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Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem

Deliverable

D1.3 – Electricity production and consumption in Dunkirk area
WP1 – Specifications and demonstration setup

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Table of Contents

List of Figures

List of Tables

Deliverable report

1 Executive Summary

1.1 Description of the deliverable content and purpose

This report reviews the consumption and production patterns of electricity in the Hauts-de-France region of France until 2018. Establishing various energy mix scenarios in France for the 2025 and 2035 horizons, a rough estimate of the available wind energy in Hauts-de-France for hydrogen production is established. A sensitivity analysis is implemented to determine the wholesale electricity spot price in France for both horizons. Along with the forecasted levelized cost of energy (LCOE) for both onshore and offshore wind, the electrical cost of hydrogen production is determined for 2025 and 2035.

Electricity in Hauts-de-France

Energy consumption in Hauts-de-France has stabilized since 2014 due to increased efficiency and development of the tertiary service sector. Consumption peaks during the winter months at > 5 TWh of electricity and troughs during the summer months at < 4.5 TWh.

Electricity production in the region is comprised predominantly of nuclear energy from the Gravelines nuclear power plant, followed by thermal power plants whose output increased significantly in the winter of 2016. Onshore wind energy is the predominant form of renewable energy production in the region, with installation and production experiencing exponential growth since 2010. A 600 MW offshore wind farm is expected to begin operation off the coast of Dunkerque in 2026. Curtailed wind energy (onshore and offshore) potentially translates to 45 000 tonnes of green hydrogen for 2025 and 71 000 – 122 000 tonnes for 2035. It is assumed that wind production in Hauts-de-France remains at roughly 26% of national production as was the case in 2018. Production from other renewable energy sources are minimal in the region and are therefore not further considered. Since 2017, Hauts-de-France has become a net exporter of energy to other regions in France. In addition, France itself is a net exporter with the United Kingdom and Belgium/Germany, however increased wind capacity installed by the latter has resulted in net imports into France during winter months when wind energy is strongest.

Energy Mix Scenarios for 2025 and 2035

Based on predictions from the PPE and RTE, renewable energy is anticipated to increase progressively from 2020 to 2030, with a goal of 40% national renewable energy production by 2030 as defined by French law. This increase in renewable penetration will be accompanied by a decommissioning of nuclear powerplants, which currently make up over 70% of national production. For 2025, the energy mix is clearly defined by the PPE and renewable production should reach roughly 28% of national production, while nuclear production will decrease to 65% as nuclear reactors that reach their lifetimes are decommissioned and not replaced. For 2035, scenarios in this study are inspired by those conceived by RTE. Consumption is expected to increase slightly to 620 – 640 TWh, with the percentage of renewable energy in the energy mix varying between 35% - 50% according to 3 scenarios. Energy exchange with the UK and Belgium/Germany is expected to increase according to these scenarios, though a strong push for renewable energy sources by these aforementioned countries may result in periods of strong overproduction and the need for storage.

Levelized Cost of Electricity from Wind

According to the 2020 PPE, the LCOE of onshore wind is expected to be 54 – 59 €2018 MWh-1 by 2025 and drops to 44 – 48 €2018 MWh-1 by 2035. For offshore wind energy, an LCOE of 31 – 35 €2018 MWh-1 is possible given current trends. Depending on the source of wind energy, the electrical cost of producing hydrogen could vary from 2 – 2.45 €2018 kg-1 by 2035.

Wholesale Electricity Spot Price

The spot price of electricity was determined under the assumption that an increasing presence of variable renewable energy will increase the operating costs of the transmission grid, thereby augmenting the wholesale electricity spot price via a downstream effect. A sensitivity test was implemented, incorporating the 3 scenarios defined previously. For 2025, the spot price to varies between 45 – 55 €2018 MWh-1. For 2035 the spot price varies between 45 – 64 €2018 MWh-1, depending on the scenario. A change in the spot price of 10 €2018 MWh-1 increases the cost of hydrogen by 0.33 €2018 kg-1.

1.2 Brief description of the state of the art and the innovation breakthroughs

N/A

1.3 Corrective action (if relevant)

N/A

1.4 IPR issues (if relevant)

N/A

2 Introduction and Objectives

Within C2FUEL, the CO_2 conversion routes into valuable chemical energy carriers rely on the use of electrolytic hydrogen. This report aims to assess the amount and the price of available electricity for hydrogen production within Dunkirk area in 2025 and 2035. For that purpose, the report will be divided into two sections:

- *The first section* will analyze the electricity surplus available in Hauts-de-France for 2025 and 2035, taking into account installed capacity, scheduled capacity, electricity consumption and production. Interregional and international (mainly Belgium, Germany and the United Kingdom) physical exchange will also be addressed.
- *The second section* will forecast the levelized cost of electricity sourced directly from renewable producers or from the electricity market.

Figure 1: The Hauts-de-France region

3 Electricity Sourcing in Hauts-de-France for 2025 and 2035

Section 2.1. will present the current energy data in the Hauts-de-France region and France, Section 2.2. will identify various scenarios for the energy mix in France along with the future installed capacity announced in Hauts-de-France, and Section 2.3. will outline the potential of a hydrogen economy in Hauts-de-France.

3.1 Current Energy Data in Hauts-de-France, 2013-2019

Energy data from RTE for the Hauts-de-France region will be investigated in three tranches: 1) consumption, 2) production (nuclear, thermal, solar, wind, hydropower, biomass), and 3) energy exchange (interregional, UK, BE-DE). [1]

3.1.1 Consumption in Hauts-de-France

As shown in Figure 2, consumption in Hauts-de-France has stabilized since 2014 at around 51 TWh year^{-1}, with a slight decrease over time. As expected, consumption peaks during the cold (≈3.7 °C in January) winter months and troughs during the warm (≈17.3 °C in August) summer months.[2] It is assumed that consumption patterns will maintain stable by horizon 2025 due to the increasing efficiency of electricity transport grid and the co-development of the tertiary service sector.[3]

