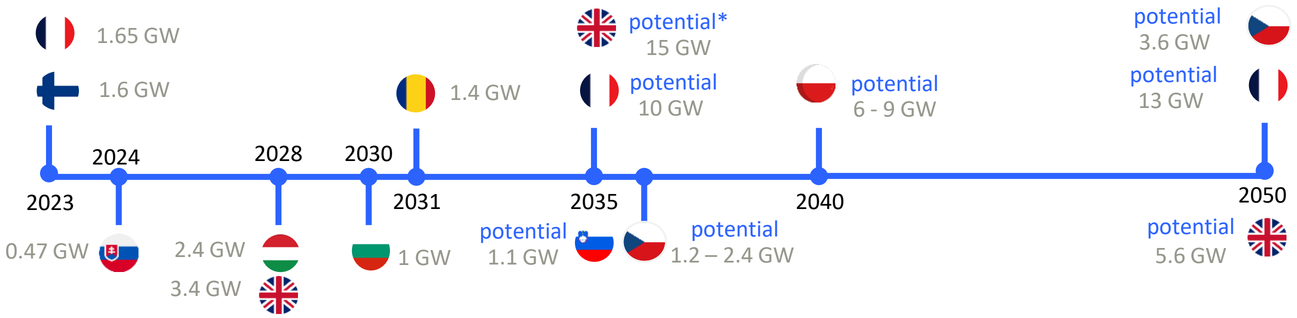
National determined plans of nuclear extensions or new projects provide indication of low-carbon generation contribution to decarbonisation in EU and UK

European countries' position on nuclear power



Timeline of new European nuclear projects' operational capacities



*Estimated capacities based on the latest announcements of nuclear plans. Range of uncertainty provided if available (Poland and Czech Republic), otherwise split over time of planned new capacity according to announcements in the specialized press. Note that announced plans for new reactors can change over time.

Sources: Accenture research October 2022, World Nuclear Association (2022), Dow Jones Factiva, International Atomic Energy Agency PRIS (2022)

European nuclear projects by stage and type of technology

Country	Reactors under construction	Planned reactors	Reactors in decision making process	Small modulars reactors**
France	1 (defined milestones)		6 (defined milestones) + 8 (undefined milestones)	
UK	2 (defined milestones)	2 (defined milestones)	8 (defined milestones)	
Czech Republic		1 (defined milestones)	3 (undefined milestones)	(announced or in study phase)
Sweden				(announced or in study phase)
Poland			6 (defined milestones)	
Finland		1 (defined milestones)		(announced or in study phase)
Bulgaria		1 (defined milestones)	2 (cancelled)	(announced or in study phase)
Hungary		2 (defined milestones)		
Slovakia	1 (defined milestones)		1 (defined milestones)	
Romania		2 (defined milestones)		(announced or in study phase)
Lithuania				(announced or in study phase)
Netherlands			(announced or in study phase)	
Slovenia			1 (defined milestones)	

Defined milestones — Undefined milestones — Cancelled — Announced or in study phase

**Only publicly announced studies are reported. In Sweden, a feasibility study on building 2 SMRS at Ringhals is to be completed by 2024. In Romania, the US government partners with Nuclearelectrica and provide support for the engineering and design study for 6 SMRs.

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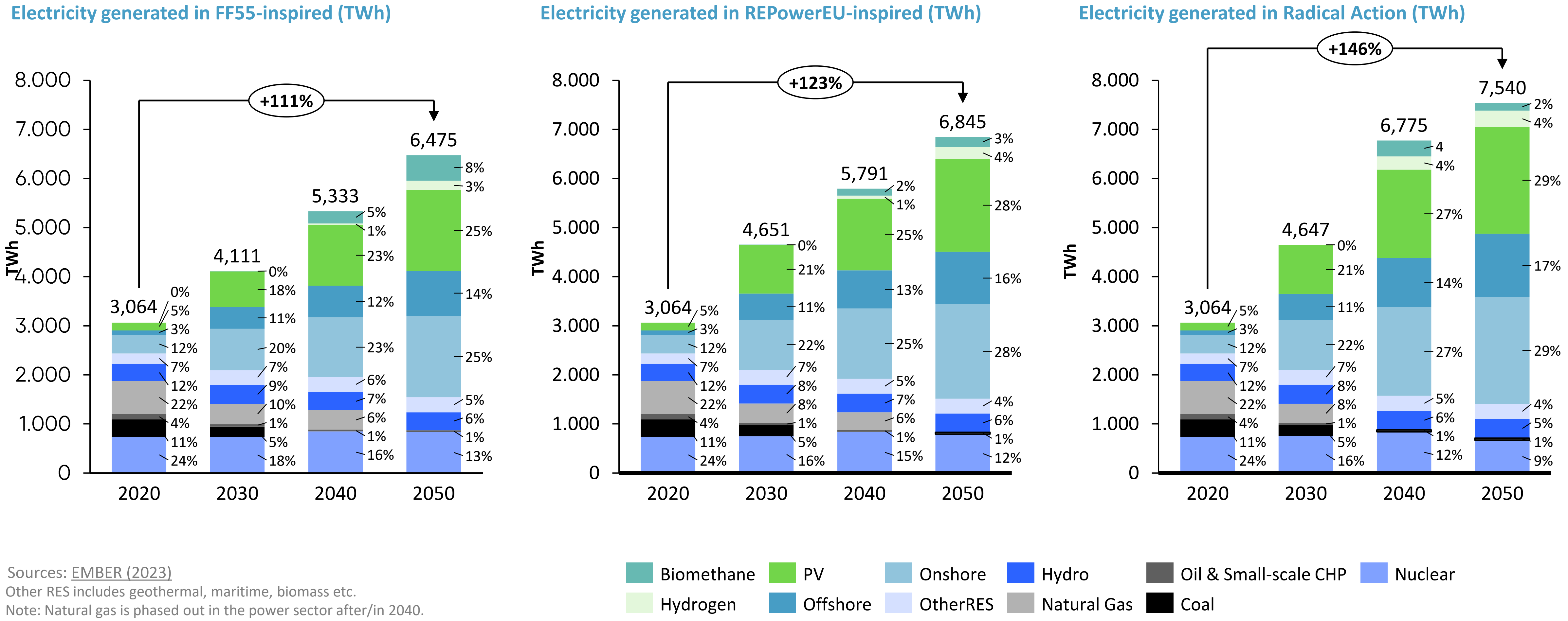
The 2050 electricity generation mix will be dominated by renewables, complemented with other clean generation technologies

Development of the electricity generation over the timeframe of 2020 until 2050 for all scenarios in EU27+UK



Sources: EMBER (2023)
Other RES includes geothermal, maritime, biomass etc.
Note: Natural gas is phased out in the power sector after/in 2040.

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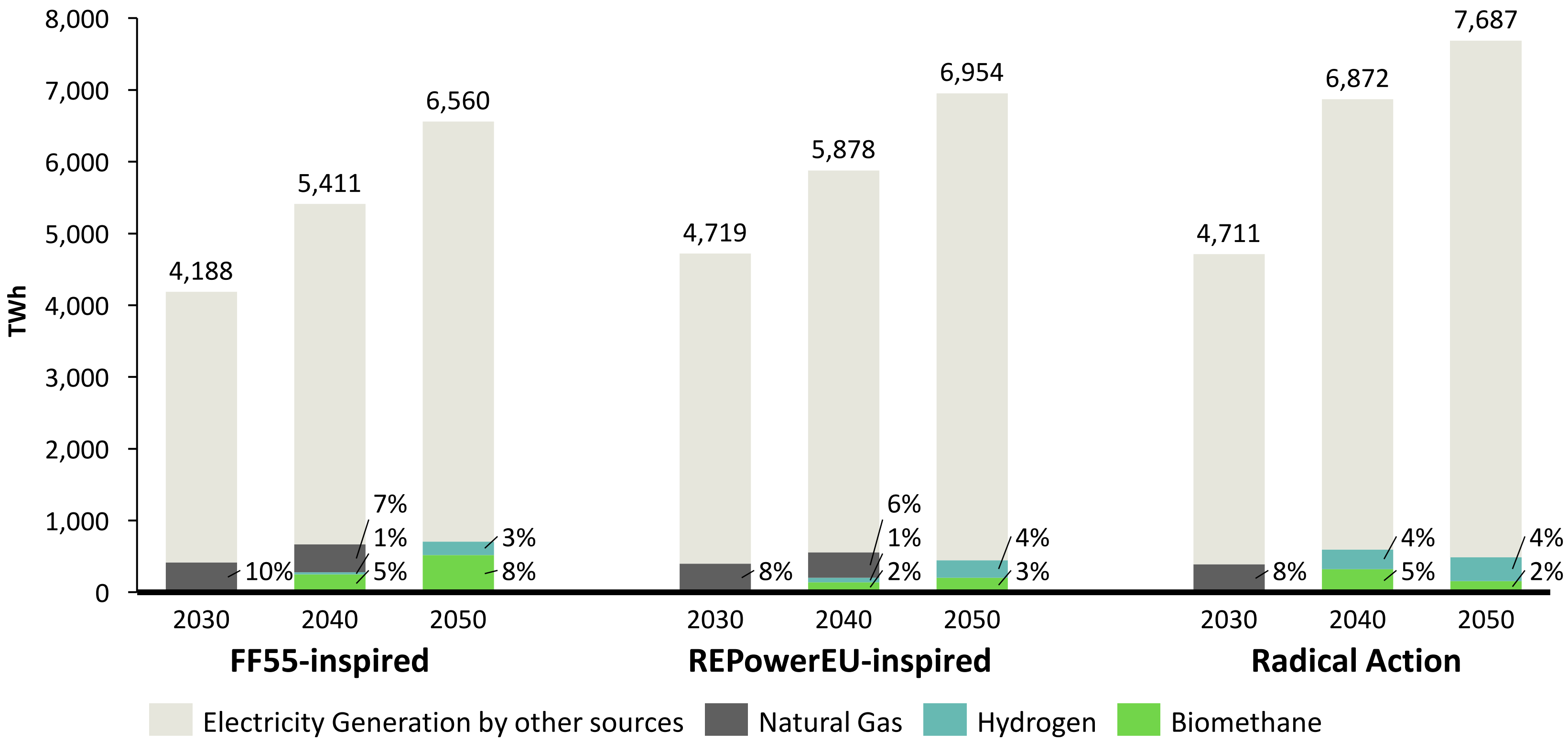
To a relatively small extent, the power sector will rely on gases and their associated controllable generation to balance the power system

Electricity generation from gas in comparison to other sources in EU27+UK (TWh)

The figure below shows the electricity generation by gas compared to the overall electricity generation for all scenarios and target years



Key Take-Aways:

- The power sector is reliant on a share of controllable capacity such as gas units, even in the long term, to provide system inertia*.
- Throughout all target years and scenarios, the share of gases is between 6% (2050: Radical Action) and 13% (2040: FF55-inspired)
- An accelerated uptake in RES capacities (REPowerEU-inspired & Radical Action) reduces the dependency on gas within the power sector

Approach

- Fuel availabilities are iteratively adjusted and parameterized in order to reduce the share of Hydrogen in the power sector while at the same time fulfilling the 50/50 Hydrogen import constraint with a 5 % error margin, as results of further model iterations.
- See the appendix section on hydrogen and biomethane for further details.

Cost of Hydrogen & Biomethane:

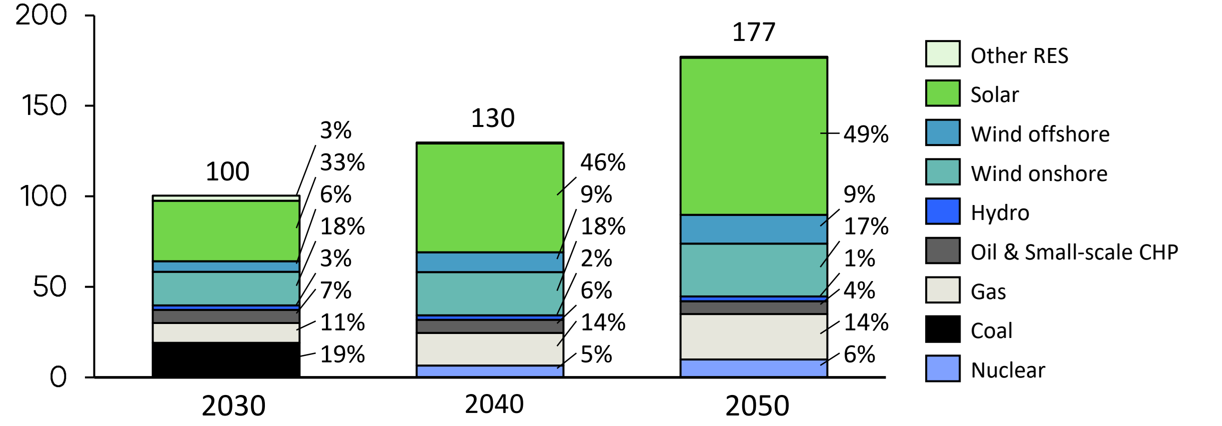
- With regards to the marginal fuel costs, we assumed a lower variable costs for hydrogen compared to biomethane in the modelling.
- Equal CAPEX costs for the construction of gas units running on hydrogen or biomethane are considered.

*Note: Power system inertia refers to the energy which is stored in the large generators. This temporary storage of energy can assist in seconds when power plants fail. Current capacity mix with high shares of thermal power plants offers sufficient storage. With future power system with high RES penetration, a minimal amount of inertia is required (NREL – 2020)

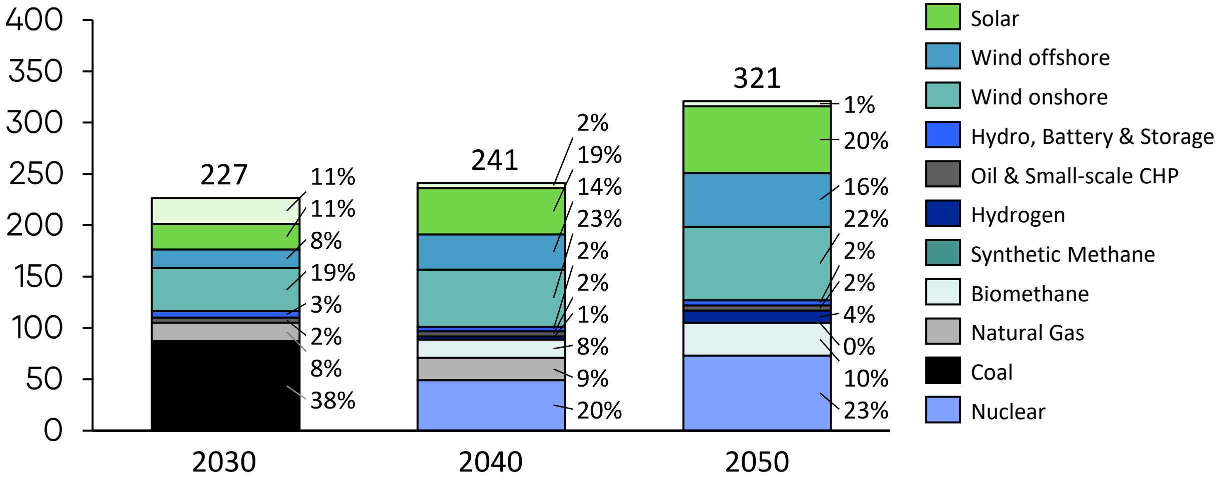
Case Study: Development of the Polish electricity system in FF55-inspired

Poland's generation landscape is undergoing a significant change - Based on current expansion trends, Poland achieves installed offshore wind capacities of at least 16 GW in 2050 being one of the most ambitious targets in EU27+UK in FF55-inspired.

Installed capacities Poland – FF55-inspired (GW)

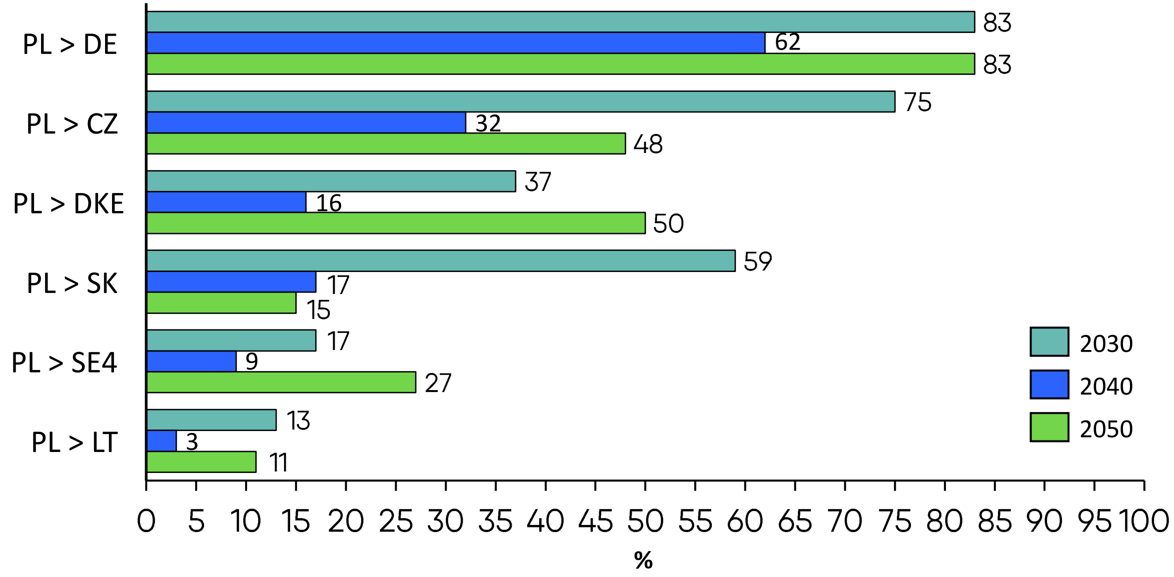


Electricity generation by fuel type in Poland – FF55-inspired (TWh)



Note: The shown scenarios assume a phase out of coal until 2040 what is more ambitious than the national plans which set that date further in time. This results in higher investments in gas. Furthermore, a higher electrolyser capacity is assumed.

Average yearly interconnector saturation[1] in Poland – FF55-inspired (%)



- Poland accelerates the expansion of RES capacities and will reach 135 GW in 2050. This increase will cause significant investment costs of around 111 bn. €.
- The large uptake in RES capacities between 2030 and 2050 results in a more variable electricity generation. To flatten the generation, new nuclear and gas capacities with zero emissions will be installed too.
- The new power mix creates the potential to become an exporter while zero emissions can be reached in 2050.

1. Interconnector saturation displays the average utilization of the aggregated Net-transfer-capacity (NTC) over the given year

Note: Other RES includes geothermal, maritime, biomass etc.

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The variability of RES feed-in offers a great opportunity for flexibility offerings to step in and to help balance out supply and demand

Flexibility defined

Flexibility refers to the ability of an electricity system to **respond variations** in electricity **supply** and **demand**.

These variations can occur over **differing timeframes**, from seconds (e.g. a wind turbine tripping out) to months (e.g. seasonal differences in energy consumption).

Flexibility can be supplied by any element in the electricity system which can **controllably and dynamically** increase or reduce its supply or demand characteristics.

Three categories of flexibility and offerings

Demand

Three main offerings from the demand side included:

- V1G EV (smart charging) in transport
- DSR in Industry
- Heat pumps in buildings

Storage

Four offering can be distinguished:

- V2G EV in transport
- Prosumer scale batteries (BtM***)
- Utility scale batteries (FtM***)
- Pumped hydropower storage

Supply* (generation)

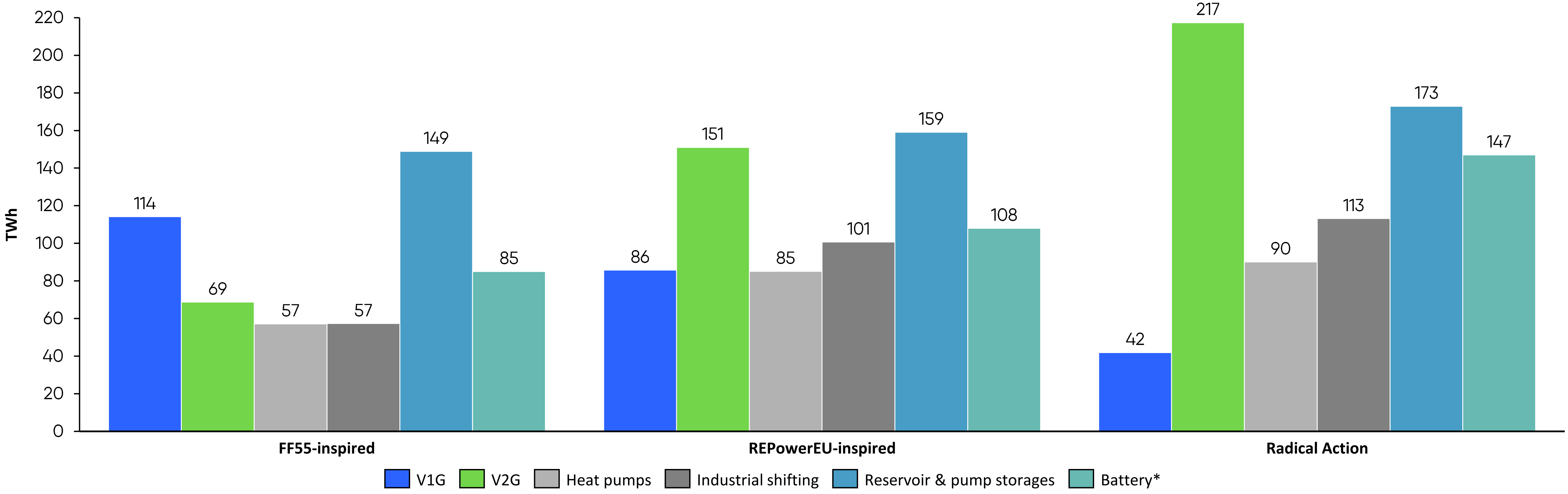
Electricity generation can implicitly respond via changing generation supply based on demand. Today's supply side flexibility is mainly offered by gas fired** generation plants and by hydro power plants such as turbines and pump storages.

*Supply or generation is not explicitly approached as flexibility option in the market model
** Fired via natural gas, hydrogen or biomethane.
Note: more flexibility offerings and tools will become available, only the main offerings are assessed here. New business models on grid utilization and DSM will become increasingly important.
*** FtM = Front of the meter. BtM = Behind the meter.

A decarbonised power system with high share of variable RES requires a significant amount of flexibility: 531 TWh – 782 TWh in 2050

- Flexibility activation (TWh) of storage technologies such as hydro power reservoir and pump storages as well as batteries is assessed via the flexible electricity generation and the activation of load shifting processes such as Heat pumps or Industrial shifting is assessed via the activated load decrease of the load-shifting processes
- Within the model reservoir and pump storages incorporate the flexible share of the overall hydro power generation and will play the main role as provider of flexibility.
- The importance of the transport sector in particular electric mobility is significant for the power system, as V1G and V2G provide the second largest amount of flexibility in 2050 in all scenarios.
- See the flexibility appendix section for further elaboration on flexibility, the capacities in GW and the assumptions made.

Overview of the use of selected flexibility sources in a decarbonised power system in 2050 (TWh)



Note: *Battery includes prosumer-scale and utility-scale batteries, with approximately equal capacities. Conventional capacities also provide flexibility to overall power system; however they provide additional net electricity generation and hence, are less comparable to demand side management and storage technologies. Hydropower reservoirs and pump storages are combined in this overview.

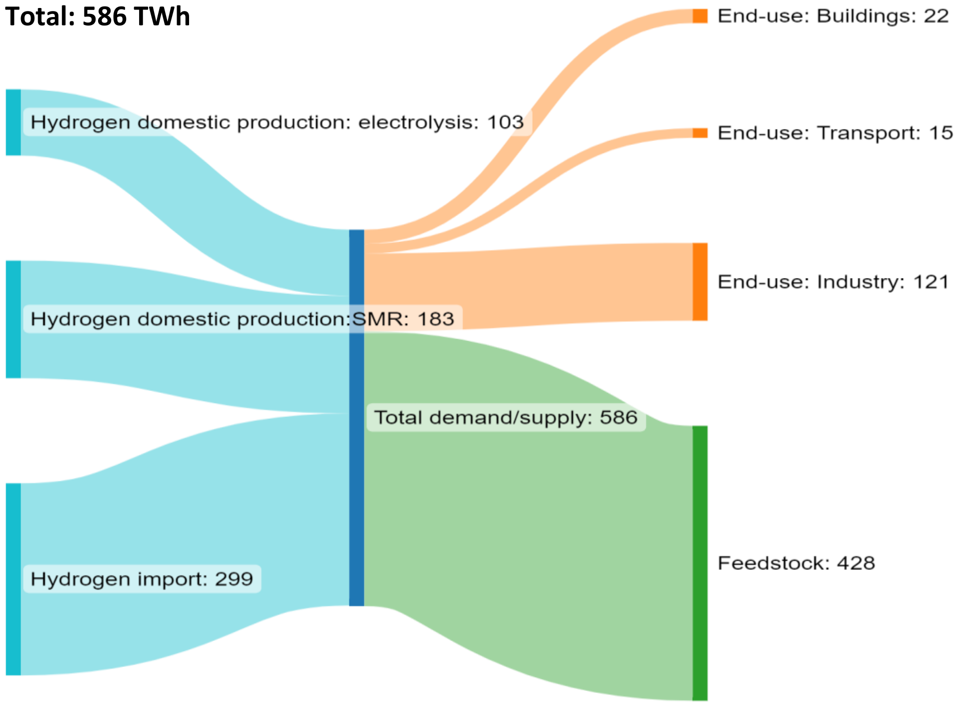
eurelectric

Hydrogen and other decarbonised fuel solutions will play an important role, albeit under certain ramifications only, mainly in heavy industries, the transport sector and to provide flexibility to the power sector

Flow of hydrogen: FF55-inspired in 2030 (TWh)

In 2030 still 183 TWh of hydrogen is produced via Steam Methane Reforming (SMR). ~51% of the total demand will be imported. Most of the demand is used for feedstock, where hydrogen is input for a production process. Hydrogen for end use refers to hydrogen used as energy carrier for final energy demand, dominated by industry. Hydrogen will only contribute to decarbonisation if produced via clean sources.

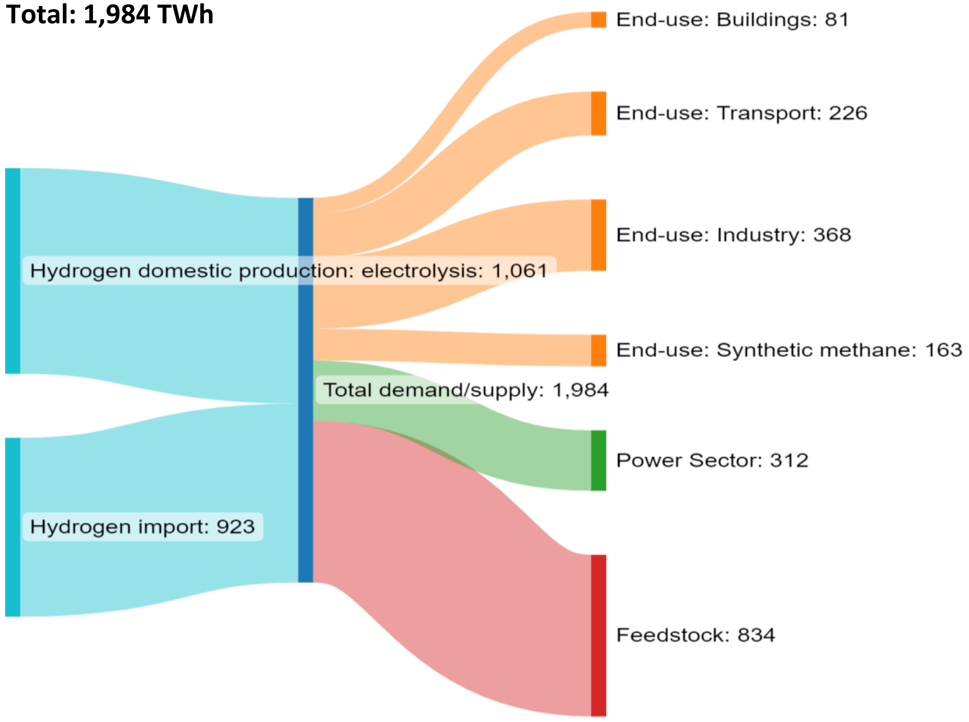
Total: 586 TWh



Flow of hydrogen: FF55-inspired in 2050 (TWh)

In 2050 the total hydrogen demand accounts for 1,984 TWh. Furthermore, all hydrogen in scope is created via electrolysis. ~46% of the total hydrogen is imported. Clean hydrogen end use has increased in all sectors, including the demand of synthetic methane. ~312 TWh is used for the power sector, providing controllable generation via seasonal storage. Feedstock in 2050 comprises of 834 TWh, constant over all scenarios.

Total: 1,984 TWh



Note: See appendix section on hydrogen for the other scenario hydrogen flows

Electrolyser capacities need to grow in order to meet the increased domestic production of clean hydrogen in the future

Availability of hydrogen is ensured via domestic production and import

- A ratio of 50% import and 50% domestic production is approached, in line with the REPowerEU targets for 2030.
  - A 5% error margin is taken, as result of model iterations and the interdependencies.
- Domestic production will shift from dominantly Steam Methane Reforming towards electrolysis via clean electricity

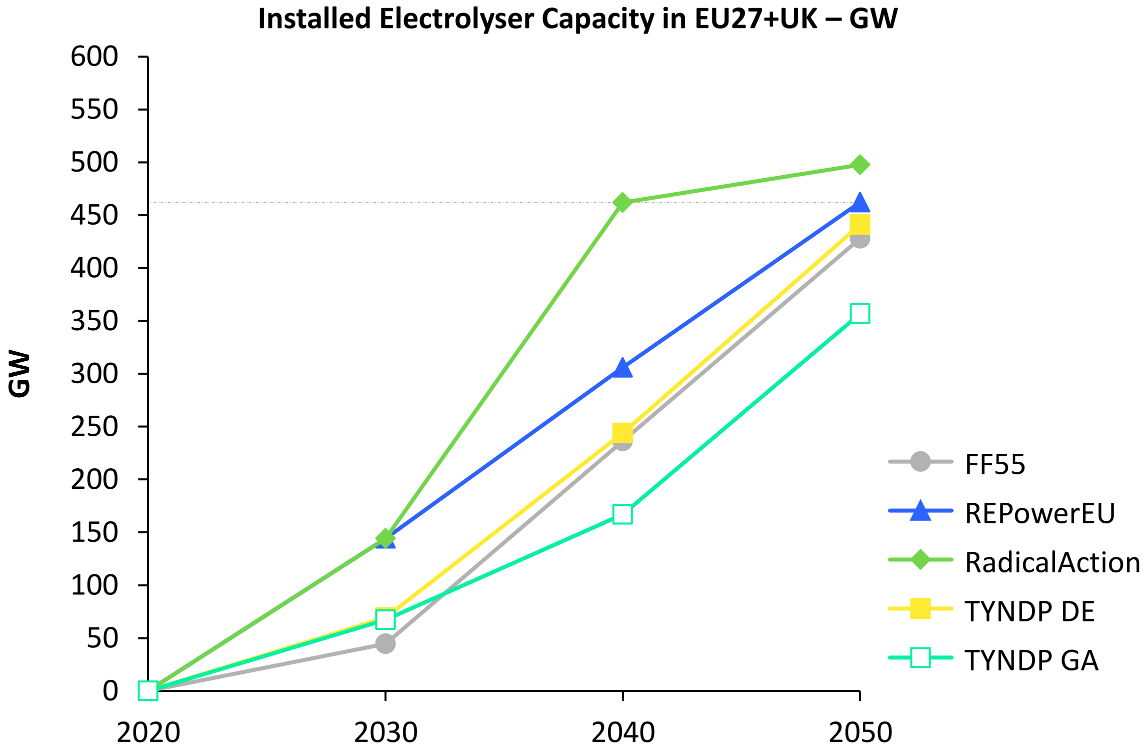
Cost of hydrogen will decrease further due to cost reductions in electricity and electrolysers

- Levelized Cost of Electricity (LCOE) and cost of electrolysers are the main drivers of the production costs of hydrogen.
- Dominant types of electrolysers are Proton Exchange Membrane (PEM) and Alkaline, accounting for 55% and 44% of the installed capacity in Europe[5]
- Average efficiencies of the total fleet on the market are: 2030:69% 2040:71% 2050:74%
- Cost of transportation & distribution depend on the mode of transport, the distance of transportation, the hydrogen form (gaseous / liquefied), the amount in Mt hydrogen, the cost of storage, terminal and import/export fees, and potential (re)-conversion[4].
- Cost of electrolysers are expected to fall: from 2,130 EUR/kW in 2020 to 520 EUR/kW in 2030[5]

Sources: 1. European Commission (2022) 2. Irena (2020) 3. IEA (2022) 4. IEA (2021)

Electrolyser Capacity to increase to meet domestic production

To meet the needed domestic hydrogen production, the expansion of electrolysers must be massively accelerated. Comparison to TYNDP shows the ambitious targets of REPowerEU-inspired and Radical Action. FF55-inspired shows similar development compared to TYNDP DE.



