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Fuel for the future

More molecules or deep electrification of Belgium's energy system by 2050

October 2020

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Federal Planning Bureau

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Fuel for the Future

More molecules or deep electrification of Belgium's energy system by 2050

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Abstract – In a period in which we try to come to grips with the sanitary and economic effects of the coronavirus pandemic, a lot of high-level announcements on recovery plans containing e.g. fiscal stimuli to avoid further economic catastrophes are being uttered. This happens on both national and supranational level. An often-heard remedy to climb out of the recession is to start building the hydrogen economy. To that purpose, the European Commission formulated a strategy eyeing 40 GW of renewable hydrogen electrolysers by 2030.

In this report, the Federal Planning Bureau sets out to scrutinise the place hydrogen can occupy in the future Belgian energy system by 2050. In fact, this report focuses on two divergent evolutions of energy (end) uses: on the one hand, a far-reaching electrification of the final energy consumption, on the other, a sustained and increased use of gas for transport, (industrial) heating and power generation. In this report, different outcomes of the two future visions such as the required investments in infrastructure (interconnections, electrolysers, storage) are described.

This study necessitated a methodological adaptation of the Crystal Super Grid model that is frequently being used by the Federal Planning Bureau for its electricity sector analyses: next to extensive power system modelling, the uptake of detailed and dedicated gas infrastructure modelling was considered imperative, as well as the further flexibilization of demand.

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 a period in which we try to come to grips with the sanitary and economic effects of the coronavirus pandemic, a lot of high-level announcements on recovery plans containing e.g. fiscal stimuli to avoid further economic catastrophes are being uttered. This happens on both national and supranational level. An often-heard remedy to climb out of the recession is to start building the hydrogen economy. To that purpose, the European Commission formulated a strategy eyeing 40 GW of renewable hydrogen electrolysers by 2030. Belgium already mentioned its hydrogen ambition in its Long-Term Strategy, handed over to the European Commission in February 2020.

In this report, the Federal Planning Bureau sets out to scrutinise the place hydrogen can occupy in the future Belgian energy system by 2050. In fact, this report focuses on two divergent evolutions of energy (end-) uses: on the one hand, a far-reaching electrification of the final energy consumption, on the other, a sustained and increased use of gas for transport, (industrial) heating and power generation. These different future pathways provide the basis for the definition of two distinct scenarios, called respectively *'Deep Electrification'* and *'Diversified Energy Supply'*.

Both scenarios do respect and are compatible with the 1.5°C temperature increase limit as stated in the 2015 Paris Agreement: they both set sail towards a full decarbonisation (net zero greenhouse gas emissions) in 2050. To achieve this goal of full decarbonisation, both direct and indirect electrification are assumed to (take off and) increase dramatically. Direct electrification means that fossil fuels used for certain energy end-uses (like e.g. transport and heating) are replaced by electricity: this is actually what happens when buying an electric car or installing an electric heat pump. Indirect electrification means that electricity is being used in (an) industrial process(es), hence, is being converted into something else like hydrogen or ammonia. The latter two can then be used to satisfy the consumer's energy demand, be it for transport, heating, industrial processes or power generation.

Although both scenarios integrate (in)direct electrification, the degree to which they do, diverges. The scenario *'Deep Electrification'* is primarily based on direct electrification, whilst *'Diversified Energy Supply'* integrates more indirect electrification.

The present analysis contains a selection of indicators (called KPIs or *Key Performance Indicators*) to investigate the impact of more (in)direct electrification on the future Belgian power system. In general, in both scenarios, total power demand in 2050 increases dramatically compared to today's levels: it is up to three times higher than 2018 demand. On top of that, the partial flexibilization of power demand is proving to be an important aid in supporting the future energy system operation.

In 2050, supply of electricity originates in a combination of domestic production (88%) and net imports (12%). The former is based on a highly renewable energy system: the share of renewable energy sources in the electricity production mix lies between 67 and 68%. This, however, does not mean that gas units are singing their swan song anytime soon. Gas, which is composed of e-gas, biogas and some remaining fossil gas burnt in thermal units equipped with carbon capture and storage, occupies a third (32 to 33%) of the future power mix.

Belgium remains a net importer of electricity in 2050: it imports more power than it exports. Net imports reach, on average, 29 TWh. A cold winter, as simulated in one of the investigated climate years, decreases the domestic production of electricity (and hydrogen for that matter) and increases net imports. Nevertheless, Belgium does export (and transmit) power. Its major clients are France and the UK which both have nuclear energy in their capacity mix. Belgium primarily imports from the Netherlands, followed by Germany.

Curtailment is low in both scenarios and generation adequacy can be assured, even during rather harsh winter conditions (mimicking the winter of 2010), according to the current legal (double) criteria. System marginal costs, a proxy for wholesale power prices, are, on average, comparable between scenarios.

Where the two scenarios differ, is, first, in their need of flexibility and in their (use of) flexibility instruments. Flexibility in future power systems is crucial since the penetration of variable renewable energy sources (wind and solar) is high: they represent 58 to 60% of domestic generation. Since these renewables are weather dependent (they only produce electricity when wind is blowing and sun is shining), other generation, demand and storage units have to fill the gaps. Above that, the dynamics of demand (daily peaks, weekday-weekend, seasonal patterns) add to the flexibility needs. The need for flexibility is higher in *'Diversified Energy Supply'* and electrolysers combined with gas-fired power plants are the main daily, weekly and annual flexibility providers. In *'Deep Electrification'*, electricity imports together with electric vehicles become more important daily and weekly flexibility suppliers: they compensate for the lower installed electrolyser capacity. The latter nevertheless contribute substantially to ease the flexibility needs, even in *'Deep Electrification'*, in which they provide half of the annual flexibility needs.

Both scenarios do make use of the (existing) gas infrastructure, but how much they use it and its main purpose differs: in *'Diversified Energy Supply'*, it is primarily used to satisfy energy end-uses, whilst in *'Deep Electrification'*, it provides an important means of flexibility for the power system.

Another interesting finding is that more trade takes place in *'Deep Electrification'*: more imports, but also more exports can be observed. This can be explained by two factors: 1) its somewhat higher Net Transfer Capacity, 2) the system possessing a higher degree of flexible electricity demand that can be traded off for interesting electricity import and export opportunities.

The aggregate demand for hydrogen (including pure hydrogen and hydrogen further processed into e-gas and e-liquids) in Belgium is substantial. If Belgium is interested in producing a (large) part of this hydrogen on its own territory, it should foresee ample renewable energy sources (including biogas). Domestic production of hydrogen via electrolysis can amount up to 99 (80) TWh in '*Diversified Energy Supply*' (*'Deep Electrification'*). Importing hydrogen is another option: if there is little or no cheap electricity available and/or if the price of producing hydrogen elsewhere and transporting it to our country ('*shipping the sunshine*') is more attractive, imports will increase.

As regards the exploitation costs of the power system, *'Deep Electrification'* seems to have somewhat lower costs compared to *'Diversified Energy Supply'*. The difference between the two scenarios, nonetheless, is rather small, certainly when it is being compared to the total energy system cost.

The exploitation costs, however, do not comprise the investment costs (or annuities) of the different systems, they only relate to the costs incurred by electricity system operations (production, curtailment and loss of load). The investment costs (not reported in this publication) will be considerable given that the energy system of the future is infrastructure (capex) heavy and a lot of investments (still) need to be (re)done or upgraded. In 2050, both scenarios count on an installed capacity of 39 GW of solar PV and 25 GW of wind. The capacity of electrolysers, interconnectors and gas-fired units, however, differs according to the scenario. The first amounts to 19.1 (10.6) GW in *'Diversified Energy Supply'* (*'Deep electrification'*), the second reaches 14 (14.4) GW whilst the last amounts to 11.0 (15.8) GW.

In order to entice potential stakeholders to invest capital in the construction of a such system, it is of paramount importance to create a stable regulatory and policy environment. In this respect, in addition to the ambition already shown in the Green Deal, the latest European Commission proposal on the total greenhouse gas emission reduction target for 2030 and its imminent climate law are not voluntary announcements, but create a framework within which national future-proof policies should be embedded.

Finally, additional studies on investment costs, potential risks for market participants or necessary market design adaptations associated to both future systems would be valuable complements to this report. That, however, is food for other publications.

Synthese

In een periode waarin we grip proberen te krijgen op de sanitaire en economische gevolgen van de coronapandemie, zijn verschillende herstelplannen aangekondigd die fiscale stimulansen bevatten om een verdere economische catastrofe te vermijden. Dit gebeurt zowel op nationaal als op supranationaal niveau. Een oplossing die vaak wordt aangehaald om uit de recessie te geraken is de opbouw van de waterstofeconomie. Met het oog daarop heeft de Europese Commissie een waterstofstrategie geformuleerd die streeft naar een elektrolysecapaciteit op basis van hernieuwbare waterstof van 40 GW tegen 2030. België heeft zijn waterstofambitie al vermeld in zijn langetermijnstrategie, die in februari 2020 aan de Europese Commissie werd overhandigd.

In dit rapport wil het Federaal Planbureau de plaats die waterstof kan innemen in het toekomstige Belgische energiesysteem tegen 2050 onder de loep nemen. Dit rapport richt zich in feite op twee uiteenlopende evoluties van het (eind)energieverbruik: enerzijds een verregaande elektrificatie van het finaal energieverbruik en anderzijds een voortgezet en groter gebruik van gas voor vervoer, (industriële) warmte en elektriciteitsopwekking. Deze verschillende toekomsttrajecten vormen de basis voor de definitie van twee uiteenlopende scenario's: *'Deep Electrification'* en *'Diversified Energy Supply'*.

Beide scenario's respecteren en zijn verenigbaar met een maximale temperatuurstijging van 1,5°C, zoals vastgelegd in de Overeenkomst van Parijs van 2015: ze zijn allebei gericht op een volledig koolstofarme economie (een netto nuluitstoot van broeikasgassen) tegen 2050. Om die doelstelling te behalen, wordt verondersteld dat de directe en indirecte elektrificatie (een doorbraak kennen en) sterk stijgen. Directe elektrificatie houdt in dat fossiele brandstoffen die worden aangewend voor een bepaalde finale energievraag (zoals bv. vervoer en verwarming) worden vervangen door elektriciteit: dit is wat er gebeurt bij de aankoop van een elektrische auto of het installeren van een elektrische warmtepomp. Indirecte elektrificatie betekent dat elektriciteit wordt gebruikt als input in (een) industriële proces(sen) en dus wordt omgezet in iets anders zoals waterstof of ammoniak. De laatste twee kunnen dan worden gebruikt om aan de energievraag van de consument te voldoen, of het nu gaat om vervoer, verwarming, industriële processen of elektriciteitsopwekking.

Hoewel beide scenario's (in)directe elektrificatie integreren, verschilt de mate waarin dit gebeurt. Het scenario *'Deep Electrification'* is voornamelijk gebaseerd op directe elektrificatie, terwijl *'Diversified Energy Supply'* meer indirecte elektrificatie integreert.

Deze analyse bevat een selectie van indicatoren (KPI's of *Key Performance Indicators*) om de impact van toenemende (in)directe elektrificatie op het toekomstige Belgische elektriciteitssysteem te bestuderen. Algemeen genomen stijgt de totale elektriciteitsvraag in 2050 sterk in beide scenario's ten opzichte van het huidige niveau: de vraag is tot drie keer hoger dan in 2018. Bovendien blijkt de gedeeltelijke flexibilisering van de elektriciteitsvraag een belangrijk hulpmiddel te zijn in de ondersteuning van de werking van het toekomstige energiesysteem.

In 2050 is het elektriciteitsaanbod een combinatie van binnenlandse productie (88 %) en netto-invoer (12 %). De binnenlandse productie is gebaseerd op een hoofdzakelijk hernieuwbaar-energiesysteem: het aandeel van hernieuwbare energiebronnen in de elektriciteitsproductiemix ligt tussen 67 en 68 %. Dit betekent echter niet dat gaseenheden binnenkort hun zwanenzang zingen. Gas, dat bestaat uit e-gas, biogas en een klein deeltje resterend aardgas dat wordt verbrand in thermische eenheden die zijn uitgerust met koolstofafvang en -opslag, vertegenwoordigt een derde (32 tot 33 %) van de toekomstige elektriciteitsmix.

België blijft een netto-invoerder van elektriciteit in 2050: de invoer is hoger dan de uitvoer. De netto-invoer bedraagt gemiddeld 29 TWh. Een koude winter, zoals gesimuleerd in een van de onderzochte klimaatjaren, vermindert de binnenlandse productie van elektriciteit (en van waterstof) en verhoogt de netto-invoer. Niettemin exporteert (en voert) België elektriciteit (door). De belangrijkste afnemers zijn Frankrijk en het Verenigd Koninkrijk, die beide kernenergie in hun capaciteitsmix hebben. België importeert vooral uit Nederland, gevolgd door Duitsland.

Stroombeperkingen (*curtailment*) zijn in beide scenario’s erg laag en de toereikendheid van de elektriciteitsvoorziening kan worden gewaarborgd, zelfs tijdens vrij strenge winters (zoals de winter van 2010), volgens de huidige wettelijke (dubbele) criteria. De marginale systeemkosten, een maatstaf voor de groothandelsprijzen voor elektriciteit, zijn gemiddeld genomen vergelijkbaar tussen beide scenario's.

De scenario's verschillen echter in de nood aan flexibiliteit en in hun (inzet van) flexibiliteitsinstrumenten. Flexibiliteit is cruciaal in toekomstige elektriciteitssystemen aangezien de penetratie van variabele hernieuwbare energiebronnen (wind en zon) hoog is: zij vertegenwoordigen 58 tot 60 % van de binnenlandse elektriciteitsproductie. Aangezien deze hernieuwbare energiebronnen weersafhankelijk zijn (ze produceren enkel elektriciteit wanneer er wind is en de zon schijnt), moeten andere opwekkings-, vraagsturings- en opslagunits de leemtes opvullen. Daarnaast draagt de vraagdynamiek (dagelijkse pieken, weekdag-weekend, seizoenspatronen) bij tot de flexibiliteitsnoden. De nood aan flexibiliteit is hoger in *‘Diversified Energy Supply’* en elektrolysers gecombineerd met gasgestookte elektriciteitscentrales zijn de voornaamste dagelijkse, wekelijkse en jaarlijkse aanbieders van flexibiliteit. In *‘Deep Electrification’* worden de elektriciteitsinvoer en elektrische voertuigen belangrijkere dagelijkse en wekelijkse aanbieders van flexibiliteit: ze compenseren de lagere geïnstalleerde elektrolysecapaciteit. Deze laatste dragen echter aanzienlijk bij tot het verlichten van de flexibiliteitsnoden, zelfs in *‘Deep Electrification’*, waar ze de helft van de jaarlijkse flexibiliteitsnoden dekken.

