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# Bon vent: setting sail for a climate neutral Belgian energy system

## Future Belgian offshore wind unravelled

October 2021

Danielle Devogelaer, dd@plan.be

Dominique Gusbin, dg@plan.be

Rue Belliard 14-18 – Belliardstraat 14-18
1040 Brussels

e-mail: contact@plan.be
https://www.plan.be

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**Federal Planning Bureau**
Rue Belliard – Belliardstraat 14-18, 1040 Brussels
phone: +32-2-5077311
e-mail: contact@plan.be
https://www.plan.be

# Bon vent: setting sail for a climate neutral Belgian energy system

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**Abstract** - In a summer when the devastating effects of climate change are becoming increasingly tangible in every corner of the globe, it is more urgent than ever to crack the climate code. The challenge is enormous, but there are opportunities. In this Working Paper, the Federal Planning Bureau examines what role offshore wind can play in helping Belgium achieve climate neutrality by the middle of the century. The Belgian Exclusive Economic Zone is of course limited and its exploitation for energy purposes cannot be extended indefinitely. Therefore, this paper looks at the development of joint hybrid offshore wind projects that both provide renewable energy capacity and can serve as interconnectors linking different countries. Two different scenarios are defined and studied, differing in the level of ambition to tap into these hybrid hubs and supply the necessary electricity for a de-fossilised Belgian economy.

This study required a methodological adaptation of the Crystal Super Grid model that is regularly used by the Federal Planning Bureau for its analyses of the electricity sector: in addition to a comprehensive modelling of the power system, it was considered necessary to include a detailed and specific modelling of the power-to-gas infrastructure, in addition to the uptake of the hybrid offshore hubs as separate production and bidding zones.

**Jel Classification** - C61, L94, Q41, Q42
**Keywords** - electricity, electricity demand, hydrogen, renewable energy sources, long-term energy projections, energy modelling, energy transition.

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# Executive summary

In line with the 2018 Special report on Global Warming of 1.5°C by the IPCC, the Mercator Research Institute on Global Commons and Climate Change estimates that the $CO_2$ budget associated with 1.5°C degrees of warming will already be exhausted in 2028 if emissions remain at the level of the late 2010s. Although the pandemic made a dent in global emissions, a new IEA report (2021) estimates that global energy-related $CO_2$ emissions are again rising by 1.5 billion tonnes of $CO_2$ equivalent in 2021, driven by a strong rebound in the demand for coal in electricity generation due to the economic post-pandemic recovery.

Meanwhile, in the summer of 2021, a series of devastating effects caused by climate change hit many areas all over the globe. Its effects are becoming increasingly tangible in all corners of the world. It is therefore more urgent than ever to crack the climate code. The challenge is enormous, but there are opportunities.

In this Working Paper, the Federal Planning Bureau (FPB) adopts the European net-zero emissions target by 2050. The focus of this publication is put on the Member State Belgium and on technologies to reach this goal. Once again, Crystal Super Grid (CSG) is employed to scrutinize the effects the European climate-neutral objective engenders on the future Belgian energy and electricity system. More specifically, this paper dives into the role offshore wind can play in the Belgian system. Of course, Belgium's Exclusive Economic Zone (EEZ) is limited with a sandy coastline of a mere 65 kilometres and its exploitation for energy purposes cannot be stretched indefinitely: its potential is assumed to be 6 GW according to Wind Europe (2019). But other options do exist.

In February 2021, the federal Minister of Energy signed a Memorandum of Understanding with her Danish counterpart on the cooperation on offshore energy infrastructure. This appears to be only the beginning since the *Fit for 55* draft legislative package provides for different Member States of the same area to coordinate their offshore planning and determine intermediate goals. Member States will also be obliged to reach at least one joint agreement for a common renewable energy project, and this already by 2025. Joint hybrid offshore wind projects that both foresee renewable energy capacity and can serve as interconnectors seem particularly *fit* for this purpose.

That is why, in this publication, it is decided to dig into different ambitions of developing hybrid offshore wind hubs[1] connected to the Belgian mainland. For this purpose, two distinct scenarios are defined, called *Offshore Baseline* and *Ambitious Offshore Development*.

The first scenario includes the installation of one offshore hybrid hub constructed in Danish waters. 3 GW of wind turbines generate power that can be additionally supplied to both Belgium and Denmark, with 2 GW of interconnections linking the hub to each country (4 GW in total). The hub can also serve as interconnector, hence increasing the total supply of electricity.

1 These hubs can be interpreted as a kind of offshore "bidding zones" in which the interconnection capacities with the different countries are decisive. The offshore hub can then be considered as a separate node.

The second scenario integrates two hybrid hubs: the one in the Danish EEZ, and an additional one in Dutch territorial waters. The former's installed wind capacity increases to 10 GWand interconnections capacity raises to 8 GW[2] in total. The latter, counting on 15 GW of installed capacity, foresees links with the UK, Belgium and the Netherlands.

How do these two scenarios relate to the previous energy publication of the Federal Planning Bureau (Devogelaer, 2020)? First, the two scenarios are based on the *Deep Electrification* scenario described in Devogelaer (2020), meaning that they copy its (in)direct electricity demand, as well as the installed renewable capacities[3]. Second, the newly built access to an additional quantity of power supply via the offshore hubs complements the results reached in Devogelaer (2020): it offers yet an alternative way to build a carbon-free energy system. Moreover, it also provides new insights into, for example, hydrogen supply or system marginal cost when more electricity can be sourced from the sea.

Of course, these hybrid hubs together with the domestic renewable capacity will not suffice to supply the entire electricity demand since there continues to be periods throughout the year when renewable power generation is low, demand peaks and imports are insufficient. For those moments, some form of large-scale, dispatchable, zero-carbon generation is needed: that is where thermal power plants enter the game. They will not run a lot (their capacity factors will be low), but they are proven to be indispensable in the system of the future under the RES deployment assumptions adopted here. Following an optimal capacity expansion run with CSG, two types of thermal plants populate the Belgian electricity scene in 2050: H22P and OCGT. The former are turbines fuelled by hydrogen; the latter run on biogas. In *Offshore Baseline* (*Ambitious Offshore Development*), they amount to 12.1 (7.6) GW and 2.8 (4.8) GW respectively.

To absorb the large quantities of variable renewable energy, other means to provide flexibility are needed as well. Part of the demand is assumed to be flexible through the massive penetration of electric vehicles and heat pumps. Another form of (demand) flexibility complements this further: electrolysis. In *Offshore Baseline* (*Ambitious Offshore Development*), 3.7 (8.8) GW of electrolysis capacity is installed on Belgian soil. It will be able to provide large chunks of the hydrogen demand (attaining 83-85 TWh) but enters into competition with imported hydrogen, priced at 65 €/MWh.

A key take-away from this study is that there are various ways to achieve climate neutrality, while at the same time safeguarding security of electricity supply (no Loss of Load was observed in any of the cases) and keeping production costs down. However, whichever scenario one looks at, a lot of capital (estimated at €12-13 billion in 2050) needs to be mobilised for the energy infrastructure. In order to entice potential stakeholders to invest their capital in building such a system, it is of utmost importance to ensure a stable regulatory and policy environment. In this respect, the Green Deal and, in the shorter term, the Recovery and Resilience plans point the way and can put society on the path not only to crack the climate code but also to thrive in a new, healthy and prosperous environment. Bon vent!

2 Also including the Netherlands and Germany, next to Belgium and Denmark, each with interconnections of 2 GW.
3 With the exception of some recent new assumptions.

# Synthèse

En cohérence avec le rapport spécial de 2018 du GIEC sur les conséquences d'un réchauffement planétaire de 1,5°C, l'Institut de recherche Mercator sur les biens communs mondiaux et le changement climatique (MCC) estime que le budget $CO_2$ associé à un réchauffement de 1,5°C degré sera épuisé dès 2028 si le niveau des émissions demeure inchangé par rapport à la fin des années 2010. Bien que la pandémie ait entraîné une baisse des émissions mondiales, un nouveau rapport de l'AIE (2021) estime que les émissions mondiales de $CO_2$ liées à l'énergie repartent à la hausse de 1,5 milliard de tonnes d'équivalent $CO_2$ en 2021, sous l'effet du net rebond de la demande de charbon pour la production électrique dans le contexte de la reprise économique post-pandémie.

Dans l'intervalle, durant l'été 2021, le changement climatique a frappé de ses effets dévastateurs de nombreuses régions du globe. Ses répercussions deviennent de plus en plus tangibles à travers le monde. Plus que jamais, l'urgence climatique appelle des solutions (« *crack the climate code* »). Le défi est certes immense, mais va aussi de pair avec des opportunités.

Le Bureau fédéral du Plan (BFP) adopte, dans ce Working Paper, l'objectif européen de zéro émission nette à l'horizon 2050 et met l'accent sur la Belgique et le rôle des technologies pour atteindre cet objectif. Cette fois encore, le modèle Crystal Super Grid (CSG) est employé pour examiner les effets de l'objectif européen de neutralité climatique sur le futur système énergétique et électrique de la Belgique. L'étude analyse plus particulièrement le rôle que peut jouer l'éolien offshore dans le système belge. Faut-il préciser que la zone économique exclusive (ZEE) de la Belgique se limite à 65 kilomètres de littoral sablonneux dont l'exploitation à des fins énergétiques ne peut être étendue indéfiniment : son potentiel est estimé à 6 GW selon Wind Europe (2019). D'autres options existent toutefois.

Ainsi, en février 2021, la ministre fédérale de l'Energie a signé, avec son homologue danois, un accord de coopération portant sur les infrastructures énergétiques offshore. Cette coopération ne semble être qu'un début puisque le projet de paquet législatif *Fit for 55* dispose que différents États membres d'une même zone coordonnent leur planification de l'éolien offshore et déterminent des objectifs intermédiaires. Les États membres seront également tenus de conclure au minimum un accord pour un projet conjoint en matière d'énergies renouvelables, pas plus tard qu'à l'horizon 2025. Les projets conjoints hybrides d'énergie éolienne offshore, qui à la fois développent une capacité d'énergies renouvelables et peuvent servir d'interconnecteurs, semblent particulièrement adaptés à cet objectif.

Dans ce contexte, il a été décidé d'étudier plus avant, dans cette publication, plusieurs niveaux d'ambition pour le développement des hubs hybrides[4] d'énergie éolienne offshore connectés au territoire belge. Deux scénarios, *Offshore Baseline* et *Ambitious Offshore Development* ont été définis dans cet objectif.

Le premier scénario prévoit l'installation d'un hub hybride offshore dans les eaux danoises. Des éoliennes d'une capacité totale de 3 GW génèrent de l'électricité qui peut être fournie en complément à la

4 Ces hubs peuvent être interprétés comme une forme de zones de dépôt des offres (les "bidding zones") dans lesquelles les capacités d'interconnexion avec les différents pays sont déterminantes. Le hub offshore peut donc être considéré comme un nœud distinct.

