2050 Holistic & Efficient Roadmap for a Zero-Emissions EU Energy

A Report to Iberdrola

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AFRY Management Consulting provides leading-edge consulting and advisory services covering the whole value chain in energy, forest and bio-based industries. Our energy practice is the leading provider of strategic, commercial, regulatory and policy advice to European energy markets. Our energy team of over 250 specialists offers unparalleled expertise in the rapidly changing energy markets across Europe, the Middle East, Asia, Africa and the Americas.

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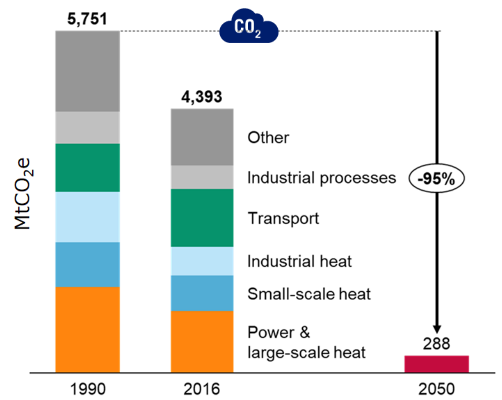
1. The Challenge of Decarbonisation

In November 2016, the Paris Agreement[1], an international agreement governing the mitigation of greenhouse gas emissions, entered into force. With more than 150 countries ratifying the agreement – including the three largest greenhouse gas emitters: China, the U.S.[2] and India – there appeared to be a very broad consensus across the globe that significant action was required urgently.

The main set at the Paris Climate Change Conference (COP21) was to limit global warming to "well below 2ºC" compared to pre-industrial levels and pursue efforts to limit the temperature increase to 1.5ºC. In Europe, it is widely accepted that achieving this 1.5ºC objective requires to reach at least a 95% economy-wide reduction by 2050 relative to 1990 in the Union. In AFRY's opinion, such an ambitious reduction practically implies the full decarbonisation of the energy sector (i.e. transport, heat and power generation), so that the remaining 5% emissions remain in other sectors where full decarbonisation will be much harder to achieve – i.e. in shipping, aviation, agriculture, food, other land use and waste.

FIGURE 1 – THE SCALE OF EUROPE'S DECARBONISATION CHALLENGE ($MtCO_2e$)



Source: national greenhouse gas inventories submitted to the UNFCCC by EU-28 Member States, Norway and Switzerland

In order for the Paris Agreement long-term goals to be met, the Agreement requires for each Party to establish Nationally Determined Contributions (NDCs)[3], which embody efforts by each country to reduce national emissions and adapt to the impacts of climate change.

The European Union's NDC under the Paris Agreement is to reduce Greenhouse Gas Emissions (GHG) by at least 40%[4] by 2030 compared to 1990 levels. This has been set as part of its wider 2030 Climate and Energy Framework, where the EU has also set an objective of at least 32% share of renewable energy by 2030 and at least 32.5% improvement in energy efficiency.

In line with the Paris agreement, Europe's ambition goes beyond 2030[5], and in December 2019 the EU presented the European Green Deal, aiming at creating a fair, competitive and carbon neutral society and economy within Europe by 2050; it was adopted by the European Parliament in January 2020. In this context, one of the main cornerstones of this political project is the European Climate Law, that will enforce the 2050 net zero emission goal legally and will provide both policy and governance guidelines to align policy frameworks with this long-term emission reduction pathway. It also highlights the need to decarbonise the electricity generation sector, in particular phasing out coal plants and fostering zero-carbon gases. To finance its Green Deal, the EU presented in January 2020 an ambitious budget of at least €1 trillion for investments in the 2020-2030 decade, leveraging on EU budget and associated instruments (for instance InvestEU) to attract private investment.

Member States such as Spain and UK have also joined this reclaim of the scientific community to promote targets of net zero emissions by 2050; In January 2020 Spain declared the climate emergency with a compromise to foster a Climate Change Law that ensures climate neutrality by 2050. The UK has taken a step further and already in June 2019 passed a law and established a target of net zero greenhouse gas emissions by 2050.

[1] The main input for the Paris Agreement was the IPCC Fifth Assessment Report published in 2013 which alerted of the clear effect of human influence on climate change.
[2] In November 2019 the US formally notified the United Nations of its withdrawal from the Paris Agreement, which will take a year to complete.
[3] The next NDCs are to be submitted by 2020, and every five years after with greater ambition.
[4] The European Green Deal published on 11 December 2019 points towards increasing this target to 50/55%.
[5] November 2018 the commission presented the "European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy by 2050".

To achieve the European Union's overall target, Member States must develop their own strategy based on the particularities of their industry and energy system, which is to be presented to the European Commission through the "Integrated National Energy and Climate Plans" (NECP). EU governments presented the first versions of their NECP in 2018; from the Commission's feedback on these draft plans, governments were due to present updated versions of their NECP by end of 2019, although some countries have delayed their contribution to early 2020.

The UK draft NECP was published in January 2019 and focuses on domestic climate targets, notably the Carbon Budgets and existing energy policies including the Clean Growth Strategy up to 2050 and the continuation of CfDs for new low carbon capacity. The Government outlined these policies as being the primary tools to achieve the targets set out in the RED, and highlights the ambitiousness of UK's 5th carbon budget which would likely surpass the 2030 target of -37% GHG. The UK has not yet submitted its final NECP.

In March 2020 the Spanish Ministry sent the final version of the Spanish NECP 2021-2030 to the European Commission. This NECP aims at achieving a 42% renewable share over final energy consumption and 74% over electric generation, it sets an emissions reduction target of 23% by 2030 compared to 1990 levels[6], one of the greatest reductions comparatively in Europe, and aims at achieving a primary energy consumption reduction of 39.5%. This ambitious transition is possible thanks to Spain's privileged situation (i.e. mild climate and renewable resource) that allows going beyond the minimums set by Europe, and also to an unequivocal political commitment to decarbonisation.

In this context, Iberdrola has commissioned AFRY to build a decarbonisation pathway towards 2050 for the overall European energy sector, with special focus on Great Britain (GB) and Spain, the two European markets where the group has a strong presence.

The commitment by each country and the overall European region is high, and so is the challenge to achieve the net-zero emissions target. This report prepared jointly by AFRY and Iberdrola aims to identify the keys to a successful and efficient decarbonisation of the energy sector by 2050 in Europe as a whole, and in GB and Spain in particular – the energy sector being in this study power generation, heat, and road and rail transport.

Additional note regarding Covid-19 crisis

In Europe the recovery from the impact of the Covid-19 crisis will be driven by some strategic investment policies. Currently, there are clear political efforts to reaffirm EU commitments to the implementation of the Green Deal – and to integrating the green transition in the Covid-19 recovery plan – as a way "to rebuild our economy and to introduce the necessary recovery plans to bring renewed, sustainable progress and prosperity back to Europe and its citizens (...) in order to mitigate the risks and costs of inaction from climate change and biodiversity losses". In an open letter published by 13 European climate and environment ministers in April 2020[7], the Green Deal is considered as "a new growth strategy for the EU, which is able to deliver on the twin benefits of stimulating economies and creating jobs while accelerating the green transition in a cost efficient way. For example, the objective of climate neutrality by 2050 as well as a strong policy framework ensures a stable and forward-looking investment environment for Europe's businesses, which is an essential precondition for green growth and job creation".

To reinforce these long term objectives and to set a clear path towards them, strong political action is needed to "increase the EU's 2030 target before the end of this year", and the "Commission is on track to present by September 2020 an impact assessed plan to raise the EU's 2030 ambitions and cut greenhouse gas emissions by 50-55% compared to 1990 levels"[7].

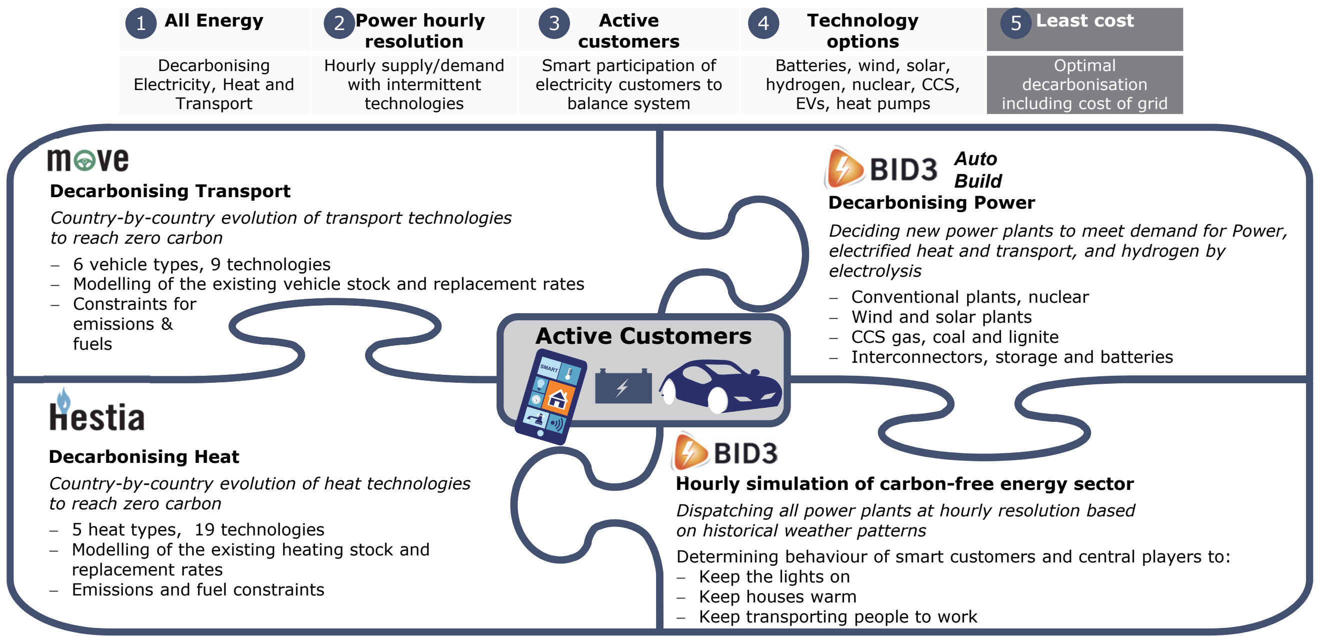
Accordingly, we expect long-term objectives to remain as they are today, as priorities for the European Union remain digitalization, decarbonisation and resilience[8]. We acknowledge that this crisis can substantially impact the energy markets in the short- to mid-term, nonetheless we foresee limited impact on the results of this analysis since it explores a longer term perspective. Although the research and modelling work behind this report was carried out before the Covid-19 pandemic reached Europe, we believe the rationales it is based on will broadly remain unchanged.