Beide scenario’s gebruiken de (bestaande) gasinfrastructuur, maar ze verschillen in hoeveel ze daarvan gebruikmaken en het voornaamste doel ervan: in *‘Diversified Energy Supply’* wordt de gasinfrastructuur voornamelijk gebruikt om aan de finale energievraag te voldoen, terwijl het in *‘Deep Electrification’* een belangrijk flexibiliteitsinstrument is voor het elektriciteitssysteem.

Een andere interessante uitkomst is dat in *‘Deep Electrification’* meer elektriciteitshandel plaatsvindt: er wordt niet alleen meer ingevoerd, maar ook meer uitgevoerd. Daarvoor kunnen twee factoren worden aangehaald: 1) de enigszins hogere interconnectiecapaciteit, 2) het feit dat het scenario een grotere flexibele vraag heeft die kan worden ingewisseld wanneer zich interessante mogelijkheden op het gebied van elektriciteitsinvoer- en uitvoer voordoen.

De totale vraag naar waterstof (bestaande uit waterstof én waterstof dat ingezet wordt om synthetisch gas en vloeistoffen te maken) in België is aanzienlijk. Als België een (groot) deel van deze waterstof op zijn grondgebied wil produceren, dient het te beschikken over voldoende hernieuwbare energiebronnen (waaronder biogas). De binnenlandse productie van waterstof via elektrolyse kan oplopen tot 99 (80) TWh in *'Diversified Energy Supply'* (*'Deep Electrification'*). Het importeren van waterstof is een andere mogelijkheid: als er weinig goedkope elektriciteit beschikbaar is in België en/of als de productieprijs (transportkosten inbegrepen) van waterstof in het buitenland aantrekkelijker is, wordt er meer geïmporteerd (*'shipping the sunshine'*).

De exploitatiekosten van het elektriciteitssysteem lijken in *'Deep Electrification'* enigszins lager te liggen in vergelijking met *'Diversified Energy Supply'*. Het verschil tussen beide scenario's is evenwel klein, vooral wanneer een vergelijking wordt gemaakt met de totale energiesysteemkosten.

De exploitatiekosten omvatten evenwel niet de investeringskosten (of jaarlijkse afbetalingen) van de verschillende systemen, aangezien die alleen betrekking hebben op de kosten die worden veroorzaakt door de werking van het elektriciteitssysteem (productie, stroombeperking en *loss of load*). De investeringskosten (die in deze publicatie niet worden onderzocht) zullen aanzienlijk zijn, aangezien het toekomstige energiesysteem infrastructuurintensief (*capex*) is en tal van investeringen (nog) moeten worden gedaan of opgeschroefd. In 2050 rekenen beide scenario's op een geïnstalleerde capaciteit van 39 GW aan zon-pv en 25 GW aan windenergie. De capaciteit van elektrolysers, interconnectoren en gasgestookte eenheden verschilt evenwel naargelang van het scenario. De eerste bedraagt 19,1 (10,6) GW in *'Diversified Energy Supply'* (*'Deep electrification'*), de tweede 14 (14,4) GW, terwijl de laatste 11,0 (15,8) GW bedraagt.

Om potentiële stakeholders te overhalen om kapitaal te investeren in de opbouw van een dergelijk systeem, is het uiterst belangrijk dat een stabiel regelgevend- en beleidskader wordt uitgewerkt. In dat opzicht zijn – naast de ambities in de Green Deal – het jongste voorstel van de Europese Commissie over de doelstelling met betrekking tot de totale broeikasgasemissiereducties voor 2030 en de nakende klimaatwet geen vrijblijvende aankondigingen, maar scheppen ze een kader waarbinnen nationale toekomstgerichte beleidsmaatregelen moeten worden verankerd.

Tot slot zouden bijkomende studies rond investeringskosten, potentiële risico's voor marktpartijen of noodzakelijke aanpassingen aan het marktontwerp waardevolle aanvullingen vormen op dit rapport. Dat is evenwel stof voor andere publicaties.

Synthèse

À l'heure où nous tentons de faire face aux conséquences sanitaires et économiques de la pandémie de coronavirus, les hautes instances tant nationales que supranationales multiplient les annonces sur des plans de relance incluant notamment des stimulants budgétaires dans le but d'éviter de nouvelles catastrophes économiques. Le développement de l'économie de l'hydrogène est une opportunité souvent citée pour sortir de la récession. Dans cette perspective, la Commission européenne a formulé une stratégie pour l'hydrogène visant à installer une capacité de 40 GW d'électrolyseurs pour l'hydrogène renouvelable à l'horizon 2030. La Belgique a déjà fait part de son ambition en matière d'hydrogène dans sa stratégie de long terme, qu'elle a transmise en février 2020 à la Commission européenne.

Dans ce rapport, le Bureau fédéral du Plan s'attache à examiner la place que l'hydrogène pourrait occuper dans le futur système énergétique de la Belgique d'ici 2050. Ce rapport se concentre plus particulièrement sur deux évolutions contrastées des usages (finaux) de l'énergie : d'une part, une forte électrification de la consommation finale d'énergie, d'autre part, une augmentation soutenue du recours au gaz pour les transports, les besoins de chaleur (industrielle) et la production d'électricité. Ces trajectoires d'avenir divergentes nous permettent de définir deux scénarios différents, appelés « *forte électrification* » et « *approvisionnement diversifié* ».

Ces deux scénarios respectent et sont compatibles avec l'objectif de limiter la hausse de la température de 1,5 °C, telle que convenue dans l'accord de Paris de 2015 : ils ouvrent la voie à une décarbonation totale (émissions nettes de gaz à effet de serre nulles) d'ici 2050. Pour atteindre cet objectif de décarbonation complète, on suppose que l'électrification tant directe qu'indirecte va (décoller et) s'intensifier considérablement. L'électrification directe implique que les combustibles fossiles utilisés pour certains usages finaux de l'énergie (comme par exemple le transport et le chauffage) sont remplacés par l'électricité. C'est exactement ce que vous faites quand vous achetez une voiture électrique ou une pompe à chaleur. L'électrification indirecte, quant à elle, signifie que l'électricité est d'abord utilisée dans des processus industriels puis convertie dans un produit tel que l'hydrogène ou l'ammoniac. Ces deux produits peuvent à leur tour être utilisés pour satisfaire la demande en énergie des consommateurs, que ce soit pour les transports, le chauffage, les processus industriels ou la production d'électricité.

Les scénarios intègrent tous deux l'électrification directe et indirecte mais dans des modalités différentes. Le scénario *'forte électrification'* repose avant tout sur l'électrification directe, tandis que le scénario *'approvisionnement diversifié'* table davantage sur une électrification indirecte.

L'analyse présentée ici fait appel à une sélection d'indicateurs (appelés ICP - indicateurs clés de performance) pour analyser l'impact d'une augmentation de l'électrification (in)directe sur le futur système électrique belge. De manière générale, dans les deux scénarios, la demande totale d'électricité augmente significativement d'ici 2050, en comparaison avec les niveaux actuels : la demande est jusqu'à trois fois supérieure à celle de 2018. En outre, la flexibilisation partielle de la demande d'électricité s'avère une aide importante pour faciliter l'exploitation du futur système énergétique.

En 2050, l'électricité sera fournie par une combinaison de production intérieure (88 %) et d'importations nettes (12 %). La production intérieure est assurée par un système composé dans une large mesure de sources d'énergie renouvelables : la part de ces sources d'énergie renouvelables dans le mix de production électrique oscille entre 67 % et 68 %. Ce large pan renouvelable ne signifie toutefois pas que le chant du cygne s'élèvera sous peu au-dessus des centrales au gaz. Le gaz, qui englobe à la fois les gaz de synthèse (renouvelables), le biogaz et du gaz naturel résiduel brûlé dans des unités thermiques équipées d'un système de capture et de stockage du carbone, représente un tiers (32 % à 33 %) du futur mix électrique.

La Belgique demeure, en 2050, un importateur net d'électricité : nous importons plus d'électricité que nous n'en exportons. Les importations nettes représentent, en moyenne, 29 TWh. Un hiver froid, comme simulé pour l'une des années climatiques investiguées, fait baisser la production intérieure d'électricité (et d'hydrogène) et croître les importations nettes. Malgré tout, la Belgique exporte (et transmet) de l'électricité. Ses principaux clients sont la France et le Royaume Uni qui disposent tous deux de centrales nucléaires dans leur mix de capacités de production en 2050. La Belgique importe essentiellement des Pays-Bas, et dans une moindre mesure de l'Allemagne.

La réduction de la production (*curtailment*) est faible dans les deux scénarios et l'adéquation de la production peut être assurée, même durant des hivers plutôt rigoureux (à l'exemple de l'hiver 2010), selon les (doubles) critères légaux actuels. Le coût marginal du système, un proxy pour les prix de gros de l'électricité, est en moyenne comparable dans les deux scénarios.

Les deux points sur lesquels les scénarios divergent sont les besoins de flexibilité et les instruments privilégiés de flexibilité. Dans les systèmes électriques d'avenir, la flexibilité est capitale dès lors que le taux de pénétration des sources d'énergie renouvelables variables (éolien et solaire) est élevé : ces sources représentent 58 % à 60 % de la production intérieure d'électricité. Puisqu'elles sont tributaires des conditions météorologiques (l'électricité n'est produite que si le vent souffle et que le soleil brille), d'autres moyens de production, de gestion de la demande et de stockage doivent pallier les insuffisances. Vient en outre s'ajouter, à ces besoins de flexibilité, la dynamique de la demande (les pics journaliers, jours de la semaine-weekend, les cycles saisonniers). Les besoins de flexibilité sont plus importants dans le scénario « *approvisionnement diversifié* » et les électrolyseurs, combinés aux centrales au gaz, assurent l'essentiel de la flexibilité sur base quotidienne, hebdomadaire et annuelle. Dans le scénario « *forte électrification* », les importations d'électricité et les véhicules électriques jouent un rôle plus important dans la flexibilité quotidienne et hebdomadaire dès lors qu'ils compensent la moindre capacité installée d'électrolyseurs. Ces derniers contribuent toutefois à alléger les besoins de flexibilité, même dans le scénario « *forte électrification* » où ils couvrent la moitié des besoins annuels.

Les réseaux gaziers existants sont sollicités dans les deux scénarios, mais les proportions et l'objectif principal recherché varient. Dans le scénario « *approvisionnement diversifié* », ils contribuent essentiellement à satisfaire les utilisations finales de l'énergie, alors que dans « *forte électrification* », ils constituent un important instrument de flexibilité du système électrique.

Un autre constat intéressant est que les échanges d'électricité sont plus nombreux dans le scénario « *forte électrification* » nonobstant des importations nettes comparables à celles du scénario « *approvisionnement diversifié* » : on y observe à la fois plus d'importations, mais aussi plus d'exportations. Ce constat peut s'expliquer par deux facteurs : premièrement, des capacités de transfert nettes légèrement plus élevées, deuxièmement, un degré plus élevé de flexibilité de la demande d'électricité qui ouvre la voie à des opportunités intéressantes d'importation et d'exportation d'électricité.

La demande totale d'hydrogène (comprenant l'hydrogène pur et l'hydrogène transformé ensuite en gaz et liquides de synthèse) est importante en Belgique. Si la Belgique envisage de produire une (grande) partie de cet hydrogène sur son territoire, elle devra prévoir un grand éventail de sources d'énergie renouvelables (y compris le biogaz). En effet, la production domestique d'hydrogène par le biais d'électrolyseurs pourrait atteindre jusqu'à 99 (80) TWh dans « *approvisionnement diversifié* » (« *forte électrification* »). L'importation d'hydrogène est une option complémentaire : elle augmentera s'il n'y a pas ou peu d'électricité bon marché disponible et/ou si le prix de la production d'hydrogène à l'étranger et de son transport vers notre pays est plus intéressant (*'shipping the sunshine'*).

Pour ce qui concerne les coûts d'exploitation du système électrique, ils semblent un peu moins élevés dans « *forte électrification* » en comparaison avec « *approvisionnement diversifié* ». Toutefois, l'écart entre les deux scénarios est plutôt réduit, surtout en comparaison avec le coût total du système énergétique.

Les coûts d'exploitation n'incluent cependant pas les coûts d'investissement (ou annuités) afférents aux différents systèmes, ils correspondent uniquement aux coûts induits par l'exploitation du système électrique (production, *curtailment* et perte de charge). Or, les coûts d'investissement (qui ne sont pas abordés dans cette publication) seront considérables. En effet, le système énergétique du futur repose sur de nombreuses infrastructures (capex) et un grand nombre d'investissements doivent encore être réalisés (réitérés) ou modernisés. Les deux scénarios comptent, en 2050, sur une capacité installée de 39 GW de solaire photovoltaïque et de 25 GW d'éolien. En revanche, la capacité d'électrolyse, d'interconnexion et des centrales au gaz varie selon les scénarios. La première s'élève à 19,1 (10,6) GW dans « *approvisionnement diversifié* » (« *forte électrification* »), la deuxième représente 14 (14,4) GW et la troisième 11,0 (15,8) GW.

Si l'on veut encourager les parties prenantes potentielles à investir des capitaux dans le développement de tels systèmes, il est de la plus grande importance de créer un cadre réglementaire et politique stable. À cet égard, outre l'ambition affichée dans le Green Deal, la dernière proposition de la Commission européenne en matière d'objectif de réduction des émissions totales de gaz à effet de serre pour 2030 et le règlement imminent sur le climat ne sont pas de simples déclarations, elles créent un cadre dans lequel devraient s'inscrire des politiques nationales pérennes.

Enfin, de nouvelles analyses centrées sur les coûts d'investissement, les risques potentiels pour les acteurs du marché ou les adaptations nécessaires du design du marché qui seraient associés aux deux systèmes étudiés ici, viendraient compléter utilement ce rapport. Ces analyses feront l'objet d'autres publications.

Glossary

Capex	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CSG	Crystal Super Grid
DD	Degree Days
EV	Electric Vehicles
FPB	Federal Planning Bureau
GCA	Global Climate Action
HP	Heat Pumps
KPI	Key Performance Indicator
LOHC	Liquid Organic Hydrogen Carriers
LOL(E)	Loss Of Load (Expectation)
LTS	Long-Term Strategy
MS	Member States
NTC	Net Transfer Capacity
P2X	Power-to-X
PSH	Pumped Storage Hydropower
PPA	Power Purchase Agreement
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
V2G	Vehicle-to-Grid
VOLL	Value Of Lost Load

1. Introduction

In a period in which we try to come to grips with the sanitary and economic effects of the coronavirus pandemic, a lot of high-level announcements on recovery plans containing e.g. fiscal stimuli to avoid further economic catastrophes are being uttered. This happens on both national and supranational level. One such example is the Next Generation EU recovery package that has as vocation to aid Member States (MS) to escape from the ongoing economic recession. Simultaneously, it also provides the necessary tools to put the MS on the road towards a zero-carbon economy by attaching green strings to the financing conditions[1]. As regards the Green Deal that was formally adopted by the European Commission on December 11, 2019, it is rather remarkable that it was not abandoned in the wake of the corona crisis. On the contrary, it received ample support from Commission President Von der Leyen and even gained a new twist by combining the ‘prepare’ for the (distant) future with a ‘repair’ the (near) future, thereby transforming the EU’s currently plagued economy into a climate-neutral, resilient and innovative future version.