Belgique et au Danemark grâce à des interconnexions de 2 GW entre le hub et chaque pays (4 GW au total). Ce hub peut également servir d'interconnecteur et ainsi accroître l'offre totale d'électricité.

Le second scénario inclut deux hubs hybrides : celui dans la ZEE danoise et l'autre dans les eaux territoriales des Pays-Bas. La capacité éolienne installée sur le premier hub passe à 10 GW et la capacité d'interconnexion passe à 8 GW[5] au total. Quant au second hub, il se caractérise par une capacité éolienne installée de 15 GW et des liaisons avec le Royaume-Uni, la Belgique et les Pays-Bas.

Comment ces deux scénarios s'articulent-ils par rapport à la publication récente du BFP dans le même domaine (Devogelaer, 2020) ? Premièrement, ces deux scénarios se fondent sur le scénario *Deep Electrification* décrit dans Devogelaer (2020) en ce sens qu'ils reproduisent sa demande (in)directe d'électricité ainsi que les capacités renouvelables installées[6]. Deuxièmement, l'accès à une offre supplémentaire via les hubs offshore vient compléter les résultats présentés dans Devogelaer (2020) : cette option constitue une autre possibilité de construire un système énergétique décarboné. De surcroît, il permet de mieux appréhender, par exemple, l'approvisionnement en hydrogène ou l'évolution du coût marginal du système électrique en cas de production accrue d'électricité en mer.

Bien évidemment, ces hubs hybrides couplés à la capacité renouvelable intérieure ne suffiront pas à répondre à la demande totale d'électricité dès lors qu'il y aura toujours des périodes durant l'année où la production d'énergies renouvelables sera faible, la demande atteindra des pics et les importations seront insuffisantes. Pour ces périodes, il est nécessaire de disposer d'une forme de production à grande échelle, pilotable, décarbonée : c'est là que les centrales thermiques entrent en jeu. Elles ne fonctionneront pas de manière intensive (les facteurs de capacité seront peu élevés), mais elles s'avèrent indispensables dans le système du futur étant donné les hypothèses retenues pour le déploiement des SER. D'après les calculs d'expansion optimale de la capacité de production réalisés avec CSG, deux types de centrales thermiques occuperont le paysage électrique belge en 2050 : les centrales H22P et OCGT. Les premières turbines fonctionnent à l'hydrogène, les secondes au biogaz. Dans le scénario *Offshore Baseline* (*Ambitious Offshore Development*), elles représentent respectivement 12,1 GW et 2,8 GW (7,6 GW et 4,8 GW).

Pour absorber les grandes quantités d'énergies renouvelables variables, d'autres leviers de flexibilité doivent être incorporés. Une partie de la demande est supposée être flexible suite à la diffusion massive des véhicules électriques et des pompes à chaleur. Une autre forme de flexibilité (de la demande) complète le tableau : l'électrolyse. Dans les scénarios *Offshore Baseline* (*Ambitious Offshore Development*), une capacité d'électrolyse de 3,7 (8,8) GW est installée sur le territoire belge. Elle permettra de répondre en grande partie à la demande d'hydrogène (83-85 TWh), mais entre en concurrence avec l'hydrogène importé, dont le prix est fixé à 65 €/MWh.

L'une des principales conclusions de cette étude est qu'il existe plusieurs voies pour parvenir à la neutralité climatique, tout en préservant la sécurité de l'approvisionnement électrique (aucune perte de charge n'a été observée dans aucun des cas) et en limitant les coûts de production. Toutefois, quel que soit le scénario envisagé, des capitaux importants (estimés à 12-13 milliards d'euros en 2050) doivent

[5] Les Pays-Bas et l'Allemagne, à côté de la Belgique et du Danemark, chacun avec une interconnexion de 2 GW.
[6] A l'exception de quelques hypothèses récentes.

être mobilisés pour les infrastructures énergétiques. Si l'on veut encourager les parties prenantes potentielles à investir des capitaux dans le développement d'un tel système, il est de la plus grande importance de créer un cadre réglementaire et politique stable. À cet égard, le Pacte vert pour l'Europe et, à plus court terme, les plans de reprise et de résilience montrent la voie à suivre et peuvent orienter la société vers la résolution de la problématique climatique, mais aussi le développement d'un nouvel environnement sain et prospère. Bon vent !

# Synthese

In overeenstemming met het speciaal IPCC-rapport van 2018 over de gevolgen van een wereldwijde opwarming van 1,5° C gaat het Mercator Research Institute on Global Commons and Climate Change ervan uit dat het $CO_2$-budget voor 1,5° C opwarming al in 2028 opgebruikt zal zijn als de emissies op het niveau van eind de jaren 2010 blijven. Hoewel de mondiale emissies gedaald zijn als gevolg van de pandemie, wordt in een nieuw IEA-rapport (2021) geraamd dat de globale energiegerelateerde $CO_2$-emissies in 2021 opnieuw met 1,5 miljard ton $CO_2$-equivalenten zullen toenemen, onder impuls van een sterke opleving van de vraag naar steenkool voor elektriciteitsopwekking als gevolg van het economische herstel na de pandemie.

Ondertussen heeft de klimaatverandering in de zomer van 2021 een reeks verwoestende gevolgen gehad in verschillende, erg verspreide regio's. In alle uithoeken van de wereld worden de klimaateffecten steeds tastbaarder. Het is nu dringender dan ooit om het klimaatvraagstuk op te lossen ('*crack the climate code*'). De uitdaging is enorm, maar er zijn mogelijkheden.

In deze Working Paper integreert het Federaal Planbureau (FPB) de Europese doelstelling van een nettonuluitstoot tegen 2050. Deze publicatie legt de focus evenwel op België en neemt een voornamelijk technologische invalshoek aan om deze doelstelling te bereiken. Opnieuw wordt Crystal Super Grid (CSG) ingezet om de effecten van de Europese klimaatneutrale doelstelling op het toekomstige Belgische energie- en elektriciteitssysteem onder de loep te nemen. Meer specifiek wordt in deze paper ingegaan op de rol die offshore windenergie kan spelen in het Belgische systeem. Uiteraard is de Belgische Exclusieve Economische Zone (EEZ) met een zandige kustlijn van slechts 65 kilometer beperkt en kan de exploitatie ervan voor energiedoeleinden niet onbeperkt worden uitgebreid: het potentieel wordt volgens Wind Europe (2019) geraamd op 6 GW. Maar er zijn andere opties.

In februari 2021 heeft de federale minister van Energie een principeakkoord ondertekend met haar Deense tegenhanger over de samenwerking op het gebied van offshore energie-infrastructuur. Dit lijkt nog maar het begin te zijn, aangezien in het voorstel van wetgevend '*Fit for 55*'-pakket wordt bepaald dat verschillende lidstaten van hetzelfde gebied hun offshore-planning moeten coördineren en tussentijdse doelstellingen moeten vaststellen. De lidstaten zullen ook worden verplicht om ten minste één gezamenlijke overeenkomst te sluiten voor een gemeenschappelijk project inzake hernieuwbare energie, en dit reeds tegen 2025. Gezamenlijke hybride offshore windprojecten die in hernieuwbare energiecapaciteit voorzien en tegelijk als interconnectoren kunnen dienen, lijken hiervoor bijzonder geschikt.

Daarom werd beslist om in deze publicatie dieper in te gaan op verschillende ambities om hybride offshore windhubs[7] te ontwikkelen die verbonden zijn met het Belgische vasteland. Daartoe worden twee verschillende scenario's gedefinieerd: *Offshore Baseline* en *Ambitious Offshore Development*.

Het eerste scenario omvat de installatie van één offshore hybride hub die in Deense wateren wordt gebouwd. 3 GW aan windturbines genereren elektriciteit die geleverd kan worden aan zowel België als

[7] Deze hubs kunnen worden geïnterpreteerd als een soort offshore biedzones ('*bidding zones*') waarin de interconnectiecapaciteiten met de verschillende landen doorslaggevend zijn. De offshore hub kan dan als een afzonderlijk knooppunt worden beschouwd.

Denemarken, met interconnecties van 2 GW die de hub met elk land verbinden (4 GW in totaal). De hub kan ook dienen als interconnector, waardoor het totale elektriciteitsaanbod verder toeneemt.

Het tweede scenario integreert twee hybride hubs: één in de Deense EEZ, de andere in Nederlandse territoriale wateren. De eerste hub heeft een geïnstalleerde windcapaciteit van 10 GW en de interconnectiecapaciteit stijgt tot 8 GW in totaal[8], terwijl de tweede een geïnstalleerde capaciteit van 15 GW heeft en verbindingen voorziet met het Verenigd Koninkrijk, België en Nederland.

Hoe verhouden deze twee scenario's zich tot de vorige energiepublicatie van het Federaal Planbureau (Devogelaer, 2020)? Ten eerste zijn de twee scenario's gebaseerd op het scenario *Deep Electrification* beschreven in Devogelaer (2020), wat betekent dat ze de (in)directe elektriciteitsvraag ervan kopiëren, evenals de geïnstalleerde hernieuwbare capaciteiten[9]. Ten tweede vormt de toegang tot een extra hoeveelheid stroomvoorziening via de offshore hubs een aanvulling op de resultaten van Devogelaer (2020): het biedt een alternatieve manier om een koolstofvrij energiesysteem op te bouwen. Bovendien levert het ook nieuwe inzichten op in bijvoorbeeld de waterstofvoorziening of de marginale systeemkosten bij een verhoogde elektriciteitsproductie op zee.

Uiteraard zullen deze hybride hubs samen met de binnenlandse hernieuwbare capaciteit niet volstaan om aan de volledige elektriciteitsvraag te voldoen, aangezien er perioden zullen zijn waarin de productie van hernieuwbare energie laag is, de vraag piekt en de invoer ontoereikend is. Voor die perioden is een vorm van grootschalige, regelbare, koolstofvrije opwekking nodig: dat is waar thermische elektriciteitscentrales in het spel komen. Ze zullen niet intensief draaien (hun capaciteitsfactor zal laag zijn), maar het is bewezen dat zij onmisbaar zijn in het systeem van de toekomst, onder aangenomen uitgangspunten voor de inzet van hernieuwbare energie. Volgens berekeningen voor een optimale capaciteitsuitbreiding met CSG zullen in 2050 twee types thermische centrales het Belgische elektriciteitslandschap vormgeven: H22P-centrales en OCGT-installaties. De eerste zijn turbines op waterstof, de tweede op biogas. In *Offshore Baseline* (*Ambitious Offshore Development*) bedragen zij respectievelijk 12,1 (7,6) GW en 2,8 (4,8) GW.

Om de grote hoeveelheden variabele hernieuwbare energie te absorberen, zijn ook andere flexibiliteitsinstrumenten nodig. Aangenomen wordt dat een deel van de vraag flexibel is door de massale penetratie van elektrische voertuigen en warmtepompen. Een andere vorm van (vraag)flexibiliteit vult dit verder aan: elektrolyse. In *Offshore Baseline* (*Ambitious Offshore Development*) wordt 3,7 (8,8) GW aan elektrolysecapaciteit geïnstalleerd op het Belgische grondgebied. Ze zal in grote mate aan de waterstofvraag kunnen voldoen (83-85 TWh), maar treedt in concurrentie met geïmporteerde waterstof, waarvan de prijs 65 €/MWh bedraagt.