[6] Considering that Spain did not reach its emissions peak in 1990, this represents a 35% reduction compared to 2017 level
[7] https://www.climatechangenews.com/2020/04/09/european-green-deal-must-central-resilient-recovery-covid-19/

[8] https://www.euractiv.com/section/economy-jobs/news/von-der-leyen-eu-bud get-should-be-the-marshall-plan-we-lay-out-together/

2. Shaping a Zero-Carbon Energy Sector

FIGURE 2 – AFRY DECARBONISATION MODELLING SUITE



AFRY has developed a whole model suite of the energy sector to quantify the benefits of allowing competition amongst the different technologies available to achieve a zero-carbon energy sector by 2050; the model suite sets the objective of a decarbonized energy sector by 2050 and then calculates the most economical pathway to reach that objective, taking into account the most up-to-date view on possible technology evolutions. The modelling environment has been set up to allow for interaction between the different models.

One of the key strengths of AFRY's decarbonisation modelling suite is that it co-optimises gas and electricity networks, which represents an important share of the total cost of decarbonisation, alongside dynamic optimisation of flexible demand side response and how this interacts with intermittent generation, allowing demand to move within day, across the week and seasonally to support generation patterns driven by weather patterns. Further details on AFRY's modelling methodology can be found in Annex B.

For the purpose of this study we imagine a fully decarbonised energy sector by 2050 across Europe – the energy sector consisting of power generation, heat, and road and rail transport. We explicitly do not consider the decarbonisation of other sectors, such as agriculture or waste; these sectors are outside the scope of this study. For the sectors of aviation and navigation, although AFRY does not develop a pathway for the decarbonisation of these sectors, for the scope of this study we have analysed the potential emissions and incorporated them to our carbon budgets[9], for further information please see Annex A.

[9] Our approach to drafting the emission constraints for this study adapts existing European and Swiss law, expanded based on best available information, and splits up ex ante and in a top-down manner the two carbon budgets for direct emissions enshrined in law into three smaller, virtual ones.

In order to be in line with the ambitious reduction target for the whole European economy amounting to -95% emissions relative to 1990[10] , we achieve a 100% decarbonisation of the energy sector, allowing for a 85% decarbonisation of the non-energy sectors (industrial processes, agriculture, etc.), as we acknowledge that these are much more difficult to decarbonise.

If it were assumed that these other sectors could not achieve the 85% decarbonisation required, the energy sector would need to deliver more than 100% decarbonisation, through negative emissions, mainly using bioenergy in CCS (Carbon Capture and Storage) installations. This has not been considered in this study.

AFRY's decarbonisation modelling suite establishes some basic principles followed for this pathway:

AFRY's decarbonisation modelling suite establishes some basic principles followed for this pathway:

— **Overall full decarbonisation of Europe's energy sector:** AFRY's decarbonisation model suite is restricted to meet European decarbonisation targets by 2050 and not individual NECP targets.

— **Decarbonisation determined by economics:** The choice between the large range of technologies ailable is mainly based on long-term economics. While many technologies are technically available in the pathway, not all of them will be featured in the results, as they are economically unattractive compared to others.

— **We assume that consumers and industrial processes don't need to make major changes in their behaviour.**

The starting point of the pathway developed with Iberdrola is AFRY's Zero-Carbon Gas pathway[11] . In this pathway, all available technologies, i.e. technologies fuelled by electricity and zero-carbon gases, are allowed to freely compete as a viable alternative to decarbonisation and contributes in several ways to fully decarbonise the energy sector by 2050 in the most economical way.

To build this pathway, a number of inputs and assumptions of AFRY's Zero-Carbon Gas pathway (see Annex A) were modified. These modifications were carefully discussed between Iberdrola and AFRY, and reflect a common position on how plausible they are regarding some key aspects of the future of the European energy markets. Among the agreed modifications to AFRY's Zero-Carbon Gas pathway, the most relevant are the following ones:

— The gradual incorporation of e-trucks, including utilisation of new e-highways, as a new technology to assist with decarbonising heavy good vehicles from 2030 onwards.

— Improvements in the efficiency of heat pumps used for space heating, with average seasonal co-efficient of performance in the period 2020-2050 from 300% in cold areas up to 400% in mild weather areas.

— The availability of heat pumps to produce heat for industrial processes up to 200ºC.

— More competitive assumptions for renewable technologies and electrolysis costs in line with an updated review of technology prospective assessments.

The programme of work for the study was structured into three workstreams, each covering one sub-sector of the energy sector:

— **Transport analysis workstream.** The transport workstream has analysed the transport sector in GB, Spain and overall Europe, considering the transition towards a zero-emissions world in 2050. This analysis was based on the current stock of vehicles and expected technology cost, capability and availability.

— **Heat analysis workstream**. In the heat workstream, the transition towards a zero-carbon system for all sectors of heating – residential, commercial and industrial – has been assessed. The basis for this analysis was the current heat supply and expected technology cost, capability and availability.

— **Power analysis workstream**. All analysis is combined in the power workstream. This model uses the outputs from the other workstreams and iterates amongst the models in order to analyse the total demand for electricity and derive the future power mix. The hourly pan-European modelling is based on a database of every power plant in Europe, detailed hourly profiles for demand, temperature, weather[12], wind speeds, solar radiation, EV charging, and electric heating, as well as assumptions for future technology cost, capability and availability.

The decarbonisation path towards a zero-carbon energy sector in 2050 follows a trajectory that is partly informed by the provisions of the two main EU-level climate instruments, the EU Emissions Trading System (EU ETS) and the Effort Sharing Decision (ESD), as well as its successor, the Effort Sharing Regulation (ESR).

[10] We have set the economy-wide target for our study period at 95% relative to 1990, which is the upper end of the range of the EU's reduction objectives, as expressed in the European Commission's Communication "A Roadmap for moving to a competitive low carbon economy in 2050" – COM(2011) 112 final. More recently, on the 11 December 2019 27 member states of the European Union agreed in principle to the 'Green Deal' which commits them to a net-zero carbon economy by 2050, increasing the challenge in the non-energy sector.
[11] Pöyry Point of View - Fully decarbonising Europe's energy system by 2050

[12] In the scope of our decarbonisation project only one weather case collection is used. We have chosen 2014 as it is considered to be an average year in terms of meteorological conditions in Europe.

3. Zero-Carbon Transport Sector

AFRY's transport model 'move' uses the current stock of vehicles across Europe as well as transport demand taken from the EU Reference scenario 2016[13], and applies linear optimisation to determine future transport stock and kilometres driven across all sectors and countries by finding the cheapest possible way of meeting demand, given a set of constraints.

As shown in Figure 3 the European transport sector gradually transitions from an almost exclusively oil-based sector towards a sector dominated by electric vehicles with a small contribution of hydrogen-based vehicles, especially relevant in the truck segment.

The road passenger segment, which includes passenger cars, buses and motorcycles, transitions towards a fully electric segment by 2050. During the transition period diesel and gasoline cars are mostly replaced by full electric vehicles, as well as some hybrids[14] during the first decade.

In the truck segment, formed by vans and medium and heavy goods vehicles (MGVs and HGVs), pure battery electric vehicles present a viable alternative to decarbonise vans, however they are difficult to implement for MGVs and HGVs due to the size and weight of batteries needed. After 2030, e-heavy duty trucks and hydrogen solutions become available for MGVs and HGVs which gradually convert to these technologies, leading to the full decarbonization of the segment by 2050.