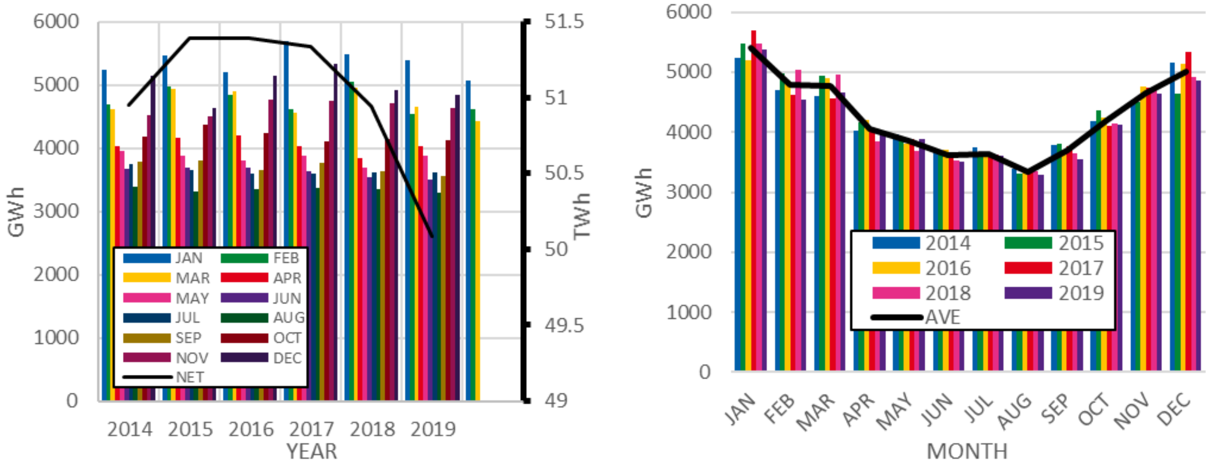


Figure 2: Energy consumption in Hauts de France, 2014-2019, annually (left) and monthly (right)

3.1.2 Production in Hauts-de-France

Figure 3 outlines the mix of energy production in Hauts-de-France for 2018. The following subsections provide details about each production type.

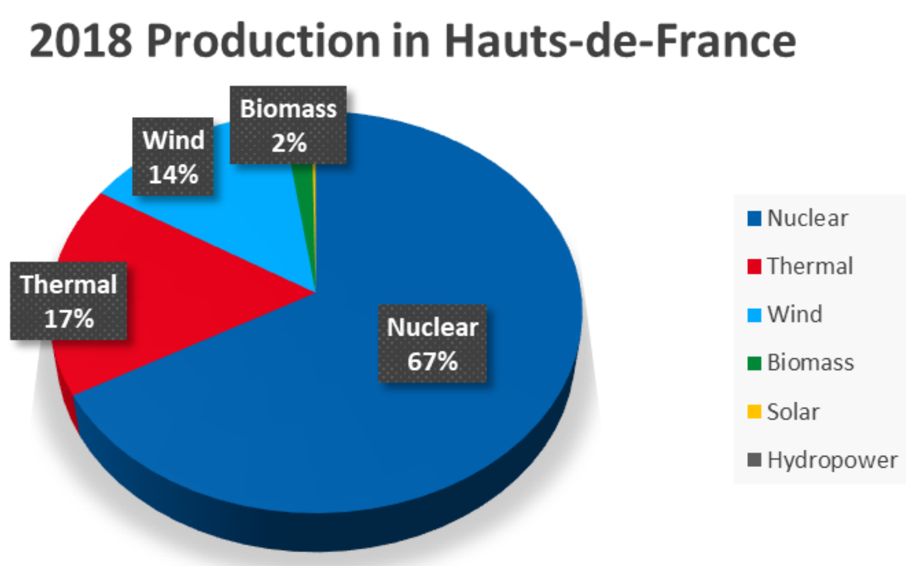


Figure 3: Energy production mix in Hauts-de-France for 2018

Nuclear production

Hauts-de-France hosts the largest nuclear power station in Western Europe.[4] The Gravelines Nuclear Power Station is composed of 6x900 MW nuclear reactors, installed between 1980-1985, and production has remained relatively steady at 34 TWh of annual production (72% capacity factor, refer to Figure 4). A positive correlation is observed between monthly nuclear energy production and demand in the region (refer to Figure 4). Political considerations in favor of French national interest will play a significant role in determining Gravelines' decommissioning. Given its age and proximity to the UK and Belgium, two heavy importers of French energy, it seems likely that Gravelines will remain operational by 2035.

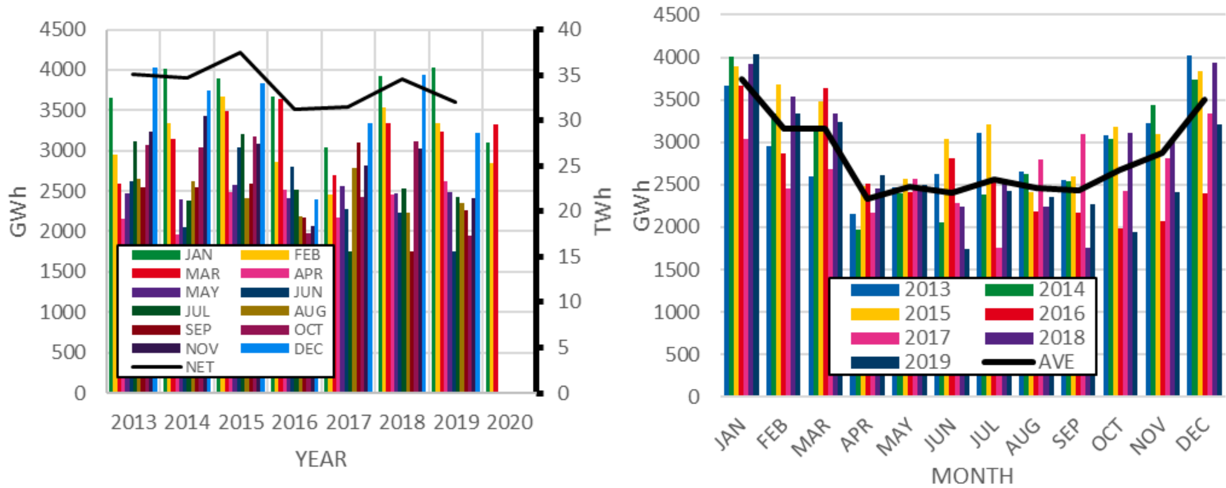


Figure 4: Nuclear energy production in Hauts-de-France, 2014-2019, annually (left) and monthly (right)

Thermal production

Hauts-de-France has seen an overall increase in thermal energy production (gas, coal and fuel), though gas-fired power plants are the predominant form of production (refer to Figure 5). Though the installation of new thermal power plants seems at odds with current climate ambitions, their use may become more relevant due to favorable gas prices[5] and an increasing need for dispatchable electricity sources as France reduces its nuclear capacity to 50% by 2030 and increases renewable penetration on the grid.