Een belangrijke conclusie van deze studie is dat er verschillende manieren zijn om klimaatneutraliteit te bereiken en tegelijk de elektriciteitsbevoorradingszekerheid te waarborgen (in geen enkel geval werd *Loss of Load* vastgesteld) en de productiekosten laag te houden. Welk scenario ook wordt beschouwd, er moet veel kapitaal (geraamd op 12-13 miljard euro in 2050) worden vrijgemaakt voor de uitbouw van de energieinfrastructuur. Om potentiële stakeholders te overhalen om hun kapitaal te investeren in de

8 Ook Nederland en Duitsland, naast België en Denemarken, elk met interconnecties van 2 GW.
9 Met uitzondering van enkele recente nieuwe hypothesen.

opbouw van een dergelijk systeem, is het uiterst belangrijk dat een stabiel regelgevend en beleidskader wordt uitgewerkt. In dit opzicht wijzen de *Green Deal* en, op kortere termijn, de plannen voor herstel en veerkracht de weg en kunnen zij de samenleving inspireren, niet alleen om het klimaatvraagstuk op te lossen, maar ook om te gedijen in een nieuwe, gezonde en welvarende omgeving. De wind in de zeilen gewenst!

# Glossary

| | |
|---|---|
| AOB | Ambitious Offshore Development |
| Capex | Capital Expenditures |
| CCS | Carbon Capture and Storage |
| CSG | Crystal Super Grid |
| DD | Degree Days |
| EEZ | Exclusive Economic Zone |
| EV | Electric Vehicles |
| FPB | Federal Planning Bureau |
| G2P2G | Gas-to-Power-to-Gas |
| H22P | Hydrogen-fired Power Plants |
| HP | Heat Pumps |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| KPI | Key Performance Indicator |
| LOL(E) | Loss Of Load (Expectation) |
| LTS | Long-Term Strategy |
| MS | Member States |
| NTC | Net Transfer Capacity |
| OB | Offshore Baseline |
| P2X | Power-to-X |
| PSH | Pumped Storage Hydropower |
| RES | Renewable Energy Sources |
| RoR | Run of River |
| SMC | System Marginal Cost |
| SMR | Steam Methane Reforming |
| TC | Test Case |
| TYNDP | Ten-Year Network Development Plan |
| vRES | variable Renewable Energy Sources |
| VoLL | Value of Lost Load |

# 1. Introduction

Summer 2021. More than a year into the global pandemic while at the same time experiencing devastating effects of the prevailing climate crisis from California and Tennessee to China's Henan, via Turkey and large parts of Europe. In Belgium alone, the number of victims of the pandemic, in addition to people who have lost their homes and possessions, is unfortunately running into the tens of thousands.

And yet, there is hope. During the last couple of months, we have observed clear signs of solidarity, vaccines are being distributed on a large scale, (new) technologies are being developed and deployed and financial means are found to fight these crises and build a better, healthier environment on a more equitable and balanced planet.

The Green Deal and the Next Generation EU have exactly that in mind: to set the stage and to put the European Union on track towards a just transition with, as final destination, a climate neutral society by mid-century. One of its instruments is the extended use of offshore wind: for Europe to reach climate neutrality, the European Commission expects offshore wind capacity to grow from 23 GW today to up to 450 GW by 2050. It is estimated that half of this capacity can be installed in the North Sea. In order to exploit this vast potential, the *Fit for 55* draft legislative package specifies that within one European area, different Member States are asked to coordinate their offshore planning and determine intermediate goals. Member States will also be obliged to reach at least one joint agreement for a common renewable energy project, and this already by 2025. Joint hybrid offshore wind projects that both provide renewable energy capacity and can serve as interconnectors seem particularly *fit* for this purpose.

Belgium currently has slightly more than 2 GW offshore wind installed in its Exclusive Economic Zone (EEZ): it thereby occupies the fifth place *worldwide* in offshore wind capacity. By 2030, Belgium plans to double this capacity. By designating a second zone for new offshore wind developments (the more western Princess Elisabeth Zone, near the border with France), it could accommodate another 2 GW. Because offshore wind is considered to be a significant contributor to the renewable energy and climate goals and because of the current role Belgium plays in its development, this paper sets out to investigate the role offshore wind can occupy in a future carbon-neutral European and Belgian energy system.

In this publication, two 2050 scenarios are being scrutinised: *Offshore Baseline* (OB) and *Ambitious Offshore Development* (AOD). These two scenarios are based on previous work done by the Federal Planning Bureau (FPB): in a publication called '*Fuel for the Future*' (Devogelaer, 2020), two carbon neutral scenarios were being studied that focussed on the role the molecule could play in the future Belgian energy system by 2050. One of these scenarios, called *Deep Electrification*, describes a future energy system in which (direct) electrification becomes preponderant[10] in the fight against climate change.

To study offshore wind in depth, this *Deep Electrification* future served as the basis to construct two new scenarios in which the focus shifts from *molecules* to *offshore wind*. Instead of zooming in on hydrogen,

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10 The use of electricity in the Final Energy Consumption (FEC) becomes decisive and occupies the largest share in both studied climate neutral scenarios, but it is and will not be the only energy vector: the molecule continues to absorb a significant part (from more than a third to almost half) of the final energy mix. To the best of the authors' knowledge, no 2050 scenarios with a 100% share of electricity in FEC exist.

they show what may happen if, simply put, part of the considerable amount of (quasi climate neutral) gas-fired power plants is being replaced by increased investment in renewable energy, i.e. solar energy and offshore wind.

As for the latter, Belgium's Exclusive Economic Zone (EEZ) cannot, of course, be stretched indefinitely. Nonetheless, the North Sea is vast and Memoranda of Understanding between different Member States (MS) have already been signed to jointly develop its enormous potential. In this publication, the impact of large-scale offshore wind hubs in the North Sea, developed within a cooperation framework in which the hubs not only produce electricity but also constitute a means to transport power between countries, is being investigated. The tool used is Artelys' Crystal Super Grid (CSG) software.

In what follows, the adopted methodology will be explained to, afterwards, dive into some of the hypotheses used. Two scenarios are being scrutinised, both compatible with the 1.5°C temperature increase limit as stated in the 2015 Paris Agreement[11] and showcasing a deep electrification philosophy. These two scenarios depict two different levels of ambition when it comes to hybrid offshore development: one installing a 'base' level (1 hybrid offshore hub connected to Belgium), the other demonstrating an ambitious offshore hub development in the North Sea by 2050. The analysis contains a selection of indicators (called KPIs or *Key Performance Indicators*) such as the production capacities, net imports, curtailment and system marginal costs. In the final chapter, the report wraps up with some conclusions.

[11] Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'.

# 2. Methodology

For this exercise, the version of Crystal Super Grid (CSG) that, next to a power module, integrates the uptake of dedicated power-to-gas infrastructure, was used (see also Devogelaer, 2020). This set-up allows to model both direct and indirect electrification. Direct electrification implies the electrification of energy end-uses (like transport and heating): the fossil fuels that are used to perform these energy services are replaced by electricity. Examples are electric vehicles (substituting internal (fuel) combustion engines) and electric heating (replacing fuel oil or natural gas boilers). Indirect electrification, on the other hand, implies that electricity is not used as a direct replacement for fossil fuels but as an input in a conversion process. Electricity is then consumed to produce hydrogen with an electrolyser. This hydrogen can be directly consumed (e.g. in the petrochemical industry) or further transformed into e-gas (with methanation) or e-liquids (via the Fischer-Tropsch process).

An overview of the model structure is provided in Graph 1: it in fact captures the interactions between the power and (partial) gas system to mimic a hybrid sector-coupled energy system infrastructure.

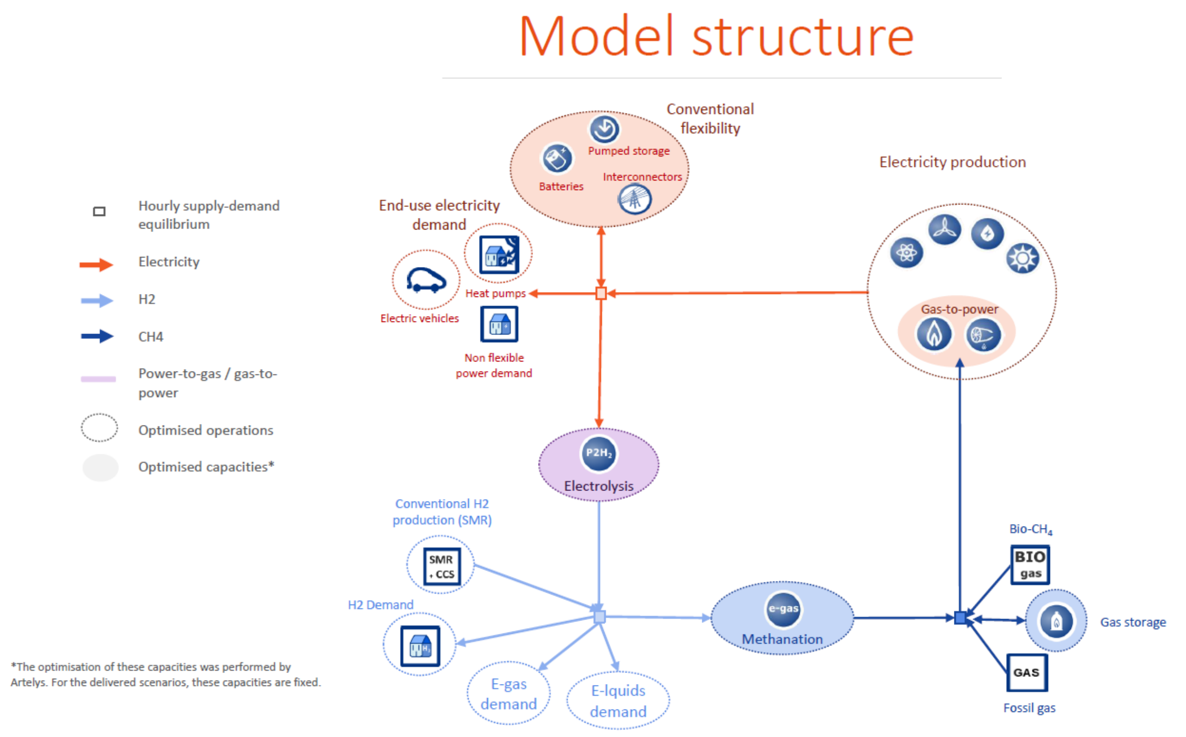
## 2.1. The model structure

The model structure is composed of, next to the traditional electricity production bubble (upper right corner in Graph 1), conventional flexibility options such as batteries, interconnections and pumped storage (PSH), next to the end-use electricity demand (upper left corner).