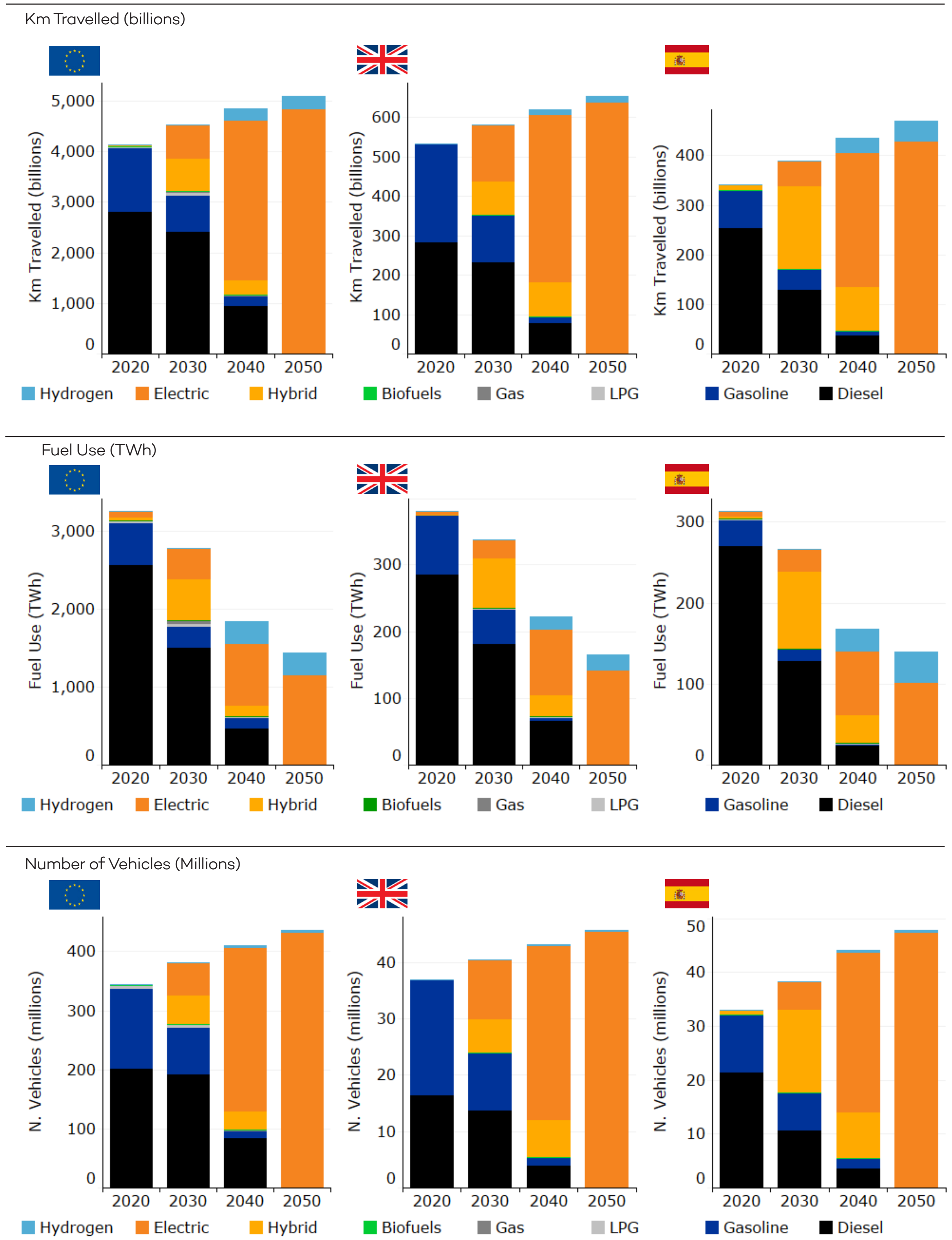
Overall fuel consumption in the transport sector declines substantially, as electric and hydrogen vehicles are more efficient than diesel and gasoline alternatives, when calculated on the basis of tank-to-wheel[15].

The decarbonisation of the road and railway transport sector in Spain and GB follows the same pathway as in Europe as a whole, although slight differences can be observed:

- In Spain, the average age of the current fleet of road passenger vehicles prompts a quick shift towards hybrid vehicles by 2030, as diesel and gasoline cars are quickly removed from circulation and electric vehicles supply chain and infrastructure are still not prepared for a rapid deployment. In GB this shift occurs at a slower pace due to the more recent fleet of vehicles.
- By 2050 there is a greater penetration of hydrogen in the transport sector in Spain than in GB – and thus a lesser electrification (see Figure 12)– due to the higher number of heavy trucks on Spanish roads.

[13] https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft publication_REF2016_v13.pdf
[14] In AFRY's models hybrid diesel and gasoline vehicles run on a fuel mix made of a minimum fossil fuel component (diesel or gasoline respectively) decreasing from 40% before 2025 to 20% until 2035 and then to 5% after 2035.
[15] Describes the use of fuel and emissions during driving

FIGURE 3 – DECARBONISATION TRANSITION OF THE ROAD AND RAILWAY TRANSPORT SECTOR IN THE EU, SPAIN AND GB



4. Zero-Carbon Heat Sector

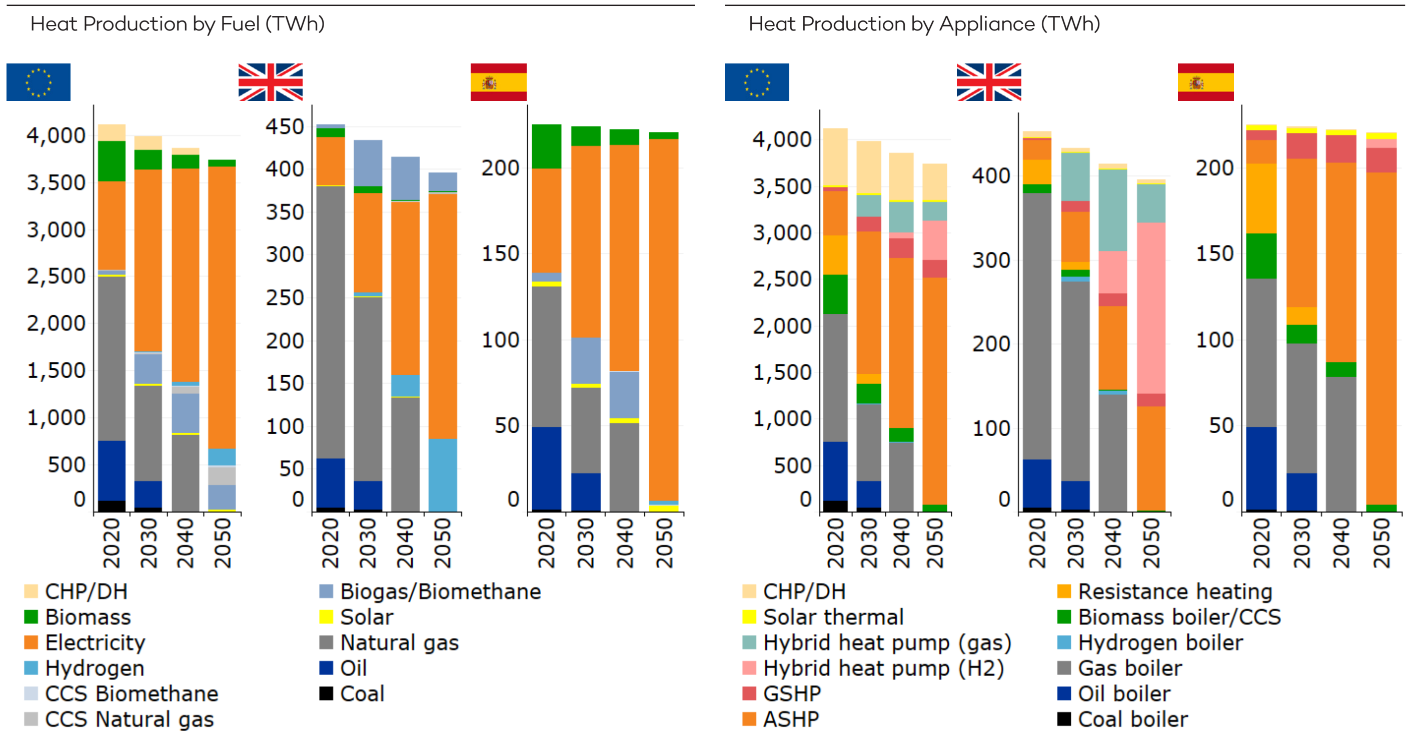
AFRY's models allow analysing the evolution of heat production for both the buildings segment (space heating, or non-process heat) and industrial processes (process heat). We take existing information on heat demand and current technology use from Fraunhofer's 'Mapping heat in Europe' study[16], updated with more recent data where available. Using this as a starting point, AFRY uses linear optimisation to determine future heating stock and output across all sectors and geographic zones by finding the cheapest possible way of meeting demand, given a set of constraints.

4.1 Zero-Carbon heat in buildings

In order to model heating in residential, commercial and industrial buildings (i.e. space heating), AFRY contemplates a wide range of available technologies, mainly in the form of heat pumps or boilers powered by electricity, hydrogen, natural gas or biomethane.

At present, Europe relies largely on natural gas for space heating; however, as unabated natural gas becomes unavailable in a zero-carbon economy, it becomes particularly relevant to transition towards heat pump technologies, fuelled mostly by electricity. This is shown in Figure 4, where from 2030 onwards there is a big increase in the use of air source heat pumps, reflecting the assumed improvements in efficiency[17], and covering 65% of total non-process heat in Europe by 2050.