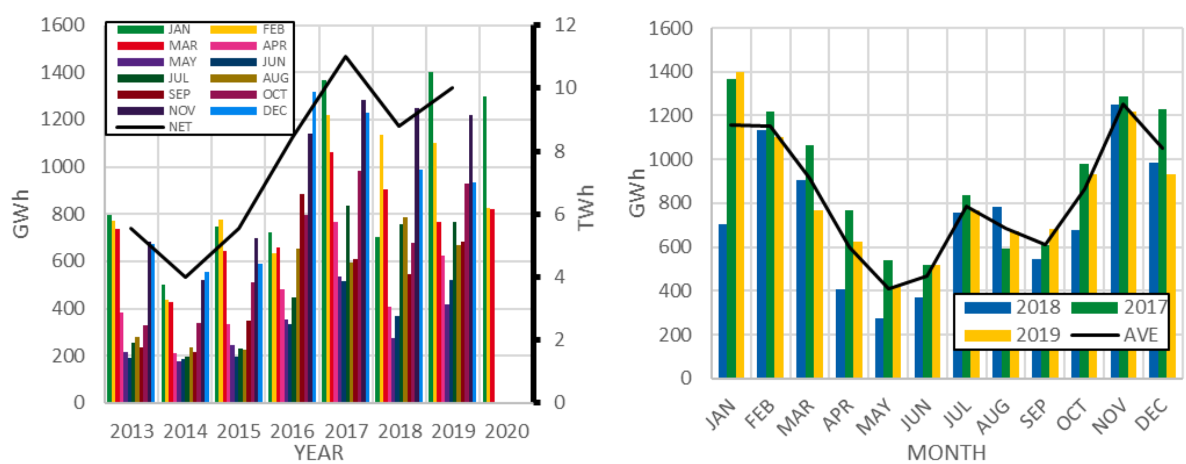


Figure 5: Thermal energy production in Hauts-de-France, 2014-2019, annually (left) and monthly (right)

Wind production

Onshore wind has been experiencing exponential growth since 2013 (refer to Figure 6). Similar growth can be expected to continue throughout 2025, though deceleration may occur by 2035 due to increased competition with other renewable sources (along with increased occurrences of curtailment) combined with lack of available land. The average capacity factor for onshore wind in Hauts-de-France peaks during winter months and troughs during the summer months, with a range of 15-35% (refer to Figure 6). Offshore wind is not expected to be produced in the region until 2026 (refer to Section 2.2.).

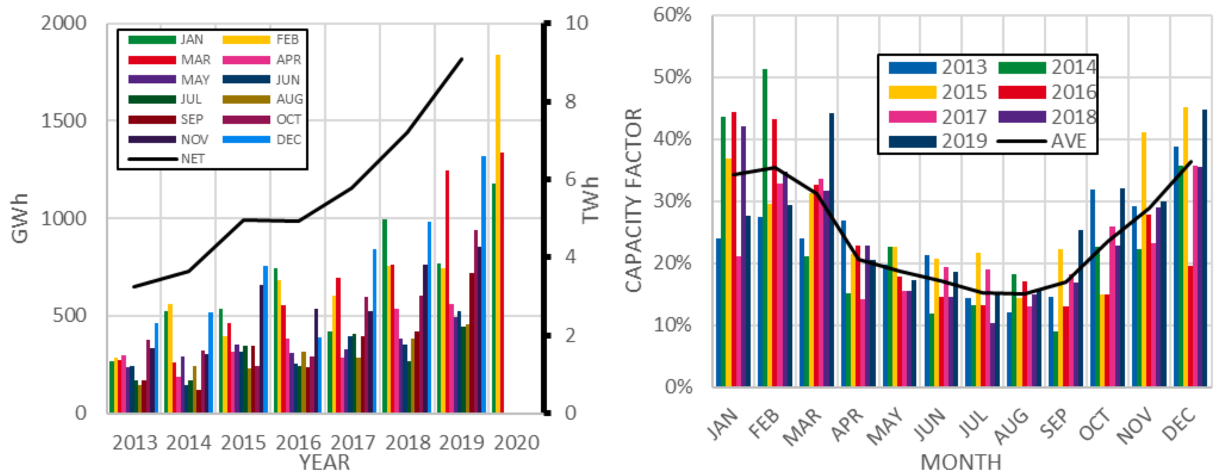


Figure 6: Wind energy production in Hauts-de-France, 2014-2019, annually (left) and monthly (right)

Solar production

This renewable energy source has experienced roughly linear growth at 7 MWh year-1 (refer to Figure 7). The capacity factor of solar energy in Hauts-de-France ranges from 4%-16%, peaking during the summer months and troughing during the winter months. This production profile is completely incongruent with the demand profile in the region. As a result, a high development of solar energy will involve a strong development of flexibility services for the grid amongst energy storage technologies such as hydrogen.