Sources: 5. European Commission (2022) 6. TYNDP Visualisation platform (2022)

Content

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03 The power sector needs to transform in order to drive decarbonisation in the energy system

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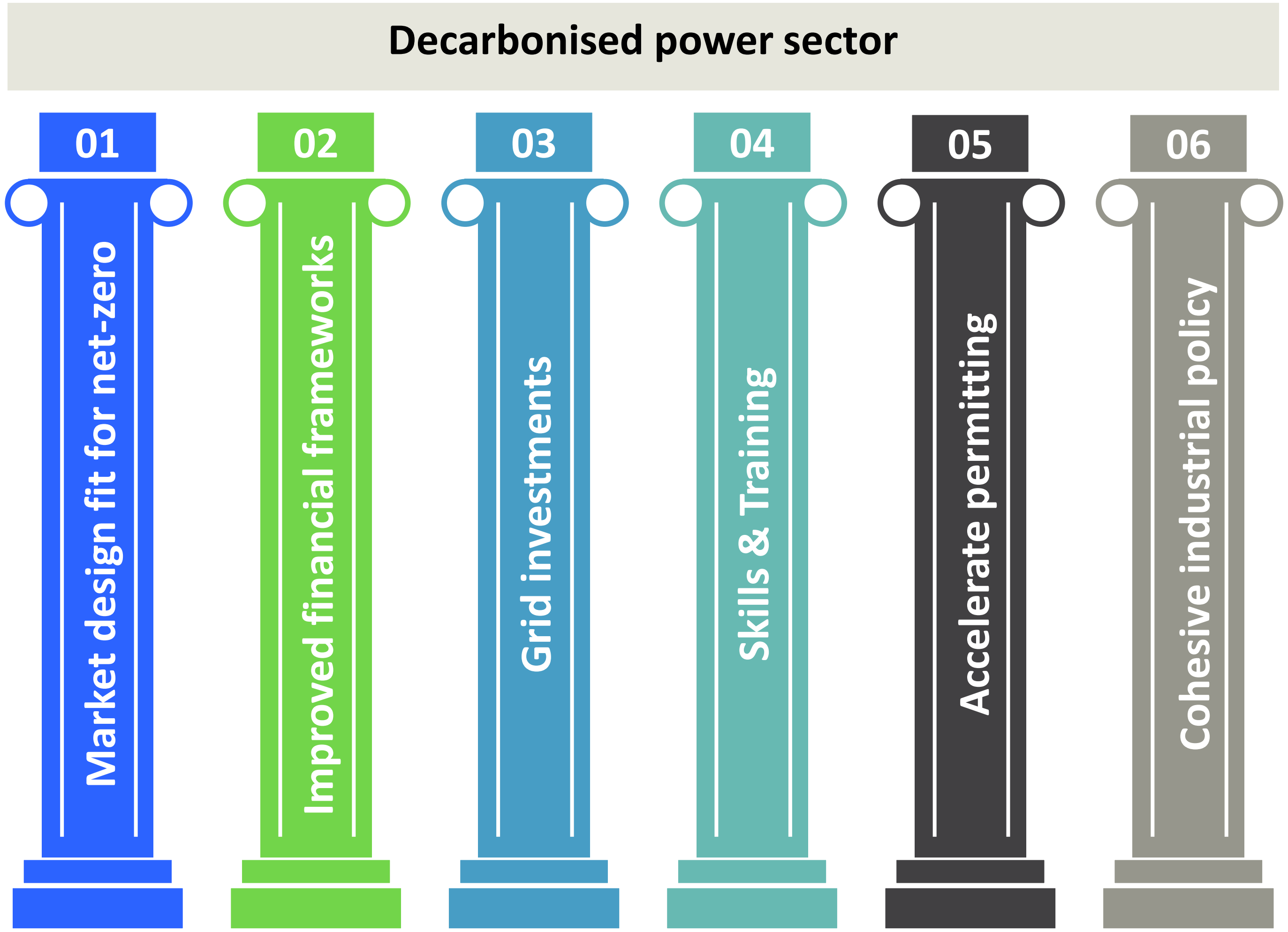
Six pillars are key to achieve accelerated decarbonisation of the power sector



Six key pillars as enablers for decarbonised power sector

The following pillars are the **key enablers** for future a net zero power system, all equally important and interdependent:

1. **Electricity Market Design fit for net-zero** providing the right investment signals – see also next slide
2. **Improved financial frameworks** to catalyze the needed investments as well as the right environment for innovation such as the next wave of decarbonised power generation technologies, e.g. Small Modular Reactors and floating offshore wind.
3. **Adequate and overdue grid investments**, in particular at distribution level, to enable the electrification and integration of new users in transport and other economic sectors
4. **Skills & training:** Investing in our personnel to fulfill the required installation and maintenance of capacities and key technologies.
5. **Accelerated permitting** and land use policies for the build-out of new power generation capacities and grids
6. **A cohesive industrial policy** to defend European industrial competitiveness and technology leadership including the secured supply of raw materials and strengthened industrial supply chains

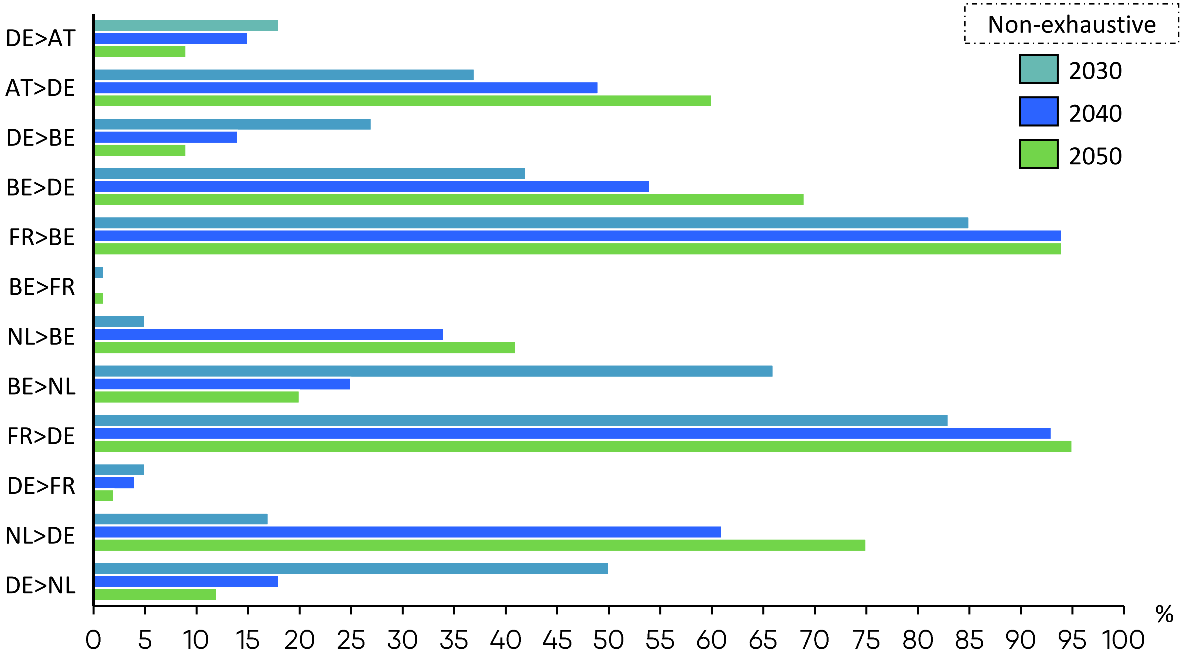
Note: the Green Deal Industrial Plan published in 2023 is an example of progress on multiple of these pillars.

Strengthening bidding zones connections benefits power system integration. Saturations of Net Transfer Capacities indicate a need for priority investment

Grid Saturation of Net Transfer Capacities between bidding zones indicate the need for increasing these connections to optimize integration of the power system

- NTC values from TYNDP are used for the simulations, since these reflect the most complete, consistent and coherent overview of the NTC values in Europe.
- NTC-Saturation in FF55-inspired indicate the major importance of France as exporter. Average utilization from France to other bidding zones in Central Western Europe is higher than 80% in all years.
- Note: also intercontinental connections can play an important role. However, these are not assessed in this analysis.

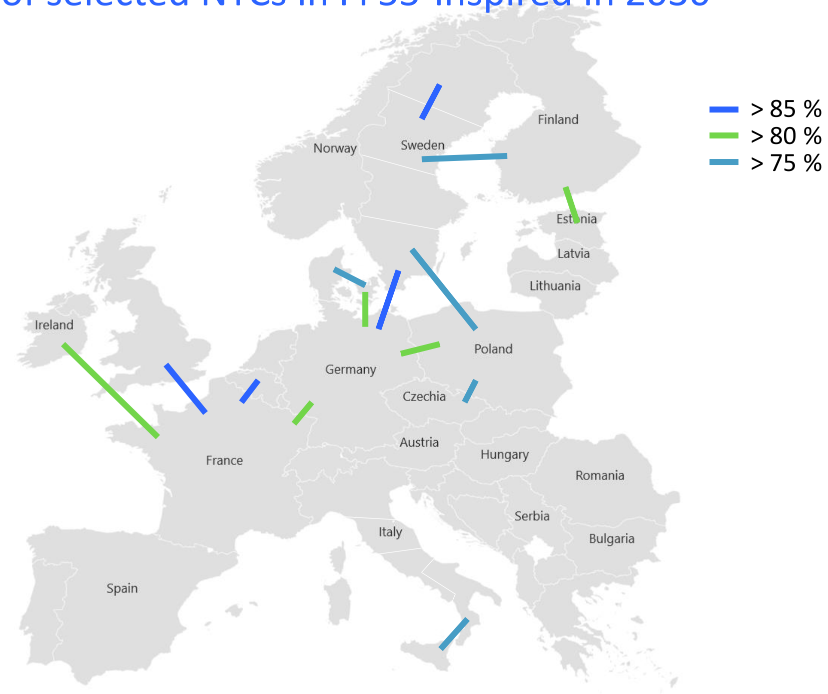
Saturation of main European Net Transfer Capacities per target year (% of max)



North West Europe and North Europe sees highest saturation between countries NTCs

- Not all connections are displayed, only the once with highest saturation (>75%).
- The figure below indicates a power flow from the North to the South of Europe in 2030. Due to the regional dependence of renewable energies, electricity must and will be distributed over long distances across Europe from countries with an advantageous connection to the rest of Europe.
- Caveat: although it is a proxy, there is no 1-to-1 correlation with saturation to future investments and many more variables play a role for future investments.

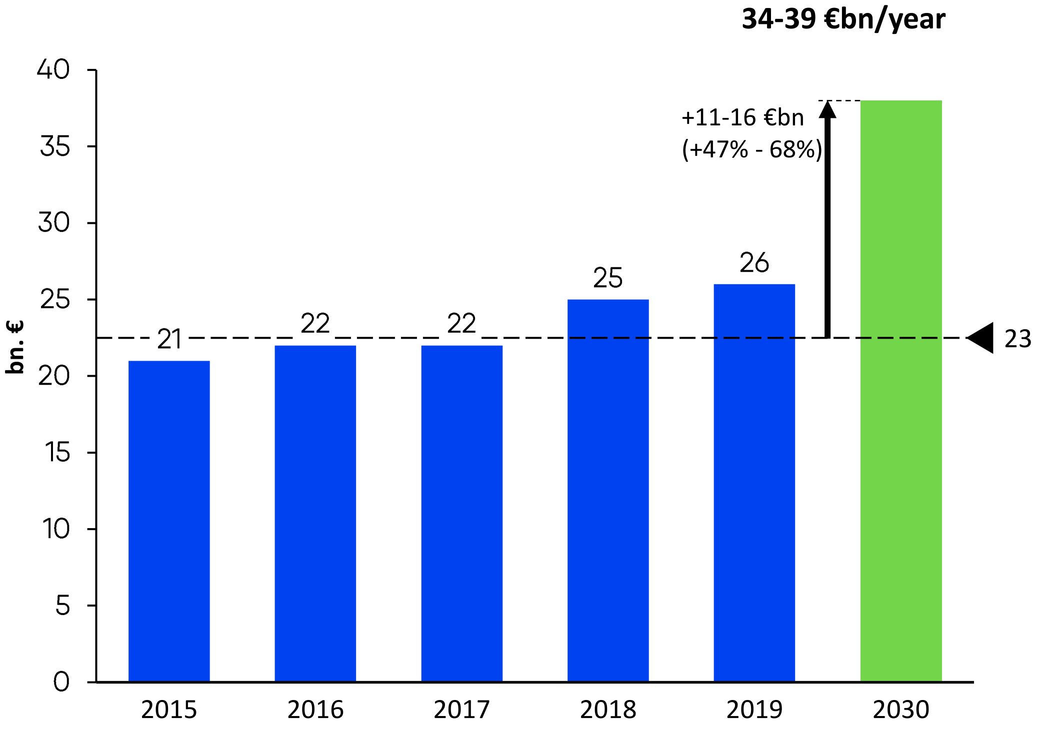
Saturation of selected NTCs in FF55-inspired in 2030



Note: not all connections are displayed, only the once with highest saturations.

Investments in DSO grids will need to increase on top of the historic efforts, to meet the majority of the RES integration on distribution level

Historic annual DSO grid investments EU27+UK (in billion euros)[2]



Sources:
1. Electricity price statistics: Eurostat (2022)
2. Connecting the dots: Eurelectric (2021)
3. GDP data for EU27 in current US dollars: Worldbank (2022)

Cumulative and yearly DSO investments per scenario based on additional TWh demand per scenario (in billion euros)[2]

DSO investments	Cumulative in 2030	Cumulative in 2050	Total Investment per year*	Of which additional / year**
TYNDP DE	€362 - €2,137	€881 - €2,726	€29 - €91	€6 - €68
FF55-inspired	€459 - €2,248	€1,012 - €2,874	€34 - €96	€11 - €73
REPowerEU-inspired	€566 - €2,369	€1,135 - €3,014	€38 - €100	€15 - €77
Radical Action	€566 - €2,369	€1,414 - €3,330	€47 - €111	€24 - €88

*For investments per year, the 2050 cumulative value was divided by 30 years. **Assuming planned investments equal the historic average of ~€23 billion average 2015-2019. Additional value per year is total investments per year minus the historic average.

- DSO grid investments in 2050 vary between €1,011 billion and €3,329 billion. Based on a range of €0.52 - €0.59 billion euro per additional TWh electricity demand[2]. The year 2020 is taken as base year[2].
- CAVEAT: Investment costs were not modeled in the electricity market model of this study.
- Extrapolation of existing studies based on the growth of final electricity demand was done to come to these investment ranges. This is an approach based only on €/TWh. In reality, many more KPIs have an impact.
- TYNDP Distributed Energy scenario is added as reference, using 3,611 TWh in 2030 and 4,606 TWh final electricity demand in 2050.
- For reference: between 2015 and 2019 annual investments in EU27+UK DSO grids increased from €21 billion to €26 billion euros. Average of historic 23 billion is taken as future planned investments.
- To compare: the combined GDP of the European Union in 2021 was 17,089 billion USD[3]. For FF55-inspired and Radical Action, the yearly investment in DSO grid would be 0.20% - 0.65% of the yearly combined GDP of EU-27 assuming an equal dollar-to-euros conversion.
- The majority of RES integration will need to happen at the distribution system level, emphasizing the need for additional investments at DSO level[2].
- Numbers taken reflected the total average annual investment needed[2]. Note that investments should not only be focused on hardware, but also software to provide smart solutions for grid usage. Future research could focus on the further specification of the allocation of investments. See the appendix section of challenges and benefits.

Total investment and operational cost of the core power system 2050 per scenario are approached. Numbers not reflect all power system components

Overview cost components for core power system

In scope of core power system costs

CAPEX generation
- RES
- Conventional/clean

CAPEX other
- Utility scale batteries
- Electrolysers

OPEX generation
- RES
- Conventional

CAPEX Grid
- DSO

Out of scope of core power system costs

CAPEX DSR offerings
- Buildings
- Transport
- Industry
- Agriculture

Hydrogen
- SMR CAPEX
- Hydrogen T&D

Capital cost & batteries
- Cost of capital
- Prosumer batteries

Carbon costs
- CCS, unabated gas
- Taxes of CO_2

CAPEX Grid
- TSO

Legend In scope | Out of scope

Important caveats

- Calculation of total system costs were not primary focus of modeling exercise, hence results are partly based on literature values and partly on model input or output values
- Inflation or deflation is not taken into account in the cost analysis
- Differentiation between results is desired in the publication via labeling:
  - **Model results**
  - **Analysis based on values from other studies**
- No further rights can be derived based on these results. The final cost values have numerous limitations, such as the different sources for cost calculations and the

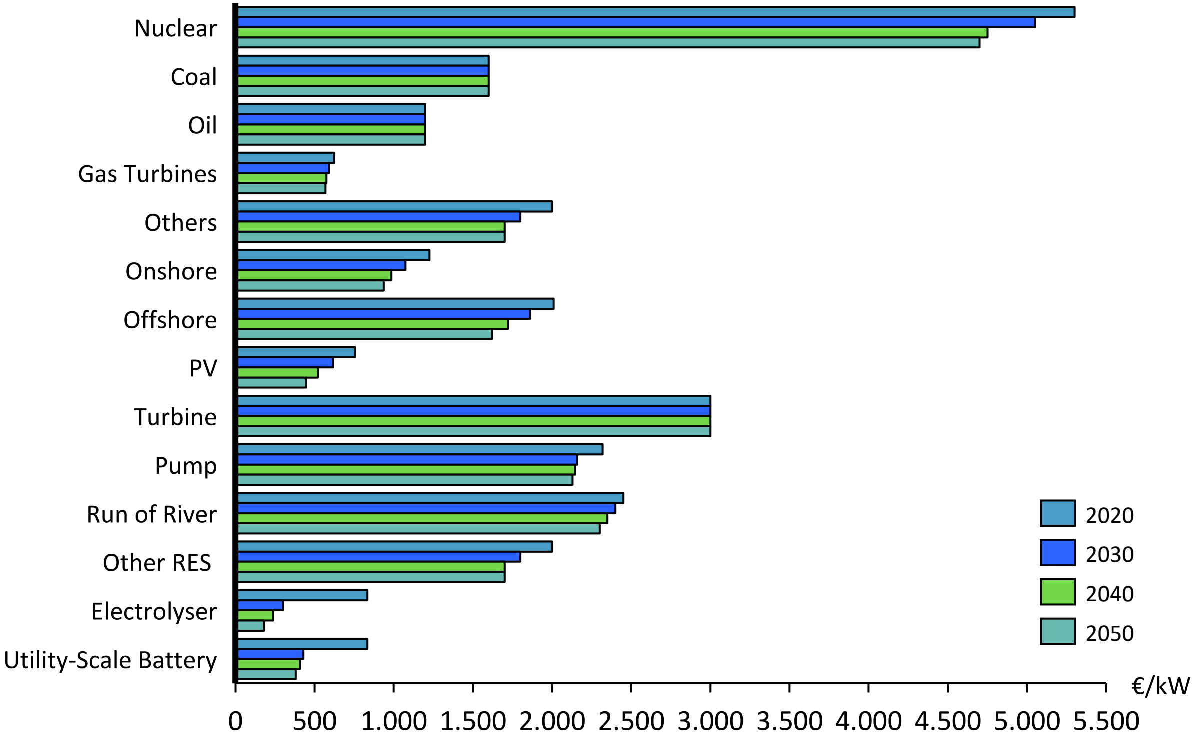
Out of scope

- Other Demand Side Response offerings. (i.e. investments for heat pumps)
- CAPEX for Steam Methane Reforming to produce hydrogen. Transmission, distribution, storage and conversion costs of hydrogen.
- CAPEX of prosumer batteries.
- Cost of capital.
- Cost off CCS.
- Taxes levies, fees and surcharges.
- OPEX for DSO & TSO grid.
- CAPEX for TSO grid.

Annual investments in new generation capacities increase, as result of the additional capacities to be built for the more ambitious scenarios

CAPEX values for relevant generation technologies in EU27+UK[1] (€/kW)

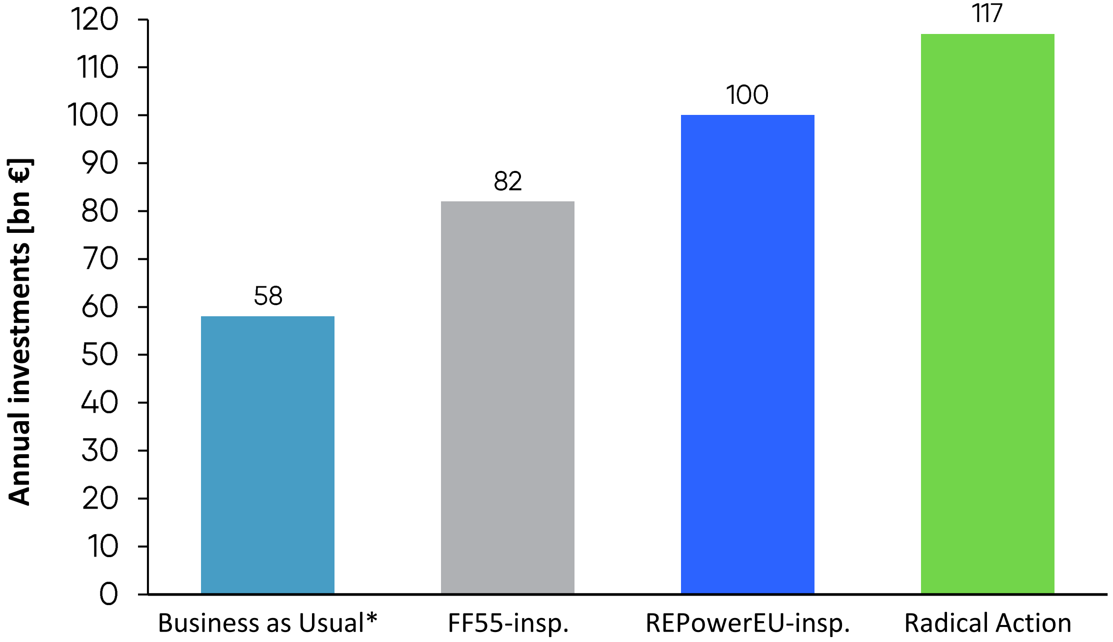
- Nuclear CAPEX values are the higest among the technologies in scope.
- Conventional technologies are not decreasing in CAPEX over target years, while the RES-related techologies do decrease over time.



Sources: 1. EMBER (2022), TYNDP 2022 scenarios: Global Ambition, Distributed Energies, National Trends. 2020 only EMBER, 2030, 2040 and 2050 average of 3 TYNDP scenarios and EMBER. For Nuclear: European Commission PRIMES Model. Note: sources differ on future CAPEX of nuclear, for the financial calculations only the Ember CAPEX values are used.
2. GDP data for EU27 in current US dollars: Worldbank (2022)

Annual Investments needed into generation capacities in EU27+UK within the period 2020-2050[3] (bn €/year)

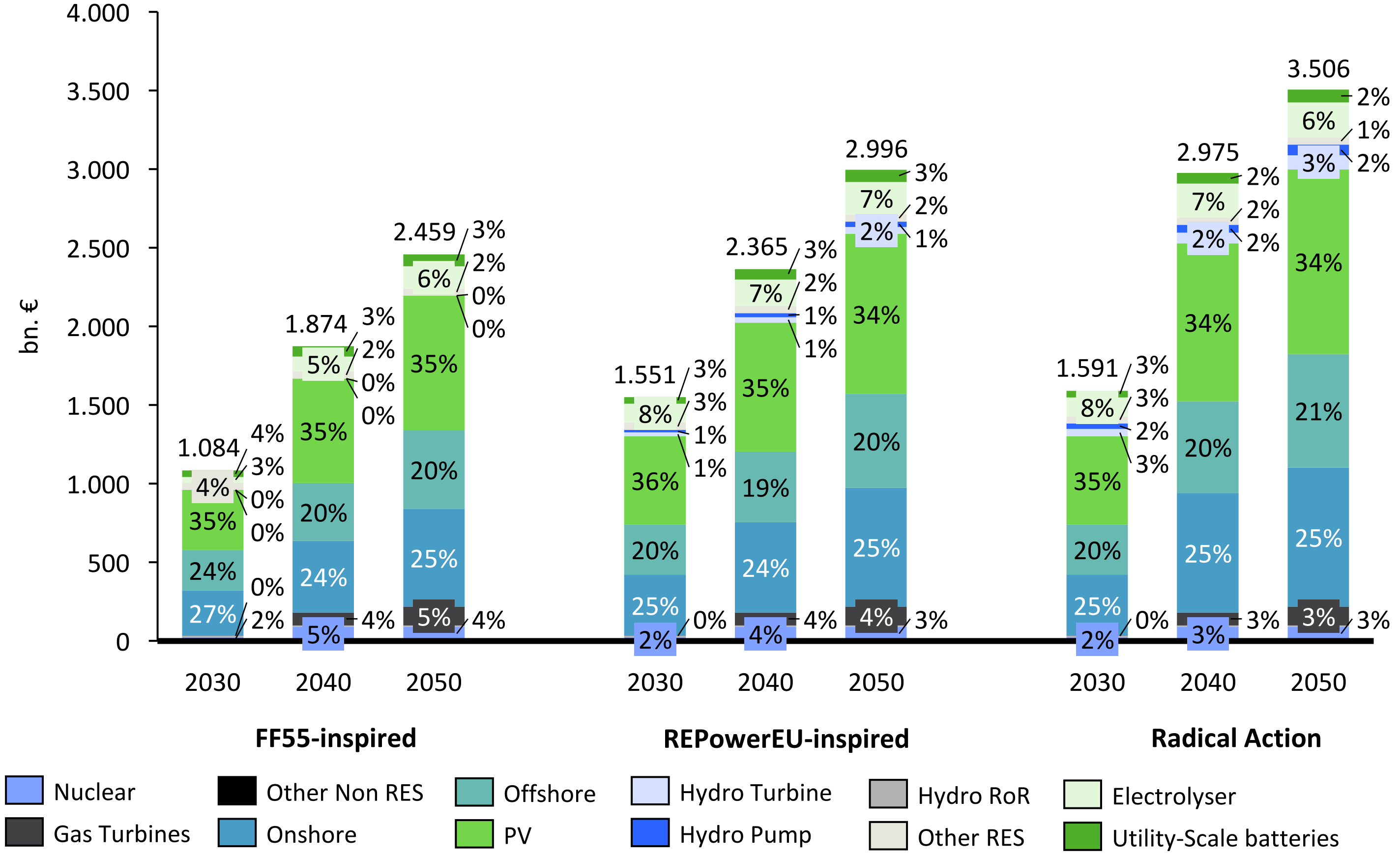
- Values are based on literature values[1] (€/kW) and capacities of the scenarios (GW).
- Business as usual is estimated for cumulative values until 2040, converted to annual investments, based on national Energy & climate Plans from countries (TYNDP). The annual investments for the Decarbonisation Speedways scenarios include higher capacities and hence higher investments.
- To compare: the combined GDP of the European Union in 2021 was 17,089 billion USD[2]. The annual investments in CAPEX for generation capacities in FF55-inspired - Radical Action are 0.48-0.68% of the yearly combined GDP of EU-27 assuming an equal dollar-to-euros conversion.



* Note: Business as usual are derived from TYNDP National Trends in 2040, converted to annual values, complemented with the underlying assumptions on CAPEX and OPEX used in this study.
3. Excluding costs on decommissioning and replacement of end-of-lifetime assets.

In order to decarbonise the electricity generation, significant investments in generation capacities are needed

Cumulative CAPEX investments into RES expansion and generation capacities in EU27+UK in 2020-2050*



Sources: 1. EMBER (2022), TYNDP 2022 scenarios: Global Ambition, Distributed Energies, National Trends. 2020 only EMBER, 2030, 2040 and 2050 average of 3 TYNDP scenarios and EMBER
Note: only top three RES technologies are displayed in percentages.

Key Take-Aways:

- In all scenarios significant investments are needed in order to shift towards renewable energy sources and clean energy technologies
- For 2050 the cumulative capex into clean generation technologies are between 2,459 bn euros in FF55-inspired and 3,506 bn euros in the Radical Action scenario.
- Radical Action: In order to decarbonise the energy system already by 2040, the cumulative investments until 2040 are especially challenging. The needed investments until 2040 in the Radical Action scenario are almost of the same magnitude of the cumulative investments until 2050 in the REPowerEU-inspired scenario.
- Note: investments in Radical Action continue, since electricity demand and thereby the installed capacities increase, after reaching net-zero in 2040.

Approach

- On the left the cumulative Investments are displayed. Within the calculation, the focus was set on the generation technologies and how a switch towards renewable energy sources and clean generation technologies can be accomplished.
- Additional capacities from the model input values were multiplied with investment values from literature[1] and summed for the years.