The end-use electricity demand may be flexible or inflexible. The non-flexible part is the power demand that, even in 2050, cannot be delayed easily or cannot be executed at any random moment in time. The flexible end-use can, if desired. Certain industrial processes and some electrical appliances or lighting in the residential and tertiary sectors fall into the first category whilst electric vehicles (EV) can be placed in the second.

Part of the flexible demand is being provided through the means of electrolysis and, where deemed cost efficient, methanation. These provide the basis for the gas molecules that may be deployed in power generation and delivered to final end-uses, together with biomethane (lower right corner).

**Graph 1 Model structure implemented in Crystal Super Grid**




Source: Artelys.

Electrolysis also meets the demand for pure hydrogen (depicted as $H_2$ demand in Graph 1), next to the (end-)use of e-gases and e-liquids (lower left corner). Hydrogen imports are also an alternative to supply hydrogen demand.

## 2.2. Electricity sector

Power demand and renewable energy capacities[12] are based on the *Deep Electrification* scenario, a scenario scrutinised in a previous FPB publication (Devogelaer, 2020). That scenario itself is rooted in the 1.5TECH scenario run for the European Commission in its Long-Term Strategy (EC, 2018). It basically ensures that, although the focus is on Belgium, the entire EU is becoming climate neutral by 2050.

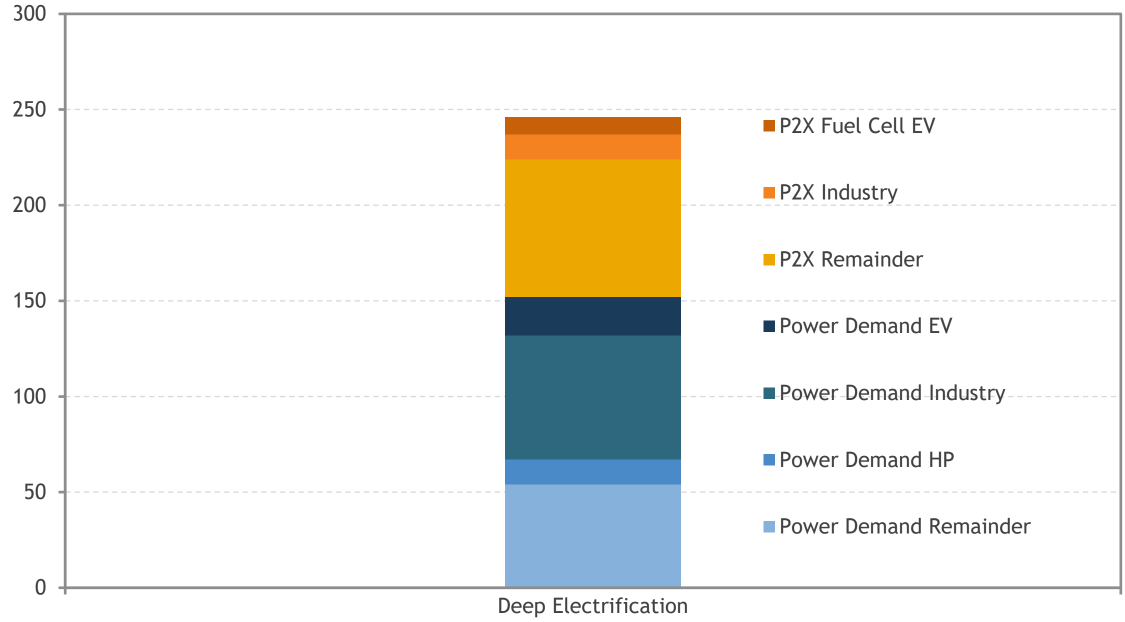
### 2.2.1. Demand

Based on current knowledge, it seems that electrification will be pushed to the limit and that the molecule will fill in the rest. In Europe, the distribution between electrons and molecules in 2050 in climate ambitious scenarios is estimated to be around 60/40 (European Commission, 2018, Eurelectric, 2018). It can be assumed that Belgium will not deviate much from this allocation. Electricity demand levels as exhibited in *Deep Electrification* therefore seem to be the preferred route given the many (known) options to electrify transport and (residential and industrial) heating.

12 Unless stated otherwise.

For both electricity and hydrogen demand, hence, the assumptions were taken from the *Deep Electrification* scenario: in Belgium, a (direct) electricity demand of 154 TWh (depicted by the blue bars in Graph 2) and a hydrogen demand of 80 TWh[13], translating into an additional (indirect) power demand of 94 TWh (depicted by the orange bars in the same graph) in 2050 is assumed.

**Graph 2 Electricity demand, Deep Electrification, Belgium, year 2050**
*TWh*




Source: Artelys, Devogelaer (2020).

CSG foresees the possibility of decomposing the power demand into different categories or assets (according to its use), attributing different 'behaviours' to each demand asset. More specifically, CSG power demand can be divided into:

– Non-flexible end-uses: even in 2050, it may be presumed that power demand is not fully (100%) flexible since some end-uses cannot be delayed easily or cannot be performed at any random moment in time.

– (Potentially) flexible end-uses: EVs, heat pumps, some industrial processes.

– P2X: electrolysis (with methanation and pure hydrogen demand).

Different behaviours can be simulated for the latter two: they can either be modelled as must-run (following a user-defined demand profile) or as flexible assets (determined by the optimisation). Depending on the behavioural setting, end results may change dramatically since flexibilization can help to smoothen system operations.

### 2.2.2. Revisiting flexible means

In CSG, the power system operation can be optimised via an *hourly optimal dispatch*. Here, the decisions to invest in *flexibility solutions* and the power system operation are jointly optimised.

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13 This hydrogen demand includes also demand for e-gas and e-liquids but excludes hydrogen used in H22P since this variable is, contrary to the other $H_2$ demand, an output of the model (see 4.3.1).

For the *Offshore Baseline* scenario, the system operation and investments are optimised for all European countries and they are based on all available climate years (see below), allowing for a robust security of electricity supply. For the *Ambitious Offshore Development* scenario, investments in flexibility solutions are solely optimised for Belgium, while other countries are supposed to keep the capacities calculated in the *Offshore Baseline* optimisation results. This allows for a better comparison between the two scenarios for Belgium.

The capacity expansion (or investment optimisation) calculation performed by Artelys is done with a limited selection of flexibility options, namely OCGT, CCGT, H22P, pumped storage, batteries, electrolysers and methanation units. Onshore interconnections, representing a flexibility solution as well, are also part of the catalogue of investment options, whilst offshore (hybrid) interconnections were determined exogenously (as part of the scenario definition).

It is important to stress that the cited selection of investment options only concerns the installed capacities, not the (hourly) system operation. For the latter, all controllable power production plants, storage, interconnections and demand response are included. Demand response encompasses all flexible end-uses i.e. smart charging of electric vehicles, flexible heat pumps with short-term thermal storage and industrial load shedding.

### 2.2.3. Climate years

The scenarios are run by taking stock of 3 different (recent) climatic years (one rather warm, one average and one cold year) in order to represent solar, wind and power demand variability as well as their correlations. These climate years relate to the years 2002, 2006 and 2010. According to the statistics on Belgian Degree Days (DD[14]), the year 2006 is an average year (2212 DD) with respect to the past 20 years (2000-2019), whilst 2002 was warmer (2090 DD) and 2010 a lot colder (2703 DD). The different climate years are covered by the use of, for every scenario, 3 distinct test cases (TC) reported in chronological order[15]: Test Case 0 (TC0), Test Case 1 (TC1) and Test Case 2 (TC2). Results of the different test cases can be reported separately (to analyse the variability of the results depending on weather conditions) or their average value may be displayed. Unless stated otherwise, the results reflect the average of the different test cases. It should be noted that while operations can differ between Test Cases, a single portfolio of installed capacities is calculated with CSG via a stochastic optimization using all Test Cases.

## 2.3. Solar

As to solar PV, the potential has, compared to *Deep Electrification*, been revised upwards.

In the previous paper (Devogelaer, 2020), 39 GW solar PV was assumed in Belgium in 2050. According to the BREGILAB project[16], the theoretical potential in Belgium is estimated to amount to 100 GW. Because of potential grid related problems in accommodating such a high number of solar PV capacity, it was chosen to work with an installed solar capacity of 60 GW in this publication. The choice of this

14 Consulted on https://www.gas.be/nl/graaddagen/ on September 7, 2021.
15 Test Case 0 mimicking the conditions of climate year 2002, etc.
16 Energyville/VITO, 2018, see https://www.energyville.be/en/press/expert-talk-high-penetration-wind-and-sun-possible-minimal-costs-grid-reinforcement.

higher PV value (60 GW) can be seen as more coherent with the underlying philosophy of the *Deep Electrification* scenario.

## 2.4. Offshore wind

As to offshore wind, the potential has, compared to *Deep Electrification*, been revised downwards.

In the previous paper (Devogelaer, 2020), 8.3 GW offshore wind in the Belgian EEZ was assumed by 2050. Wind Europe (2019), however, estimated the Belgian offshore potential to reach 6 GW. For this exercise, it was decided to take 6 GW into account (not including the hybrid offshore projects).

The hybrid offshore projects are a part of the scenario definition and will be discussed further (in chapter 3).

## 2.5. Biogas

As regards biogas, the assumption of the cost-efficient allocation of the available EU potential (as in Devogelaer, 2020) was abandoned and replaced by a cap on the maximum amount of biogas available in Belgium, set at 20 TWh (for all purposes). The available biogas can supply the CCGT and OCGT fleet.

Because it was noticed that, in the previous study, biogas was sometimes burnt to produce hydrogen (also called G2P2G or Gas-to-Power-to-Gas), an additional constraint was included in the model to make sure that there was no simultaneity between the use of biogas in CCGTs/OCGTs and electrolysis.

## 2.6. $H_2$ imports

As already stated in part 2.2.1, the demand for hydrogen was fixed at 80 TWh in both scenarios. How this demand is met, however, is an outcome of the model. The model has a choice between producing domestically (if it chooses to install electrolysers on its own soil, that is) or importing the molecule.

The price at which $H_2$ can be imported, is based on a recent report from the Hydrogen Import Coalition (2021). The report estimates the levelized cost of hydrogen (LCOH) according to different carriers and (exporting) regions for the period 2030-2035 and 2050. After scrutinising, the following prices figures (for the year 2050) were adopted:

– 65 €/MWh for Belgium and other coastal countries.

– 70 €/MWh for the other countries.

# 3. The scenarios

Two scenarios were constructed: one is called *Offshore Baseline*, the other *Ambitious Offshore Development*. Both scenarios are based on the *Deep Electrification* scenario described in FPB's Working Paper 4-20 (Devogelaer, 2020). The latter represents a carbon-neutral scenario integrating far-reaching end-use electrification and is mainly built on the deployment of new technologies.