FIGURE 4 – DECARBONISATION TRANSITION OF THE HEATING OF BUILDINGS IN THE EU, SPAIN AND GB



GSHP: Ground source heat pumps; ASHP: Air source heat pump

[16] https://www.ise.fraunhofer.de/en/research-projects/mapping-eu-heat-supply.html
[17] We have considered that recent improvements in the efficiency of heat pumps would enable air source heat pumps to reach Coefficients of Performance (COPs) of up to 400%.

The remaining heat demand is reliant on a number of new technologies such as hybrid heat pumps – which use a zero-carbon gas boiler (hydrogen or biomethane) to cover periods of cold temperatures, benefiting the system by reducing the required level of grid expansion and the need to build additional backup generation. In total, 80% of heat for buildings is produced from electricity by 2050 in Europe, either through full air source heat pumps or hybrid heat pumps.

In Spain, where temperatures are milder than European average, air source heat pumps become the dominant technology for space heating, providing around 87% of non-process heat produced for buildings by 2050; since the remaining heat is produced mainly by ground source heat pumps, electricity powers 96% of space heating in Spain by 2050.

In GB we also see a high level of heat being met from electricity, representing 72% of the total heat produced for buildings in 2050. This comes from full air source heat pumps, some ground source heat pumps in more rural areas and hybrid heat pumps.

4.2 Zero-Carbon heat in industrial processes

Figure 5 shows the transformation of the production of heat in the industrial segment. With limited technology options available to meet the specific temperature requirements of process heat, the technologies available in future years in this segment are more straightforward. In higher-temperature heat processes, and where process emissions are associated, there is a large scale roll-out of CCS gas (natural gas and biomethane); but in the low-temperature process heat there is a significant deployment of ASHPs, as they are assumed to be available at up to 200°C.

During the first decades reductions of CO_2 are achieved by switching from coal and oil boilers to natural gas and biomethane boilers, completely eliminating coal and oil technologies by 2040. Additionally, starting in the 2020's decade, air source heat pumps are deployed through the industry to provide heating at lower degree levels, reaching 34% of total process heat demand in Europe by 2050.

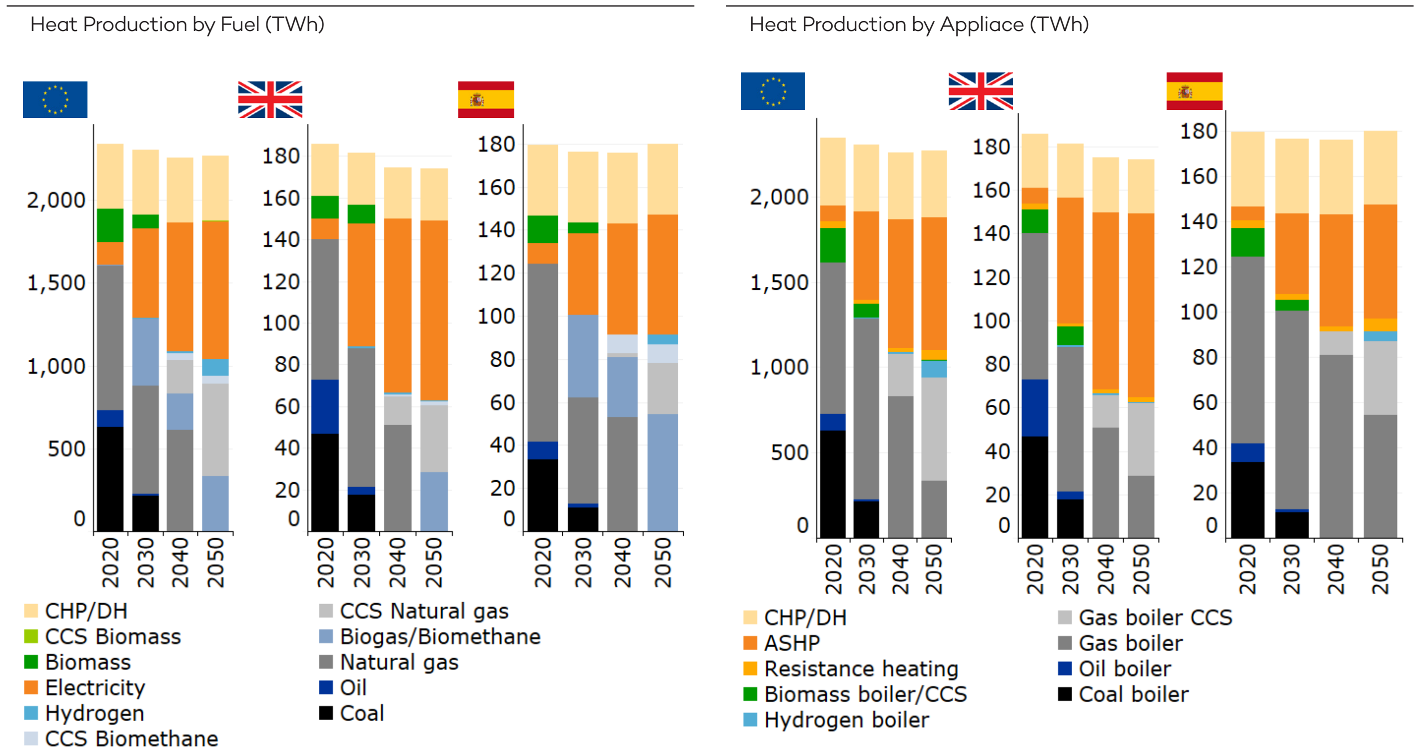
By 2040, CO_2 constraints require for CCS to start being deployed to mitigate emissions where higher temperature heat requires zero-carbon gas boilers to be used. By 2050, this technology together with biomethane supplies a total of 41% of heat demand in Europe.

During the same period there is also a small deployment of hydrogen boilers, which together with CHP and some resistance heating in the higher temperature levels (e.g. electric arc in the iron & steel industry) provide the remaining 25% of demand by 2050.

This transition follows the same trend all across Europe; however, there are some differences when comparing Spain and GB:

- In GB, where 42% of heat demand for industrial processes comes from low temperature processes (below 200°C), there is a higher penetration of heat pumps which cover 49% of process heat demand in 2050;
- In Spain, where nearly half of process heat demand comes from high temperature processes (above 500°C, e.g. ceramic and steel industries), the penetration of air source heat pumps is much lower (28%); as a result, in 2050 around half of process heat is provided by boilers using zero-carbon gases, either biomethane or natural gas with CCS.

FIGURE 5 – DECARBONISATION TRANSITION OF INDUSTRIAL PROCESS HEAT IN THE EU, SPAIN AND GB

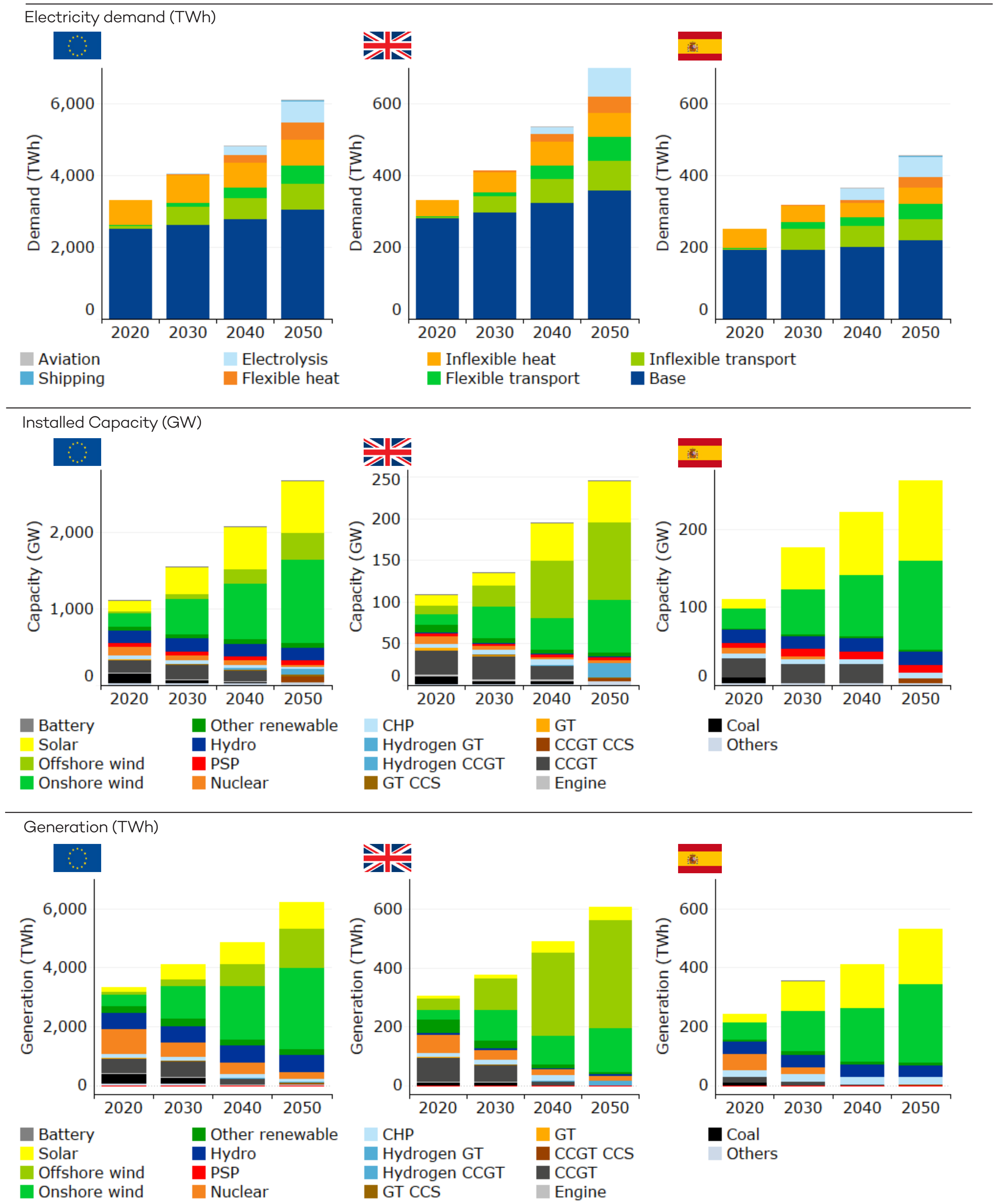


Note: Gas boilers used in 2050 without CCS use biomethane as a fuel
ASHP: Air source heat pumps; CCS: Carbon Capture and Storage; CHP/DH: Combined Heat and Power/District Heating