One of the ambitions of the Green Deal is to roll out a clean hydrogen economy in Europe. This ambition is also mentioned by Belgium in its Long-Term Strategy (LTS[2]), handed over to the European Commission in February 2020. Next to Belgium, a lot of other Member States already signalled their ambitions in the field of hydrogen. On a regional level, the Pentalateral Forum[3] urged the European Commission to set targets for renewable hydrogen to 2030 and to increase its financial backing.

The greater and still growing attention for hydrogen, further exacerbated by the sanitary crisis and its ensuing economic recovery plans, made us want to investigate the potential role the molecule can play in the future Belgian energy system. For this, a new version of Crystal Super Grid was adopted. This version combines both power and (partial) gas systems and elaborates on the potential use of electrolysers and methanation plants. Interconnections and interdependencies between the other Member States are being integrated in the model, along with power and gas systems interlinkages. Reported results, however, solely focus on Belgium and cover the year 2050 (not the trajectory towards 2050).

In what follows, the newly 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[4]. These two scenarios depict two different states of the future Belgian energy system: one with a deep electrification philosophy, the other demonstrating a more diversified (hybrid) approach in which molecules occupy a bigger share. The analysis contains a selection of indicators (called KPIs or *Key Performance Indicators*) such as production, net imports, flexibility and system marginal costs. In chapter 5, the report wraps up with some conclusions.

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[1] Member States that want to tap into the EUR 750 billion recovery package have to show that their investments are in line with the ambitious objectives of the Green Deal.

[2] The LTS is in fact one of two documents that Member States, according to the governance of the Energy Union, have to submit to the European Commission. The first document is the National integrated Energy and Climate Plan (NECP) that scrutinizes the horizon 2030 (2040), the second is the LTS which addresses the year 2050.

[3] Comprised in fact of 7 countries, being Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland.

[4] 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 French Artelys team developed a new version of Crystal Super Grid (CSG[5]) that, next to a power module, integrates the uptake of dedicated gas-based infrastructure[6]. 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 (replacing 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[7], but as an input in an industrial process. Electricity is then used to produce hydrogen with an electrolyser. This hydrogen can then 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 can 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 so 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[8]. These provide the basis for the gas molecules that may be deployed in power generation, together with biomethane and some remaining fossil gas (lower right corner).

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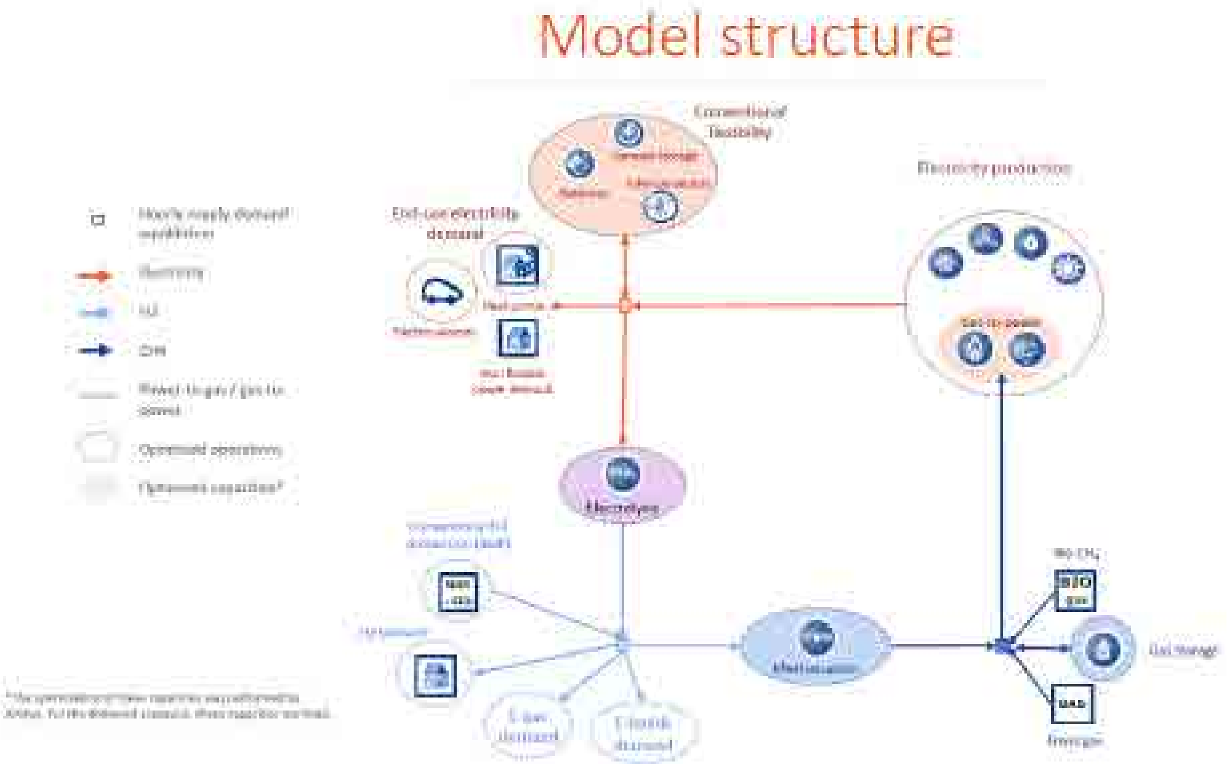
[5] Artelys' Crystal Super Grid is part of the Artelys Crystal suite that is dedicated to the economic optimization and management of energy systems. It was originally developed for the POST R&D project supported by ADEME.

[6] For a comprehensive overview of the CSG model, the interested reader is referred to https://www.plan.be/uploaded/documents/201901111032340.WP-5-DC2019_CrystalSG_11847_N.pdf.

[7] Which is the case in direct electrification.

[8] Methanation involves the reaction of hydrogen (H_2, produced during electrolysis) with carbon dioxide (CO_2) to produce methane ($4H_2 + CO_2 = CH_4 + 2H_2$).

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). Conventional hydrogen production through Steam Methane Reforming (SMR) with capture and storage of carbon dioxide (CCS) or hydrogen import at a given price are additional options[9].

2.2. Electricity sector

Renewable energy capacities and power demand are based on the 1.5TECH scenario run for the European Commission in its Long-Term Strategy (EC, 2018a) (see part 3.1 for further information). Since individual Member States' results are not available in that publication, we started from the overarching European outcomes and decided to disaggregate them. Smart allocation keys were defined on the basis of publicly available data from both the TYNDP2018 GCA (ENTSOG and ENTSO-E, 2019) and the METIS S1 2050 scenario[10] (European Commission, 2018b).

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[9] For reasons explained in section 4.3.2, the production of hydrogen with the SMR+CCS process is not considered in this study. The asset hence can be interpreted as an external source of hydrogen supply (import).

[10] Non-EU countries data are based on data from TYNDP2018 GCA. For further information, see https://eepublicdownloads.azureedge.net/clean-documents/tyndp-documents/TYNDP2018/Scenario_Report_2018_Final.pdf and https://www.artelys.com/wp-content/uploads/2019/04/S1-Optimal-flexibility-portfolios-for-a-high-RES-2050-scenario.pdf.

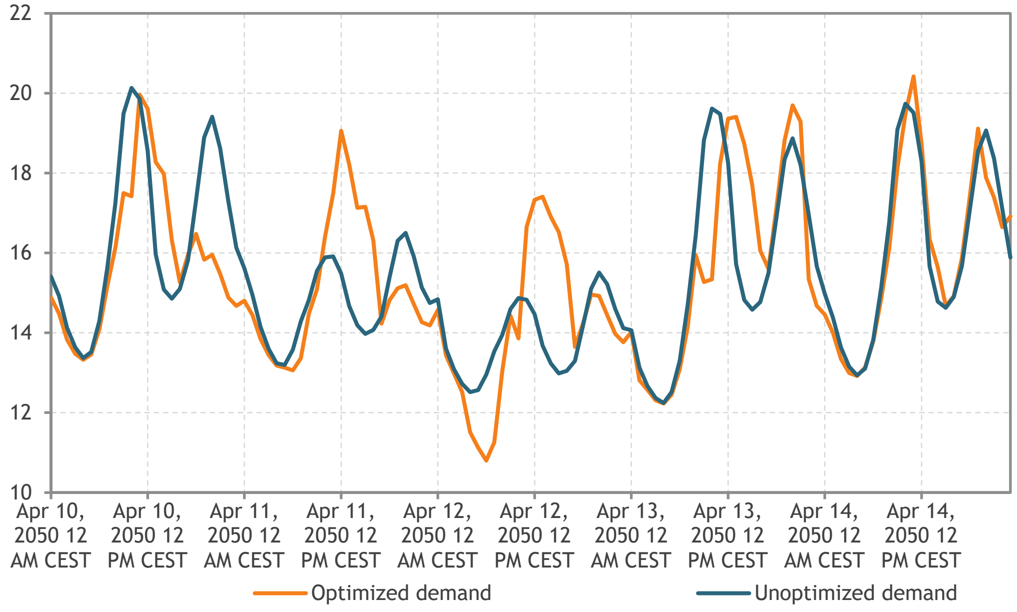
2.2.1. Electricity demand

According to that methodology, Belgian power demand has been deduced from the EU 1.5TECH scenario. Upon calculating the total power demand, CSG foresees the possibility of decomposing this 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). An illustration of those two behaviours can be found in Graph 2. Depending on the behavioural setting, end results may change dramatically since flexibilization can help to smoothen system operations.

Graph 2 **Illustration of flexible (optimised) and must-run (unoptimised) power demand, April 10-14, 2050**
GW



Source: Artelys, FPB own calculations.

2.2.2. Revisiting flexible means

In CSG, traditionally, the power system operation is being optimised (*optimal dispatch*[11]). Once the EU 1.5TECH scenario was integrated in CSG, a preliminary step (before the optimisation) had to be performed: we had to make sure that, upon increasing the use of electricity and/or molecule making in the system[12], sufficient flexibility means were present in the system at all times. This is the reason a

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[11] CSG is part of the Unit Commitment, Optimal Dispatch family of models.

[12] As is the subject of the scenarios (see section 3.2).

preceding capacity expansion calculation was performed by Artelys, yet with a limited selection of flexibility options: OCGT, CCGT, pumped storage, batteries, electrolysers and methanation units. Interconnections, representing a flexibility solution as well, were also part of the catalogue of investment options.

It is important to stress that this preliminary optimisation 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 average, one rather hot and one cold year) in order to represent solar, wind and power demand variability as well as their mutual interdependencies. These climate years relate to the years 2002, 2006 and 2010. According to the statistics on Belgian Degree Days (DD[13]), 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): 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[14], the results reflect the average of the different test cases.

2.3. Power-to-X demand

Power-to-X (also P2X) stands for (a number of) electricity conversion (and storage and reconversion) pathways that use electric power, typically during periods in which variable renewable electricity generation exceeds load. The (re)conversion of power (towards the X part in the terminology) includes many possibilities, e.g. power-to-ammonia, power-to-hydrogen, power-to-methane, power-to-power, etc. It in fact allows for the coupling (or integration) of different sectors: electricity, gas and potentially others such as transport or chemicals. These power-to-X schemes fall under the category of flexibility options and come in particularly handy in electricity systems with elevated shares of variable renewable energy sources and/or strong decarbonization targets.

In CSG, all power-to-X demand (gathering e-gas, e-liquids and pure hydrogen) is being represented by an aggregate hydrogen demand since hydrogen constitutes a basic building block (see Graph 1). The estimated quantity of this aggregate hydrogen demand is based on an in-depth study of the literature, amongst which a thorough investigation of the Belgian industrial sector (see Annex 6.1).

As already stated in section 2.2.1, hydrogen demand can be modelled in two ways:

- Satisfy the raw (non-flexible) demand (as given by the user) by the existing production means;

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[13] Consulted on https://www.gas.be/nl/graaddagen/ on July 24, 2020.

[14] Specific mentioning of the Test Case in the title of the graph or table.

- Opt for a flexible demand so as to smoothen system operation: the flexibility of the hydrogen demand can then be used to balance the production of renewable energy sources (RES) throughout the year by adapting hydrogen production to the residual load profiles.

2.4. Biomass and biogas potential

The total biomass and biogas potential is derived from the 1.5TECH scenario. In fact, the potential available per country (comprising both domestic production and net imports from within the EU) is a country decomposition of the EU potential for power generation as stated in the EU LTS (European Commission, 2018a). Smart disaggregation keys are applied based on publicly available data.

Upon comparing the estimated Belgian biogas potential based on the LTS with the figures advanced by other institutions (ICCT (2019), FTI Compass Lexecon (2018)), this potential seems to be on the more optimistic side of the spectrum. Nevertheless, it is important to remember that the latter is the sum of domestic biogas production and net imports[15].

In this report, we assumed that the available biogas in 2050 is primarily directed towards the power sector, the reason being that there is greater opportunity for carbon reductions through the use of renewable methane for electricity generation than in the transport or heating sectors, especially when considering the difference in cost (ICCT, 2019).

Last, it is worth noting that assumptions on biogas potential are highly dependent on future agricultural (and industrial) policies.

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[15] Although biogas is nowadays mostly used on site, it can also be sold to the grid, depending, among other things, on the existing gas infrastructure and connection costs.

3. The scenarios

For this study, two scenarios were drafted: one is called '*Deep Electrification*', the other '*Diversified Energy Supply*'. Both scenarios are based on a public version of the 1.5TECH scenario, documented in the European Commission's Long-Term Strategy which is a full decarbonisation scenario that is mainly built on the deployment of new technologies. For further information, the interested reader is referred to the in-depth analysis of "A *Clean Planet for all*" (European Commission, 2018a[16]).

These two 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*'. The discussed scenarios follow the latter line of reasoning by taking the 1.5°C global temperature increase as a starting point.

3.1. Based on the 1.5TECH scenario

The 1.5TECH scenario is a scenario developed for the entire EU in which the 1.5°C climate ambition is honoured and in which total EU greenhouse gas emissions are slashed by 100% (incl. sinks) by 2050. The EU in its entirety (across different sectors and countries) will be climate neutral (full decarbonisation). The major lever for achieving this is a cost-efficient combination of different abatement technologies, complemented with an enhanced use of (BE)CCS[17]. Behavioural changes are included to some extent, but compared to the 1.5LIFE scenario, another LTS scenario constructed for the EU, this occurs in a rather conservative manner. The main angle of greenhouse gas emissions reduction is technology driven.