The two offshore scenarios are compatible with the 2015 Paris Agreement in which countries agreed to cut greenhouse gas emissions with a view to '*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*'. They follow the latter line of reasoning by taking the 1.5°C global temperature increase as a starting point. In view of what is unfolding today, it seems logical to opt for ambitious climate scenarios that implement EU carbon neutrality by mid-century.

For the definition of (hence, the distinction between) the two scenarios, the level of ambition in developing hybrid offshore projects and building offshore interconnections was chosen. Inspired by the conclusion of a Memorandum of Understanding between the Belgian federal minister of Energy Tine Van der Straeten and her Danish counterpart Dan Jørgensen regarding the cooperation on offshore energy infrastructure in February of this year, two distinct offshore futures were envisioned:

– an *Offshore Baseline* in which one offshore hybrid hub is constructed in the Danish EEZ.

– an *Ambitious Offshore Development* in which Belgium can tap into two offshore wind hubs: one in the Danish EEZ, the other in Dutch territorial waters.

The hub in the first scenario accommodates 3 GW of installed wind capacity and hosts interconnections to both Belgium and Denmark (2 GW each).

In the second scenario, 10 (15) GW of wind capacity is installed in the Danish (Dutch) EEZ. The former will host interconnections to Belgium, the Netherlands, Denmark and Germany (2 GW each), whilst the latter will connect Belgium, the Netherlands and the UK (4 GW each) to the hub.

**Baseline**

- Hub DK (*in DK EEZ*):
  - **3 GW** of installed capacity
  - Interconnections:
    - BE: 2 GW | DK: 2 GW

**Ambitious**

- Hub DK (*in DK EEZ*)
  - **10 GW** of installed capacity
  - Interconnections:
    - BE: 2 GW | DK: 2 GW
    - NL: 2 GW | DE: 2 GW
- Hub North Sea (*in NL EEZ*):
  - **15 GW** of installed capacity
  - Interconnections:
    - BE: 4 GW | NL: 4 GW | GB: 4 GW

# 4. Results

## 4.1. Production capacities

One of the first outputs of the model is its optimised investments (calculated jointly with the optimal dispatch). The optimised *flexible* capacities do differ between the scenarios, and this not only in terms of level, but also in terms of share.

What can learned from Graph 3 is that:

– the installed electrolyser capacity is substantially higher (almost factor 2.5) in the *Ambitious Offshore Development* scenario compared to the *Offshore Baseline*: *Offshore Baseline (Ambitious Offshore Development*) counts on 3.7 (8.7) GW of electrolysers in 2050. The difference can be chiefly attributed to the flexibility feature to absorb the (access to) higher renewable energy production (since hydrogen demand is constant).

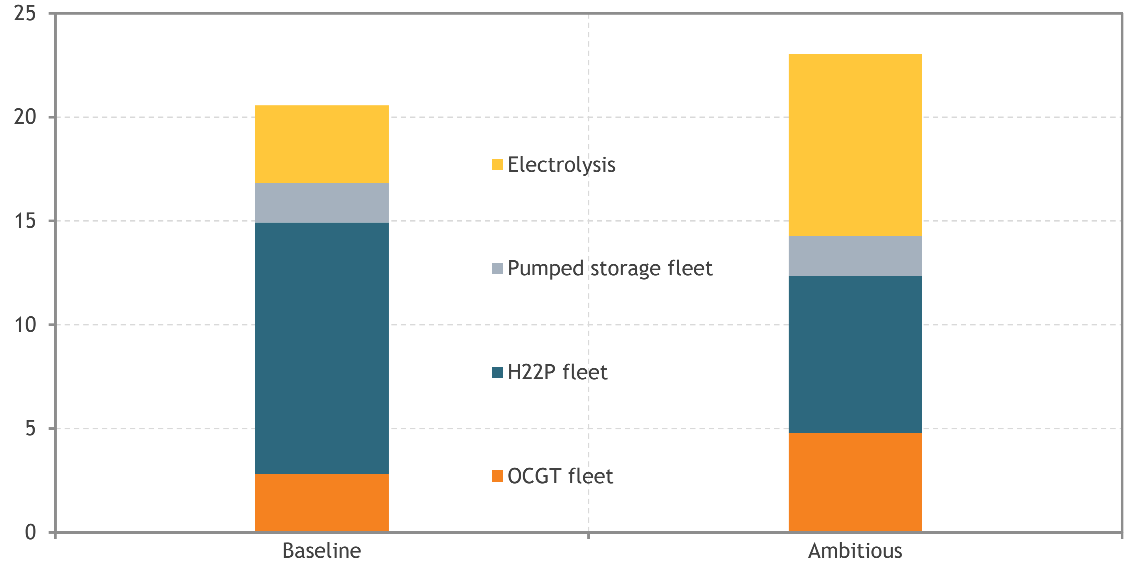
– it is no longer optimal to invest in CCGT (with CCS). Note that this result strongly deviates from the original *Deep Electrification* scenario in which the installed CCGT capacity amounted to 13.8 GW. This result comes also from the fact that the use of biogas was limited to hours when electrolysers are not running.

– the former CCGT fleet is entirely being replaced by H22P and OCGT. In *Offshore Baseline* (*Ambitious Offshore Development*), 12.1 (7.6) GW of H22P and 2.8 (4.8) GW of OCGT is installed.

– pumped hydro storage capacity reaches 1.9 GW in both scenarios.

Overall, the flexibility means (excluding interconnections) surpass 20 GW in both scenarios.

**Graph 3 Installed flexible capacities, Belgium, year 2050**
*GW*




Source: Artelys.
Note: Baseline = Offshore Baseline; Ambitious = Ambitious Offshore Development.

## 4.2. Interconnections

The difference in flexible power generation capacity between the two scenarios[17] can be partly explained by the greater presence of interconnection assets in *Ambitious Offshore Development* (Graph 4).

As regards the interconnections, a difference has to be made between onshore (optimised) and offshore (exogenously defined) interconnections.

### 4.2.1. Onshore

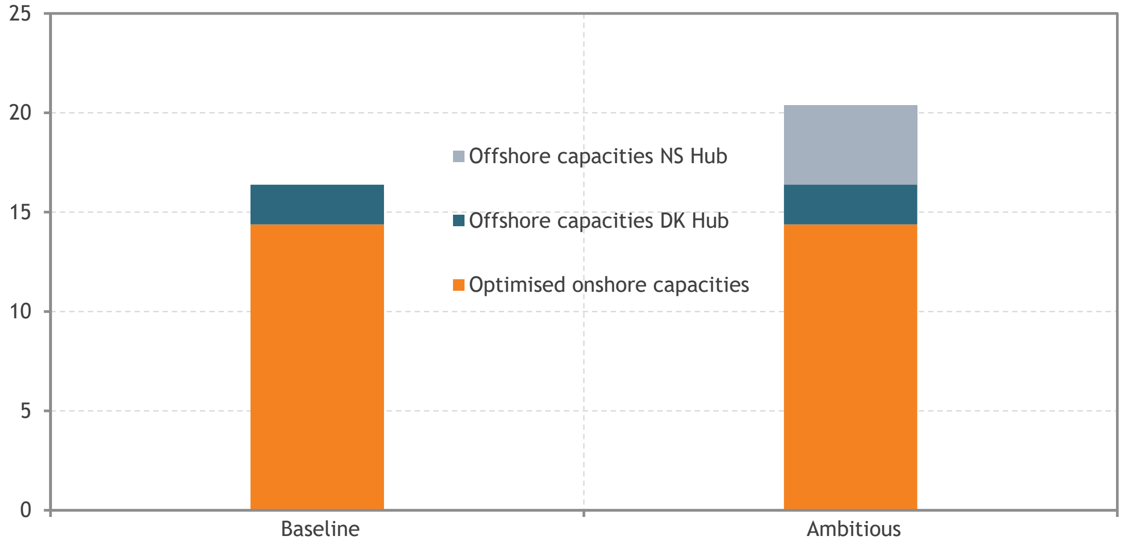
Although the first category (onshore) is being optimised, it has been limited to 14 GW[18]. This choice was made given the significant capital investments and the potential public acceptance issues that the construction of a large number of land-based cross-border power lines may entail.

Onshore interconnections comprise bidirectional links with the Netherlands (3.9 GW), UK[19] (2 GW), Germany (2 GW), France (5.8 GW) and Luxembourg (0.7 GW).

### 4.2.2. Offshore

The second category (offshore) is user-defined and assumes the creation of wind power production hubs in the North Sea. In *Offshore Baseline*, 2 GW of interconnections with an offshore hub built in the Danish EEZ (DK hub) is foreseen; in *Ambitious Offshore Development*, the same interconnection with the Danish hub is integrated, but a second one of 4 GW linking Belgium with a production hub in the Dutch EEZ (NS hub) is added.

**Graph 4 Installed interconnection capacities, Belgium, year 2050**
*GW*




Source: Artelys.
Note: Capacities count only one direction (imports and exports capacities are symmetric).
Baseline = Offshore Baseline; Ambitious = Ambitious Offshore Development. NS = North Sea; DK = Denmark.

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17 Which can be visualised in Graph 3 by excluding the electrolysers.

18 This upper bound is based on the capacity optimisation done in the previous exercise (Devogelaer, 2020).

19 It may seem somewhat odd to classify the BE-UK interconnection as 'onshore' but this choice is based on the fact that, as for the other onshore interconnections, its NTC is being optimised.

### 4.2.3. Net imports

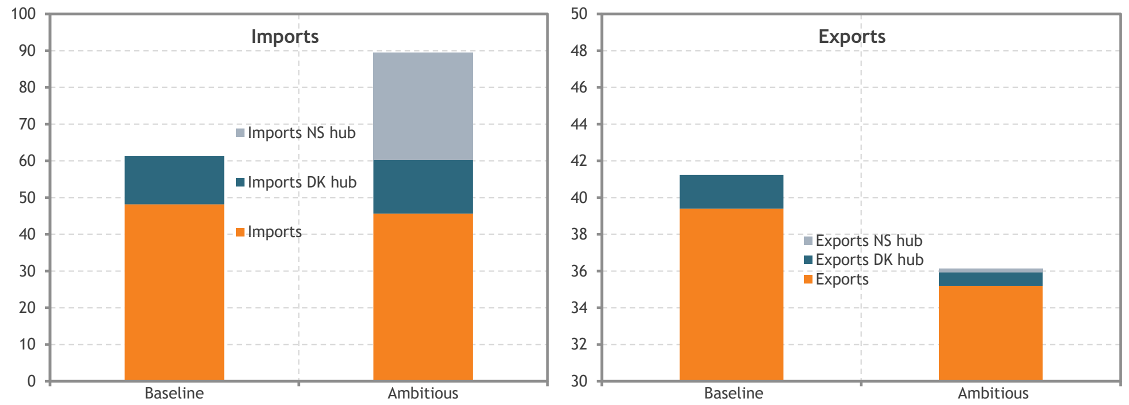
These considerable amounts of interconnection capacities give way to significant import and export flows to and from the mainland.