5. Zero-Carbon Power Sector

5.1 Power demand and production

FIGURE 6 –ELECTRICITY DEMAND, INSTALLED CAPACITY AND GENERATION IN THE EU, GB AND SPAIN



In the power sector, the electrification of heat and transport and the increase in green gas production lead to a significant increase of electricity demand over time; demand increases by 80%, from c. 3,300TWh in 2020 to c. 5,900TWh in 2050 in the whole of Europe.
Most of this increase in demand comes from the electrification of the heat and transport sectors, as well as an increased consumption for hydrogen production through electrolysis; this power consumption to produce hydrogen is required to assure the coverage of hydrogen demand for other uses (e.g. transport and heat).

In GB this increase in demand is expected to be much higher than European average, reaching 82%, due in particular to a faster demand growth for hydrogen production, resulting from the higher use of this fuel for heat and EVs. The increase in demand in Spain is in line with the European Union.

The overall amount of installed generation capacity in Europe (excluding interconnectors) increases from c. 1,100GW in 2020 to c. 2,800GW in 2050. Between 2020 and 2050 an extra c. 550GW of solar PV capacity, c. 900GW of onshore wind and c. 300GW of offshore wind is installed in Europe, while nuclear capacity continues to decline as the current nuclear power plants are decommissioned throughout the modelled period. By 2050 most of the firm capacity is provided either by hydro (c. 200GW), CCGTs fitted with CCS or hydrogen CCGTs and GTs (c. 175GW) and nuclear (34GW). Batteries have also been modelled, however, given our assumptions on the availability of electric vehicles to bring flexibility to the system, they end up being uncompetitive; their use is assumed to be limited to the provision of ancillary services.

In GB, generation capacity increases by almost 170%, driven by a strong growth in renewables and thermal plants fuelled by green hydrogen. By 2050 solar PV capacity reaches 49GW, onshore wind 63GW and offshore wind 94GW. Additionally, due to the high wind potential of Great Britain and the competitive cost of electrolysis, this allows for the production of green hydrogen and the appearance of firm capacity that uses this fuel (17GW).

In Spain, installed capacity is expected to reach 270GW in 2050 (146% increase), with solar reaching 100GW and onshore wind 114GW. Nuclear capacity is decommissioned in line with latest news on the agreement reached between the Spanish government and the Spanish nuclear owners; in addition, we have considered that the current fleet of Spanish CCGTs remains operative until meeting a lifetime of 40 years. From 2040 onwards, firm capacity is mainly provided by hydro and pumped storage plants (PSP), and the remaining firm capacity is provided through interconnectors and flexible demand. Some CCGTs fitted with CCS are also considered to provide firm capacity. According to our modelling it is more economical to fit existing CCGTs with CCS than to build new hydrogen-fired plants.

Total generation follows a similar trend as capacity. In Europe generation increases 82% between 2020 and 2050, with 80% of generation being provided by solar and wind in 2050. Coal generation reduces from 2030 and completely disappears by 2040, and CCGTs fill part of the gap with an increased generation share in 2030, before fading away rapidly. By 2050 the remainder generation is provided by nuclear, hydro and some hydrogen CCGTs and GTs.

The realisation of this net-zero pathway for renewables deployment are dependent on a wide range of factors being favourable including the availability of suitable land, national and local planning regimes, and the acceptability of development to local communities. Additionally, the growth in renewable generation and power demand comes with increased needs of security of supply and flexibility. This is provided by various sources:

— existing firm capacity in the form of nuclear, hydro, etc.;

— remaining gas plants fitted with CCS ensure system security at times of low renewable output;

— a significant increase in interconnection capacity between countries (See Section 5.2); and

— an increased flexibility from demand (See Section 5.4).

This last point, the increased flexibility from demand, is especially relevant to understand the high levels of renewable penetration achieved. The level of flexibility that demand is able to provide in AFRY's modelling approach allows for a system in which there are high levels of inflexible generation enabled by a flexible demand.

AFRY's power model ensures that security of supply is assessed and guaranteed through the whole modelled period:

— The main criteria in the model is to minimise the loss-of-load within Europe; in order to do so, interconnectors are used following a security criteria (i.e. not following economics) in order to assure that the countries in deficit can cover their demand with the support of those countries in surplus.

— Renewables are assumed to provide security of supply depending on their expected generation (i.e. if a wind project generates 10MW in a given hour, this capacity is used to cover the demand).

— Conventional generation is assumed to contribute with capacity up to their seasonal availability levels.

— Flexible generation is optimised so that it assures on an hourly basis that overall demand can be covered (See Figure 9).

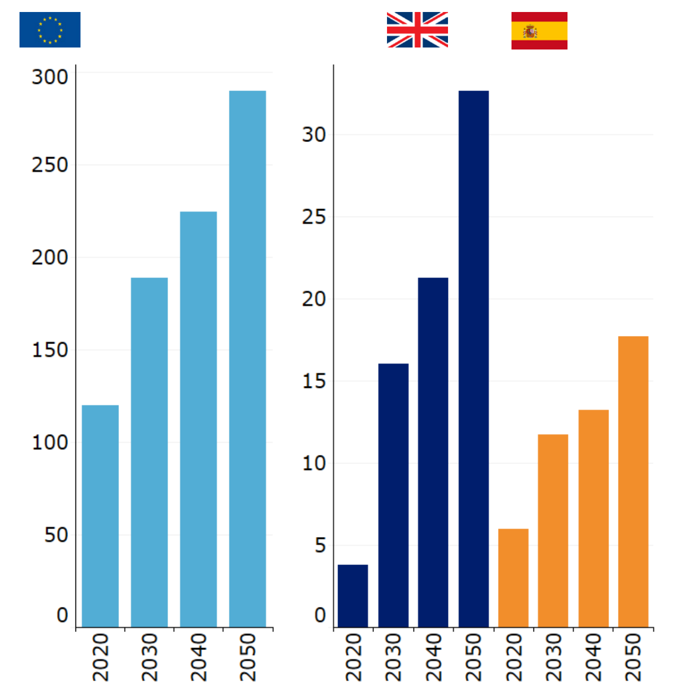
5.2 Interconnections

One of the prerequisites is that in order to avoid overbuilding generation capacity and maximise the value of intermittent renewables, European countries co-operate on interconnections and a substantial increase in interconnections can be seen.

Figure 7 shows the evolution of interconnection capacities: the evolution of the capacity mix towards decarbonisation requires the development of 169GW additional interconnection capacities across Europe by 2050. This is particularly noticeable in GB where interconnection capacity grows from 4GW in 2020 to 33GW in 2050; in Spain, the evolution is less sharp, from 6GW in 2020 to 17.5GW in 2050.

The number of new interconnectors, as well as the way they are used are optimised within AFRY's power model; as an example, the interconnection capacity and flows between Spain and France in 2050 are outputs of AFRY's modelling, and not hardcoded inputs resulting from historical analysis or given assumptions, this is, the capacity built and the flows will be the ones that assure the coverage of electricity demand in Europe while minimising the overall costs of the system.

FIGURE 7 – INTERCONNE CTION CAPACITY IN EUROPE (GW)



5.3 Hydrogen demand and production

By 2030, production of hydrogen is still low as it is not required neither for heat nor for transport. However, demand increases rapidly over time, reaching c. 400TWh in 2040 and c. 800TWh in 2050, as shown in Figure 8. Although all of Europe follows the same trend, the transition varies amongst countries:

— In GB, the use of hydrogen for space heating creates a demand already by 2030 and this continues to expand all the way to 2050. Hydrogen production accelerates considerably in the 2040's decade alongside the continued expansion of renewable capacity.

— In Spain, total hydrogen demand is lower than in GB due to a limited demand from the non-process heat sector, which delays development of hydrogen production to the 2030's decade, alongside with the rapid growth of solar capacity.

5.4 Demand flexibility

One of the key elements of this decarbonisation pathway is the greater need for flexibility in the electricity system, which is due to a number of factors:

— Overall demand increase: The increase in the volume of demand also means higher absolute fluctuations of demand

— Generation uncertainty: The main source of zero-carbon electricity comes from intermittent sources such as wind and solar power. The uncertainty and volatility of generation leads to increased balancing requirements, both at the day-ahead but also at the balancing stage.

