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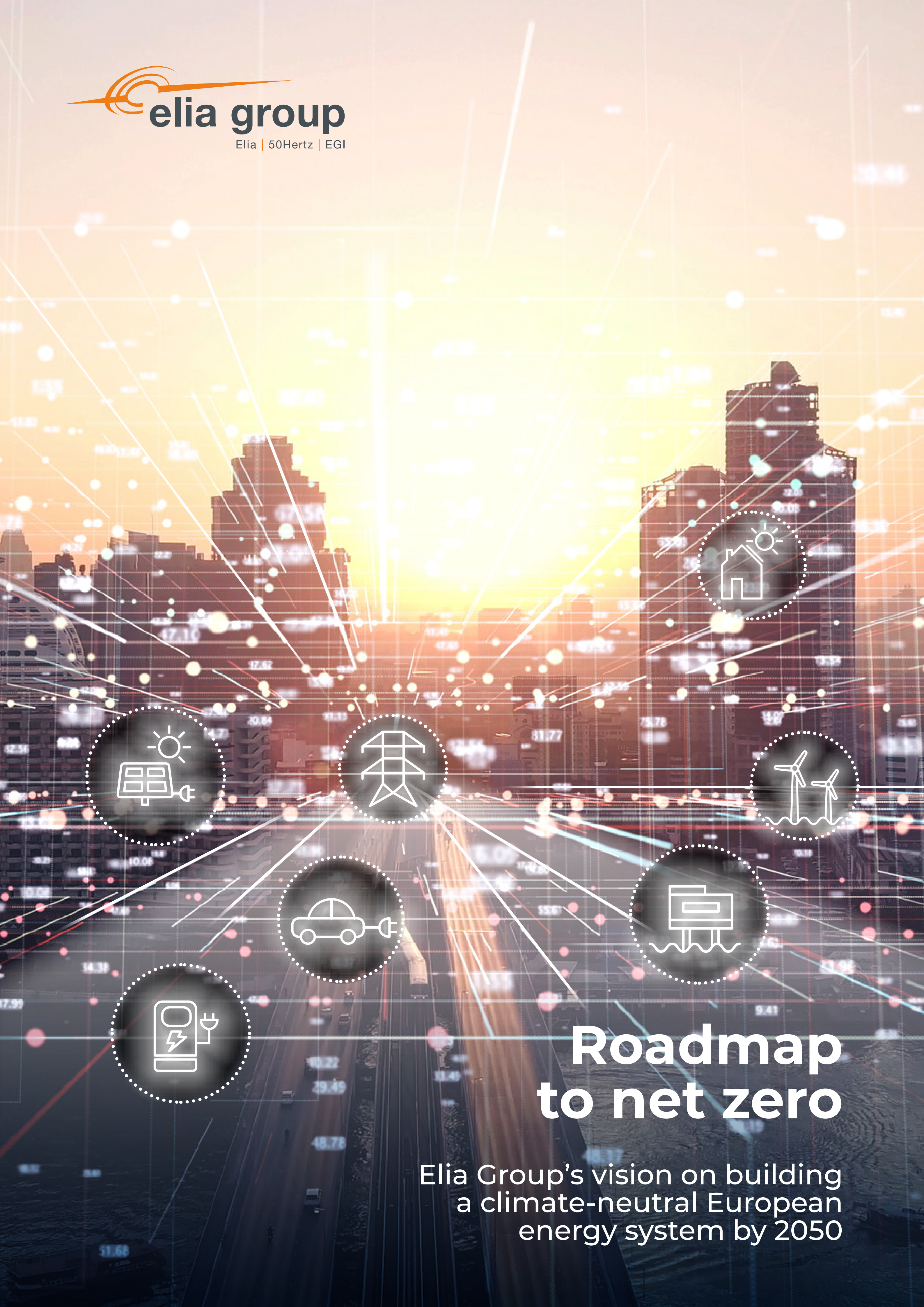


Roadmap to net zero

Elia Group's vision on building a climate-neutral European energy system by 2050

“Fit for 55” is just the beginning

IN SHORT

- Although the need to reach climate neutrality is clear, uncertainty remains about the necessary policies and roadmap that can lead us to net zero.
- Our study includes key insights into three dimensions of the electricity system: energy balance, flexibility and adequacy.
- Based on these key insights, we identified a roadmap consisting of different focus points.

Dear reader,

This summer’s floods in Belgium and Germany and the forest fires in the Mediterranean region served Europe with a stark reminder of the consequences of global warming.

Over the same period, the European Commission adopted the “Fit for 55” package, its largest legislative framework related to the pursuit of climate goals. It puts the continent on track to reach the Green Deal target of net zero by 2050.

It seems that Europe understands that tremendous efforts from across society will be required to reach climate neutrality. Work needs to be scaled up and accelerated. Listening to all good intentions expressed during the recent COP26 Climate Conference in Glasgow, players from the rest of the world are joining in.

Although we have a clear idea of the ultimate goal, uncertainty remains about the necessary policies and the roadmap that can lead us to net zero. It is this uncertainty that triggered our present Elia Group study, which focuses on the electricity system and includes key insights into three of its most important dimensions: energy balance, flexibility and adequacy.

As these insights are explored, we address a number of questions, including:

Will Europe have sufficient domestic renewable energy to cover its 2050 energy demand - both for direct electrification and the production of green molecules? How can the electricity system cope with a high amount of renewable energy sources (RES), which are inherently intermittent? How much flexibility is needed to keep the balance between demand and supply? How can the electricity system cope with longer periods of low RES infeed?

What key messages can be taken away from this study?

Firstly, as it is unlikely that Europe will have sufficient RES to cover its entire energy demand in 2050, renewables are to be considered a scarce resource.

The good news is, Europe’s direct electricity demand can be met, but only if we accelerate RES expansion by a factor of three; maximise electrification when it is the most efficient option; increase efficiency; and build more interconnectors to balance out the uneven distribution of RES across Europe. However, there will not be enough RES to also cover indirect electrification. Imports of green molecules from other continents will be required.

Our second finding is quite surprising: while large amounts of green molecules will be needed overall, the electricity system is able to cope with seasonal variations in the electricity supply and demand without using big quantities of them. Instead, to maintain the balance and cope with fluctuations associated with renewables, you need a well-designed system. We can minimise long-term fluctuations with a good balance between wind and solar energy, so avoiding a seasonal mismatch between summer and winter. We can manage mid-term fluctuations by increasing interconnectors, which reduce the impact of local supply dips. Finally, we can cover daily fluctuations by unlocking end user flexibility and the potential held in EVs and heat pumps.

Thirdly, there will still be times of stress (e.g. dark, windstill and cold weeks in winter) when demand is high but renewable production is low. For these short periods of time, we’ll need dispatchable capacities.

Our study starts with an assessment of Europe’s total energy needs, from which conclusions about the future electricity system are drawn. Based on the key insights above, we identified a roadmap consisting of different focus points. This roadmap may be relevant for Europe as a whole, for stakeholders from across the energy sector and for policymakers. We see a crucial role for the latter to play, since they can influence investment conditions, infrastructure planning and market arrangements.

Our teams in Belgium and Germany sincerely hope that this study contributes to defining the most efficient way to reach net zero, since we need clear policies and the right frameworks to make it happen.

Enjoy the read!

CHRIS PEETERS, CEO ELIA GROUP

I
Executive Summary

Introduction

What could a decarbonised European energy system look like in 2050? Does Europe have sufficient renewable energy sources (RES) to fully decarbonise?

How will we balance demand and supply in a high RES system and keep the lights on during longer periods with little or no wind and sun?

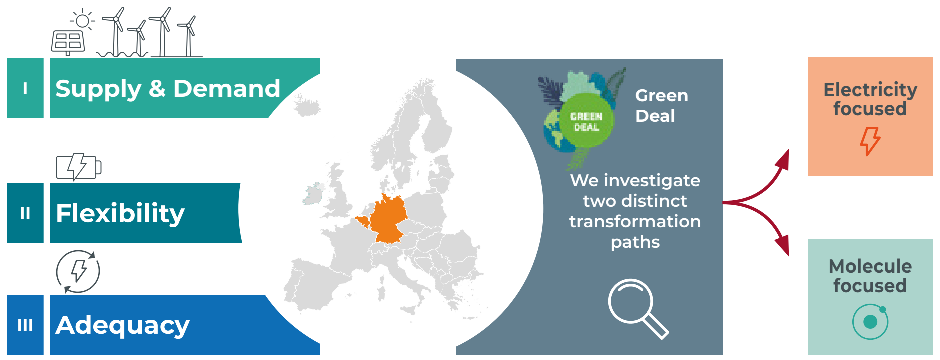
This new Elia Group study addresses these and many other questions. We considered them from a European perspective, whilst zooming in on our home countries, Germany and Belgium.

Three dimensions and two transformation pathways

To understand how the European electricity system might work in 2050, we explored three of its most important dimensions: energy balance; flexibility; and adequacy (see Figure 1). Following this, we investigated two distinct transformation pathways to net zero. These pathways are not exhaustive and breakthroughs in technology or policy changes may well happen. However, they are useful for understanding the challenges and opportunities that lie ahead. Both pathways assume that Europe's final energy demand will decrease by 2050, whilst electricity consumption will be higher than it is today. The pathways are based on European and national studies and scenarios (see Part II, Chapter 1).

1. **The ELEC-pathway:** under this first pathway, Europe's final electricity demand in 2050 is assumed to increase by 70% compared with today's demand as a result of strong electrification.
2. **The MOL-pathway:** under this second pathway, Europe's final electricity demand in 2050 is assumed to increase by 30% due to a higher share of 'green molecules' in the final energy consumption.

FIGURE 1: THE THREE DIMENSIONS OF THE CLIMATE-NEUTRAL ENERGY SYSTEM IN 2050 (LEFT) AND PATHWAYS (RIGHT) WHICH WERE INVESTIGATED



Key insights

This study begins by outlining key insights into the three dimensions of the electricity system we have examined: energy balance, flexibility and adequacy. Based on these insights, we identified a roadmap consisting of different focus points that could help to accelerate the pathway to net zero in an efficient way (see page 10).

INSIGHT 1

ENERGY BALANCE

Will Europe have sufficient domestic RES to cover its 2050 energy demand (including both direct electrification and the production of green molecules)?

Europe is short on the renewables it needs to achieve net zero by 2050. Our analysis reveals that there will be insufficient domestic RES to cover its total energy demand. While Europe will have sufficient RES to cover its direct electrification needs, imports of green molecules from other continents will be required.

USE RES TO THEIR FULL EXTENT AND LEVERAGE EFFICIENCY GAINS FROM ELECTRIFICATION

Direct electrification brings increased energy efficiency

As it is unlikely that Europe will have sufficient domestic RES to cover its entire energy demand in 2050, RES are to be considered a scarce resource. To reduce the RES need and accelerate the decarbonisation process, it is clear that energy efficiency on the demand side is the most important measure for achieving net zero.

As shown in Figure 2, electrification on its own results in significant energy savings. The ELEC-pathway requires a lower supply of RES compared to the MOL-pathway, because certain electrified end appliances (electric vehicles and heat pumps) are very efficient and because producing green molecules carries high conversion losses. This demonstrates the importance of stimulating electrification where it is the most efficient option.

Under both pathways, Europe will be able to meet much more of its energy demand with domestic resources than today - even more so if cooperation between European countries is increased and Europe's final energy demand is widely electrified. Nevertheless, it is clear that, given its limited RES potential, Europe will need to import green molecules from outside its borders.

Accelerate RES expansion by a factor of 3

Our study shows that we need to speed up the RES expansion rate by at least a factor of 3 (BAUx3)* compared to today, to make sure that Europe will be able to cover its final electricity demand (see Figure 2). This means that, in the run-up to 2050, Europe's annual RES expansion rate needs to be three times the average RES expansion rate over the past 5 years. This will be a challenge and requires strong action.

*BAUx3 = Business As Usual x3

FIGURE 2: STRONG ELECTRIFICATION OF END USE (AS UNDER THE ELEC-PATHWAY) SAVES UP TO 1,800 TWH AT THE EUROPEAN LEVEL COMPARED TO THE MOL-PATHWAY. DIRECT ELECTRICITY DEMAND UNDER THE ELEC-PATHWAY INCREASES BY 70% COMPARED TO TODAY'S DEMAND. A TRIPLING OF TODAY'S RES EXPANSION RATE IS NEEDED TO MEET THIS DIRECT ELECTRICITY DEMAND

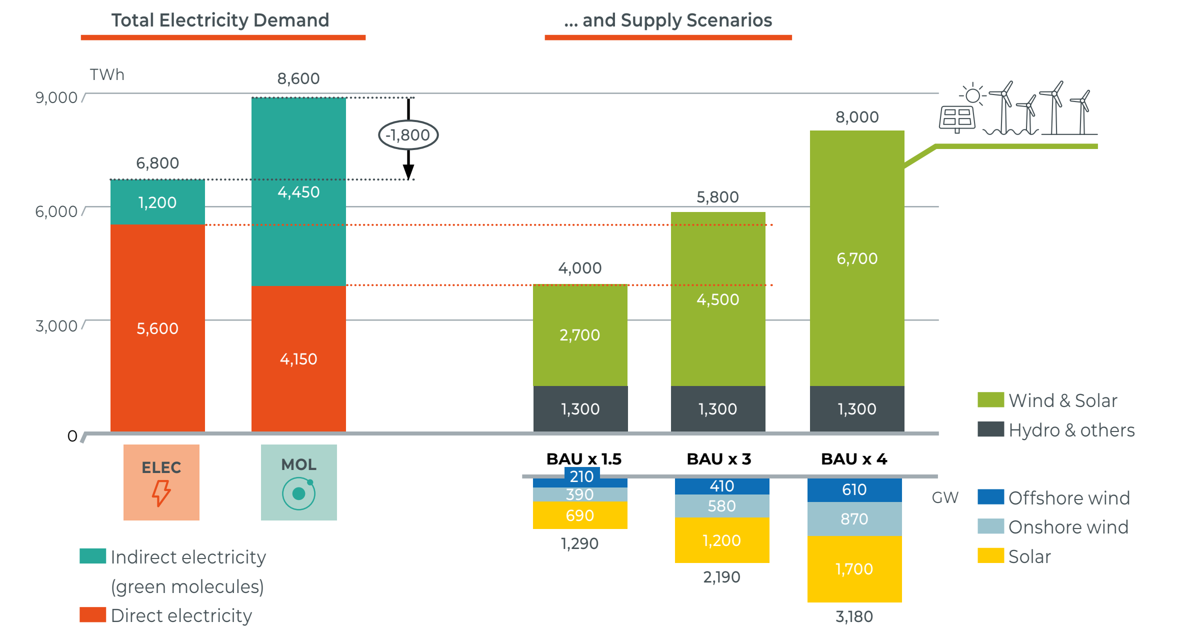


Figure 2 (on the left-hand side) shows the total electricity demand for Europe in 2050 under the two pathways. This total electricity demand comprises both the direct electricity demand (for electrified appliances) and the indirect electricity demand (for the production of green molecules). Whilst electrons for direct electrification need to be produced in Europe (or very nearby), green molecules (indirect electrification) can be produced outside European borders and imported.

The assumed RES capacities are shown on the right-hand side of Figure 2, under scenarios where the RES expansion rate is accelerated 1.5, 3 and 4 times compared to today's rate (which is termed 'business as usual', or BAU). These scenarios are referred to as BAUx1.5, BAUx3 and BAUx4 respectively.

Figure 2 shows that the total electricity demand under the MOL-pathway is 1,800 TWh higher than under the ELEC-pathway. This is equivalent to the annual production of about 400 GW of offshore wind or three times today's electricity demand in Germany.

This is due to conversion losses in the production of green molecules and the higher efficiency of electrified end appliances. Moreover, the figure demonstrates that both under BAUx1.5 and BAUx3, Europe will have insufficient RES to cover its total electricity demand.

Although in theory Europe has sufficient RES potential for the BAUx4 scenario, it is unlikely that these volumes of RES can be developed by 2050. Such a scenario involves an extreme RES expansion rate. As an example, the vast amounts of onshore wind (870 GW in Europe) assumed under the BAUx4 scenario will not come without challenges in terms of spatial planning, permitting procedures and public acceptance. Therefore, our study takes the BAUx3 scenario as a very ambitious but more realistic reference. More details can be found in Section 2.1.

INTERCONNECTORS BALANCE OUT THE UNEVEN DISTRIBUTION OF RES ACROSS EUROPE

Excesses balance out deficits

The potential for RES is unevenly distributed across Europe. In order to share this potential, interconnectors are needed between countries that have an excess in RES and those that have an RES deficit. Figure 3 provides an overview of countries with RES volumes that reach beyond their own needs (excess) and those countries which have an RES deficit.

Focus on Belgium

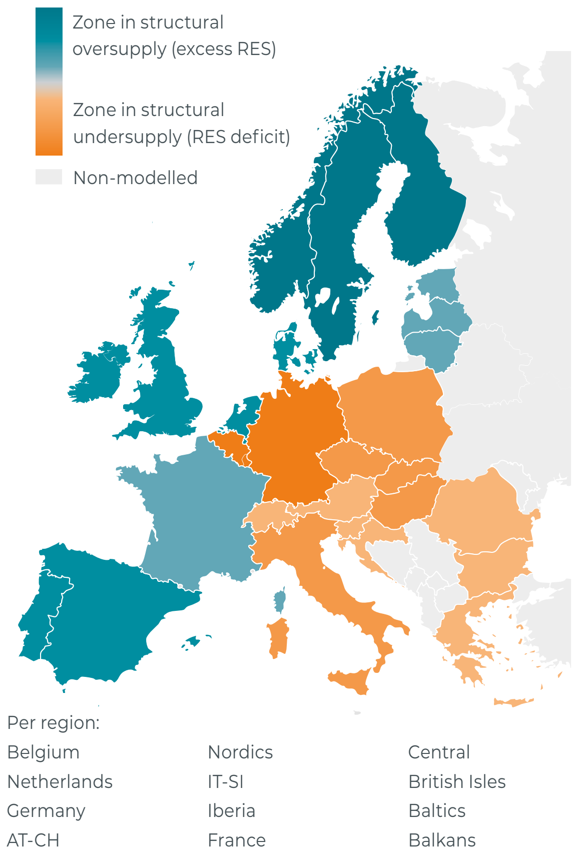
Our scenarios show that about half of Belgium's direct electricity demand in 2050 will need to be covered by non-domestic RES, given its scarce domestic RES potential (BAUx3, ELEC-pathway). This should not be a problem, as Belgium is well located: it has a North Sea coastline, where sufficient offshore RES potential is available. Belgium will have to establish international partnerships with other EU Member States as well as with the UK and Norway, which have an abundance of (offshore) RES potential. More detailed information on the situation for Belgium can be found in Section 2.2.

Focus on Germany

Our scenarios show that Germany might just be able to cover its direct electricity demand under the ELEC-pathway with its domestic RES (BAUx4 scenario). This would require an unprecedented RES expansion and very high onshore wind volumes, which are unlikely to be reached.

Therefore, and on the basis of economic and technical grounds, Germany will also have to look for partnerships which will support the development of non-domestic offshore wind power. More detailed information for Germany can be found in Section 2.2.

FIGURE 3: THE UNEVEN DISTRIBUTION OF RES ACROSS EUROPE. WHILE BELGIUM AND GERMANY ARE SHORT ON RES, THERE IS AN ABUNDANCE OF RES IN NORTHERN EUROPEAN COUNTRIES



INSIGHT 2

FLEXIBILITY

How can the system cope with a high amount of RES, which are inherently intermittent? How much flexibility is needed to keep the balance between demand and supply?

RES are inherently intermittent, causing daily, weekly and seasonal fluctuations in energy supply. A well-designed RES system will be able to manage these fluctuations in an efficient way.

A WELL-BALANCED RES MIX DOES NOT CAUSE A STRUCTURAL SEASONAL MISMATCH BETWEEN DEMAND AND RES SUPPLY

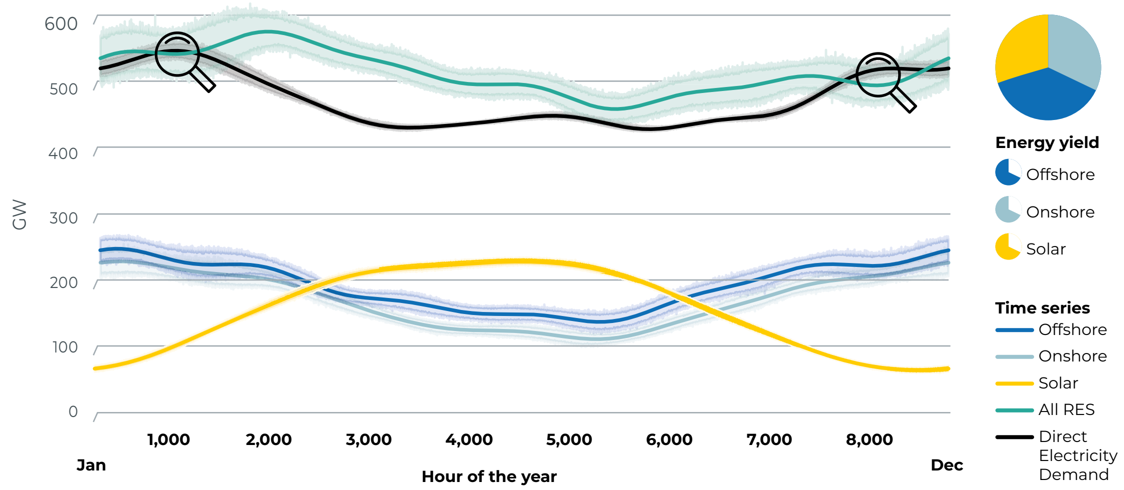
Complementarity of wind and solar power

The generation patterns of wind and solar energy in Europe are complementary: wind energy production is most abundant in winter, whilst around 40% of solar energy is produced between June and August. Figure 4 shows the long-term fluctuations (over a time scale of 1 to 12 months) in the BAUx3 RES supply in Europe in 2050, and of the direct electricity demand (ELEC-pathway). Achieving the right balance between wind and solar production in the energy mix avoids a structural seasonal mismatch between supply and demand in summer (e.g. oversupply of solar energy) and winter (e.g. undersupply because of low solar infeed).

No need for large-scale volumes of green molecules to cope with seasonality in the power sector

The BAUx3 RES expansion scenario does not reveal a structural seasonal mismatch between supply and demand on a European level under the ELEC-pathway in 2050. This means that there is no need in the power system for large-scale seasonal storage via green molecules. The role of green molecules will be limited to covering periods of 1 up to 2 weeks with exceptionally low RES infeed. Belgium and Germany can achieve a balanced RES mix by building interconnectors with countries with a complementary RES mix.

FIGURE 4: SEASONAL PATTERN OF ELECTRICITY GENERATION AND DEMAND (FLUCTUATIONS 1 TO 12 MONTHS). THE RIGHT MIX OF WIND AND SOLAR POWER AVOIDS A SEASON-LONG MISMATCH BETWEEN ELECTRICITY DEMAND AND SUPPLY IN EUROPE IN 2050 (BAUX3 RES, ELEC-PATHWAY)



MORE INTERCONNECTORS ARE KEY FOR MANAGING MID-TERM FLUCTUATIONS

Dual role for interconnectors

Aside from their key role in enabling the exchange of RES between countries that are 'long' (which have excess RES) and 'short' (which have an RES deficit), interconnectors level out a large share of weekly RES fluctuations, which are mainly associated with fluctuations in wind production. Our study shows, for example, that weekly fluctuations in wind infeed are about 50% lower at a European level compared to fluctuations at the Belgian level. Therefore, interconnectors are also important for reducing the impact of local (national) RES supply dips.

ELECTRIFICATION OF END USE PROVIDES SUFFICIENT FLEXIBILITY TO THE POWER SYSTEM TO MANAGE DAILY FLUCTUATIONS

Fast uptake of end user electrification

Once they have been widely rolled out, electric vehicles, heat pumps and home batteries can provide significant amounts of short term storage and demand-shifting potential for the system in 2050. Widespread digitalisation is the key to making this happen. Such applications can provide enough flexibility to compensate for the daily fluctuations in solar infeed. They can also mitigate part of the weekly fluctuations stemming from wind generation.

Our study shows that end use and industrial flexibility can reduce the amount of days where there is both an oversupply and undersupply of RES by more than 90% in the 2050 power system (BAUx3, ELEC).

Hence, it is important that the fast uptake of solar panels, which cause most daily variations, is accompanied by sufficient flexibility on the side of the end user.

INSIGHT 3

ADEQUACY

How can the system cope with longer periods of low RES infeed?

Even with a high level of interconnection and end user flexibility in the power system, a significant volume of 'dispatchable' capacity will be needed in 2050 to cover periods lasting up to several weeks with low RES supply and high demand. These periods will mainly occur in winter.

SIGNIFICANT CAPACITY, LIMITED RUNNING HOURS

Our simulations show that, depending on the level of interconnection across Europe and the amount of flexibility in the system, Europe will need between 240 and 400 GW of dispatchable capacities by 2050 (BAUx3, ELEC-pathway). It is therefore important to closely monitor security of supply on the way to net zero and make sure that a sufficient level of dispatchable (backup) capacities is available at all times to guarantee security of supply.

These dispatchable capacities will only be activated for a limited amount of running hours in 2050, since the duration and occurrence of periods with sustained low RES infeed will be both short (they will typically last less than a week) and rare. These periods will often be characterised by sustained low (mainly onshore) wind production.

THE CHOICE OF TECHNOLOGY DOES NOT NEED TO OCCUR TODAY

Over the next decade, existing and new thermal plants will have to take up the role of dispatchable capacities in the system. Over time, the rapid expansion of RES will reduce their running hours and hence, in the case of fossil fuel plants, their GHG emissions. This highlights the importance of rapid RES expansion as a first priority.

It's only in a next step, when the dispatchable capacities themselves have to be fully decarbonised, that a choice about their future technology will need to be made. Different climate-neutral technologies are on the table today to take up this role, such as hydrogen fired gas turbines, fuel cells, biomass and (pumped) hydro power, thermal storage plants, etc. Some of these technologies are already mature, whilst others are still under development, with their cost efficiency yet to be demonstrated. New technologies can appear as a result of technological breakthroughs on the way to 2050. In any case, given the limited projected running hours, technologies with low investment costs will be best suited to addressing adequacy in Europe's future energy system.

Focus points on the road to net zero

Reaching climate neutrality in Europe by 2050 will require a fundamental transformation of the energy system. The insights outlined above led us to identify a number of focus points. These focus points are non-exhaustive and complement other well-known measures that are equally important for reaching net zero, such as enabling significant efficiency gains to reduce primary energy needs.

FOCUS POINT 1

ENSURING AN EFFICIENT USE OF RES POTENTIAL

To make optimal use of the continent's scarce capacity of RES, Europe needs to set up frameworks for partnerships between countries with different levels of RES potential.

FACILITATE RES EXPANSION PARTNERSHIPS BETWEEN COUNTRIES

Europe's RES potential is unevenly distributed across the continent. Belgium, Germany and several other European countries will need access to non-domestic RES to meet their future direct electricity demand (BAUx3, ELEC). Setting up a framework for partnerships related to RES expansion is therefore recommended, particularly for offshore projects.

Our simulations show that Europe can cover its total direct electricity demand with domestic RES by 2050. For this to happen, Europe should encourage agreements to be signed about the exchange of green electrons between countries that need non-domestic RES to cover part of their direct electricity demand and countries which have excess RES potential. Green molecules then need to be imported from other continents which have high RES potentials and favourable conditions for low-cost green molecule production.

As green molecules can be more easily transported over large distances, such a system will be more efficient than encouraging Member States to focus on the domestic production of green molecules for their own needs. This could lead to a shortage of green electrons in Europe to cover its direct electricity demand.

The requirement that each Member State engages in at least one joint cross-border RES project (as outlined in the European Commission's revision of the Renewable Energy Directive, or REDII) is a good step in the right direction, but needs to be significantly extended.

ACCELERATE THE BUILDING OF INTERCONNECTORS

Interconnectors offer two benefits: they facilitate access to RES (e.g. hybrid interconnectors with offshore wind farms) and flexibility assets (e.g. large-scale hydro power plants) across Europe, whilst also levelling out local fluctuations in wind power. They allow countries to make optimal use of Europe's RES potential and reduce the need for countries to build dispatchable capacities within their own borders. Building interconnectors between countries with different levels of RES potential and/or non-correlated RES generation patterns should therefore be explored and accelerated.

Europe would benefit from a framework that encourages 'leading infrastructure,' i.e. hybrid interconnectors and energy hubs that are built before a final decision is taken about the wind farms that need to be connected to them. This would provide a more stable investment environment for the wind industry in Europe.

KEY PARTNERS FOR EUROPE: UK & NORWAY

Given Europe's limited RES potential, cooperative relationships with the UK and Norway would be beneficial and needed, as their offshore RES potential in the North Sea is particularly high (>30% of total potential). Any revision of the EU's internal market regulations and support for offshore wind power cooperation needs to account for the importance of these two countries for Europe to reach climate neutrality.

GLOBAL COOPERATION FOR GREEN MOLECULES

Even if strong efforts are undertaken in terms of energy efficiency and RES expansion, Europe won't have sufficient domestic RES to cover all of its energy demand in 2050 (BAUx3, ELEC). It therefore needs to explore partnerships with non-European countries that have excess RES potential from whom it can import green molecules.

Typically, green molecules (e.g. hydrogen, ammonia, methanol, etc.) can be transported more efficiently than electrons over very long distances. Moreover, while such partnerships will be important in the near future, Belgium and Germany – along with their partners across the EU – will have to work towards a global market for green molecule supply in the long term. The rules and standards of this market will need to be established.

FOCUS POINT 2

TRIPLE THE SPEED OF RES EXPANSION

Policymakers at all institutional levels need to focus on measures that create the right investment framework and reduce the throughput time of RES expansion projects and the realisation of the necessary grid infrastructure.

HALVE THE PERMITTING PROCEDURE TIME

To reach climate neutrality by 2050, RES development will need to occur at a speed that is about three times faster than it is currently occurring at. Belgium and Germany need to fully harness their domestic RES potential. Unprecedented efforts to realise new solar installations as well as on- and offshore wind power generation need to be undertaken by industry, policymakers and civil society. Concrete actions should be pursued to enable this acceleration of RES expansion, like halving the permitting procedure time.

As well as ensuring a stable and attractive investment environment for the development of RES and its supporting infrastructure, policymakers need to address obstacles to further RES expansion, in particular with regard to wind power. To accelerate the expansion of onshore wind power, current permitting procedures need to be revised. In terms of offshore wind power, marine spatial planning should set priorities for green energy supply and reserve sufficient areas for offshore electricity production. Moreover, an appropriate framework should be in place to optimally repower RES sites that have been decommissioned.

Regarding grid infrastructure planning, building 'leading' infrastructure capacity which can accommodate further RES in future should be pursued. This will avoid grid infrastructure becoming a bottleneck on the pathway to net zero.

ACHIEVE THE RIGHT RES MIX

Wind and solar power will become the main sources of RES in a climate-neutral Europe. Both technologies are complementary: wind turbines have a higher output in winter, whilst solar panels reach their peak generation in summer. The right energy mix is important to avoid a structural, season-long mismatch between electricity supply and demand. For northern Europe, the right mix is approximately: 2/3 energy yield from wind and 1/3 from solar.

Whilst the RES potential needed to reach this mix is available at a European level, it is not consistently available at a national level, highlighting the importance of building interconnectors between countries that complement each other in terms of their RES mix. As we approach 2050, it is important to ensure that the expansion of wind power keeps pace with solar expansion to maintain a balanced RES mix at all times.