Graph 5 demonstrates that, in 2050, import levels for Belgium reach 61 (90) TWh in *Offshore Baseline* (*Ambitious Offshore Development*), whilst export levels amount to 41 (36) TWh, leading to net imports of 20 (53) TWh.

Studying the different scenarios, it can be observed that imports in *Offshore Baseline* from the DK hub are somewhat higher than 10 TWh, whilst exports hover around 2 TWh. Note that in this scenario[20], the total interconnection capacity of the DK hub (being 4 GW) is higher than its installed production capacity (3 GW). Interconnection capacity is therefore largely sufficient to, at all times, export the generated wind electricity.

Imports in *Ambitious Offshore Development* are more elevated due to the higher production capacity of the DK hub and (more importantly) the integration of the additional NS hub. The latter allows for an extra 30 TWh of electricity import to Belgium (see Graph 5). At the same time, exports from Belgium are lower, both onshore as towards the offshore hubs. This can be explained by the greater presence of electrolysers in this scenario which both consume more power and compete with interconnectors to cover the flexibility needs. To further support this point: in *Ambitious Offshore Development*, the domestic production of hydrogen goes up by a factor of 2.6 (with respect to *Offshore Baseline*) whilst hydrogen imports decrease by 42% on average. One can then state that, while electricity imports increase in this scenario, hydrogen imports decrease, pointing to the fact that hub supplied electricity can be imported at prices (way) lower than 55 €/MWh.

**Graph 5 (Composition of origin of) imports (left) and exports (right), Belgium, year 2050**
*TWh*




Source: Artelys.
Note: Baseline = Offshore Baseline; Ambitious = Ambitious Offshore Development; NS = North Sea; DK = Denmark.

[20] See also chapter 3.

### 4.2.4. Offshore hubs: further unravelled

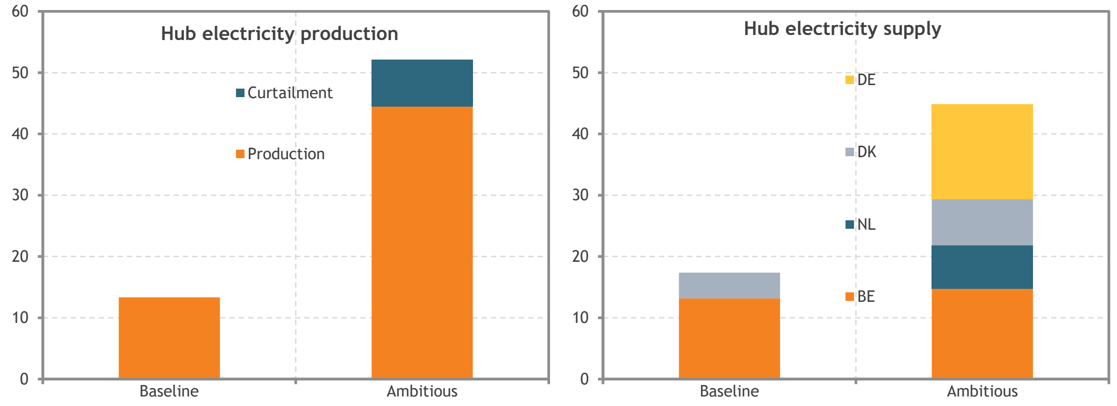
CSG allows to delve even deeper into the role the various offshore hubs can play. In what follows, the two hubs are further analysed.

#### a. DK hub

The DK hub offers both production (wind offshore exclusively, with an average capacity factor of 50.8%) and trade of electricity (via interconnections).

In *Offshore Baseline*, 13 TWh of power is being supplied via the hub installed wind turbines, 4 TWh comes from export from connected countries to the hub. The former is visualized in Graph 6 in the left graph (called 'hub electricity production'), the latter can be derived by subtracting this hub electricity production from the total supply (called 'hub electricity supply') in the right-hand side. Belgium is the main offtaker of the hub's electricity, importing a total of 13 TWh, whilst Denmark can tap into an additional supply of 4 TWh.

**Graph 6 Average power generation (left) and electricity supply (right), DK hub, year 2050**
***TWh***




Source: Artelys.
Note: Baseline = Offshore Baseline; Ambitious = Ambitious Offshore Development; DK = Denmark; NL = the Netherlands; BE = Belgium; DE = Germany.

In *Ambitious Offshore Development*, 45 TWh of power is being supplied via the wind turbines, 8 TWh originates from export to the hub. Germany and Belgium each consume about a third of this supply, whilst Denmark and the Netherlands split the final third in half. About 8 TWh is being *curtailed*.

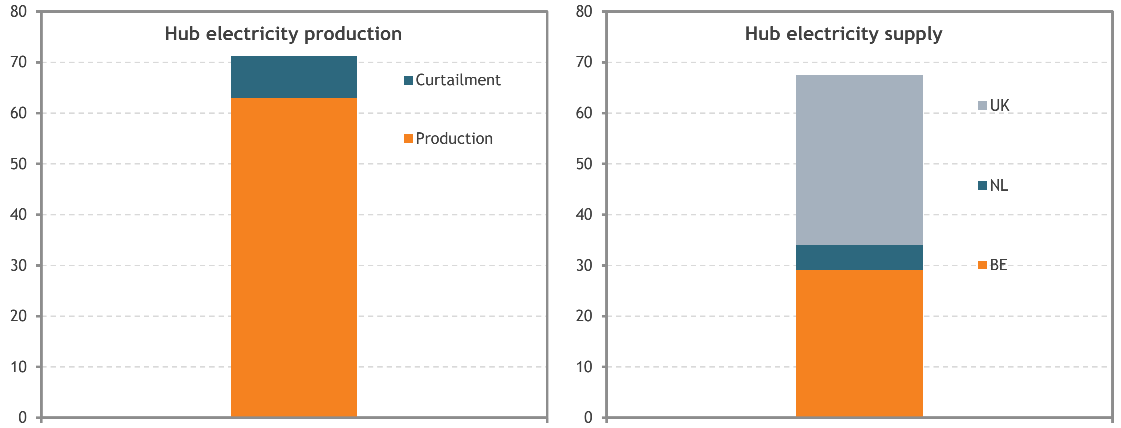
#### b. NS hub

The North Sea hub is only present in the *Ambitious Offshore Development* setting. Recall that this hub assumes a 4 GW interconnection with Belgium and that a similar level of interconnection capacity is taken for the undersea cables linking both the Netherlands and the UK. The average capacity factor of the installed wind park amounts to 47.9%.

In *Ambitious Offshore Development*, the NS hub supplies 63 TWh of power via the wind turbines and 13 TWh via exports to the hub. The UK and Belgium consume around 30 TWh (respectively more and slightly less), the Netherlands import 5 TWh and 8 TWh is being curtailed.

**Graph 7 Average power generation (left) and electricity supply (right), NS hub, Ambitious Offshore Development, year 2050**

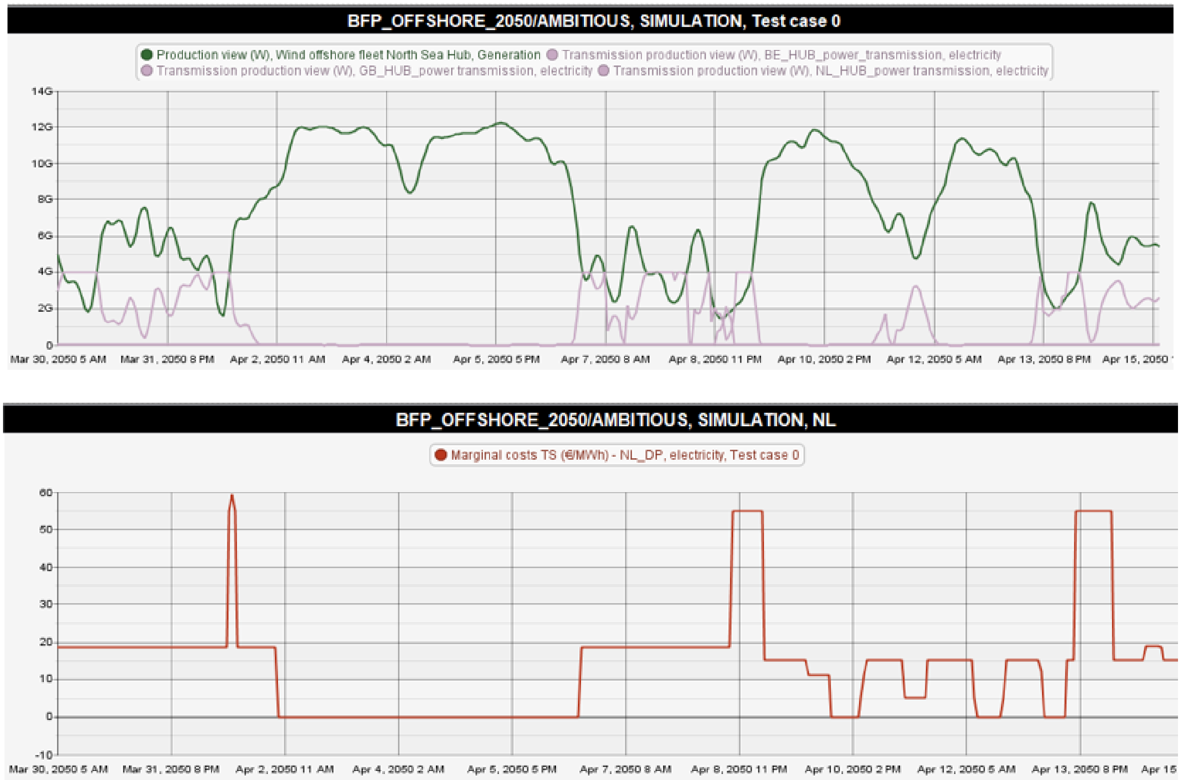
*TWh*




Source: Artelys.
Note: NS = North Sea; NL = the Netherlands; BE = Belgium; UK = United Kingdom.

To really grasp the functioning of the hubs, the illustration below may be useful. Graph 8 shows that during periods of abundant wind power production at the hub (shown in the top part of the graph), marginal costs/prices (shown in the bottom part of the graph) and imports to the hub (shown in the top part of the graph) take a deep dive. However, when wind production is low, it is being supplemented by onshore imports and prices start to mount.

**Graph 8 Illustration of supply (top) and marginal costs (bottom), NS hub, Ambitious Offshore Development, Test Case 0, Belgium, March 30-April 15, 2050**
*W (top) and €/MWh (bottom)*




Source: Artelys.
Note: NS = North Sea.

## 4.3. Gas in the power system

In the previous sections, it became clear that the capacity mix mainly consists of renewable energy sources (chiefly solar and wind). Despite their overwhelming size, they do not suffice to, at all times, cover the load. Some thermal power plants seem to be indispensable in the future Belgian electricity system under the adopted RES development assumptions. Although small in share, their presence is crucial, especially at times of peak demand (and) when overall renewable generation is low. In other words, they provide the flexibility needed to complement the variability of vRES production.