— Seasonality: The demand for heating usually coincides with low output from solar generation, leading to additional electricity supply needs in the winter season when significant amounts of electric heating is deployed.

— Generation uncertainty: The main source of zero-carbon electricity comes from intermittent sources such as wind and solar power. The uncertainty and volatility of generation leads to increased balancing requirements, both at the day-ahead but also at the balancing stage.

— Seasonality: The demand for heating usually coincides with low output from solar generation, leading to additional electricity supply needs in the winter season when significant amounts of electric heating is deployed.

In this context, European wholesale electricity markets – which are still characterised by a predictable and inflexible pattern of demand covered by the dispatch of flexible generation capacity – will need to find new sources of flexibility to meet a mostly inflexible dispatch. This new flexible demand will be key to allow for a very high penetration of renewables, and thus the decarbonisation of the energy sector

New sources of flexibility include the flexibility offered by the new sources of demand, such as electric vehicles and heat pumps. Both of these sources can offer flexibility regarding the times when they actually consume electricity, and, especially in the case of EVs, can even contribute to electricity supply by providing power to the system (vehicle-to-grid) at peak times[19]. This form of distributed storage, together with the development of smart grids will be key to reach an ambitious decarbonisation target and mitigate periods of potential curtailment or load loss as shown in Figure 9.

We assume only residential and commercial heat has the potential for flexibility; industrial electricity demand for heat processes and residual demand remains 100% inflexible. As a result, by 2050 in Europe around 42% of electric transport demand and 51% of electric heat demand from buildings is considered to be flexible. As result, 16% of total electricity demand has flexible characteristics.

The non-flexible demand shown in Figure 9 has been assumed to be completely inflexible and follow some assumed patterns for heat, transport and other residual demand. However, AFRY reckons that the picture could

FIGURE 8 – HYDROGEN DEMAND (TWH)

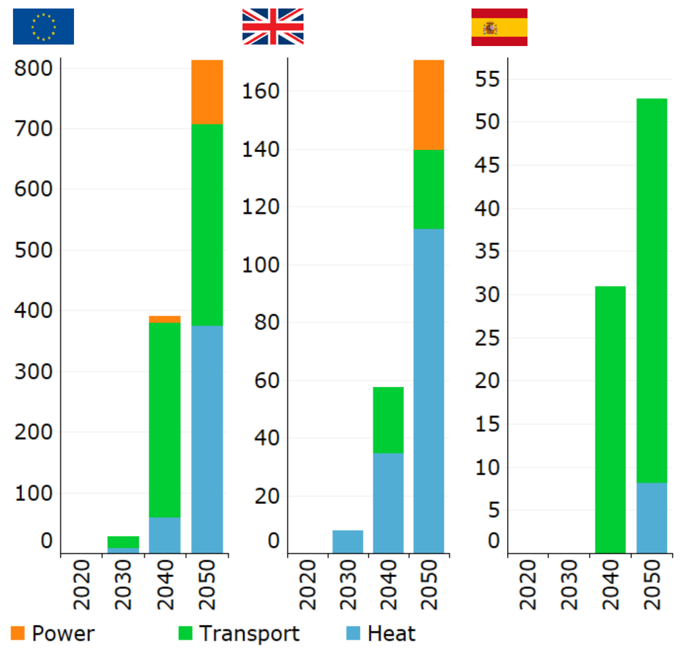
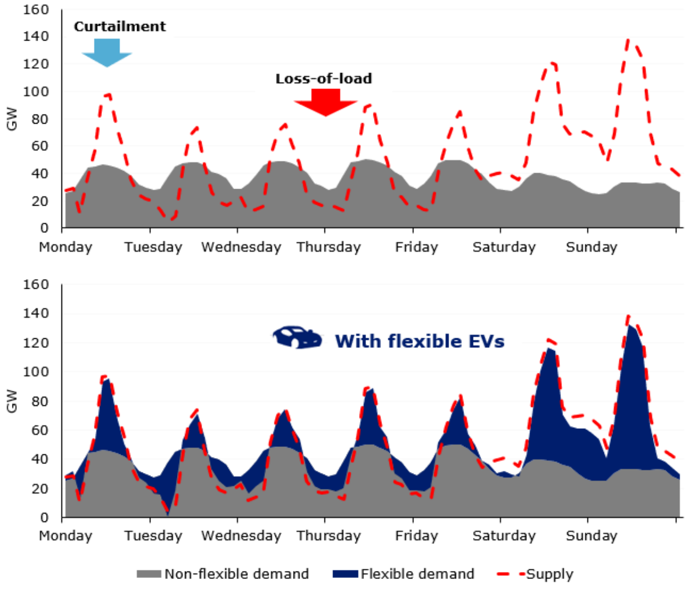


FIGURE 9 – FLEXIBLE EVS DEMAND BALANCES INTERMITTENT RENEWABLES IN A WINTER WEEK OF 2040



be different if some of this non-flexible demand was to become flexible, for example, through intelligent home appliances; the impact of such a change is not captured in AFRY's modelling. This potential new sources of flexibility would increase the integration of renewables (i.e. decrease curtailments), decrease the need of new renewable capacity to reach zero emissions, improve the security of supply prospects and reduce the need for firm capacity.

Hydrogen production from electrolysis is another potential source to bring flexibility to the power system. AFRY assumes that all hydrogen production from electrolysis has the potential to be stored, and production is 100% flexible. This is especially useful in countries such as Spain, where in hours when demand net of renewable generation is negative, production of hydrogen through electrolysis plays a role in balancing the system.

[18] Hydrogen produced is assumed to be consumed locally, i.e. in the country of production.
[19] This may degrade the car batteries so there is a cost assumed for such usage in the modelling

6. Conclusions

FIGURE 10 – KEY RESULTS

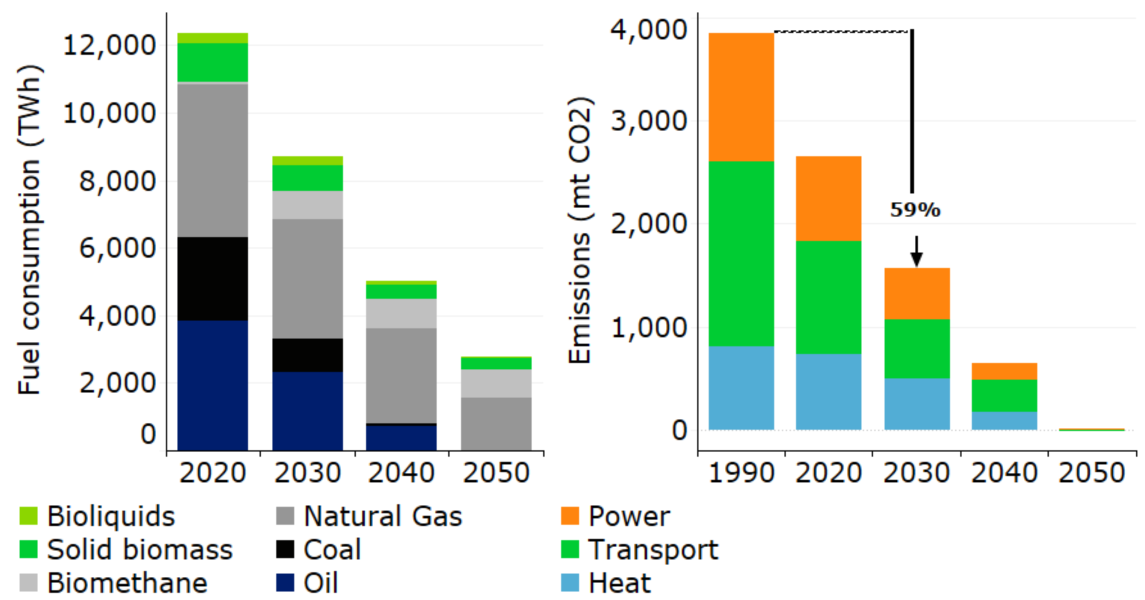
This pathway represents a future where economics determine which technologies are deployed in order to fully decarbonise the energy sector

Transport Electric vehicles dominate the transport sector with a small contribution of fuel cell vehicles, specially relevant in heavier transport segments	**Heating** Heat pumps play an important role in decarbonising heating; boilers and hybrid heat pumps provide a solution when electricity is not possible; CCS installations are used widely in industry
Power generation While renewable sources account for the vast majority of capacity and generation, some CCGTs with CCS and hydrogen CCGTs help to balance the system along with greater interconnections and demand flexibility	**Smart networks** Power networks are upgraded and expanded to allow smart two-way demand side response; some gas distribution networks convert to hydrogen and a CO_2 network is established

This study conducted by AFRY and Iberdrola shows that decarbonising the European energy system by 2050 is ambitious, but possible. It implies an important electrification of the transport and heat sectors in order to allow for a very high penetration of renewable generation and reduce the share of unabated gases in the energy balance. The key findings of the report are summarized in Figure 10.

Fuel consumption decreases quickly as coal and oil disappear from the system, as shown in Figure 11. By 2050, mostly natural gas with CCS is used as a fuel.

FIGURE 11 – TOTAL PRIMARY FUEL CONSUMPTION AND TOTAL EMISSIONS BY SECTOR



Note: Fuel consumption only includes input fuel. Does not include use of electricity or hydrogen

Emissions also decrease accordingly; by 2030, the energy sector will see a 59% reduction of emissions compared to 1990 values as the power sector sees a quick decrease due to the rapid closure of coal plants. These values are in line with EU 2030 objectives as well as the revised value proposed by the European Green Deal.