The necessary expansion of onshore wind power in particular may be difficult, since gaining sufficient public acceptance for it will be challenging. Being a core pillar of a climate-neutral energy system, this technology requires special attention and support from national and regional policymakers. If the development of onshore wind is restrained, the targets for offshore wind will need to be increased accordingly in order not to introduce a seasonal shortage of electricity during wintertime.

FOCUS POINT 3

ELECTRIFY, ELECTRIFY, ... NOW!

The electrification of mobility, heating and end-use appliances should be prioritised, as it is key for reaching climate neutrality. Electrification unlocks flexibility to facilitate the further integration of RES and reduces the final energy demand.

DIRECT ELECTRIFICATION IS A DOUBLE WIN

Direct electrification is the most efficient way to reach carbon neutrality. As stated above, Europe will have a lower need for total electricity (amounting to 1,800 TWh per year) in 2050 if it follows the ELEC-pathway that is based on strong direct electrification. The difference in primary energy need arises for two reasons: firstly, direct electrification does not carry the same conversion losses that are associated with the production of green molecules; and secondly, certain electrified appliances are more efficient.

EFFICIENT BUILDINGS: A TOUGH CHALLENGE

The potential for reducing the building sector's primary energy demand for heating is tremendous. However, given the fragmented ownership structure of building stock, high costs and long investment cycles, clear policies are needed to activate this potential. For example, increasing energy efficiency via insulation can halve the demand for heat; for this to happen by 2050, renovation rates need to triple compared to today.

Important steps to improve the efficiency of buildings could include the introduction of renovation obligations (and subsidies), minimum standards and demolition premiums. In addition, a gradual ban on the installation of new heating devices which use fossil fuels could accelerate the speed of emissions reduction. We see governments taking effective steps in this direction, while at the same time ensuring the feasibility and acceptance (fair & just) of the new regulations.

Once buildings have been properly insulated, a widespread switch to the use of heat pumps can further decrease the energy demand (by a factor of more than 3). To optimally integrate these heat pumps into the power system, sufficient information should be provided about their optimal use (e.g. heat pump and thermostat settings,...), since these appliances and their optimal settings differ from those associated with today's conventional heating systems. The capacity of the heat pumps will be an important aspect. In case the heat pump has a 'resistor' heater to assist on very cold days, the increase in electricity demand during these days must be considered. This effect can be mitigated by installing a heat pump with a slightly higher capacity. These aspects need to be taken into consideration early on, given the life cycle of these types of equipment.

A NEW MARKET DESIGN AND DIGITALISATION

Next to being an efficient way to reach decarbonisation, EVs and heat pumps carry added benefits: short term storage and demand-shifting potential. These benefits are essential for integrating increasing amounts of intermittent RES into the system. Unleashing this potential requires a framework that enables residential and industrial consumers to adjust their consumption patterns to the total system infeed of RES without any loss of comfort, unlocking environmental and economic benefits as they do so.

Today, regulations often incentivise consumers to maximise the consumption of their own electricity generation (e.g. from rooftop solar panels) and to minimise their demand peaks. This framework should be extended so that end user flexibility is also encouraged to follow overall RES production within the boundaries of available grid capacity across the transmission and distribution grids. For example, a household with solar panels should - on a cloudy winter day - be incentivised to optimally use on- and offshore wind generation.

A more consumer focused market design opens the door to new ways for consumers to interact with the power system. It allows the efficient integration of more renewable energy into the system and allows consumers to reap the benefits of their investments in flexible assets (such as EVs, heat pumps and home batteries), so supporting the decarbonisation of society.

In addition to changes to the market design and efficient (dynamic) congestion management across transmission and distribution grids, the development of technical standards for the activation of the flexibility of heat pumps, electric mobility and home batteries (including both smart charging and injections into the grid) will be important enablers for the development of end user flexibility.

Efficient data exchange and communication between all players involved, including consumers, is required. The development of digital identities for consumers by a trusted government agency will be required, so that consumers can share their data in such a way that their privacy is respected and that all parties, who will provide services designed to enable this flexibility, can access it openly.

REDUCTION OF TAXES AND LEVIES ON ELECTRICITY

The use of electricity-based technologies in the transport and heating sectors (for appliances such as EVs and heat pumps) requires up to three times less energy compared to the use of molecule-based technologies. They are therefore key enablers for efficient and fast decarbonisation. Today's taxes and levies on electricity are higher than those on gas or other fossil fuels in Belgium and Germany. This disadvantages electricity as an energy vector, despite the fact that the electrification of applications is a key enabler for reaching climate neutrality as fast as possible.

A taxation system for energy carriers that reflects these benefits is required to reap efficiency gains.

FOCUS POINT 4

AVOID LOCK-IN EFFECTS FOR EFFICIENT DECARBONISATION

The use of green molecules to replace grey hydrogen and decarbonise sectors where electrification is not an option is a priority.

PRIORITISE GREEN MOLECULES IN "NO REGRET" APPLICATIONS

Green molecules will remain a scarce resource over the next decade, as global decarbonisation efforts will ramp up. During this time, the focus needs to be on making green molecules available to sectors and applications that cannot be efficiently decarbonised in another way (e.g. to replace grey hydrogen or as industrial feedstock). This will accelerate the global reduction in CO_2 emissions and avoids the lock-in of green molecules into sectors where other, often more energy efficient, solutions exist (e.g. electrification of heating in building sector, electric vehicles, etc.).

Support schemes for green molecules, therefore, need to focus first on "no regret" applications: sectors where electrification is not an option.

AVOID LOCK-IN EFFECT THROUGH THE DOMESTIC GENERATION OF GREEN MOLECULES

In the run-up to net zero, Europe needs to make sure that there is sufficient domestic RES supply to cover its direct electricity demand at all times before engaging in the large-scale production of green molecules.

Otherwise, electrification (which is the fastest way to decarbonise) will be hindered. In such a case, it would be better to import green molecules from other continents. Apart from small-scale applications and dedicated pilots, to gain technology and value chain maturity in Europe, countries which have insufficient domestic RES to cover their direct electricity demand (such as Belgium and Germany) should refrain from engaging in the large-scale domestic production of green molecules that would reduce the availability of RES for direct electrification needs. This underpins the need for Belgium and Germany to explore options to become a green molecule hub.

First reactions on our study

“

Giles Dickson, CEO of Wind Europe

Net zero requires a huge expansion in wind energy in the EU. Already by 2030 we need over 450 GW to be on track. This means building 30 GW of new wind farms a year, requiring increased effort by all parties, especially those building the wind farms and those such as Elia Group who are making the vital investments in the grid connections, both offshore and onshore.

“

James Watson, Secretary General of Eurogas

To achieve our ambitious target of climate neutrality by 2050, we will need to have both decarbonised molecules and electrons. The challenge will be to bring on renewable and low carbon hydrogen quickly enough in Europe. But we don't need to do this alone. The whole world must decarbonise and a global trade in hydrogen could be a great way to bring the climate friendly fuels we need in the EU – at affordable prices.

“

Patrick Graichen, Executive Director of Agora Energiewende

We need direct electrification because that is the cheaper way to decarbonize the energy system compared to molecules. We have all the technologies available for that. We have heat pumps, we have electric cars, we have the electric appliances in industry. That is the way forward.

“

Ronnie Belmans, Professor Emeritus at KU Leuven

Electrification is the key. Thermodynamics is clear. If you have electricity, use it as electricity. Of course, some applications cannot be electrified. For this we will need molecules.

“

Hilde Tonne, CEO of Statnett

We need to have ambitions, we need to have collaboration and we need to have decisiveness and tempo in this. The importance of international collaboration and international exchange is highlighted in the Elia Group study. I highly appreciate that and look forward to further collaboration.

“

Kathrin Goldammer, Managing Director of Reiner-Lemoine-Institute

The encouragement of end user flexibility is a very important point. One of the key questions is: How is this going to be done? We need to talk about what kind of flexibility we would like to incentivize -and how- over the next few years.

“

Jacques Vandermeiren, CEO of Port of Antwerp

The reliability and comfort of a robust and flexible energy system that complements local production of green energy with the import of renewable molecules is needed to cover Europe's future energy demand in a cost-efficient way.

“

Thomas Egebo, CEO of Energinet

The electrification of Europe will not succeed without a tremendous leap in the generation capacity of renewable energy resources. But it will also not succeed unless we move forward and establish interconnectors between countries with ample renewable energy sources and countries with less access to such resources.

“

Andreas Kuhlmann, CEO of German Energy Agency (dena)

We do need molecules, quite a bit actually. However, we don't know yet where we will get them from. So it is very important to optimise the system in a way that we don't use them for the wrong purpose.

“

Kristian Ruby, Secretary General Eurelectric

One of the key challenges is to add very big amounts of generation capacity over the next decade or two. We need to have a lot of new wind turbines and solar panels and we need dispatchable plants to support. We need to think new to make that happen at this pace that is now needed. We need to review the permitting rules that are currently in place and slowing down deployment. We need to take a fresh look at how to involve local communities and make sure that we get the public acceptance.

“

Jean-Michel Glachant, Professor at Florence School of Regulation

With European cooperation - a friendly but serious one - we will make our journey quicker, safer and cheaper.

“

Jan Rosenow, Principal and European Programme Director at Regulatory Assistance Project (RAP)

The transformation of the buildings sector needs to start now. Further insulating homes is a no-regret solution and the energy efficiency can be further increased by the introduction of electric heat pumps.

“

Barbara Praetorius, Professor at HTW Berlin

Accelerated expansion of renewable energies is the single most important prerequisite for climate neutrality. Increased cooperation with our European electric neighbours will allow realising this transition faster and at lower cost.

II

A climate-neutral European energy system

The time to act is now

The goal is set: the European Union (EU) is striving for net zero greenhouse gas (GHG) emissions by 2050. Europe is to become the first climate-neutral continent. In December 2019, the European Commission published its European Green Deal, an ambitious package of measures that should transform the EU into a modern, resource-efficient and competitive economy, with an economic growth that is decoupled from resource use. The Green Deal is based on the Commission's 2018 strategic long-term vision for establishing a prosperous, modern, competitive and climate-neutral economy by 2050 [SCE-1]. On 14 July 2021, these ambitions were further put into practice by the European Commission's publication of the so-called Fit-for-55-package, aligning key legislation with the goal of reducing GHG emissions by at least 55% by 2030 (compared to 1990 levels), in order to reach carbon neutrality by 2050. Some European countries intend to achieve climate neutrality even earlier; Germany plans for climate neutrality by 2045.

Dimensions of our study

Reaching net zero will require a fundamental transformation of the energy system, with increased energy efficiency, large-scale expansion of renewables and electrification of end-use applications being key elements. The power system will link different sectors together and therefore is at the heart of this transformation. With our study we outline three main dimensions that are important to make the transition happen and the Green Deal a reality. These are shown in Figure 1. Firstly, the energy balance between supply of renewable energy sources (RES) and demand for electricity, be it for direct use or for indirect use to produce so called 'green' molecules must be ensured. Secondly, sufficient flexibility is required in the power system to obtain an adequate system that can cope with the high volatility of RES infeed. And finally, the system must be able to manage periods under stress, with very low RES infeed. This requires some dispatchable capacities to cope with these short and rare periods. The next chapters follow these three dimensions.

FIGURE 1: THREE INVESTIGATED DIMENSIONS OF THE POWER SYSTEM AND CONSIDERED TRANSFORMATION PATHWAYS

Chapter I gives insights into the definition of the distinct transformation pathways and RES supply scenarios and continues with a brief description of the methodology and modelling tools used to come to the results. For the scenario description, both the demand side as well as the supply side are described in more detail. This is followed by an introduction into ANTARES, the market modelling tool used to simulate the European electricity market. The chapter wraps up with a description of the Fourier analysis, a mathematical tool used for the analysis of fluctuations of RES infeed and related flexibility needs.

Chapter II addresses the future energy balance of RES supply and energy demand. When discussing these findings it should be noted that the transformation of the energy system towards 2050 incorporates a lot of uncertainties in terms of future technology developments, behavioural aspects and economic outlook. Therefore, the two transformation pathways named 'ELEC' and 'MOL', presented hereunder should not be interpreted as an accurate forecast of the future energy system. These pathways are not exhaustive and breakthroughs in technology or policy changes may well happen. However, they are useful for understanding the challenges and opportunities that lie ahead. Furthermore, the chapter focuses on the distribution of the renewable energy sources across the European continent. Often, the nationally available RES potential is not in line with the national energy demand. Therefore, we address the need to share this potential across country borders in order to enable carbon neutrality for the entire continent.

Chapter III closes with an analysis on the fluctuations of RES infeed and highlights what is needed to make such a fluctuating system work. For this, our investigation splits up those fluctuations into different time scales (from daily to seasonal). This chapter then provides a deeper analysis for all of these time scales, giving a better understanding of the characteristics of these fluctuations. The chapter concludes with the insights on a system under stress, linked to longer periods of time where the infeed of RES is low. It provides several ways to reduce the impact of these periods, but shows that dispatchable capacities will be needed in a system with high shares of RES.

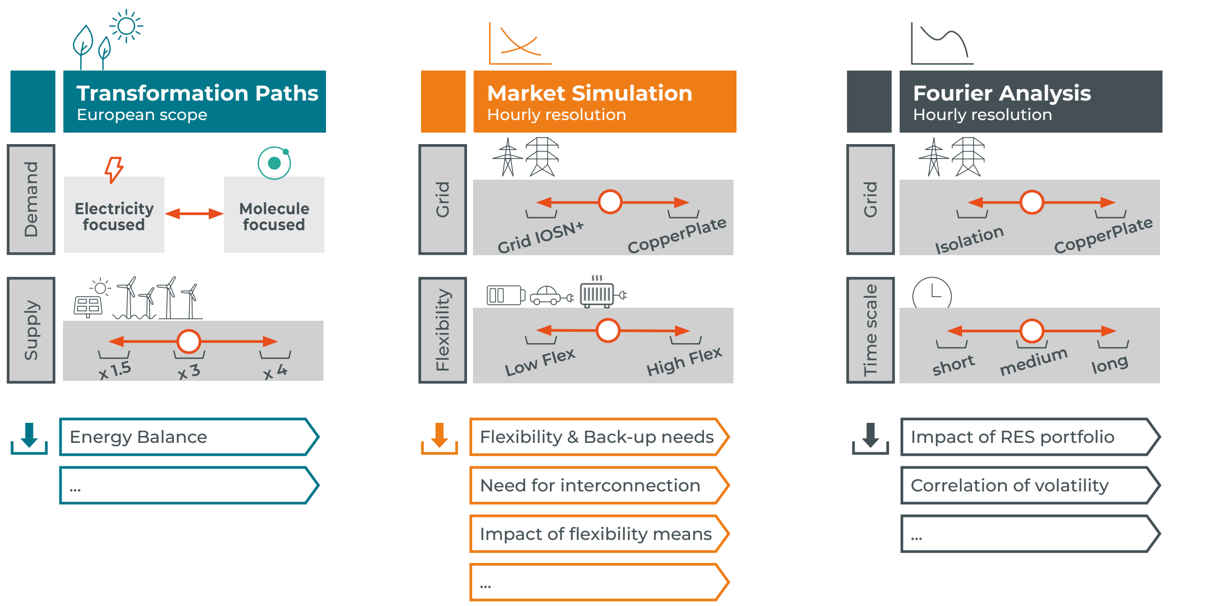
The technical annex (Part III) provides more in-depth information on the scenario development, applied methodology and investigated sensitivities on grid and flexibility.

1. SCENARIO DEFINITION AND METHODOLOGY

1.1 Scenarios and methodology

In order to provide a good understanding of the performed analyses, the first chapter gives more information on the two considered transformation pathways for energy demand towards 2050 (ELEC and MOL) and the three different scenarios for RES supply. These are shown in Figure 2, which also shows the applied methodology for our simulations. Section 1.2 starts off with a detailed description on how the demand transformation pathways are constructed based on the assumed evolutions of the energy consuming sectors. This is followed by an overview of the considered RES supply scenarios and the main assumptions taken to define them (Section 1.3). Finally, Section 1.4 focuses on the analysis methodology. It consists of a description of the market modelling and the Fourier analysis.

FIGURE 2: OVERVIEW OF DEMAND TRANSFORMATION PATHWAYS, RES SUPPLY SCENARIOS AND METHODOLOGY



1.2 Direct and indirect electrification are the key to decarbonisation

All demand sectors will need to undergo a significant transformation to reach climate neutrality by 2050. One uncertainty is the level of direct electrification in this transformation. In order to understand the effect of having different levels, two distinct transformation pathways have been developed for the purpose of this study. They vary by the application of different energy carriers in end use, but share the same assumptions on energy intensity, demographic and economic developments. These assumptions are based on the 1.5TECH scenario described in the European Commission's in-depth analysis accompanying its "A clean planet for all" communication [SCE-2] published in 2018. These pathways are ELEC (electricity-focused) and green MOL (molecule-focused). Other studies have used similar pathways. [SCE-16]

Two transformation pathways with reference to the European Commission's 1.5TECH scenario

The 1.5TECH scenario presents a fully decarbonized European energy system with net zero greenhouse gas emissions by 2050, while realizing continued economic growth. With real GDP being about 2.5 times larger than in 1990, economic output will be completely decoupled from the emission of greenhouse gases. Next to the decarbonisation of energy supply, this decoupling is realized by a strong increase in energy efficiency, resulting in a doubling of the economic output per energy unit consumed by 2050. Among other measures, these energy efficiency gains are realized by a strong increase in direct electrification of final energy demand. This increases from about 23% today to around 50% in 2050.

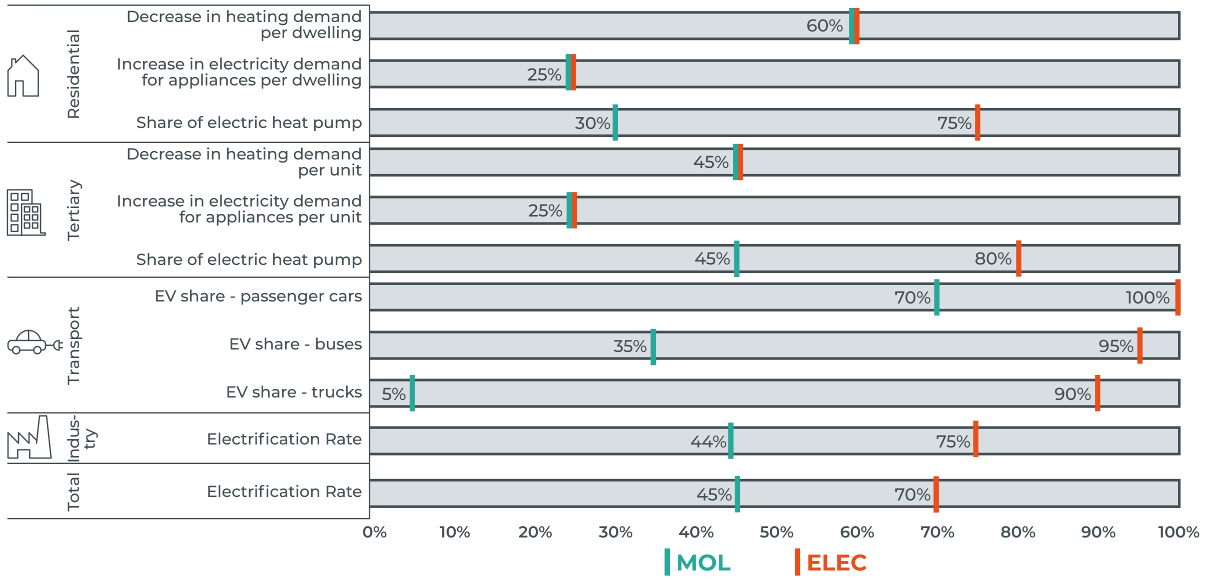
The developments described in 1.5TECH are the basis for the two transformation pathways described in this study. However, not only their level of direct electrification differs from 1.5TECH, but also the energy mix of the residual energy demand. 1.5TECH still includes significant amounts of fossil fuels. Consequently, it relies on negative emissions via deployment of biomass with carbon-capture and storage (BECCS) in order to reach net zero emissions by 2050. Both transformation pathways in this study diverge as they don't consider the use of fossil fuels by 2050. Instead, they rely on increased levels of direct electrification or use of synthetic green molecules (indirect electrification). Therefore, the need for carbon-capture and storage is assumed to be limited to compensation of non-energy related emissions (e.g. process emissions in industry). In the following, the storyline of the two transformation paths is described in more detail. An overview of the main characteristics of the distinct pathways can also be found in Figure 3.

In the ***MOL pathway***, the share of direct electrification increases from 23% today to 45% by 2050. Direct electricity demand in Europe increases with 30% compared to 2018. The pathway focuses on a relatively high share of molecule-based energy supply, especially "green molecules" that comprise hydrogen and its derivatives (e-gases and liquid e-fuels). The pathway is further characterized by high levels of 'indirect electricity demand', needed to produce the green molecules (on the basis of the electrolysis process). In this scenario a large share of heating is assumed to be based on (e-)gas boilers and hydrogen fuel cells. For heavy freight transport, hydrogen fuel cells and e-fuels are taken as the main energy vector. Passenger and lightweight transport are considered to be (almost entirely) electrified. In industry, e-gas is given an important role to play for high temperature heat, whereas hydrogen and e-fuels are applied in specific industrial processes and as non-energetic feedstock. Bioenergy plays a role in industry.

In the ***ELEC pathway***, direct electrification is strongly deployed in all sectors. Direct electricity demand in Europe increases with 70% in absolute terms compared to today and the electrification rate increases to about 70%. Electric heat pumps deliver the majority of heat in buildings. All lightweight, and to a large extent heavy freight transport, are assumed electric. In industry, most low temperature heat as well as an important share of medium to high temperature heat is considered to be electrified. Furthermore, new breakthrough technologies would also allow the application of electricity-based processes in certain industrial processes. Hydrogen, e-fuels and e-gas are applied in heaviest freight transport segment, as non-energetic feedstock and in specific industrial processes.

The 1.5 TECH scenario presents a transformation pathway for EU28 on aggregate, with no data on country level being publicly available – and not including Norway and Switzerland. Therefore, a bottom-up model was developed, which quantifies the multi-energy demand for the different sectors per country (incl. residential, tertiary, transport and industrial sector). Based on EUROSTAT methodology, the countries' final energy demand does not comprise the energy demand for international aviation and maritime shipping. International transport is therefore not part of the analysis in this study. While this is only a minor part of the total energy demand for most countries (e.g. less than 5% for Germany) it is a significant aspect for Belgium (~20%). More information on the demand scenarios can be found in A.1 Scenario development.

FIGURE 3: EVOLUTION OF THE DIFFERENT DEMAND SECTORS IN EUROPE TOWARDS 2050 FOR BOTH TRANSFORMATION PATHWAYS



1.3 Wind and solar power as main pillars of the future energy supply

To reach climate neutrality, wind and solar power will need to be expanded on an unprecedented scale. In order to assess the implications of different ambition levels in RES expansion, three scenarios were defined. The scenarios reflect an acceleration of the annual expansion of wind and solar power by 50% (BAUx1.5), by 200% (BAUx3) and by 300% (BAUx4) respectively, compared to the average annual European RES expansion during the last five years (BAU - business as usual) for every year until 2050. More details can be found in Annex A.1.

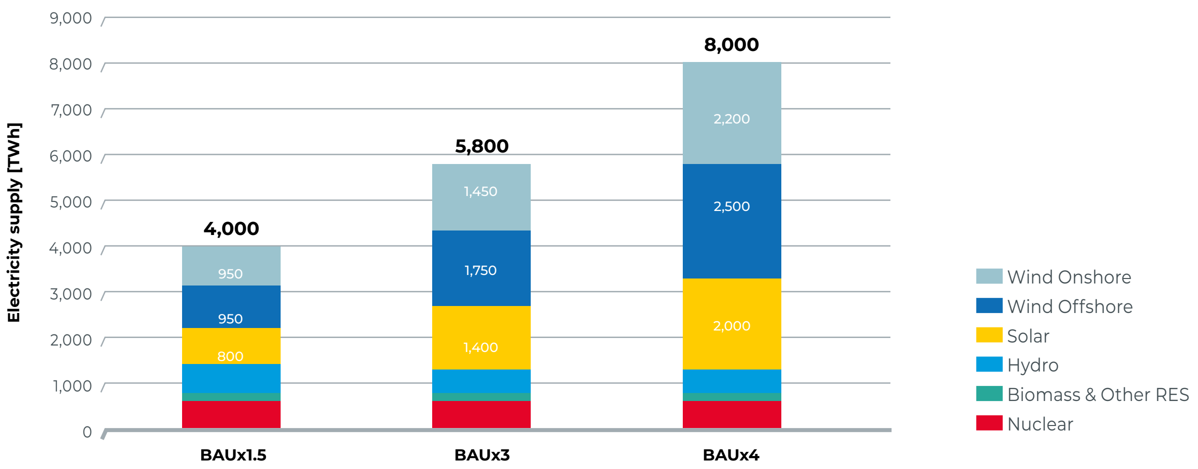
Assumptions on the distribution of wind and solar capacities across technologies and countries are based on relevant European and national studies (comprising both studies on RES potentials and scenario studies to reach policy targets). On European level, these studies comprise for example ENTSO-E's TYNDP2020 [SCE-3], JRC's ENSPRESO [SCE-4] datasets on regional RES potentials and WindEurope's study on offshore wind potentials [SCE-5]. In addition, the BAUx3 scenario considers the EU27's target for 300GW offshore wind power capacity until 2050.

Although in theory Europe has sufficient RES potential for the BAUx4 scenario, it is highly unlikely that these volumes of RES can be available by 2050. Such a scenario involves an extreme RES expansion rate. As an example, the vast amounts of onshore wind (870 GW in Europe) assumed under the BAUx4 scenario will not come without challenges in terms of spatial planning, permitting and public acceptance. Therefore, our study takes the BAUx3-scenario as a very ambitious but more realistic reference.

Next to electricity generation from wind and solar power, the scenarios account for a share of additional climate-neutral generation technologies (based on TYNDP2020), such as nuclear and hydro power. Bioenergy is also considered in electricity supply, but only to a very small extent. The assumption being that the scarce amount of bioenergy unlocks more value in other sectors (e.g. heat and feedstock production). The electricity generation of these other climate-neutral generation technologies does not vary between the scenarios, as this study focuses on the contribution of wind and solar power to cover Europe's future energy demand.

Figure 4 depicts the annual electricity generation of the three supply scenarios on European level. It shows that wind and solar power may constitute up to 85% of the future electricity generation mix.

FIGURE 4: EUROPEAN ELECTRICITY SUPPLY IN 2050 [TWh] IN SCENARIOS BAU x 1.5, 3 AND 4



1.4 Analysis methodology

This section covers the methodology and tools used to achieve the results presented in this paper. European market modelling was done by a unit commitment model (ANTARES). A mathematical analysis based on Fourier was performed to investigate fluctuations in RES supply and power demand. A more detailed description of both methodologies can be found in the technical annex (A.2 Market modelling and A.4 Fourier analysis).

Electricity Market Modelling

In this study, electricity market simulations are performed with ANTARES [SCE-6] -a cost-minimizing dispatch tool- to analyse the future demand, supply and exchange of electricity in a climate-neutral European electricity system. For each hour of the simulation year (2050), the tool determines the cost-optimal solution regarding the dispatch of electricity generators, the use of storage, flexibility means and the exchange of electricity between market areas. The simulated perimeter constitutes EU27, as well as Norway, the United Kingdom and Switzerland. All countries are modelled as separate market areas; electricity exchanges between market areas are constrained by the amount of interconnectors represented via net transfer capacities. The simulations are run in an hourly resolution with one week of perfect foresight on several climate years.

Market simulation aims to assess the electricity market by looking at the direct electricity demand. On top of this, the model includes electrolysers that are running when generation from RES or nuclear is available (beyond direct electrification needs) in order to assess the part of indirect electrification which can be produced at European level.

The results of the market simulations shown in this study are based on the ELEC pathway with a BAUx3 RES supply. Two kinds of sensitivity analyses are performed to understand the effect of i) additional short term flexibility and ii) additional interconnection capacity regarding RES integration and system adequacy. The flexibility sensitivities comprise simulations with low availability of flexibility means (Low Flex) and simulations with high end-user flexibility (High Flex), e.g. from electric vehicles, heat pumps, batteries. Regarding interconnection, a scenario setup reflecting the grid determined for 2040 in ENTSO-E's TYNDP2020 Identification of System Needs (IoSN) [SCE-7] result was considered (incl. additional Belgian and German interconnection projects that are under discussion, see Annex A.3) and in addition a scenario setup that disregarded exchange restrictions and assumed a single European market area (Europe as CopperPlate). Concretely, this means that one set of simulations for 2050 was performed with an expanded, but still considerably restricted transmission grid, not reflecting all needs for a 2050 climate-neutral system and another set was performed with an infinitely strong grid, overshooting the 2050 needs. This approach allows us to derive conclusions on the impact of transmission grids on the various indicators, knowing that the most likely outcome will be somewhere between both sets of simulation results. Further investigations are needed to define a 'fit-for-purpose' 2050 transmission grid. For each market simulation, a dedicated analysis is performed to determine the required amount of dispatchable back-up capacities per country in order to reach a predefined adequacy level.

Fourier Analysis

Additional investigations are performed in this study on the basis of a Fourier analysis. This is a mathematical methodology allowing to break down the fluctuations of the mix of RES generation into its individual contributors. The tool helps to identify the ‚fingerprint' of each RES technology in the generation mix. A better understanding of these fluctuations allows to plan for a more robust power system. The Fourier analysis helps to make this fingerprint visible and to understand why and when a given technology dominates the mix and shapes its volatility. Solar for instance shows a very distinct pattern of peak infeed during the day and none at night. In addition it is seasonal, meaning that European solar irradiation is stronger during summer, leading to overall higher infeed compared to winter.

Fourier analysis is applied to the hourly time series data for RES generation and residual load for Europe as a whole and for Belgium and Germany individually. The residual load time series shows the part of electricity demand that is not covered by domestic renewables (i.e. it represents the national electricity demand minus domestic renewables infeed). This data is decomposed into three time scales of volatility, namely long, medium and short term. Short term volatility (daily variations) is here understood as fluctuations that occur between 1 hour and a full day. Long term volatility (seasonal variations) denotes a timescale of 1 month up to a full year. Medium term (weekly variations) comprises everything in between (1 day up to a full month). Then, the analysis of volatility drivers and possible mitigation options is performed for each time scale individually. This disentanglement clears the view on the volatility in the system and on solutions to cope with these fluctuations. For instance, addressing weekly volatility of moving wind fronts will require a different strategy than flattening daily peak infeed of solar modules, hence both time scales can be studied separately. Fourier makes sure that this separate analysis is quantitatively accurate and robust. Annex A.4 gives more information on the assumptions and the implementation of the method.