These indispensable thermal power plants can run on different types of gas. In a carbon-neutral power system, two fuels make up the entire future Belgian gas mix: hydrogen and biogas.

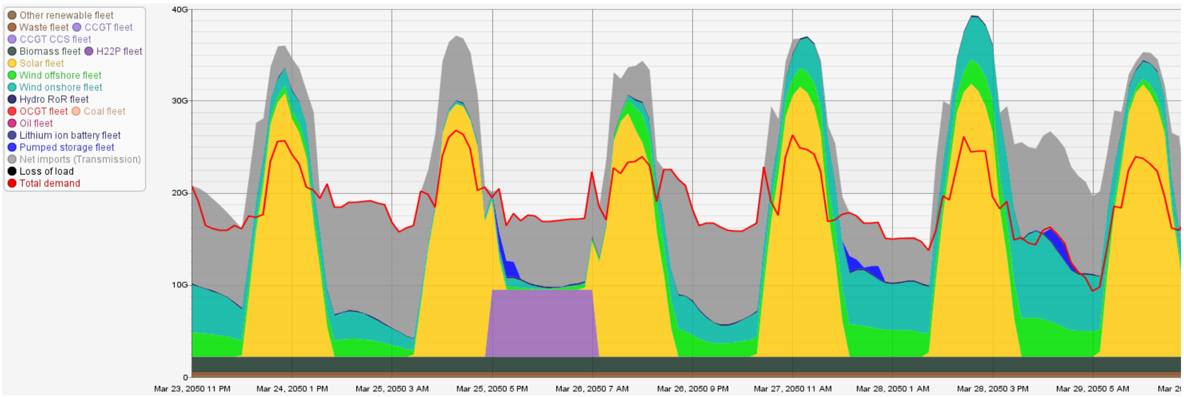
### 4.3.1. Hydrogen

One of the many applications of hydrogen is that it can serve as a fuel in hydrogen-fired power plants (H22P). Since the option is left open to invest in dedicated H22P and a certain amount of H22P is being installed in both scenarios (see section 4.1), hydrogen needs to be available to fuel these types of turbines. In order to determine this additional amount of hydrogen (on top of the predetermined hydrogen demand, see section 2.2.1), the optimal dispatch calculations, which vary from scenario to scenario, provide the result.

### a. Installed capacity

With an installed H22P capacity of 12.1 (7.6) GW in *Offshore Baseline* (*Ambitious Offshore Development*), 5.5 (3.1) TWh of hydrogen is being consumed to produce[21] 3.5 (1.9) TWh of electricity. The capacity factors, hence, are very low in both scenarios (reaching only 3% on average), yet this equipment is indispensable during peaks in demand and/or (very) low production of renewable electricity. In Graph 9, the hydrogen-fired electricity production is illustrated (in violet) at a moment[22] when there is hardly any wind or solar energy available and imports from Germany, France and the Netherlands are quasi non-existent[23].

**Graph 9 Graphical illustration of cumulated power generation, Ambitious Offshore Development, Test Case 0, Belgium, March 24-29, 2050**
*W*




Source: Artelys.
Note: The red curve called 'Total demand' in the graph only represents the end-use (direct) power demand. Production surpluses exceeding the red curve are used to meet the P2X (indirect) electricity demand.

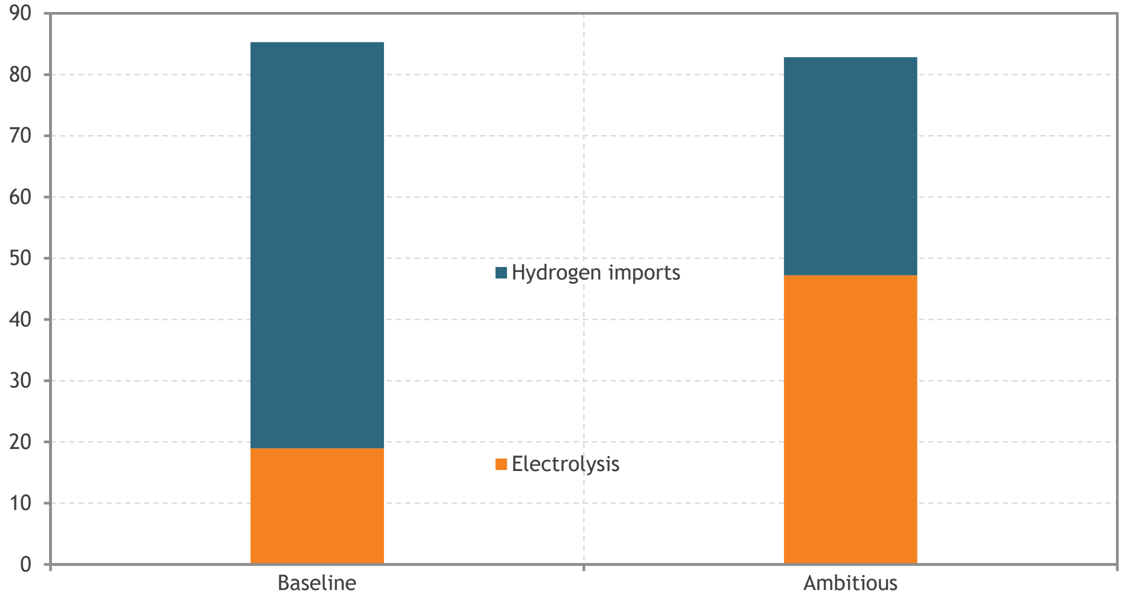
### b. Total hydrogen supply

Total hydrogen demand then boils down to 85 (83) TWh in *Offshore Baseline* (*Ambitious Offshore Development*). Supplying hydrogen can be done in two different ways: producing the molecule domestically and importing. Graph 10 shows the distribution according to the different scenarios.

In *Offshore Baseline* (*Ambitious Offshore Development*), one imports more (less) and produces less (more) molecules. In the *Offshore Baseline* (*Ambitious Offshore Development*), hydrogen imports on average amount to 66 (36) TWh, the remaining 19 (47) TWh are produced through home-made electrolysis. The lower import share in the latter can be ascribed to the higher amount of electrolysers installed. It can also be noticed that in Test Cases with lower renewable generation, imports become more important.

21 The zero-carbon emitting H22P have an average efficiency of 63%.
22 Between 5 PM and 7 AM.
23 The imports depicted in Graph 9 at the moment the H22P turn, originate from the UK and both hybrid offshore hubs.

**Graph 10 Hydrogen supply, Belgium, year 2050**
*TWh*




Source: Artelys.
Note: Baseline = Offshore Baseline; Ambitious = Ambitious Offshore Development.

### 4.3.2. Biogas

As regards the (other) gas supply for power generation, this boils down to the use of biogas. When scrutinising the hourly dispatch of biogas plants throughout the year, it is noticed that:

- their use is confined to moments in which demand peaks and renewable generation is low or absent.
- they are used for fuelling the OCGT fleet which complements the production of the H22P fleet.

To determine the final amount of biogas consumed, it is important to explain how biogas (burnt in gas-fired power plants) is modelled in CSG. In the previous exercise (Devogelaer, 2020), it was noticed that biogas was used as quasi baseload in the power system (but still relying on its flexible characteristics to serve the residual load). This also means that biogas was in part burnt to create… hydrogen[24]. In order to avoid this Gas-to-Power-to-Gas cycle, a constraint was added to ensure that biogas won't be used in power plants when electrolysers are operating. This leads to a serious restriction of its use, leading to the consumption of, on average, less than 1 TWh of biogas in the future Belgian power sector.

## 4.4. Curtailment

Since CSG includes an *Optimal Dispatch* model, the operation of the generation units is not fixed in advance: capacity activation is a model result. Compared to total production, excess electricity (defined as electricity that is not being consumed instantaneously or stored for later use) is very low, basically because there is ample flexibility in the system through electricity consuming processes like EVs, heat pumps and P2X.

[24] While such a behaviour (simultaneous electrolysis and CCGT operations) can happen when electrolysers are not connected to the grid, here it is assumed that electrolysers are fed via the transmission grid. Therefore, avoiding using biogas to generate hydrogen is essential.

RES curtailment nonetheless can be observed in both scenarios (see Table 1), which is not that surprising given the large amounts of renewable capacity installed, but it is marginal. It amounts to 1.7 (0.4) TWh on average in *Offshore Baseline* (*Ambitious Offshore Development*). Note that Belgian production curtailments are lower in the *Ambitious Offshore Development* scenario because of the larger presence of electrolysers.

**Table 1 Curtailment, Belgium, year 2050**
*TWh*

| | Offshore Baseline | Ambitious Offshore Development |
|---|---|---|
| Test Case 0 | 2.3 | 0.5 |
| Test Case 1 | 1.6 | 0.4 |
| Test Case 2 | 1.4 | 0.3 |
| Mean | 1.7 | 0.4 |

Source: Artelys, FPB own calculations.

## 4.5. Loss of Load

Since the optimisation of investments is carried out simultaneously[25] for the 3 test cases (and thus takes into account the three different climate years), no Loss of Load is noted in Belgium in any of the test cases. The optimisation based on 3 climate years hence allows for a robust security of electricity supply[26].

Although no real Loss of Load can be observed at any time (supply is able to cover demand at any time), one can notice some particularly high prices in the model outcome. These high price moments can be interpreted as hours in which the system is (very) close to Loss of Load, also called moments of *scarcity*. They amount to 16 consecutive hours and only occur in Test Case 1.

This lack of Loss of Load (LoL) in Belgium is an important explanatory factor for the lower average SMC compared to the original *Deep Electrification* case (see section below), another one being the restrained use of biogas in the power system.

## 4.6. Costs

### 4.6.1. System Marginal Costs

System marginal costs (SMC) are defined as the variable production costs of the last unit activated to supply the load (see also Devogelaer, 2018). CSG reports on the hourly SMC per Test Case (TC): this allows for more detailed calculations to be carried out.

The average (over 8760 hours) SMC are shown in Table 2. Although the differences between Test Cases are large, deviations between the scenarios are very small (less than 3%). The low SMC in Test Case 0 catches the eye, driven by the benign climate conditions causing favourable variable renewable production levels that are characterised by (very) low marginal costs. SMC are the highest in Test Case 1. This can be ascribed to one moment of the year in which wind generation is very low. On top of that, imports

[25] In the previous study, this was not the case: the optimisation was based on a single climate year.

[26] As a matter of fact, looking at Belgium's neighbouring countries, only Austria and Germany demonstrate a LoL of respectively 5 and 7h in Test Case 2.

from France, the UK, the Netherlands and the North Sea hub are lacking or low, leading to prices that go up sharply (the so-called *scarcity* prices). This single event has an important upwards effect on the average prices of TC1. Even though on average, TC2 has the lowest capacity factors for wind generation and the highest thermosensitive demand, its average SMC is lower than that of TC1.

**Table 2 Average System Marginal Costs, Belgium, year 2050**
*€/MWh*

| | Offshore Baseline | Ambitious Offshore Development |
|---|---|---|
| Test Case 0 | 41.9 | 42.9 |
| Test Case 1 | 88.0 | 89.1 |
| Test Case 2 | 55.4 | 54.8 |
| Mean | 61.8 | 62.3 |

Source: Artelys, FPB own calculations.