Of all scenarios investigated by the European Commission in its LTS (see Graph 3), the 1.5TECH demonstrates the highest installed power generation capacity, both in total as in (variable) renewable energy sources ((v)RES). As regards the large-scale deployment of vRES, the installed EU capacity mounts to 2300 GW by 2050. A significant part of the electricity production based on vRES is used for indirect electrification. The estimated amount of installed capacity of electrolysers in 2050 reaches 500 GW.

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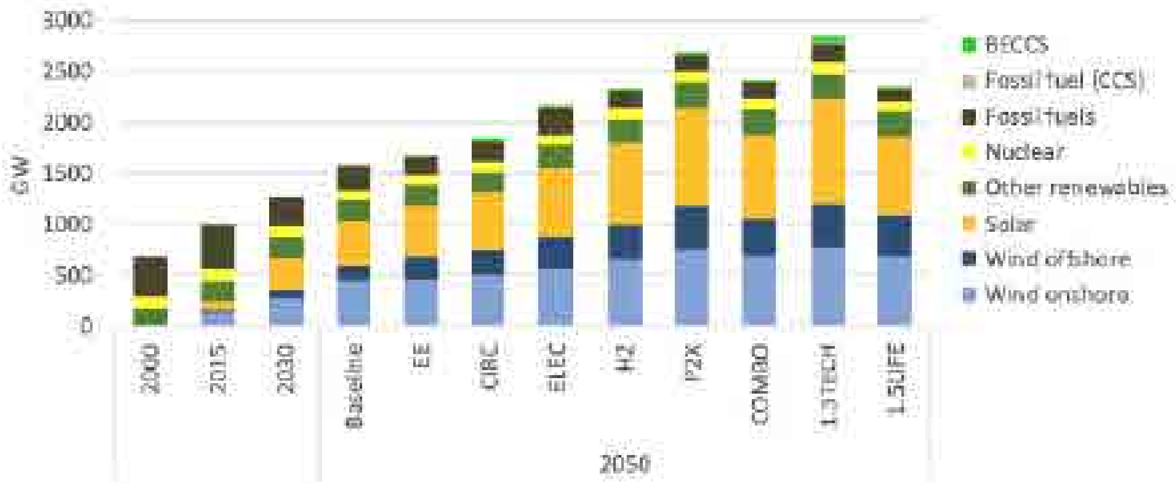
[16] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf.

[17] (BE)CCS stands for (bioenergy with) carbon capture and storage. The capture of carbon dioxide from bioenergy sources effectively removes CO_2 from the atmosphere, leading to so-called negative emissions. For more information, see e.g. https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf.

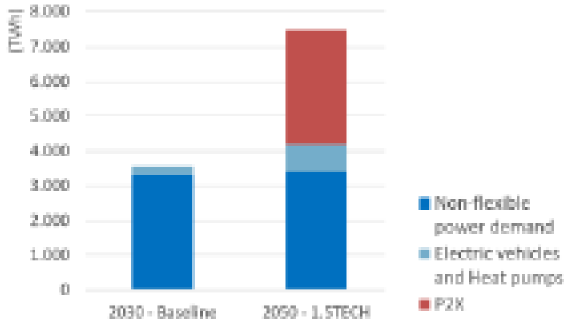
Graph 3 Installed EU power generation capacities in the different LTS scenarios, 2000-2050
GW



Source: EC, 2018a.

In regard to the fuel consumption, direct and indirect electrification largely replace the use of fossil fuels in all sectors. By 2050, natural gas has mostly switched places with hydrogen and carbon-free gases, thermal generation is powered by e- and biogas.

Graph 4 EU power demand, 2030 (baseline) and 2050 (1.5TECH)
TWh



Source: EC, 2018a.

When it comes to electricity demand, a significant increase compared to the 2018 (last available observation) and 2030 level can be spotted. This increase is mainly driven by indirect electrification through the production of hydrogen, e-gas and e-liquids (P2X, depicted as the red bar). As a matter of fact, more than a third of future electricity demand will be solely destined to P2X. Direct electrification (through the increased deployment of electric heat pumps (HP) and electric vehicles (EV), depicted as the light blue bar) also increases. Combined, the total power demand by 2050 will double (almost triple) compared to a baseline projection in 2030 (2018 statistic).

3.2. The 2 FPB scenarios

In this section, we take a deeper look at the two Belgian scenarios called '*Deep Electrification*' and '*Diversified Energy Supply*'. In a nutshell, the '*Diversified Energy Supply*' scenario relies more on molecules to pave the way to societal decarbonisation, whilst '*Deep Electrification*' bets on a more direct use of the juice.

As already stated, the two scenarios are based on the 1.5TECH scenario. Why are the scenarios studied in depth for Belgium based on and not taken from the 1.5TECH scenario? Because the LTS results are not published on country level, only on the aggregate EU level. Hence, a tailored approach had to be implemented. This approach consists in using publicly available data in order to define disaggregation keys for the different Member States. Afterwards, the Belgian context is adapted as to accommodating way more electricity (in the '*Deep Electrification*' scenario) or more of a combination of electricity and gas (in the '*Diversified Energy Supply*' scenario).

An example of the disaggregation approach can be found in the estimation of the power consumption of electric vehicles (EV). To get an idea of the power consumption of battery driven vehicles in Belgium in the year 2050, the total European electric consumption of EV is taken from the LTS public data. The repartition between the different countries then is performed using a second study from the European Environmental Agency, called '*Electric vehicles and the energy sector, impacts on Europe's future emissions*' (https://www.eea.europa.eu/publications/electric-vehicles-and-the-energy/). Combining both sources delivers an estimation of the Belgian EV power uptake.

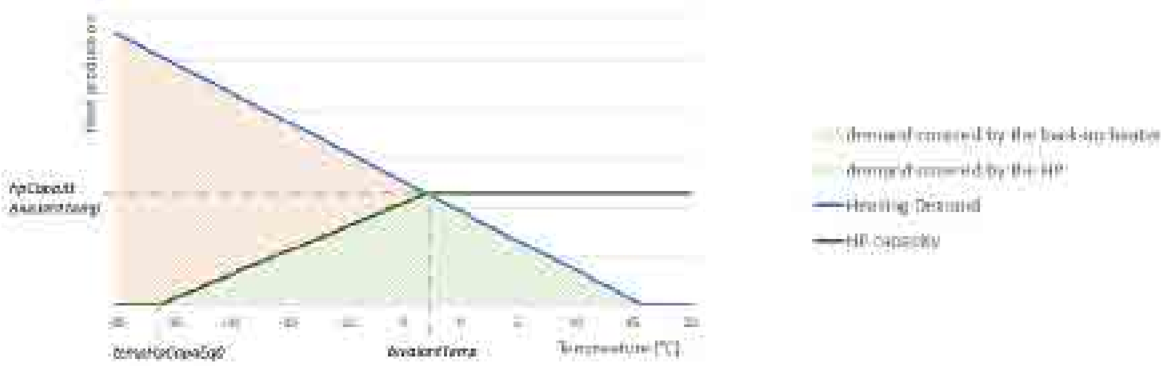
3.2.1. Buildings

As regards residential heating in 2050, heat pump deployment is widespread. Both scenarios demonstrate a large distribution of heat pumps, but there are some noticeable differences. In the '*Diversified Energy Supply*' scenario, two categories of heat pumps (HP) are being installed: electric HP and hybrid HP. The former (accounting for 20% of the installed HP capacity) integrates partial flexibility through thermal storage, whilst the latter (the remaining 80%) is equipped with gas back-up allowing peak shaving. In '*Deep Electrification*', the degree of electrification of space heating is assumed to be 10 percentage points higher than in '*Diversified Energy Supply*'. Only flexible electric heat pumps with thermal storage are part of the system.

Box 1 Functioning of a Heat Pump

A heat pump is a technology based on the use of (renewable) heat from the environment (air, geothermal, etc.) to provide the necessary heat for space heating and cooling and water heating. An electrically driven pump is, however, needed to drive the compressor and circulate the working fluid.

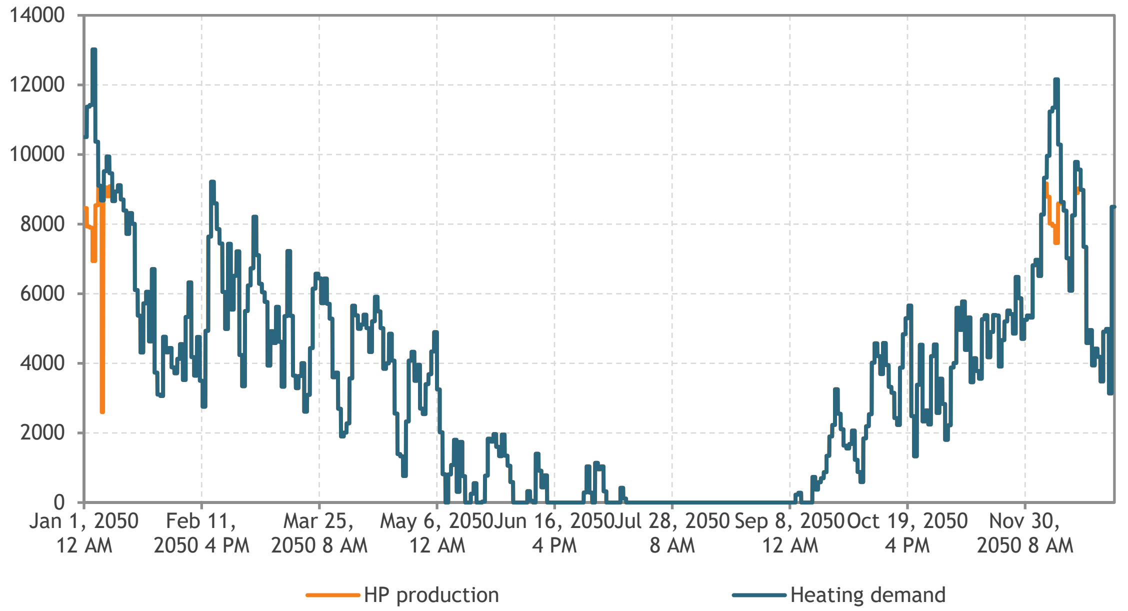
As regards the functioning of a heat pump, it can be remarked that the capacity of a heat pump decreases linearly with the temperature, and falls to zero below -26°C. This leaves a gap between the rising heat demand when temperature decreases, which is an obvious linear relation depicted by the blue line in the graph below, and the HP capacity, the black line. The temperature at which the heat pump capacity equals the heating demand is called the bivalent temperature. Below this temperature, the use of a back-up heater is required to cover the remaining heating demand.



Source: Artelys.

The heating demand is exogenously determined by Artelys as a function of the national temperature profile, while taking temperature related performance losses into account. A graphical illustration is provided in Graph 5 (blue line). The resulting heat production by the Heat Pumps is shown as the orange line, largely coinciding with (hence, fulfilling) the heating demand. Only on some limited occasions during the winter, the orange line is situated below the blue line: at those specific moments in time, back-up heating is necessary. Also interesting to see is that during summer, (almost) no heat production takes place.

Graph 5 **Heating demand and Heat Pump production, Diversified Energy Supply, Test Case 0, year 2050**
MW



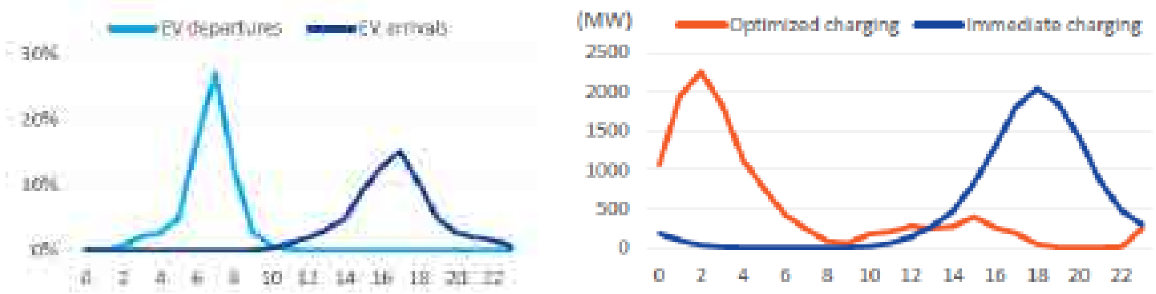
Source: Artelys.

3.2.2. Transport

As regards passenger road transport, the two scenarios diverge in terms of the share of electric and fuel cell vehicles. The '*Diversified Energy Supply*' scenario integrates a more balanced distribution of both types of technologies (60% electric, 36% fuel cell, 4% other) whilst '*Deep Electrification*' counts on a share consistent with the LTS numbers: 80% electric, 16% fuel cell and 4% other powertrains.

Smart charging is implied in both scenarios. Smart charging means that each vehicle, once connected to the grid, can decide when best to charge its battery given grid constraints. One condition: it has to be fully loaded before departure from its terminal. During its journey, the vehicle will (partially) discharge. In '*Diversified Energy Supply*', smart charging is activated in 80% of all EV's and 50% has the option to feed electricity back to the grid (V2G[18]). In the '*Deep Electrification*' future, smart charging applies to all EVs (100%), whilst 80% is equipped with the V2G option, providing additional flexibility to the system.

Graph 6 **Smart charging versus immediate charging of EVs, graphical illustration**



Source: Artelys.

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[18] V2G can be interpreted as a storage facility for the power grid provided by the batteries of the connected EVs.

3.2.3. Industry

The assumptions for industry in '*Diversified Energy Supply*' are based on the idea that decarbonisation happens in a rather balanced way, with a combination of both (in)direct electrification, biomass/biogas boilers and CHP. In '*Deep Electrification*', direct electrification gains further ground: both low and medium temperature processes are based on electricity, whilst high temperature applications may be more diversified. For more information on the industrial energy demand modelling, the reader is referred to the Annex.

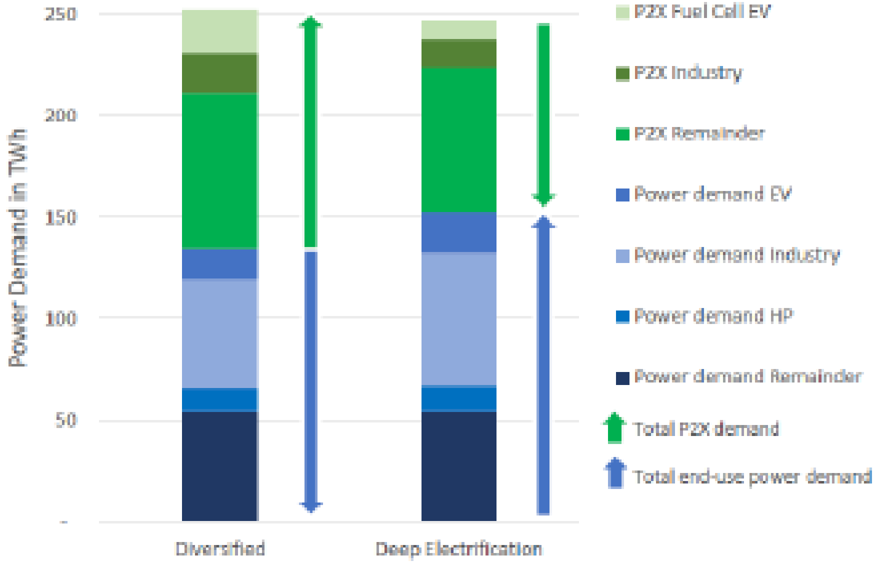
After the description of the end-use assumptions, the focus in the next subsections comes to lie on the power sector: total power demand and the necessary energy infrastructure to supply it are outlined.