2. FUTURE ENERGY SUPPLY AND DEMAND

2.1 Using Europe’s RES potential in an optimal way

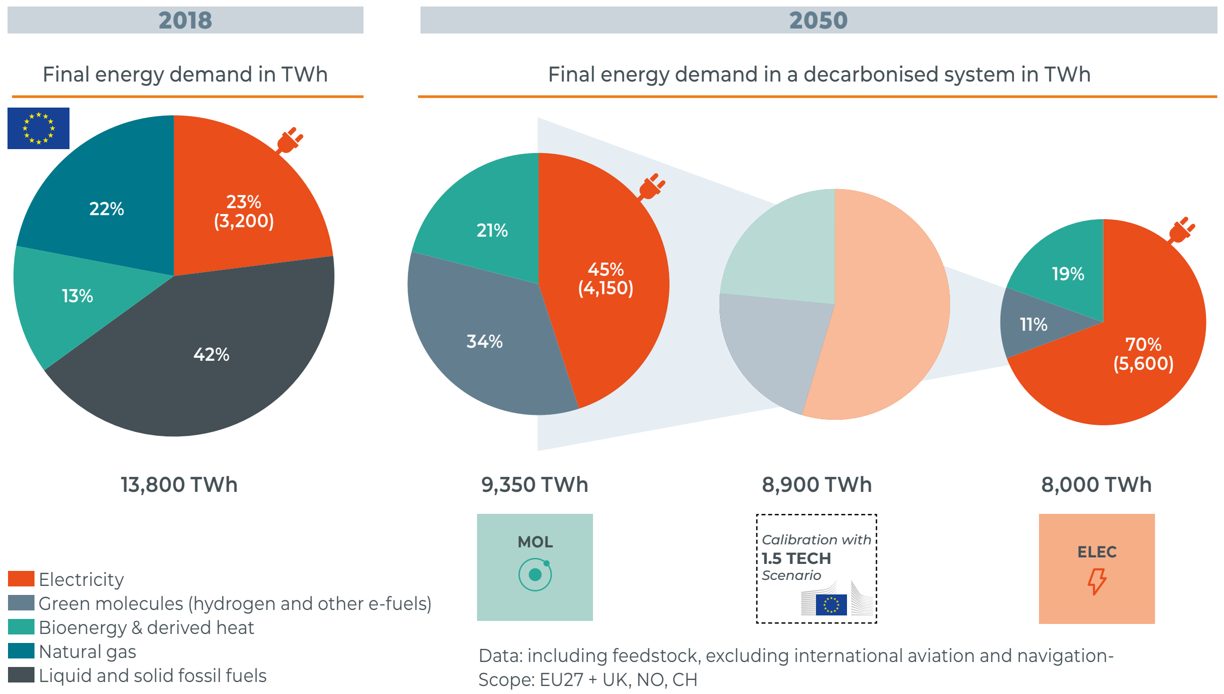
The amount of renewable energy that can be exploited on the European continent is limited –by total potential, by public acceptance and spatial planning. In addition, annual RES expansion rates will be further limited by practical feasibility. Savings in primary energy demand that decrease the need for further RES expansion will therefore help (and increase the speed of) reaching climate neutrality by 2050.

This section takes a closer look at the transformation needs on both the demand and the supply side of the European energy system towards net zero in 2050. The focus in this section is on the European scale and on annual level. Section 2.2 builds on this with more detailed analyses regarding the regional and temporal dimension.

Direct electrification is the most efficient way to cover final energy demand

Both the MOL and ELEC pathway imply a strong decrease in final annual energy demand in 2050. Compared to 2018, there is a reduction in demand by 33% in the MOL and 42% in the ELEC pathway (Figure 5). This is mainly achieved by energy efficiency gains (e.g. better insulation,...) and electrification of end-use (e.g. electric vehicles instead of internal combustion engines). The electrification rate of final energy demand is the main difference between the two pathways, but increases significantly in both. It rises from 23% in 2018 (incl. feedstock) to 45% in the MOL pathway and 70% in the ELEC pathway respectively. Thus, increased energy efficiency and electrification of end-use play a vital role in reaching climate neutrality in both investigated pathways.

FIGURE 5: EVOLUTION OF THE FINAL ENERGY DEMAND IN EUROPE FROM 2018 TOWARDS 2050 FOR THE DIFFERENT PATHWAYS (EU 27 + NO, CH & UK)

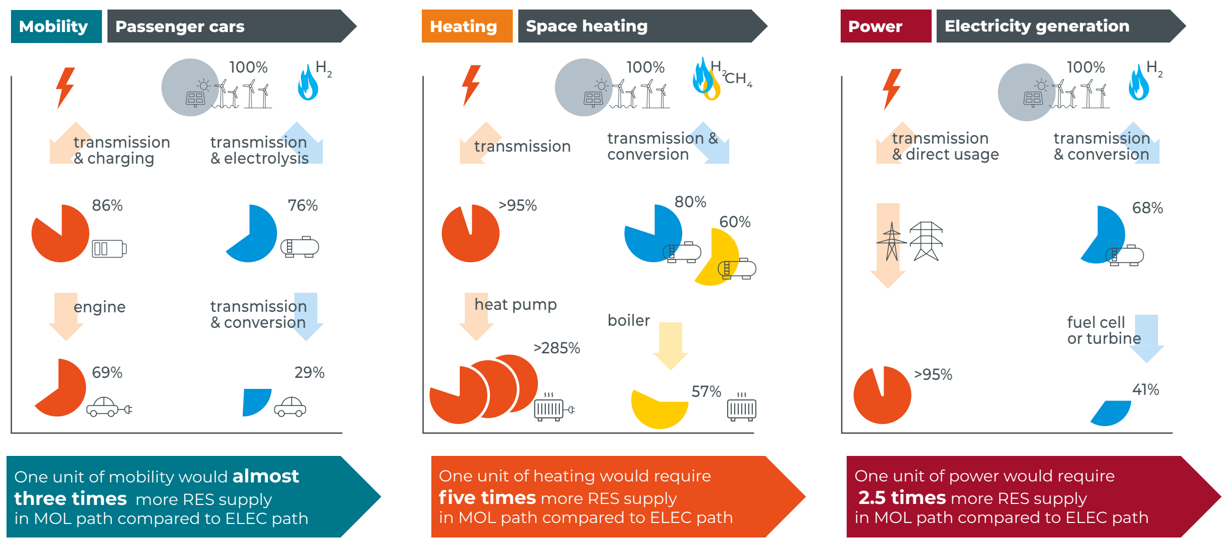


Data: including feedstock, excluding international aviation and navigation-Scope: EU27 + UK, NO, CH

The higher level of direct electrification makes the final energy demand in the ELEC pathway around 1,350 TWh lower than in the MOL pathway. However, taking into account the energy needed to produce the green molecules, the difference in primary energy demand between the two transformation pathways increases further (see below). According to market outlooks (e.g. [SCE-14]), electrolysis ('green hydrogen') is expected to become the most economic way to produce carbon-neutral hydrogen towards 2030. Hence, our study assumes this technology as the reference for 2050. This implies that the use of green molecules (i.e. the indirect use of electricity) comes with efficiency losses compared to the direct use of electricity, due to the conversion process.

In addition, some electricity based appliances (such as heat pumps or electric vehicles) tend to be more efficient than their molecule-fuelled equivalents. This difference in overall efficiencies of electricity-based and molecule-based applications in transport, space heating and power sector is shown in Figure 6. It is clear that, from an efficiency perspective, electricity-based technologies are favourable to molecule-based ones. Nevertheless, some of the molecule-based technologies will play an important role in the future energy system, e.g. in industry as feedstock, international shipping and aviation, or for dispatchable capacities, when there is low electricity generation from wind and solar power for multiple days (see Section 3.2).

FIGURE 6: COMPARISON BETWEEN THE EFFICIENCIES OF DIRECT AND INDIRECT ELECTRIFICATION

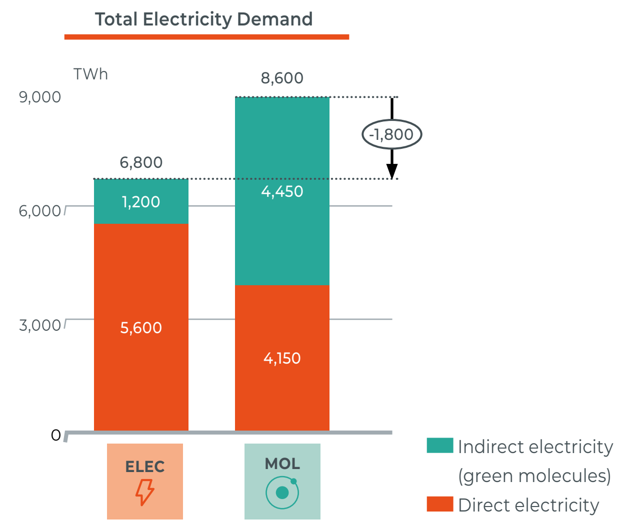


Data: [SCE-13] with updated assumptions on:
H_2 electrolysis 80%, P2G methanation: 75%, H_2 storage 90% [SCE-13]

Considering the conversion losses for producing green molecules from electricity increases the difference in primary energy demand between the MOL and the ELEC pathway to 1,800 TWh on European level. As Figure 7 shows, the direct electricity demand is significantly higher in the ELEC pathway, but the large indirect electricity demand needed to produce green molecules makes the MOL pathway the more energy intensive scenario. The difference of 1,800 TWh between the two pathways is equivalent to the annual energy yield of roughly 400 GW of installed offshore wind capacity or three times today's electricity demand in Germany.

> **Patrick Graichen, Executive Director of Agora Energiewende**
>
> **We need direct electrification because that is the cheaper way to decarbonize the energy system compared to molecules. We have all the technologies available for that. We have heat pumps, we have electric cars, we have the electric appliances in industry. That is the way forward.**

FIGURE 7: TOTAL EUROPEAN ELECTRICITY DEMAND FOR THE ELEC AND MOL PATHWAYS BY 2050



As shown before, the higher efficiency related to direct electrification makes it – where possible – the preferred option from a system perspective. By reducing the overall energy demand, direct electrification reduces the need for RES expansion – which is essential, considering Europe's limited RES potential (see Section 2.2). Both in the MOL and the ELEC pathway, the volume of direct electrification is higher in 2050 compared to 2018 (45% and 70% respectively).

Leverage efficiency gains from electrification

Major changes are needed to unlock energy efficiency gains in the building sector via electrification of heating

The efficiency associated with electrifying the heating sector is clear: heat pumps are (up to) more than 3 times more energy efficient than conventional heating systems. Taking into account conversion losses in the production of green molecules, the difference increases further. However, to reach these high COPs (coefficient of performance), heat pumps do require houses with high insulation levels. The main reason being that heat pumps provide their heat on a relatively low temperature. This low temperature heat also means that heat pumps typically need heating elements with large(r) surfaces, like floor heating. So in order to unlock the benefits of direct electrification, a large part of the housing stock needs to undergo renovations over the next three decades. Given the fragmented ownership structure of building stock, high costs and long investment cycles, clear policies are needed to activate this potential. Our pathways show that energy demand for the domestic heating sector could be reduced by approx. a factor 6 in case of strong penetration of heat pumps and increased building insulation. As an added benefit, heat pumps can also provide useful flexibility to the power system.

Local and district heating networks are expected to play a more important role in the future. They are able to provide climate-neutral heat where decentralized technologies are not a favourable option, especially in densely populated areas. Heating networks can also integrate waste heat from industry to distribute it to nearby households. As heating networks are typically equipped with a variety of technologies (heat pumps, combined-heat-and-power plants, heat boilers), they offer valuable flexibility to power the system by either consuming or producing electricity next to their heat supply.

> **Jan Rosenow, Principal and European Programme Director at Regulatory Assistance Project (RAP)**
>
> **The transformation of the buildings sector needs to start now. Further insulating homes is a no-regret solution and the energy efficiency can be further increased by the introduction of electric heat pumps.**

DEPLOYING ALL-ELECTRIC HEAT PUMPS

All-electric heat pumps are most energy efficient for space heating in (well-insulated) residential and tertiary buildings. They outcompete hybrid heat pumps and gas boilers in terms of performance. The simulations for the ELEC pathway show that, from a system's perspective, high shares (up to 75%) of all electric heat pumps are possible.

One of the aspects that needs to be taken into account when massively installing all electric heat pumps is the presence or not of a ‚resistor' heating component that provides extra heating capacity during coldest days (i.e. assists the heat pump that is underdimensioned for these days). This could lead to an increase in electricity consumptions, as the resistor heating doesn't have a COP of around 300% (air source heat pump) or even 400% (ground source heat pump).

This effect has to be monitored well during the deployment of these heat pumps. Having resistor's widely deployed, could have an impact on the need of dispatchable capacities on the coldest days. This effect can be overcome by installing a heat pump with a slightly higher heating capacity.

Another important aspect for high insulated houses with heat pumps is linked to behavioural aspects. Typically, it makes more sense in such a situation to have a relatively constant temperature throughout the day. This compared to less insulated buildings with conventional heating technologies, where it makes more sense from energetic perspective to set colder temperatures during the nights. This will also have a positive impact on the electricity peak demand stemming from these heat pumps.

The combination of higher insulation and all-electric heat pumps will also unlock flexibility for the grid. Indeed, by allowing the temperature in a house to vary in a small band around the desired temperature (without loss of comfort), the heating demand can be shifted to moments with highest RES infeed and/or lowest price.

The adoption of electric transport is gaining momentum, but it's just the beginning

Compared to internal combustion engines and climate-neutral alternatives such as fuel cells, electrifying passenger cars entails high efficiency gains. Battery electric vehicles (BEV) running on renewable electricity have an efficiency of 70%, whilst the production of green hydrogen and its subsequent use in fuel cell vehicles results in an overall efficiency that is almost three times lower (see Figure 6). The higher energy efficiency, as well as projected cost decreases have initiated the mass deployment of electric vehicles. However, significant efforts are still needed to realise this pathway, e.g. investments in an adequate charging infrastructure or digitalisation to enable the optimisation of charging processes and to provide new services to the EV owners. Electrification via batteries or overhead lines is possible for freight transport. In contrast, a large part of the aviation and shipping sectors is unlikely to undergo direct electrification, but will rely on liquid synthetic fuels instead.

> **Kristian Ruby, Secretary General Eurelectric**
>
> **One of the key challenges is to add very big amounts of generation capacity over the next decade or two. We need to have a lot of new wind turbines and solar panels and we need dispatchable plants to support. We need to think new to make that happen at this pace that is now needed. We need to review the permitting rules that are currently in place and slowing down deployment. We need to take a fresh look at how to involve local communities and make sure that we get the public acceptance.**

> **Giles Dickson, CEO of Wind Europe**
>
> **Net zero requires a huge expansion in wind energy in the EU. Already by 2030 we need over 450 GW to be on track. This means building 30 GW of new wind farms a year, requiring increased effort by all parties, especially those building the wind farms and those such as Elia Group who are making the vital investments in the grid connections, both offshore and onshore.**

Electrification is one important way for industry to achieve climate neutrality

There is a huge potential for direct electrification in industry as well, especially regarding heating processes. While direct electrification is most efficient for low temperature heat supply (see above), also the efficiency of electrifying high temperature applications (above 500°C) is higher than the efficiency associated with using green molecules when accounting for the conversion losses in making the molecules. Green molecules (hydrogen, ammonia, methanol,...) together with bio-energy will definitely play an important role as feedstock, for example in the chemicals and steel industry. In some industrial sectors, such as the cement industry, there are process emissions that cannot be avoided through electrification or the use of green molecules. In such cases, carbon capture and storage or usage (CCS/U) will be needed to reach carbon neutrality.

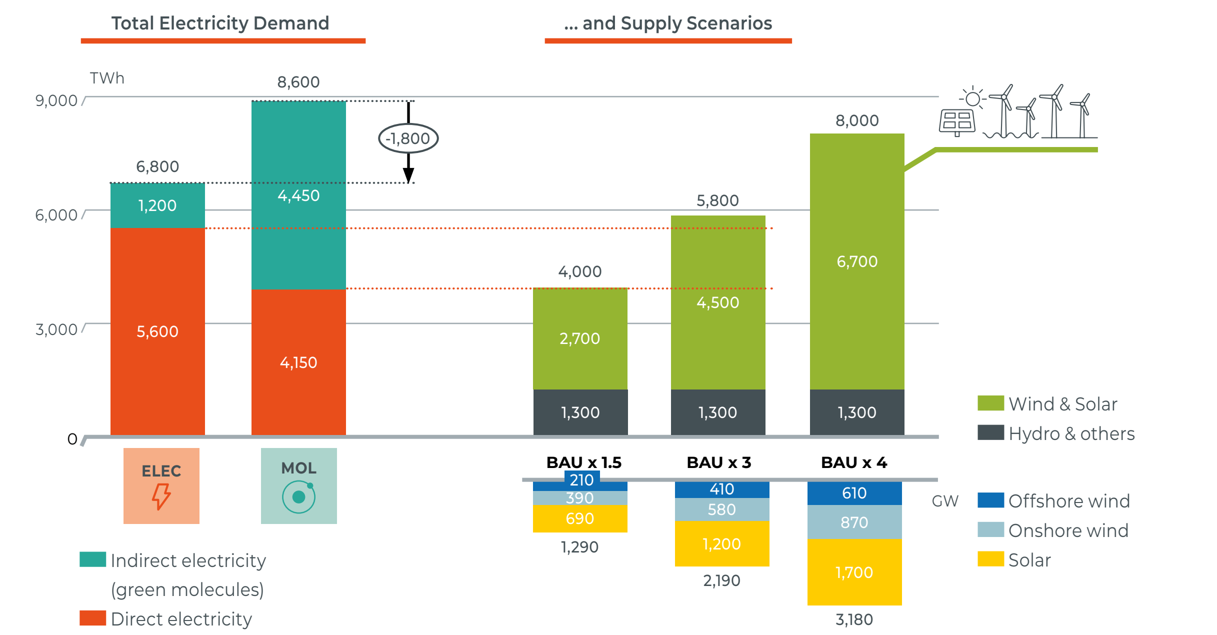
Speeding up annual RES expansion with a factor three is essential to realise climate neutrality

Figure 8 compares the total electricity demand for both pathways with the RES supply under the three assumed scenarios. The indirect electricity demand reflects the need for additional electricity to produce the green molecules consumed in the pathways. The production of these green molecules can also take place outside of Europe, since molecules can be transported over large distances by pipeline or boat.

The figure shows that Europe has sufficient RES potential available to cover its direct electricity demand in the ELEC pathway, when accelerating the RES expansion by at least a factor 3. The same holds for the MOL pathway. Leaving aside the very unlikely BAUx4 RES supply scenario, it is clear that Europe will need to import energy by 2050. However, under the BAUx3 scenario, Europe will become less dependent from imports than today. The MOL pathway requires a much higher expansion of RES to cover the demand for green molecules. Given the limited potential, this demand needs to be covered (partially) by RES on other continents.

In any case, it is important to increase the speed of RES expansion with at least a factor 3 to enable a net zero energy system by 2050. As stated in Chapter 1, we also included a fixed volume of other technologies (nuclear, hydro and bioenergy) in all three supply scenarios. These volumes are based on scenarios in other studies and reflect existing policies and regulations.

FIGURE 8: COMPARISON BETWEEN THE TOTAL ELECTRICITY DEMAND AND THE ELECTRICITY SUPPLY FOR BOTH TRANSFORMATION PATHWAYS AND ALL THREE SUPPLY SCENARIOS ON A EUROPEAN LEVEL IN 2050



The expansion of wind power requires extra policy attention

In order to realize the increase of RES expansion with a factor three, unprecedented efforts regarding the expansion of solar power, wind power and the supporting grid infrastructure need to be undertaken. Ensuring a stable and attractive investment environment for RES projects is needed but not enough. Policymakers need to address technology-specific obstacles to further RES expansion, in particular with regard to wind power whose expansion rate is still far away from the required level. To accelerate the expansion of onshore wind power, current permitting procedures need to be revised. In terms of offshore wind power, marine spatial planning should set priorities for green energy supply and reserve sufficient areas for offshore electricity production. Moreover, an appropriate framework should be in place to repower RES sites that are decommissioned in an optimal way.

Regarding grid infrastructure planning, building 'leading' infrastructure capacity which can integrate more RES at a later stage should be pursued. This will avoid grid infrastructure becoming a bottleneck on the pathway to net zero.

Europe will need to import green molecules

A RES expansion rate that is triple today's rate is very ambitious and requires significant policy support. Going further, up to an expansion that is four times today's rate, seems almost out of reach and would lead to installed RES capacities that go beyond today's projected levels for 2050. Therefore, Europe needs to explore partnerships with non-European countries that have excess RES potential to import green molecules.

> **James Watson, Secretary General of Eurogas**
>
> **To achieve our ambitious target of climate neutrality by 2050, we will need to have both decarbonised molecules and electrons. The challenge will be to bring on renewable and low carbon hydrogen quickly enough in Europe. But we don't need to do this alone. The whole world must decarbonise and a global trade in hydrogen could be a great way to bring the climate friendly fuels we need in the EU – at affordable prices**

When comparing the total need for energy import amongst the two pathways, the level required in the MOL pathway is much higher than for ELEC. Covering this increased demand would mean additional transformation efforts in the exporting countries. Given the small number of countries that will achieve climate neutrality long before the middle of the century, importing all these green molecules will be a challenge. This implies that the RES potential that is available in Europe should be used as effectively and as efficiently as possible. This also implies that direct electrification of end use is the fastest way to decarbonise consumption. Therefore, the focus of the analyses presented in the following focuses on the ELEC pathway (reducing energy needs) combined with BAUx3 (ambitious RES uptake). The analyses provide valuable insights regarding future flexibility and interconnection needs to make a climate-neutral and highly electrified energy system possible. In the end, public acceptance for domestic RES expansion, international market prices for green molecules and other factors will determine the future role of green hydrogen and its derivatives in final energy demand and the future import share of these molecules.

Green molecules should first be used to replace grey hydrogen and decarbonise sectors where electrification is not an option

Prioritise green molecules in "no regret" applications

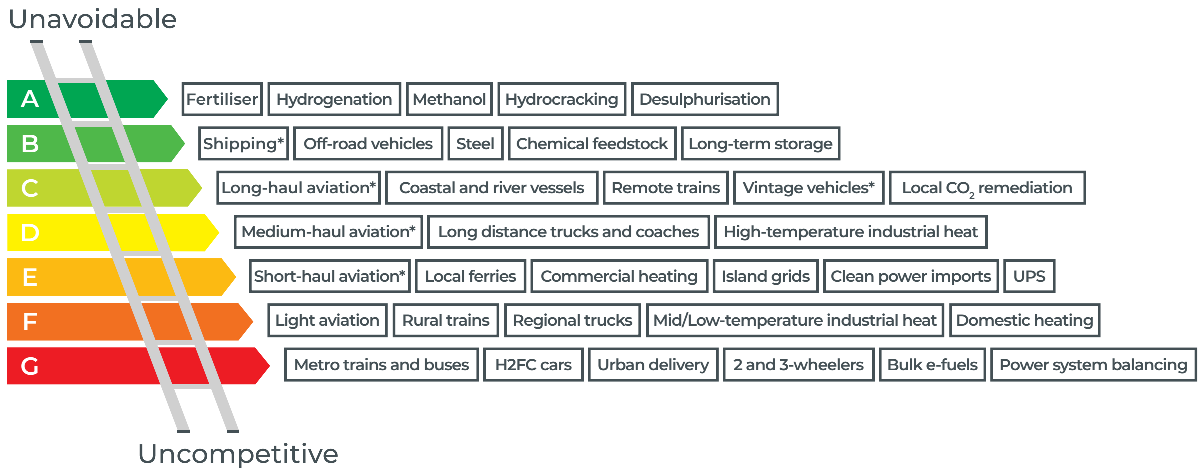
Green molecules will remain a scarce resource over the next decade, as global decarbonisation efforts will ramp up. During this time, the focus should be on making green molecules available to sectors and applications that cannot be efficiently decarbonised in another way (e.g. to replace grey hydrogen or as industrial feedstock). This will accelerate the global reduction in CO_2 emissions and avoids the lock-in of green molecules into sectors where other, often more energy efficient solutions, exist (e.g. electrification of heating in building sector, electric vehicles, etc.).

Support schemes for green molecules should therefore focus first on "no regret" applications: sectors where electrification is not an option. As a general guideline, the clean hydrogen ladder [SCE-15] (Figure 9) can be used. This shows that the application of green molecules should focus first on replacing grey hydrogen.

> **Andreas Kuhlmann, CEO of German Energy Agency (dena)**
>
> **We do need molecules, quite a bit actually. However, we don't know yet where we will get them from. So it is very important to optimise the system in a way that we don't use them for the wrong purpose.**

> **Jacques Vandermeiren, CEO of Port of Antwerp**
>
> **The reliability and comfort of a robust and flexible energy system that complements local production of green energy with the import of renewable molecules is needed to cover Europe's future energy demand in a cost-efficient way.**

FIGURE 9: CLEAN HYDROGEN LADDER [SCE-15]



* Via ammonia or e-fuel rather than H2 gas or liquid

Source: [SCE-15]

Avoid lock-in effect through the domestic generation of green molecules

In the run-up to net zero, Europe should make sure that there is sufficient domestic RES supply to cover its direct electricity demand at all times before engaging in the large-scale production of green molecules. Otherwise, electrification (which is the fastest way to decarbonise) will be hindered. In such a case, it would be better to import green molecules from other continents. Apart from small-scale applications and dedicated pilots, to gain technology and value chain maturity in Europe, countries which have insufficient domestic RES to cover their direct electricity demand (such as Belgium and Germany) should refrain from engaging in the large-scale domestic production of green molecules that would reduce the availability of RES for direct electrification needs. This underpins the need for Belgium and Germany to explore options to become a green molecule hub.

EUROPE IS SHORT ON THE RENEWABLES IT NEEDS TO ACHIEVE NET ZERO BY 2050. OUR ANALYSIS REVEALS THAT THERE WILL BE INSUFFICIENT DOMESTIC RENEWABLE ENERGY SOURCES (RES) TO COVER ITS TOTAL ENERGY DEMAND. WHILE EUROPE WILL HAVE SUFFICIENT RES TO COVER ITS DIRECT ELECTRIFICATION NEEDS, IMPORTS OF GREEN MOLECULES FROM OTHER CONTINENTS WILL BE REQUIRED.

Electrification on its own results in significant energy savings. The ELEC pathway requires a lower supply of RES (1,800 TWh) compared to the MOL-pathway, because electrified end appliances (electric vehicles and heat pumps) are very efficient and because producing green molecules carries conversion losses. This demonstrates the importance of stimulating electrification where possible.

To make sure that Europe will be able to cover its final direct electricity demand, the RES expansion rate in Europe needs to increase by at least a factor of 3 (BAUx3) compared to today.

“

Barbara Praetorius, Professor at HTW Berlin

Accelerated expansion of renewable energies is the single most important prerequisite for climate neutrality. Increased cooperation with our European electric neighbours will allow realising this transition faster and at lower cost.

2.2 The energy transition goes beyond national borders

The previous section showed that even though renewable energy will be scarce in Europe, there is enough potential under the BAUx3 RES supply scenario to cover at least the direct electricity demand, even in the ELEC pathway. However, the energy demand and the RES potential are unevenly distributed across Europe. Therefore, intensified international cooperation is key to provide clean and affordable renewable electricity across Europe. Our study shows that especially Belgium and –to a lesser extent- Germany will be short on RES to cover their direct electricity demand. A joint European approach is therefore required to enable efficient decarbonisation. Intensified international cooperation is needed so that all Member States have sufficient RES to cover their direct electrification needs, as green molecules can be imported more easily from outside of Europe.

In a MOL pathway, the picture slightly changes. For most countries (except some, like Belgium) the direct electricity demand can be covered by domestic RES. However there is a massive increase in the total indirect electricity demand, which means that Europe will need to rely heavily –and much more than in the ELEC pathway– on the import of green molecules from other continents.

Belgium and Germany need to go beyond domestic RES

A bottom-up model was developed to allow for specific insights on national transformation pathways, primarily for Belgium and Germany. Figure 10 and Figure 11 show, for Belgium and Germany, resulting national (direct and indirect) electricity demand and RES supply for 2050. For both countries, no nuclear is considered and the share of domestic hydro, biomass (mainly applied in other sectors, e.g. as feedstock) and other RES in electricity generation is relatively small, meaning that most of the generation comes from solar, wind onshore and wind offshore.

Belgium can only cover 28% (MOL) to 37% (ELEC) of its total electricity demand with domestic RES potential

In general, Belgium reaches a slightly lower electrification rate than the EU average which is mainly explained by the high importance of harder to electrify industrial sectors. Additionally, non-energy feedstock for the chemical sector has a relatively high importance in Belgium (18% of total final demand versus 9% for Europe in 2018). In the described transformation pathways, Belgium’s direct electricity demand increases by about 35% to +100% compared to today for the MOL and ELEC pathway respectively. Looking at the total electricity demand, i.e. including electricity demand for the production of green molecules, the picture changes. For the ELEC pathway, the total electricity demand increases with almost a factor 3 compared to today, compared to almost a factor 4 for the MOL pathway. In absolute volumes, the total electricity demand under the MOL pathway is 80 TWh higher, which is almost today’s annual electricity demand in Belgium.

The main difference between direct and indirect electrification is that in the former, green electrons need to reach Belgium, whilst in the latter, the green electrons can be produced abroad to make green molecules, which are then in a later stage imported to Belgium. Nevertheless, as shown in Section 2.1, green molecules will need to be imported anyway from other continents, as the potential in Europe to cover the demand for green molecules is limited.

Belgium should exploit its geographical location next to the North Sea. Over the upcoming decades, the North Sea will become an important source of energy for Europe. Our study shows that sufficient (offshore) RES potential is available in Europe (incl. UK and Norway) to cover the direct electricity demand of all of its Member States. Hence, Belgium should look into partnerships for non-domestic RES expansion, mainly in the North Sea, to make sure it can cover its direct electricity demand in the ELEC pathway. In absolute volumes, there is a need for about 80 TWh of non-domestic green electrons (which equals the annual yield of around 18 GW of installed offshore capacity). This is roughly 5% of the expected installed offshore capacity (410 GW) in our scenarios BAUx3. These green electrons can come to land either via the Belgian coast, or via existing and new onshore interconnections. In the MOL pathway, Belgium would need around 25 TWh of non-domestic RES to cover its direct electricity demand.

With regards to its demand for green molecules, Belgium would need to look for the non-domestic deployment of 75 TWh (slightly below today’s annual electricity demand in Belgium) of RES for their production in the ELEC pathway, compared to 210 TWh (roughly 2.5 times today’s electricity demand in Belgium) for the MOL pathway. It is also clear that for both investigated pathways, Belgium has insufficient domestic RES potential to engage in large-scale production of green molecules, that would reduce the availability of RES for direct electrification needs. Hence, in both pathways, Belgium will need to develop partnerships and import infrastructure for green molecules. Belgium should limit its domestic green molecule production to small-scale applications and dedicated pilots to gain technology and value chain maturity. It can be concluded that the ELEC pathway is more efficient and reduces considerably the volume of non-domestic RES potential Belgium needs to tap into.

FIGURE 10: COMPARISON BETWEEN THE TOTAL ELECTRICITY DEMAND AND THE ELECTRICITY SUPPLY FOR BOTH TRANSFORMATION PATHWAYS AND ALL THREE SUPPLY SCENARIOS FOR BELGIUM IN 2050

Germany needs to speed up domestic and non-domestic RES expansion to realise its 2045 climate neutrality target

Germany’s electricity demand is expected to increase significantly until 2050. In the ELEC scenario, direct electricity demand increases to 80% above today’s level, reaching nearly 1,000TWh – without considering the electricity demand for the production of green molecules (see Figure 11). The MOL scenario results in a direct electricity demand that is 20% above today’s level, but naturally implies a much higher indirect electricity demand for the production of green molecules. Total electricity demand consequently rises to about 1,210 TWh in the ELEC pathway and 1,560 TWh in the MOL pathway. The difference between the two transformation pathways is equivalent to the electricity generation of about 80 GW offshore wind power - more than 1/4th of the total offshore capacity target of the whole EU for 2050.