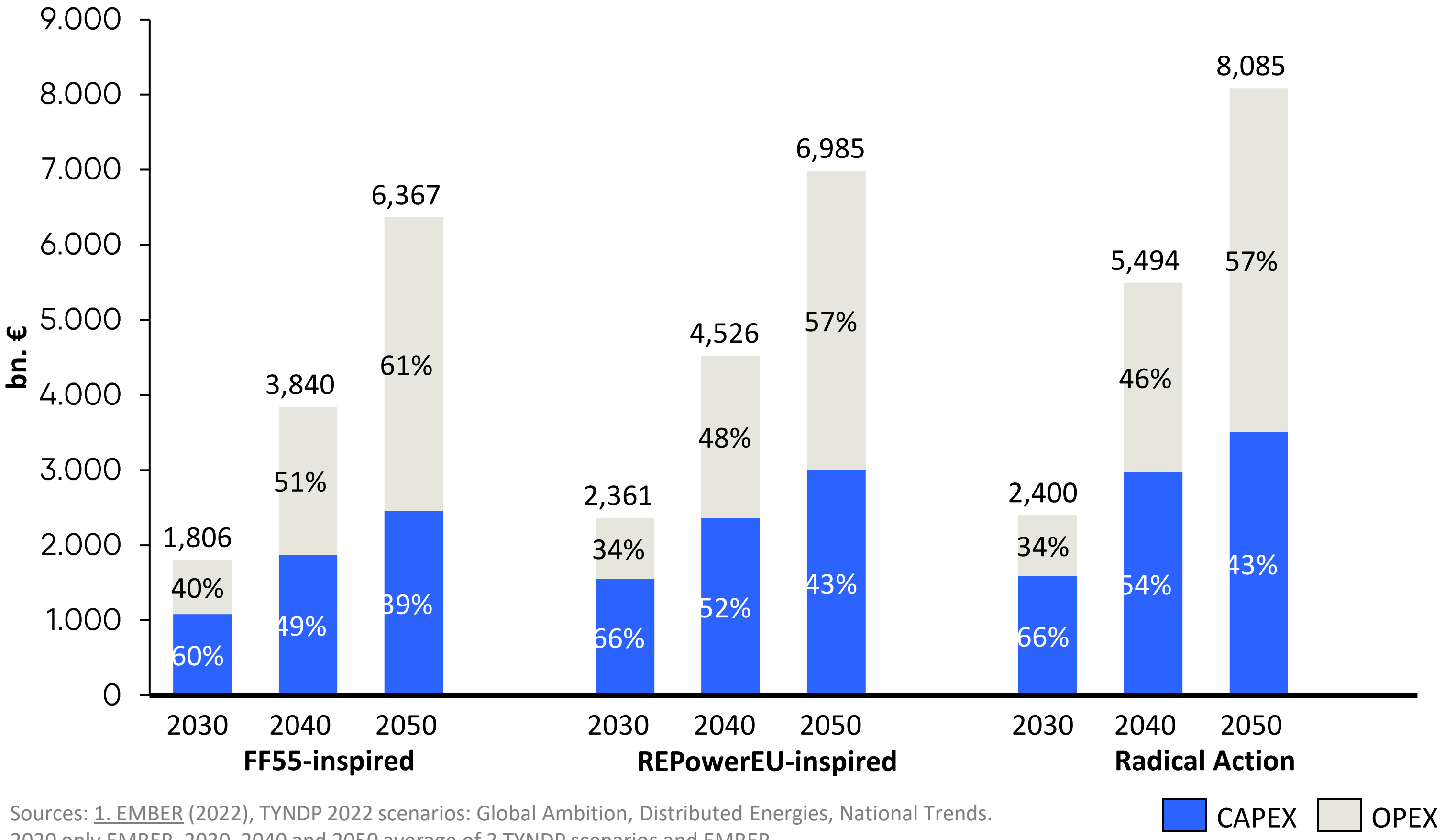
*Caveats:

- Sources used based on modeling outcomes and further analysis with literature values on CAPEX values.
- Increase in gas turbines apply, but are considered multi-fuel gas turbines for biomethane, hydrogen and natural gas.
- Within this figure the investments needed for the power grids are not included.
- The investments are to be interpretated as over night investments.
- Excluding replacement of end-of-lifetime assets.

Both CAPEX and OPEX for electricity generation grow over time and over the scenarios

Cumulative CAPEX and OPEX of the power sector for clean generation in EU27+UK for 2020-2050*

Comprising CAPEX for the installment of new RES or clean generation technologies as well as the Investments into utility-scale batteries and electrolysers. OPEX comprises the fixed and variable OPEX (e.g. Fuel costs) for 2020-2050*



Sources: 1. EMBER (2022), TYNDP 2022 scenarios: Global Ambition, Distributed Energies, National Trends. 2020 only EMBER, 2030, 2040 and 2050 average of 3 TYNDP scenarios and EMBER

Key Take-Aways

- Not only the investments needed into the enablement of clean and renewable electricity generation are significant, but also the operational costs need to be managed.
- The share of both variable as well as fixed operational expenses increases over time due to the following aspects:
  - Overall installed capacities are increasing causing the overall maintenance and service cost to increase as well.
  - Currently used energy carriers such as natural gas, hard coal, lignite will be replaced by cleaner carriers such as hydrogen or biomethane.

Approach

- CAPEX calculations are based on the approach described on CAPEX slide, with literature values[1] and input capacities.
- OPEX of electricity generation consists of two components:
- Fixed OPEX: Costs incurred for operational readiness as well as maintenance. This is not linked to the amount of dispatch in TWh.
- Variable OPEX: Costs incurred during operation such as fuel costs, ramp-up, start-up costs. This is dependent on the amount of dispatch in TWh.
- Includes also the operational expenses of electrolysers and batteries. The consumed electricity is to be considered the fuel for operating these technologies.

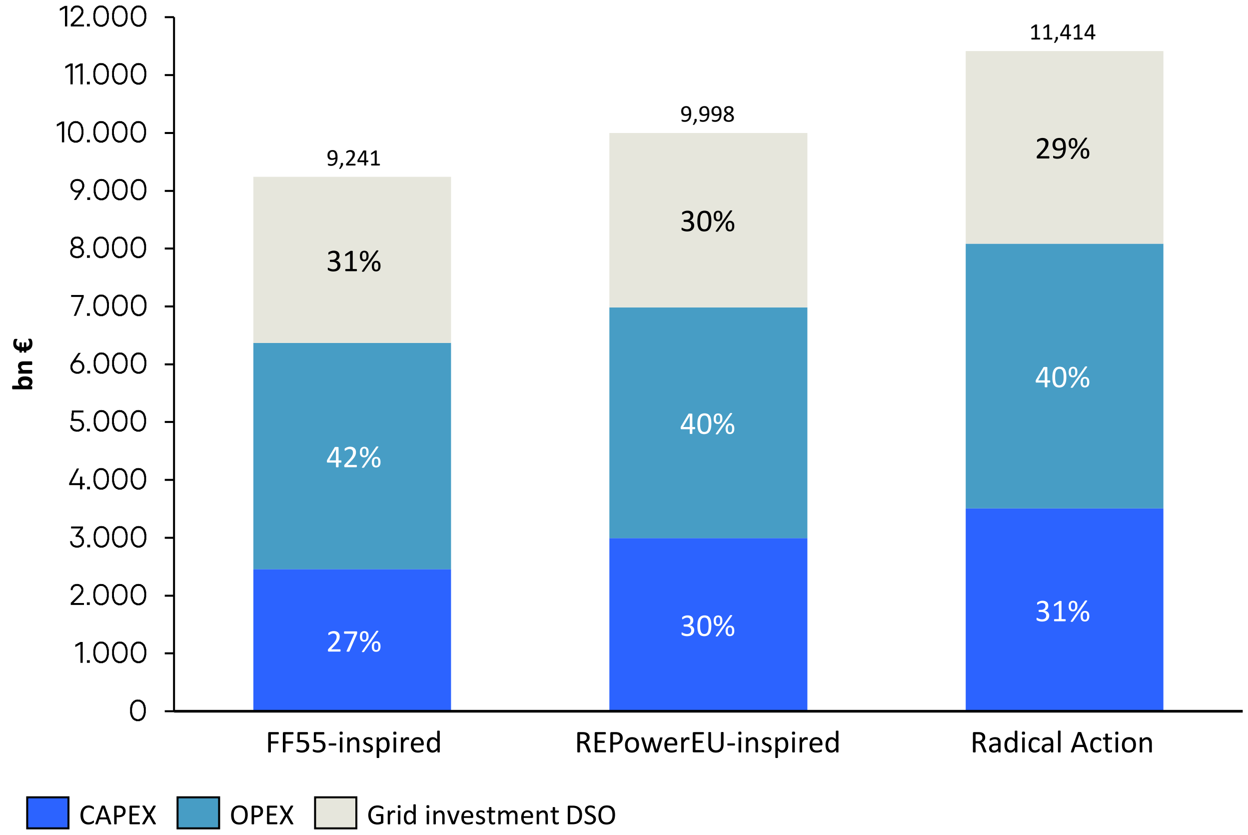
*Caveats

- Interpolation is applied for OPEX to arrive at cumulative values, so assumptions are made for the target years which were not in scope of the model. Excluding grid investments.

Total cumulative investments and operational cost of the core power system in 2050 per scenario

Total investments of the core power sector for the period in EU27+UK in 2020-2050*

Comprising CAPEX for the installment of new RES and other generation technologies plus the investments into utility-scale batteries and electrolysers plus the CAPEX for DSO grids plus the OPEX and variable OPEX (e.g. fuel costs).



Key Take-Aways

- Investments into renewable and clean energy technologies are around a quarter of the total costs of the power system.
- Second largest part will be the needed investment into the Distribution Grid. To enable a power system based on Renewable energy sources, a modernization and transformation of the distribution grid is necessary.
- Operational expenses are not to be neglected in the energy transition.
- To compare: the combined GDP of the European Union in 2021 was 17,089 billion USD[3]. The total investments in CAPEX and OPEX for generation capacities, and the CAPEX for the DSO grid in FF55-inspired - Radical Action are 54-67% of the 2021 combined GDP of EU-27 assuming an equal dollar-to-euros conversion.

Approach

- For CAPEX, variable and fixed OPEX, the approach is described on the slides before.
- Maximum values for estimated DSO investments are taken into account. The investments are extrapolated based on additional TWh and the reference to the "connecting the dots" study[2].

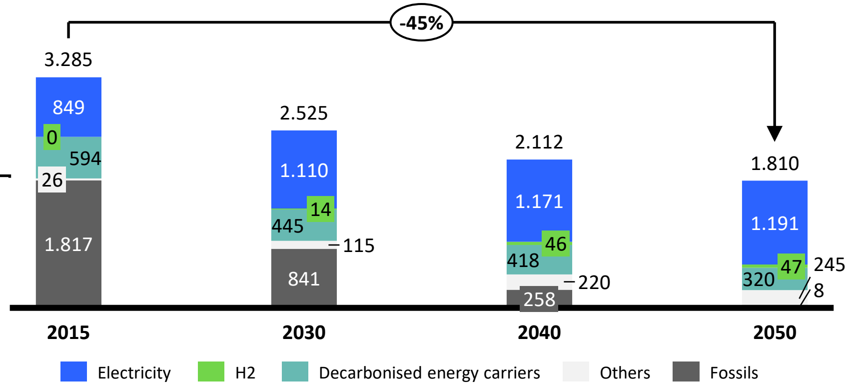
*Caveats

- Includes only core power system. Not DSR offering investments (i.e. EV charge points), no prosumer batteries, no hydrogen SMR CAPEX or hydrogen T&D costs, no CCS or unabated gasses costs or emission taxes and no TSO costs are included.
- Excluding replacement of end-of-lifetime assets.
- Total costs are no direct model outcome. Additional literature values are used to come to these total investments.

Sources:
1. EMBER (2022), TYNDP 2022 scenarios: Global Ambition, Distributed Energies, National Trends. 2020 only EMBER, 2030, 2040 and 2050 average of 3 TYNDP scenarios and EMBER
2. Connecting the dots: Eurelectric (2021)
3. GDP data for EU27 in current US dollars: Worldbank (2022):

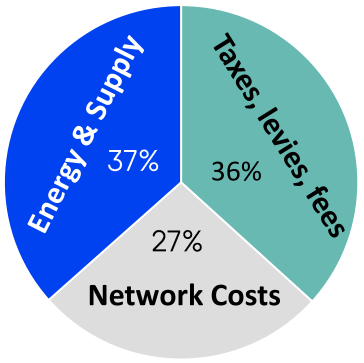
Electrification is an opportunity to lower energy household bills, since fossil fuels will be phased out. Benefits of the decarbonised power system outweigh the costs

Energy consumption residential buildings in FF55 (TWh)



Distribution of components of household electricity bill[2, 3]

Energy & supply Components[3]: Overall energy use in residential buildings decreases by 45% in 2050 compared to 2015 in the FF55-inspired scenario.



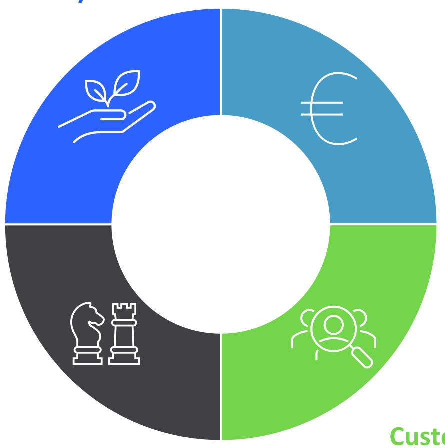
Energy household bills are expected to go down since fossil fuels are phased out and the energy use in residential will decrease due to efficiency gains.

Societal benefits of the Energy Transtition[1]

Non-exhaustive

Sustainability
- **€27-22bn** annual CO_2 savings
- **€40-140bn** annual savings in health and better air quality
- **58,000** premature deaths avoided
- **460 Mtoe** less of final energy consumption by 2030,
- achieving **32.5%** of efficiency target
- Better preservation of **biodiversity and ecosystems**

Economy
- **€30-35bn** of annual revenues for EU companies (e.g. manufacturers & service providers)
- **440-620k** quality jobs per year related to DSO grids
- **€30-35 bn** annual sales in equipment
- Advantage in **circular economy**



Competitiveness
- **Territorial cohesion** and promotion of local economies
- **€28-37bn** average electricity cost reduction (thanks to **50-65%** lower RES than fossil generation)
- **€+175bn** annual savings in fuel imports
- Increased **competitive position** European clean technologies
- **Lower footprint** of European produced products

Customer Empowerment
- **~40 GW** self-consumption capacity added
- **50-70m** EVs with smart charging
- **New Services**: Storage, electric heating, smart appliances, aggregators
- Higher **food and water** securities

Sources: 1. Eurelectric connecting the Dots (2021) 2. Eurostat – electricity prices for household consumers (2022) 3. Eurostat – Electricity prices components for household consumers (2022)
Note: see appendix section on challenges and benefits for further elaboration

The incentive to act now has never been higher. If we do not act, we will lose the opportunity to speed up decarbonisation forever

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04 All scenarios call for an acceleration of installing new, clean electricity generation sources

05 Integrating high shares of variable renewable power sources requires sufficient flexibility

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- Abatement
- Hydrogen & Biomethane
- CCS
- Flexibility
- Hydropower
- Challenges ahead & benefits
- Sensitivity analysis
- Assumptions
- Reference list

Scenario background

Historical EU commitments on climate reduction targets do not reflect the scope of work needed to achieve net zero in 2050

Introduction

During last decades, the causes and consequences of climate change from human activities became more evident. The IPCC urges society to take action in her latest report, to prevent a climate disaster with a scale and impact that would mean the end of human society as we know it[1]. Over time, increased emission reduction targets were set in the European Union. Although the EU consisted of different countries at the different moments in time, targets increased as depicted in the graph on the top right, leading to the
ambition set for 2050.

To realise the latest goals, a significant change of pace in emitting greenhouse gasses is needed (see graph bottom right). We have recognized, studied and understood the impact of climate change for over 30 years, but so far society has failed to realise the offset of faster emission reductions.

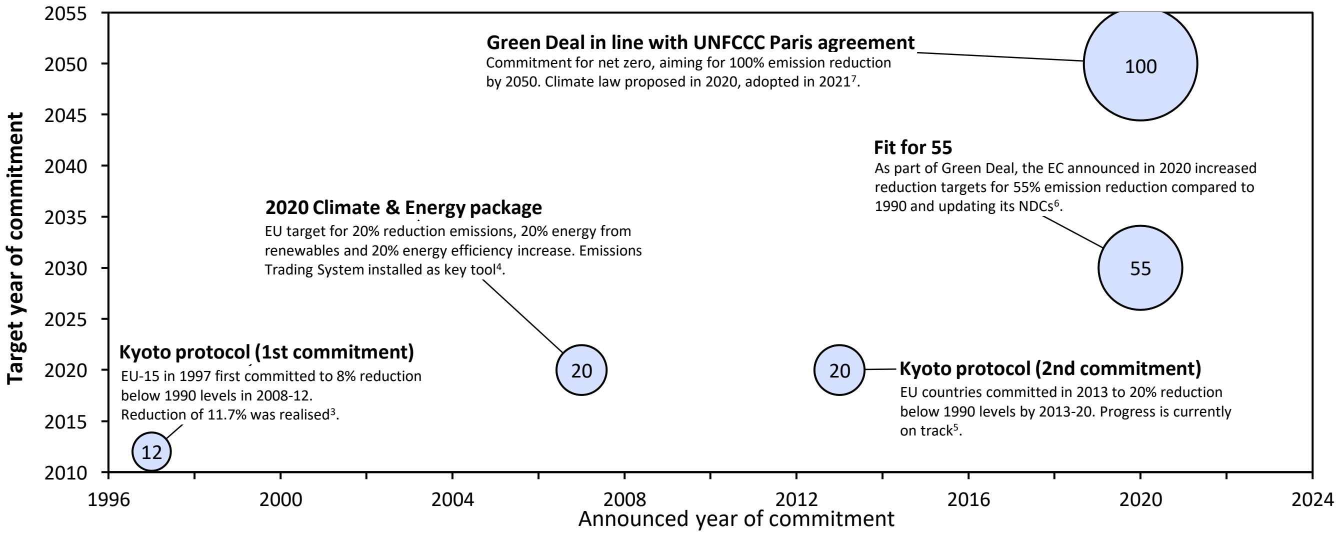
The current energy crisis, as well as new insights and innovations, lead to the need for an updated study where the opportunity to decarbonise even faster than set out in our previous ambitions is explored. Market changes in relation to the previous study include, but are not limited to:

- The increased need for independency from Russian gas;
- Soaring energy market prices;
- New insights into the development of the hydrogen value chain, and;
- Innovations on the usage of flexibility on both demand and generation.

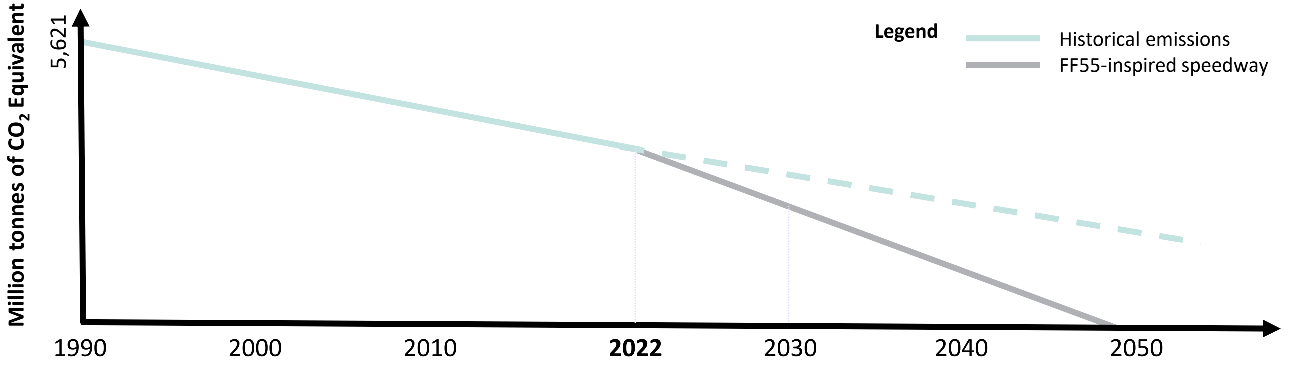
Let us use this momentum to accelerate our decarbonisation efforts. If we do not seize this opportunity to act, it is very unlikely that we will succeed at any point in the future. The time to act is now.

Commitments of emission reduction targets for EU

Bubble size reflect the percentage emission reduction targets.



Change in pace of emission reductions per year to achieve net zero goals



Sources: 1. IPCC (2022) & Emissions: EEA 2. IPCC (2022) 3. EC: Kyoto 1 (2022) 4. EC: 2020 package (2022) 5. EC:Kyoto 2 (2022) 6. EC:2030 Climate & energy framework(2021) 7. Green Deal (2022)

Note graph 1: targets included different EU countries in history.
Note graph 2: illustrative; emissions do not decline in a linear fashion.

An all-energy scenario approach for EU27+UK using TYNDP DE and changing main drivers, based on literature and expert input

Scope

The key outcome for all scenarios presented in this study is the final energy demand for the sectors buildings, transport and industry[1]. The energy carriers that make up the final energy demand change in each scenario based on the main drivers for decarbonisation. Changes to the scenarios are made according to the methodology described below. Out of scope for this phase is the energy generation as well as the use of potential energy carriers as feedstock.

01 TYNDP DE	02 Expert Input	03 Literature Research	04 FF55-inspired	05 REPowerEU-inspired	06 Radical Action
• TYNDP Distributed Energy (DE) as starting point • Focus on buildings, transport and industries sector[1]	• Interviews with Eurelectric stakeholders • Steering committee members[2] • Expert interviews	• Existing energy scenarios and outlook studies • Scientific studies • Industry reports • Policy packages	• Based on Fit for 55 policy package • Reaching net zero in 2050	• Based on REPowerEU policy package • Accelerated electrification towards 2030 • Reaching net zero in 2050	• Radical action reaching net zero energy market by 2040 • Continuing the decarbonisation pace of REPowerEU until 2030

FF55 policy package → 04; REPowerEU policy package → 05

Legend
- Dataset as starting point
- Input for modifications
- Scenarios

1. The agricultural sector and other smaller sectors are taken into account in our calculations, but not explicitly shown in our results as they represent a very small share of the total final energy demand.
2. Next to the Steerco meetings, scorecards were used to gather the values for input data such as future fuel costs for 2030, 2040 & 2050.

Heat pumps & district heating

The transition from traditional- to electric heating is the most critical driver to electrify buildings

Two heat pump technologies explained

1. **Air source heat pumps**
   The most common heat pump technology, works by extracting residual heat from outside air and adding energy to produce heat and can be split into three types:
   - All-electric heat pumps;
   - Hybrid heat pumps which usually operate in combination with a gas boiler;
   - Reversible heat pumps: work both ways and can also provide cooling.
2. **Ground source**
   Less common type of heat pumps which works by transferring heat from the ground.

Sweden is frontrunner in heat pump installations (2022)

Sweden has 19,510 heat pumps per 100,000 inhabitants thanks to policy accounting for 2 million installed heat pumps in the country.[1] Factors that have contributed to Sweden's success in electrical heating[2]:

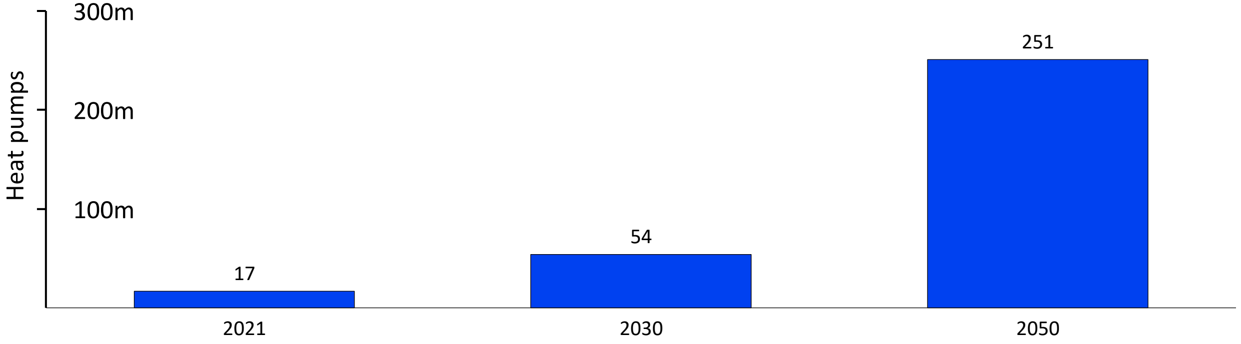
- It is mandatory to install heat pumps in a newly built homes;
- Government funded R&D;
- Government funded training of workforce;
- Financial incentives: tax credits for replacement of gas and oil boilers and tax on heating oil;
- Strong energy infrastructure and low electricity prices;
- Historically not dependent on fossils for heating.

Sources: 1. The eco expert (2021) 2. IEA (n.d.) 3. EHPA (2015) 4.Spitler et al. (2019) 5. JRC – Heat pumps in the EU (2022) 6. EHPA (2022)

Energy prices drive uptake heat pumps

The sales of heat pumps in Europe grew in 2021 by 34% mainly driven by higher energy prices[6].

Estimation of installed heat pumps required for REPowerEU inspired (EU27+UK) in millions



Graph based on REPowerEU-inspired[7] and JRC[5] data. Number for 2050 is estimated via total electricity use per heat pump[4], the share of electricity use of a heat pump per household and the electricity demand for buildings in 2050 in REPowerEU-inspired.

Challenges and opportunities

Challenges

- Installation capacity; accelerating the installation of heat pumps can be hampered by:
  - Supply chain and manufacturing limitations;
  - Having enough trained personnel to execute the installations
- Technical performance can be further improved.

Opportunities

- Heat pumps can decarbonise heating and create strong energy efficiency gains,
- Cost competitiveness can drive market growth:
  - As the market matures and becomes more competitive, prices are likely to decrease;
  - Better electricity infrastructure and electricity supply and more attractive electricity prices (compared to fossils) favour electric heating (as the case of Sweden).

7. REPowerEU target of 50 million heat pumps excludes UK. UK plans for 600,000 installations per year until 2028, arriving at 54.47 heat pumps in 2050. Assuming same growth rate for UK in 2029 and 2030.

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District heating will play an increasing role in the future in Europe, using more renewable heat sources to heat or cool buildings

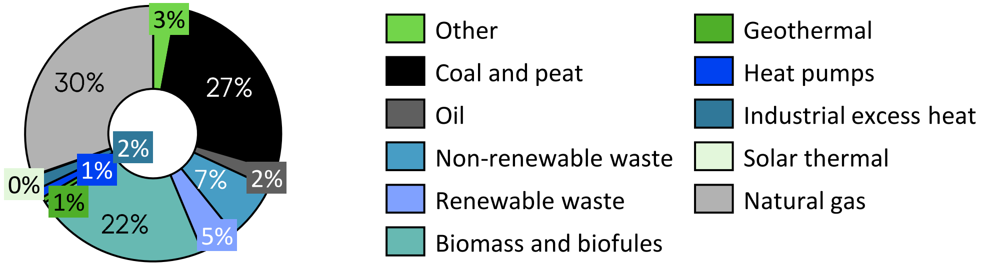
Different types of district heating: decentralized versus centralized

- The centralized system uses a limited number of centralized heat sources based on fossil fuels or biomass. The distribution temperature is above 65 °C.[3]
- The decentralized system uses multiple decentralized heat sources which are mostly sustainable. This kind of heat sources produce heat at low temperature. The distribution temperature is between 25 °C and 65 °C.[3]
- Both cooling and heating will be relevant in the future.
- Sources, types, active market players and regulations for district heating vary highly among countries.

Three main steps can be distinguished in the district heating value chain[3]

Production & storage	Transport & Distribution	Supply
Production of heat / cold in the form of steam or hot / cold water at a temperature that is derived from the source. Storage via aquifers is possible if needed.	The produced heat / cold is transported from the source to the distribution network that distributes it within the district heating customer area.	The heat organization supplies the heat to the customers and has a contract with the customers to pay, according to the tariff, for the heat usage.

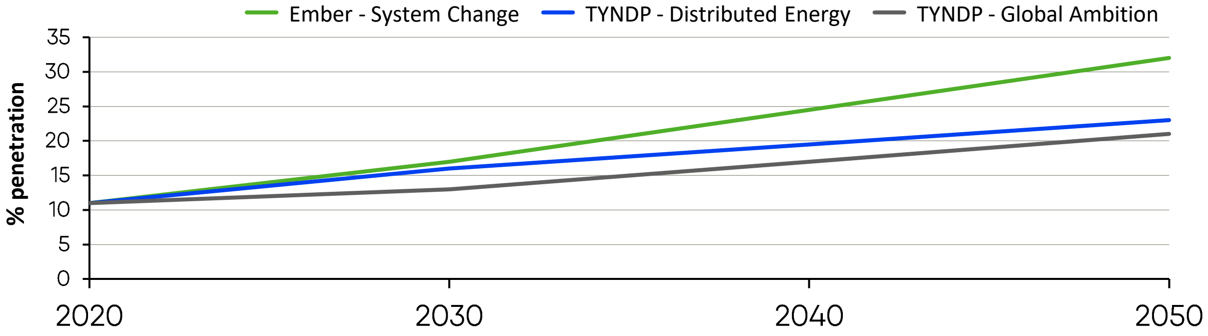
EU27 District heating supply fuel mix in 2018[4]



Sources: 1. EMBER (2022) 2. IEA (2022) 3. Accenture (2020) 4. EC (2022) 5. TYNDP (2022)

District Heating penetration increase in EU27 – (% of buildings connected)[1, 5]

- District Heating and Cooling represents ~12 % of the EU's heating market in residential and service sector in 2018.[2]
- Ember and TYNDP predict 21%-32% of buildings to be connected to district heating system in 2050[1, 5].
- Sources will be dominated by electricity and ambient heat. Coal and oil will be phased out.



Main challenges & opportunities ahead

Challenges:

- District energy infrastructure is highly capital intensive for utilities and requires high upfront investments and long construction periods, making Return On Investments challenging.[2]
- Dependent on country's regulations, various parties are included in the value chain, which can complicate the governance.[5] Consumers can delay role out dependent on their power of influence.
- Finding scalable and replicable business models, ownership structures, and financing schemes[2].