3.2.4. Power demand

Total electricity demand in Belgium in '*Diversified Energy Supply*' ('*Deep Electrification*') amounts to 249 (243) TWh, which is about 3 times higher than today's level. It might seem paradoxical that electricity demand in '*Deep Electrification*' is not higher (even the opposite) than in '*Diversified Energy Supply*'. This can be attributed to three elements (see also Graph 7):

1. the power demand gathers all ((in)direct) demand for power (including transformation);
2. transformation means conversion losses. Transforming electricity into hydrogen (or other fuels) always comes at a loss: the efficiency of the electrolysis process reaches 85%. Since '*Diversified Energy Supply*' is built on way more indirect electrification, its P2X (indirect) power demand hence is higher: it attains 117 TWh compared to 94 TWh in '*Deep Electrification*';
3. although end-use (direct) power demand is higher in '*Deep Electrification*' (154 TWh versus 134 TWh in '*Diversified Energy Supply*'), the surplus does not compensate for the lower indirect electricity consumption.

Graph 7 Total power demand in both scenarios, Belgium, year 2050
TWh



Source: Artelys.
Note: The direction of the arrows indicates the relative level of the specific (P2X or end-use) electricity demand: upwards (downwards) means a higher (lower) level compared to the other scenario.

3.2.5. Energy infrastructures

When it comes to the necessary energy infrastructure, four types can be distinguished: electrolysers, gas storage infrastructure, electricity interconnectors and power generation capacities.

a. Electrolysers

As stated in section 2.2.2, electrolysers are part of the capacity optimisation package: 19.1 GW is installed in '*Diversified Energy Supply*' versus 10.6 GW in '*Deep Electrification*'. The main reason for the difference is the fact that capital expenditures (capex) are assumed to be rather low (in line with the LTS assumptions) in the '*Diversified Energy Supply*' scenario whilst in '*Deep Electrification*', they are presumed to be considerably higher (up to 3 times higher compared to the LTS hypotheses).

b. Gas storage infrastructure

Since the gas system is assumed to provide a lot of flexibility to the 2050 power system, no specific constraints are added ex ante to the potential level of gas storage: it is modelled to be 'infinite' in both scenarios. The actual use of gas storage, however, is being optimised by the model on an hourly basis[19].

c. Electricity interconnections

As regards electricity interconnections, they too were part of the capacity optimisation package, leading to the fact that the Net Transfer Capacity (NTC) in the '*Diversified Energy Supply*' scenario is somewhat lower (-0.4 GW) than in '*Deep Electrification*'. This result can be explained by the fact that the larger

---

[19] Ex post, we see that the use of gas storage (for providing flexibility to the power system) is marginal given that there is a myriad of end-use gas applications.

electrolyser capacity in the former scenario compensates for the additional flexibility being provided by the electricity interconnectors in the latter scenario (see also section 3.2.5.d).

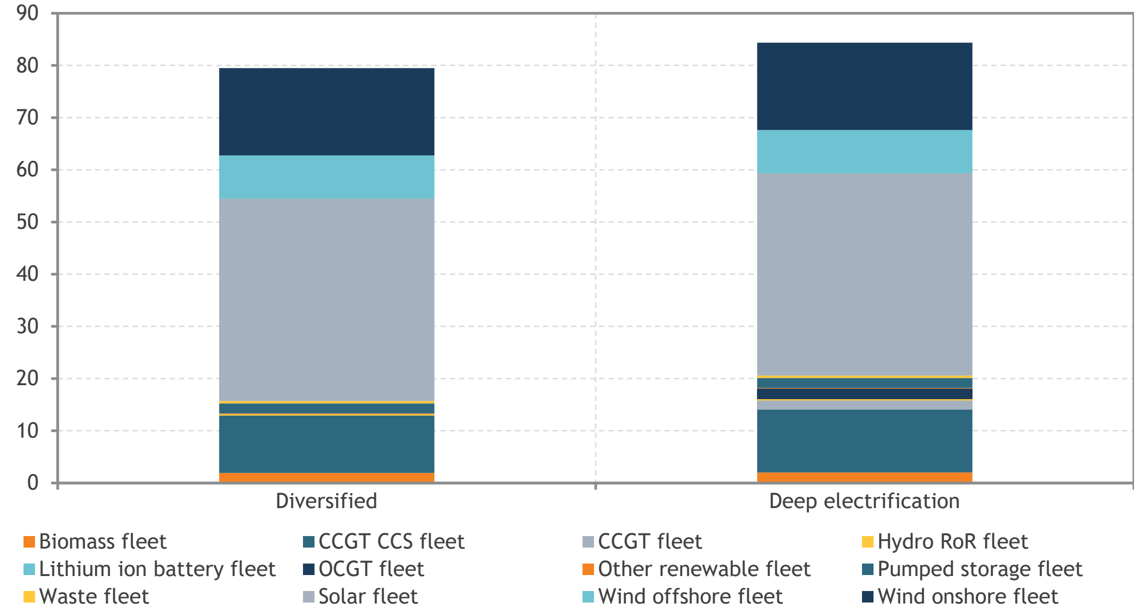
d. Power generation capacity

General

Total installed power generation capacity in both scenarios in 2050 is substantial: it largely exceeds (by a factor of almost 4) the current level of domestic capacity.

Graph 8 **Installed power generation capacity in both scenarios, Belgium, year 2050**

GW



Source: Artelys, FPB own calculations.

Although the absolute level of installed capacity is rather similar[20], its composition shows some more divergences (see Graph 8). Both scenarios count on a significant amount of solar and wind (both onshore and offshore): by 2050, 39 GW of solar PV is installed in Belgium, next to 25 GW of wind[21]. Together, they represent (almost) 80% of the capacity mix. Differences can be spotted in the (presence and) installed amount of biomass units, CCGT, OCGT and batteries: all are (somewhat) higher in '*Deep Electrification*'.

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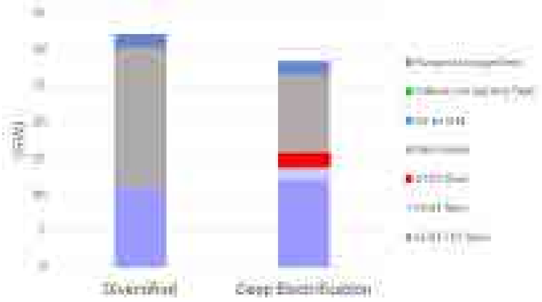
[20] The difference represents less than 6%.

[21] Of which offshore takes 8.3 GW.

Flexible means

Graph 9 Flexibility portfolio in both scenarios, Belgium, year 2050
GW



Source: Artelys.

As part of the installed capacity, it is worth spending a few extra words on the flexible means. As stated in section 2.2.2, the flexibility portfolio is being optimised by the model (an extended version of CSG) before the actual dispatch calculations take place. From Graph 9, it becomes obvious that the gas-fired capacity (OCGT, CCGT and CCGT equipped with CCS) in '*Deep Electrification*' is superior, principally due to the higher end-use (direct) electricity demand (see section 3.2.4). On the other hand, the installed electrolyser capacity is significantly lower than in *'Diversified Energy Supply'*, which can be ascribed to the lower P2X (indirect) demand. Both scenarios count on an equal amount of pumped storage (1908 MW[22]) and hardly show a penetration of stationary batteries. The latter can be explained by the fact that P2X and flexible end-uses directly compete with batteries for daily flexibility, resulting in very low additional investments in stationary batteries.

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[22] Pointing at an extension of the current installed capacity of pumped storage in Belgium (1300 MW) provided by the installation of a third basin in Coo or a large-scale storage facility in the Belgian part of the North Sea.

4. Results

In this section, the two scenarios are being scrutinised. We will systematically start with the analysis of the *'Diversified Energy Supply'* scenario to afterwards compare it to *'Deep Electrification'*. Several KPI's will be documented: (power and hydrogen) demand and supply, flexibility, Loss of Load and (some) costs.

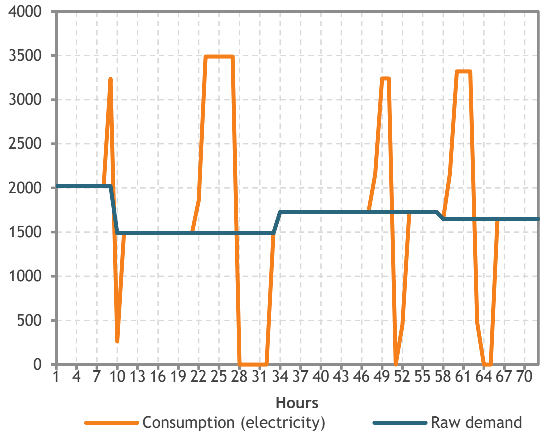
4.1. Demand

4.1.1. Power

The end-use (direct) power demand amounts to 134 (154) TWh in '*Diversified Energy Supply*' ('*Deep Electrification*'), of which industry consumes 53 (65) TWh, heat pumps 12 (13) TWh and EVs 15 (20) TWh[23]. As already explained in section 2.2.1, that is an input to the model. What we then calculate, is how this demand[24] changes upon 'optimising' it or, in other words, how it changes when it becomes flexible and can be shifted to moments when the renewable electricity production is (the) high(est).

One such example is given by heat pumps. By preheating when the price of electricity is low and halting the consumption of the device when price skyrockets (and supply might be tight), the overall system is helped without a loss of comfort. Graph 10 demonstrates the operation of the aggregate Belgian Heat Pump demand in *'Deep Electrification'*. The blue (orange) line depicts the real (flexible, optimised) electricity consumption following a heating demand during a couple of days in March.

Graph 10 Comparison of optimised HP demand with non-flexible (raw) demand, Deep Electrification, Test Case 0, March 6-9, 2050
MW



Source: Artelys, FPB own calculations.

More systematically, we can compare the flexible (optimised) with the must-run (non-optimised) end-use power demand and level it out across test cases and time to see the real impact of optimisation during an average day. Graph 11 is the result of that exercise. In that graph, we see, for the two scenarios, how optimisation (flexibilization) helps to smoothen out peaks and valleys. Heat pumps with thermal storage and EVs that are charged when prices are low(er) (hence, the system is not tight) are at the root of the orange curves. Gaps between optimised and unoptimised demand are bigger in *'Deep Electrification'*, basically because of the higher (flexible) end-use power demand.

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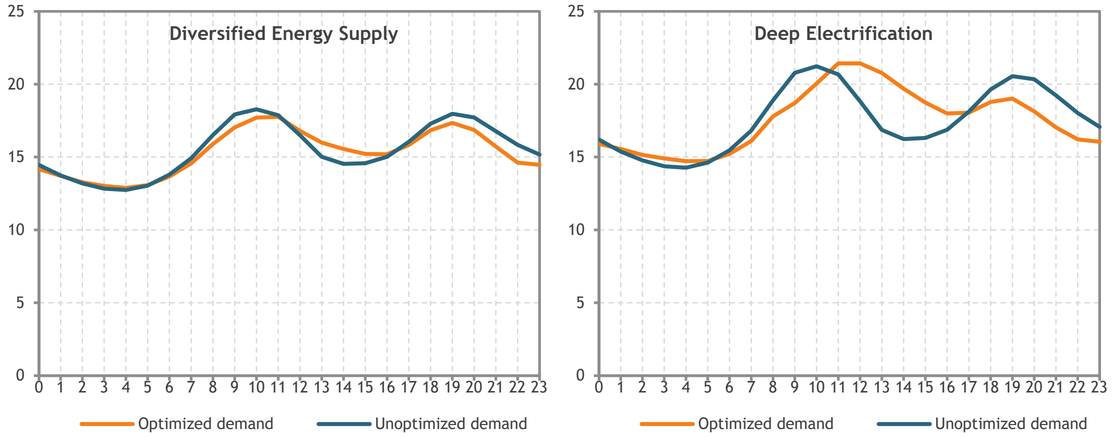
[23] The remainder being made up of electrical appliances, lighting, etc.

[24] The demand profile, to be exact.

Graph 11 (Un)optimised power demand levelled out over a day and all test cases, Belgium, year 2050
GW



Source: Artelys, FPB own calculations.

4.1.2. Hydrogen

As explained in section 2.3, the aggregate hydrogen demand represents all P2X demand, gathering the demand for e-gas, e-liquids and pure hydrogen. The initial estimation of this demand is based on an in-depth study of the literature.

Total hydrogen demand attains 99 (80) TWh in *'Diversified Energy Supply'* (*'Deep Electrification'*), of which industrial demand[25] represents 16 (11) TWh and fuel cell EV 18 (8) TWh. The remainder is used in the (other) final demand sectors, both in pure form (hydrogen) and as a commodity to meet the e-gas and e-liquids demand. The quantity of electricity needed to assure the total hydrogen demand amounts to 117 (94) TWh. Like electricity, hydrogen demand can be optimised. Moreover, hydrogen has another interesting feature: it can be stored (it is, after all, a gas).

4.2. Domestic generation

4.2.1. Power

Demand has to be supplied, and there are two options to do just that: domestically generate electricity and/or import electricity from abroad. In this part, domestic production is discussed, section 4.3 will comment on Belgium's net export position.

Electricity production amounts to 218 (213) TWh on average in *'Diversified Energy Supply'* (*'Deep Electrification'*). The slightly higher demand in *'Diversified Energy Supply'* (+2%) leads to a somewhat higher domestic production.

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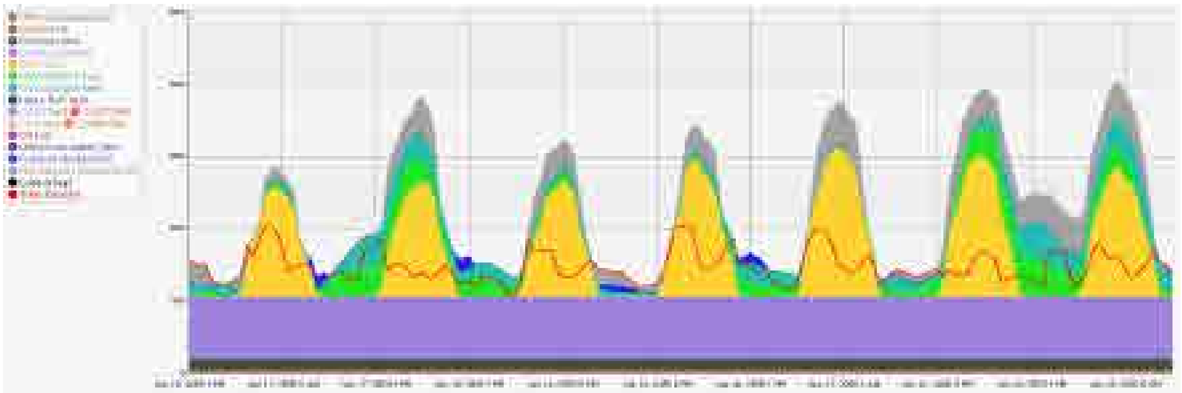
[25] Feedstocks not included. In 2018, feedstocks amounted to 90 TWh in Belgium (Eurostat, 2020). In 2050, they can be estimated to reach 77 TWh of which 54 TWh of hydrogen (ICF & Fraunhofer ISI, 2019).