Comparing the demand values with the available RES potential reveals that Germany will remain a net importer of energy in the future. As the demand for green molecules could be satisfied both from European sources but also from abroad, Germany should continue to develop international partnerships and support the development of a global market for green molecules. However, even with a global market it is questionable whether sufficient amounts of sustainably produced green molecules can be provided to Germany at affordable prices to realise the MOL pathway. Focus should therefore be on energy efficiency and a high level of direct electrification.

“

Jean-Michel Glachant, Professor at Florence School of Regulation

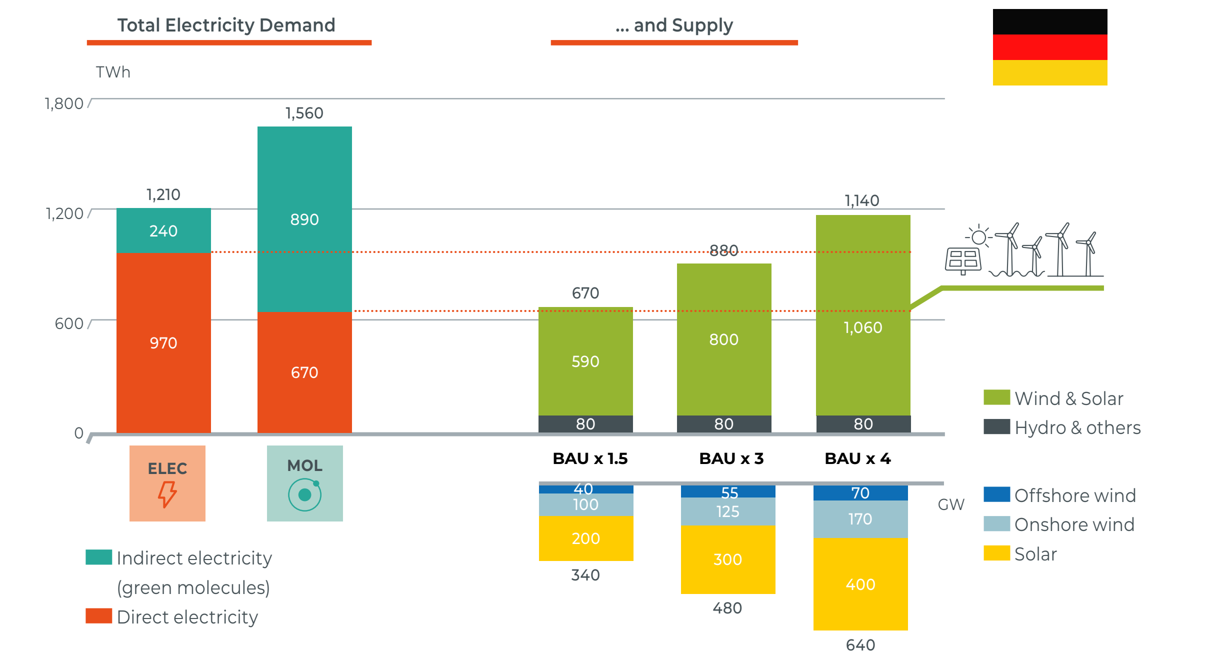
With European cooperation - a friendly but serious one - we will make our journey quicker, safer and cheaper.

As Figure 11 suggests, Germany has sufficient RES potential to cover its direct electricity demand with domestic resources even when realising a high level of direct electrification as described in the ELEC pathway. However, this would require an unprecedented RES expansion (BAUx4 scenario) that might go beyond the limits of public acceptance and practical feasibility. Next to that, from an economic perspective, there is no reason to strive for self-sufficiency given the abundance of RES potential in neighbouring countries.

So to cover its future electricity demand, Germany should make use of non-domestic resources. These resources, e.g. from offshore wind parks outside Germany's exclusive economic zone (EEZ), become even more important when considering the German goal to become climate-neutral by 2045. To reach this, Germany needs to increase the international cooperation with its European neighbours to realise the access to additional non-domestic RES potential. In the BAUx3 scenario, this amounts to 90TWh of electricity or the annual energy yield of approx. 21 GW of offshore wind.

Aside international cooperation, all available levers have to be used to speed up domestic RES expansion. Permitting procedures need to be accelerated and sufficient areas have to be dedicated to onshore wind power development. Also at sea, a revised prioritisation of wind power in spatial planning would help to maximise the use of the domestic RES potential. An expansion of the transmission grid is needed both to bring domestic and non-domestic RES to the end-users of electricity.

FIGURE 11: COMPARISON BETWEEN THE TOTAL ELECTRICITY DEMAND AND THE ELECTRICITY SUPPLY FOR BOTH TRANSFORMATION PATHWAYS AND ALL THREE SUPPLY SCENARIOS FOR GERMANY IN 2050



> **Hilde Tonne, CEO of Statnett**
>
> **In order to deliver on the net zero society towards 2050, we need to have ambition, collaboration, decisiveness and tempo. The ambitions are there: close to 300-400 GW of offshore wind in the North Sea by 2050. For this, collaboration is highly needed across borders and across sectors.**

RES will be unevenly distributed over Europe

Northern Europe has an abundance of RES potential

While Belgium and Germany have insufficient domestic RES to cover their energy demand in 2050, there are several countries in close proximity that are expected to have an abundance of RES. As Figure 12 shows, especially the Northern countries have a RES potential that exceeds their domestic needs by far (ELEC/BAUx3). The reason for this lies in the available area for RES deployment – both on land and especially on sea. By setting up partnerships with these countries, their resources could significantly contribute to covering a.o. Belgium's and Germany's energy demand.

FIGURE 12: OVERVIEW OF ENERGY BALANCE BY ZONE IN 2050 FOR THE ELEC PATHWAY AND BAUX3 RES SUPPLY SCENARIO

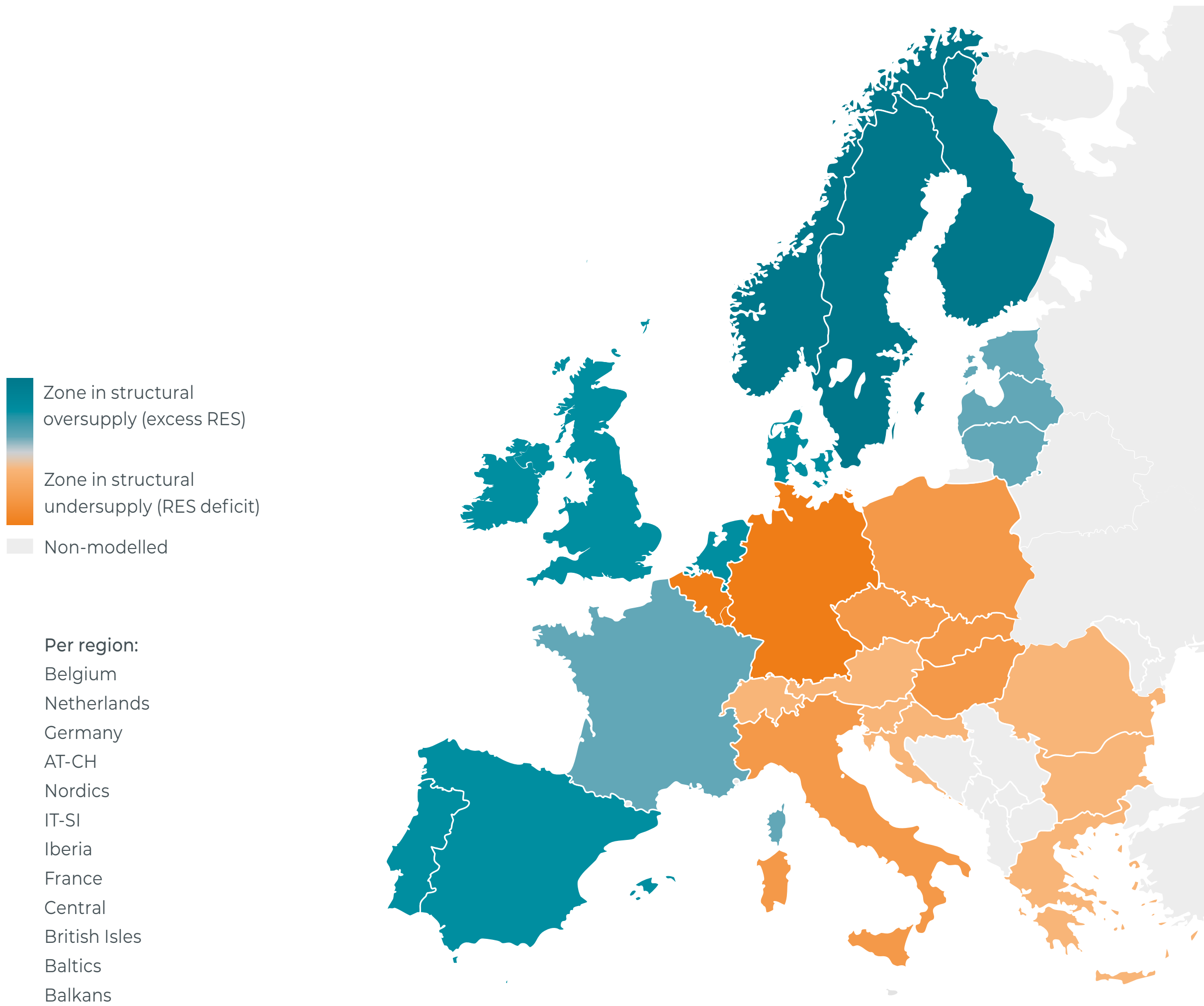
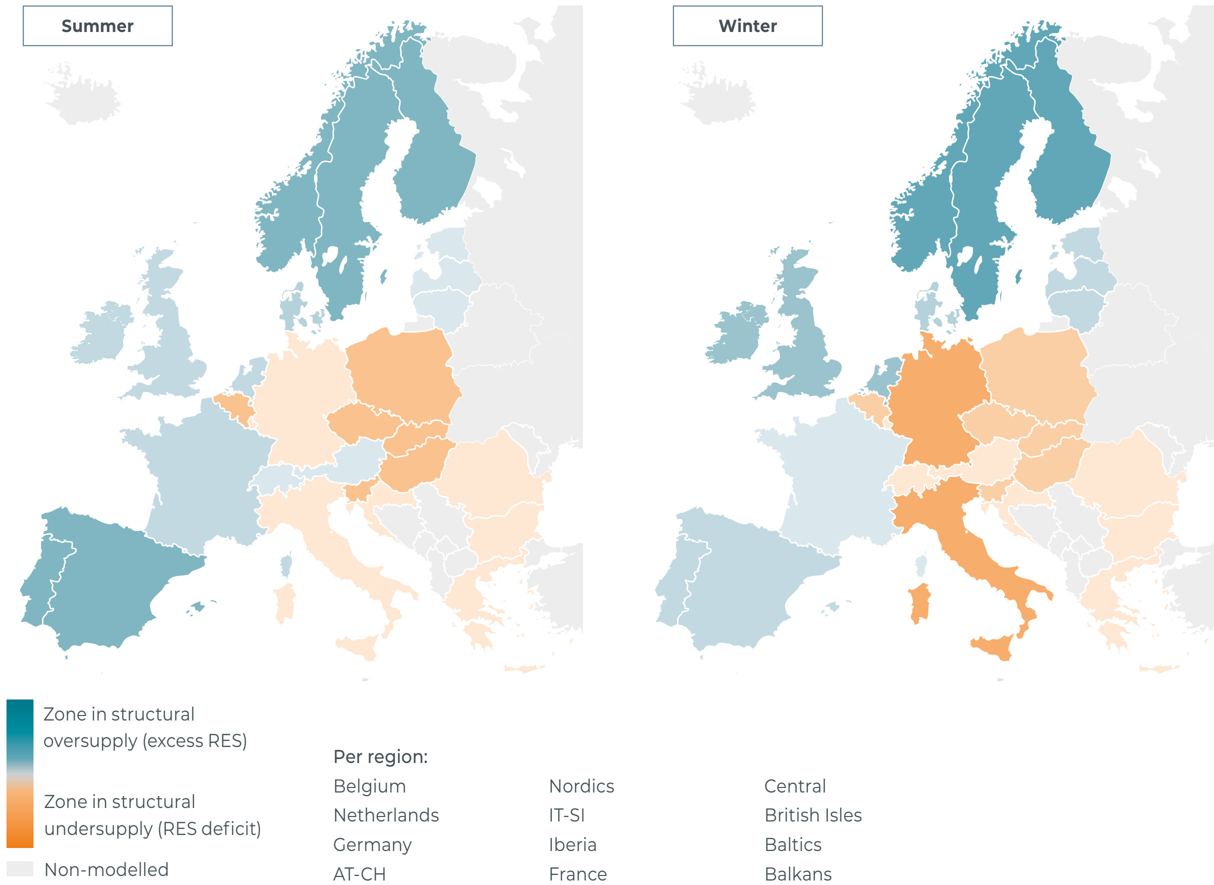


Figure 13 shows the seasonality of electricity supply and demand for different European regions. Southern countries benefit more from solar potential, leading to more generation available in summer and reduced generation in winter. Northern countries on the other hand benefit from the large offshore wind potential of the North and Baltic Seas, leading to more available generation in winter and a structural oversupply for the whole year. The countries in central Europe, without access to large offshore wind potential or high solar generation, will need to rely on non-domestic RES expansion in order to cover their structural undersupply in winter.

FIGURE 13: SEASONALITY OF THE UNDER- OR OVERSUPPLY BY REGION IN 2050 FOR THE ELEC PATHWAY AND BAUx3 RES SUPPLY



Increased interconnection is key for reaching net zero in an efficient way

The efficient transition to climate neutrality in Europe will require an ambitious increase in interconnection capacity. Countries with an undersupply of RES need interconnection with countries that have RES excesses. Next to facilitating access to RES across Europe, interconnectors also reduce both short- and long-term flexibility needs by connecting systems with different weather conditions, RES mixes and demand patterns together (see Section 3.1).

Figure 14 shows –for the European market simulations with unlimited grid capacity (CopperPlate assumption)- an overview of bulk energy flows across Europe. The arrows represent - in the ELEC pathway and BAUx3 RES supply scenario - the difference between 90th percentile of observed market exchanges [GWh/h] over the year in a CopperPlate configuration and today's grid [GW]. It is assumed in this figure that the offshore wind capacity is allocated to the country in which EEZ it is located. However, radial connections of those offshore wind farms to other countries should not be excluded. This figure confirms the huge RES potential in the Northern Seas, which will become the future 'power source' for Europe. Also important to notice is the huge potential in Norway and the UK, leading to increased interconnection with continental Europe.

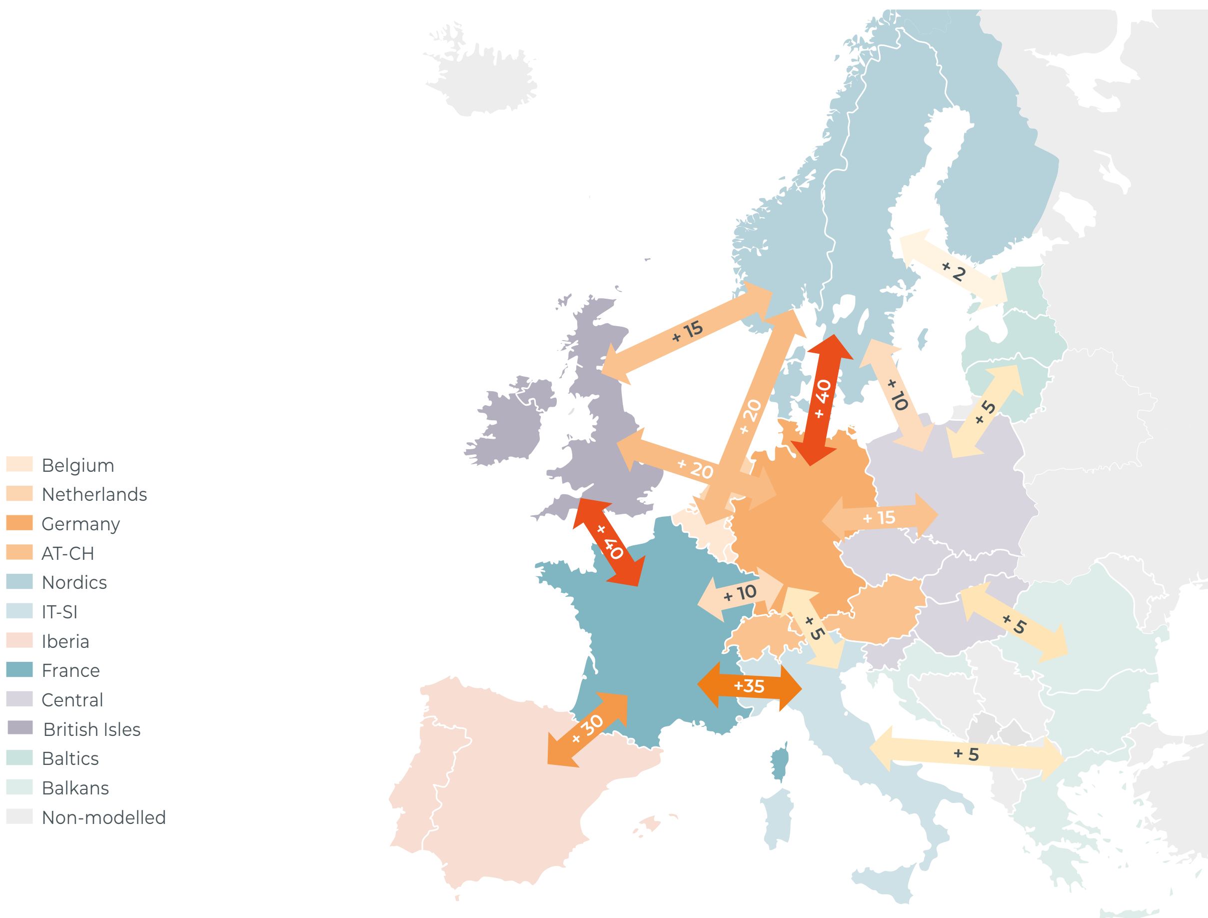
As a follow-up of this study, a more in-depth look into the required transmission infrastructure is needed. To give a first idea of the impact of infrastructure, Section 3.2 provides an overview of the need for dispatchable capacities and flexibility in case of the IoSN+ grid configuration (i.e. underdimensioned grid for 2050) and a CopperPlate grid (i.e. overdimensioned grid for 2050).

INTERCONNECTORS BALANCE OUT THE UNEVEN DISTRIBUTION OF RES ACROSS EUROPE

The potential for renewable energy sources is unevenly distributed across Europe. In order to share this potential, interconnectors are needed between countries that have an excess in RES and those that have an RES deficit. Given Europe's limited RES potential, cooperative relationships with the UK and Norway would be beneficial and needed, as their offshore RES potential in the North Sea is particularly high.

The unique location of Belgium and Germany next to the North and Baltic Seas will enable them to meet their energy demand in a carbon neutral way via connection to non-domestic RES.

FIGURE 14: DIFFERENCE IN OBSERVED MARKET EXCHANGES (90TH PERCENTILE) IN COPPERPLATE [GWh/h] AND EXISTING GRID [GW] FOR ELEC PATHWAY AND BAUX3 RES SUPPLY SCENARIO IN 2050



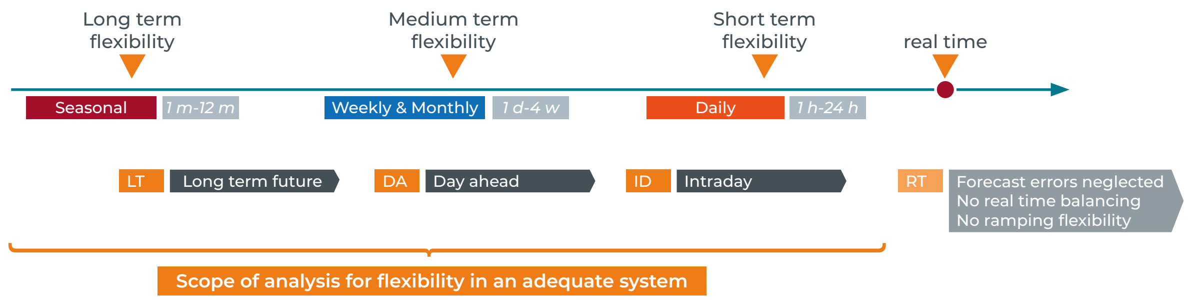
> Thomas Egebo, CEO of Energinet
>
> **The electrification of Europe will not succeed without a tremendous leap in the generation capacity of renewable energy resources. But it will also not succeed unless we move forward and establish interconnectors between countries with ample renewable energy sources and countries with less access to such resources.**

3. ADEQUACY AND FLEXIBILITY

3.1 Coping with the fluctuations of RES

This study looked into the required level of flexibility to come to an adequate system in 2050 by means of European market modelling and Fourier analysis. All simulations in this chapter are based on the ELEC pathway and BAUx3 RES supply scenario. The analyses are performed under the assumptions of 'perfect foresight', i.e. not taking into account forecasting errors or fast variations (e.g. ramping imbalances) from RES, demand forecast errors and unexpected outages (see Figure 15). This means that operational flexibility is not taken into account and should be further investigated. Finally, the impact of different levels of interconnection and end-use flexibility are assessed via sensitivity analyses.

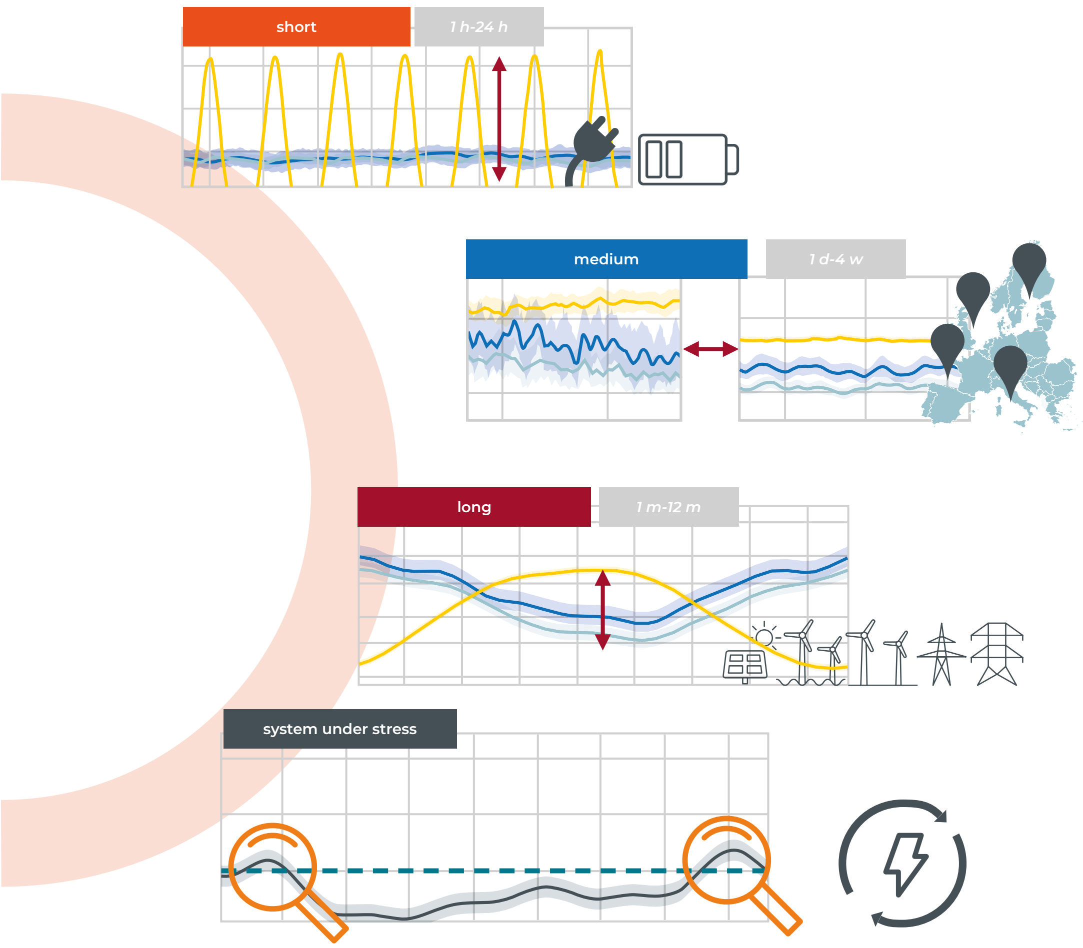
FIGURE 15: OVERVIEW OF THE TIME SCALES FOR THE MARKET MODELLING AND FOURIER ANALYSIS



In the BAUx3 RES supply scenario, 85% of produced energy in Europe stems from RES. Wind and solar power are the main drivers for the transformation towards net zero, but also come with a number of challenges for the system. The previous chapter discussed on the limited domestic RES potential in, and their uneven distribution across, Europe. The third challenge that needs to be addressed are the fluctuations in RES electricity generation.

This section discusses how these fluctuations can be managed to come to an adequate, high RES system. It is structured along the time scales of these fluctuations. The short term time scale comprises the daily patterns (1 to 24h) in RES supply; the medium term includes everything from one day to a month; and the long term time scale covers seasons (1 to 12 months). Figure 16 gives an overview of these different time scales. In addition, the aspect of a system under stress, due to sustained low RES infeed, is added to the overview as it was analysed alongside the other flexibility horizons (see Section 3.2).

FIGURE 16: DIFFERENT TIME SCALES OF THE FLUCTUATIONS OF RES FROM DAILY UP TO SEASONAL, TO CONCLUDE WITH OCCURENCES OF LOW RES EVENTS

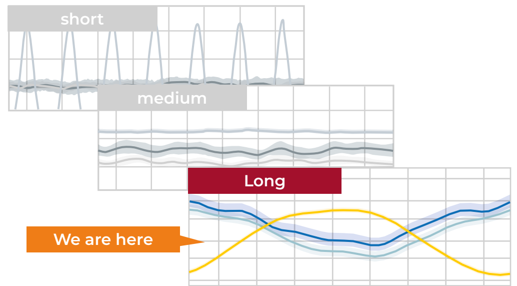


For example, while solar fluctuates strongly on a daily basis and seasonal scale, wind is rather stable but much more variable on a weekly scale. Wind also shows a seasonal component, however this is complementary to solar with a winter peak and summer valley in infeed. Understanding these patterns of volatility can help to design a robust electricity system.

To investigate, these fluctuations in the RES supply, the market simulations are supplemented by a Fourier analysis. This analysis is a mathematical approach to screen time series for repeating patterns, in this case of volatility. In the context of this study, it is used to quantify and visualise the challenge ahead. This screening is done outside the market model and purely based on the hourly input data on demand and RES generation for various climate years. Hence, European results are obtained based on a Copper-Plate analysis and country-wise results for Belgium and Germany are obtained based on an isolated setting (i.e. no cross-border capacities assumed). More information on the methodology of the Fourier analysis and the investigated time scales can be found in Section 1.3 and Annex A.4. The sensitivities on grid infrastructure and level of end-use flexibility are explained in detail in Annex A.3.

The goal of this analysis is to provide insights and solutions on how such a highly electrified net zero system can work in 2050. Throughout the sections, for every time scale (long – medium – short term) the identified solutions are explained in detail. However, the analyses show that these solutions cannot fully mitigate the need for dispatchable capacities to cope with periods of up to several weeks with sustained low RES. Section 3.2 will therefore conclude on the residual need for dispatchable capacities.

A balanced mix of wind and solar power avoids structural mismatch between supply and demand.

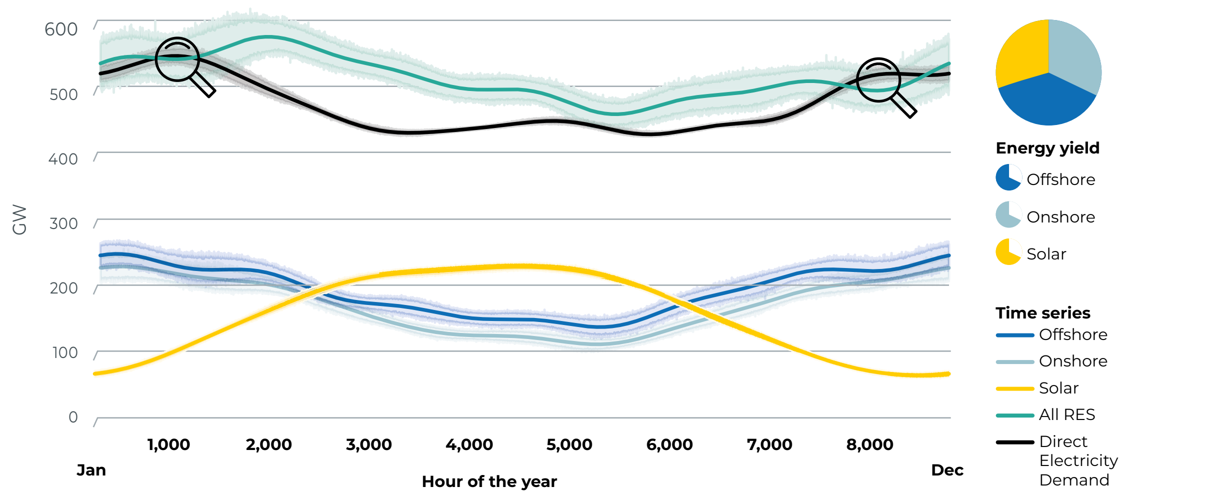


This section demonstrates to what extent the mix of renewable energy sources influences the long term volatility in the power system. It addresses the question whether or not there are season-long flexibility needs and which parameters drive it. The analysis itself is based on multiple climate years to consider yearly variations. The shaded areas show the range over the climate years.

Wind and solar power show complementary seasonal patterns of infeed

Wind and solar power will be the main sources of renewable energy in a climate-neutral Europe. Analysing the seasonal component of their electricity generation profile reveals complementarity between the two. While solar generation is highest during summer, electricity generation from wind power is highest in wintertime, as Figure 17 shows on the European level in 2050. While both wind and solar show a significant spread in seasonal infeed, their joined sum (offshore, onshore and solar) is more balanced.

FIGURE 17: SEASONAL FLUCTUATIONS OF THE EUROPEAN RENEWABLE ELECTRICITY SUPPLY AND DIRECT ELECTRICITY DEMAND FOR THE ELEC PATHWAY AND BAUx3 RES SUPPLY IN 2050



No structural season-long mismatch between RES supply and electricity demand on European scale

Figure 17 not only shows the seasonal component of the RES generation time series, but also of the European direct electricity demand. The demand curve is almost always below the supply curve throughout the year.

The seasonality of electricity demand (which is a.o. driven by higher space heating needs during the cold winter season) is matched well with the parallel high of onshore and offshore wind generation. The figure shows that electrifying Europe with about 2/3 wind power and 1/3 solar (annual energy yield) in the electricity mix results in good seasonal match between demand and supply. In general, higher direct electricity demand in winter requires higher levels of wind power in the RES mix.

With such a RES generation mix, Europe does not show shortages in RES supply lasting for months or entire seasons. This means that dispatchable capacities will not need to run for long periods to support RES infeed to cover demand. There are only limited periods, typically in early February and late November, when total RES generation is falling below the direct electricity demand. This means that there is no need in the power system for large-scale volumes of green molecules (seasonal storage). However, they might be used to fuel dispatchable capacity that is needed to cover periods of up to several weeks with exceptional low RES infeed (see Section 3.2). These findings show the importance of a balanced RES mix on the robustness of the system. Additionally, having a balanced system in the long term time scale (1 month up to seasons) does not exclude challenges in other, shorter time scales.