Opportunities:

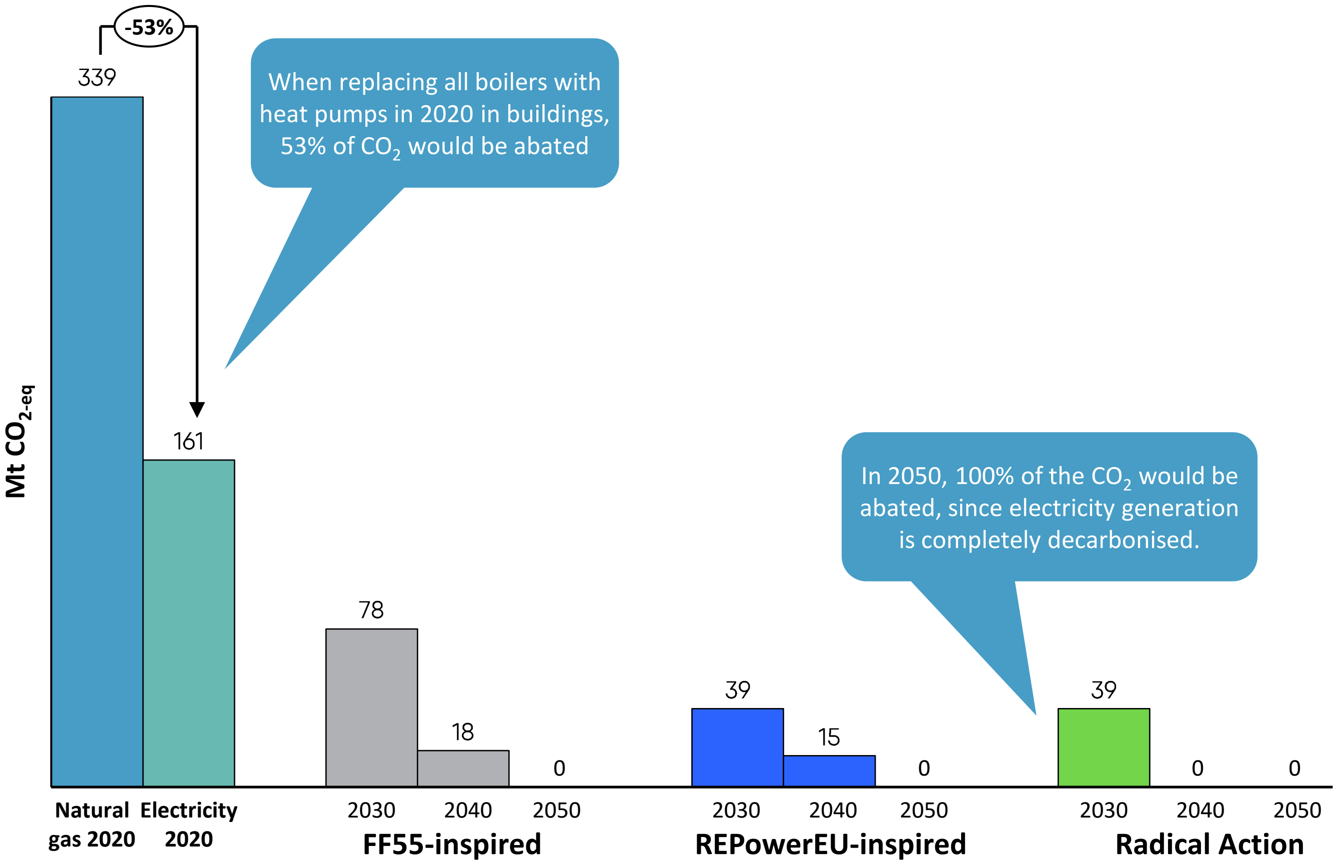
- Especially in dense urban environments, district heating is a cost effective approach[2] since they offer economies of scale and high efficiency potential, and flexibility (via thermal storage).[5]
- With rising number of CCS and PtX capacities in the near future, the generated residual heat will increase, district heating enables the usage of this waste.[2]
- Integration of low-temperature district energy can boost integration of various other heat sources and industries complemented with the integration of heat pumps, RES and smart and digitized thermal grids.[2]
- Using renewable heat sources (i.e. solar thermal), district heating could significantly reduce CO_2 emissions.[3]

Abatement

Decarbonising buildings via heat pumps has the highest impact when electricity sector is further decarbonised in the coming decades

Abatement of GHG emissions by replacing gas boilers with heat pumps in buildings

Overview of Mton CO_2 emitted in status quo for space and water heating in buildings versus the emissions per scenario when heating via heat pumps and the associated emissions of electricity in that year



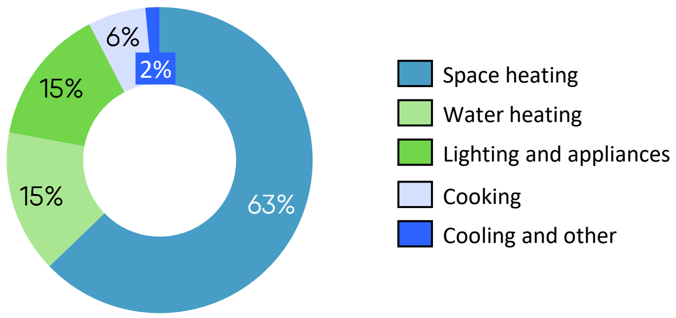
Sources:
1. Eurostat – Energy consumption in households (2022)

Description & approach

The values for each scenario display the carbon emissions that would be emitted if the current demand for water- and space heating would be completely electrified. First, the graphs displays the reduction in emissions in case of electrification of all heating (space- and water heating) in buildings, this reduction is mainly the result of heat pumps that have a higher seasonal performance factor (more efficient). The remaining emissions result from electricity generation. Thus, the sooner the power sector decarbonises, the sooner heating in buildings will be emission free.
Since the power sector decarbonises faster for the ambitious scenarios, REPowerEU-inspired and Radical Action display lower emissions compared to FF55-inspirerd.

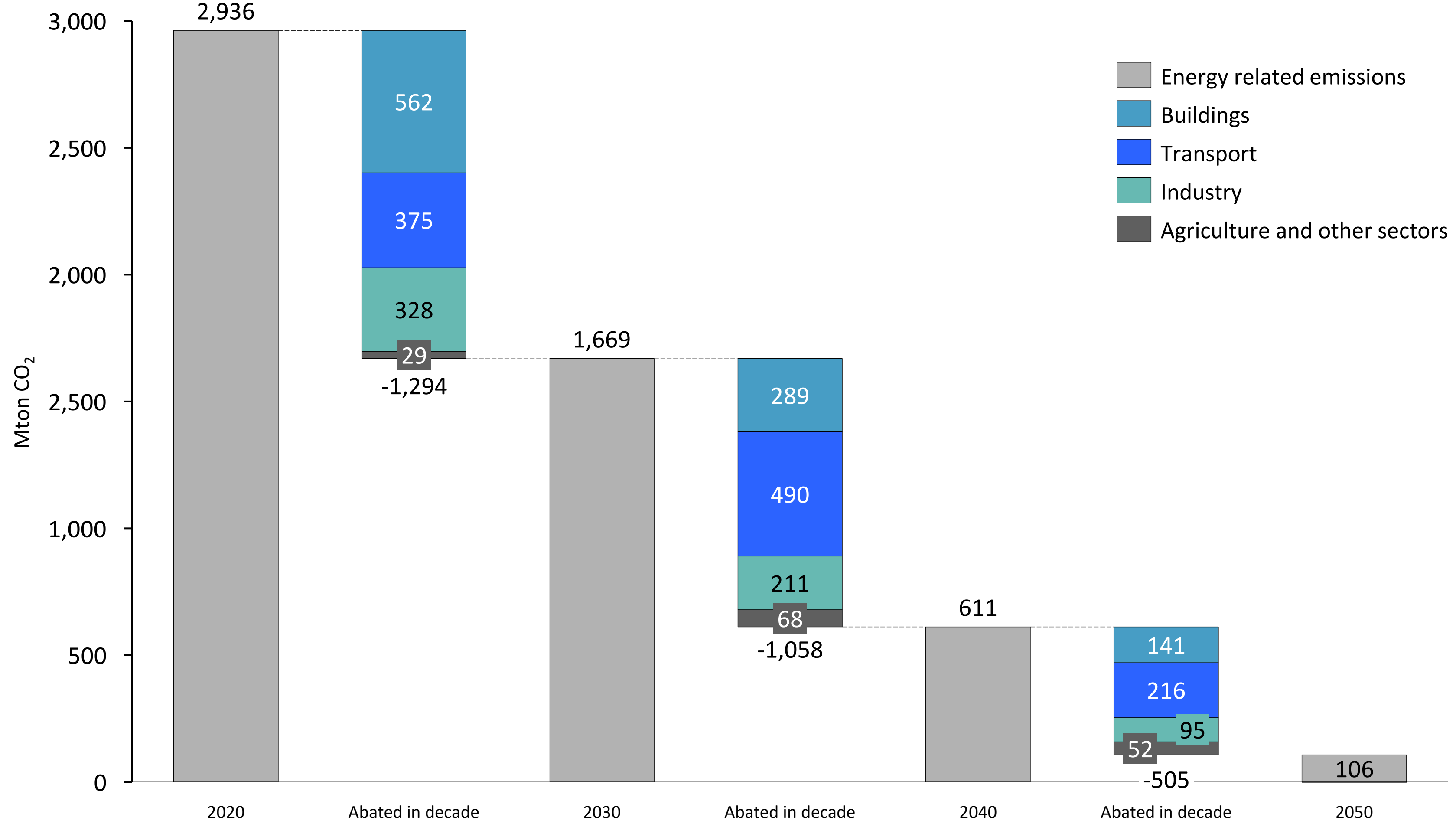
Energy consumption for EU households – mainly space heating (2020)

- Space heating accounts for majority of energy consumption of households, followed by water heating and lighting and appliances[1]
- Natural gas is currently the main energy carrier used in residential buildings in Europe, which will be replaced mainly by electricity



Buildings realises most abatement of emissions in the first decade. Transport abates most in the last two decades. ~106 Mton CO_2 is remaining in 2050

FF55-inspired abatement in emissions per sector and per decade



* See appendix section on CCS in final report

Elaboration of results

Key insights

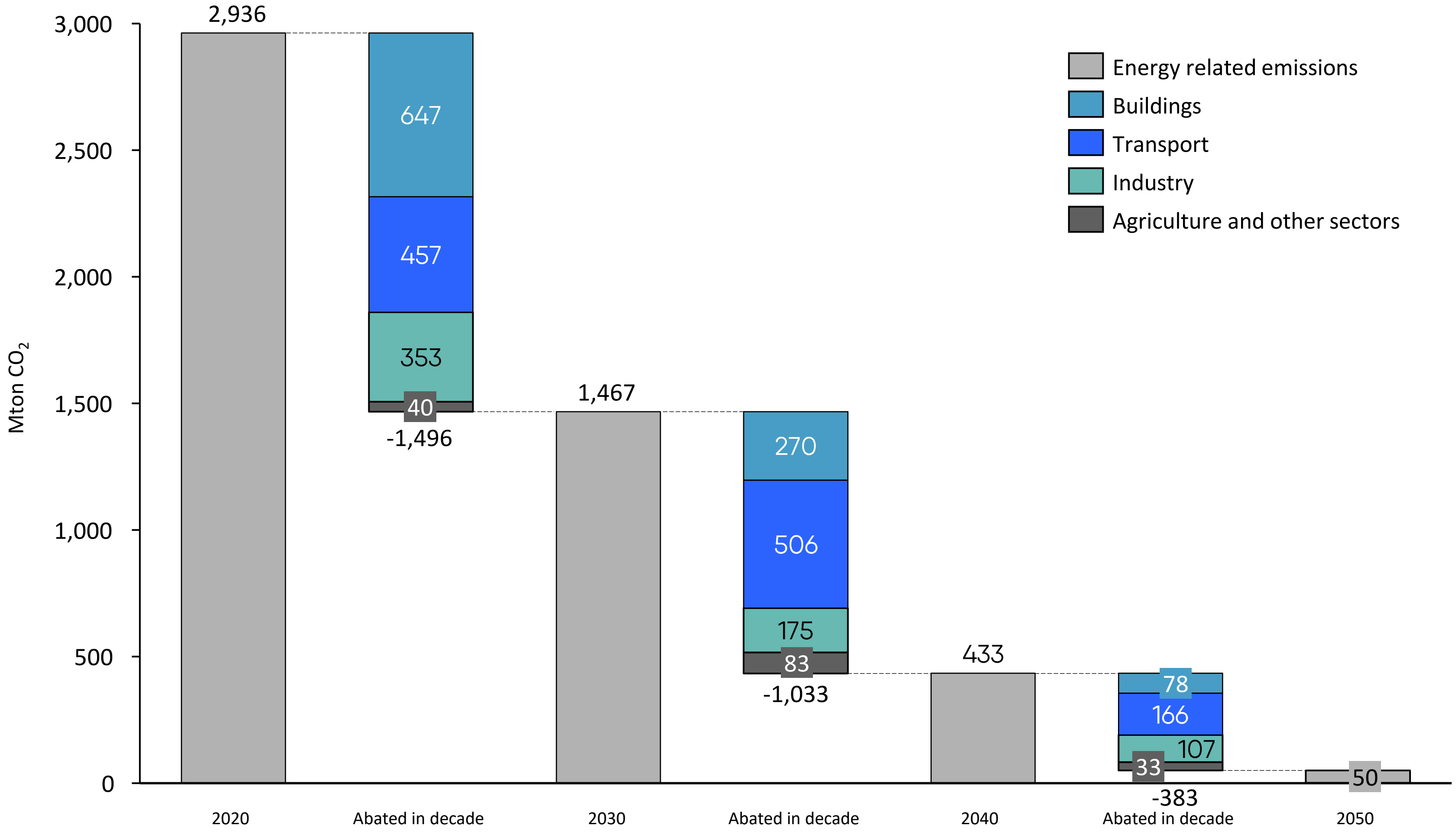
- Largest abatement is achieved in first decade with 1,294 Mton CO_2.
- Buildings abate most in the first decade, in the last two decades transport accounts for the highest abatement in Mton CO_2
- In 2050, 106 Mton CO_2 is remaining as final energy emissions. CCS* can be applied to achieve net-zero.

Main assumptions

- Final energy demand in TWh per sector from the demand framework is used and translated to emissions with the emissions factors per energy carrier.
- Non energy emissions (Agriculture non-energy, waste, industrial heat processes, LULUCF) are excluded in this overview, since these values diverge and are out of scope of the study.
- CCUS is not shown as it was not in scope of the modelling exercise. However, we do assume that CCUS covers the remaining emissions to achieve net-zero based on a meta-analysis of the CCUS potential in EU27+UK. This is further elaborated on in the appendix.

Buildings realises most abatement of emissions in the first decade. Transport abates most in the last two decades. ~50 Mton CO_2 is remaining in 2050

REPowerEU-inspired abatement in emissions per sector and per decade



1. See appendix section on CCS in final report

Elaboration of results

Key insights

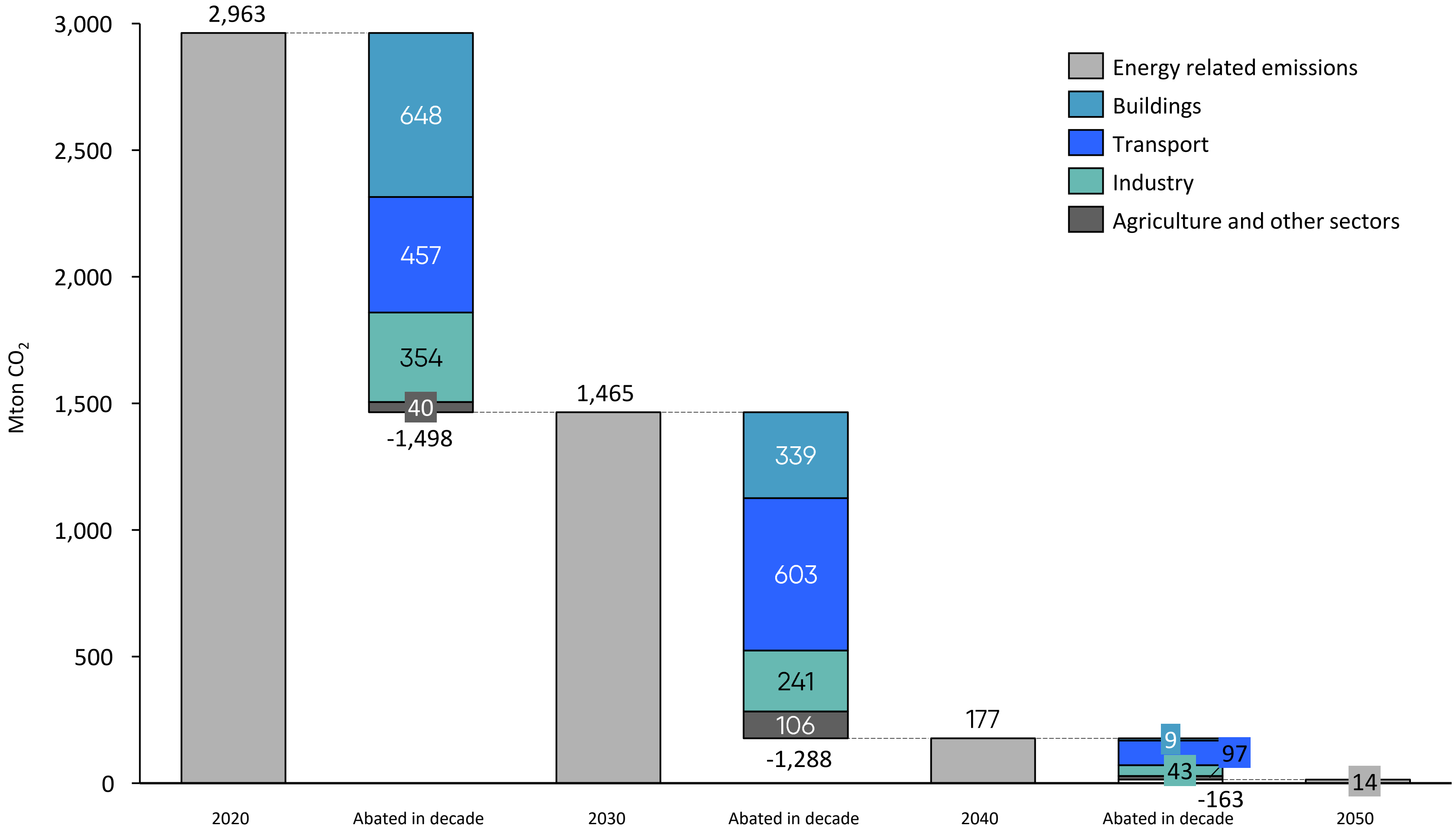
- Largest abatement is achieved in first decade with 1,496 Mton CO_2.
- Buildings abate most in the first decade, in the last two decades transport accounts for the highest abatement in Mton CO_2
- In 2050, 50 Mton CO_2 is remaining as final energy emissions. CCS[1] can be applied to achieve net-zero.

Main assumptions

- Final energy demand in TWh per sector from the demand framework is used and translated to emissions with the emissions factors per energy carrier.
- Non energy emissions (Agriculture non-energy, waste, industrial heat processes, LULUCF) are excluded in this overview, since these values diverge and are out of scope for this study.
- CCUS is not shown as it was not in scope of the modelling exercise. However, we do assume that CCUS covers the remaining emissions to achieve net-zero based on a meta-analysis of the CCUS potential in EU27+UK. This is further elaborated on in the appendix.

Buildings realises most abatement of emissions in the first decade. Transport abates most in the last two decades. ~14 Mton CO_2 is remaining in 2050

Radical Action abatement in emissions per sector and per decade



1. See appendix section on CCS in final report

Elaboration of results

Key insights

- Largest abatement is achieved in first decade with 1,458 Mton CO_2.
- Buildings abate most in the first decade, in the last two decades transport accounts for the highest abatement in Mton CO_2
- In 2050, 14 Mton CO_2 is remaining as final energy emissions. CCS[1] can be applied to achieve net-zero.

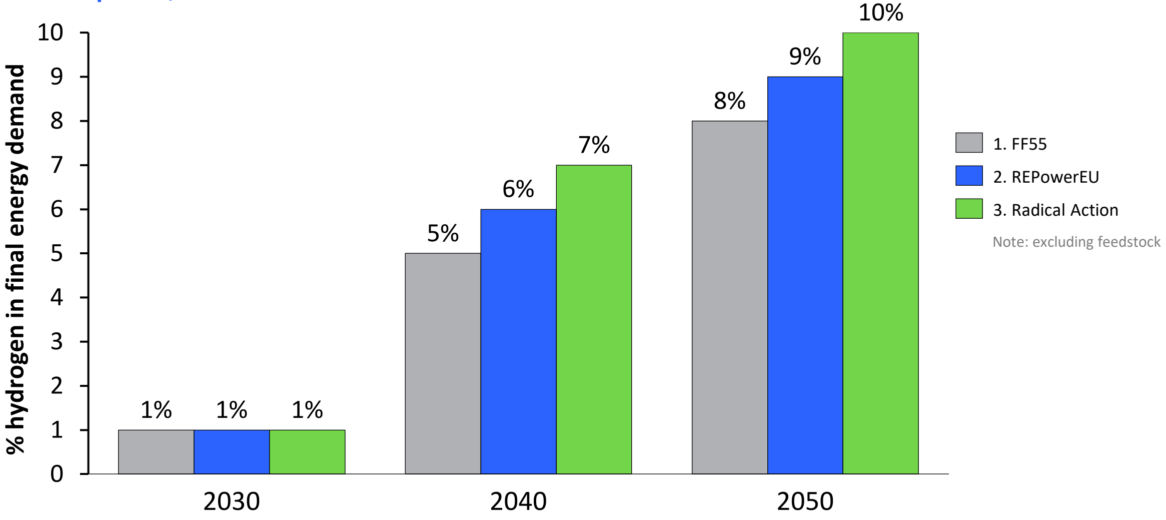
Main assumptions

- Final energy demand in TWh per sector from the demand framework is used and translated to emissions with the emissions factors per energy carrier.
- Non energy emissions (Agriculture non-energy, waste, industrial heat processes, LULUCF) are excluded in this overview, since these values diverge out of scope for this study.
- CCUS is not shown as it was not in scope of the modelling exercise. However, we do assume that CCUS covers the remaining emissions to achieve net-zero based on a meta-analysis of the CCUS potential in EU27+UK. This is further elaborated on in the appendix.

Hydrogen & Biomethane

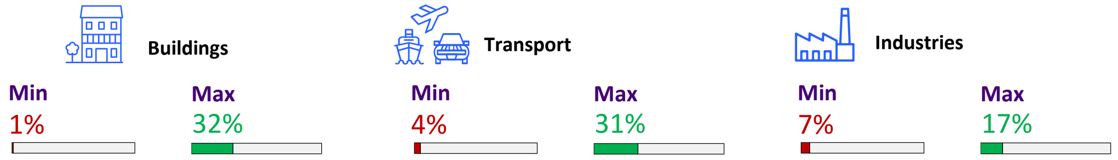
Zero carbon hydrogen is key to decarbonise the hard-to-abate sectors such as heavy transport and heavy industries

Hydrogen share in final energy demand scenarios for buildings, transport, and industries



Literature research and expert opinions used for hydrogen values

Hydrogen will still focus on hard to abate sectors, like heavy duty transport and high temperature heat processes in industries. Literature values diverge and expert opinions were used in addition to come to the hydrogen values for the scenarios.
Below an overview of the spread in literature values per sector for hydrogen demand in 2050, excluding feedstock.



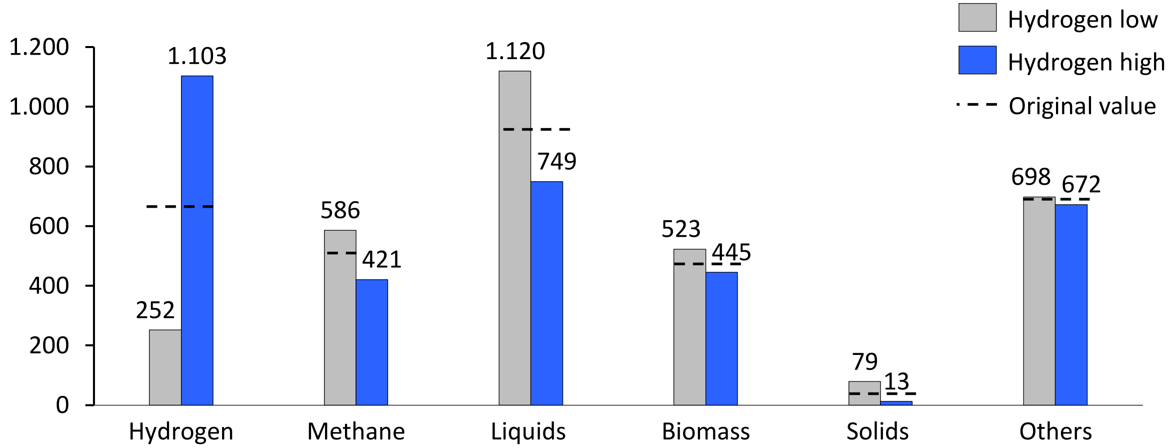
Sources: 1. WEF (2021) 2. Accenture (2020) 3. DNV (2022)

Development of hydrogen demand

While hydrogen is the most abundant element in the universe, its extraction is limited by the current cost of technology. Therefore, on the short- to medium term, hydrogen demand is expected to be fully driven by policy, where governments will implement incentives to drive down the levelized cost of hydrogen (LCOH). On the longer term (2035 onwards), zero carbon hydrogen from dedicated renewable electrolysis and low carbon hydrogen production from steam methane reforming with CCS will further drive down the LCOH.[3] Note that the current study assumes that hydrogen demand in scope (for energy use) is either zero carbon or low. Both are considered carbon neutral. Power grids are not considered a bottleneck for hydrogen production in the scenarios, due to potential local production to avoid transport dependency. High installed RES capacities will enable production of hydrogen in periods of abundant RES feed in and low electricity demand. Seasonal storage can provide controllable generation for the power system.

Effect of variations in hydrogen demand on final energy demand (FF55-inspired, 2050)

As future demand (and supply) for the use of hydrogen as an energy carrier is very uncertain, which affects demand of other energy carriers. Mainly demand for liquid energy carriers and methane are largely influenced by varying hydrogen demand. The graph displays a 'high' and 'low' sensitivity scenario for hydrogen demand in 2050 compared to the original values used in the FF55-inspired speedway focussing only on the demand of buildings, transport and industries.



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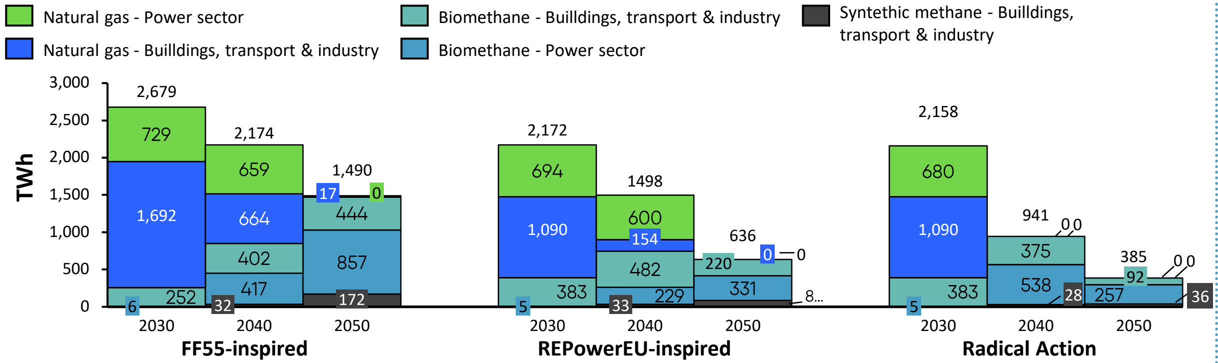
Clean alternatives biomethane and synthetic methane will put an end to natural gas as transition fuel in buildings, transport, industries, power sector

Methane development – buildings, transport & industries vs power sector (TWh)

Demand for natural gas will decline over time while demand for bio-alternatives will increase. Synthetic alternatives emerge in 2030 but remain low. Total biomethane demand in 2050 reaches 1,301 TWh. Biomethane in the power sector is the highest in FF55-inspired scenario, since in the other scenarios the higher installed RES capacities and flexibilities cover for the remaining electricity demand.

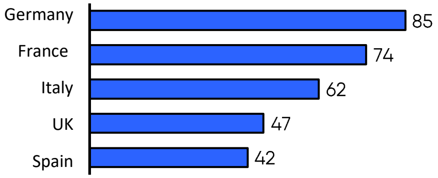


Biomethane potential in 2030 per technology and country

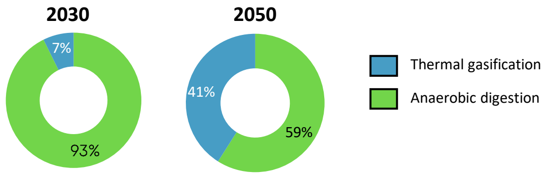
The top 5 countries represent 68% of the total biomethane potential. The total potential is 41 bcm in 2030, which equals ~435 TWh in 2030[1].

Biomethane can be made via gasification at high temperatures (thermal gasification), or a process of bacterial digestion of biomass without oxygen (anaerobic digestion). Of the 41 bcm in total, 38 (~403 TWh) is produced via anaerobic digestion in 2030[1].

2030 Biomethane potential per year (TWh)



Biomethane technology



Uncertainty of biomethane potential over time

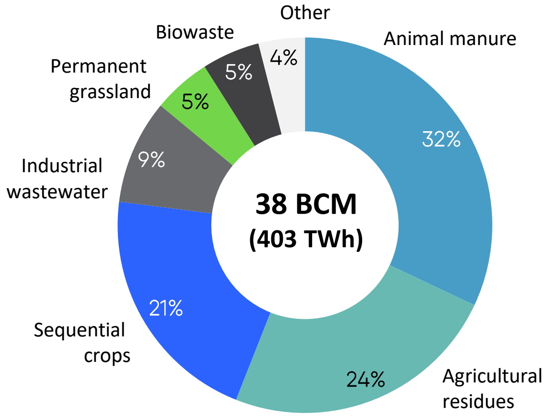
Potential according to the literature

In the literature, values for biomethane diverge. The European biogas association investigated 30-40% of European gas consumption could be made up from biomethane. In 2050 it can account for 1,000-1,700 TWh[2]. Guidehouse and the gas for climate report find there is sufficient potential in terms of sustainable feedstock to reach the REPowerEU target of 35 bcm (~371 TWh) in 2030[1]. A study by Engie finds 1,700 TWh in 2050 including EU27+10 (including Turkey, UK and smaller neighbouring countries). A study by Ecorys estimates biogas demand in a scenario study ~20 Mtoe(~233 TWh) in 2030 and 30 Mtoe (~371 TWh) in 2050[5].

Biomethane in the final energy demand framework & power sector

Whereas most studies increase biomethane demand, it is decreased in the final energy demand framework, due to the overall increase of electricity at the expense of methane. The split between natural gas, biomethane and synthetic methane is varied over the years and scenarios (see assumptions excel). As a result, values for 2030 are in line with REPowerEU targets for REPowerEU-inspired scenario, but values decrease for all scenarios in 2040 and 2050 and lower carbon alternatives are preferred in the long term. In the power sector, biomethane replaces natural gas mainly after 2030.

Anaerobic digestion potential in 2030 per feedstock



Potential challenges in feedstock

- A revision of the European Renewable Energy Directive includes a proposal to tighten the criteria for bioenergy[6]. This can also impact the scope for biomethane.
- The volume of biomass is limited, so it should be applied where lower carbon alternatives are not feasible.
- Analysis of the National Energy & Climate Plans per country, found only 10 countries detail further source of biomass feedstock, while 13 countries not elaborate on this[7].