When it comes to the electricity mix, wind takes the lead in both scenarios[26] and provides, on average, 90 TWh, whilst solar produces 37 TWh. Differences can be spotted in the production of the other generation units, most notably in the operation of the CCGT (and PSH[27] and OCGT to a far lesser extent). CCGT equipped with CCS produce 73 (67) TWh in *'Diversified Energy Supply'* (*'Deep Electrification'*). The delta amounts to 6 TWh.

Graph 12 Graphical illustration of power generation, Diversified Energy Supply, Test Case 0, Belgium, April 16-23, 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.

In both 2050 states of the Belgian power system, a future for gas is still envisioned. The gas that is burned in CCGTs (equipped with the CCS technology) will be indispensable to absorb the tremendous amounts of additional power demand due to the (in)direct electrification. As can be seen in Graph 12, it provides a solid 'baseload' to fulfil the total electricity demand: its share in total production reaches 33 (32)% on average in *'Diversified Energy Supply'* (*'Deep Electrification'*) and its capacity factor 75 (63)%.

This also means that renewables occupy the remaining 67 (68)% of the cake, with wind onshore, wind offshore, solar and biomass and waste taking pieces of respectively 25 (26), 17 (17), 17 (17) and 8 (8)% in *'Diversified Energy Supply'* (*'Deep Electrification'*).

4.2.2. Hydrogen

Although hydrogen can store and deliver usable energy, it typically does not exist by itself in nature[28] and must be produced from compounds that contain it. Various resources can be used to generate it. Currently, most hydrogen is being manufactured from fossil fuels, mainly natural gas, through a process called *Steam Methane Reforming* (SMR). This is a high-temperature process in which steam reacts with a hydrocarbon fuel to form hydrogen. Electricity from the grid or from renewable energy sources (e.g. wind or solar) can also be used to produce hydrogen. The hydrogen production method then consists in taking water and separating the H_2O molecule into oxygen and hydrogen, a process known as *electrolysis*. Electrolysis takes place in an electrolyser which functions much like a fuel cell in reverse: instead of using the energy of a hydrogen molecule like a fuel cell does, an electrolyser produces

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[26] Since availabilities in each test case are assumed to be identical, variable renewable production is also.

[27] PSH stands for Pumped Storage Hydro. It is in fact no generation but a storage unit.

[28] In the form required for energy end-uses (di-hydrogen).

hydrogen from water molecules. In CSG, both production methods (SMR and electrolysis) can be integrated.

When we look at the quantities of domestically produced hydrogen in Table 1, we see that way more hydrogen is being generated in *'Diversified Energy Supply'* than in *'Deep Electrification'*. Higher demand, higher electrolyser capacity in addition to offering much needed flexibility to a highly renewable power system can be identified as main causes.

Table 1 Hydrogen production, Belgium, year 2050
TWh

	Diversified Energy Supply	Deep Electrification
Mean	95.9	73.7
TC0	99.5	79.7
TC1	99.4	79.5
TC2	88.7	62

Source: Artelys, FPB own calculations.

The considerably lower production in Test Case 2 (TC2), both in *'Diversified Energy Supply'* as in *'Deep Electrification'*, stands out: it can be attributed to the particularly high system marginal costs (SMC[29]) in TC2, making domestic production of hydrogen relatively more expensive compared to the import option (see section 4.3.2).

To shed further light on the matter, a sensitivity was run in which the import price of hydrogen was considerable lowered. Numbers in Table 1 then change into Table 2.

Table 2 Hydrogen production, Sensitivities with lower import price for hydrogen, Belgium, year 2050
TWh

	Diversified Energy Supply_Low price	Deep Electrification_Low price
Mean	70.0	47.0
TC0	98.0	74.8
TC1	78.0	55.7
TC2	34.0	10.5

Source: Artelys, FPB own calculations.

The impact of the lower hydrogen import price can immediately be observed: domestic production of the molecule falls on average with 27 (36)% in *'Diversified Energy Supply'* (*'Deep Electrification'*) to the benefit of net imports (see section 4.3.2). Domestic production even decreases dramatically when SMC increases.

Graph 13 demonstrates the sensitivity of hydrogen production (or, more accurately, the electricity consumption of the electrolysers to produce hydrogen) to the system marginal costs (SMC): when SMC increase (all else being equal), hydrogen production decreases. Since the graph merely wants to illustrate this inverse relation, only one Test Case in one scenario (*'Diversified Energy Supply'*) is depicted. It is important to stress, however, that this behaviour is optimal from a system point of view: market arrangements such as Power Purchase Agreements (PPA) or hydrogen support schemes may strongly influence this finding[30].

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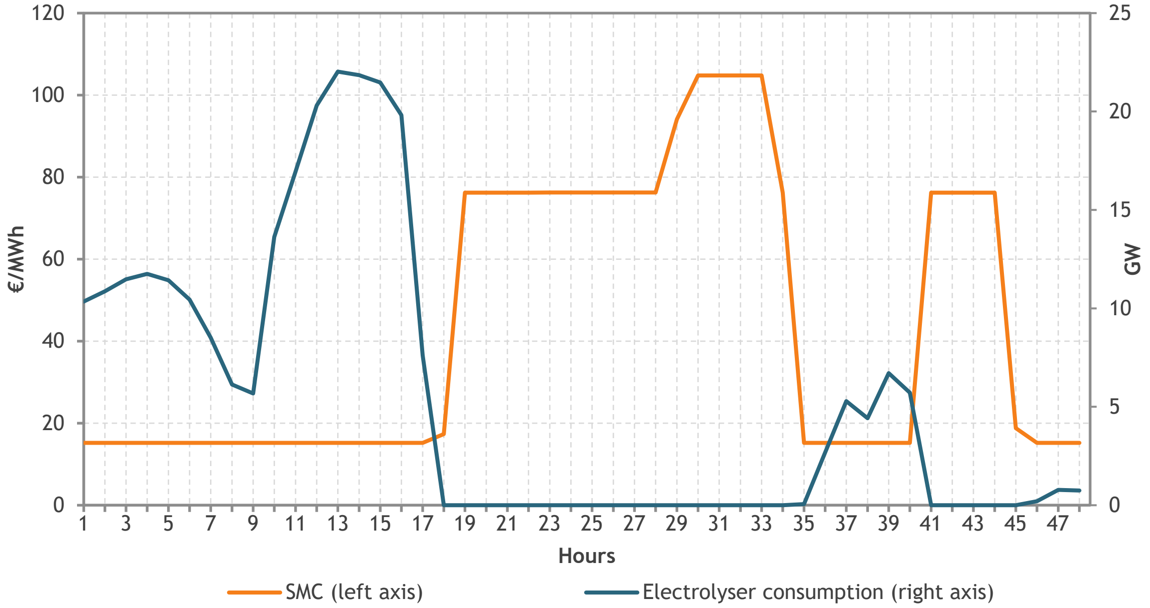
[29] SMC can be seen as a proxy for wholesale power prices, although there are some important nuances (see Devogelaer, 2018).

[30] These market arrangements, hence, may result in sub-optimal use of power.

Graph 13 **Illustration of power consumption of the electrolysers versus the system marginal costs (SMC), Diversified Energy Supply, Test Case 0, February 16-18, 2050**



Source: Artelys, FPB own calculations.

4.3. Net export position

4.3.1. Power

Next to domestic generation, demand can be fulfilled through transmission. Although interconnection capacity is somewhat higher in *'Deep Electrification'* (see section 3.2.5.c), both scenarios do not diverge (much) in terms of their annual net export position (defined as exports minus imports) in 2050: -29.4 TWh on average in *'Diversified Energy Supply'* and -29.0 TWh in *'Deep Electrification'*.

Notwithstanding comparable net export levels, more trade seems to take place in *'Deep Electrification'*: more imports, but also more exports can be observed. This can be ascribed to 1) the somewhat higher interconnection capacity (netting out additional imports and exports), 2) a higher degree of flexible electricity demand. The latter may be traded off for interesting electricity import and export opportunities.

Graph 14 depicts the (average) net export position of the three test cases (TC's) of the *'Deep Electrification'* scenario: it visualises for the different TC's and their average value the duration curve of Belgium's net export position in 2050[31]. Belgium continues to be a net importer of electricity, but during a limited amount of time (9% on average), it exports more electricity than it imports. Maximum net export (import) amounts to 10 (14) GW.

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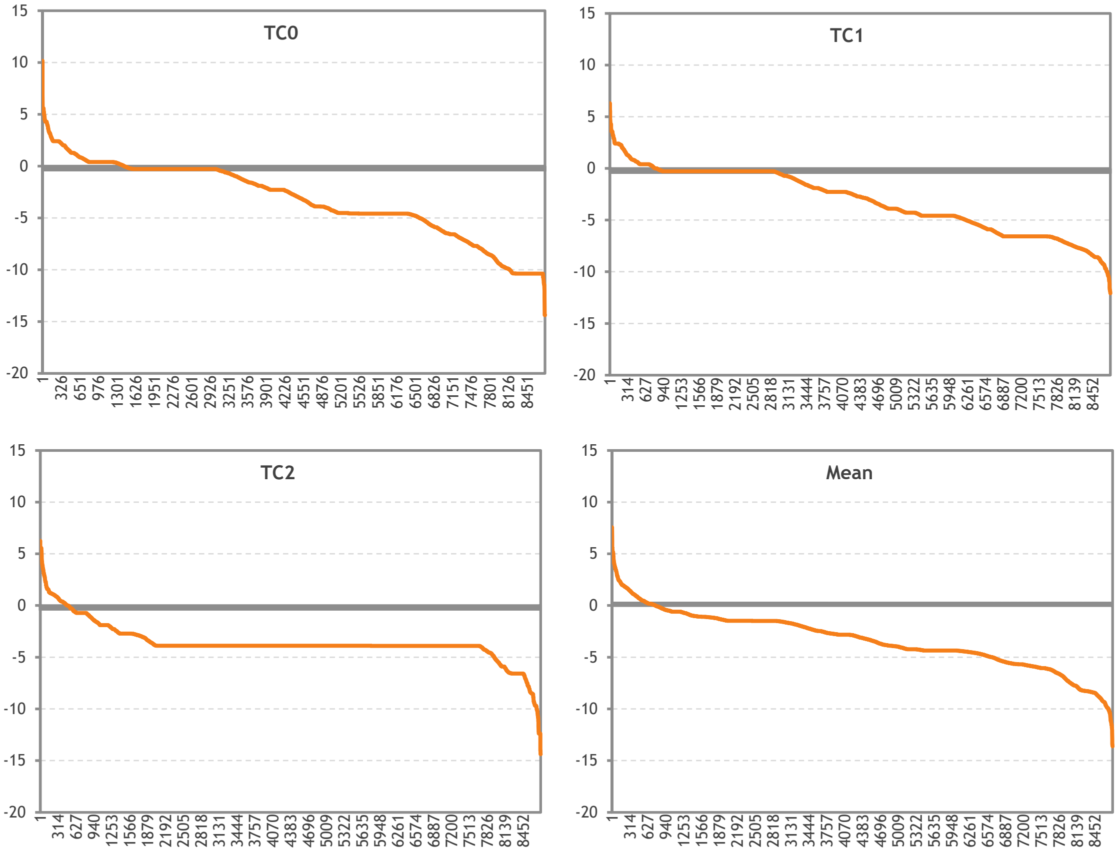
[31] Since the differences with *'Diversified Energy Supply'* are small, only one scenario will be shown.

Graph 14 Net export position duration curve, Deep Electrification, year 2050

GWh

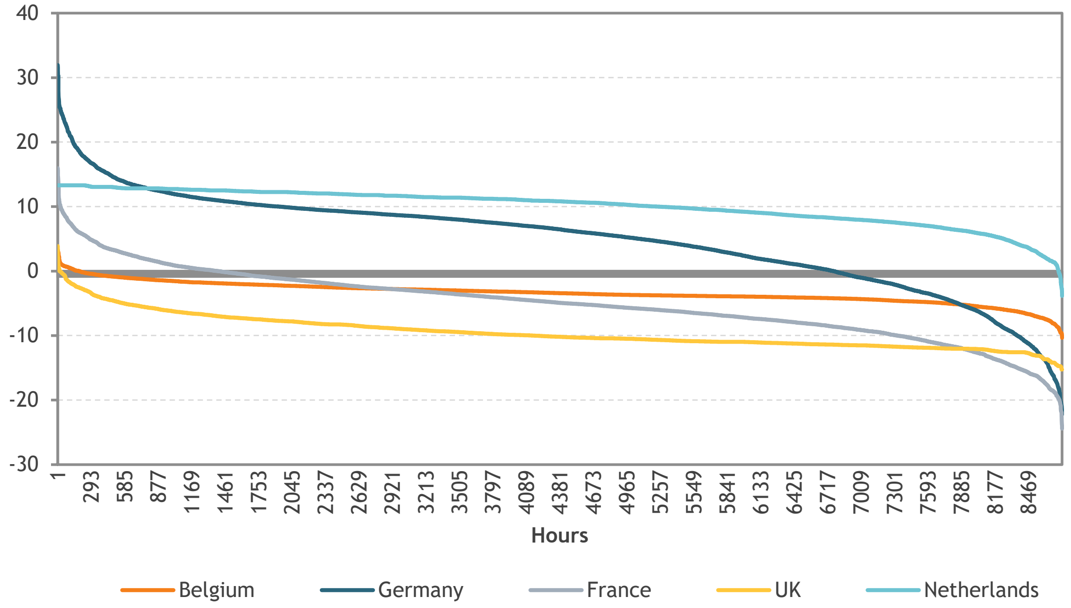


Source: Artelys, FPB own calculations.
Note: TC stands for Test Case.

Graph 15 shows the net average export position of Belgium next to its neighbours in *'Deep Electrification'*. It becomes obvious that in this scenario, the Netherlands and Germany are net exporters of electricity, whilst France, Belgium and the UK are net importers.

Graph 15 Net position duration curve, Deep Electrification, Belgium and its neighbouring countries, year 2050

GWh



Source: Artelys, FPB own calculations.