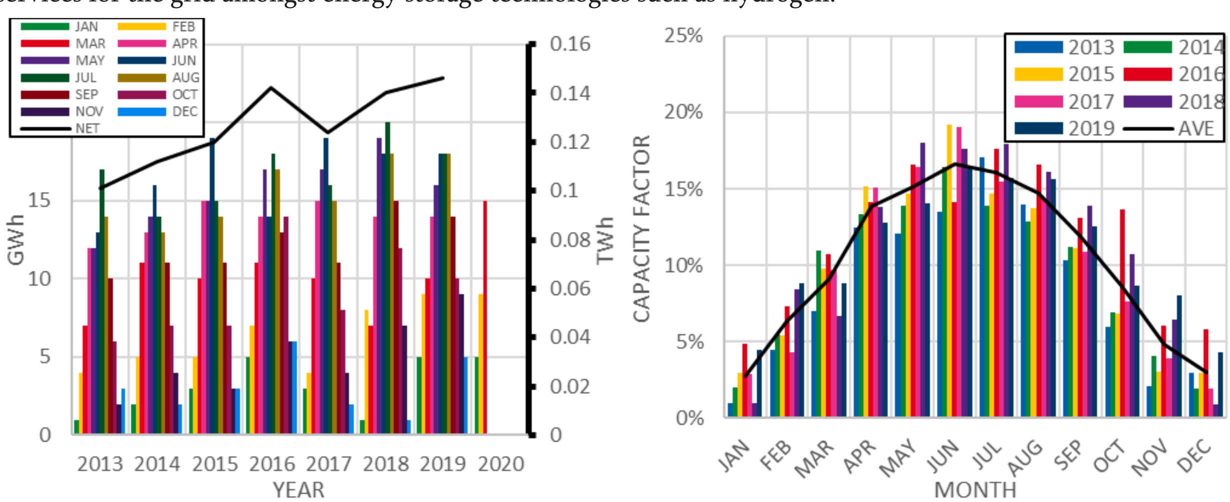


Figure 7: Solar energy production in Hauts-de-France, 2014-2019, annually (left) and monthly (right)

Hydro-/Biopower production

Hydropower energy has remained stable in the region, while biomass/gas power plants have grown at 69 MWh year^{-1} (refer to Figure 8).

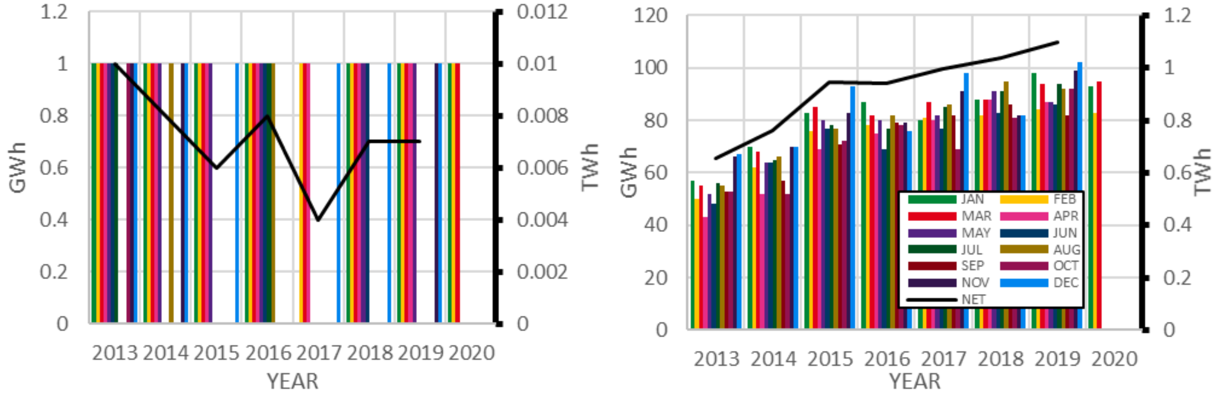


Figure 8: Hydropower (left) and biomass/gas power (right) production in Hauts-de-France, 2014-2019, annually

3.1.3 Exchange

Over the last few years, Hauts-de-France has become a net exporter of energy to other regions in France (refer to Figure 9). This appears to coincide with the increased production of thermal and wind energies in the region. France is also a net exporter to the United Kingdom (refer to Figure 10). Given its strategic importance, energy production and development in Hauts-de-France will necessarily be coupled with shifts in the UK energy strategies.

France is a net exporter to Belgium and Germany during summer months, but has recently become a net importer of energy during winter months (refer to Figure 10). This is no doubt due to the excess wind energy produced by German onshore wind farms. As the wind sector develops in Hauts-de-France, undesired overproduction of wind energy may present an opportunity and operational strategy for the hydrogen sector in the region.