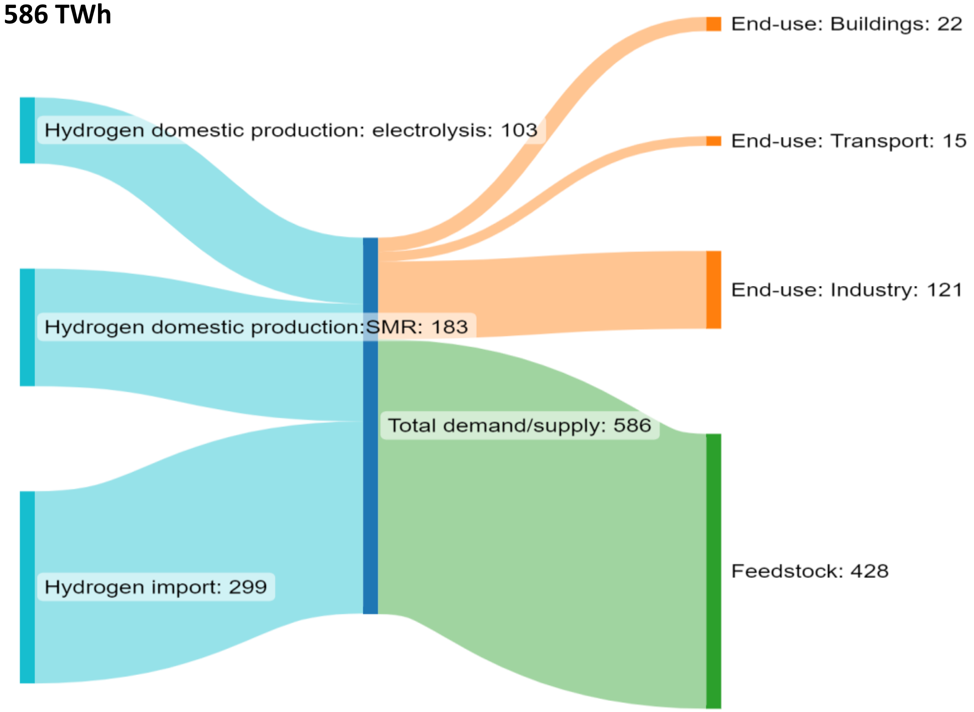
Sources: 1. Guidehouse (2022) 2. European biogas Association (2021) 3. TYNDP 2022 4. ENGIE (2021) 5. Ecorys & EC (2017) 6. European energy directive 7. Trinomics & FERN (2021). Note: 1 bcm of biomethane equals ~10.61 TWh (European Biogas p.23)

Hydrogen and other decarbonised fuel solutions will play an important role, albeit under certain ramifications only, mainly in heavy industries, the transport sector and to provide controllable electricity generation

Flow of hydrogen: FF55-inspired in 2030 (TWh)

In 2030 still 183 TWh of hydrogen is produced via Steam Methane Reforming (SMR). ~51% of the total demand will be imported. Most of the demand is used for feedstock, where hydrogen is input for a production process. Hydrogen for end use refers to hydrogen used as energy carrier for final energy demand, dominated by industry.

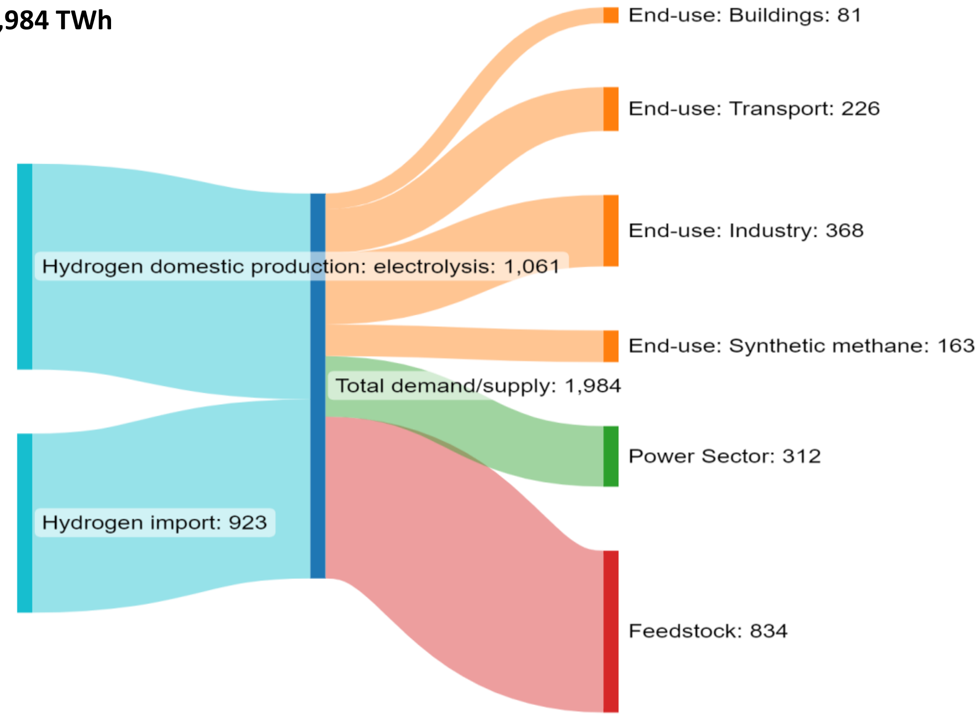
Total: 586 TWh



Flow of hydrogen: FF55-inspired in 2050 (TWh)

In 2050 the total hydrogen demand accounts for 1,984 TWh. Furthermore, all hydrogen in scope is created via electrolysis powered by RES. Of the total hydrogen ~46% is imported. Hydrogen end use has increased in all sectors, including the demand of synthetic methane. ~312 TWh is used for the power sector, providing controllable generation via seasonal storage. Feedstock in 2050 comprises of 834 TWh, constant over all scenarios.

Total: 1,984 TWh

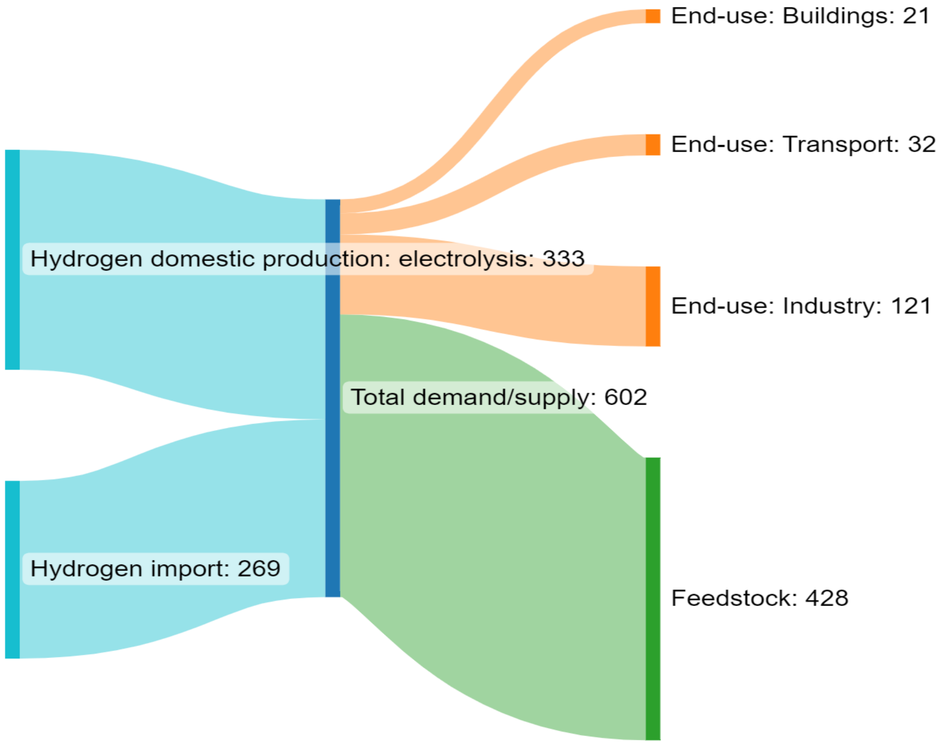


REPowerEU-inspired aims for ~10 Mton of clean hydrogen domestically produced and ~10 Mton of clean hydrogen imported

Flow of hydrogen: REPowerEU-inspired in 2030 (TWh)

In 2030 in REPowerEU-inspired no hydrogen is produced via SMR. In total 602 TWh of hydrogen is in the system.

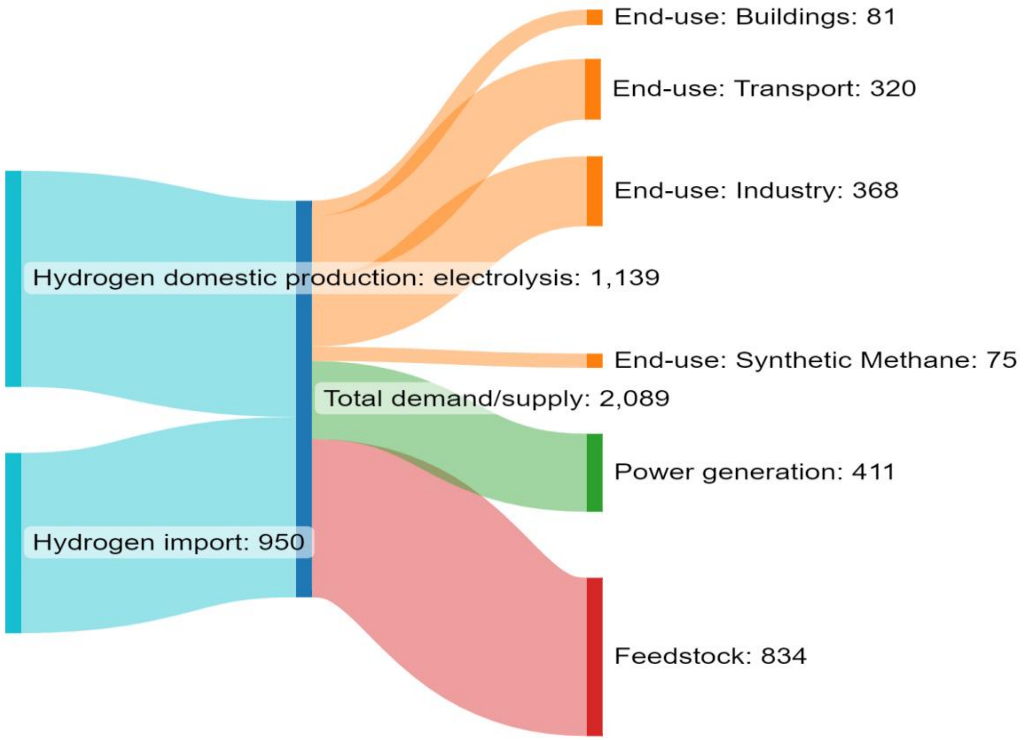
Total: 602 TWh



Flow of hydrogen: REPowerEU-inspired in 2050 (TWh)

In 2050 in REPowerEU-inspired there is a strong growth in transport and industry end use. Furthermore, 411 TWh of hydrogen is used for controllable electricity generation.

Total: 2,089 TWh

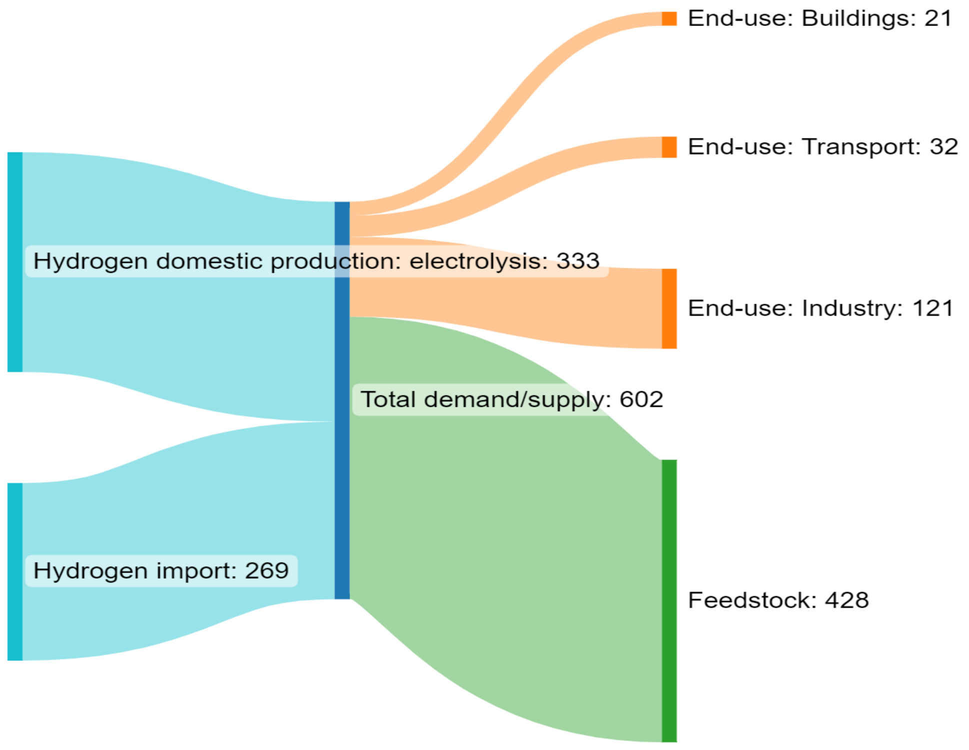


Radical Action sees the most ambitious hydrogen values in 2050, in line with the highest installed capacities of RES to produce hydrogen via electrolysis

Flow of hydrogen: Radical Action in 2030 (TWh)

Radical Action in 2030 sees the similar flow as REPowerEU-inspired in 2030 regarding hydrogen production and consumption. All hydrogen is clean hydrogen.

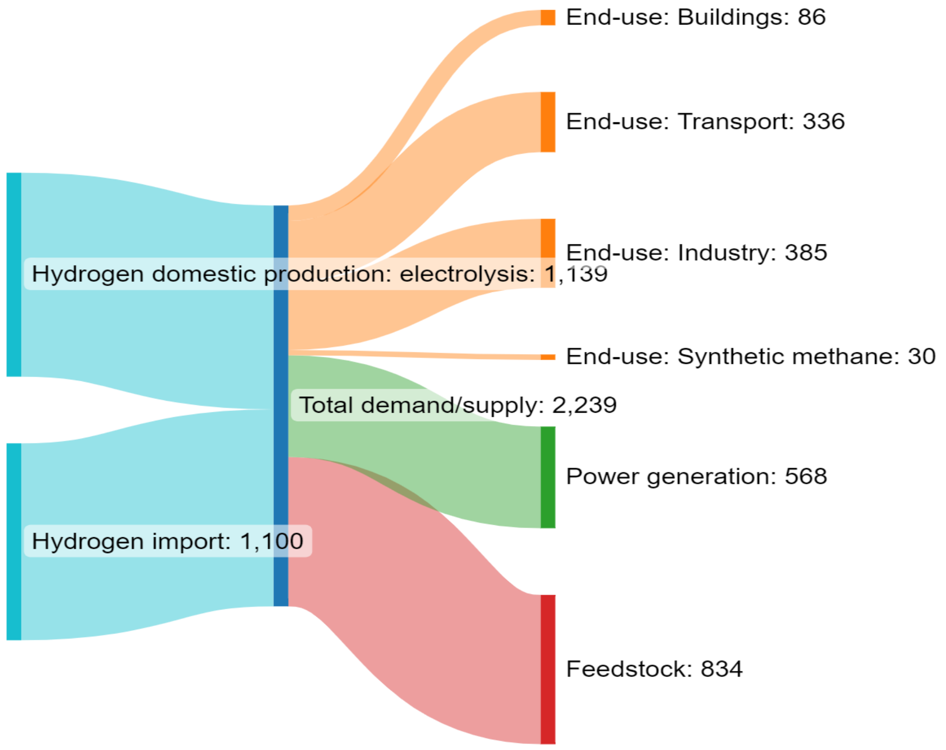
Total: 602 TWh



Flow of hydrogen: Radical Action in 2050 (TWh)

Strong uptake of hydrogen, 51% domestically produced. Radical Action shows the most ambitious hydrogen values in 2050, which are increased in line with the increased capacities of wind and solar. All hydrogen is clean hydrogen.

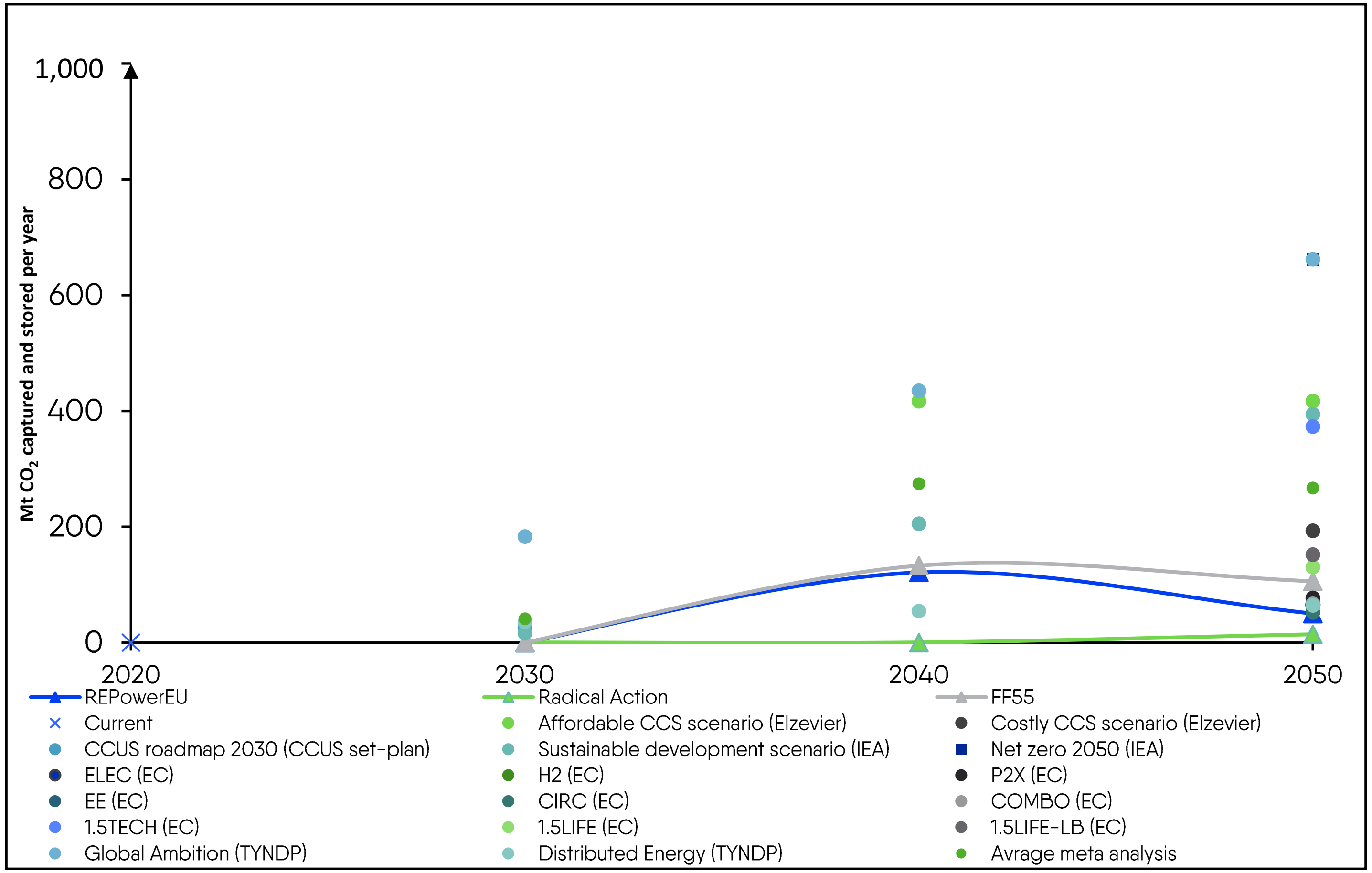
Total: 2,239 TWh



CCS

CCS feasibility remains questionable and literature values on CCS diverge. Earlier decarbonisaton of power sector in 2040 this is possible via extra CCS

Benchmarking of CCS for all sectors and target years in EU27+UK – CCS targets in the power sector in case of decarbonisation in 2040 for FF55-inspired & REPowerEU-inspired



Sources: 1. Elsevier (2021) 2. IEA (2021) 3. European Commission (2018) 4. CCUS set-plan (2021)
Note: CCS targets were derived via an iterative approach based on the final energy demand and emissions of the various sectors of the scenarios.

Scope

- Includes CCS with point sources in different sectors plus direct air capture.
- Main sectors mentioned in these studies are the power sector and industries, with high potential in the cement and clinker sector[1].
- Focus is on CCS and excludes utilization.
- CCS was not explicitly modelled in this study.

Studies used

- Two international energy agency (IEA) studies (2019 and 2021)
- CCUS roadmap (2021)
- Scientific paper from Elsevier (Holz et al, 2021)
- European Commission's long term strategy scenarios (2018)
- TYNDP (2022)
- Minimum required CCS to reach the targets in the three scenarios of this study

Explanation and methods

- The 2050 values represent the remaining energy end use emissions to be captured to achieve a net zero system.
- The 2040 values represent the emissions required to capture to achieve a net zero power sector.
- The first two Decarbonisation Speedways scenarios (FF55 & REPEU) show a decrease in the need for CCS from 2040 to 2050 for a decarbonied power sector in 2040.
- This can be explained by the approach used in this study:
  - The CCS values are the result of what is required to reach increased decarbonisation targets for the power sector.
  - REPEU and FF55 have higher emissions in the power sector in 2040, compared to the remaining emissions in 2050.
- Radical Action shows an increase between 2040 and 2050
- Explained by limited CCS required to reach a net zero economy in 2050, and an already decarbonised power sector in 2040.

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CCS could be used to achieve net zero earlier. To reach a net zero power sector in FF55-inspired in 2040, 133 Mton CO_2 would need to be captured

CC(U)S different types and challenges – feasibility remains questionable

Point of view

Although CCS is no silver bullet, but there is currently no plan to get to net zero without it. The main challenge for full decarbonisation is massive electrification and building a resilient and clean power generation mix. However, hard-to-abate industrial processes and some modes of transport are unlikely to decarbonise on their own before 2050. Therefore, CCS can be seen as a bridge technology that avoids the hard-to-abate emissions towards 2050.

The CC(U)S technologies

1. **Carbon capture**
   - **Direct air capture (DAC)**: an energy intensive process that extracts CO_2 directly from the atmosphere. The CO_2 can then be stored (CCS) or utilized (CCU) .
   - **Point source carbon capture (PSCC)**: includes technologies that captures CO_2 directly at its source. Mostly at industrial sights such as a cement plant or gas power generation plant.
2. **Carbon storage** usually in deep geological formations. Often such geological formations have a high storage capacity, and the process has a limited land and water footprint.
3. **Carbon utilization** is when CO_2 is used, for example to produce fertilizers, beverages or synthetic fuels. To further enhance CCU, the market for CO_2 should grow by finding new uses (e.g. synthetic fuels or uses in consumer products). Note that reduction in emissions by carbon utilization is out of scope of this study as it does not necessary lead to emission reduction.

Challenges

- Feasibility of CCIS remains questionable. Two main hurdles are scale and costs:
- Scaling: currently CCUS capture about 45Mt CO_2 globally, but this needs to increase. Also, announced projects will not be sufficient to meet climate targets.
- Costs: the costs of carbon capture are currently too high to be economically feasible. With the help of government and company's support installations can be build, nevertheless. Cost are expected to go down in the longer term as the technology matures.

Sources: IEA – DAC (2022) 2. IEA – CCUS (2022) 3. European Commission (2019)

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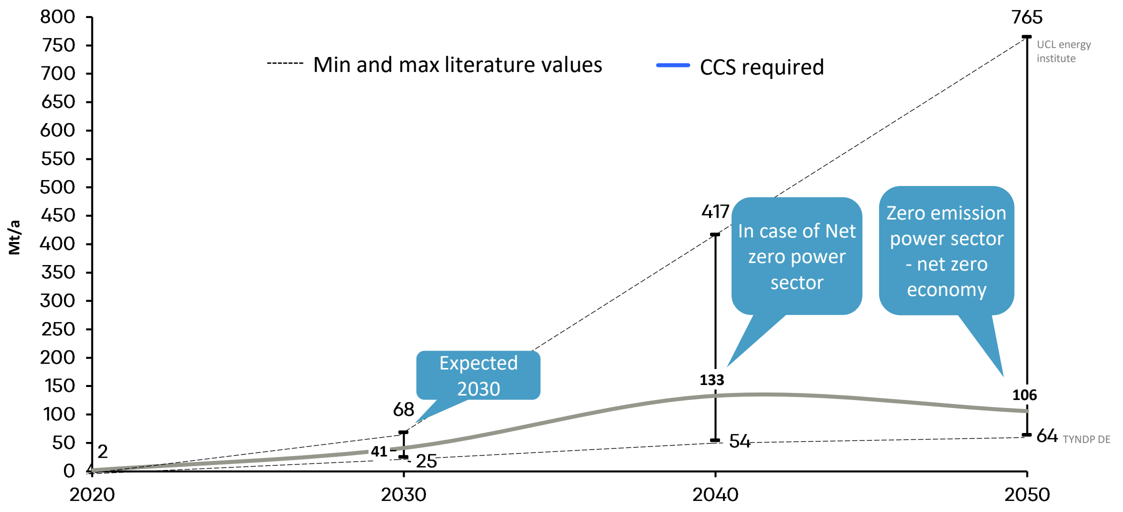
CCS required to be net zero in 2050 in Fit for 55-inspired speedway in Mt per year vs minimum and maximum literature values



Approach of this study

The development of CCS technologies is crucial to reach the net zero target, and thus, this study includes CCS in its emission calculations. The graphs above show the volumes in million tonnes annual captured and stored CO_2 for the Fit for 55-inspired speedway. Note that utilization of carbon is not in scope. Also, the way CCS is used is slightly different per target year:

- 2030: projected CCS based on meta-analysis.
- 2040: the CCS value covers the remaining emissions from the power sector when the power sector is hypothetically net zero in 2040, the end use energy emissions are not covered or reduced by CCS.
- 2050: the power sector is assumed not to emit any GHGs, at least 106 Mt CO_2 emissions from end use needs to be covered in the FF55-inspired speedway to reach a net zero economy. Additional CCS is nice to have.

- REPowerEU-inspired uses the same approach, Radical Action achieves a net zero economy in 2040.

Different components of CCS include capture transport and storage, all with different cost ranges associated

Examples of CCS projects

Northern lights CCS project, Norway

To be the first ever cross-border, open-source CO_2 transport and storage infrastructure network. Financed by Shell, Total Energies and Equinor, it will offer companies in Europe the opportunity to store CO_2 permanently deep under the seabed in Norway. Northern lights is building two dedicated carbon carriers and will ship captured CO_2 to an onshore terminal on the Norwegian west coast. From there, it is transported by pipeline to an offshore storage location where the CO_2 will be stored in a geological formation under the North Sea. The project will be completed by summer 2024 with a capacity of up to 1.5 Mt of CO_2 per year amounting to 1.6bn USD of investments[1]. The project has the ambition to increase its storage capacity to 5Mt CO_2 per year depending on demand.

Humber CCS hub, United Kingdom

Drax power limited operates two pilot bioenergy with CCS facilities in North Yorkshire with plans to commercialize in 2027. The existing power plant has installed a carbon capture technology on its bioenergy turbines with 1 ton of daily capture capacity. The project is part of the ambition to make Humber the world's first net-zero industrial cluster by 2050.[3]

Porthos, Netherlands

Porthos (Port of Rotterdam CO_2 transport hub and offshore storage) is developing a system for CO_2 transport from industry in the Port of Rotterdam to an empty geological formation under the North Sea. Porthos will store 2.5 Mt CO_2 per year for approximately 15 years duration planned to be operational in 2024/2025.

Sources: 1. Upstream (2020) 2. IEA (2022) 3. IEA (2022) 4. Porthos (2022) 5. United Nations (n.d.)

Cost of CCS

Capture

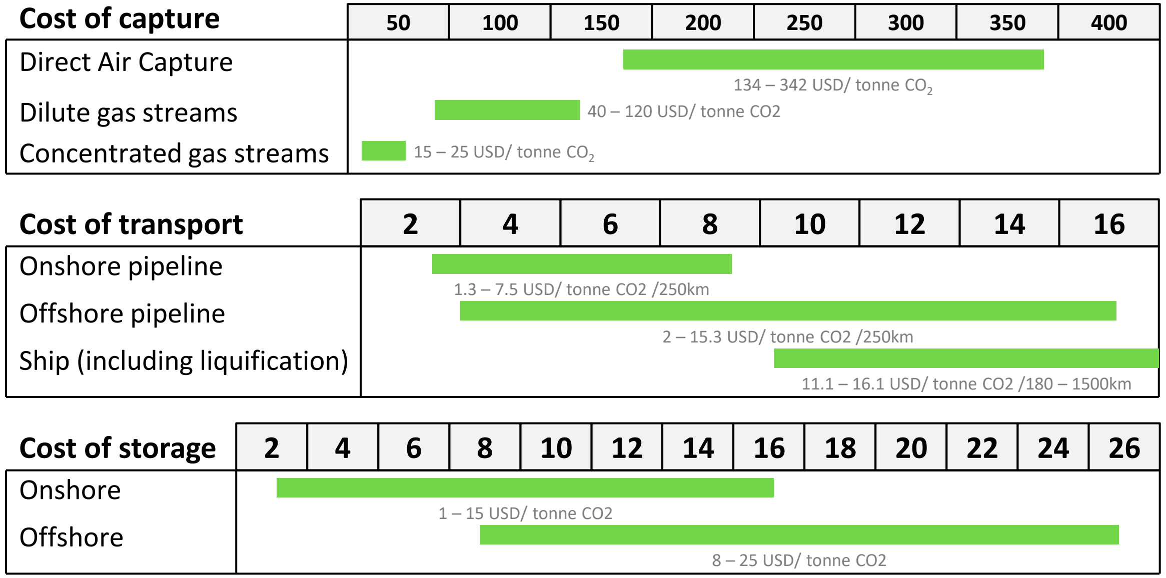
The costs can vary largely depending on the carbon intensity of the source. Three types of point sources are distinguished: direct from the air, dilute gas streams such as cement production and power generation and concentrated or from "pure" gas streams such as ammonia production.

Transport

Feasible methods of transporting CO_2 include both pipeline transport and shipping. The costs shown here are for pipeline transport of compressed CO_2. Note that costs for transport are highly dependent on distance, volume and transportation method.

Storage

Practical storage location for storing CO_2 are empty geological formation such as oil and gas fields, deep saline formations and unminable coal deposits.