As a matter of fact, Belgium imports most (in all scenarios and test cases) of its electricity from the Netherlands, and chiefly exports to France and the UK. It seems that Belgium is exporting (or transmitting) flexibility to neighbouring countries that still have nuclear energy in their capacity mix. This observation is corroborated by the analysis of the SMC (see section 4.6).

It is also possible to gain an insight into the use of the transmission lines. This indicator calculates, for each power interconnection (and direction of the flow), the total usage defined as the total flow during the length of the period divided by the maximum theoretical flow. The transmission usage of the Dutch cables (direction towards Belgium) is very high: on average, it reaches 92 (93)% in *'Diversified Energy Supply'* (*'Deep Electrification'*), so almost all the time, electricity is flowing in from (through) the Netherlands. The German transmission to Belgium is less heavily used: it amounts to 53 (54)% in *'Diversified Energy Supply'* (*'Deep Electrification'*). In the opposite direction, transmission usage from Belgium to the UK amounts to 53 (47)% in *'Diversified Energy Supply'* (*'Deep Electrification'*); to France, the numbers are 20 (28)%.

4.3.2. Hydrogen

Next to the domestic production of hydrogen, the molecule can also be imported. Since end of 2019, a number of major industrial players (Deme, Engie, Exmar, Fluxys) in Belgium, together with two port authorities (Port of Antwerp, Port of Zeebrugge) and WaterstofNet teamed up to scrutinize the possibility of massively importing hydrogen, also from outside the EU. In the LTS (EC, 2018a), however, none of the pathways considers the import of decarbonised gas (biomethane, hydrogen, etc.) from outside the EU. Since the LTS forms the basis of the two scenarios discussed in this study, originally, no non-EU imports of the molecule were envisaged. Given the existence and mission of the consortium and the fact that it is generally acknowledged, given the required amount of hydrogen needed, that, by

2050, hydrogen imports towards Belgium from countries where it is cheap to generate the molecule[32] will occupy a significant share of future supply, we decided to construct an asset to simulate an additional available amount of hydrogen (be it from EU or non-EU countries) being fed into the Belgian system.

This 'external supply' of hydrogen can be interpreted as either being supplied by the combined process of SMR+CCS in Belgium or originating from other countries and being exported to Belgium. It is modelled as a physical asset delivering hydrogen at a preset (modeller defined) price. Just to be clear: it is only the price that has been set beforehand (exogenously), the amount of additional hydrogen needed (through Belgian SMR or import) and the trade-off between domestically produced (through electrolysis) and this additional amount is the result of the optimisation run. In the rest of the analysis, however, we consider the additional hydrogen source to be imported[33] from abroad (no production of hydrogen through the SMR+CCS process in Belgium was assumed).

At the preset price of 90 €/MWh (or 3.6 €/kgH_2[34]), import of hydrogen is virtually non-existent in both scenarios. Only in TC2, when the marginal cost of producing electricity becomes high (see section 4.6.1), the import of hydrogen is significant: it amounts to 11 (18) TWh in *'Diversified Energy Supply' ('Deep Electrification')*. Since the price of importing hydrogen is likely to be a key uncertainty in the future, a sensitivity analysis was performed in which it was set at 50 €/MWh (or 2.0 €/kgH_2). Imports change dramatically and reach up to 69 TWh or 87% (*'Deep Electrification'*, TC2) of the total hydrogen supply.

4.4. Flexibility

4.4.1. (Contribution to) flexibility needs

CSG enables the user to calculate both the flexibility needs of the power system and the specific technology contribution to ease these flexibility needs.

a. Flexibility needs

The flexibility needs indicator reports daily, weekly and annual flexibility needs per country. The indicators are based on an analysis of the dynamics of the residual load, in which the residual load is defined as

Residual load = Demand - Solar generation - Wind generation - Hydro RoR[35] generation

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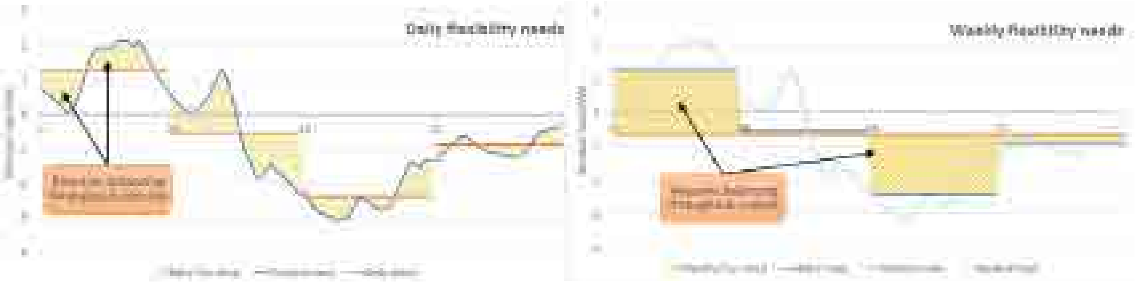
[32] If solar panels are used to generate the necessary electricity to fuel the electrolysers that produce hydrogen (or Liquid Organic Hydrogen Carriers, LOHCs, for that matter) that afterwards can be exported (by ship) to Europe, the process is referred to as *'shipping the sunshine'* (Federal Ministry for Economic Affairs and Energy (June 2020), *The National Hydrogen Strategy*, https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf).

[33] Since Belgium does not possess any indigenous sources of natural gas, all natural gas that is being consumed in Belgium has to be imported. The choice then basically boils down to importing readily produced hydrogen or importing natural gas that has to be converted into hydrogen whilst capturing the released carbon dioxide, transporting the latter and storing it (most likely somewhere abroad). This process will have an undeniable impact on the demand for electricity, further inflating it, next to being exposed to the future volatile price of natural gas.

[34] Including transport costs. Transport costs depend on the distance, the transport mean (e.g. pipelines versus ships or trucks), the state of the hydrogen transported (e.g. gaseous versus liquid) and its volume.

[35] RoR stands for Run of River.

Graph 16 Evaluation of flexibility needs, graphical illustration



Source : Artelys.

As can be seen in Graph 16, the daily flexibility needs (left graph) then equal the area between the residual load (blue curve) and the daily average residual load (orange curve), whilst weekly flexibility needs (right graph) are depicted as the area between the daily average residual load (blue curve) and the weekly average residual load (orange curve). Daily flexibility needs are primarily driven by the deployment of solar power and the day-night pattern of consumption, whilst weekly flexibility needs are mainly caused by the deployment of wind power and the weekday/weekend pattern of consumption. Annual flexibility needs, on the other hand, are primarily triggered by the deployment of variable renewable energy sources (solar, wind) and the portfolio of heating/cooling technologies.

Table 3 Average flexibility needs, Optimised Demand, Belgium, year 2050
TWh

	Diversified Energy Supply	Deep Electrification
Annual	11.9	11.0
Weekly	17.7	13.2
Daily	21.6	14.9

Source: Artelys, FPB own calculations.

Table 3 gives the average flexibility needs when demand is being optimised. If it is not optimised, unsurprisingly, average flexibility needs increase: one of its flexible instruments (flexible demand) is lost. Results are shown in Table 4.

Table 4 Average flexibility needs, Unoptimised Demand, Belgium, year 2050
TWh

	Diversified Energy Supply	Deep Electrification
Annual	12.9	11.1
Weekly	18.0	14.2
Daily	22.9	19.8

Source: Artelys, FPB own calculations.

In both tables, flexibility needs in *'Diversified Energy Supply'* exceed the ones in *'Deep Electrification'*. This basically can be attributed to the former's higher (indirect) electricity demand (since RES production is the same). We also note that needs tend to decrease with longer time horizons. This can be explained by the complementarity of the variable renewable energy sources. Given the important share of solar in both scenarios, daily flexibility needs are high whereas annual flexibility needs are remarkably lower: the effect of wind generation (which is higher in winter than in summer) partially counterbalances the effect of solar generation (which is higher in summer than in winter).

b. Flexibility contribution

The flexibility contribution indicator gives an insight in the contribution of different technologies to the computed needs. How to measure the contribution of a certain technology X to the computed flexibility needs? First, daily flexibility needs are calculated based on the net demand. Then the residual daily flexibility needs are computed based on the net demand minus the generation profile of the technology X. The difference between the two quantities is the contribution of technology X to the flexibility needs.

Upon analysis of the contribution to flexibility, it seems that the electrolysers combined with gas-fired power plants are the main daily, weekly and annual flexibility providers in *'Diversified Energy Supply'*. In the *'Deep Electrification'* scenario, electricity imports together with EVs become more important daily and weekly flexibility providers: they compensate for the lower installed electrolyser capacity. The latter nevertheless contributes substantially to flexibility and even provides half of the annual flexibility needs.

4.4.2. Curtailment

Since CSG is a *Unit Commitment, 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. The electricity to be curtailed in 2050 on average amounts to 0.7 MWh in *'Diversified Energy Supply'* and 2860 MWh in *'Deep Electrification'* (the latter barely representing 0.001% of domestic production).

4.5. Loss of Load

In the Electricity Act of April 29, 1999 and its ulterior amendments concerning the organisation of the electricity market, a legal criterium as to generation adequacy is defined, expressed in LOLE. The LOLE or Loss of Load Expectation represents the number of hours in a year in which, over the long-term, it can statistically be expected that supply will not meet demand. When that occurs, the national TSO needs to turn to additional means to keep the power system in balance. TSOs are usually able to solve this without major impact on the system, i.e. by using instruments such as temporary voltage reductions or the selective disconnection of large industrial users.

Because of a current lack of harmonised standards on European or regional ('zonal') level, Belgium defined its own double LOLE criterium. It states that the LOLE cannot exceed a maximum of 3h for a statistically speaking 'normal' year and a maximum of 20h for a statistically 'exceptional' year. Interesting to know is that 3h of LOLE translates into a system security level of 99.97%, meaning that 99.97% (1-(3/8760)) of the year, there will be no expected Loss of Load caused by insufficient generating capacity.

Upon scrutinising the different scenarios, it appears that Loss of Load does not occur (0h). Generation adequacy in both a deep electrified as a more molecule-based society can be guaranteed. The only exception is Test Case 2 (in both scenarios). In Test Case 2 (which is mimicking in fact rather harsh winter conditions), 17h (16h) of LOL can be observed in *'Diversified Energy Supply'* (*'Deep Electrification'*). Since LOL is still below the cited 20h of the Electricity Act, it can be interpreted as a statistically speaking 'exceptional' year. Overall, the 2050 scenarios meet the current legal conditions.

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 the hourly SMC per test case (TC): this allows more detailed calculations to be carried out.

The average (over 8760 hours) SMC are shown in Table 5. Large differences between test cases can be distinguished. Especially the low SMC in Test Case 0 (TC0) catch the eye, driven by the rather benign climate conditions causing favourable variable renewable production levels that are characterised by (very) low marginal costs.

Table 5 Average System Marginal Costs, Belgium, year 2050
€/MWh

	Diversified Energy Supply	Deep Electrification
Mean	74.7	74.3
TC0	30.9	37.3
TC1	85.7	78.3
TC2	107.6	107.3

Source: Artelys, FPB own calculations.

Digging a bit deeper into the low SMC in TC0, we notice that, upon comparing TC0 with TC2 (rather harsh winter conditions), the thermosensitive electricity demand in TC0 is 14% lower whilst wind (on- and offshore) generation is 13% higher. On top of that, the LOL hours in TC2 (which are absent in TC0) drive up the average SMC, all the more so since the Value of Lost Load (VOLL) is estimated at 15,000 €/MWh[36].

When we examine the case somewhat further, other interesting results can be detected. Since we also have access to the hourly marginal costs of the neighbouring countries, 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. We notice that, in all cases, the Netherlands is the top exporter to Belgium in 2050 (see also section 4.3.1). The Netherlands do have the lowest[37] SMC in 67% (56%) of the hours in *'Diversified Energy Supply'* (*'Deep Electrification'*).

Table 6 displays the average SMC for both scenarios. Some interesting conclusions are that the average Belgian SMC are systematically lower than the UK's (and the French in *'Deep Electrification'*), except in Test Case 2. This can be attributed to the fact that Belgium (together with Germany and the Netherlands) experiences LOL in TC2, whilst France and the UK do not. The occurrence of LOL pulls the average SMC upwards.

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[36] The VOLL is user-defined: the parameter was uniformly preset to a value of 15,000 €/MWh. Changing this value of course has an influence on the (average) SMC in those test cases in which LOL occurs.

[37] More than one country may be producing at the lowest SMC.

Table 6 Average System Marginal Costs, Belgium and its neighbouring countries, year 2050
€/MWh

	Diversified Energy Supply					Deep Electrification				
	BE	DE	FR	GB	NL	BE	DE	FR	GB	NL
TC0	30.9	23.8	30.1	62.1	16.2	37.3	25.3	42.7	62.4	17.4
TC1	85.7	60.0	85.5	85.9	31.5	78.3	56.5	82.4	81.9	28.9
TC2	107.6	121.0	78.2	78.0	59.4	107.3	121.0	78.4	78.1	59.1

Source: Artelys, FPB own calculations.

Table 6 also hands over the reason why the average Belgian SMC in TC0 are considerably higher in *'Deep Electrification'* than in *'Diversified Energy Supply'*: more electricity imports (+13%) at a higher SMC take place in the former scenario.

4.6.2. Total costs

This section summarizes the costs associated to satisfying the total electricity demand. Total costs are defined as the sum of the production costs, the loss of load costs and the curtailment costs. Note that investment costs and annuities are not part of the equation.

On average, total costs are 273 million euro lower in *'Deep Electrification'* compared to *'Diversified Energy Supply'*. This may be attributed to the slightly higher (CCGT) production, average SMC and number of LOL hours in *'Diversified Energy Supply'* with respect to *'Deep Electrification'*. Compared to the entire energy system cost[38] which, according to the Federal Planning Bureau (Devogelaer & Gusbin, 2018), can be estimated to be around 80 billion euro in 2040[39], it appears to be negligible.

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[38] Comprising the entire energy production and consumption system (not only the power sector) as well as the capital costs. The definition given in the forementioned publication is *"Total energy system cost encompasses capital costs (related to energy producing installations, energy consuming equipment and energy infrastructure), energy purchase costs (fossil and RES fuels, electricity and heat) and direct efficiency investments costs (such as expenditures for insulation)"*.

[39] Since scenarios do not exactly match and numbers for 2050 are not available, the comparison is only illustrative.

5. Conclusion

At the end of this report, some conclusions can be drawn. We are, and will be for some time, in a period in which we try to come to grips with the sanitary and economic effects of the coronavirus pandemic. A lot of high-level announcements on recovery plans are being uttered nowadays. One such economic recovery route seems to be to stimulate the creation of a hydrogen economy. This is also one of the ambitions stated in the Green Deal and discussed in the Commission's Hydrogen Strategy for a climate-neutral Europe. Belgium already mentioned its hydrogen ambition in its Long-Term Strategy, handed over to the European Commission in February 2020. In addition to Belgium, other Member States including some big players like Germany, France and Spain with dedicated hydrogen budgets of respectively 9, 7.2 and 9 billion euro, signalled their prospects and plans in the field of hydrogen.