One of the key implications of this rapid decrease of emissions and use of fossil fuels is the increase of electrification levels across all sectors in European countries, as shown in Table 1.

TABLE 1 – TOTAL LEVELS OF ELECTRIFICATION BY SECTOR[20] - FINAL ENERGY

	2030			2050		
	Spain	GB	EU	Spain	GB	EU
Transport	11%	9%	14%	72%	83%	80%
Buildings	51%	35%	44%	95%	68%	70%
Industry	38%	49%	39%	43%	61%	48%
Total	34%	31%	35%	65%	69%	62%

Electrification seems to be the clear pathway in some segments of the energy sector such as transport and heating in buildings, where the use of electric vehicles and heat pumps fuelled mostly by electricity is the most economical way to decarbonise the energy sector. Additionally, as zero-carbon gases such as hydrogen or biomethane will not be widely spread before 2030, it is relevant to understand the prominent role electricity has to play during the 2020's decade, as by 2030 electricity is expected to provide 35% of total final energy demand in Europe.

BOX 1 – TOTAL LEVELS OF ELECTRIFICATION BY SECTOR IN 2050 - USEFULL ENERGY DEMAND

The values of electrification reach higher levels when analysed by percentage of useful energy demand. Useful electrification of energy could reach up to 95% of total km travelled and up to 86% of heat demand from buildings in Europe.

	Spain	GB	EU
Transport	91%	97%	95%
Buildings	97%	82%	86%
Industry	56%	73%	61%

[20] Electrification levels in terms of final energy by sector have been calculated by using Eurostat data to split electricity demand

Zero-carbon transport: Fast penetration of EVs is needed to reach the full electrification of light vehicles by 2050; hydrogen can fuel a relevant share of heavy trucks

The high level of electrification of the transport sector shown by this study entails significant benefits, as it provides significant volumes of flexible demand-side response in the power market. Even in the HGVs segment, developments of electric solutions that compete with hydrogen fuel-cell technologies would deliver even further benefits.

Zero-carbon heat: Heat pumps play the main role in the decarbonisation of buildings and complement the deployment of CCS in the decarbonisation of industry

Electric heat pumps, complemented by hybrid heat pumps in geographies with high seasonality or very cold, will play the main role in the decarbonization of buildings, contributing to the reduction of primary fuel use and emissions in Europe.

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In the industrial segment electric based solutions such as air source heat pumps for lower temperatures and electric arcs in industries such as iron & steel will speed up the reduction of emissions. However, the deployment of CCS is critical in the industry, especially to address the decarbonisation of high temperatures heat production.

The transition in power generation: The challenge of an inflexible generation mix

Incorporating massive renewable capacity and phasing out thermal power plants[21] mean that the generation mix becomes highly inflexible. To avoid curtailments, revenue losses for renewable plants, and the global oversizing of the generation mix and the electricity grids across Europe, it is key to make electricity grids smart and have customers involved in the transition so their behaviour contributes to foster flexibility on the demand side. This flexible demand will allow to meet supply, shifting from current situation in power markets where supply meets demand.

Indeed, electrification of transport and heat can contribute to reduce peak demand and stress on networks. This is achieved by EVs and heat pumps being operated flexibly (charging when and where optimal from a grid standpoint), and in some occasions providing electricity to the grid (vehicle-to-grid). This flexibility is a major requirement to make full decarbonisation of the energy system possible in this pathway. Of course, this flexibility needs to be unlocked by providing the necessary improvements to the grids and services to consumers.

[21] CCGT`s have been kept open in Spain until 2040 in order to guarantee security of supply.

Annex A - Aviation and Navigation

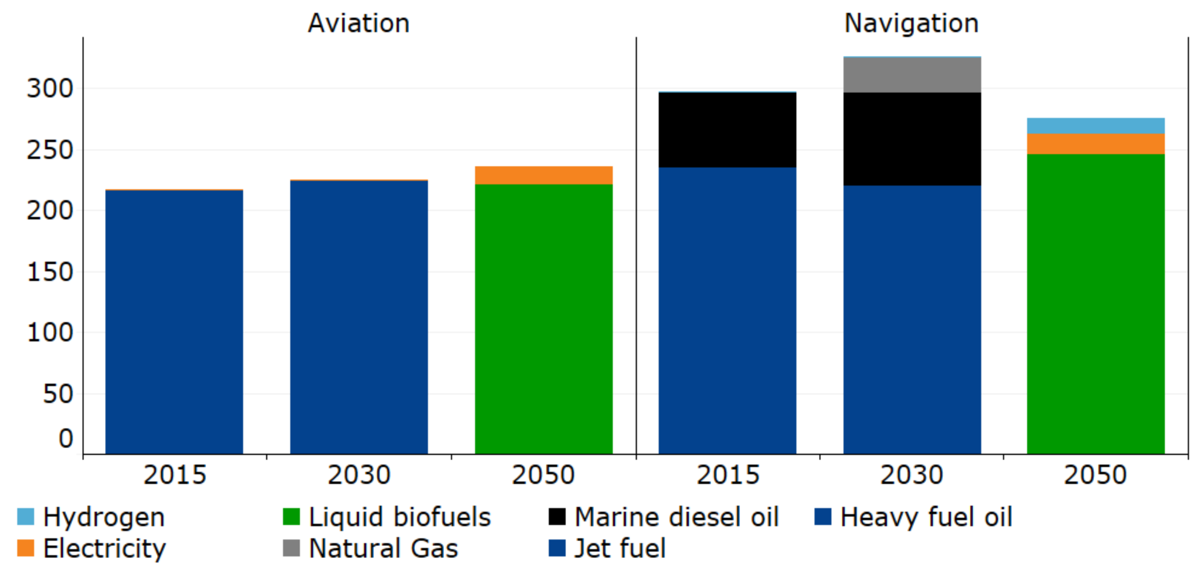
AFRY does not model the decarbonisation of the aviation and navigation sectors. However, for the scope of this report, AFRY has developed its view on the evolution of fuel demand and emissions from these sectors, based on the analysis developed by the European Commission[22]. AFRY's views for this pathway are shown in Figure 12.

Both for aviation and navigation AFRY has followed the Commission's 1.5Tech scenario for these segments and has adjusted to be in line with AFRY's fundamental modelling assumptions as follows:

— For 2030 AFRY's view is in line with the Commission's: Aviation will still depend on jet fuel's while navigation will see an increase in the use of natural gas.

— By 2050, given that AFRY's scenario aims at achieving net-zero emissions, the view differs; The level of electrification and hydrogen is the same in both pathways, however, AFRY does not allow for the use of fossil fuels by 2050 and so the remaining fuel is considered to be liquid biofuels[23].

FIGURE 12 – AVIATION AND NAVIGATION FUEL CONSUMPTION AS PROJECTED BY THE EC



[22] In-depth analysis in support of the commission communication COM (2018) 773
[23] AFRY has analysed the availability and sustainability of biomass and other bioenergy carriers in order to ensure that this pathways view on levels of biomass consumption does not breach any fundamental limits on biomass availability.

Annex B - Modelling and Assumptions

B.1 Study approach and methodology

This study investigates the decarbonisation of the energy sector, including power generation; residential, commercial, industrial and district heating; and land passenger and freight transport sectors. It does not include the non-combustion use of energy carriers such as gas or oil products used as feedstocks in industrial processes. The model aims at achieving the most economic to decarbonise the energy sector.

B.1.1 Main elements of the pathway

While the aim of the pathways is to create and analyse a decarbonised future, there needs to be some underlying main elements that oversee the development of the pathway. In this study, these elements are:

— Carbon emissions: Net emissions across all sectors reach zero by 2050.

— Existing technologies: Only technologies that are currently either being deployed or at least under development are considered.

— Consumer behaviour: It is assumed that flexibility will be available from the development of smart technologies, e.g. smart appliances, two-way EV batteries. However, no major shifts in driving, e.g. car sharing or pooling, heating behaviour or appliance availability are assumed

B.1.2 Modelling framework

In order to estimate future capacity, output, and system costs, we use optimisation models for each sector. These models determine the optimal capacity mix and operation given the specific assumptions and constraints set for a particular pathway. Existing supply, scrapping rates and future demand are entered as inputs. The model then selects the optimal mix of new technologies, based on the need for new capacity, the cost and capabilities of the new capacities, including emissions, and deployment constraints, e.g. maximum amount commissioned in any year.

Modelling all elements of system costs in an integrated manner ensures consistency between the three sectors as some constraints extend across sectors (emissions, fuel source availability) or outputs from one model are inputs in other models (e.g. electricity and hydrogen demand from transport and heat feed in to the power model).

B.1.3 Transitioning heat and transport

While the aim of the pathways is to create and
For this study we have used our recently developed new models for transport ('move') and for heat ('Hestia'). These are capable of determining the future stock and output for transport and heat across Europe.

The transport and heat models are organised in similar ways, as they both provide outputs on an annual basis for future vehicle and heating stock numbers, heat generation or km output, as well as costs, fuel use and emissions. The transition towards a zero-carbon system is modelled on the basis of the capabilities and costs of new technologies, as well as their availability, which is determined by supply chain constraints and political factors.