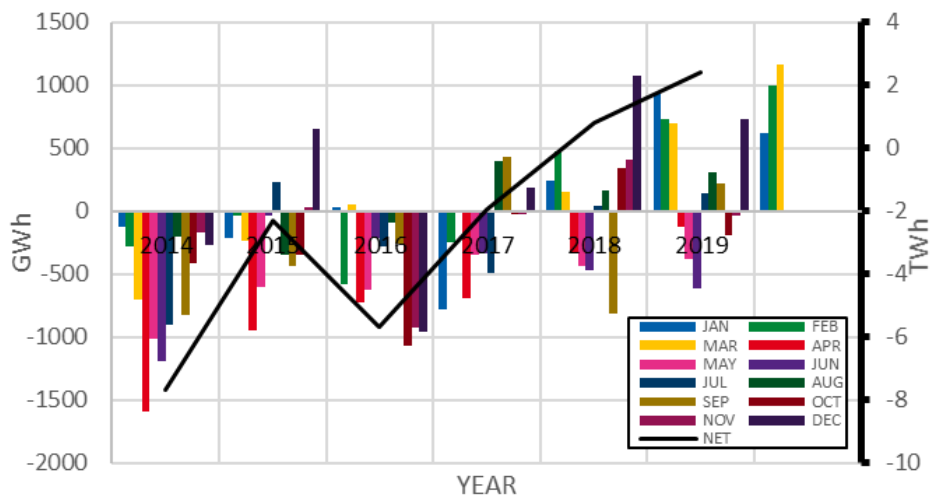


Figure 9: Annual interregional energy exchange for Hauts-de-France, 2012-2019

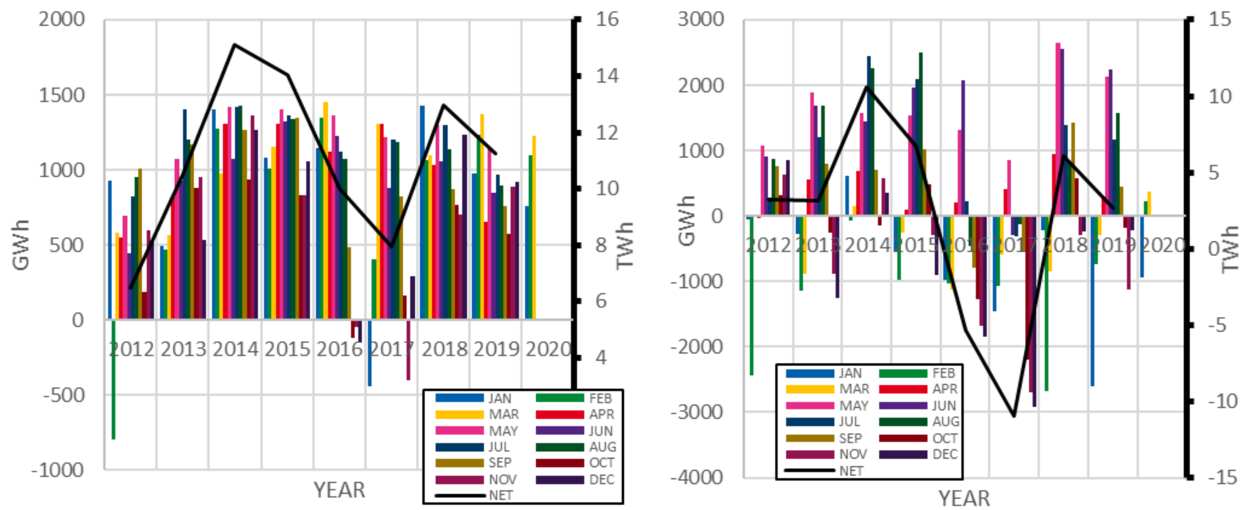


Figure 10: Annual France vs. UK (left) and France vs. Belgium-Germany (right) energy exchange, 2012-2019

3.2 Projection Scenarios and Future Installed Capacity

For horizon 2025, the energy mix of France is outlined by the *Programmations Pluriannuelles de l'Énergie* (PPE),[6] which predicts a decrease in electricity consumption of 440 TWh in 2023 to 426 TWh in 2028 (not including exports and grid losses). French law fixes an objective of 40% renewable energy production by 2030. As shown in Figure 11, the focus will be on strong integration of wind and solar capacity. In terms of nuclear energy, the 2x900 MW reactors at Fessenheim will be decommissioned in 2020, while a 1650 MW EPR reactor at Flamanville will be running by 2022. Under these conditions, Figure 11 outlines the expected energy mix for 2025.

In addition, Figure 12 outlines three different scenarios for the 2035 energy mix in France considered in this analysis:

- 2035A - the push for renewables (50%) is strong, squeezing nuclear (46%) and thermal (4%) energy production. Nuclear reactors older than 40 are automatically decommissioned,
- 2035W, renewable (35%) energy integration is far below levels outlined by French law, with an energy mix still dominated by nuclear (60%) energy, and
- 2035V, renewable (40%) energy increases in tandem with demand, gradually displacing nuclear (56%) energy.

These scenarios are inspired by predictions conceived by RTE[3] (refer to Figure 12) and assume that 2035 energy production will be between 620 – 640 TWh, with domestic consumption accounting for 72 – 75% of production. Assuming 2% for transmission grid losses, this implies that 23 – 26% of production will be exported to neighboring countries (with 4 – 5% exported to the UK and 2 – 3% exported to Belgium-Germany assuming similar behavior to 2018).

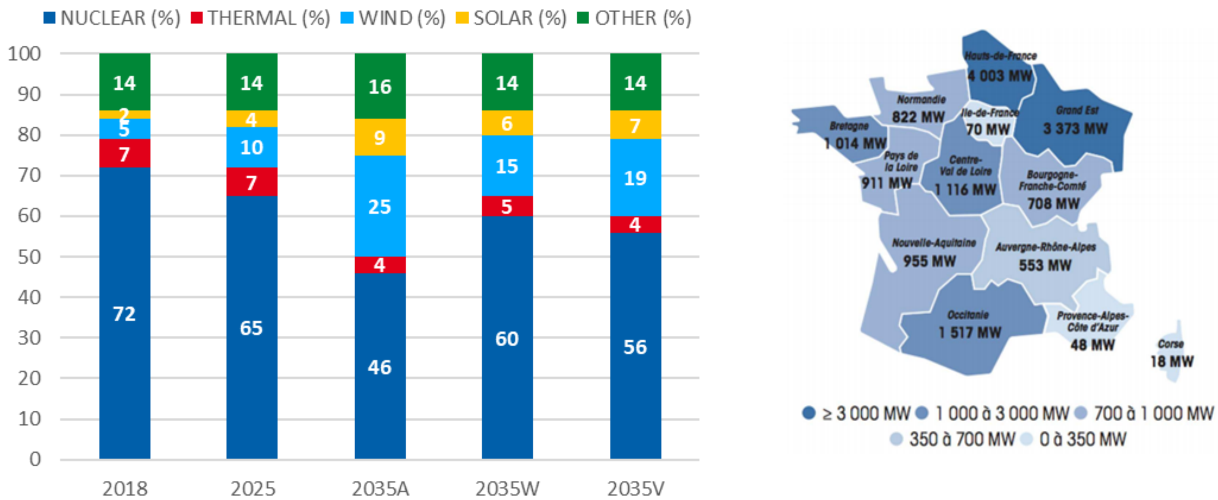


Figure 11: Scenarios for the energy mix in France for 2025/2035 (left) and installed wind energy capacity in France for 2018 (right), Source: PPE 2020

As shown in Figure 11, wind energy from Hauts-de-France accounted for almost 26% of all wind production in France for 2018 (28 TWh), and trends indicate exponential growth throughout 2020. While it is unlikely that such growth will persist throughout 2030, it is reasonable to assume that wind energy (onshore and offshore) in Hauts-de-France will account at least for the same fraction of national wind production. Therefore, roughly 15.4 TWh of wind energy will be produced (7 GW installed) in Hauts-de-France for 2025, and between 24.2 – 41.6 TWh of wind energy will be produced (12 – 20 GW installed) in Hauts-de-France for 2035.