When the costs are examined somewhat further, other interesting results can be detected. Since the hourly marginal costs of the neighbouring countries are also available, it is possible to derive which country (countries) has (have) the lowest marginal cost during a specific hour, hence, is (are) likely to export to Belgium in case of residual demand.

**Table 3 Average System Marginal Costs, Offshore Baseline, Belgium and its neighbouring countries, year 2050**
*€/MWh*

| | BE | DE | FR | UK | NL |
|---|---|---|---|---|---|
| Test Case 0 | 41.9 | 38.5 | 50.6 | 56.6 | 19.0 |
| Test Case 1 | 88.0 | 54.1 | 94.7 | 99.1 | 52.7 |
| Test Case 2 | 55.4 | 72.2 | 57.5 | 63.3 | 26.9 |
| Mean | 61.8 | 54.9 | 67.6 | 73.0 | 32.9 |

Source: Artelys, FPB own calculations.
Note: BE = Belgium; DE = Germany; FR = France; UK = United Kingdom; NL = the Netherlands.

**Table 4 Average System Marginal Costs, Ambitious Offshore Development, Belgium and its neighbouring countries, year 2050**
*€/MWh*

| | BE | DE | FR | UK | NL |
|---|---|---|---|---|---|
| Test Case 0 | 42.9 | 31.4 | 49.4 | 54.2 | 17.9 |
| Test Case 1 | 89.1 | 47.0 | 94.7 | 96.6 | 57.0 |
| Test Case 2 | 54.8 | 59.0 | 56.6 | 61.7 | 26.9 |
| Mean | 62.3 | 45.8 | 66.9 | 70.8 | 33.9 |

Source: Artelys, FPB own calculations.
Note: BE = Belgium; DE = Germany; FR = France; UK = United Kingdom; NL = the Netherlands.

It is noticed that:

- the Netherlands have the lowest (average) SMC (except in TC1).
- Belgium's average SMC is systematically lower than that of the UK and France, the latter two counting (a.o.) on the atom for their national electricity supply[27]. It is no coincidence that these two countries are the largest importers of Belgian electricity: exports from Belgium to the UK (France) amount to 15 (15) TWh in *Offshore Baseline* and 14 (13) TWh in *Ambitious Offshore Development*.

[27] In terms of nuclear production capacity, they respectively have 14 and 38 GW installed in 2050.

### 4.6.2. Total (production) costs

Total (production) costs are defined as the sum of the production costs, the loss of load costs and the curtailment costs. Note that investment costs (through annuities) in order to build such a future energy system are not part of this concept of total costs: they are discussed in the next section.

On average, total costs appear to be €62 million (less than 10%) lower in *Ambitious Offshore Development* compared to *Offshore Baseline*. This can be attributed to the lower curtailment in the former scenario, as the SMC do not seem to be that different and LoL does not occur in any of the contexts.

### 4.6.3. Investments

Although total (production) costs do not integrate the annuities related to investments, it is possible to compare the investments necessary to supply the required power in 2050 since CSG reports on a separate 'investment cost' indicator. Investments include energy infrastructure except those related to interconnectors and hybrid hubs.

Looking at the (admittedly, partial) investments, one can observe that, although *Offshore Baseline* (OB) notes higher production costs than *Ambitious Offshore Development* (AOD), it is characterised by lower investment costs. This can be explained by the former demonstrating a lower installed capacity of OCGT and significantly less electrolysers. The annual capex of these technologies can be checked in Table 5 (annex). Overall, *Offshore Baseline* necessitates €260 million less investment costs[28] in 2050.

It is also instructive to compare the *Offshore* scenarios (OB and AOD) with the original *Deep Electrification* scenario described in Devogelaer (2020). The estimated total investment costs in these three climate-neutral scenarios fluctuate around €12 to 13 billion in 2050. Differences between the *Offshore* scenarios and *Deep Electrification* can be found in, on the one hand,

– installed **solar** capacity: solar was revised upwards from 39 GW in *Deep Electrification* to 60 GW in both *Offshore* scenarios, leading to an additional investment of €2 billion.

– **OCGT**: the optimised capacity reaches 2.8 (4.8) GW in *Offshore Baseline* (*Ambitious Offshore Development*) compared to 2.0 GW in *Deep Electrification*.

– **biomass** fleet: the optimised capacity reaches 2.2 GW in the *Offshore* scenarios compared to 2.0 GW in *Deep Electrification*.

– **H22P** fleet: the *Offshore* scenarios count on this technology whilst *Deep Electrification* did not foresee any H22P investments. H22P investments amount to €961 (601) million in *Offshore Baseline* (*Ambitious Offshore Development*).

on the other hand,

– **offshore wind** installed in the Belgian EEZ was revised downwards (from 8.3 GW in *Deep Electrification* to 6 GW in the *Offshore* scenarios). Its investment costs, hence, decrease by approximately €700 million.

[28] Being the sum of Capex and Fixed Operating Costs.

- **CCGT** (with CCS) have an installed capacity of 13.7 GW in *Deep Electrification* whilst the *Offshore* scenarios do not include this type of generation units.
- **electrolysers** are lower in the *Offshore* scenarios, hence investment costs decrease by €672 (175) million in *Offshore Baseline* (*Ambitious Offshore Development*).

Higher investments in the first category of technologies are more than compensated by lower costs in the second group: *Deep Electrification*, hence, is the most capital intensive when it comes to production technologies. The delta in investment costs between *Deep Electrification* and *Offshore Baseline* (*Ambitious Offshore Development*) amounts to €420 (160) million in 2050.

# 5. Conclusion

At the end of this report, some conclusions can be drawn. We are still, and will remain for some time, in a period characterised by a double crisis: the coronavirus is not yet singing its swan song and SARS-CoV-2 variants are still to be feared, while the bulk of the serious climate consequences are ahead of us, not behind us. Yet solutions to the latter issue can be found, and the development of joint hybrid off-shore infrastructure to tackle climate-related challenges seems to be one of them, especially for a small country with limited territorial waters.

In this publication, the Federal Planning Bureau examines what role offshore wind can play in helping Belgium achieve climate neutrality by the middle of the century. Since the Belgian Exclusive Economic Zone (EEZ) is restricted and its exploitation for energy purposes cannot be expanded indefinitely, the development of joint hybrid offshore wind projects is scrutinised. These hybrid hubs can at the same time provide renewable energy capacity and serve as interconnectors linking different countries. Two different scenarios called *Offshore Baseline* and *Ambitious Offshore Development* are studied, differing in the level of ambition to tap into these hybrid hubs and supply the necessary electricity for a de-fossilised Belgian society.

In *Offshore Baseline*, 2 GW of interconnections with an offshore hub built in the Danish EEZ (*DK hub*) is foreseen; in *Ambitious Offshore Development*, the same interconnection with the Danish hub is integrated, but a second one of 4 GW linking Belgium with a production zone in the Dutch EEZ (*North Sea hub*) is added. The installation of these different hubs gives Belgium access to an additional supply of [13-44] TWh of electricity according to the scenario: the *DK hub* provides Belgium with an extra 13 (15) TWh in *Offshore Baseline* (*Ambitious Offshore Development*), the *North Sea hub* delivers another 29 TWh to Belgium in *Ambitious Offshore Development*.

In 2050, the Belgian power capacity mix primarily consists of renewable energy sources: 60 GW of solar, 16.7 GW onshore wind, 6 GW offshore wind, 2.7 GW biomass and waste and 0.3 GW of run-of-river (hydro). To accommodate these vast amounts of (mostly) variable renewables that Belgium builds and buys, the simultaneous construction of ample flexibility means is indispensable. Interconnections (both on- and offshore) provide one instrument, another is the build-out of electrolysers that can absorb excess generation and store it in the form of molecules. Installed electrolyser capacity on the territory amounts to 3.7 (8.8) GW in *Offshore Baseline* (*Ambitious Offshore Development*).

When browsing the above list of installed capacities, one type of generation technology seems to be lacking: dispatchable thermal. Although small in share, their presence is crucial, especially at times of peak demand (and) when overall renewable generation is low. In a carbon-neutral power system, two fuels make up the entire thermal (gas) mix: hydrogen and biogas. In *Offshore Baseline* (*Ambitious Offshore Development*), 12.1 (7.6) GW of hydrogen-fuelled H22P and 2.8 (4.8) GW of biogas-based OCGT are installed. They respectively consume 5.5 (3.1) TWh of hydrogen and less than 1 TWh of biogas in 2050.

Loss of Load does not and curtailment seldom occurs, the latter due to ample flexibility in the system via electricity consuming processes like EVs, heat pumps and P2X. Although security of electricity supply seems to be guaranteed, there is one climate year in which *scarcity* prices are observed for 16 consecutive hours, pushing the annual average system marginal costs to their highest level of 88 and 89 €/MWh respectively.

Total hydrogen demand reaches 85 (83) TWh in *Offshore Baseline* (*Ambitious Offshore Development*). Supplying hydrogen can be done either through producing the molecule domestically or through importing. In *Offshore Baseline* (*Ambitious Offshore Development*), hydrogen imports on average amount to 66 (36) TWh, the remaining 19 (47) TWh are generated through home-made electrolysis. In *Ambitious Offshore Development*, the domestic production of hydrogen hence goes up by a factor of 2.6 (wrt *Offshore Baseline*) whilst hydrogen imports decrease by 42% pointing to the fact that additional access to cheap electricity imports (hub supplied electricity can be imported at prices (way) lower than 55 €/MWh) can substantially increase Belgian hydrogen production.

Finally, production and investment costs do not differ significantly in percentage terms between scenarios. In 2050, the former are €62 million higher in *Offshore Baseline* compared to *Ambitious Offshore Development*, but investment costs are €260 million lower.

# 6. Some hypotheses

**Table 5 Selection of hypotheses used in this publication, year 2050**

| | | Unit | Source |
|---|---|---|---|
| Carbon price | 350 | €/t$CO_2$ | European Commission (2018) |
| Price of natural gas | 39.6 | €/MWh LCV | European Commission (2018) |
| Price of coal | 14.1 | €/MWh LCV | European Commission (2018) |
| Price of biogas | 85 | €/MWh LCV | Artelys |
| Price of hydrogen import | 65 | €/MWh LCV | Artelys |
| VOLL | 15,000 | €/MWh | Artelys |
| Capex electrolyser | 58,436 | €/MW/year | European Commission (2018), Artelys |
| Capex OCGT | 54,034 | €/MW/year | European Commission (2018), Artelys |
| Capex CCGT | 64,321 | €/MW/year | European Commission (2018), Artelys |
| Capex CCGT with CCS | 128,641 | €/MW/year | European Commission (2018), Artelys |
| Capex H22P | 64,321 | €/MW/year | Artelys |

Note: LCV = Low Calorific Value.

# 7. References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