The greater and still growing (inter)national attention for hydrogen made us want to investigate the potential role the molecule can play in the future Belgian energy system. Two scenarios depicting two different states of the Belgian energy system in 2050 were constructed for that cause: one with a deep electrification philosophy (called *'Deep Electrification'*), the other demonstrating a more diversified (hybrid) approach in which molecules occupy a big(ger) share (called *'Diversified Energy Supply'*). Both scenarios do respect and are compatible with the 1.5°C temperature increase limit as stated in the 2015 Paris Agreement as they set sail towards full decarbonisation (net zero greenhouse gas emissions) in 2050.

To achieve the goal of full decarbonisation, both direct and indirect electrification were assumed to (take off and) increase dramatically. Although both scenarios integrate (in)direct electrification, the degree to which they do, diverges. The scenario *'Diversified Energy Supply'* integrates more indirect electrification, whilst *'Deep Electrification'* is primarily based on direct electrification.

The present analysis contains a selection of indicators (called KPIs or *Key Performance Indicators*) to investigate the impact of more (in)direct electrification on the future Belgian power system. In general, in both scenarios, total power demand in 2050 increases dramatically compared to today's levels: it is up to three times higher than 2018 demand. On top of that, the partial flexibilization of the power demand is proving to be an important aid in supporting the future energy system operation.

Supply of electricity originates in a combination of domestic production (88%) and net imports (12%). The former is based on a highly renewable energy system: the share of renewable energy sources in the electricity production mix lies between 67 and 68%. Gas units, on the other hand, are not singing their swan song anytime soon. Gas, which is composed of e-gas, biogas and some remaining fossil gas burnt in thermal units equipped with carbon capture and storage, occupies a third (32 to 33%) of the future power mix.

Belgium remains a net importer of electricity in 2050: it imports more power than it exports. Net imports reach, on average, 29 TWh. A cold winter, as simulated in one of the test cases, decreases the domestic production of electricity (and hydrogen for that matter) and increases the net imports. Nevertheless, Belgium does export (and transmit) power. Its major clients are France and the UK which both have nuclear energy in their capacity mix. Belgium primarily imports from the Netherlands, followed by Germany.

Curtailment is negligible in both scenarios and generation adequacy can be assured, even during rather harsh winter conditions (mimicking the winter of 2010), according to the current legal (double) criteria.

System marginal costs, a proxy for wholesale power prices, are, on average, comparable between scenarios. They are only marginally higher in *'Diversified Energy Supply'*, which may be attributed to the slightly higher demand, (CCGT) production, net imports as well as number of LOL hours.

Where the two scenarios differ, is, first, in their need of flexibility and in their (use of) flexibility instruments. Flexibility in future power systems is crucial since the penetration of variable renewable energy sources (wind and solar) is high: they represent 58 to 60% of domestic generation. Since these renewables are weather dependent, hence, do not produce electricity 'on demand' (they, basically, generate electricity when wind is blowing and sun is shining), other generation, demand and storage units have to fill the gaps. Above that, the dynamics of demand (daily peaks, weekday-weekend, seasonal patterns) add to the flexibility needs. The need for flexibility is higher in *'Diversified Energy Supply'* and electrolysers combined with gas-fired power plants are the main flexibility providers. In the *'Deep Electrification'* scenario, electricity imports together with EVs become more important flexibility suppliers: they compensate for the lower installed electrolyser capacity. The latter nevertheless contribute substantially to flexibility, even in *'Deep Electrification'*, in which they provide half of the annual flexibility needs.

Another interesting finding is that more trade takes place in *'Deep Electrification'*: more imports, but also more exports can be observed. This can be explained by the somewhat higher Net Transfer Capacity, but also by the system possessing a higher degree of flexible electricity demand which can be traded off for interesting electricity import and export opportunities.

The domestic production of hydrogen through electrolysis is considerable and amounts to, on average, 96 (74) TWh in *'Diversified Energy Supply'* (*'Deep Electrification'*). The import of hydrogen takes off when the system marginal cost of producing power becomes high (above 86 €/MWh) and/or the import price of hydrogen decreases (under 90 €/MWh or 3.6 €/kgH_2).

As regards the exploitation costs of the power system, *'Deep Electrification'* seems to demonstrate somewhat lower costs (-273 million euro) compared to *'Diversified Energy Supply'*. These costs, however, do not comprise the investment (capital) costs (or annuities) to build the system. The difference is rather small, certainly when it is being compared to the entire energy system cost[40] which, according to the Federal Planning Bureau (Devogelaer & Gusbin, 2018), can be estimated to be around 80 billion euro[41].

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[40] Comprising the entire energy production and consumption system (not only the power sector) as well as the capital costs. The definition given in the forementioned publication is *"Total energy system cost encompasses capital costs (related to energy producing installations, energy consuming equipment and energy infrastructure), energy purchase costs (fossil and RES fuels, electricity and heat) and direct efficiency investments costs (such as expenditures for insulation)"*.

[41] Since scenarios do not exactly match and numbers for 2050 are not available, the comparison is only illustrative.

6. Annex

6.1. Industrial demand

The 1.5TECH scenario from the LTS neither shows details on the energy repartition per country nor per subindustry. Since this information is crucial to project future industrial energy demand in Belgium, the industrial data in *'Diversified Energy Supply'* for 2050 was established by means of both the IDEES database (see below) and the aggregate 1.5TECH outcome. The IDEES database contains details of industry consumption per energy, subsector and industrial process. The industry demand per energy form from 1.5TECH was used for the projection towards 2050. The disaggregation between countries, subindustries and process was based on the IDEES data from 2015.

6.1.1. JRC-IDEES

The "*Integrated Database of the European Energy Sector*" (JRC-IDEES) is a one-stop data-box that incorporates in a single database all information necessary for a deep understanding of the dynamics of the European energy system. JRC-IDEES is developed and maintained by the European Commission's Joint Research Centre. It offers a consistent set of disaggregated energy-economy-environment data, compliant with the EUROSTAT energy balances, as well as widely acknowledged data on existing technologies. It provides a plausible decomposition of energy consumption, allocating it to specific processes and end-uses. Throughout all sectors it quantifies in a vintage-specific manner the characteristics of the energy (and non-energy related) equipment in use, along with the stock's average operation, identifies different drivers and provides insights on their role by sector, fully acknowledging structural differences across countries. The complete output of JRC-IDEES is accessible to the general public.

6.1.2. Industrial mix in 2050

a. Diversified Energy Supply scenario

Based on this method, the *'Diversified Energy Supply'* industrial energy demand[42] is derived to reach, in 2050, 2571 TWh in the EU and 89 TWh in Belgium, of which electricity (hydrogen, including hydrogen for e-gas) respectively occupies 1344 (499) TWh and 53 (16.5) TWh.

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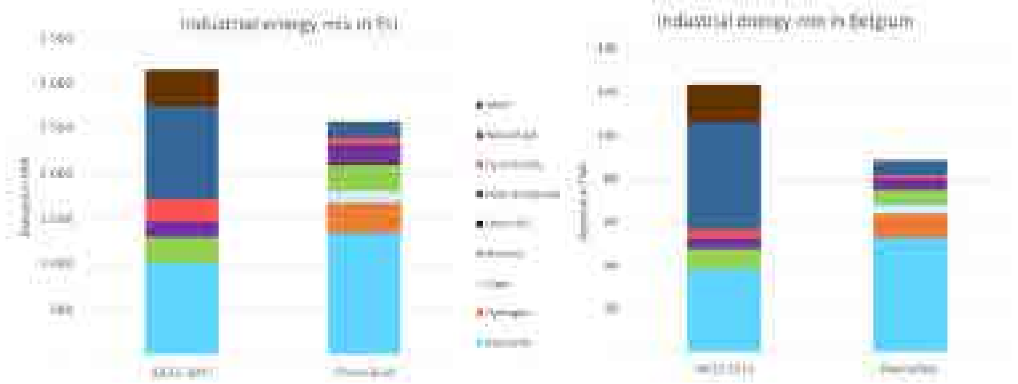
[42] Feedstocks are not included in the industrial gas demand. In 2018, feedstocks amounted to 90 TWh in Belgium (Eurostat, 2020). In 2050, they can be estimated to reach 77 TWh of which 54 TWh of hydrogen (ICF & Fraunhofer ISI, 2019).

Graph 17 Industrial energy mix in the EU (left) and in Belgium (right), Diversified Energy Supply, year 2050
TWh



Source: Artelys.

b. Deep Electrification scenario

To construct the numbers for the Deep Electrification scenario, some further data manipulations had to be performed. First, the substitutable part in the total industrial energy consumption had to be identified (and quantified) to, afterwards, increase the electricity demand while simultaneously reduce the demand for hydrogen. It is important to keep in mind that not all processes and energy uses in industry can be easily substituted: it highly depends on and varies from industry to industry and process to process.

The methodology used to build the industrial demand consists in the

- classification of all industrial processes into 3 distinct temperature levels (low, medium, high) according to the process used.
- analysis of the heat demand and classification into (non-)substitutable uses according to sectors, processes, consumed energy and temperature. Typically, high temperature processes are hardly replaceable by electricity whereas low temperature processes fuels can more easily be replaced by boilers (medium and low) and HP (low). However, it depends on the specificity of the industry and its process[43].
- construction of industrial demand: based on the substitution of fuels in low and medium temperature processes by electricity. The electricity demand in this scenario was based on data from the ICF & Fraunhofer ISI study (2019), more specifically, on the *'Electric'* (3d) scenario. Fuels consumed in processes in low and medium temperature levels can be substituted by electricity. The equivalent demand is then removed from the hydrogen demand in industry. The useful electricity demand was calculated considering a ratio of 10% HP and 90% boilers.

Graph 18 then depicts the approach taken, whilst Graph 19 visualises the industrial energy mix in both scenarios.

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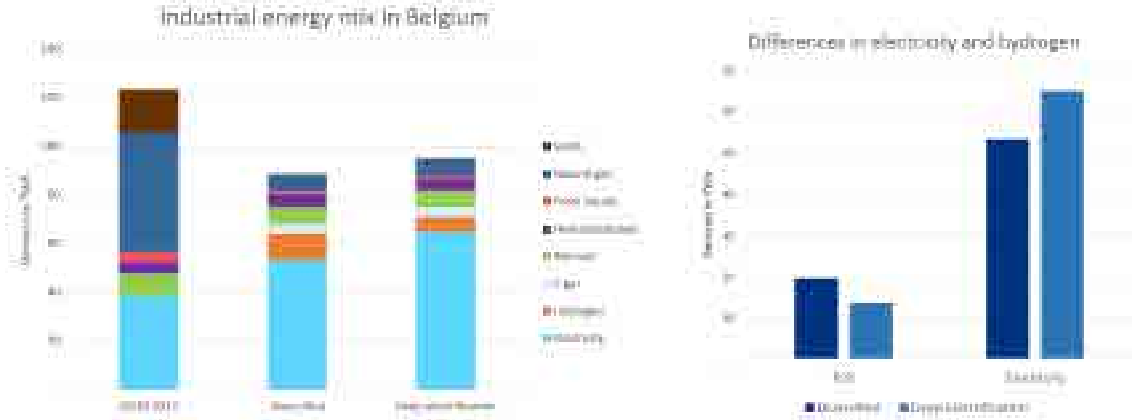
[43] Electricity used for specific electricity (lighting, fans, etc.) and feedback are not accounted for in the substitutable and non-substitutable scope.

Graph 18 Useful industry demand, Belgium, year 2050
TWh

Source: Artelys.

To summarize, the total electricity demand from the *'Deep Electrification'* scenario is based on the ICF & Fraunhofer ISI *'Electric'* scenario. Fuel uses for low and medium temperature processes are substituted by electricity. The hydrogen demand is adapted accordingly. All in all, total industrial electricity demand in *'Deep Electrification'* is 12 TWh higher[44] than in *'Diversified Energy Supply'*.

Graph 19 Industrial energy demand level and mix, Belgium, year 2015 and 2050
TWh



Source: Artelys.

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[44] The variation in the energy demand is compensated by a decrease in e-gas demand in buildings and a decrease in hydrogen demand in industry.

6.2. Some hypotheses

Tabel 7 Selection of hypotheses used in the publication, year 2050

		DES	DE	Unit	Source
Price	Carbon	350	350	€/tCO_2	European Commission (2018)
	Natural gas	39.6	39.6	€/MWh LCV	European Commission (2018)
	Coal	14.1	14.1	€/MWh LCV	European Commission (2018)
	Biogas imports	61.2	61.2	€/MWh LCV	European Commission (2018), Artelys
	VOLL	15,000	15,000	€/MWh	Artelys
Capex	Electrolyser	17,531	58,436	€/MW	European Commission (2018), Artelys
	OCGT	54,034	54,034	€/MW	European Commission (2018), Artelys
	CCGT	64,321	64,321	€/MW	European Commission (2018), Artelys
	CCGT with CCS	128,641	128,641	€/MW	European Commission (2018), Artelys

Note: DES (DE) stands for the ‘*Diversified Energy Supply*’ (‘*Deep Electrification*’) scenario.

7. References

Devogelaer D. (2018), *Beschrijving en gebruik van Crystal Super Grid*, Document opgesteld in het kader van de voorbereidende werkzaamheden van de doorrekening van de verkiezingsprogramma's van 2019, Federaal Planbureau, December

Devogelaer D. and D. Gusbin (2018), *Insights in a clean energy future for Belgium, Impact assessment of the 2030 Climate & Energy Framework*, Federal Planning Bureau, WP5-18, May

ENTSOG & ENTSO-E (2019), *TYNDP2018, Scenario report*, Main report & Dataset

European Commission (2018a), *A Clean Planet for all, A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*, In-depth analysis in support of the Commission Communication COM(2018) 773, November

European Commission (2018b), *Optimal flexibility portfolios for a high-RES 2050 scenario*, METIS Studies, Study S1, December

European Commission (2020), *A hydrogen strategy for a climate-neutral Europe*, COM(2020) 301 final, July

Federal Ministry for Economic Affairs and Energy (2020), *The National Hydrogen Strategy*, https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf

FTI Compass Lexecon (2018), *Study on the role of gas in Belgium's future energy system*, Executive Summary, April

ICCT (2018), *The potential for low-carbon renewable methane in heating, power, and transport in the European Union*, Working Paper 2017-26, October

ICCT (2019), *The potential for low-carbon renewable methane in heating, power, and transport in Belgium*, Working Paper 2019-08, March

ICF Consulting Services Limited and Fraunhofer Institute for Systems and Innovation Research (2019), *Industrial Innovation: Pathways to deep decarbonisation of Industry*, Report for the European Commission, DG Climate Action

Navigant (2019), *Gas for Climate, The optimal role for gas in a net-zero emissions energy system*, Report for Gas for Climate, March