It is worth noting that of the wind energy produced, 2.37 TWh will be produced from a future 600 MW offshore wind park located 10 km off the coast of Dunkirk (assuming 45% capacity factor based on capacity factors for offshore wind farms in Beatrice, UK and Galloper, UK in the English Channel).[7] Constructed by EDF, this park is expected to supply 40% of the energy demand of the surrounding department by 2026.[8]

Regarding other renewable energy sources in Hauts-de-France, their growth in Hauts-de-France is comparably lower (solar – 7 MWh year^{-1}, biofuel – 70 MWh year^{-1}, hydropower – negligible). Unless a major breakthrough in the efficiency of solar/biofuel occurs, these energy sources will have a weak presence in the region.

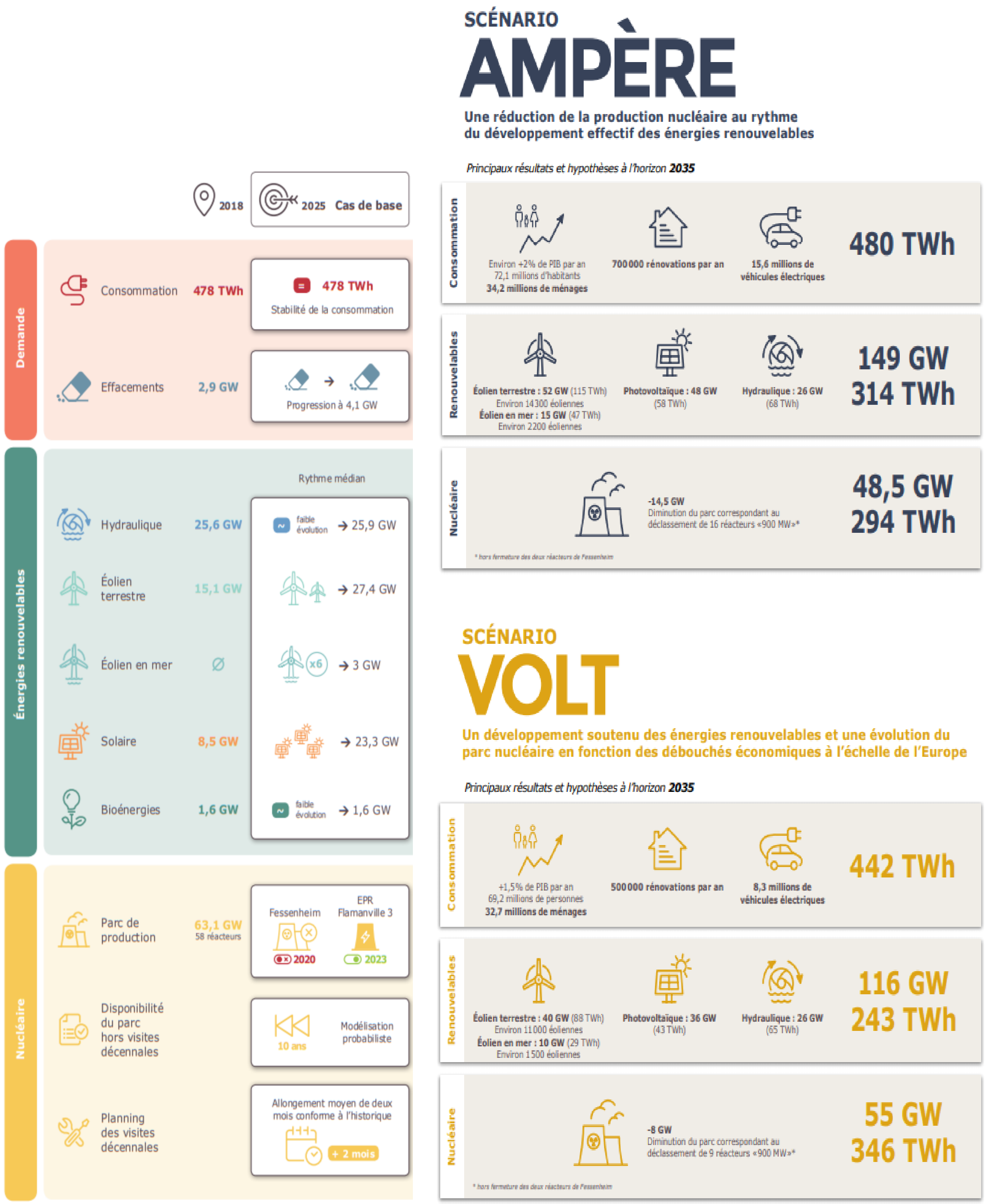


Figure 12: RTE predictions for 2025 French energy mix (left), scenario Ampère for 2035 energy mix (top), scenario Volt for 2035 energy mix (bottom). Source: RTE

3.3 A Hydrogen Economy in Hauts-de-France

Given the dominant growth of wind power in Hauts-de-France compared to other renewable energy sources, it is assumed that a hydrogen economy will revolve around the evolution of wind energy in the region.

Assuming that only 10% of all wind energy produced in Hauts-de-France is used to produce green hydrogen at a specific consumption of 3.05 kWh Nm^{-3}, this implies an annual production of 45 000 tonnes of hydrogen for 2025 and 71 000 – 122 000 tonnes of hydrogen for 2035. Furthermore, curtailment rates in northern Europe can vary from 0 – 5% of energy produced.[9] Given the proximity of Hauts-de-France to various high demand areas (Paris, London, Brussels) and the multiple interconnectors between France and other European nations (refer to Figure 13), it is reasonable to assume that curtailment will not be excessively high for the region. **Nevertheless, curtailed wind energy potentially translates to < 35 000 tonnes of green hydrogen for 2025 and < 61 000 tonnes for 2035**.

Considering the situation where, as a result of increased offshore wind installations in the North Sea, energy exchange with the UK is 2% as opposed to 4 – 5% as predicted for 2035, a resulting 365 000 – 565 000 tonnes of green/blue hydrogen can theoretically be produced from this excess energy. Such a situation is currently occurring with Germany, whose onshore wind capacity results in net imports for the French transmission grid during the winter months. As more European countries strive to cut carbon-intensive energy sources, France's unique situation of nuclear energy with high renewable penetration risks adversely affecting the profitability of operational nuclear power plants, particularly with feed-in tariff mechanisms which benefit renewable energy sources. To avoid incurring costs which inevitably fall on the consumer, France should promote and develop the infrastructure necessary for a hydrogen economy. By coupling the electricity to complementary energy carrier infrastructures (either gas or liquids), France can ensure a heightened level of national security while promoting synergies between robust, dynamic energy markets.