The findings on European level change when zooming in on the balance of individual countries. The next paragraphs provide further insights for Belgium and Germany.

A sufficient share of on- and offshore wind in the RES mix is key to avoid structural supply shortages during winter

The seasonality of electricity demand and RES generation defines the seasonality of residual load (residual load equals electricity demand minus domestic RES infeed). After analysing the European level, the relationship between RES mix and seasonality of residual load is now further investigated for the case of Belgium (see Figure 18) and Germany (see Figure 19). In the ELEC/BAUx3 pathway, Belgium is short in domestic electricity supply by around 9 GW on average. Here, we investigate which type of RES would best fit to close this gap.

FIGURE 18: IMPACT OF CLOSING THE GAP IN DIRECT ELECTRICITY DEMAND FOR BELGIUM. TWO THEORETICAL SCENARIOS ARE PRESENTED, HIGH OFFSHORE (MIDDLE) AND OFFSHORE-SOLAR (RIGHT) IN 2050 (ELEC / BAUx3)

Long term residual load volatility in Belgium

Lines show mean, shades show range for climate years

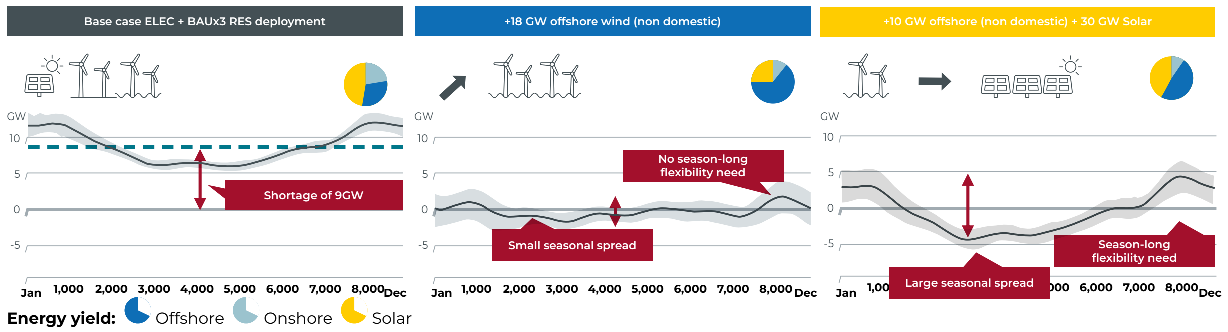


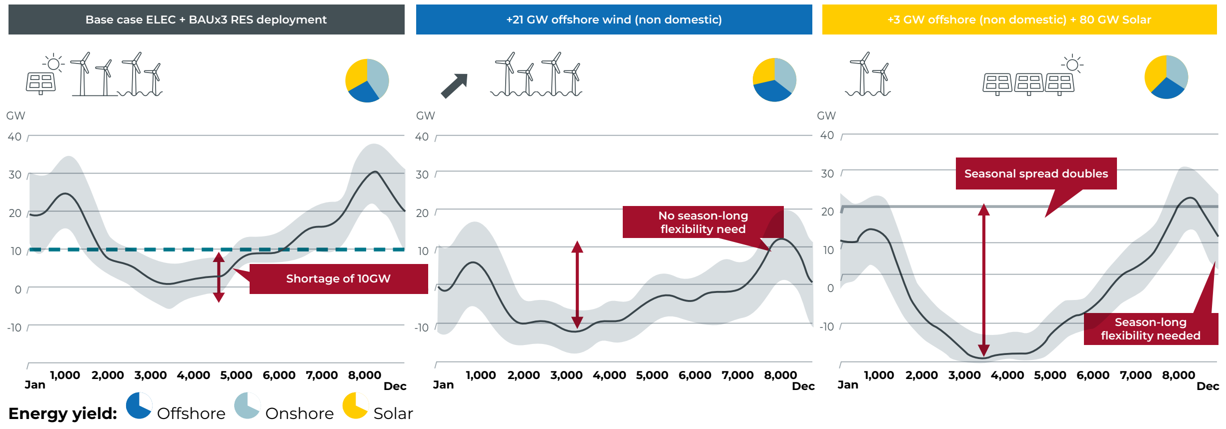
Figure 18 shows on the left the long term volatility of residual load in Belgium for 2050. The middle and right frame relate this volatility to two hypothetical sensitivities that would make the country adequate on annual basis, without taking any interconnections into account (isolated case). The graph in the middle represents a sensitivity where we assume that the shortage in electricity supply is fully covered with 18 GW (non-domestic) additional offshore wind. These wind farms are assumed across the North Sea and British Channel to mimic a hypothetical offshore grid that would deliver this power and connect it – directly (via Belgian coast) or indirectly (via onshore interconnectors) – to Belgium. The graph on the right replaces some of this additional offshore wind (8 GW) by domestic solar (30 GW) instead, assuming identical yearly energy yield.

This hypothetical exercise reveals that adding even more solar to the solar-dominated Belgian RES mix (assuming 40 GW of solar capacity in Belgium by 2050 in the BAUx3 scenario) would double the seasonal volatility in residual load. In fact, it will introduce a season-long flexibility need of several months in a row where the Belgian system would be short in energy. On the contrary, the offshore variant reveals not only a significantly reduced seasonal spread in residual load. It also avoids a season-long mismatch in the Belgian power mix, reducing the adequacy challenge to a sub-seasonal (i.e. weekly or daily) challenge. So from a seasonality point of view, adding offshore wind power would be the preferred option.

FIGURE 19: IMPACT OF CLOSING THE GAP IN DIRECT ELECTRICITY DEMAND FOR GERMANY. TWO THEORETICAL SCENARIOS ARE PRESENTED, HIGH OFFSHORE (MIDDLE) AND OFFSHORE-PV (RIGHT) IN 2050 (ELEC / BAUx3)

Long term residual load volatility in Germany

Lines show mean, shades show range for climate years



A similar hypothetical comparison can be made for the German system. Again, no interconnections are taken into account. Figure 19 on the left shows that it is short by around 10 GW on average and can become adequate by adding approx. 21 GW of non-domestic offshore wind from both Baltic and North Sea wind farms. While the seasonal spread in residual load is still visible, there is no structural season-long flexibility need in such a case. Replacing 18 GW offshore wind with 80 GW solar (keeping the same overall annual energy yield) introduces a high seasonality in residual load, that also in the German example, leads to a season-long flexibility need.

This sensitivity check on the effect of RES mix on residual load volatility in Belgium and Germany is a simplification, since it is drawing an extreme case of covering the supply gap in both countries with just one major means (offshore or solar generation). Alternatives like increased interconnection to other countries or other technologies in the mix have been neglected here. These sensitivities do however shed a light on the relevance of a balanced RES portfolio, whether it is realised domestically or via interconnection. They highlight the importance of the North and the Baltic Sea for the Belgian and German energy supply.

To conclude, on- and offshore wind developments should keep pace with expansion of solar. For onshore wind there needs to be sufficient attention on the permitting procedures and public acceptance, for wind farms and required transmission infrastructure. For offshore wind, policy makers need to foresee sufficient space in the maritime spatial planning for wind production, as well as making sure that international cooperation is put in place to make optimal use of offshore energy (see Section 2.2). If onshore wind expansion would fall behind, from a seasonality point of view, it would be best replaced by additional offshore wind capacity. As shown, introducing additional solar capacity on top of the already high volumes in the BAUx3 scenario for 2050 would introduce seasonality issues into the power system.

“

Ronnie Belmans, Professor Emeritus at KU Leuven

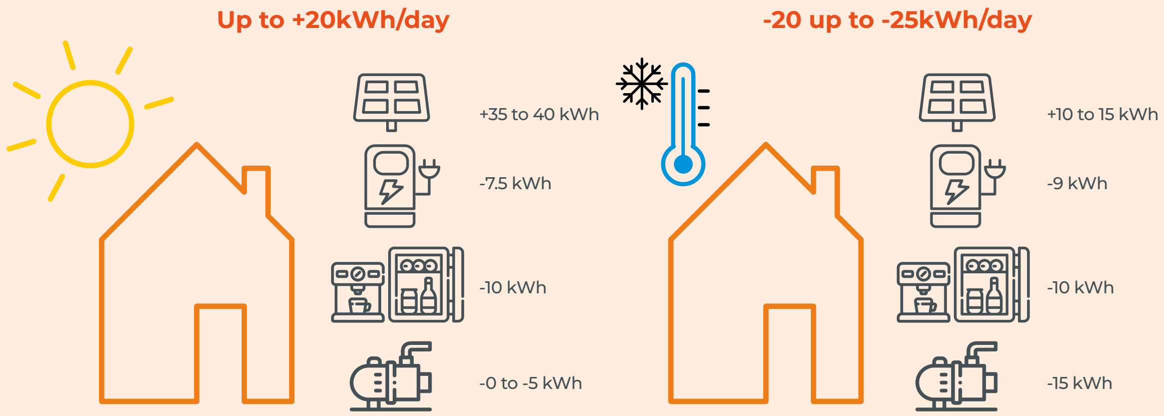
Electrification is the key. Thermodynamics is clear. If you have electricity, use it as electricity. Of course, some applications cannot be electrified. For this we will need molecules.

SEASONALITY FROM THE PERSPECTIVE OF A PROSUMER

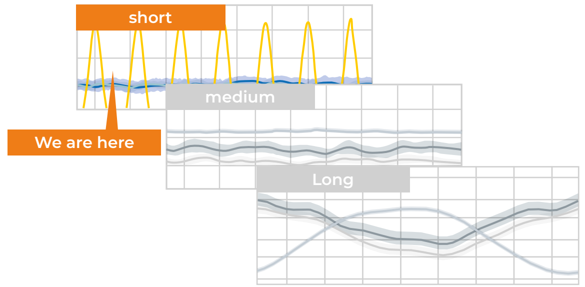
Rooftop solar panels will be a core pillar of the future electricity supply. With a sufficiently large roof size, households can generate enough electricity to supply the annual demand of their domestic appliances, their electric vehicle and their heat-pump with the electricity generation from their solar panels. Doing so can be economic for the household and at the same time contribute to the decarbonisation of the electricity system.

However, considering the seasonality of solar electricity generation, self-sufficiency on an annual scale still implies significant electricity exchanges with the grid throughout the year. The main part of solar electricity generation happens in summer, while the main part of household electricity demand occurs in winter (mainly because of the additional demand from heat pumps). This results in a seasonal mismatch that cannot be addressed by home batteries. In contrast, many households will feed their excess generation into the public grid during summer, and in winter rely on the system's high wind power generation. This effect describes also what was explained before: wind energy will deliver the bulk volume of supply during winter, whilst solar will do so during summer time. The future market mechanisms should make sure that households, in addition to optimising auto-consumption (e.g. with batteries and solar panels), can also efficiently optimise on a wider scale (e.g. can align their consumption with the infeed of wind during winter time).

FIGURE 20: ILLUSTRATIVE EXAMPLE OF THE ENERGY BALANCE FOR A HOUSEHOLD WITH 10KWP SOLAR PANELS TO COVER ITS DAILY ELECTRICITY DEMAND FOR A WARM, SUNNY AND A COLD, CLOUDY DAY



Electrification of end-use provides flexibility to cover daily (and part of weekly) RES fluctuations

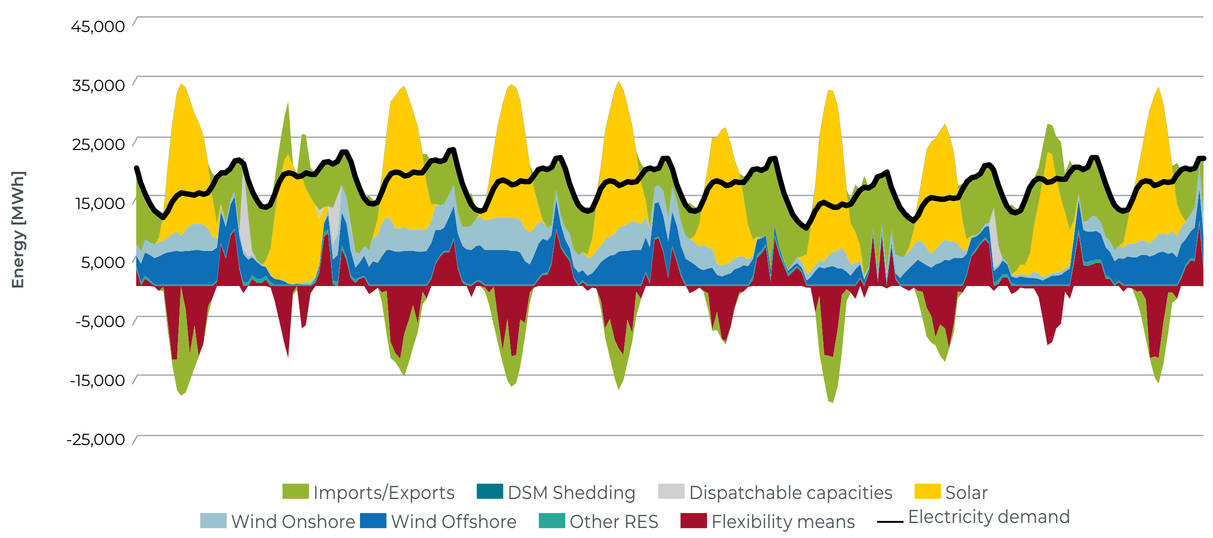


This paragraph focusses on short term volatility on a time scale from 1 hour up to a day. Solar power will be the driving force in daily volatility. The market simulation results reveal to what extent short term flexibility stemming from end-users (EVs, HPs,…) can absorb these fluctuations, thereby enabling even higher levels of RES (mainly solar) integration. EVs can deliver the flexibility on a daily, but also on an intra-weekly level. This means that either energy can be stored up to multiple days, or charging sessions can be delayed for multiple days. A digitalised infrastructure makes sure that the comfort level of the consumer is not impacted and that they can even benefit from providing these additional services. Heat pumps would require a similar infrastructure, however their flexibility concerns the intradaily up to daily time scale.

Short term flexibility enables effective integration of solar energy into the future power system

On a daily time scale, both generation from solar and direct electricity demand follow a similar pattern. Demand is high during the day when solar infeed is high as well. In the BAUx3 / ELEC scenario, the solar production during a sunny day will even overshoot the demand. However, there is a significant mismatch in some hours of the day and during the night, where solar generation is (close to) zero and demand is not. This leads to the short term flexibility need, either transferring surplus energy from hours where it is generated to hours where it is needed or adjusting demand patterns to shift load peaks to periods in the day where generation is higher. In conclusion, the extent to which solar energy can be effectively integrated into the power system without substantial curtailment depends on the available short term flexibility. An example of this is shown in Figure 21. Flexibility absorbs solar energy during the day, and releases this energy during the night or less sunny hours.

FIGURE 21: EXAMPLE OF A SIMULATED DISPATCH OUTPUT FOR A SUMMER PERIOD IN BELGIUM BY 2050 (BAUX3 / ELEC), WITH A HIGH LEVEL OF FLEXIBILITY AND AN IOSN+ GRID CONFIGURATION



> **Kathrin Goldammer, Managing Director of Reiner-Lemoine-Institute**
>
> **The encouragement of end user flexibility is a very important point. One of the key questions is: How to make the end user part of the system, digital, and metered in a way that would help the system to make use of its flexibility? We need to talk about what kind of flexibility we would like to incentivize - and how - over the next few years.**

The increase in RES needs to be accompanied by an increase in flexibility means

On a European scale, the daily volatility of the RES mix leads to residual fluctuations over 600 GW (before activation of flexibility) in 2050 between day and night in summer. Even in winter, when solar infeed is structurally lower, days with an oversupply of solar energy during the day can occur. The daily spread can still reach up to 400 GW, which underlines the need for short term flexibility throughout the year. So in order to integrate large volumes of solar, a robust power system of the future requires an uptake of (digitalised) short term flexibility resources (e.g. EVs, HPs,...) in parallel with the expansion of solar.

Figure 22 shows the occurrence of days with oversupply and/or undersupply in Germany in 2050 for one particular climate year before dispatchable back-up capacities (see Section 3.2) are added to the system in order to avoid undersupply. This with the purpose of showing what high end-user flexibility and increased level of interconnection (grid) can do in terms of RES integration. In reality, with the dispatchable capacities defined in Section 3.2 in the system, the amount of undersupply would be much lower and respecting the thresholds in current policies.

All days are divided in 4 categories. The days are considered in the undersupply category if energy is not served at least during one hour of the day. They are considered in the oversupply category if RES energy is either converted using P2X or curtailed at least during one hour of the day. However, if both of these happen during the same day, that day will be categorised as being both in under- and in oversupply. Finally, the days shown on the origin of the chart have neither over- nor undersupply.

Four configurations have been studied, considering the variations of 2 dimensions: the level of flexibility (low vs high, as presented Section A.3 in the technical annex, to assess the impact of end-user flexibility) and the grid configuration considered (IoSN+ grid configuration vs. CopperPlate). For the considered grid variants, it is important to mention that the IoSN+ grid configuration can be considered as an 'under-dimensioned' grid for the 2050 timeframe. Hence, it will show more undersupply situations, as part of the available RES generation on European level will not be able to be transferred to Germany. The CopperPlate grid on the other hand represents an 'over-dimensioned' grid for 2050, resulting in lower undersupply situations.

With limited flexibility in the market simulations, 44% of the days show both oversupply and undersupply situations, In other words, during almost half of the days RES energy is curtailed or converted using P2X during one hour of the day, whilst in another hour of the day there was not sufficient RES energy to cover direct electricity demand. This means that intraday variations, mainly stemming from solar infeed, are not dealt with efficiently since 'oversupply' of RES is not sufficiently absorbed to be released at other moments.
Going from low flexibility to high flexibility levels reduces the number of days with both oversupply and undersupply almost to zero. Short term flexibility (like EVs, home batteries,...) absorbs the peaks of RES infeed, and releases the energy at other moments of the day when there is insufficient RES available. Although there are still days with either oversupply or undersupply, this result shows that the high flexibility scenario solves almost all intraday variations.

Going from an IoSN+ grid configuration to a CopperPlate configuration allows to deal with the remaining intraday variations. The main impact of the CopperPlate configuration is that the number of days without undersupply or oversupply strongly increases (from 24% to 55%), meaning that more energy can be shared between the days. The grid configuration has therefore an impact of both intraday and weekly variations and the required level of dispatchable capacities (see Section 3.2).

FIGURE 22: THE IMPACT OF DIFFERENT LEVELS OF END-USE FLEXIBILITY AND INTERCONNECTION ON THE OCCURRENCE OF OVERSUPPLY AND UNDERSUPPLY DURING A SINGLE DAY FOR GERMANY IN 2050 (BAUX3 / ELEC)

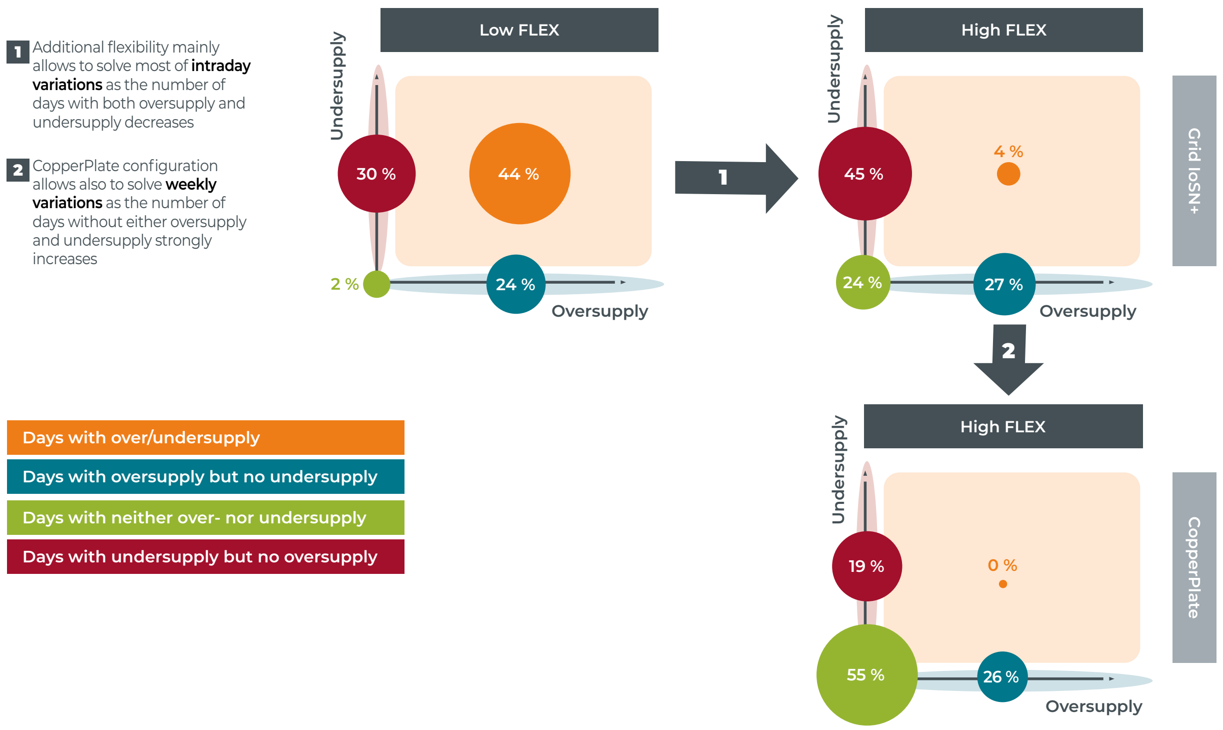
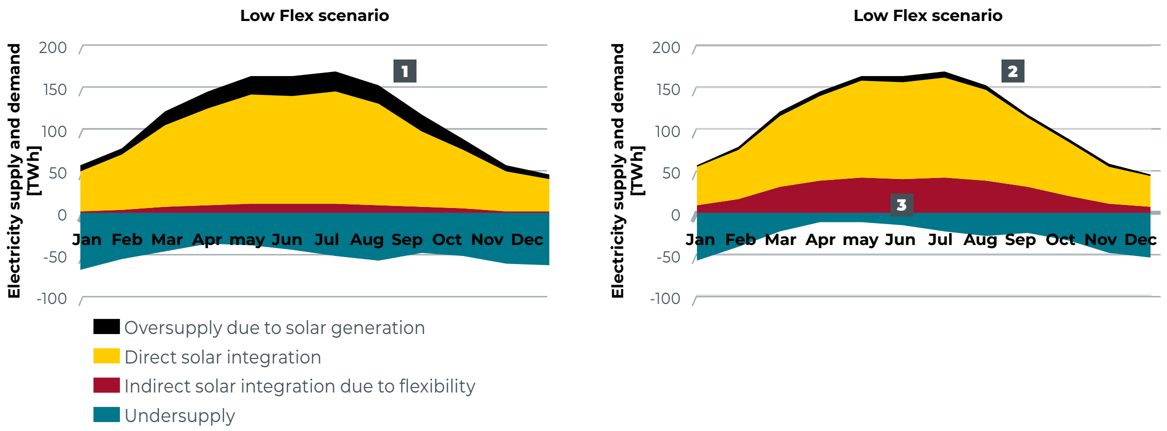


Figure 23 provides an in-depth analysis of the impact of flexibility on the integration of solar generation at European level in 2050. The total solar generation is shown on a monthly level for the ELEC pathway and the BAUx3 RES supply scenario (with the 'under-dimensioned' IoSN+ grid configuration). It is then split in three categories. The solar generation can be directly integrated (i.e. directly consumed), indirectly integrated (via demand-side shifting or storage) by the different flexibility means (via demand side shifting or storage) or not used in the electricity market, meaning that the solar generation is either converted into another energy vector or curtailed.

On the left side, with low flexibility, it can be seen that a large amount of solar generation is directly integrated (yellow part). The share of indirect integration (red part) by flexibility means is limited. The solar generation (black part) not used on the electricity market is significant but remains limited because it is assumed that the RES oversupply is split between the different technologies (a weighted average is performed between technologies to curtail or convert the excess of energy). Finally, it can be observed that the undersupply of RES is more or less constant throughout the year.

Going from low flexibility to High Flexibility significantly improves the different indicators. Solar generation is integrated more efficiently which implies a more limited amount of converted or curtailed energy and a significant decrease of RES undersupply during the summer and interseasonal periods. However, the impact of higher flexibility on undersupply is limited during winter due to lower solar generation and low assumed interconnection capacity in Europe for the selected scenario (i.e. IoSN+ grid configuration).

FIGURE 23: EFFECT OF SHORT TERM FLEXIBILITY ON THE INTEGRATION OF SOLAR POWER PER MONTH ON EUROPEAN LEVEL IN 2050 (BAUX3 / ELEC / IOSN+ GRID CONFIGURATION)



1 Significant share of solar generation not used on the electricity market (curtailed energy or conversion to X).

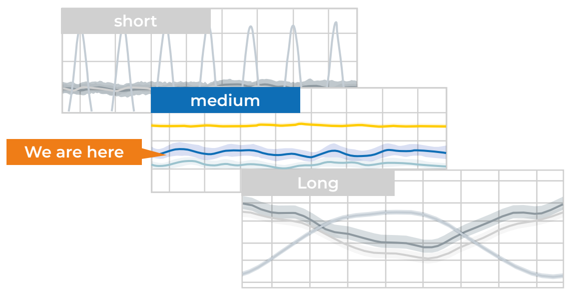
2 Solar generation is used more efficiently on the electricity market by adding additional flexibility to the system. The share of converted or curtailed energy is therefore limited.

3 Higher Flexibility leads to a more efficient utilization rate of solar energy enabling to decrease the amount of energy not served because of intraday variations during summer and interseason.

End users need to be empowered through digitalisation and regulation to supply flexibility

A cost-efficient RES integration will require the active participation of end users. Investments required to optimise EV charging and the operation of heat pumps or home batteries are limited. Given the right regulatory framework and appropriate digitalisation of appliances and processes, they can -without loss of comfort- significantly contribute to supplying the flexibility needed in a RES-based power system and even benefit from providing these services. In 2050, the flexibility provided by end users can balance up to 90% of intraday variations (see Figure 22). New electricity consumers such as electric vehicles and heat pumps do therefore not only offer an energy efficient way to decarbonize final energy demand (Section 1.1), but also valuable flexibility to the system that facilitates higher levels of RES integration. Further RES expansion should therefore go hand in hand with electrification of end-use.

Interconnection levels out weekly fluctuations in RES supply



Between the short term, being shaped by solar and demand day-night cycles, and long term volatility, being shaped by the seasonality of wind and solar power, there is the medium term. It stretches from 1 day up to a month and mainly relates to wind power, since the fluctuations of wind often happen on a weekly basis. This weekly volatility of wind stems from moving wind fronts over Europe. Daily fluctuations in wind infeed are less pronounced, compared to solar. In other words, if a week is windy, two subsequent days of that week are likely to be windy as well. Since these fluctuations are too long to be (fully) covered by short term flexibility of end users, additional means are required to reduce volatility on this time scale.

Interconnection across sea basins and countries levels out medium term volatility of wind infeed

As the distance between wind farms increases, so does the chance that there is electricity generation at either one of them. Figure 24 exemplifies this phenomenon for the case of Belgian offshore wind power. Taking the Belgian exclusive economic zone (EEZ) as index, it shows the correlation of weekly volatility across Europe in relation to the Belgian EEZ. In other words, it quantifies to what extent windy weeks in the southern North Sea occur simultaneously to windy weeks in other parts of the Sea or indeed other sea basins (and vice versa).

As can be seen, the correlation of the weekly component in the generation time series of offshore wind farms decreases with larger distance. Having access to the energy of remote parks can therefore significantly reduce additional flexibility needs for the medium term time scale. Especially increased interconnection across sea basins can leverage non-correlated wind conditions between Baltic Sea, North Sea, Mediterranean Sea and Atlantic Ocean respectively. Both onshore interconnection between market areas as well as direct and hybrid connection to offshore wind farms can unlock this geographical levelling. Hybrid interconnectors are offshore interconnectors between market areas that incorporate offshore wind farms along their trajectory.

While the map shows this effect for the Belgian EEZ only, the trend in far distant non-correlation of offshore wind is visible with a German index area as well. We witness a 40-50% reduction in weekly volatility when pooling European offshore wind as compared to the weekly volatility of the individual countries alone. This means that interconnection can significantly reduce the volume of medium term flexibility (e.g. dispatchable capacities) needed to cope with these fluctuations in RES infeed. It also shows a benefit for countries to connect to more remote offshore wind farms. For example, Figure 24 shows that there is a relatively low correlation between Belgian offshore wind and Danish wind, which is relevant for the ongoing discussions on a potential Belgian – Danish hybrid interconnector.

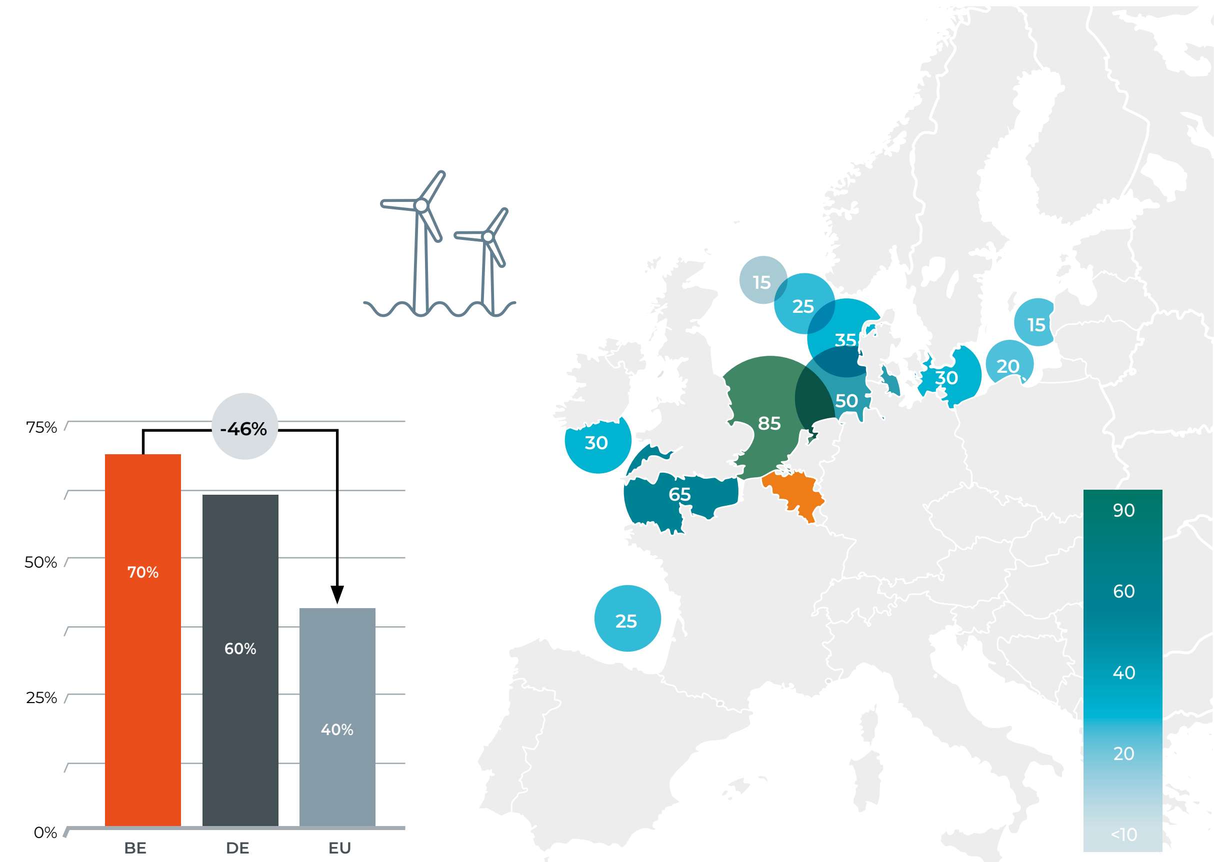
FIGURE 24: WEEKLY VOLATILITY OF OFFSHORE WIND AND CORRELATION OF OFFSHORE WIND ACROSS EUROPE

Weekly volatility of offshore wind in % of installed capacity

Covering p99.97

Correlation of Belgian offshore wind infeed with Europe in %

Statistics on fluctuations that occur simultaneously from one day up to a month



Similar to the lower correlation of distant offshore wind sites, the onshore wind generation can be smoothened with increased interconnection across Europe as well. Figure 25 illustrates this with the example of Belgium as the index country. The map shows the correlation of onshore wind for selected regions across Europe and reveals the same pattern as the offshore analysis. Pooling all European onshore wind can help reducing weekly volatility by 45-60% for Belgium and Germany respectively, again reducing significantly the need for medium term flexibility solutions.