Sources graphs: Schmelz et al (2020), IEA, Zero Emissions Platform

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Flexibility

Future power system will be heavily reliant on multiple flexibility offerings to balance out demand and generation. The order is dynamic

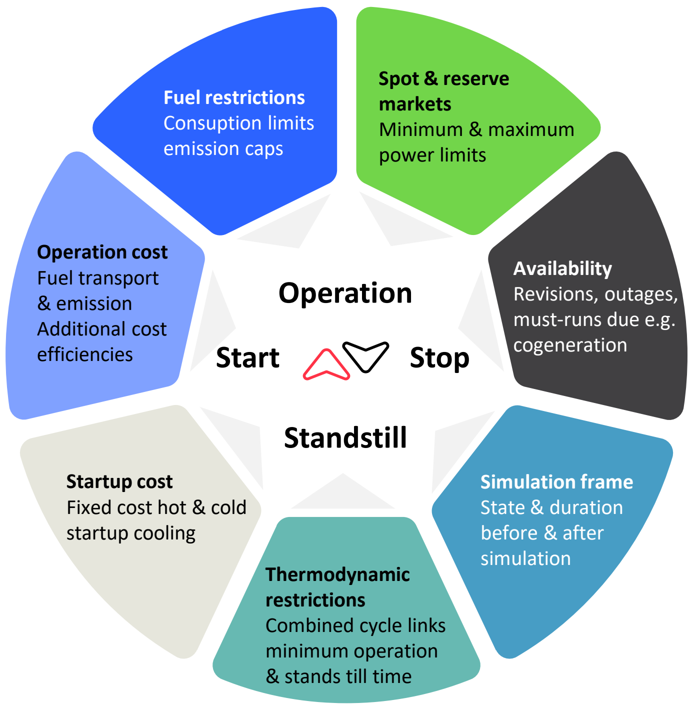
Types, modelling and description of flexibility offerings – order is dynamic

Actual activation of flexibility offerings is the outcome of an optimization problem, in which the application of these offerings is calculated dynamically depending on three major drivers cycling efficiencies of offerings, shifting potential of flexibility offerings and cost of activation. Depending on the driving forces of the flexibility offerings, the activation order changes over time. For instance, load-shifting processes allow only short-time flexibility (e.g. Heat pumps have maximal shifting potential of 3 hours and V1G has a maximal shifting potential of 5 hours). At the same time, reservoir and pump storages act as seasonal storages. Furthermore, the costs and cycling efficiencies are decisive for the actual activation order. While for load-shifting processes a cycling efficiency of 100% is assumed, the charge-discharge process of batteries is subject to losses.

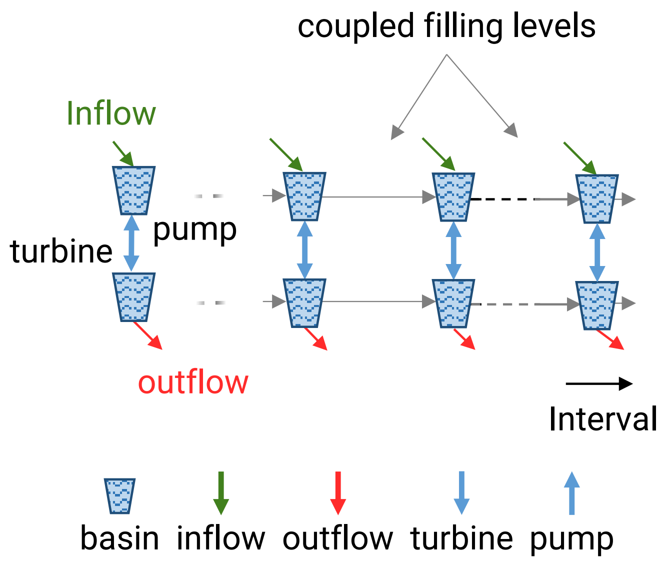
Type	Category	Implemented as…	Description / Explanation
Demand Side Response	Electrolysis: H_2-Production	Consumption	Electrolysers are modelled as pumps with a fixed electricity demand they need to consume in order to produce the needed hydrogen. These electrolysers react to market incentives and produce hydrogen in hours with low spot prices (e.g. hours with surplus renewable electricity generation).
Demand Side Response	Smart charging (V1G)	Load-shifting	Load-shifting refers to a process in which demand is shifted from one point in time to another point in time under the constraint that the load increase equals the load decrease. The assigned activation price is set to be quite low in order to create a flexible power system. If the optimiser recognises a price difference between two hours that is higher than the activation price, the load will be shifted accordingly.
Demand Side Response	Heat pumps	Load-shifting	
Demand Side Response	Industrial load-shift	Load-shifting	
Demand Side Response	Vehicle to grid (V2G)	Load-shifting	
Storage	Batteries	Storage	Storage technologies are unique within the power system since they offer flexibility into two directions. In hours of surplus solar and wind generation with low spot prices, the technologies will consume and charge the batteries / fill up the reservoirs and at the same time, they embody the capability of supplying electricity instantaneously. Both processes, consuming and generating electricity is combined with costs. The consumption of electricity is connected to the current spot price and hence, the assumption is made that load will be shifted via DSR processes before batteries start to charge or reservoirs will be filled. Storage technologies react to market incentives.
Storage	Pump storages	Storage	
Generation	Reservoir power plants	Generation	Electricity generation by reservoir power plants.
Generation	Nuclear, gas or coal fired power plants	Generation	If needed and if the current spot price is above the marginal price of the generation technologies, the conventional generation technologies will adjust their power to meet the demand.
Generation	(Clean) Gas fired power plants	Generation	
Demand Side Response	Industrial load-shedding	Load shedding	Load-shedding refers to a process in which demand is reduced. Unlike the shifting process, the reduced load will not be consumed at a later or earlier point in time. Load-shedding is the last measure to be taken with highest costs.
Import/Export	Electricity exchange with other bidding zones	NTC-Interconnection	Dependent price differences and net positions of two bidding zones, they will exchange electricity in order to meet the demand in both bidding zones.

Generation and consumption model options for flexibility: modelling based on various technologies

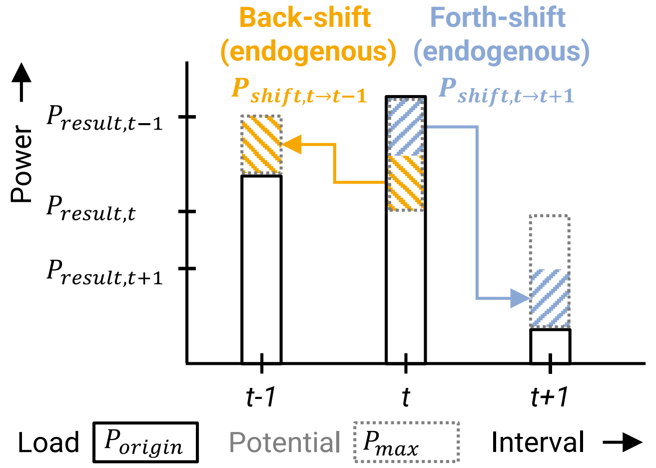
Flexible thermal



Flexible storage



Flexible RES/DSR



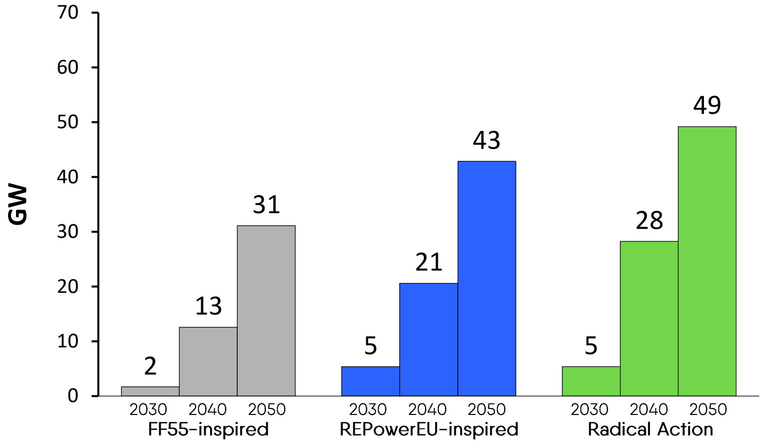
*Note: Generators based on Renewable Energy Sources (RES) and Demand-Side-Response (DSR).
Note: startup costs in thermal flexible are not used

Demand side flexibility is required to balance the power system. Heat pumps, electric cars and industrial consumption account for 115 - 137 GW in 2050

Demand Response capacity by application over time and scenarios in EU27+UK (GW)

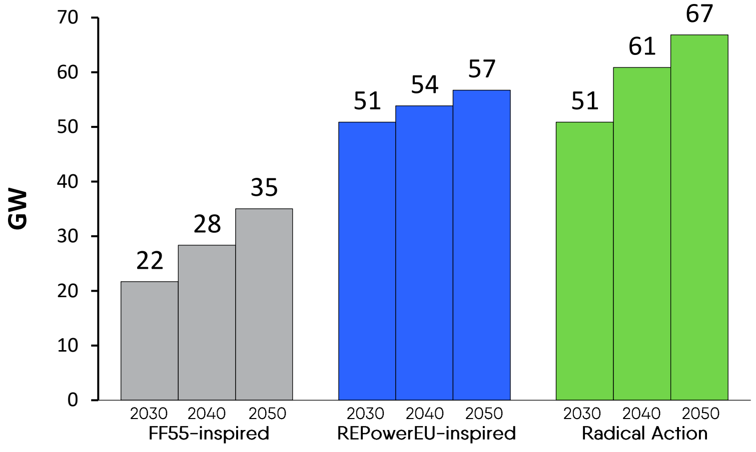
Heat pumps

- Heat pumps with internet connection can deliver flexibility via postponing heating or cooling of buildings.
- The increased roll-out of heat pumps will also drive the growth of flexible capacity in buildings over time.
- Demand shifting potential up to 3 hours is assumed.



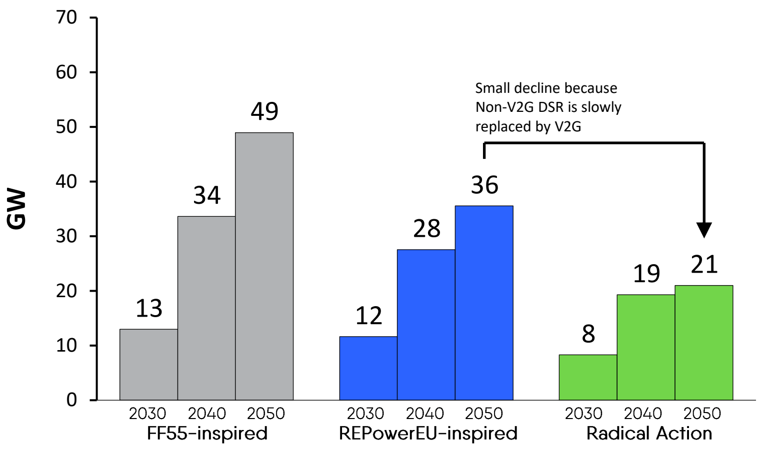
Industrial consumption

- Industrial consumption plays a large role in shifting or shedding of demand.
- Electricity intensive processes which are not bound to specific timing, can relieve the power system when less or more demand is needed.
- Demand shifting potential up to 4 hours is assumed.



Smart charging (V1G)

- Smart charging (V1G) refers to charging your vehicle when electricity prices are lower, avoiding the periods of peak demand.
- Over the scenarios, the installed capacities decrease, since V2G capacities increase. V2G (charging your vehicle AND delivering back to the grid) is less mature as of now.
- Demand shifting potential up to 5 hours is assumed.

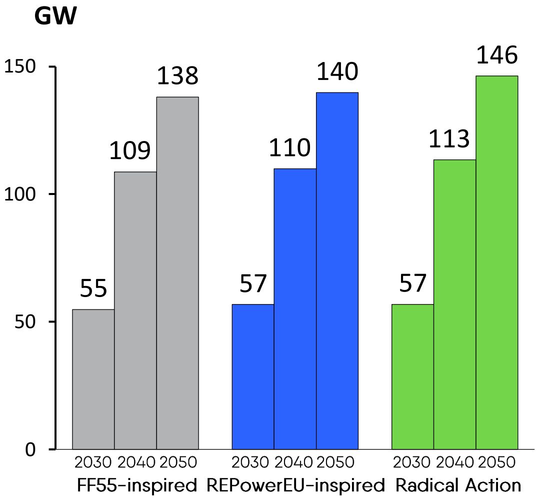


Storage offerings offer together between 361 and 486 GW of flexible capacity to the power system in 2050

Storage capacity by application over time and scenarios in EU27+UK (GW)

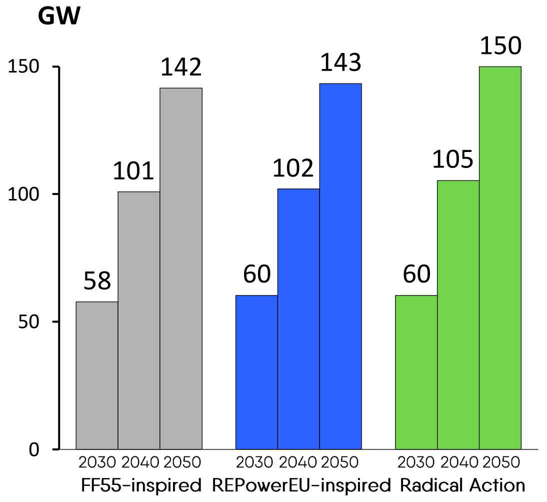
Utility scale batteries

- Utility scale batteries include large scale batteries (size several to hundred MWh)1)
- These batteries located in front of the utility meter (FtM).
- Average power to capacity storage ratios range between 3.99 in 2030 to 5.76 in 20503.



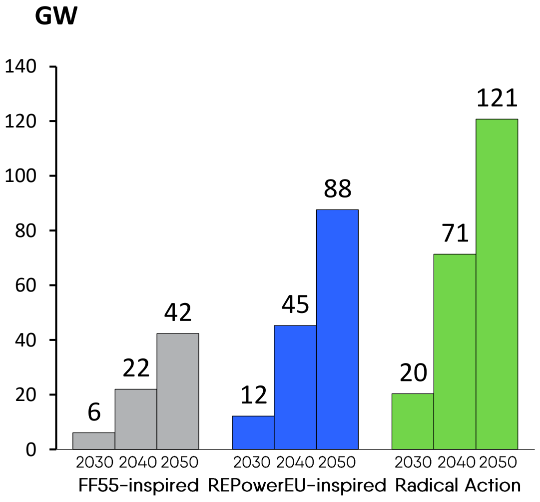
Prosumer scale batteries

- Prosumer scale batteries include small scale batteries (size 3 kW to 5 MW)[2]
- These batteries located behind the utility meter (BtM).
- Average power to capacity storage ratios range between 3.99 in 2030 to 5.76 in 2050[3].



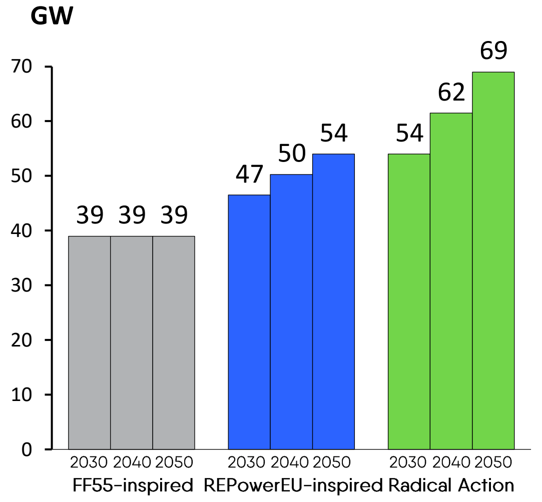
V2G

- Vehicle-to-Grid includes both smart charging of the vehicle, and delivering back electricity to the grid which is temporarily stored.
- 5 Hours of shifting and/or storing is considered



Hydropower: pump

- Hydropower pump storage pumps the water to higher altitude when electricity is cheap and releases it when the system is in need.
- No maximum limit is considered regarding the timeframe of storage.
- See hydropower section for other categories

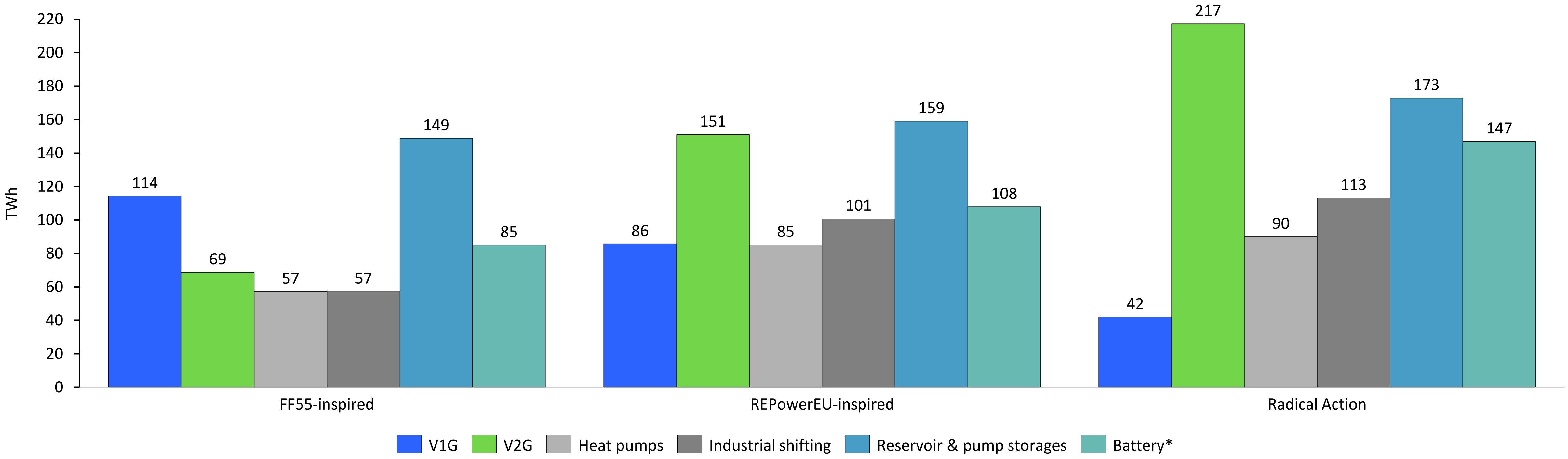


Sources: 1. IRENA - Utility scale batteries (2019)
2. IRENA – Behind the meter batteries (2019)
3. See appendix section on flexibility for battery duration literature analysis

A decarbonised power system with high share of variable RES requires a significant amount of flexibility: 531 TWh – 782 TWh in 2050

- Flexibility activation (TWh) of storage technologies such as hydro power reservoir and pump storages as well as batteries is assessed via the flexible electricity generation and the activation of load shifting processes such as Heat pumps or Industrial shifting is assessed via the activated load decrease of the load-shifting processes
- Within the model reservoir and pump storages incorporate the flexible share of the overall hydro power generation and will play the main role as provider of flexibility.
- The importance of the transport sector in particular electric mobility is significant for the power system, as V1G and V2G provide the second largest amount of flexibility in 2050 in all scenarios.
- See the flexibility appendix section for further elaboration on flexibility, the capacities in GW and the assumptions made.

Overview of the use of selected flexibility sources in a decarbonised power system in 2050 (TWh)



Note: *Battery includes prosumer-scale and utility-scale batteries, with approximately equal capacities. Conventional capacities also provide flexibility to overall power system; however they provide additional net electricity generation and hence, are less comparable to demand side management and storage technologies. Hydropower reservoirs and pump storages are combined in this overview.

Vehicle to Grid – V2G – In Transport

Vehicle to Grid serves as mobile residential battery storage

Vehicle to Grid (V2G) serves as mobile residential battery storage. It is assumed that mainly passenger vehicles will provide V2G services, as commercial transport is scheduled to optimize their daily commute pattern and will therefore most likely use fast chargers without flexibility.

TYNDP assumes up to a 26% penetration rate of V2G technology in 2050. This seems quite optimistic, as V2G requires both a hardware change to the charging stations as well as to the vehicle itself. Therefore, it seems more likely that initially the largest share of EV flexibility will be provided through smart charging (see next page).

General assumptions made:

- Only light transport vehicles are assumed to participate in V2G. Other transport sub-sectors are excluded.
- The share of EVS participating in V2G plus the share of EVs participating in V1G, sums up to 100%.
- The adoption rate of V1G EVs in 2030 is higher compared to V2G. V1G penetration rates decrease over time, V2G penetration rates increase.
- The car is connected to a private home or office charger. Fast charging and public chargers are excluded from V2G services in our assumptions;
- An activation price of 1.00 €/MWh is taken in the dispatch model, higher compared to other DSR, since some battery degradation is assumed for delivering flexibility to the grid via your electric vehicle.
- The State of Charge (SoC) before delivering flexibility is more than 50%[4].
- If parked, the vehicle must also be connected to a charging station, and the charging stations must be equipped with V2G functionalities, and the owner must be willing to participate, and there must be a need for flexibility in the power system. Given these conditions, availability for 8%-10% is assumed, increasing from 2030 towards 2050 due to improved incentives, constant over scenarios.
- On average, cars are assumed to be parked 90% of the time.
- For every hour spent charging, the car is connected for 2.8 hours[6]. This is derived via average connection time charging in hours/ average time charging per session. $\frac{7\ hours}{2.5 hours} = 2.8\ hours$

Challenges ahead to be resolved:

Transformation of cars and charging stations to match hardware and software with V2G functionalities. Regulatory standards in Europe, price incentives for consumers, battery degradation, efficient conversion of alternating current vs direct current, discharge capacity limitations.

Calculation

TYNDP provides the total electricity use by passenger vehicles. Total passenger vehicle electricity usage in 2050 in FF55-inspired = 397 TWh/year.
We assume that an electric passenger vehicle on average consumes 1,800 kWh/year[5].
This means that the amount of electric passenger vehicles is $\frac{397 TWh/year}{1800\ kWh/year}$ = 221 million.

TYNDP indicates that up to 26% of all passenger vehicles are able to support V2G.
Therefore, 0.26*221 million vehicles = ~57 million vehicles can support V2G.

- Cars are parked ~90% of the time. Out of the total energy usage, electric cars on average charge 70% of the energy at a private charger at home or at work[1,2].
- In 2050, the average car is assumed to be only 10% of the time available for V2G.
- The average charging power of charging station is 7.4 kW[3]

This means that 10% * 57million vehicles * 7.4 kW = 42 GW of flexible power capacity is available through V2G in FF55-inspired in 2050.

Results

	FF55-inspired			REPowerEU-inspired			Radical Action		
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050
Number EVs (Million)	64	158	221	69	170	237	69	179	244
Share EV using V2G (%)	16%	21%	26%	30%	40%	50%	50%	60%	70%
Time of the year available for V2G (%)	8%	9%	10%	8%	9%	10%	8%	9%	10%
V2G flexibility (GW)	6	22	42	12	45	88	20	71	121

Besides this bottom-up approach, the final installed capacities were validated with internal and external experts.

Sources: 1. RAC (2012) 2. RVO – Charging research (2021). 3. The average charging power is taken as 7.4kW, or 32A one phase charging. Home charging power typically ranges from 3.6kW (16A single phase) to 11kW (16A three phases). Exceptionally, 22kW is installed (32A three phases). 7.4kW is taken as an average value for our calculations.

4. Tortos et al - Statistical representation of EV charging (2018) 5. Bucher et al. (2015) 6. Sorensen et al (2021). Derived via dividing average connection time charging in hours/ average time charging per session

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Smart Charging – V1G – in Transport

Most electric vehicles are able to provide DSR flexibility

DSR flexibility – adapting the demand

V1G can be provided in different ways For example:

- Ramping charging speed up and down. Instead of delivering power back to the grid, charging speed can be in- or decreased when the charging speed is not set to a maximum level when the car is plugged in. E.g. when the maximum charging power is 6.4kW, the car can be set to charge at 4.4 kW. It can then ramp up to 6.4kW and down to 2.4kW. (Charging power cannot fall below 2.4kW according to the Open Charge Point Protocol).
- Delayed charging. Since cars are parked 90% of the time, charging can often be delayed to avoid peak demand.

Main assumptions

- For simplification reasons, it is assumed every charging station can provide 3kW of upward and downward flexibility.
- Even though TYNDP only assumes a share of V2G, we assume that almost all remaining light vehicles are able to provide DSR flexibility.
- V1G capacities will decrease over scenarios, due to higher penetration rates of V2G assumed for the more ambitious scenarios.
- For reasons of simplicity and because we do not model grid constraints in phase II, we assume flexibility by EV DSR is provided by method I as described above.
- If parked, the vehicle must also be connected to a charging station, the owner must be willing to participate, and there must be a need for flexibility in the power system. Given these conditions, a similar availability for 8%-10% is assumed, increasing from 2030 towards 2050 due to improved incentives, constant over scenarios.

Differences V2G

In comparison with V2G, there are several differences:

- From a hardware perspective, all cars are able to deliver DSR flex.
- V2G flex can always be provided when the car is plugged in. However, DSR flex can only be provided when the car is plugged in and when the car is still charging. Once the battery is full, flexibility cannot be provided. This is assumed in the time of the year availability with more V1G charging stations compared to V2G.

Calculation

TYNDP provides the total electricity use by passenger vehicles. We assume that only passenger vehicles participate in DSR and none of the other transport subsectors do.

Total passenger vehicle usage in 2050 in FF55-inspired = 397 TWh/year.
We assume that an electric vehicle on average consumes 1,800 kWh/year.
This means that the amount of electric passenger vehicles is $\frac{397TWh/year}{1800\ kWh/year}$ = 221 million.

We assume that 74% of all light vehicles are able to provide DSR flex. This is derived via subtracting the V2G share (100%-26%).
Therefore, 0.74*221 million vehicles = 163 million vehicles can support DSR flex.
163 million Evs are able to provide 3 kW of flexible capacity for 8-10% of the time.

Based on the metrics above, 49GW of V1G flexibility capacity can be provided by electric passenger vehicles in 2050.

Results

	FF55-inspired			REPowerEU-inspired			Radical Action		
Year	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Number EVs (Million)	64	158	221	69	170	237	69	179	244
Share EV using V1G (%)	84%	79%	74%	70%	60%	50%	50%	40%	30%
Time of the year available for V1G (%)	8%	9%	10%	8%	9%	10%	8%	9%	10%
V1G flexibility (GW)	13	34	49	12	28	36	8	19	21

Besides this bottom-up approach, the final installed capacities were validated with internal and external experts.

Heat pumps in buildings

Heat pumps provide DSR flexibility in the building sector

Heat pumps can provide grid flexibility. Depending on the technology used (hybrid or full electric), the household characteristics (level of insulation, household size etc), the power and the amount of flexibility provided by a heat pump varies.

How can a heat pump provide flexibility?

- In both hybrid and full electric heat pumps, an electric heating element is used to heat the water tank. The water should always be kept at a minimum temperature to eliminate salmonella risk. Nonetheless, the water temperature can be varied slightly, providing some flexibility.
- Flexibility in space heating can be provided by:
  - Pre-heating to avoid grid peaks (both hybrid and full electric);
  - Varying room temperature within end user comfort (both hybrid and electric)
  - Fuel switching (only hybrid).

Based on literature[1], the flexibility provided by each heat pump is on average 0.18kW:

- The average heat pump provides 4kWth, which translates to 0.75-1.5kWel, depending on the COP used.
- It is assumed that flexibility is only used within peak demand, 40% of the time.
- It is assumed that 40% of the power can be consumed flexibly.
- Therefore: 0.4*0.4*0.75kW = 0.12kW, up to 0.4*0.4*1.5kW = 0.24kW. Arriving at an average of 0.18kW.

Which heat pumps are flexible?

What heat pumps are flexible is determined by technology and choice of user.

1. Regarding technology it is depends if the heat pump is connected to the internet and equipped with flexibility software. Currently 23% is connected[3]. In 2050, 75% of is expected to be connected in FF55-inspired.
2. The choice of the heat pump owner is driven by the prices offered on the flex market. This will depend on the different price bands for DSR and the incentives created by governments and companies.

Other assumptions made

- Electricity usage in buildings for scenarios in 2050: FF55: 2,145 TWh REPEU: 2,314 TWh RADA:2,546 TWh
- Average electricity use of heat pumps: 3,903.5 kWh / year[4]
- Average share of electricity usage in buildings used for heat pumps: 42% [2, 5, 6]
- Current share of internet connected heat pumps (23%)[8]. Increased over time and scenarios.
- Heat pumps in 2021 in EU were 17 million[6]
- Sanity check on number of buildings(131 million)[7] and households (197 million in 2021)[8] in EU in 2021.

Sources: 1. Accenture - Flexibele inzet warmtepompen (2021) 2. Statista: Share electricity use for heat pumps in household 3.Delta - Market insight on flexible connected devices (2019) 4.Spitler et al. Heat pump performance – (2019), Wolf – electricity consumption of heat pumps (2022) 5. IEA – future of heat pumps (2022) 6. JRC – Heat pumps in the EU (2022) 7. RICS – buildings EU (2022) & Eurostat – households EU (2022) 8. Delta & FAN – energy grid need smart heat pumps (2019)

Calculation

TYNDP 2018 provides input data regarding the amount of electric heat pumps in the different scenarios. For 2030, this corresponds to 17.1 million heat pumps in 2030.
REPowerEU announced increased installation of electric heat pumps, reaching ~50 million in 2030 in EU27.
The average share which can be used for flexibility is 0.18 KW per heat pump[1]. This is derived from an Accenture study on various heat pumps in different houses[1].
Total heat pumps (#) * share of heat pumps connected to internet (%) * flex capacity heat pump (GW) = total flex capacity (GW)

In REPowerEU-inspired in 2030, the target of heat pumps for EU27is used[9]. This accounts for:
54 million * 55% *0.18kW = 5.4 GW of flex capacity for heat pumps in 2030.

For other years, the amount of heat pumps is derived from the electricity usage in buildings from the scenarios, multiplied with the share of electricity used for heat pumps, divided by the average electricity use of heat pumps in a year. To arrive at the flexibility, this is multiplied with the average flexibility per heat pump (0.18 kW).

Results

		FF55-inspired			REPowerEU-inspired			Radical Action		
Year	2021	2030	2040	2050	2030	2040	2050	2030	2040	2050
Share heat pumps on internet (%)	23%	38%	55%	75%	55%	75%	95%	55%	95%	99%
Total heat pumps (million)	17	24	127	231	54	153	251	54	165	276
Heat pumps to provide grid flexibility (million)	3.9	9	70	173	30	115	239	30	157	274
Flexibility by heat pumps (GW)	?	1.6	13	31	5.4	20.6	43	5.4	28.3	49.3

Besides this bottom-up approach, the final installed capacities were validated with internal and external experts.

9. Note: No ancillary services for heat pumps are in place as of now. Focus is only on wholesale market
Flexibility of heat pump during winter can be a lot higher, but are not included in the scope.
REPowerEU target of 50 million heat pumps excludes UK. UK plans for 600,000 installations per year until 2028, arriving at 54.47 heat pumps in 2050. Assuming same growth rate for UK in 2029 and 2030.

Industrial DSR in industries

Various industries can provide DSR flexibility to electricity markets

Although industrial DSR is not very common in most countries, it can play a large role in balancing the future power system with high shares of variable power sources. With increased electrification, the potential of the industry sector to offer flexibility to the electricity market increases. Limited literature is available on the projected growth potentials.