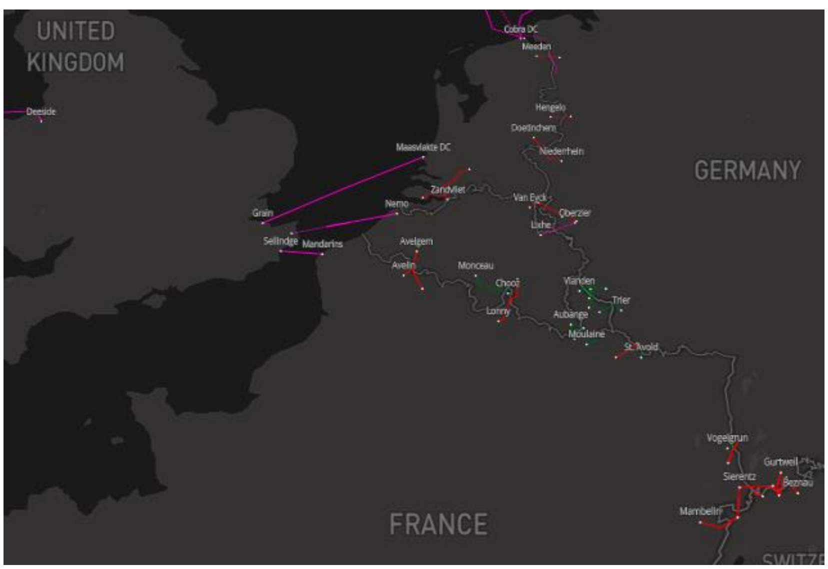


Figure 13: Map of interconnectors between European countries. Source: ENTSO-E

4 The cost of electricity for 2025 and 2035

The previous section is dedicated to assessing the potential electricity surplus available for hydrogen production within Hauts-de-France region. The following section focuses on the cost of these available electricity. Section 4.1. will identify the levelized cost of renewable wind energy for horizons 2025 and 2035 in Hauts-de-France, Section 4.2. will outline the methodology used to determine the spot price of electricity in France for both horizons.

4.1 Levelized Cost of Electricity of Wind for 2025 and 2035

4.1.1 LCOE of onshore wind

Onshore wind in France has achieved an LCOE of 63 – 68 €$_{2018}$ MWh^{-1}, possessing a strong potential for innovation and reduction in capital/operational expenditures. According to the 2020 PPE[6], onshore wind is seeing a roughly 2% annual reduction in costs. By 2025, the LCOE is expected to be on the order of 54 – 59 €$_{2018}$ MWh^{-1}, and by 2035, the LCOE is expected to drop to 44 – 48 €$_{2018}$ MWh^{-1}.

In France, feed-in tariffs have a 15-year duration for onshore wind energy,[10] with a fixed tariff at 82 €$_{2018}$ MWh^{-1} for the first 10 years of the wind farm and a variable tariff at 28 – 82 €$_{2018}$ MWh^{-1} for the last 5 years of the project. This variable tariff is changed annually depending on the hourly costs of labor and the price of production. In theory, the feed-in tariffs should function as an amortization of the wind farm. In practice, however, the life span of wind farms can extend well beyond 20 years with minor repairs, resulting in an incredibly low LCOE after 15 years of use.[11] By virtue of the feed-in tariff mechanism, however, wind energy effectively has "zero marginal cost" of production and benefits from priority dispatch in the merit-order system of the electricity market.

According to the national registry as of 2018, 29 kW → 61 MWh year^{-1} of wind energy in Hauts-de-France no longer benefit from feed-in tariffs. By 2025, this capacity is expected to increase to 1.1 MW → 2.3 GWh year^{-1}, and by 2035 it will reach 4.1 MW → 8.6 GWh year^{-1}.

4.1.2 LCOE of offshore wind

The LCOE of embedded offshore wind farms has reached 60 €$_{2018}$ MWh^{-1}, with an annual reduction of about 4% in costs. For 2026, the strike price of 44 €$_{2018}$ MWh^{-1} for the offshore wind farm off the coast of Dunkirk was reached through tendering. By 2035, it is reasonable to assume that further cost reduction coupled with system optimizations will result in an LCOE of 31 – 35 €$_{2018}$ MWh^{-1}. As for floating offshore wind farms, the LCOE by 2028 is expected to reach 150 €$_{2018}$ MWh^{-1} during the technology's infancy. By 2035, an LCOE of 95 €$_{2018}$ MWh^{-1} is foreseeable.[6]

In France, feed-in tariffs have a 20-year duration for offshore wind energy and are currently valued at 131 – 155 €$_{2018}$ MWh^{-1}.[12] This figure will most likely change as the technology develops.

4.1.3 Electrical cost of hydrogen

Assuming a specific consumption of 3.05 kWh Nm^{-3} expected for a high temperature electrolyzer, a TURPE which increases by 4% every four years – 18 $€_{2018}$ MWh^{-1} for 2018 – and renewable energy certificates whose price are inversely proportional to the amount of renewable energy – 3.16 $€_{2018}$ MWh^{-1} for 2018[13] – the onshore wind prices established in Section 3.1.1. will lead to electrical costs for hydrogen in 2025 at 23 – 25 $c€_{2018}$ Nm^{-3} (2.56 – 2.78 $€_{2018}$ kg^{-1}). In 2035, depending on the scenarios in Section 2.2., the production cost of hydrogen will be 20 – 22 $c€_{2018}$ Nm^{-3} (2.23 – 2.45 $€_{2018}$ kg^{-1}).

As for offshore wind energy, the prices mentioned in Section 3.1.2. will lead to an electrical cost for hydrogen of 20 $c€_{2018}$ Nm^{-3} (2.23 $€_{2018}$ kg^{-1}) in 2025 and 16 – 18 $c€_{2018}$ Nm^{-3} (1.78 – 2 $€_{2018}$ kg^{-1}) in 2035, depending on the scenarios in Section 2.2. If a 25% reduction rate is provided to hydrogen producers who use otherwise curtailed energy, these costs fall to 15 $c€_{2018}$ Nm^{-3} (1.67 $€_{2018}$ kg^{-1}) in 2025 and 12 – 14 $c€_{2018}$ Nm^{-3} (1.34 – 1.5 $€_{2018}$ kg^{-1}) in 2035.