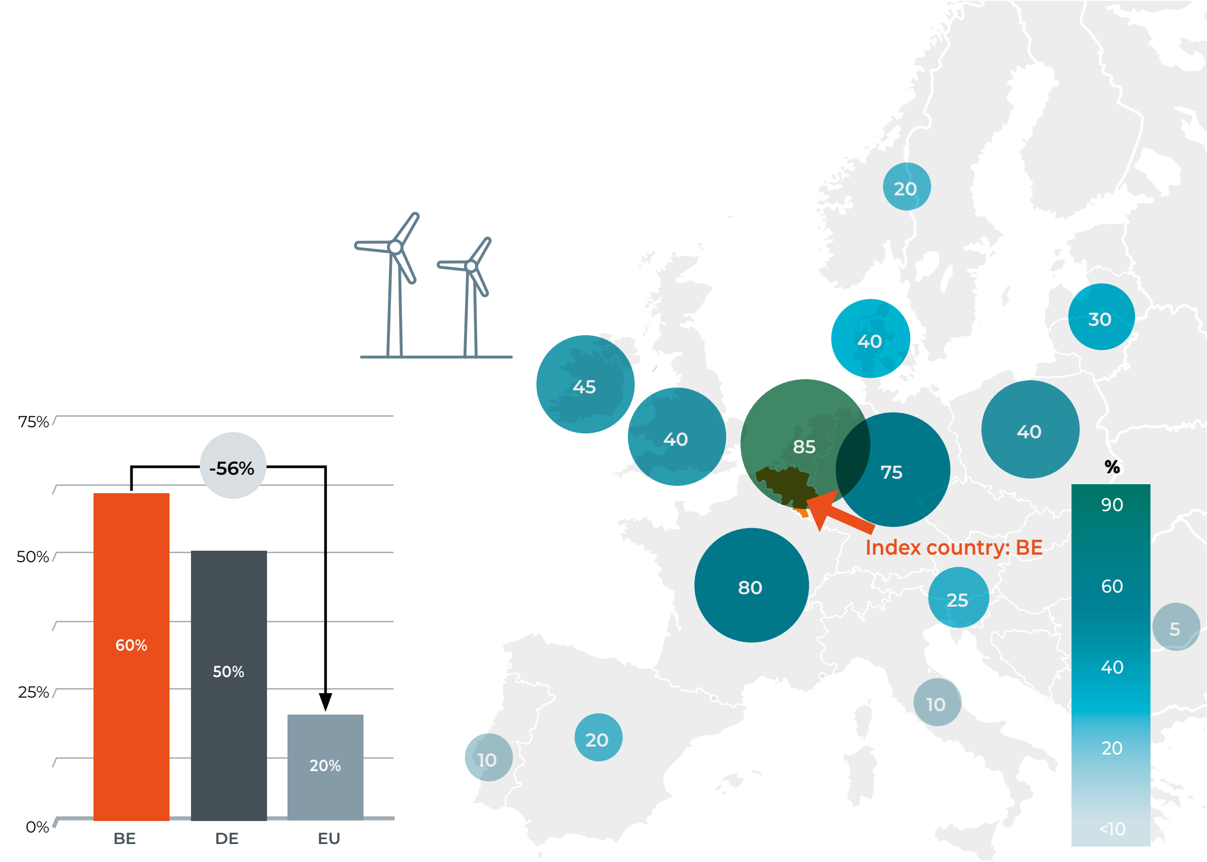
FIGURE 25: WEEKLY VOLATILITY OF ONSHORE WIND AND CORRELATION OF ONSHORE WIND ACROSS EUROPE

Weekly volatility of onshore wind in % of installed capacity

Covering p99.97

Correlation of Belgian onshore wind infeed with Europe in %

Statistics on fluctuations that occur simultaneously from one day up to a month



RES ARE INHERENTLY INTERMITTENT, CAUSING DAILY, WEEKLY AND SEASONAL FLUCTUATIONS IN ENERGY SUPPLY. A WELL-DESIGNED RES SYSTEM WILL BE ABLE TO MANAGE THESE FLUCTUATIONS IN AN EFFICIENT WAY.

1. Achieving the right balance between wind and solar generation in the energy mix avoids a structural seasonal mismatch between supply and demand in summer (e.g. oversupply of solar energy) and winter (e.g. undersupply because low solar infeed).
2. If short term storage (electrical vehicles) and demand-shifting solutions (heat pumps) are quickly rolled out and this is accompanied by widespread digitalisation, the system will have enough flexibility to compensate the daily fluctuations in solar infeed (and to a lesser extent weekly fluctuations caused by wind infeed).
3. Interconnectors level out a large share of weekly fluctuations coming mainly from wind production.

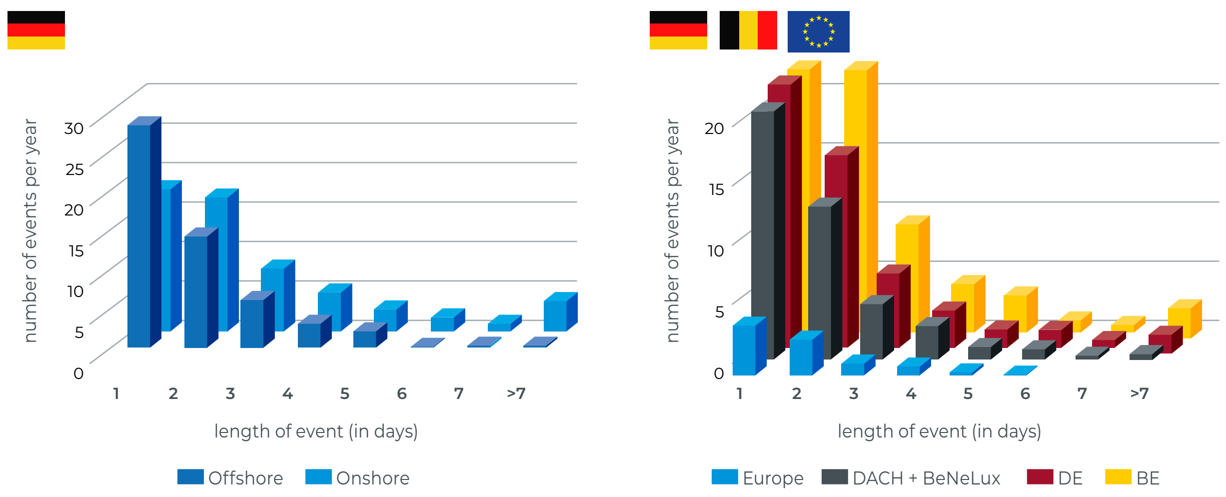
3.2 Coping with periods with low RES infeed

The previous section provided insights on how to handle the fluctuations of RES. Next to the repeating fluctuations, more extreme, rare events with low RES infeed also occur. The previously presented flexibility means are not able to fully bridge such events. This section determines the resulting need for additional dispatchable capacities to cover those.

Prolonged situations of low RES generation are characterised by local wind fluctuations during winter

First, situations with a prolonged shortage of RES infeed are analysed in more depth. Such periods span over several days and, for the purpose of this exercise, are (arbitrarily) defined by a level of electricity generation from wind and solar power that falls below 20% of their installed capacity on a 24 hourly average. These periods occur mostly in winter when solar generation is typically low and are characterised by low (mainly onshore) wind infeed.

FIGURE 26: OCCURRENCE OF LOW RES INFEED EVENTS PER YEAR AND LENGTH FOR GERMANY IN 2050 (MEAN OVER SEVERAL CLIMATE YEARS)



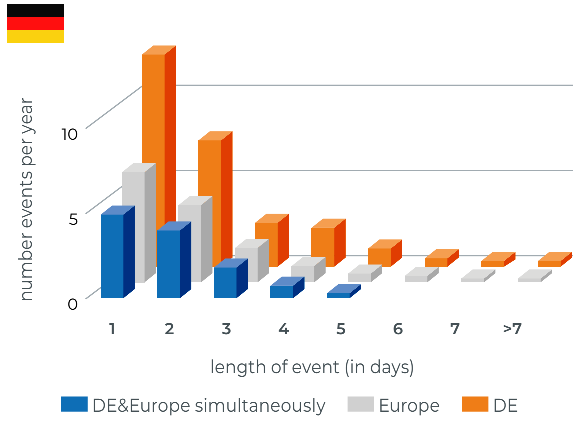
The left part of Figure 26 shows how often a low wind generation event occurs on average per year over a set of various climate years in Germany. The plot reveals that low generation events (in line with criteria defined before) of more than 5 days hardly ever occur for offshore wind, but up to 4 times per year for onshore wind. Hence, onshore wind generation is more prone to longer periods of low infeed compared to offshore wind. Having a larger share of offshore wind in the mix will therefore reduce the occurrence and length of low RES events in the German power system.

Sustained periods of low RES infeed rarely occur simultaneously across entire Europe.

The second part of the figure aggregates the occurrence of low RES events for Belgium and Germany. This occurrence is compared to a pooled system of the DACH region (DE, AT and CH) with BeNeLux and then again to a pool of all European countries. The figure shows that the number of situations of low RES infeed in a pool of countries is reduced significantly. In fact, on European level there are hardly any low RES events longer than 4 days.

A similar observation on the effect of pooled countries can be made for high residual demand events. In the scope of this study they are defined as periods with a residual demand that is at least 20% above its long time mean on a 24-hourly average. Although this 20% threshold is arbitrary, it allows for valuable insights. Given the averaging over 24 hours, no activation of short term flexibility is considered. Figure 27 shows at the example of Germany how often sustained periods of high residual demand occur per year on average over several climate years. It demonstrates that short periods (1-2 days) of high residual demand occur between 8 and 12 times per year, whereas long periods of longer than a week occur only every 2-3 years. When screening for simultaneous high residual demand events of Germany with the European mix, both occurrence and lengths are reduced drastically. With strong interconnection across the continent, extreme events of exceptionally high residual load can be balanced out in the pool. Doing so, high residual load periods of 5 days occur only once every other year.

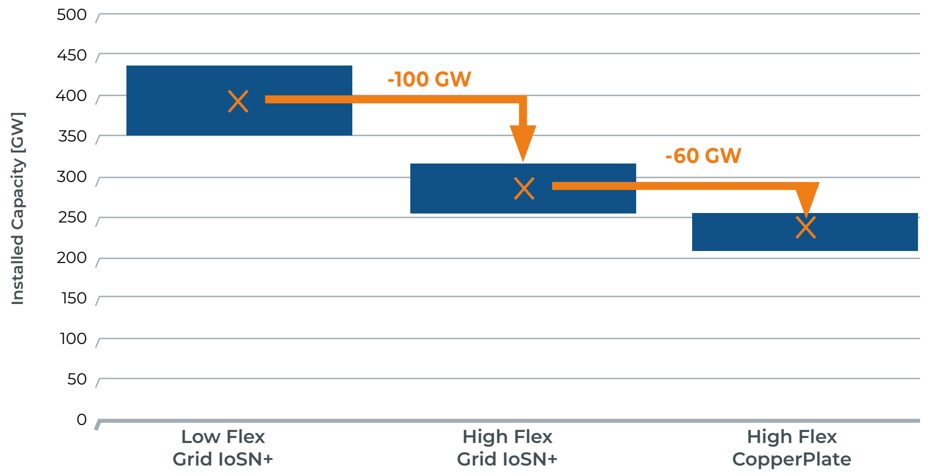
FIGURE 27: OCCURRENCE OF EXCEPTIONAL HIGH RESIDUAL LOAD PER YEAR AND LENGTH FOR GERMANY IN 2050 (MEAN OVER SEVERAL CLIMATE YEARS). SCENARIO: ELEC PATHWAY / BAUX3 RES SUPPLY



Dispatchable capacities are needed to cover sustained periods of low RES infeed.

In order to assess the need for additional dispatchable back-up capacities, a detailed adequacy analysis considering several climate years is performed within the market simulations (ELEC / BAUx3). The need for dispatchable capacities is driven both by developments on the demand side and on the supply side. On the supply side (as discussed above), the weather dependency of wind and solar power results in periods of sustained RES shortage that may last for several days up to several weeks. On the demand side, a strong increase of the annual electricity demand leads to higher peak electricity demand. Situations of low RES generation and high direct electricity demand define the need for additional back-up capacity.
The market simulations show that significant amounts of such dispatchable back-up capacity will be needed to ensure sufficient electricity supply at all times. Figure 28 depicts the dispatchable back-up capacity need on European level for ELEC/BAUx3. The stated ranges are related to the amount of available short-term flexibility and the level of European interconnection (see Annex A.3 for more information). The need is especially high in countries, such as Belgium and Germany that are short on large-scale hydro storage or other climate-neutral dispatchable generation technologies. As a result, the required back-up capacity for Belgium and Germany amounts to about 7.5 -15 GW and 40-70 GW respectively, depending on the level of flexibility and grid interconnection in the system. It is important to stress the level of uncertainty in these simulations. Hence, close monitoring of the need for dispatchable capacities on the road to net zero is required.

FIGURE 28: REQUIRED BACK-UP CAPACITY ON EUROPEAN LEVEL IN 2050. SCENARIO: ELEC PATHWAY / BAUx3 RES SUPPLY



The need for operating dispatchable back-up capacities can be strongly reduced by a balanced RES mix, sufficient interconnection and the availability of short term flexibility.

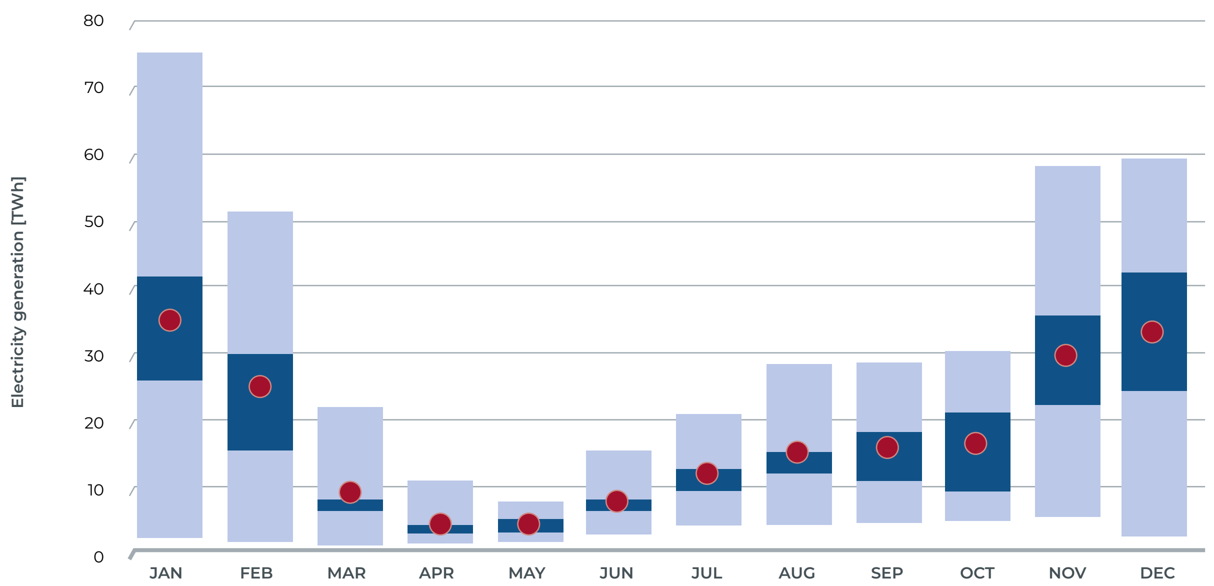
End user flexibility, batteries, a balanced RES mix and interconnection are essential for levelling out fluctuations in supply and demand. When used to their full potential, both short term (day and night) and long term (seasonal) mismatches between supply and demand can be reduced to a minimum – and thus also the need for operating dispatchable back-up capacities. Hence, they have a large effect on the required energy [TWh] delivered by dispatchable capacities. Their effect on the required dispatchable capacity [GW] is less strong.

Situations of RES shortage occur less often (effect on TWh), but when they occur they require a significant amount of dispatchable capacities (effect on GW). Nevertheless, as Figure 28 shows, the capacity need can be reduced by about 40% in case of strong European interconnection and high end-user flexibility.

Dispatchable back-up capacities have low running hours

Periods of low RES supply mainly occur in winter. Therefore, dispatchable back-up capacities are also mostly needed at this time. As Figure 29 shows, electricity generation of dispatchable capacities during spring and summer is significantly less than during winter. Given sufficient flexibility and interconnection, dispatchable back-up capacities cover about 6% of all electricity supply on European level during the winter months. The exact share varies significantly across climate years (in some years reaching as much as 15%), but overall, it is not required that these capacities run (or are activated) continuously throughout winter.

FIGURE 29: ELECTRICITY GENERATION OF DISPATCHABLE CAPACITIES BY MONTH ON EUROPEAN LEVEL IN 2050. THE RED DOTS SHOW THE AVERAGE OVER SEVERAL CLIMATE YEARS, THE BLUE BARS GIVE THE RANGE ACROSS CLIMATE YEARS (DARK BLUE COVERING 40TH TO 60TH PERCENTILE, LIGHT BLUE COVERING 10TH TO 90TH PERCENTILE). SCENARIO: ELEC PATHWAY / BAUx3 RES SUPPLY, HIGH FLEXIBILITY AND COPPERPLATE



SIGNIFICANT CAPACITY, LIMITED RUNNING HOURS

Our simulations show that, depending on the level of interconnection across Europe and the amount of flexibility in the system, Europe will need between 240 and 400 GW of dispatchable capacities by 2050 (BAUx3, ELEC-pathway). It is therefore important to closely monitor security of supply on the way to net zero and make sure that a sufficient level of dispatchable (backup) capacities is available at all times to guarantee security of supply.

These dispatchable capacities will only be activated for a limited amount of running hours in 2050, since the duration and occurrence of periods with sustained low RES infeed will be both short (they will typically last less than a week) and rare. These periods will often be characterised by sustained low (mainly onshore) wind production.

THE CHOICE OF TECHNOLOGY DOES NOT NEED TO OCCUR TODAY

Over the next decade, existing and new thermal plants will have to take up the role of dispatchable capacities in the system. Over time, the rapid expansion of RES will reduce their running hours and hence, in the case of fossil fuel plants, their GHG emissions. This highlights the importance of rapid RES expansion as a first priority.

It's only in a next step, when the dispatchable capacities themselves have to be fully decarbonised that a choice about their future technology will need to be made. Different climate-neutral technologies are on the table today to take up this role, such as hydrogen fired gas turbines, fuel cells, biomass and (pumped) hydro power, thermal storage plants, etc. Some of these technologies are already mature, whilst others are still under development, with their cost efficiency yet to be demonstrated. New technologies can appear as a result of technological breakthroughs on the way to 2050. In any case, given the limited projected running hours, technologies with low investment costs will be best suited to addressing adequacy in Europe's future energy system.

Glossary

Direct electricity	Electricity that is directly consumed as electrical power by the demand side. This includes for instance electrical furnaces, vehicles, heat pumps and others.
End-user flexibility	Flexibility to shift demand over time from appliances and industry. They include electric vehicles, air conditioning, heat pumps, district heating, domestic batteries and DSM from industry.
EV	Electric vehicles. We assume both, V1G vehicles that can charge flexible but not return electricity into the grid and V2G vehicles which can charge flexible and feed-in electricity back into the grid like a battery.
EEZ	Exclusive Economic Zone, denoting the offshore area of a given country, where offshore wind farms are typically placed.
Fourier Analysis	Mathematical method to analyse time series data for reoccurring patterns of volatility.
HP	Heat pumps.
Hybrid interconnection	Offshore transmission system for electricity (submarine cable) that, while connecting two countries with each other as an interconnector, also links at least one wind farm along the way with the system. Hybrid interconnection serves a dual purpose of integrating offshore wind into the grid and linking several market areas at once.
Indirect electricity	Equal amount of electricity that would be needed to produce green molecules given efficiency losses during the process.
RES	Renewable energy sources. In this report, the term is mainly used for solar power, offshore wind and onshore wind.
Residual load	Electrical load that remains, when RES generation is deducted from demand. Positive residual load can be covered by imports via interconnectors, feed-in from batteries, or dispatchable back-up capacities. It can also be reduced by flexible demand reduction.
Short term/Long term Flexibility	In the context of our flexibility analysis with Fourier, short term flexibility denotes means that address volatility of residual load from one hour to 24 hours. Long term addresses everything from one month up to up to a year. In between is medium term that covers the rest.

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III Technical Annex

This technical annex provides further details about the assumptions and tools used in this study. Annex A.1 starts with a description of the demand pathways and supply scenarios. As already mentioned, these pathways are non-exhaustive and do not necessarily represent the future (which is uncertain), but are valuable as they reveal the possible impacts of following distinct pathways. The annex continues with a description of the market modelling (see Annex A.2) and the analyses that were performed regarding flexibility and interconnection sensitivities (see Annex A.3). Finally, Annex A.4 explains the Fourier analysis in more detail and also covers the methodological approach used for the statistical analysis of low RES generation events.

A.1 Scenario development

This section provides additional information about the scenario development regarding future energy demand and supply. It complements (and should be read in conjunction with) Chapter 1 of the main text. The scenarios were developed taking into account the EU27 Member States plus Switzerland, the United Kingdom and Norway. The chosen perimeter allowed us to adequately assess the interdependence of the interconnected European energy system. In the following, the expression "European level" always refers to this set of countries.

A.1.1 Future energy demand

Two demand pathways are considered in this study, each of which is associated with a specific share of electricity in the total energy consumption. Both scenarios share the same global assumptions (such as energy efficiency, demographics, ...) and are calibrated on the **1.5 TECH** scenario from the European Commission [SCE-1], assuming carbon neutrality is reached in 2050. The two variations were performed in order to evaluate a system with a higher (**ELEC** pathway) and lower (**MOL** pathway) electrification rate.

The 1.5 TECH scenario presents a transformation pathway for EU28 (including UK) on aggregate, with no publicly available data at country level (it does not include Norway or Switzerland). Therefore, a bottom-up model was developed to quantify the multi-energy demand for the different sectors per country (including the residential, tertiary, transport and industrial sectors). Country-specific starting points and assumptions were incorporated for defining their individual pathway towards 2050. Additional sources such as national public studies were used to benchmark the values obtained per country to ensure that the results were representative of the EU as a whole and of individual countries.

The final annual demand per country, sector and energy vector was defined in two stages. First, the demand intensity was modelled per sector based on assumptions regarding demographics, economic activity, behavioural levers, urbanisation, energy efficiency and circularity. Secondly, given the intensity of demand, a range of energy carriers was considered to satisfy the quantified need. The 1.5 TECH scenario was used as a basis to calibrate these parameters related to final energy demand per sector and per energy vector. In the following sections, the developments in the different sectors under the ELEC and MOL pathways are described in more detail. Afterwards, results are shown for Europe as a whole as well as for Belgium and Germany separately.

Sector-specific transformation pathways towards 2050

Residential and tertiary sectors

In the residential and tertiary sectors, a huge wave of renovations is assumed to take place all across Europe. On average, demand for space heating is assumed to be reduced by 60% for a residential dwelling, and by 45% for a tertiary building in comparison with 2018. These savings stem from improved insulation in the building shell. Electrical appliances (e.g. lighting, personal computers, kitchen appliances, washing machines,...) also have assumed efficiency gains, but their increased usage offsets the efficiency savings, leading to an assumed overall growth in energy demand for appliances per building by 25%. Furthermore, the final energy demand for space cooling is also expected to increase in the run-up to 2050, which is mainly caused by a large increase in the number of cooling systems. However, an increase in the overall efficiency of these units slightly compensates for this.

Under the **MOL pathway**, molecule-based heating technologies are assumed to play a more important role. Gas condensation boilers, gas heat pumps and hydrogen fuel cells deliver up to 40% of heating requirements. Direct electrification is limited; (hybrid) heat pumps reach a share of around 30% for residential units and 45% for tertiary units. District heating is assumed to reach a share of 10%-15%. The remaining amount of heat is supplied by biomass (which decreases in importance when compared with today) and solar thermal.

Under the **ELEC pathway**, the electrification of heating is assumed to be maximised by the mass deployment of all-electric heat pumps. In this way, the share of heat pumps reaches 75% for residential dwellings and 80% for tertiary units. Under this scenario, gas-based types of heating are assumed to be phased out. District heating and biomass supply the remaining share of heating with the same relative importance as under the MOL scenario.

Transport sector

In 2018, 93% of the final annual consumption in the European transport sector was based on liquid fossil fuels such as gasoline, diesel, kerosene and heavy oils. The 2050 scenarios in this study assume a continuous growth in the distance covered by passenger-related transport (up by 35% when compared with 2015 levels). Freight transport (in terms of ton per kilometre) increases by around 50% compared to today and is mainly driven by economic growth and the projected growth in e-commerce. Although transport needs are assumed to increase by 2050, a reduction in final energy demand for transport is expected under both pathways. Apart from a modal shift towards more rail and public transport, the main driver for this is the replacement of internal combustion engines by battery-electric engines with a much higher overall efficiency. Note that the final energy demand from international aviation and maritime shipping was left out of the analysis, following the methodology from EUROSTAT. They nevertheless remain an important part of the consumption of biofuels or e-fuels. Further investigation is needed into how these sectors will evolve in the future.

Under the **MOL pathway**, the push towards direct electrification is less outspoken and more molecule-based types of transport such as hydrogen fuel cells and e-fuels are considered in a wider segment of transportation modes. Battery-electric passenger cars and lightweight commercial vehicles reach a market share of 70% with the remainder being hydrogen fuel cells (20%) and a mixture of e-fuels and biofuels. Hydrogen fuel cells and e-fuels are assumed to play a major role for heavyweight vehicles, where the share of battery-electric vehicles in this scenario only reaches 35% for coaches and buses and 5% for trucks. Today, both inland navigation and domestic aviation are almost fully powered by oil derivatives. In this segment, biofuels and e-fuels are assumed to be the main decarbonisation options under this pathway, since the electrification potential based on today's known and upcoming technologies is limited and mostly applies to the more lightweight applications within this segment. Finally, the rail segment reaches an electrification rate of about 95%; only a small share of less frequented routes are assumed to make use of e-fuels.

Under the **ELEC pathway**, the direct electrification of transport is maximised. In line with the current market development, passenger cars and other lightweight vehicles are assumed to be 100% battery-electric by 2050. Breakthrough innovations in battery technology would also allow powering more heavyweight segments of transport. In this way, trucks, coaches and buses reach a market share of more than 90% battery-electric, the remainder being split between hydrogen fuel cells and e-fuels. For domestic aviation and inland navigation, the potential remains limited (based on today's known evolution) with an assumed market share of 10% for electric drivetrains. E-fuels and biofuels are still supposed to play an important role in this sector, as is the case under the MOL pathway.

Industry

The projections for energy demand in the different industrial sub-sectors diverge considerably. Three key developments drive the final energy demand for each industrial sub-sector: the production output; overall energy efficiency gains; and the substitution of energy vectors. The industrial *production output* is in large part determined by the expected increase in added value towards 2050. Publications by the European Commission state such growth rates per Member State and per sub-sector. However, the relationship between economic activity and production output is not linear, as a lot of EU countries have seen a decoupling between the two metrics over the last decades. *Energy efficiency* for the industrial sector is defined by the final energy need for a certain production output. In reality, it is driven by three elements: process optimisation (for example integrated control and energy management systems or combustion optimisation), circularity (e.g. the re-use of certain outputs as an input for a new process or the recuperation of heat) and the use of more efficient technologies (e.g. heat pumps for low temperature heating or high efficiency burners). When it comes to the *substitution of energy vectors*, most sectors will undergo a shift away from solid and liquid fossil fuels towards methane and finally (or directly) towards sustainable energy drivers such as electricity, green molecules (hydrogen, e-fuels,...), biogas, biofuels, biomass and derived heat. The pathways in this study limit the use of carbon capture and storage (CCS) or usage (CCU) in industry to non-abatable process emissions. Today, there is a high level of uncertainty on how industry will look like in 2050 and how it will decarbonise. Therefore, assumptions on this sector need to be further investigated, and regularly updated, in close cooperation with industry.

Under the **MOL pathway**, the shift from fossil fuels is assumed to be mainly towards green molecules (synthetic fuels, such as hydrogen, e-gas and liquid e-fuels). Low temperature heat is expected to be largely electrified using mature technologies such as industrial heat pumps. Moreover, derived heat recovered from other industrial processes is also used to satisfy part of this heating demand. Most processes involving medium-to-high temperature heat will be powered by green molecules, as well as biomass in the sectors where this is readily available (such as the paper, wood and food & beverage industries). Furthermore, green hydrogen will also have a role to play in specific processes such as the gas-based direct reduction of iron (DRI) route for producing primary steel which is considered fully deployed in the iron & steel industry.

Under the **ELEC pathway**, most of the low temperature heat is assumed to be electrified using already existing technologies. This includes industrial heat pumps together with the recovery of derived heat from other industrial processes. Apart from low temperature heat, direct electrification is also assumed to play an important role for medium and high temperature heat supply. Industrial heat pumps, microwaves, infrared heaters, induction and resistance heaters in the metal sector, electric boilers and crackers in the chemical sector, electric arc furnaces in the steel industry and electric kilns in the cement industry are all considered commercially available and implemented at scale by 2050. They allow a shift away from liquid fossil fuels and methane. For the most hard to electrify processes, such as high temperature heat, green molecules have a role to play as well as biomass in the sectors where this is readily available (such as the paper, wood and food & beverage industries).

Finally, non-energetic feedstock constitutes a very important share of the final industrial demand, which is mainly delivered to the chemical sector. In 2018, the feedstock mainly consisted of oil products and is used to produce ammonia, ethylene and methanol, which in turn are basic elements for manufacturing fertilizers, polymers & other chemicals. A slight increase in demand for non-energetic feedstock is assumed towards 2050 to 1,300 TWh (versus 1,200 TWh in 2018), mostly due to an increase in the expected demand for final products. Hydrogen already plays a key role in feedstock today, although almost all of it is currently being produced from liquid fossil fuels and methane. By 2050, green hydrogen and its derivatives are expected to play a key role in decarbonising this segment and can deliver more than 50% of feedstock demand. Other energy vectors such as biofuels (like bio-ethanol), and biogas will also be important. Finally, there is a great potential for biomass and, more importantly, waste such as recycled plastics to decarbonise non-energetic feedstocks.