Demand Side Response for non-time critical business processes

Two processes can be distinguished: processes which are required at a certain time and processes which are not required to take place at a specific moment in time. For the latter category, flexible demand can be orchestrated.

Assumptions

- Using industrial electricity demand for EU27+UK for the scenarios and target years.
- Although for this study the shift of up to 4 hours of demand in industry is considered, various timeframes can be offered, at a variety of capacities, for a variety of price ranges.

Areas for future research

- Possible enablers which foster transparency to measure industrial DSR benefits and costs.
- Optimal communication measures between actors across borders on optimal DSR actions.
- Standardized measuring of costs & benefit across member states and EU centralized orchestration on current regulations and future policy developments.
- Assessing which processes in which industries are most suited for flexibility and which actors are willing to pay what price for demand shifting or shedding, for what time periods.

Calculation

For the Netherlands, the Dutch TSO assumed 700 MW of flexible capacity provided by industry. For 2030, this is expected to be 1,900 MW according to their study to on the future of industrial demand and response.

These values are used to approach the flexibility for the other countries in 2020 and 2030, using their proportionate share of the electricity usage in industry sector from TYNDP.

So Netherlands has a share of 0.03 of the total electricity consumption in the industry in EU27+UK. Then the flexible industry capacity in EU27+UK is 700/0.03=20,549 MW.

The values for 2040 and 2050 are calculated using the relative growth of the electricity demand in TYNDP between 2030 and 2040 and 2050.

This results in a total flex capacity from industry in 2050 of 57 GW, used for REPowerEU-inspired. Other capacities of scenarios defined based upon electricity growth between scenarios.

Results

EU27+UK - GW Flexible capacity from industry	2030	2040	2050
FF55-inspired	22	28	35
REPowerEU-inspired	51	54	57
Radical Action	51	61	67

Besides this bottom-up approach, the final installed capacities were validated with internal and external experts.

Source:
1. Tennet & DNV - De mogelijke bijdrage van industriële vraagrespons aan leveringszekerheid (2021)
2. Smart Energy Europe & DNV – Demand Side Flexibility (2022)

Average battery discharge ratio increases from 3.5 in 2020 to 5.76 in 2050. Newest installed batteries in 2050 reach a ratio of 1:6

Approach on battery discharge, as ratio between the capacity installed (GW) versus the total energy stored (GWh)

Definition

Power to capacity storage ratio is defined by NREL as:
" The amount of time storage can discharge at its power capacity before depleting its energy capacity. For example, a battery with 1 MW of power capacity and 4 MWh of usable energy capacity will have a storage duration of four hours." [1]

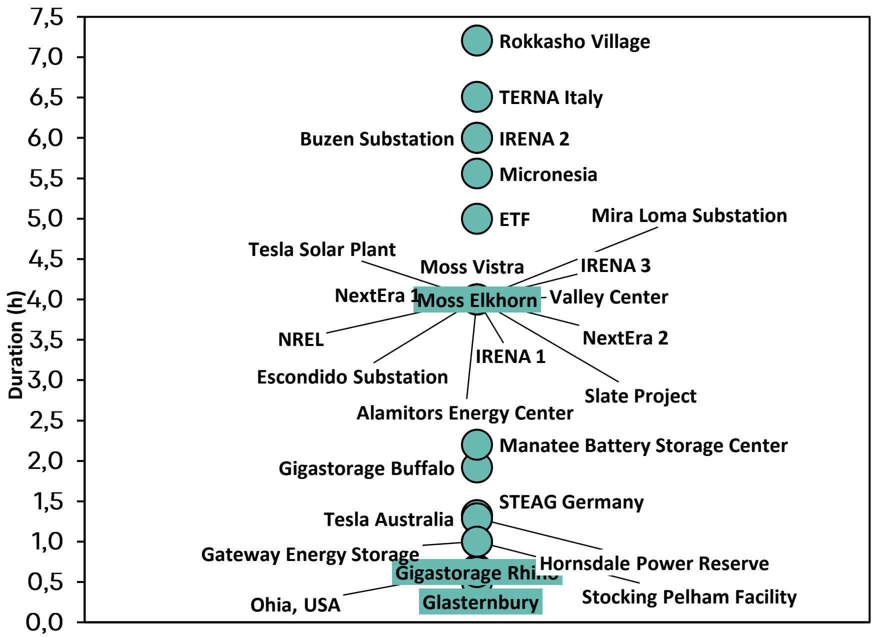
Key assumptions

- Total battery capacities for scenarios include prosumer and utility scale.
- Current average ratio between capacity (GW) and energy stored (GWh) of battery project is 3.5
- Target value of 6 taken for newest installed batteries[2]
- Total average for three scenario are taken per target year, since values have relatively low spread
  - (max difference per target year: 0.2)
- Installed capacity is assumed to last for the next decade, but will be replaced in the decade after that
  - i.e. 2 GW currently installed is still there in 2030 but is replaced in 2040.

Methods

1. Define total GW of batteries installed from input files
2. Calculate new installed or replaced capacity: difference between total installed capacity per target year versus what was installed the target year before
3. Define assumptions on battery discharge per target year. (i.e. 6 in 2050)
4. Calculate weighted average battery capacity:
   - (installed GW*respective discharge ratio) / total GW installed

Utility Scale battery power to capacity storage ratios – literature benchmarking



Impact
A higher value of discharge, implies energy can be stored for a longer time. This is of added value since it helps to matching supply and demand in a variable power system with high RES penetration

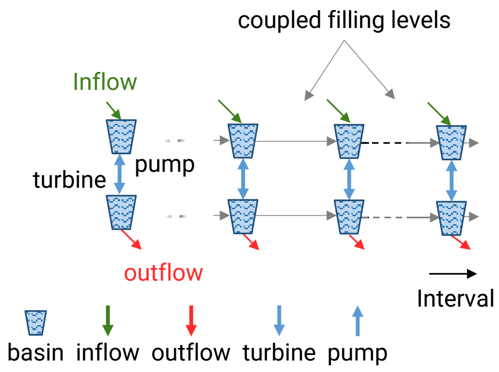
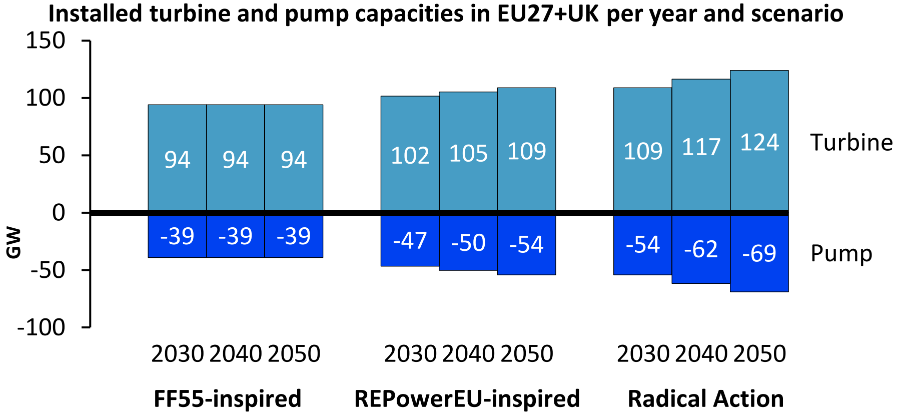
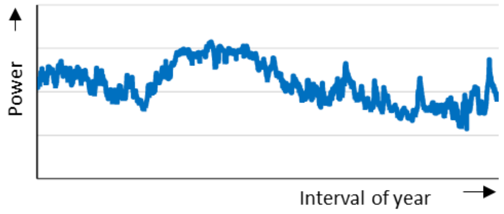
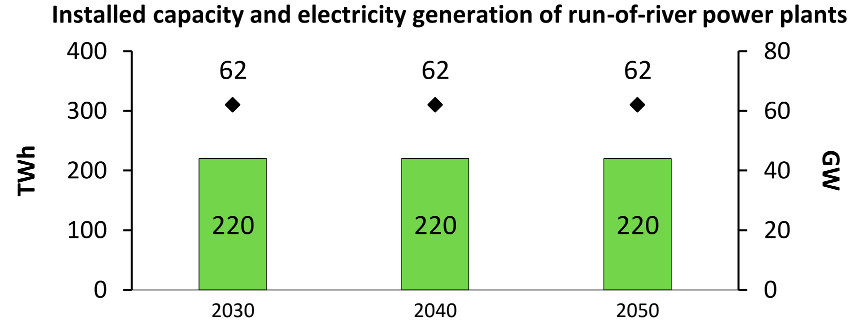
Calculation for average battery discharge (equal for all scenarios)

Year	Ratio	total (GW)	new installed / replaced capacity	3.5	4	5	6	Weighted average
2020	3.5	2	2	2				3.5
2030	4	123.4	121.4	2	121.4			3.99
2040	5	210.2	88.8		121.4	88.8		4.43
2050	6	280.3	195.5			88.8	193.5	5.76

Source: 1. NREL (2019) 2. Interview EDF (2022)

Hydropower

Within this study, a distinction is made between flexible and inflexible hydropower

	Types of hydro power	Category	Example	Description	Installed Capacities
Flexible	Reservoir & pump storages	Generation & Flexibility		Hydro power plants are modelled as complex and detailed hydro networks and consist of basins, turbines and pumps. Hydro flows are linked in turbines to electricity generation and in pumps to electricity consumption. Within this modelling approach, hydro network constraints such as basin limits, historic inflows, historic flexibility potentials are considered.	
Inflexible/must-run	Run-of-river	Inflexible Generation		Fixed generation of electricity via conversion of water movement to electricity. Inflexible power output time series results from the inflows of the respective rivers based on the weather year 2018.	 Based on the weather year 2018 a fixed time series for the electricity generation by run-of-river power plants is used. This time series is held constant over all scenarios and target years. It is assumed that the current capacity and generation are close to the theoretical potential.

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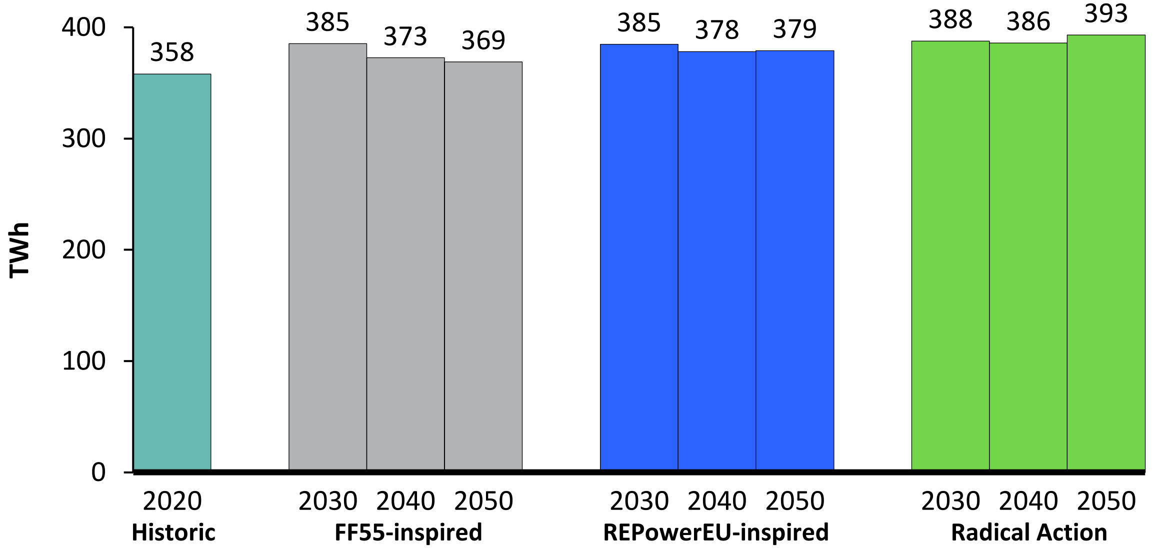
MAON

Hydropower plays a major role in meeting Europe's ambitious energy transition goals - Enhancing EU security of supply and system stability

Hydropower not only as key enabler to meet the electricity demand in hours with low contribution of variable Wind and Solar generation...

- Hydro power plants still contribute 369 TWh (FF55-inspired) to 393 TWh (Radical Action) of renewable electricity in 2050.
- Hydro is crucial in meeting the electricity demand in hours of low variable wind and solar feed-in.
- Within all scenarios and target years the full load hours of the hydro power plants lie in the range between 2,100 and 2,500 h.
- In all scenarios, electricity production from hydro generation plants increases over time compared to electricity production from hydro plants of 358 TWh in 2020.[1]
- Hydropower has the highest efficiency rates of all generation technologies.

Electricity Generation by all hydro power plants in EU27+UK - all scenarios
including reservoirs, pump storage and run of river



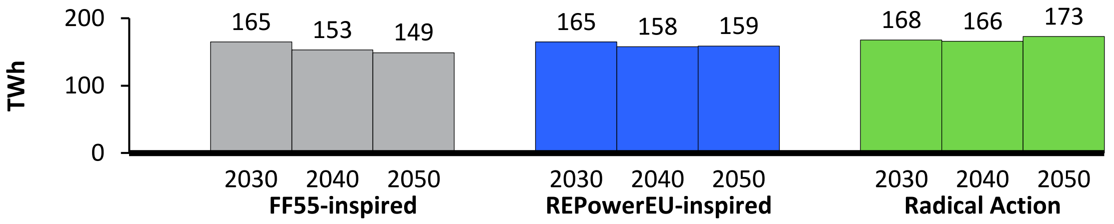
...but also as opportunity to store, consume and use surplus renewable wind and solar generation...

- Apart from their electricity generation in hours with low variable solar and wind feed-in, pump storages offer the opportunity to consume electricity in hours of surplus solar and wind generation.
- As seasonal storages, pump storages allow to shift energy over longer periods of time.

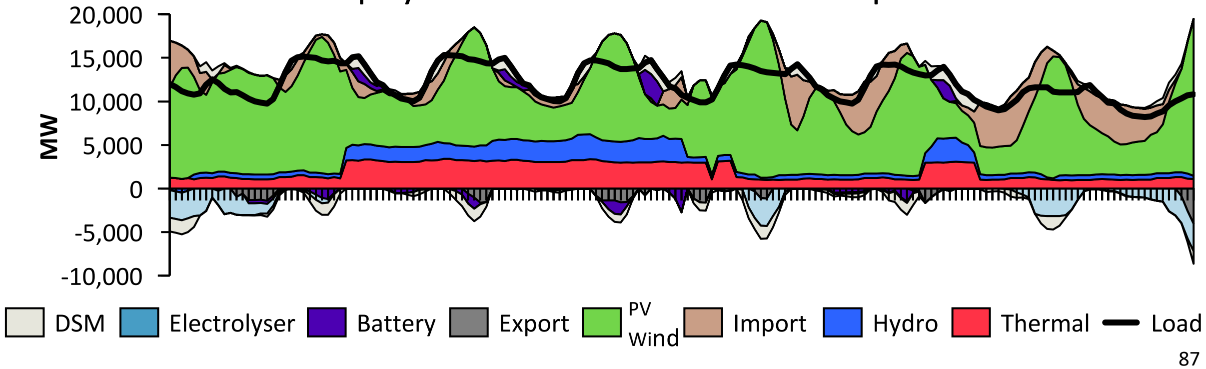
...and further as flexibility offering to stabilise the system and secure the supply

- Hydro power plants enable instantaneous supply adjustments to meet the demand and hence, contribute to keep the frequency stable.
- Furthermore, hydro power plants are almost irreplaceable for the power system due to their black start capability.

Flexible electricity generation by reservoirs and pump storages in EU27+UK



Exemplary winter week in Austria in REPowerEU-inspired 2030



Source: 1. Eurelectric (2018)
Note: Pump storages can either generate electrcity or consume electricity depending on their operation state. While being in "pumping" mode, they consume electricity.

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Challenges ahead & benefits

There are numerous other challenges to overcome for full decarbonisation, including scarcity of personnel, materials, and grid constraints

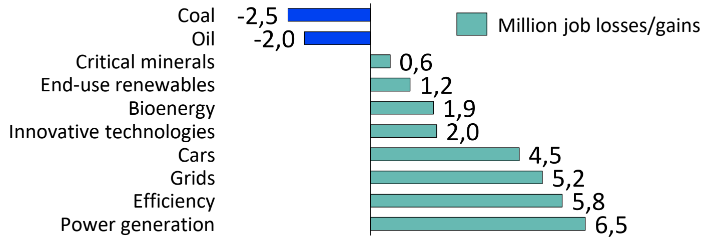
Overview of challenges and first mitigating actions to complete the energy transition (non-exhaustive)

Scarcity of Personnel

Challenges

Enough skilled personnel is critical to fulfil the required installation for the energy transition. Especially technical professionals are needed to design, build and maintain the assets required for the energy transition. In 2020, 1.3 million people were (in)direct employed in the renewable energy sector[1].
IEA estimates global job increase of almost 24 million jobs in clean energy in 2030 in the net zero emissions scenario[2]:

Net job global increase / decrease in 2030 in energy fields



Mitigating actions

Europe-On was launched to acquire attention on the required skills for climate[3,4]. In March 2022 policy makers of members states were asked to:
1. Assess the gap between available and required installation professionals to achieve climate targets.
2. Launch an EU campaign to stimulate attractiveness of technical education among all people
3. Set up a skills for climate platform to collaborate with all relevant stakeholders.

Sources: 1. EC – Joint declaration on skills in clean energy sector (2022) 2. IEA – world energy outlook (2021) 3. EuropeOn-Skills-4-Climate (2022) EC – employment EU renewable energy sector (2022)

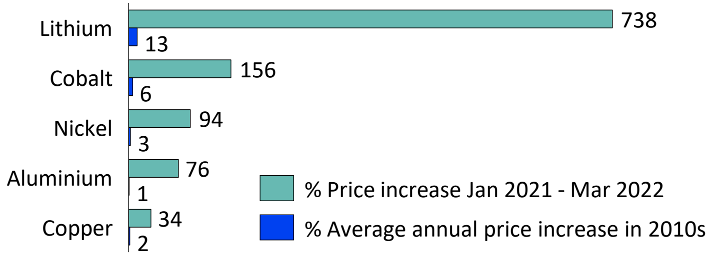
Scarcity of raw materials

Challenges

Raw materials are an important component to realise the green transition. Three obstacles to overcome are:

- **Location of source**: Lithium, Cobalt Nickel, Copper and Aluminium are key elements for battery production, but have limited sources in the Europe.[4]
- **Metal refining capacity:** Not located in Europe, but dominated by China, for Lithium (~70%), Nickel(~80%) and Cobalt (~82%). Recycling of current metals used is key to limit resource dependency.[5]
- **Price development:** Prices are increasing as result of scarcity of critical materials, see overview of IEA[6] below.

Percentage price increase of critical raw materials



Mitigating actions

The EC launched the critical raw materials act, which focusses on: 1. strategic application focus 2. Network of European agencies to enter the market. 3. More resilient supply chain via investments 4. create level of playing field via standards.

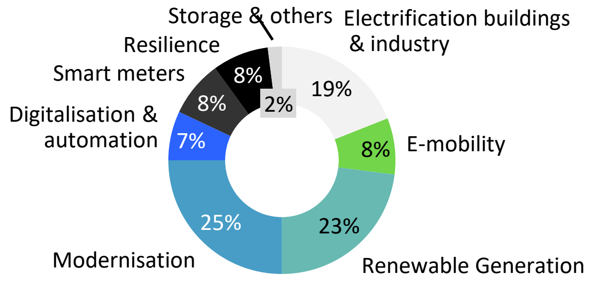
Sources: 4. IEA – price increase critical raw materials (2022) 5. Economist (2022) 6. EC – critical raw materials act (2022)

Grid constraints

Challenges

Increasing electricity demand asks for an improved electricity grid. With increasing amount of RES capacity in the energy system, power supply will be increasingly intermittent and will not only deliver power at the connections, but also absorb power from locations where it is fed back to electricity grid. Power outages, transmission losses and cyber-attacks are other challenges.
In 2030, addition DSO investment of €375-425 billion is needed according to Eurelectric study in 2021[7].
This accounts for an increase of annual investments in DSO grids of 50-70% to 34-39 billion per year.

Key investment drivers and weight (2020-2030)



Mitigating actions

Current additional investment plans will be announced by the European commission delivering €584 billion to digitalise the European energy system, moving away from Russian gas[8].

Sources: 7. Eurelectric – Connecting the dots (2021) 8. IEEFA – EU draft calls eu584 billion investment 2030 to modernize grid (2022)
Note: other challenges such as social barriers for acceptance and different political views are not to be neglected.

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Total land area needed for wind and solar deployment to deliver on the REPowerEU 2030 targets for RES is relatively small

Schematic indication of land area needed for wind and solar deployment to deliver on the REPowerEU-inspired targets in 2030.

Onshore wind

487 GW = 97,600 km^2 - 195,000 km^2

Offshore wind

178 GW = 18,400 km^2 - 42,100 km^2

Utility scale solar

905 GW = 18,000 km^2 - 37,000 km^2

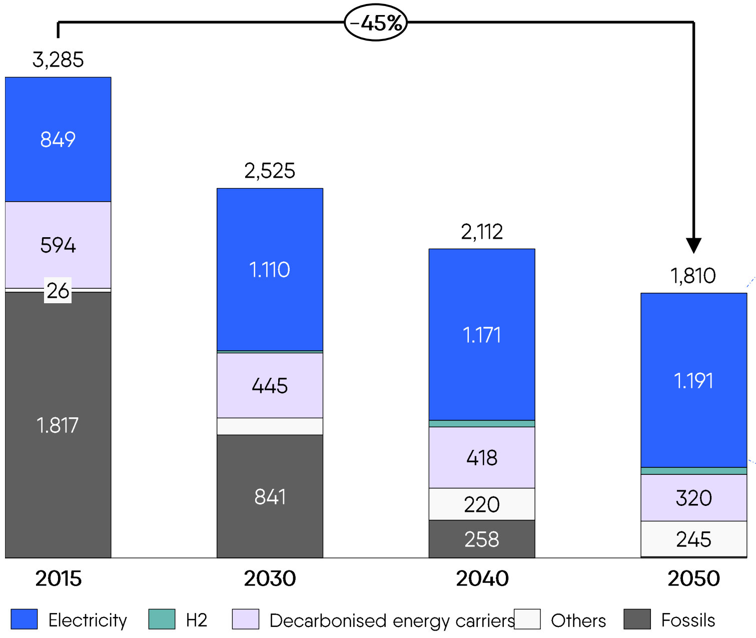
Approach and assumptions

- Note that the total surface area of EU27+UK is ~4476 million km^2
- The area that is needed for wind energy was considered in the analysis, including required distances between the turbines.
  Onshore[2]: 200 - 400 km^2 / GW. Offshore range[3]: 103.56-236.8 km^2 / GW
- Solar PV – The area required for utility scale solar parks was calculated in the analysis, accounting for the distance between panels etc. In this illustration, it is assumed that the entire PV capacity target is satisfied with only utility scale solar (rooftop and other residential solar do not exist in this example but will play a significant role in the future). Solar PV[1] range 20.25-40.5 KM^2 / GW.
- Part of the land can still be used for agriculture or biodiversity projects. Note that the scale of the square area is indicative and based on eye-ball estimations.
- Natural synergies between RES deployment, biodiversity preservation and regeneration are possible, as demonstrated in the Eurelectric's Power Plant project.

Sources:1. SEIA (2023), 2. IRENA (2019) 3. Bilgili & Alphan (2022) 4. Eurelectric (2022)

Electrification is a strong opportunity to lower energy household bills, since natural gas will be phased out and efficiency gains of electrification apply

Energy consumption residential buildings in FF55 (TWh)



- **Overall energy use** in residential buildings decreases 45% in 2050 compared to 2015 in the FF55-inspired scenario.
- **Natural gas is replaced** by electricity as main energy carrier in 2050.
- Electricity consumption will **increase 29% - 39% in 2050 (FF55-inspired - Radical Action)**
- **Others** include heat for example solar thermal energy
- **Decarbonised energy carriers** include biomass, biomethane, synthetic methane / liquids, or liquid biofuels.

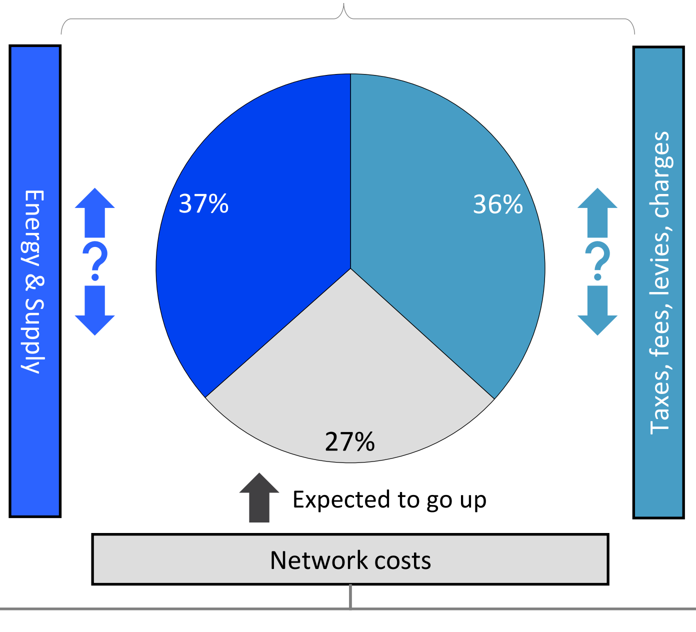
Sources: 1. Eurelectric connecting the Dots (2021) 2. Eurostat – electricity prices for household consumers (2022) 3. Eurostat – Electricity prices components for household consumers (2022)

Distribution of components of household electricity bill[2]

Overall increase is expected in electricity usage, marginal system costs, network costs. Taxes and fees differ highly per country and are uncertain.

Energy & supply Components[3]
Consists of: Generation, aggregation, balancing costs, supplied energy costs, customer services, after-sales management and other supply costs.

What can increase
- Electricity use will increase by 29% - 39% in 2050 due to electrification
- Electricity marginal system costs[4] differ per country



Overview of tax categories[3]
Taxes are divided in five categories by Eurostat:
- Value added taxes (VAT)
- Renewable taxes
- Capacity taxes
- Environmental taxes
- Nuclear taxes
- All other taxes

Can increase or decrease
Highly dependent on country specific policies and circumstances.

DSO investments costs
investments in shorter distance grids, low to medium voltage below 36,000 volt[1].
- In 2021, on average 80% of the network costs on the consumer household electricity bill were dedicated to DSOs[2].
- Cumulative DSO investments in 2050 are €1,012 - €2,874 in FF55-inspired and €1,414 - €3,330 in Radical Action[1]

TSO investment costs
Investments in transmission grids, longer distance, higher voltage above 36,000 volt[1]
- In 2021, on average 20% of the network costs on the consumer household electricity bill were dedicated to TSOs[2].

4. Marginal system costs include: the OPEX of generation, Flexibility cost, balancing cost, emission cost and willingness to pay for demand-shaving at very high market prices.

Energy and supply (focus of this study) | Network costs | Taxes, fees, levies and charges

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The benefits of a decarbonised energy system outweigh the associated costs, taking into account the long-term effects of climate change

Benefits of decarbonised power sector (benefits are interdependent)

Non-exhaustive

Climate change

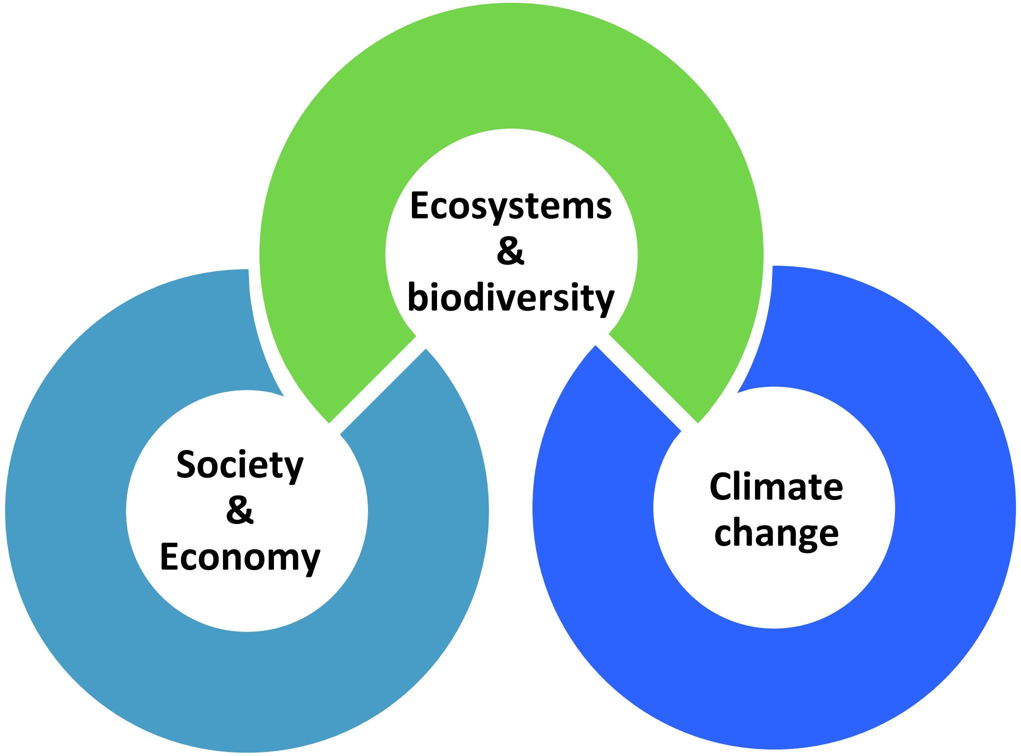
- **Lower risk of loss biodiversity**
- **Less disruption of ecosystems**

Ecosystems and biodiversity benefits

- **Lower risk of severe droughts**
- **Lower risks of floodings**
- **Lower risks of storms and hurricanes**

Society & Economy

- **Better health due to improved air quality**:
  In 2019 air pollution attributed to 307,000 premature deaths[7] in EU-27.
- **Lower risk of mass migration as result of climate change**
- **Lower risk of water and food insecurities**
- **Industrial competitiveness of economy**
- **Avoided fossil imports & costs**: 40% of current international shipping is shipment of fossil fuels[6].
- **Job creation in energy transition**
  - IEA estimates a net global job increase of almost 24 million jobs in clean energy in 2030 in the net zero emissions scenario [1,2]
- **Energy security & Independence:** Prices of raw materials
- **Circular economy**
- **Lower footprint of products produced in Europe**
- **European competitive position on clean technology**



Sources: 1. EC – Joint declaration on skills in clean energy sector (2022) 2.IEA – world energy outlook (2021) 3.EuropeOn-Skills-4-Climate (2022) EC – employment EU renewable energy sector (2022) 4. IEA – price increase critical raw materials (2022) 5. EC – critical raw materials act (2022) 6. Review maritime transport - UNCTAD (2022) 7. Health impact air pollution – EEA (2019)

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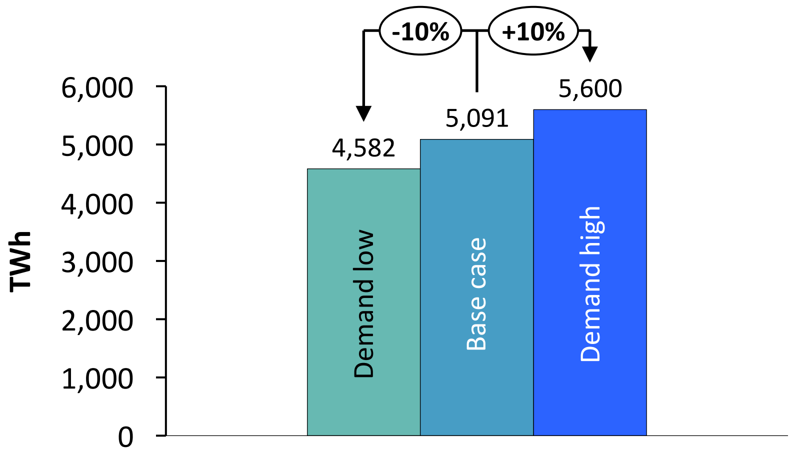
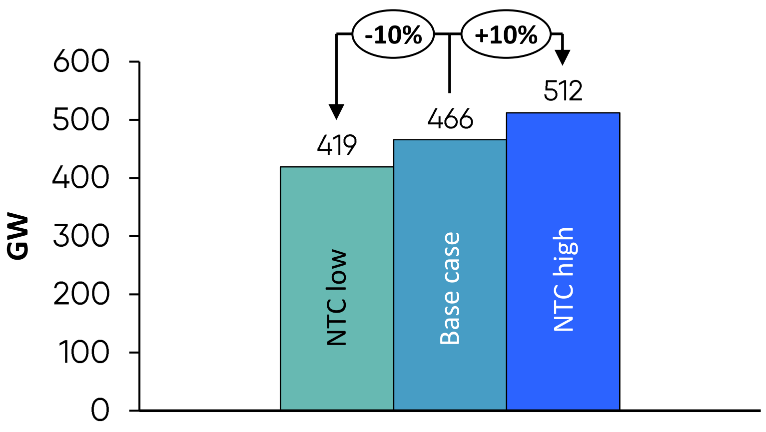
Sensitivity analysis

Sensitivity Analysis in Phase II is carried out for REPowerEU-inspired 2050 – Analysis is performed as ceteris paribus investigation for specific parameters

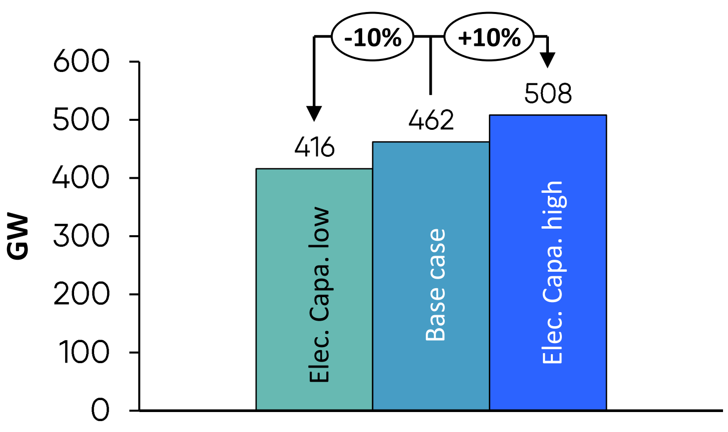
Demand



NTC – Interconnector capacity



Electrolyser Capacity



Scope

Sensitivity analysis is performed to analyse the influence of selected input parameters on the model results. To ensure readability, this sensitivity analysis focuses on the **REPowerEU-inspired scenario** and target year 2050 in EU27+UK. Furthermore, the sensitivity analysis provides insights into the interactions within the electricity market and the interdependencies of specific parameters.