B.1.4 Power model – BID 3

In the power sector modelling, we use our existing market model, BID3. This model already includes key characteristics such as:

— Plant parameters: Efficiencies/availability, risk of unexpected outages, time taken to ramp to full capacity, reduced efficiencies when ramping up and down more frequently.

— Historical weather patterns: Application of historical weather patterns with hourly wind speeds, solar irradiation and temperatures being applied to future years to ensure an internally consistent temperature variance outcome on demand alongside actual levels of generation from wind and solar.

— Security standards: Ensures that the power generation mix provides sufficient back-up for times when inter-mittent generation is very low and demand is very high.

For the purposes of this study we have used our further enhanced BID3 with two major features:

— Flexibility of demand: With the increase of smart meters and appliances, electric heating and electric vehicles, electricity demand is expected to become much more flexible. New flexible hourly demand profiles have been developed for end use of electricity for heat and transport, including variations from the temperature dependence of heat pump efficiencies and electric vehicle ranges.

— Hydrogen production: The mix between the different available technologies is optimised both in the long-term (investment decisions) and short-term (dispatch). Electrolysis competes with the flexibility offered by electric vehicles and heating.

B.1.5 Granular modelling of electricity demand and supply

In order to understand how future electricity supply and demand will interact it is critical to understand the flexibility of these demands, i.e. ability to shift demand away from peak periods or across a day, a week or a season.

For all demand segments (transport, heat and residual), hourly demand profiles have been defined. A certain share of demand is defined as flexible, which means that BID3 can dynamically optimise the shifting of demand within this segment, within certain limits.

Hourly analysis of flexible demand is critical to calculating the total system costs for any specific scenario; otherwise the peak electricity may be over-estimated, extra peaking generation built, and alternative storage options developed when they would not actually have been required.

B.2 Key Assumptions

B.2.1 Demand projections

Macro assumptions have been taken from the EU Reference Scenario 2016[24], reflecting the critical aim of delivering full decarbonisation without major behavioural changes and introducing inconsistencies between demand assumptions. Population grows slowly, and GDP grows moderately with sector contributions to GDP remaining largely flat, including industrial output.

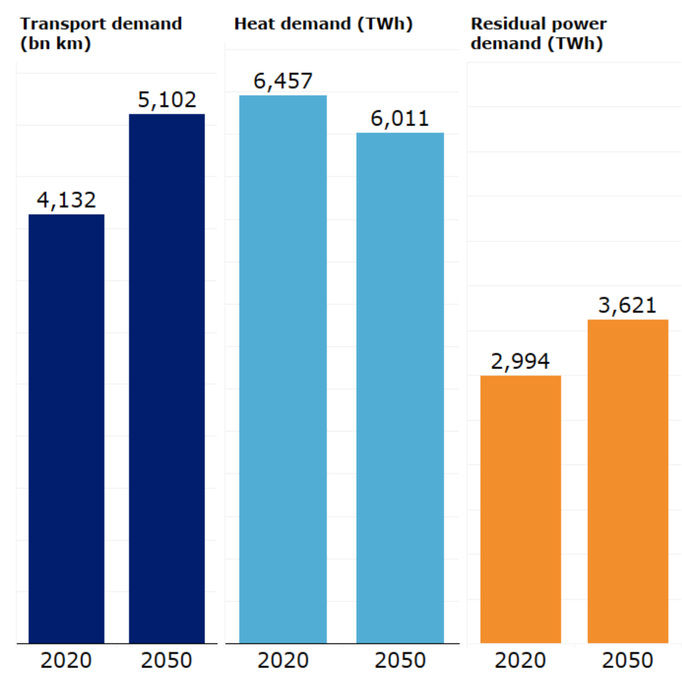
Demand for heat was adapted from Fraunhofer's 'Mapping EU heat supply'[25] study from 2016. In the non-process heat sectors (space and water heating and cooling in buildings) demand declines over time, as energy efficiency increases due to better building standards and insulation of existing buildings. In the process heat segment, output grows moderately, in line with GDP growth assumed in the EU reference case.

Residual power demand, which excludes demand from heat and transport, covers provision of lighting, and electric appliances (TVs, washing machines, fridges, etc.). This share of demand is projected to increase despite some improvement in appliance energy efficiency, as the number of electric appliances is expected to grow, especially in newer Member States, and digitalisation in businesses and homes is anticipated to rise.

[24] European Commission. "EU Reference Scenario 2016. Energy, Transport and GHG Emissions Trends to 2050." 2016.
[25] Fraunhofer Institute for Systems and Innovation Research (ISI). "Mapping and analyses of the current and future (2020-2030) heating/cooling fuel deployment." 2016

Figure 13 provides an overview of the underlying demand assumptions.

FIGURE 13 – DEMAND ASSUMPTIONS



B.2.2 Transport technology characteristics and costs

In the transport sector, the existing road vehicle fleet data was obtained from Greek consultancy Emisia[26]. Based on this data, our 'move' model splits the transport sector into segments based on fuel, size and use. For the rail sector it looks at the distances travelled for both passenger and freight transport.

The level of flexibility from EVs is a crucially important factor and for this study we assume private passenger EVs are only required to be fully charged on Mondays at 8am (equivalent to a weekly tank re-fuelling) whilst freight and public transport are required to be fully charged at 7am every morning.

B.2.3 Heat technology characteristics and costs

The future deployment of heat technologies will depend on the relative efficiency, heat rate, capex, opex, appliance lifetimes and conversion costs, e.g. 'behind-the-meter' costs to allow air-source heat pumps to work in a wet heating environment or converting gas equipment to use hydrogen.

Additionally, deployment restrictions are applied in the modelling to reflect the time required to build supply chains for new technologies, e.g. limitations on number of heat pumps that can be deployed in each future decade.

A new technology type included in the pathway is the hybrid heat pump. This provides a core level of heat via an air-source heat pump with additional heat from a boiler that uses natural gas, biomethane or hydrogen. When the ambient temperature drops below -10°C all heat demand is met by the boiler.

B.2.4 Power technology characteristics and costs

Iberdrola's power generation cost assumptions to 2050 have been incorporated for the development of this pathway[27]. We have ensured all technology build rates are within reasonable limits from a construction, resource potential[28] and supply chain perspective. Decisions to prohibit nuclear build in 12 countries have been respected.

[26] Emisia existing fleet values have been updated to reflect 2018 vehicle fleet, based on Eurostat and national statistics
[27] 2050 capex assumptions for offshore wind, onshore wind, solar PV, batteries and electrolysis are reduced by 50%, 23%, 32%, 57% and 48%, respectively, compared to 2020 estimates.
[28] For GB we have incorporated the CCC's resource potential from its 'Net Zero Technical Report', namely 29-96 of GW of onshore wind, 145-615 GW of solar power and 95-245 GW of offshore wind in the UK.

B.2.5 Other costs

Prices for commodities that are being phased out, such as coal, lignite or oil, are assumed to be flat at current levels (taken from the 2016 EU Reference Scenario).

Gas prices are assumed to grow by 30%-40% until 2030, and then to remain flat in real terms, aligning with the IEA's 450 Scenario from the WEO 2016 for consistency with significant levels of global decarbonisation. Biomass prices also follow the same trajectory as gas.

Carbon prices have been initially set using values from the EU Reference Scenario. BID3 then produces the additional shadow price of carbon required to provide the price support necessary to meet not only the emissions limit but also investment hurdle rates.

Hydrogen production costs with methane reforming are based on a report produced for the Committee on Climate Change in GB[29] with electrolysis costs based on Iberdrola's view.

Our electricity modelling accounts for the production of hydrogen, using either electrolysis from power to gas (P2G) or reforming natural gas (which includes costs for the carbon capture and storage) using either steam reforming (SMR) or autothermal reforming (ATR).

The level of hydrogen produced from power to gas depends on the amount of renewable production that makes economic sense to convert using electrolysis. The value that electrolysis can capture and its load factors will be influenced by the levels of demand side flexibility and other forms of flexibility (e.g. battery storage) that effectively competes with any excess renewable generation in both intra-day and longer timeframes.

Network costs, including both transmission and distribution, for electricity and natural gas are captured as new and replacement capex plus opex. These values are based on GB data and then adjusted to reflect individual countries' labour costs. For hydrogen networks we assume a 20% increase compared to gas for new build[30], or conversion capex if gas networks are converted to hydrogen[31].

Carbon capture and storage cost assumptions have been taken from the 'Electricity Generation Cost Report'[32], which includes both the cost of the plant, e.g. boiler or turbine, and the costs associated with CCS (capture, transport and storage).

B.2.6 Bioenergy sustainability

Bioenergy solutions will need to account for sustainability constraints. From our perspective, the limitations reflect overall availability of feedstocks, constraints on imports and competition for resource from other sectors, e.g. aviation and shipping.

Accordingly, we have limited biomass pellets to 3,000TWh and biomethane to 860TWh, the latter sourced from 10% of Europe's arable land, 35% of waste manure and imports from Russia and Ukraine.

[29] E4tech, UCL Energy Institute, and Kiwa Gastec."Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target." 2015
[30] Dodds, Paul E., and Will McDowall. "A review of hydrogen delivery technologies for energy system models." 2012.
[31] Northern Gas Networks, Kiwa Gastec, Amec Foster Wheeler, and Mike Haines. "H21 Leeds City Gate." 2018.
[32] Leigh Fisher and Jacobs. "Electricity Generation Costs and Hurdle Rates." 2016.

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