Energy demand per region for 2050

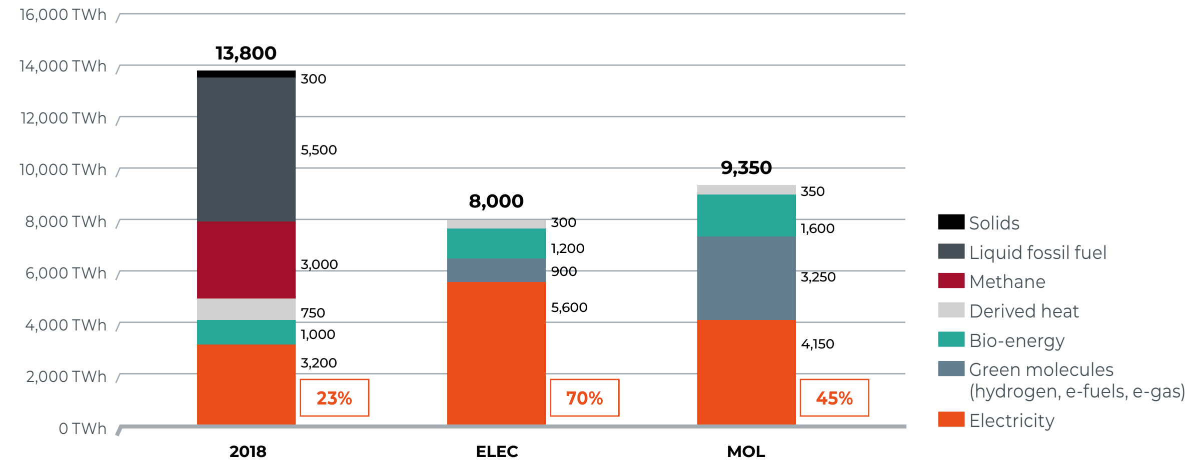
Adding all the different sectors together provides an overview of the final annual energy demand. The values for Europe, Belgium and Germany are presented below:

Europe

Figure 30 shows the resulting final annual energy demand for both investigated pathways on European level in 2050. As a short recap:

- In terms of ***energy efficiency,*** there is a reduction in the final annual energy demand by 33% under the MOL and 42% under the ELEC pathway compared with 2018.
- Under the 2050 pathways, direct ***electrification*** plays a vital role in decarbonising demand. Both pathways show an increase in electrification rate compared to 2018. The MOL and ELEC pathway have an electrification rate of 45% and 70% respectively, compared to 23% in 2018.
- ***The higher the electrification, the lower the total final annual demand*** in general. This is explained by the fact that electrification in buildings and transport mainly incorporates higher efficiencies, for example due to heat pumps and battery-electric vehicles. In industry, energy savings can also be made due to electrification, however, at high temperatures this additional efficiency is less outspoken. In addition, the ELEC pathway has lower conversion losses for production of green molecules.

FIGURE 30: FINAL ANNUAL ENERGY DEMAND IN TWh, INCLUDING FEEDSTOCK AND GRID LOSSES AND EXCLUDING INTERNATIONAL SHIPPING AND AVIATION - EUROPE IN 2050



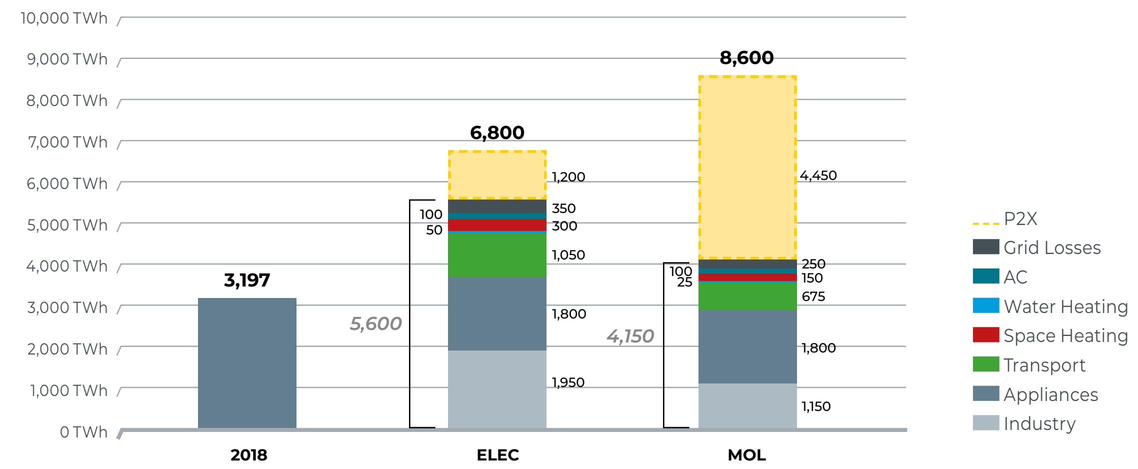
When looking at total (primary) electricity demand, a split can be made into direct electrification and indirect electrification, the latter representing the electricity demand for the production of green molecules (Figure 31). The figures include grid losses, but exclude energy needs for international shipping and aviation.

The major share of **direct electricity demand** comes from industry and appliances. Transport also becomes an important source of electricity demand by 2050. Note that annual electricity demand for space heating is relatively limited, even though heat pumps reach a medium to high share under the pathways. This is due to high energy savings by insulation and inherent efficiency gains by the heat pumps themselves.

The **indirect electricity** demand represents the electricity needed to produce the green molecules. The difference in indirect electricity demand between both pathways is even more pronounced than the difference in green molecule demand. The reason for this is the efficiency losses associated with the production of green hydrogen and its derivatives (e-gases and liquid e-fuels) from electricity. The efficiencies vary between 60% and 80%, depending on the synthetic fuel to be produced. Hydrogen can be produced with an efficiency of 80% via electrolysis, e-gas and liquid e-fuels are associated with lower efficiencies. As green molecules can also be produced outside of Europe and then be transported to the demand location, this indirect electricity demand is not necessarily located in Europe.

Although direct electricity demand is highest under the ELEC pathway, the total electricity demand (including the indirect electricity demand to produce green molecules) is much higher under the MOL pathway (assuming all hydrogen, liquid e-fuels and e-gas are produced by electrolysis). On the other hand, the green molecule demand could also be imported and does not necessarily need to be produced domestically.

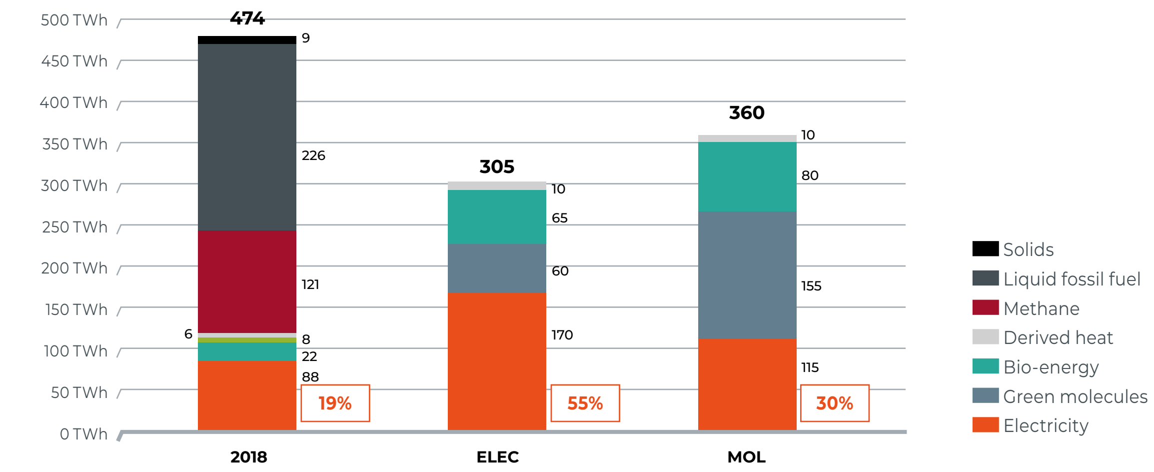
FIGURE 31: TOTAL 2050 ANNUAL ELECTRICITY DEMAND OF EUROPE IN TWh. P2X DENOTES THE INDIRECT ELECTRICITY DEMAND NEEDED FOR THE PRODUCTION OF GREEN MOLECULES



Belgium

In 2018, fossil fuels in Belgium amounted to almost 75% of the final energy demand, whereas electricity only accounted for 19%, which is below the EU average of 23%. Looking towards the 2050 scenarios, the final annual energy demand is reduced between 25% under the MOL and 35% under the ELEC pathway, when compared with 2018. All fossil fuels were assumed to be excluded from the mix and mainly shifted towards electricity and green molecules depending on the scenario. In general, Belgium reaches a slightly lower electrification rate than the EU average, which is mainly explained by the high importance of harder to electrify industrial sectors such as chemistry, iron and steel. Additionally, non-energy feedstock for the chemical sector has a relatively high importance in Belgium. The values shown here do not include energy for international shipping and aviation. For Belgium, this sector represented 21% of the final energy demand in 2018. Further investigation is needed with regard to how this will evolve in future.

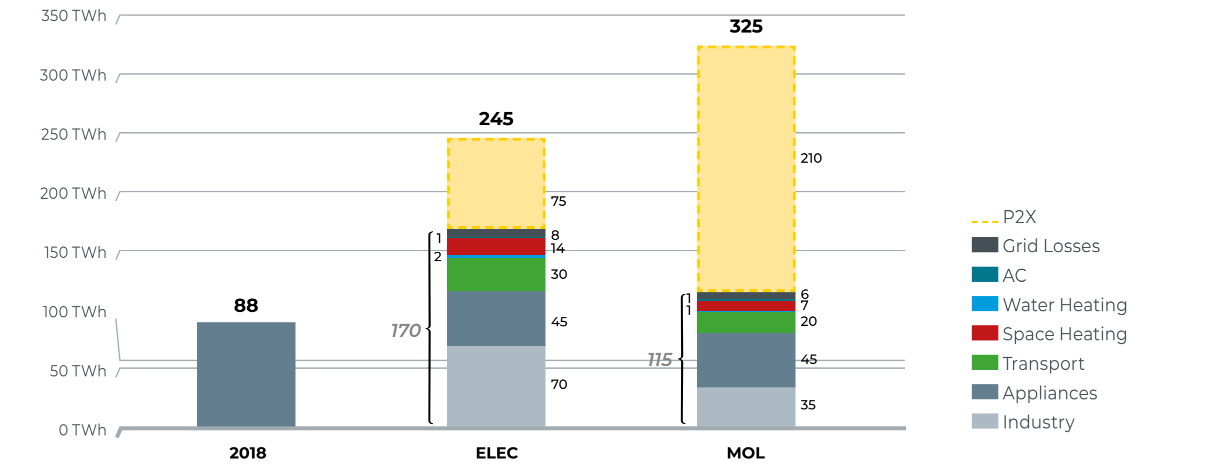
FIGURE 32: FINAL ANNUAL ENERGY DEMAND IN TWh, INCLUDING FEEDSTOCK AND GRID LOSSES AND EXCLUDING INTERNATIONAL SHIPPING AND AVIATION - BELGIUM IN 2050



Compared to 2018, the scenarios show a strongly increased direct electricity demand ranging from 115 TWh (MOL) to 170 TWh (ELEC). As for the European level, it is mainly industry and appliances which will consume the main share of electricity.

Taking into account the electricity demand for the production of green molecules results in a total electricity demand that is increased by almost a factor 3 under the ELEC pathway and by almost a factor 4 under the MOL pathway, compared to 2018. Note that in the case of Belgium, the country will be mainly dependent on imports of green molecules in which case the indirect electricity demand will not add to domestic electricity needs.

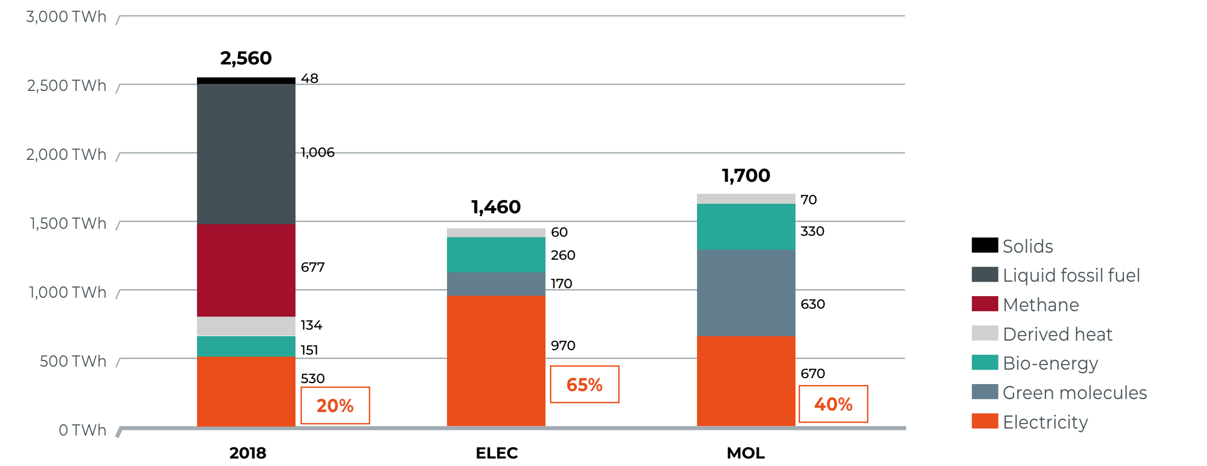
FIGURE 33: TOTAL 2050 ANNUAL ELECTRICITY DEMAND OF BELGIUM IN TWh. P2X DENOTES THE INDIRECT ELECTRICITY DEMAND NEEDED FOR THE PRODUCTION OF GREEN MOLECULES



Germany

In 2018, Germany had a 67% dependency on fossil fuels, which is around the EU average (64%). Germany reaches a higher electrification rate than Belgium under the 2050 scenarios. The final annual energy demand is reduced between 33% under the MOL pathway and 42% under the ELEC pathway.

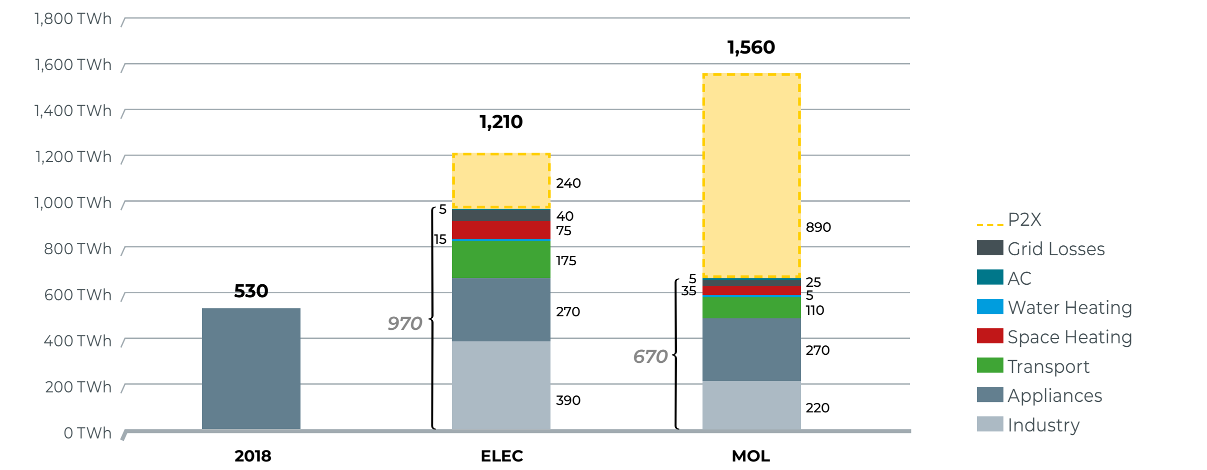
FIGURE 34: FINAL ANNUAL ENERGY DEMAND IN TWh, INCLUDING FEEDSTOCK AND GRID LOSSES AND EXCLUDING INTERNATIONAL SHIPPING AND AVIATION - GERMANY IN 2050



Compared to 2018, the pathways show a relative increase in direct electricity demand ranging from 26% (670 TWh) under the MOL scenario to 82% (970 TWh) under the ELEC scenario. As for the European level, it is mainly industry and appliances which will consume the main share of electricity. Translating the demand for green molecules into an equivalent amount of electricity would add an additional 240 TWh (ELEC) and 890 TWh (MOL) to the total electricity demand.

If Germany would produce all of its green hydrogen and e-fuel demand domestically, this would strongly increase electricity demand, especially under the MOL scenario where the indirect electricity demand would be higher than the direct electricity demand (see Figure 35). As shown in Section 2.2, Germany will need to rely on imports of green molecules.

FIGURE 35: TOTAL ANNUAL ELECTRICITY DEMAND OF GERMANY IN TWh. P2X DENOTES THE INDIRECT ELECTRICITY DEMAND NEEDED FOR THE PRODUCTION OF GREEN MOLECULES



A.1.2 Future energy supply

The three supply scenarios outlined in this study are designed to evaluate different levels of future wind and solar power expansion in Europe. The scenarios reflect an acceleration of the business as usual rate (BAU, where the annual average expansion rate matches annual rate over the last five years at a European level) by a factor of 1.5, a factor of 3 and a factor of 4. These scenarios do not represent the technical potential in Europe, but take practical limitations and associated challenges into account. A description of the scenario building regarding wind and solar power capacities is already given in the main text (Section 1.2). In addition, Table 1 provides an overview of the capacities for these technologies. Before evaluating the total electricity generation potential at a European level and for Belgium and Germany, this section gives more information about the supply sources that are considered next to wind and solar power.

TABLE 1: INSTALLED CAPACITY IN 2050 PER TECHNOLOGY AT A EUROPEAN LEVEL (AND FOR EU27 IN BRACKETS) IN GW

Total installed capacity in GW (of which in EU27)	BAUx1.5	BAUx3	BAUx4
Solar	690 (660)	1,200 (1,080)	1,700 (1,560)
Onshore Wind	390 (350)	580 (530)	870 (800)
Offshore Wind	210 (150)	410 (300)	610 (450)

Other supply sources

Next to wind and solar power, additional climate-neutral electricity generation technologies were taken into account. These include nuclear, hydro power, biomass and other RES. While the generation capacity of wind and solar power varies between the scenarios, the capacity of these other supply sources was assumed to be constant across all three scenarios. Moreover, additional dispatchable backup capacities were added to the model in order to ensure adequacy, allowing all countries to comply with their assumed reliability standards.

Hydro power

Hydro power includes **run-of-river** plants which are non-dispatchable and whose power depends only on hydrological inflows, **storage plants** which possess a reservoir to defer the use of water and **open- or closed-loop pumped-storage plants (PSP)** that have pumps to store electricity. Regarding hydro, the data sources and modelling were based on the latest available European model performed at ENTSO-E level. Hydro capacities were fixed to the value defined for 2030 time horizon. No further hydro expansion was considered on top of this. Note that marine energy (tidal energy, marine current power, osmotic power or wave energy) was not explicitly considered in the scenario due to a lack of available information regarding both installed capacities and expected hourly generation profiles.

Nuclear power

Nuclear was taken into account in the different scenarios as a dispatchable technology, depending on a set of technical and economical parameters. Indeed, it is considered as a carbon neutral technology, as defined in the assumption from the "Net Zero by

2050" report from the IEA [SCE-8]. In the framework of this study, only one trajectory by country has been defined, based on national studies, targets from TYNDP2020 and an in-depth analysis of the current national nuclear power plants. The assumed capacity for France is aligned with the "Futurs énergétiques 2050" study by RTE [SCE-9]. The present study took into account the maintenance of 16 GW of existing nuclear capacity (as under 4 out of 6 supply scenarios in the RTE study) plus 18 GW of new EPR (between scenarios N1 and N2 of the RTE study).

Biomass and other RES

Biomass and other RES technologies are included in the scenarios, based on the 2040 targets set for each country in TYNDP2020. However, some updates were made based on national studies. Biomass includes dispatchable plants available in each country, modelled on a unit per unit basis, while other RES include a predefined profile, including the aggregation of small biomass units, geothermal and waste. Note that biomass is mainly used as primary energy for heating and for industry as a feedstock.

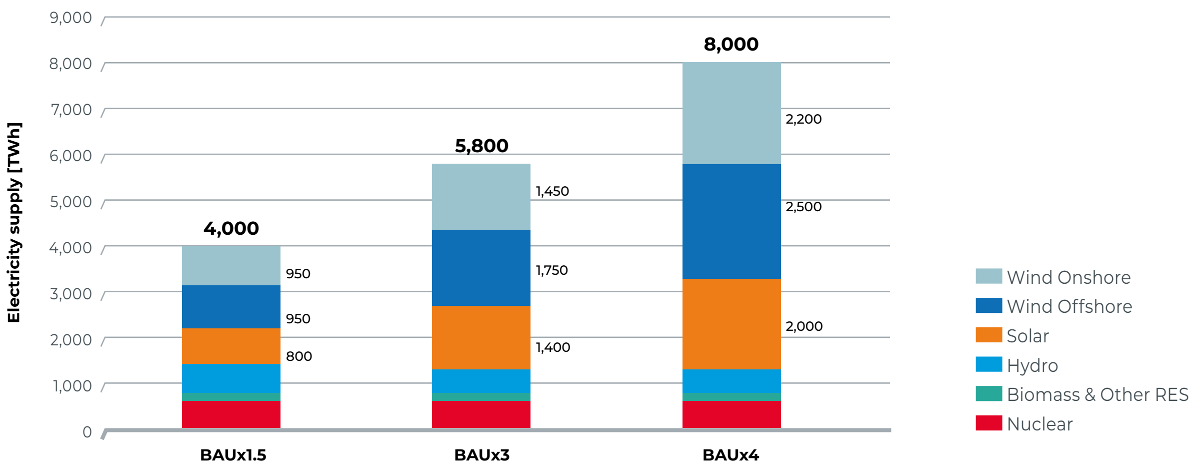
Annual electricity generation

Once the installed capacities had been defined, these could be converted into an hourly energy time series. For weather dependent RES this was done based on ENTSO-E Pan-European Climate Database. The sum of those hourly energy time series over the whole year led to the annual generation by technology.

Europe

For each scenario, the expected generation associated with each type of technology is outlined in Figure 36 for the EU27+3 perimeter. Non-weather dependent technologies are shown with their average capacity factor. Their final dispatch was an output of the market model. Additional dispatchable capacity that was added endogenously by the model for adequacy (see Section A.2) is not considered in the figure.

FIGURE 36: EUROPEAN ELECTRICITY SUPPLY IN 2050 IN TWh IN SCENARIOS BAU x1.5, x3 AND x4



Under BAUx1.5, the total European electricity generation is expected to be around 4,000 TWh. This amount increases to 5,800 TWh under BAUx3 and to 8,000 TWh under BAUx4. Under all scenarios, RES generation from solar and wind represents the main part of electricity generation.

Belgium and Germany

Figure 37 and Figure 38 present the potential electricity generation of Belgium and Germany in 2050. No nuclear is foreseen for either country and the share of hydro, biomass and other RES is assumed to be relatively marginal, meaning that most of the generation comes from solar, wind onshore and wind offshore.

FIGURE 37: BELGIAN ELECTRICITY SUPPLY IN 2050 IN TWh IN SCENARIOS BAU x1.5, x3 AND x4

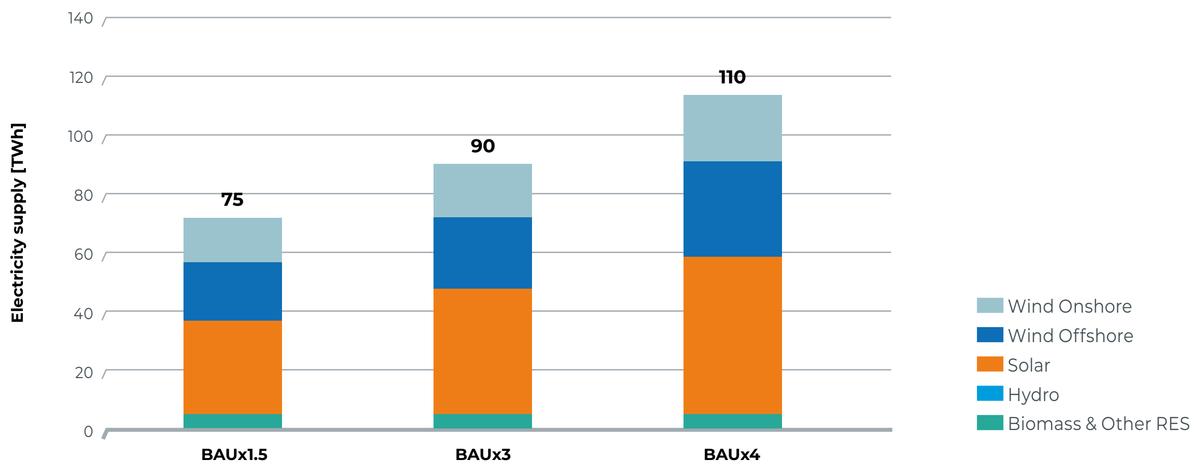
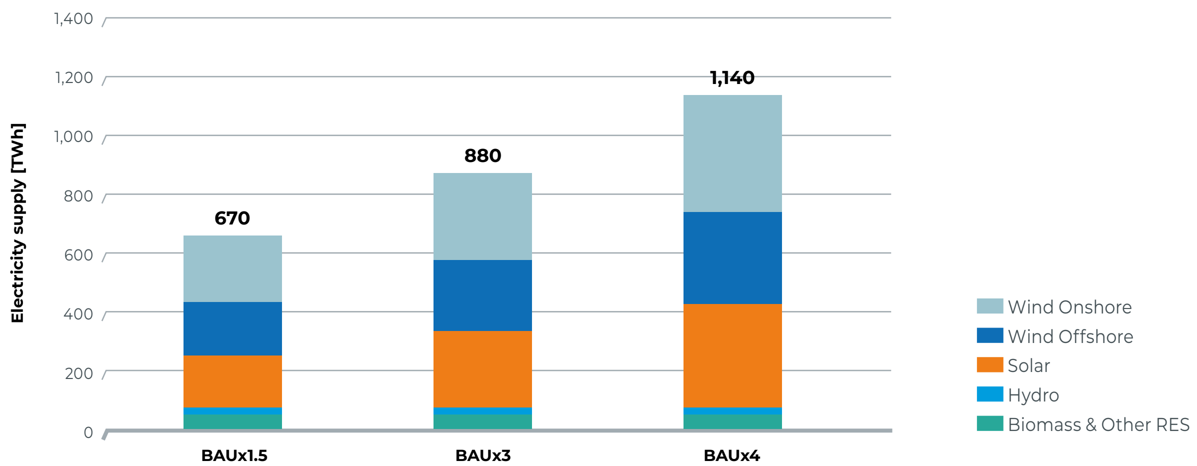


FIGURE 38: GERMAN ELECTRICITY SUPPLY IN 2050 IN TWh IN SCENARIOS BAU x1.5, x3 AND x4



A.2 Market modelling

An overview of the market modelling methodology is already provided in the main text (Section 1.3). The model simulated the European electricity market with an hourly resolution and with each European country being treated as a separate market area. All simulations were performed at a European level including all EU27 countries as well as Switzerland, the United Kingdom and Norway. The market simulations took into account multiple climate years and required a detailed set of input data, including for example:

- hourly electricity demand profiles for each climate year;
- hourly generation profiles of wind and solar power for each climate year;
- dispatchable generation capacities with their technical and economic parameters;
- capacity of storage facilities with their associated efficiency and reservoir constraints;
- available demand flexibility and their associated constraints; and
- interconnection capacity between market areas.

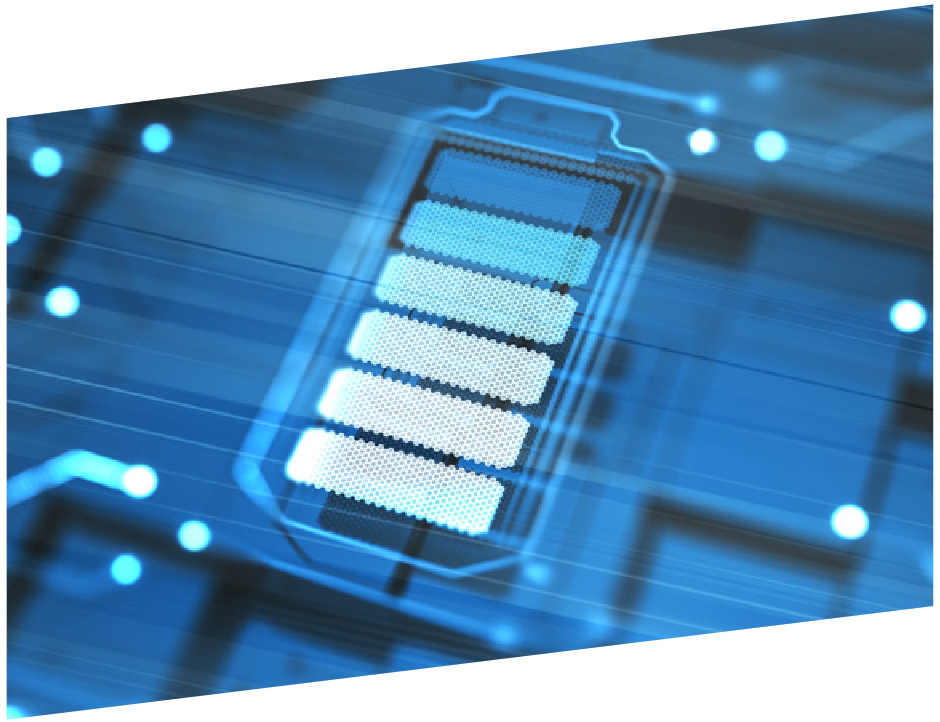
Based on this input data, the market simulations determine the cost minimal solution to serve a given electricity demand by optimising the dispatch of generation, storage and flexibility technologies as well as the exchange between market areas, considering all given constraints and cost parameters. Investments into capacities were not optimised; the capacities were set exogenously and defined by the scenario.

Electrolysers

The purpose of the performed market simulations was to analyse the characteristics of a future European electricity system and in particular how the direct electricity demand in all countries can be met at all times. In contrast to the direct electricity demand, the demand for green molecules can be met both by European production and production from abroad. The analysed scenarios include 40 GW of electrolysers, namely the 2030 target of the European Commission's hydrogen strategy [SCE-10]. They were modelled as a flexible electricity demand that is activated in times of low electricity prices (i.e. high RES supply). This results according to the simulations in a capacity factor of around 50% and a production of approx. 200 TWh of green hydrogen. Given that Europe will be short on RES in 2050, it will need to rely on green molecule imports from other continents.

Additional dispatchable backup capacities

For each scenario considered, additional dispatchable capacity is added to the market model in order to ensure each country complies with its assumed reliability standard. Those backup capacities are carbon-neutral, dispatchable and depend on a set of technical and economic parameters. Note that the potential additional energy demand required to fuel those capacities should be added to the primary energy demands (not included in this study).



A.3 Sensitivity analysis related to interconnectors and flexibility

This section provides more information about the scope and characteristics of the performed sensitivity analysis runs. Next to the two variations on the demand side (MOL and ELEC pathways, see Annex A.1.1) and the three variations on the supply side (BAU x1.5, x3, x4, see Annex A.1.2), two further dimensions were considered in the sensitivity runs, namely the level of interconnection and the level of short term flexibility.