Conditions

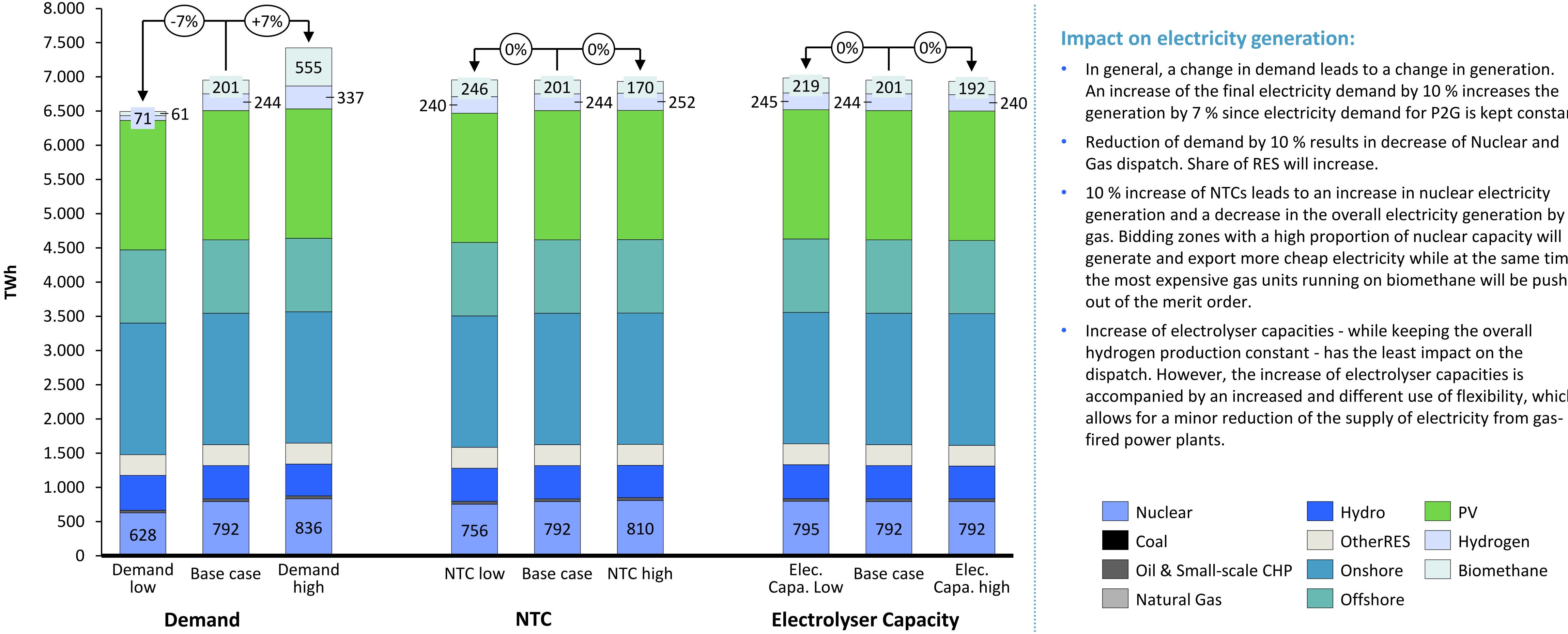
Within the analysis only one parameter is varied while keeping all other parameters constant (ceteris paribus). The results show the influence of the changed parameters on the system. The parameters shown on the right are part of the performed sensitivity analysis.

Parameter	Description	Low	High	Investigated Outputs
Electricity Demand	The final electricity demand in each bidding zone is in-/decreased by 10 % using the existing relative load profile.	-10 %	+10 %	1. Electricity generation 2. Curtailment 3. Energy not served 4. Exchange
NTC	The available NTC between bidding zones is in-/decreased by 10 % between all bidding zones.	-10 %	+10 %	
Electrolyser Capacity	The installed electrolyser capacity is in-/decreased by 10 % while keeping the overall hydrogen production constant.	-10 %	+10 %	

Note: The sensitivity analysis assesses the scenario REPowerEU-inspired 2050. However, similar conclusions and effects can be observed in all scenarios. Nevertheless, the absolute values could vary over the scenarios.

While the magnitude of influences varies among the sensitivity parameters, the electricity generation is influenced by all of them - especially electricity generation by gas and nuclear

Electricity generation by fuel type in EU27+UK [TWh]



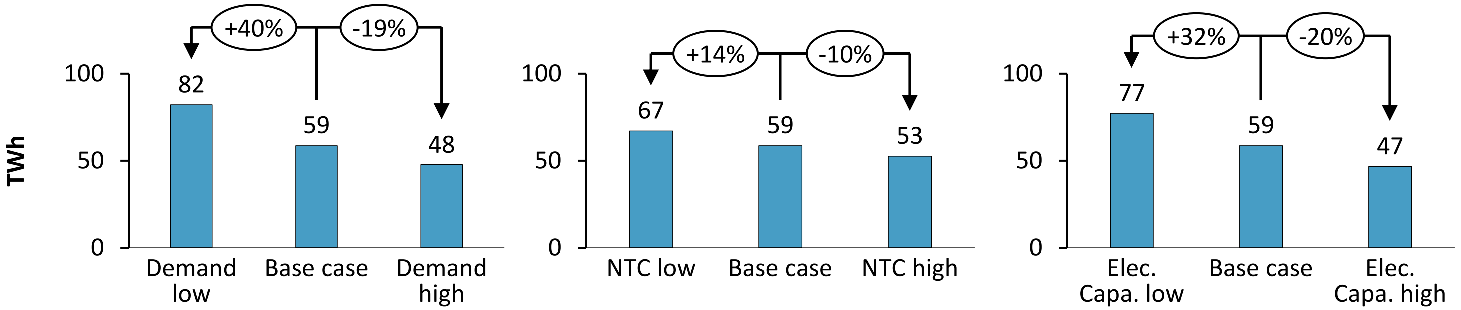
Impact on electricity generation:

- In general, a change in demand leads to a change in generation. An increase of the final electricity demand by 10 % increases the generation by 7 % since electricity demand for P2G is kept constant.
- Reduction of demand by 10 % results in decrease of Nuclear and Gas dispatch. Share of RES will increase.
- 10 % increase of NTCs leads to an increase in nuclear electricity generation and a decrease in the overall electricity generation by gas. Bidding zones with a high proportion of nuclear capacity will generate and export more cheap electricity while at the same time the most expensive gas units running on biomethane will be pushed out of the merit order.
- Increase of electrolyser capacities - while keeping the overall hydrogen production constant - has the least impact on the dispatch. However, the increase of electrolyser capacities is accompanied by an increased and different use of flexibility, which allows for a minor reduction of the supply of electricity from gas-fired power plants.

Note: Displayed Electricity Generation does not include the dumped or curtailed electricity.

Curtailment shows high sensitivity regarding all chosen inputs. Energy not served is mainly affected by increase of demand. Cross border capacities as enabler for integration of RES.

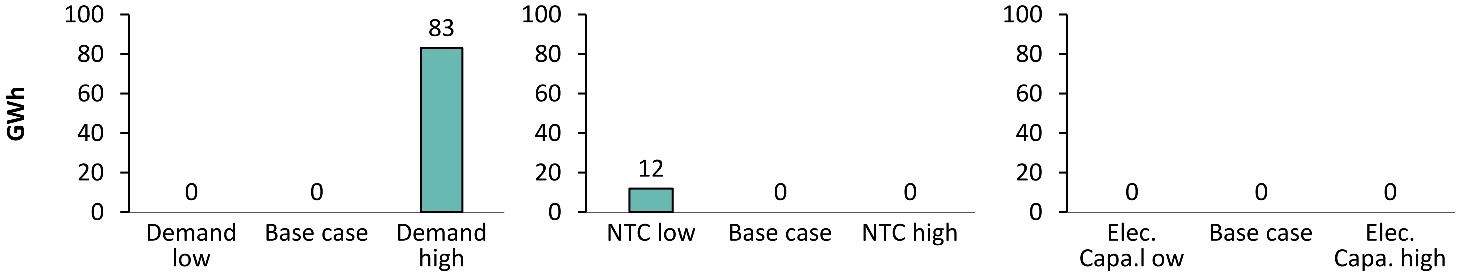
Curtailment in EU27+UK [TWh]



Impact on curtailment:

- Reduction of demand by 10 % results in an increase of the curtailed electricity by 40% (23 TWh), ceteris paribus.
- 10 % increase of NTCs cuts the curtailment by 10 % (6 TWh), ceteris paribus. Increase of NTCs strengthens the interzonal electricity trade and enables an integration of more RES capacities.
- Increase of electrolyser capacity (more flexibility) significantly reduces the curtailment since surplus electricity can be used more balanced / flexible.

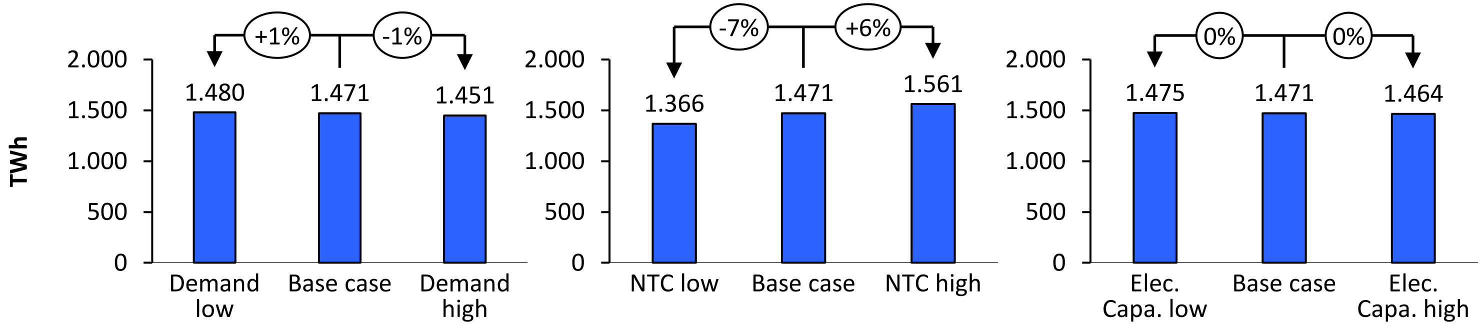
Energy not served in EU27+UK [GWh]



Impact on energy not served (ENS):

- Increase of demand by 10 % results in an increase of ENS by 83 GWh, ceteris paribus. This increase indicates that the developed generation landscape could not fulfill a further increase of electricity demand by 10 %.
- 10 % reduction of NTCs increases ENS by 12 GWh, ceteris paribus. This emphasizes the importance of cross border trade.
- An increase / decrease of the electrolyser capacity has no to little effect on the ENS in the REPowerEU-inspired scenario in 2050.

Exchange – Sum of Exports in EU27+UK [TWh]



Impact on Exports:

- Changing demand by 10 % has a small effect on exports. An Increase of demand leads to a minor reduction of exports.
- Changes in NTCs affect trade significantly. An increase of NTCs by 10 % leads to an increase of electricity exports by 40 TWh, ceteris paribus. Increasing NTCs enable more trade of cheap electricity across bidding zone borders.
- Changing the overall electrolyser capacity hardly affects the overall electricity exports.

Assumptions

Key Assumptions (1/6)

#	Category	Subcategory	Topic / scenarios	Assumptions	Phase
1	Sectors	Buildings	TYNDP tertiary	The tertiary sector (adopted from TYNDP) includes all of the structures occupied by public authorities, associations and companies providing services (excluding farms that are categorized in agriculture and excluding buildings that are categorized in industry).	1
2	Energy carriers	Hydrogen	Hydrogen volumes	The hydrogen volumes in the speedways are not based on prices (or levelized costs). However, the volumes are based on a combination of the policy packages, projections in literature, required hydrogen per sector (especially hard to abate sectors) and expert judgement.	1
3	Sectors	Industry	Data model: industries end use	The TYNDP breakdown into subsectors is used for all main sectors, except for industry, as TYNDP does not provide a breakdown. Therefore, Eurostat 2018 data was used to calculate the proportional size of energy carriers in light-, medium- and- heavy industry.	1
4	Other assumptions	Methods	Electrification rates	The electrification rates in decarbonisation pathways 2018 serve as minimum electrification values for this study (when applicable) because this study should always be more ambitious than the previous study (Decarbonisation pathways).	1
5	Sectors	Transport	Road transport – light vehicles	Light vehicles include vehicles under 3.5 tonnes. Heavy vehicles are over 3.5 tonnes.	1
6	Energy carriers	Methane	Synthetic methane	• Synthetic methane is made from hydrogen and carbon dioxide. • The hydrogen used is produced via electrolysis. • The carbon used is traded as a net-zero commodity (e.g. produced by carbon capture). • Synthetic methane is the only form of 'e-gas' other than hydrogen considered in this study.	1
7	Energy carriers	Bioenergy	Biomass, biomethane and biofuels (bio-energy)	Biomass is used for different purposes in TYNDP's scenarios. It is directly used as final demand for heating and in industrial processes. Furthermore, biomass is used as a feedstock to produce biofuels and biomethane. As such, the biomass is converted to other energy carriers, which are subsequently used in the end use sectors for mobility, heating and other applications.	1
8	Energy carriers	Methane	Import/export	There are no net methane exports. Europe exports a low volume of methane, which is negligible.	1
9	Definitions and scope	Definition	Net zero	Reaching net zero in 2050 (or earlier) means that the final energy demand and electricity generation do not emit GHGs (after CCS).	1
10	Definitions and scope	Scope	Other emission	LULUCF and fugitive emissions are placed out of scope (EC's targets used are modified so that these exclude such emissions). The scope of the study is only the energy sector. However, the LULUCF and fugitive emissions were accounted for when deriving the emission ceiling for the power sector.	1
11	Definitions and scope	Scope	Scope framework	Non-energy use is out of scope (e.g. fossils used as a raw material).	1
12	Energy carriers	Solids	Solids breakdown	For the final energy demand, solids includes coal and lignite within TYNDP. No further specific assumptions on the ratios between these are made in TYNDP nor in the final demand framework of this study. Emissions were calculated by assuming an average emission factor for hard coal and lignite.	1

Key Assumptions (2/6)

#	Category	Subcategory	Topic / scenarios	Assumptions	Phase
13	Energy carriers	Other	Heat	The category "other" differs per sector according to separate interview with TYNDP for final energy demand: • In Residential and Tertiary: solar thermal. • In Industry: distributed steam (main component) and diesel oil, solar, refinery gas, LPG, derived gas. • In Agriculture: solar, geothermal and derived heat. • In Energy branch: other RES.	1
14	Other assumptions	Electricity generation	Other RES in generation	Includes bio-fuels, marine, geothermal, waste, and any other small renewable technologies. CO_2 content is net-zero; it is carbon neutral.	1
15	Sectors	Other sectors	Energy branch	Includes the amount of energy that is required to fill/start a process. E.g. gas extraction: the energy used to extract gas. Hydrogen methanation is not included in this sector. Transmission and distribution losses are not included here, they are not included in the final energy demand framework.	1
16	Other assumptions	District heating	District heating	District heating is in TYNDP and in this study not considered as separate energy carrier category. The energy source used for district heating is included in demand for the respective energy carrier (for example coal or biomass).	1
17	Other assumptions	Methods	GDP growth	Average GDP growth is 1.5% per year.	1
18	Sectors	Buildings	Electrification buildings and heat pumps	This study assumes that for a large part the electrification of the building sectors is a result of the replacement of traditional boilers with heat pumps.	1
19	Sectors	Agriculture and other sectors	Methods	The sectors (adopted from TYNDP DE) agriculture, energy branch and other sectors were not extensively modified as was done for buildings, transport and industry. For these sectors, the FF55 speedway was constructed by simply taking the TYNDP DE values. The REPowerEU inspired and Radical Action speedways on the other hand, have modified values (compared to TYNDP DE) by increasing electricity demand and decreasing other energy carriers in such a way that it contributes to reaching the scenario's targets.	1
20	Energy carriers	Methane	Methane breakdown	For reporting purposes as well as calculating emissions, methane was broken down in natural gas, biomethane and synthetic methane for the target years (2030, 2040 and 2050).	1
21	Sectors	Transport	Road transport	Light vehicles category contains 2-wheelers, passenger cars and light trucks (such as delivery trucks and vans)	1
22	Other assumptions	Methods	Sensitivity analysis	For the sensitivity analysis, an approach was used were high and low values per sector were determined based on literature and expert input (see tabs 1 and 2 for rates), instead of a traditional sensitivity analysis where a standard bandwidth is taken (e.g. 10% or 20% higher or lower than the current value).	1
23	Definitions and scope	Scope	Scarcity of materials/ supply chain constraints	Raw material scarcity and supply chain constraints are out of scope of the study	1
24	Definitions and scope	Scope	Grid constraints	Grid expansion and investments are out of scope of the study. Only NTC values between bidding zones are modelled as a constraint and provided as input for the model.	1

Key Assumptions (3/6)

#	Category	Subcategory	Topic / scenarios	Assumptions	Phase
25	Definitions and scope	Scope	Phase 2	Electricity market modelling is in scope but in phase 2 (this file focusses on phase 1)	1
26	Definitions and scope	Scope	Skilled workers	Lack of skilled workers to realise renewable energy projects etc. is not a factor in scope of this study	1
27	Definitions and scope	Scope	Breakthrough technologies	Breakthrough technologies such as small modular reactors, solid state batteries, flywheels and nuclear fusion are out of scope of the study. If such a technology would break through before 2050, it could heavily influence the future energy supply and demand.	1
28	Other assumptions	Framework	Countries	Usually, when adjustments or modifications were made in the framework, this was done on the level of EU27 + UK and afterwards distributed over the countries using the proportional size of the respective energy carrier of each country from TYNDP.	1
29	Other assumptions	Emissions	CCUS	CCUS is used to compensate for remaining emissions that exceed the ceiling that was set. Ideally the volume of required CCUS is minimized. CCUS is not in scope of the market model used in phase II.	1
30	Sectors	Buildings	Efficiency factors	For residential and tertiary, the same efficiency factors were used - i.e. no distinction was made between the efficiency of appliances in commercial vs residential buildings.	1
31	Luxembourg gets included into Germany	Generation/Demand	all scenarios	Since Luxembourg and Germany are one Bidding Zone, the Capacities and Demand of Luxembourg will be included in Germany	2
32	Northern Ireland will be included in the UK	Generation/Demand	all scenarios	Northern Ireland will be included in the UK	2
33	Distribution of Country Capacities to Bidding Zones	Generation/Demand	all scenarios	Following the ratio of the TYNDP20_DE30, the country-specific values will be distributed across the underlying Bidding Zones. TYNDP20_DE30 serves as a base year to distribute the overall capacity into the respective Bidding Zones.	2
34	Fictional Nodes	Generation/Demand	all scenarios	Fictional Nodes such as PLE (Poland Export) or PLI (Poland Import) will be neglected.	2
35	Small Countries / Islands	Generation/Demand	all scenarios	There are smaller countries or Islands in Europe that play only a minor role within the European Electricity Market (e.g. Island, Corsica) and thus will be considered in the dispatch model, but not assessed in the result analysis.	2
36	Non-EU Countries	Generation/Demand	all scenarios	For all non-European countries, the TYNDP20_DEA30 values were used. Exceptions: Due to the critical role of Norway and Switzerland within the European Power Market, both countries will be taken into account while drafting the scenarios.	2
37	Hydro Capacities / Pump	Generation	all scenarios	Between the scenarios and target years, an increase of the installed capacity of the turbines and pumps is assumed. The starting point of the pump capacity (39 GW in FF55 all years) is based on the TYNDP 22 and analysis of historical data. Due to restorations and upgrading of the Pumps, the pump capacity will increase: REPowerEU: 2030: 46,5 GW; 2040: 50,25 GW; 2050: 54 GW Radical Action: 2030: 54 GW; 2040: 61,5 GW; 2050: 69 GW	2

Key Assumptions (4/6)

#	Category	Subcategory	Topic / scenarios	Assumptions	Phase
38	Hydro Capacities / Turbine	Generation	all scenarios	Between the scenarios and target years, an increase of the installed capacity of the turbines and pumps is assumed. The starting point of the pump capacity (94 GW in FF55 all years) is based on the TYNDP 22 and analysis of historical data. Due to restorations and upgrading of the Pumps, the pump capacity will increase: • REPowerEU: 2030: 101,5 GW; 2040: 105,25 GW; 2050: 109 GW • Radical Action: 2030: 109 GW; 2040: 116,5 GW; 2050: 124 GW	2
39	Hydro Capacities / RoR	Generation	all scenarios	The Run-of-River dispatch is based on historical data from 2018 and is calibrated accordingly.	2
40	Other RES	Generation	all scenarios	Other RES is completely included within the Time Series of Biomass (Other RES includes: Bio-fuels, marine, geothermal, waste and any other small-scale renewable technologies	2
41	Other Non RES	Generation	all scenarios	Other Non RES is completely included within the Time Series of small-scale CHP	2
42	Type of Technology	Generation	all scenarios	Conventional: Nuclear, Coal and Lignite, Gas, Oil, Other Non RES (CHP) Renewables: Wind Onshore, Wind Offshore, Photovoltaic, Hydro, Other RES (bio)	2
43	Climate Year	Generation	all scenarios	The historic Climate Year 2018 is used.	2
44	NTC-Values	Generation	all scenarios	The NTC-Values from the TYNDP2022 will be used. Assumption: All Network Expansions with a completion date before the Scenario Year are included.	2
45	Electrolyser efficiencies	Generation	all scenarios	Energy conversion efficiency factors based on TYNDP building guidelines and Gorre et al (2019): • 2030: 69% • 2040: 71% • 2050: 74%	2
46	Electricity demand for hydrogen production	Generation/Demand	all scenarios	• 2030: partly via electrolysis, partly via Steam Methane Reforming. Ratios differ per scenario. • 2040: interpolated between 2030 and 2050. • 2050: 100% via electrolysis Source: Expert Scorecards of the SteerCo Members and discussions during Steerco meetings	2
47	Modelling of Hydrogen in the Electricity Market Model	Demand	all scenarios	Hydrogen production is modelled via pumps with a fixed Electricity Demand (Electricity Demand for Hydrogen - see above). The Capacity of the pumps is represented by the Electrolyser Capacities of each Country. By adding the Hydrogen demand via flexible Loads, we can reduce the Peak-Loads since the Hydrogen production will be closely linked to the RES generation and to market incentives.	2
48	Electricity demand for Synthetic Methane Production	Demand	FF55	The efficiency to produce Synthetic Methane via the usage of electricity is based on own calculations. Efficiency from Power-To-Synthetic Methane: • 2030: 0,64 • 2040: 0,66 • 2050: 0,69	2

Key Assumptions (5/6)

#	Category	Subcategory	Topic / scenarios	Assumptions	Phase
49	TimeSeries Onshore, Offshore, Photovoltaic	Generation	all scenarios	The Time Series for the Technologies Onshore, Offshore, and Photovoltaic is derived from the Time Series of the TYNDP20_GA30 scenario of the MAON Electricity Market Model. The Time Series are normalized to the Installed Capacity of the TYNDP20 GA30 scenario. A comparison between the BT18 and the GA30 shows a sufficient fit between the two scenarios. However, in the BT18 scenario, a few countries had installed capacities of 0 MW, and hence, there were no values in BT2018. Due to this fact and to keep it consistent, the Time Series of the TYNDP20_GA30 scenario (in most BZ they should be identical with the BT2018 scenario) are used.	2
50	TimeSeries Other RES, Other NonRES	Generation	all scenarios	The Time Series for the Technologies are derived from the Time Series of the TYNDP20_GA30 scenario of the MAON Electricity Market Model. The Time Series are normalized to the peak value of the dispatch time series.	2
51	Missing Onshore TimeSeries	Generation	all scenarios	In some bidding zones where capacity greater than zero is expected in the long term, time series were partially missing (e.g. Bidding Zone SE1, NON). For these countries, the following simplifications were made. They got assigned the time series of the closest neighbouring bidding zone.	2
52	Missing PV TimeSeries	Generation	all scenarios	In some bidding zones where capacity greater than zero is expected in the long term, time series were partially missing (e.g. Bidding Zone SE1, NON). For these countries, the following simplifications were made. They got assigned the time series of the closest neighbouring bidding zone.	2
53	Missing Offshore TimeSeries	Generation	all scenarios	In some bidding zones where capacity greater than zero is expected in the long term, time series were partially missing (e.g. Bidding Zone SE1, NON). For these countries, the following simplifications were made. They got assigned the time series of the closest neighbouring bidding zone or the onshore time series of the specific bidding zone was allocated to the bidding zone.	2
54	Norway and Switzerland	Demand / Generation	all scenarios	Switzerland and Norway were modelled according to the modelling data of the TYNDP DEX0 scenario.	2
55	Distribution of Hydrogen Production Capacities in Italy	Demand	all scenarios	The Electrolyser Capacities are distributed in accordance to the share of the Electricity Demand and the assessment of the dump energy per bidding zone.	2
56	Distribution of Conventional Power Plants in Italy	Generation	all scenarios	The conventional Power Plant Capacities will be distributed in accordance to the ratio of the DE2030 scenario.	2
57	Non-EU Countries	Demand/Generation	all scenarios	For Non-EU countries (such as Albania, Serbia etc.) the fallback solution from the TYNDP20 Distributed Energy Scenario is used.	2
58	Coal and Lignite distribution	Generation	all scenarios	TYNDP22 publishes combined capacities for lignite and hard coal power plants. In the test run the combined capacity is divided into lignite and hard coal capacities based on the installed capacities ratio from TYNDP20 DEX0.	2
59	Hydrogen Import dependency	Generation	all scenarios	All scenarios were developed to target an Import Dependency of 50 % for Hydrogen after discussions with the Steerco. However, with a 5% error margin between TWh imported vs domestically produced as result of iterations between model outcomes and further input values.	2

Key Assumptions (6/6)

#	Category	Subcategory	Topic / scenarios	Assumptions	Phase
60	Efficiency Gains of FLH of Wind Technology	Generation	all scenarios	Within this study, an efficiency gain of the wind technology is assumed. Therefore, the FLH will be increased by 5 % in 2040 and by 10 % in 2050.	2
61	Fuel prices	Hydrogen price	all scenarios	Hydrogen fuel prices are based upon TYNDP 2022 and further validated with a scorecard, where Steerco members could provide values per target year. No distinction is made in different origins of hydrogen in terms of market price.	2
62	Fuel prices	Biomethane price	all scenarios	Biomethane fuel prices are based upon CE Delft and TYNDP and further validated with a scorecard, where Steerco members could provide values per target year. Based on further discussions, fuel limitation were applied to not overshoot the theoretical limits of biomethane or hydrogen and to limit the hydrogen usage in the power sector.	2
63	Flexibility	DSR	all scenarios	V2G, or Vehicle-to Grid, is modelled as DSR since this is parameterized as such during the latest model runs. In last feedback rounds it was considered more realistic to categorize as storage.	2
64	Costs	CAPEX	all scenarios	Literature values from TYNDP and EMBER are used, multiplied with the additional installed capacities from the scenarios.	2
65	Costs	OPEX	all scenarios	OPEX includes fixed and variable OPEX. For fixed OPEX: literature values from EMBER report are used (€/kW). For Variable OPEX, model outcomes are used for the target years. The values for the not modelled target years (i.e. 2031-2039) are interpolated.	2
66	Costs	Inflation	all scenarios	Inflation rates are not included in costs calculations and assumed to be 0%	2

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