A.3.1 Interconnection

Two sensitivities were considered for the grid configuration: a "grid IoSN+" and a "CopperPlate". The sensitivities differ with regard to their level of interconnection between market areas, which was modelled using net transfer capacities (NTC). These NTC values define the maximal possible commercial exchanges between two bidding zones.

The **"grid IoSN+"** configuration was the reference. The values were based on the NTC values determined in the IoSN (Identification of System Needs) for 2040 from TYNDP 2020. On top of this grid configuration, some additional interconnectors that are currently being explored, were considered:

- the Nautilus project, which is due to involve 1,4 GW of interconnection capacity between Belgium and the United Kingdom;
- the BE-DK project, which is due to involve up to 2 GW hybrid interconnection capacity between Belgium and Denmark; and
- the Bornholm energy island, which is due to see (up to) 2 GW offshore wind power integrated into the hybrid offshore interconnector between Denmark and Germany.

Overviews of the "IoSN+" configuration for Belgium and Germany are presented in Figure 39 and Figure 40 respectively.

In the **"CopperPlate"** configuration, no restrictions on commercial exchanges between market areas were considered, meaning that all NTC values were set to infinite. The CopperPlate pathway therefore allowed an assessment of the benefits of additional interconnection capacities between European market areas and shows to what extent additional interconnection capacity would actually be used at different borders. The analyses of such an unrealistic CopperPlate scenario complement the analysis of the 'IoSN+' grid configuration scenario, which represents a European network that is deemed reasonable for the year 2040, but that is likely to be underdimensioned for a 2050 system. Further investigation into the optimal infrastructure for 2050 is needed; this is beyond the scope of the present study.

FIGURE 39: GRID CONFIGURATION OVERVIEW FOR BELGIUM

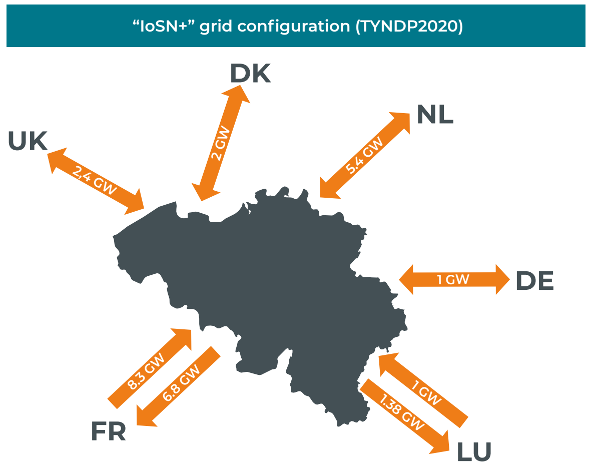
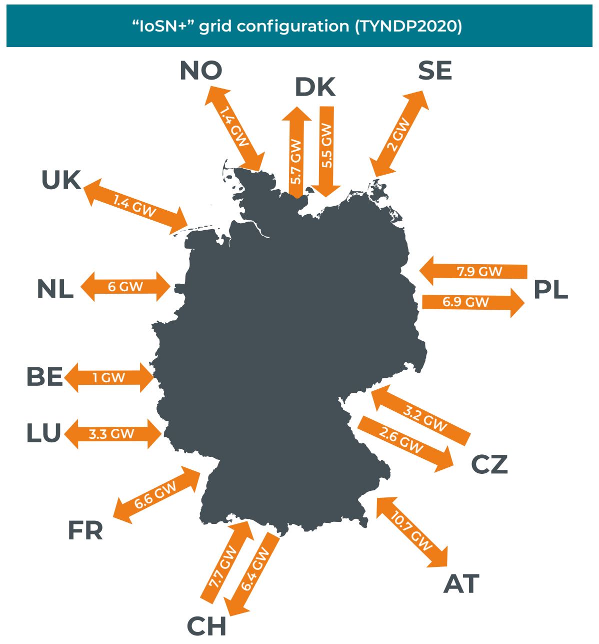


FIGURE 40: GRID CONFIGURATION OVERVIEW FOR GERMANY



A.3.2 Short-term flexibility

Two sensitivities regarding the level of short term flexibility were considered in the market simulations. Short term flexibility is assumed to be flexibility from mobility (electric vehicles), from heating and cooling (heat pumps and air conditioning), from industry and from batteries. Those flexibility means are converted into levels of storage and demand side response in the market modelling. Two variations regarding the level of storage and demand side response available in the electricity system were assumed:

- a scenario with **low flexibility** (Low Flex), with limited evolution in terms of energy and installed capacity of short term flexibility compared to today; and
- a scenario with **high flexibility** (High Flex), in order to evaluate the role and impact of additional batteries and 'end user' flexibility on the energy market.

Flexibility in the framework of this study refers to the different levers which allow the energy demand[1] to better match the variable RES supply. This includes multiple technologies or flexibility means acting at different time scales that will be presented in the first part of this section. Then, two flexibility sensitivities were developed, acting on end-user flexibility which provides flexibility on daily and -to lesser extent- weekly time scale.

Overview of flexibility means

Figure 41 provides an overview of the flexibility means considered in this study. It presents the technologies that were included in the market simulations. Every flexibility means acts at a specific time scale in the market model.

The difference between low and high flexibility sensitivities comes from end user flexibility means, including electric vehicles, heating flexibility, domestic batteries. The share of Demand Side Management (DSM) shedding from industry was assumed to be constant under the two sensitivities.

The level of interconnection provides the system with additional flexibility and is covered separately in Annex A.3.1.

The potential for additional hydro reservoirs is rather limited, as presented in Annex A.1.2, and the level of large-scale batteries was kept constant in the different scenarios, meaning that large-scale storage capacity will be the same between the low and high flexibility sensitivities.

FIGURE 41: OVERVIEW OF FLEXIBILITY MEANS AND TIME SCALE ASSOCIATED IN THE MARKET MODEL

Future Flexibility in the energy system				Time horizon: Seasonal	Weekly	Daily
	Interconnections			X	X	X
	End-User Flexibility	Electric Vehicles	V1G			X
			V2G		X	X
		Heating flexibility	Air Conditionning			X
			Heat Pumps			X
			District Heating			X
		Domestic batteries			X	X
		DMS Shedding from industry			X	X
	Large-scale storage	Large-scale batteries			X	X
		PSP			X	X
		Hydro reservoir		X	X	X

1 This study did not include the aim of performing a flexibility assessment, as was included in Elia's latest Adequacy and Flexibility Study [SCE-11].

Electric vehicles

Electric vehicles (cars, buses and trucks) will play a significant role in the future electricity system. The modelling of electric vehicles was inspired by the methodology from Elia's latest Adequacy and Flexibility Study [SCE-11]. The charging profile of EVs can be modelled in three different ways:

1) **'Natural' charging:** The time series of this charging behaviour is derived from e-mobility study [SCE-12] and the ENTSO-E database. The observed pattern is one in which people charge their EVs when needed, mostly after work. This means that the charging of EVs coincides with the use of other electric appliances (for cooking, entertainment, etc.). The electric vehicle profile therefore overlaps with the evening electricity consumption peak.

2) **'Optimised charging' V1G:** Electric vehicles are combined with unidirectional smart charging technology (without the ability to inject electricity back into the network) to shift charging to periods with high RES infeed. In this framework, electric vehicles are assumed to be connected with smart meters and have incentives to smoothen their consumption when the grid is under stress. The optimisation profile is constructed based on the hourly residual load, obtained after subtracting the solar and wind generation from the consumption of each country. The V1G charging profile is therefore different for each country and each day considered.

3) **'Vehicle-to-Grid' V2G:** Electric vehicles are combined with bidirectional smart charging technology to shift their charging away from periods with higher residual load but also to use the spare battery capacity to store energy and inject it back to the grid. This type of charging behaviour is modelled as an additional storage device that can be used by the system. The total battery capacity available for V2G is assumed to be equal to 50% of the battery capacity of each individual electric vehicle. Hence, V2G is more flexible than V1G. V2G acts on a daily and also on a weekly level.

For each flexibility sensitivity, a split was performed between the different flexibility means available for electric vehicles.

Heating devices

As for electric vehicles, increased electrification in heating and cooling impacts the total electricity consumption but may also provide additional flexibility for the system. The heating flexibility is divided into three groups:

1) **Heat pumps:** The flexibility of heat pumps is based on the distribution of the heat pump consumption across the year. This heat pump consumption shows a strong seasonal variation as heating demand is mainly driven by the outside temperature. The flexibility of heat pumps consists of a certain percentage of the consumption that can be moved to another moment within the day (unique requirement set in the model). This kind of flexibility mean can be used to optimise the consumption profile in relation to electricity prices or other signals. For each hour of the day, the total amount of energy that can be 'stored' is equal to the percentage of the heat pump consumption of that hour and the total amount of energy that can be 'produced' is equal to the maximum energy generation of the heat pumps. This methodology was then applied for every country and every climate year simulated.

2) **Air Conditioning:** The flexibility of air conditioning is modelled with the same methodology as for heat pumps. The only difference is that the seasonality of air conditioning demand is inversely proportional to the seasonality of demand of heat pumps, as cooling demand increases with higher temperature. This profile will then be strongly related to the one belonging to solar generation.

3) **District Heating:** District heating networks may comprise several heat sources, such as heat pumps, industrial waste heat, heat boilers, combined-heat-and-power (CHP) plants or geo- and solar thermal technologies. In addition, heat storage can be part of a district heating system. The interplay of these technologies is an important source of flexibility. Heat supply can either be associated with electricity demand (heat pumps) or electricity supply (CHP units). Above a certain electricity price, heat pumps are switched off and CHP units are kept running, leading to a decrease in the heating demand associated with heat pumps. In the modelling, a certain part of the heat pump time series was therefore considered as demand side response shedding, with a reduced consumption depending on the market price.

For each flexibility scenario, a percentage of the electricity demand for heat pumps and for air conditioning was assumed to be flexible and available for demand side shifting in the model. Moreover, a certain percentage of district heating was modelled as demand side shedding with a given activation price. The different percentages and parameters were the same for all countries.

Batteries

Domestic and large-scale batteries are both considered to be part of the 'battery' category. Electricity can be stored in batteries to be dispatched later. Batteries are defined by a set of parameters, including loading and unloading capacity, energy contents and round-trip efficiency.

Domestic and large-scale batteries were modelled the same way, but the underlying assumptions differ. For domestic batteries, the model assumed that a certain percentage of the total solar capacity of each country will be backed up by stationery batteries, with an energy content of 3h. For large-scale batteries, the installed capacity was fixed by the TYNDP2020 scenario for 2040. For both types, a round-trip efficiency of 90% was assumed.

Batteries provide mainly flexibility on a daily basis but can also store energy on a longer period, allowing to solve issues on a weekly basis.

Demand side shedding from industry

Demand side response from industry was modelled through shedding of the demand from this sector, according to the demand data set in Annex A.1.1. A given percentage of the total industry demand was assumed to bring flexibility to the system. This flexible demand will only be activated when electricity prices are above a certain threshold (and therefore after all the available generation capacity and other flexibility means are dispatched). This makes it possible to replicate the impact of demand side response shedding, which is assumed to be mostly industrial load that can reduce part of its consumption when prices are above a certain activation price. The percentage was defined such that its value is common for every country and the installed capacity is aligned with the national ambitions set in European or national studies.

Level of flexibility in the sensitivities

For each of the two flexibility sensitivities, the parameters associated with each flexibility mean are presented in Table 2. Note that the percentage for demand side shedding from industry was considered to be the same for Low and High Flex, as the percentage of the Low Flex is already ambitious compared to the target fixed in national studies. By analysing a 'Low Flex' and a 'High Flex' sensitivity, it was possible to show the value of - and need for - unlocking flexibility in a carbon-neutral power system.

The "Low Flex" scenario is based on limited ambitions. It assumes a limited share of electric vehicles and heating to deliver flexibility to the power system. Moreover, the number of batteries (V2G, domestic batteries and large-scale batteries) are limited to 70GW across Europe, according to the values from TYNDP2020 for 2040.

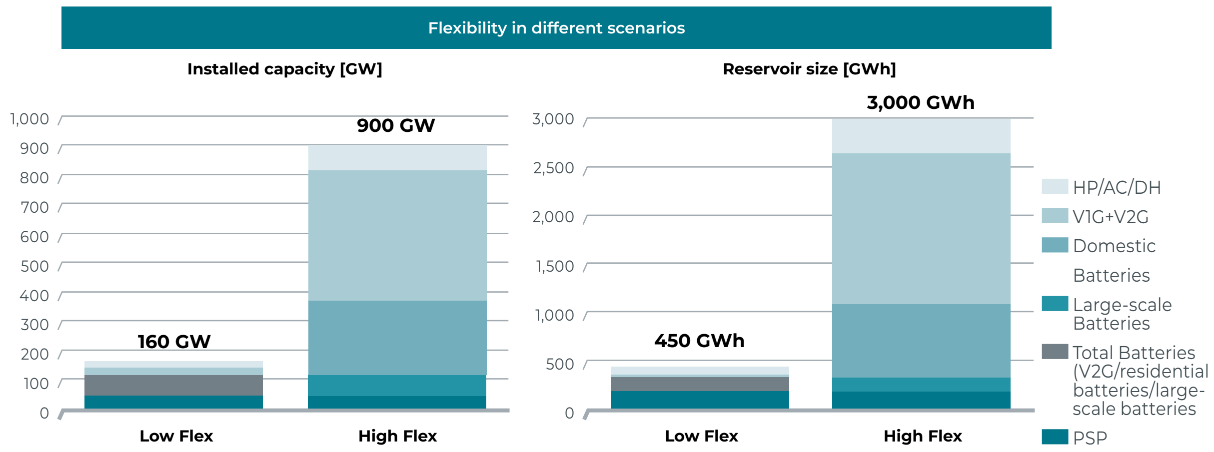
The "High Flex" scenario includes more flexibility from end users. Under this scenario, district heating flexibility is added and the contribution of heat pumps and air conditioning is more than quadrupled. Regarding transport, 60% of the electric vehicles are optimally charged (including passenger cars, busses and trucks) (V1G) and 20% of them are assumed to be connected with bidirectional smart charging (V2G) technology at all times. The domestic battery capacity equals 20% of the installed capacity of solar photovoltaics and the capacity of large-scale batteries remains equal to the 70 GW value from TYNDP2020 for 2040.

TABLE 2: FLEXIBILITY SCENARIO ASSUMPTIONS

Flexibility Means	Sensitivities	
	Low Flex	High Flex
Heat Pumps / AC (share of devices)	20%	80%
District Heating (share of devices)	0%	80%
EV - V1G	20%	60%
EV - V2G		20%
Domestic batteries	TYNDP2020 for 2040	20% of solar installed capacity
Large-scale batteries		TYNDP2020 for 2040
Demand side shedding from industry (share of power)	15%	15%

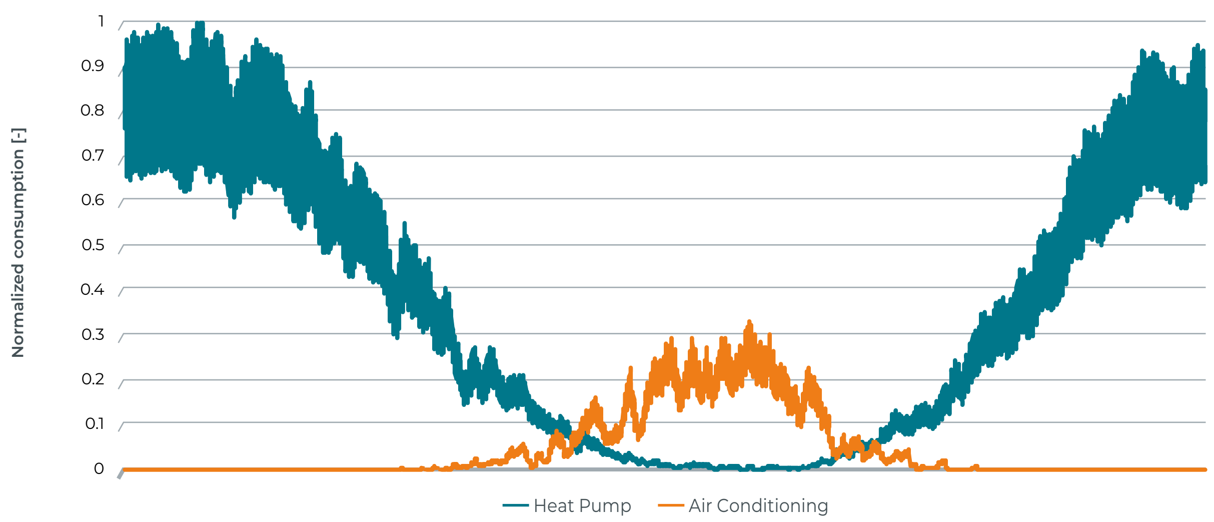
Based on the parameters mentioned in Figure 42 and the ELEC demand pathway, the total flexible installed capacity and reservoir size considered at European level in 2050 for each sensitivity are presented in Figure 43. The flexibility means installed capacity is equal to 160 GW in the "Low Flex" pathway and 900 GW under the "High Flex" sensitivity for Europe in 2050. Around 2.5% of this flexibility is available in Belgium and 17% in Germany.

FIGURE 43: FLEXIBILITY SENSITIVITIES FOR EUROPE IN 2050 FOR THE ELEC PATHWAY



Note that the contribution of heat pumps and air conditioning strongly depends on the location and the season. The contribution of heat pumps is much more important in winter for northern countries, allowing additional flexibility to integrate the high amount of wind energy available. The contribution of air conditioning is much more important in summer for southern countries, hence providing additional flexibility to integrate the daily fluctuations of solar generation. This principle is illustrated in Figure 44 for Belgium. It can be seen that the average contribution of heat pumps throughout the year is much lower than its contribution during winter periods. The same conclusion is valid for air conditioning in summer.

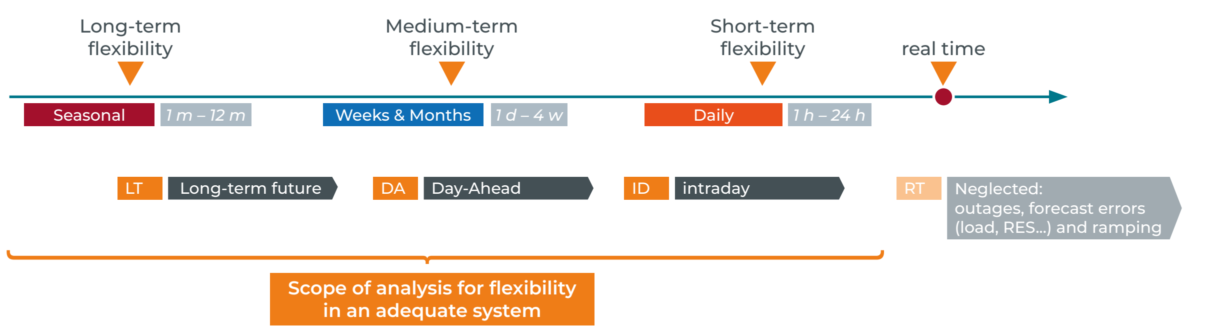
FIGURE 44: ELECTRICITY CONSUMPTION OF HEAT PUMPS AND AIR CONDITIONING FOR BELGIUM IN 2050 (ELEC PATHWAY)



A.4 Fourier analysis

The purpose of the Fourier flexibility analysis was to disentangle the drivers of volatility in the energy mix per time scale. Whilst the total RES infeed seems random at first, it is merely a result of overlapping oscillations that - to a large extent - repeat themselves after a given period in time. The following sections aim to introduce the concept of the Fourier flexibility analysis, major assumptions taken and how it was implemented in the study. This methodology is a genuinely accepted approach in academia. It is mathematically robust and has been applied for similar purposes by [FLX-2, 3, 4] before.

FIGURE 45: TIME SCOPE OF THE FLEXIBILITY ANALYSIS



Fingerprints of volatility

For this analysis, three relevant periods were identified in which most oscillations repeat themselves. They include short term (from one hour up to one day), medium term (from one day up to a month) and long term (from one month up to a year) volatility. A vivid example for short term volatility is the day-night cycle of solar infeed with maximum availability during the day and no infeed during the night. Every 24 hours this cycle repeats, making it an oscillation that can be clearly distinguished from underlying seasonal and monthly offsets. An example for a medium term scale are weekly wind fronts moving across Europe. The long term time scale spans everything from one month to a whole year. With that, one can capture the seasonality of demand, which is higher during the cold winter season compared to summertime. Also, solar and wind infeed are seasonal. Solar power generation peaks during summertime and is lowest in winter, while wind complements this cycle with a summer valley and winter peak.

The volatility of RES infeed strongly shapes the volatility of residual load (defined as power demand minus renewable infeed) as well. Each individual RES technology such as solar, onshore and offshore wind have their own "fluctuation fingerprint", which makes a tracking of their impact on the total volatility feasible. This tracking was accomplished via the performed Fourier analysis. It allowed the quantification of the time scale over which the residual load fluctuates and by how much.

Using these findings, individual fluctuations that impact total flexibility needs the most could be depicted. Different assumptions about the RES portfolio and available flexibility measures led to various trends in volatility and how the flexibility means cope with it. This allowed a standalone analysis of scenarios, in addition to the results of the market model, to compare different stages of flexibility provisions (high vs. low) and different shares of RES (high solar vs. high offshore) with each other and obtain changes in flexibility needs per time scale.

The Fourier analysis should be considered as a parallel analysis track in this study. It was intended to allow further insights to be gathered from the input data and to complement the market simulation results. The main task of the Fourier analysis was to screen for flexibility drivers and quantify needs. This can be done at a European level (considering a CopperPlate), but can also provide insights into the volatility drivers in specific countries (isolated set-up, without cross-border interconnection). One must be careful with the flexibility needs for isolated countries, as interconnectors will have a strong reducing impact on the overall needs.

Inputs and outputs of the Fourier analysis

The Fourier analysis used the same input data as discussed earlier in this report for the market model. For each country, hourly RES infeed and demand time series data for various climate years were taken as inputs. The analysis was conducted twice – once with countries being isolated (no interconnection), and once with countries being part of a European CopperPlate (infinite interconnection). This simplification was necessary, since the Fourier analysis does not replicate the market model and cannot account for discrete transmission capacities per border.

The output of Fourier was a set of time series plots that show the volatility of the original data in three separate time scales, namely short, medium and long term. For each time scale an hourly time series can be plotted, indicating ranges between climate years in the database. The result was a set of plots that could be studied individually to understand drivers and complements of volatility in the input data. Note that no modelling or optimisation took place in the processing. In other words, the Fourier analysis results can be understood as a transparent view "behind" the initial input data.

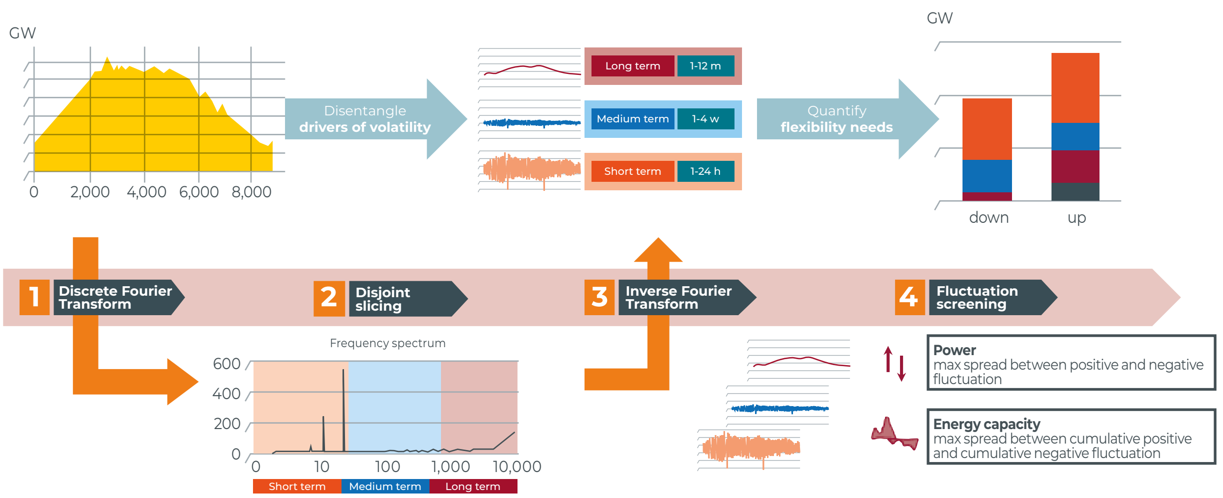
The flexibility analysis is technology agnostic. It only returns a systems need that should be covered by a theoretical body of technology over the given time scale horizon at a given capacity and energy. It does not reveal which technologies should be dispatched to achieve this. Such an optimisation is left to the market simulation. As a consequence, no economic assessment of the flexibility needs and no efficiency mark ups were calculated that could increase energy capacity or power rating in some cases.

Fast Fourier Transformation (FFT) algorithm – technical description

A Fourier analysis describes the recreation of any given time series as a number of periodical sinusoidal functions. It reveals to what extent certain fluctuating components contribute to the total signal, i.e. if there is a dominating fluctuation that overlaps all other noise in between. For example, with solar infeed, Fourier can reveal how large the daily fluctuation is compared to the seasonal fluctuation and if other components on a weekly or monthly basis are relevant or not. Four processing steps are conducted to perform the Fourier analysis. They are summarised in Figure 46.

1. Discrete Fourier transformation to obtain the frequency spectrum of relevant fluctuation components and noise;
2. Disjoint slicing of the frequency spectrum according to the aforementioned time scale;
3. Inverse Fourier transform per time scale (per slice from step two) to obtain a signal in the time domain again;
4. Screening of each time slice for flexibility needs in power and energy.

FIGURE 46: STEPS OF THE FOURIER ANALYSIS



Step 1: The Fourier transformation is implemented with the fast Fourier transform algorithm [FLX-1] and converts the time series data into the frequency domain. The frequency spectrum now indicates for each frequency what amplitude it reaches, i.e. how influential a given cyclic volatility pattern is in the original data. Amplitudes of zero or close to zero denote frequency components that do not contribute to the total signal: over these time scales, the time series does not fluctuate (significantly). A higher or peak amplitude means a larger impact on the total fluctuation of the original time series. At these time scales, the time series shows (major) repeating patterns of fluctuations.

Step 2: The frequency spectrum is sliced according to the predefined time scales. E.g. a time scale of one to seven days translates into 24 – 168 hours. In our analysis, we applied disjoint slicing, i.e. the frequency spectrum was sliced such that no overlaps occurred between the slices and no part of the spectrum is left out. Hence, if all separate intervals are stitched together again, the total frequency spectrum was obtained. This disjoint slicing approach is necessary to avoid double counting in the flexibility needs assessment (step four) and to clearly disentangle short, mid- and long-term fluctuations. It also ensures that no fluctuations are "lost" in the process and a separate interpretation of the disentangled time series (step three) is possible.

Step 3: For each frequency interval, the inverse fast Fourier transform is calculated. This results in one time series per sliced interval which entails only the fluctuation components of the given time scale. In other words, there now exist three time series, representing long, mid and short term series respectively. Note that these fluctuations only denote the deviation from a mean component. For the complete recreation of the original signal, it suffices to sum the three different time series and the mean value.

Step 4: For each disentangled time series, the flexibility needs that allow all fluctuations to be mitigated were obtained. This entailed the calculation of the minimum power rating that would be required to meet the largest oscillation in the time series. Next to the required volume of flexibility needs [GW], the analysis also provided the required energy capacity [GWh] respectively. This rating was first calculated for downward flexibility needs, i.e. a potential need for flexible load increase (or storage discharge, backup capacity, imports), and second for upward flexibility needs, i.e. a potential need for flexible load decrease (or storage charging, export, curtailment). This analysis was applied for weekly wind fluctuations in Section 3.1.

For the power need in GW, each time scale was simply screened for the minimum and maximum deviation respectively. To exclude extreme outliers in our analysis, we include values up to the 99,97th percentile of all fluctuations.

Sensitivity analysis

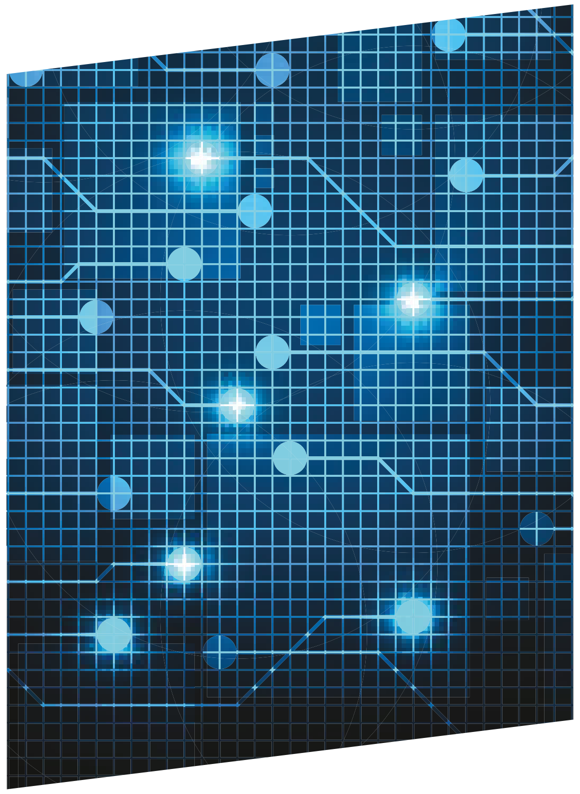
In a sensitivity analysis, the Fourier analysis was repeated on different RES portfolio assumptions for Belgium and Germany to investigate the impact of individual technologies on the resulting flexibility needs. This sensitivity produced further insights into which type of additional (non-domestic) RES production matches best the electricity demand – starting from the observation that both countries are short on domestic RES supply. In the framework of this analysis, the gap was filled hypothetically either with additional generation from offshore wind (high offshore variant) or solar (high solar variant) to showcase the impact of these technologies on residual load volatility. It's important to note that this was a theoretical exercise that only highlights which non-domestic RES would best complement the available domestic one. The results are meant to facilitate the discussion on the complementarity of RES supply sources and the impact of a RES expansion policy on a necessary provision of flexibility.

Analysis of low RES events

For the analysis in this study, sustained periods of low RES infeed and their overlap with high demand were assumed to be:

1. Sustained periods of low RES: periods with a RES infeed below 20% of installed capacity on a 24 hourly average. This definition followed the notion that shorter drops in RES supply are smoothened in the mix and can eventually be dealt with by short term flexibility. Hence, we started counting such events from one day or more and put the focus on the interpretation on events that last up to a week or longer.
2. Sustained periods of low RES infeed overlapping with high demand: these periods were defined by a deviation in residual demand with more than 20% from its long-term mean on a 24 hourly average. This definition was based on the observation that low RES infeed is not critical when demand is low also. However, when demand is high and infeed is low, the residual demand (i.e. the difference between the nominal demand and the RES infeed), peaks. For extreme low RES infeed, this peak can be exceptional with respect to its long-term mean, hence the 20% threshold was introduced.

Note that these parameters were arbitrarily chosen to demonstrate the effects of technologies and regions relative to each other. The academic literature available on this matter discusses a wide range of thresholds both for capacity factors and time windows to smoothen. The choice of parameters for the purpose of this study was inspired by this discourse to fit the purpose of this analysis.



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