These results reflect the electrical cost of hydrogen, and ignore the CAPEX of the electrolyser, pre-/post-processing of hydrogen, and storage expenditures.

4.2 The Spot Price of Electricity for 2025 and 2035

4.2.1 Factors

As shown in ***Erreur ! Source du renvoi introuvable.***, the penetration of renewable energy into the French electricity market has the paradoxical effect of increasing the wholesale electricity spot price[14], with an increase of 11 c€ MWh^{-1} $\%^{-1}$ of renewable energy in the energy mix. The 0% renewable energy intercept is 42 € MWh^{-1}, which corresponds to the LCOE of nuclear energy fixed by the ARENH mechanism for French consumers.[6]

Figure 14: Wholesale Electricity Market Price (left, Source: AleaSoft) and Effect of Renewable Penetration on Annual Electricity Spot Prices (right)

The overall reason for this effect involves many complex and interdependent variables, but the robustness of the grid plays a primary role. The integration of renewables requires the fortification and modernization of transmission/distribution grids, investments which are estimated to total 33 G€ by 2035.[15] These updates include construction of new transmission lines for offshore wind farms, fortification of interconnectors and an increased capacity for international energy exchange, and digitization of the system.

Part of the efforts to modernize transmission grids is the standardization of grid balancing markets across interconnected European countries. The Frequency Containment Reserves (FCR) Cooperation established in 2017 a common market for the procurement and exchange of FCR amongst participating transmission system operators (TSOs) from Austria, Belgium, Switzerland, Germany, Denmark, France, and the Netherlands. Under this regime, market mechanisms have driven down the cost of FCR to an average of 5 € MW^{-1}. Similar efforts for automatic Frequency Restoration reserves (aFRR - PICASSO), Replacement Reserves (RR – TERRE), and manual Frequency Restoration reserves (mFRR – MARI) are currently in development and will result in a similar drop in cost.[16] It is clear that the effective integration of renewable energy must coincide with increased cooperation from EU member states.

In addition, dynamic demand response is key to addressing the intermittency of renewable energy production. Though the impact of demand response is quantitatively difficult to address, Märkle-Huß et al. were able to demonstrate a 500 M€ decrease in electricity expenses if a load shifting strategy is adopted.[17]

Under these considerations, a sensitivity analysis was conducted which varies the influence of the energy mix percentage of renewables (r.%) on the spot price of electricity (€ MWh^{-1}) according to Table 1. The product of this variable with the percentage of renewable energy for the scenarios defined in Figure 11 is then added to the LCOE of nuclear energy (42 € MWh^{-1}) fixed by the ARENH mechanism to forecast the spot price. It is assumed that the LCOE of nuclear stays stable with time and that any variation in this price or other market variables (supply/demand, carbon tax, etc.) has a linearly independent effect on price.

Table 1: Scenarios for the Effect of Renewable Energy on the Annual Electricity Spot Price

ω → 10.5 c€ MWh-1 r.%-1	χ → 21 c€ MWh-1 r.%-1	α → 42 c€ MWh-1 r.%-1
- Grid fortification is proactive - EU electricity markets are coordinated and standardized - Demand response is elastic	→	- Grid fortification is reactive - EU electricity markets remain unchanged - Demand response is inelastic

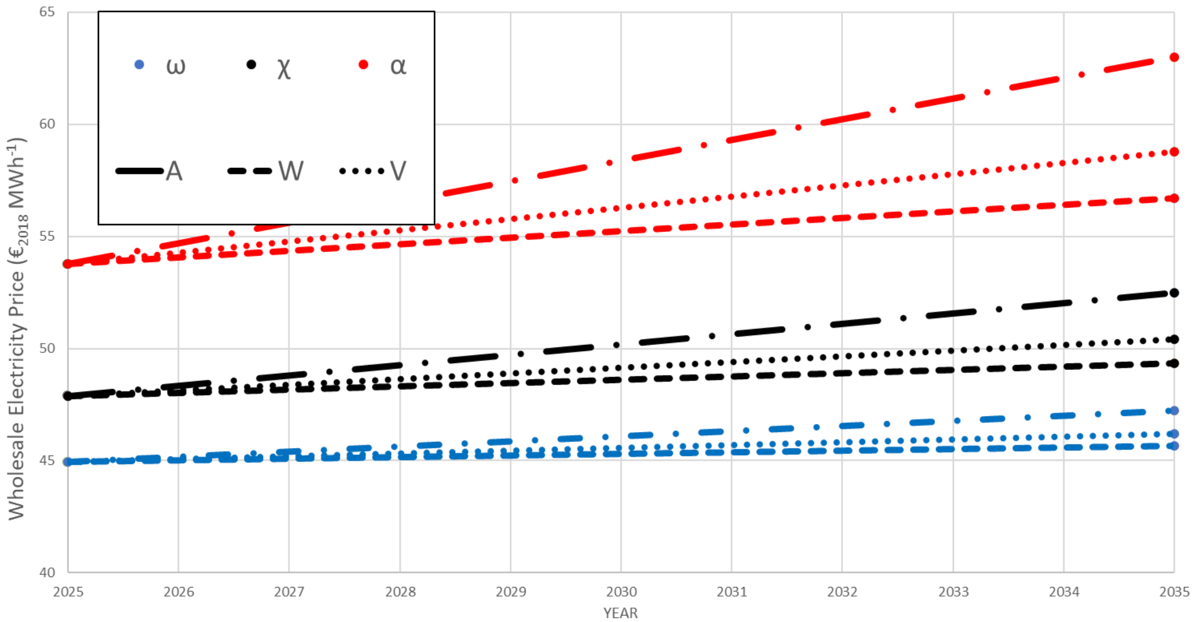


Figure 15: Spot Prices of Electricity for 2025 and 2035 for Different Scenarios

As shown in ***Erreur ! Source du renvoi introuvable.***, the price of electricity can vary dramatically depending on the scenarios. For 2025, the cost of renewable integration can cause the electricity spot price to vary between 45 – 55 $€_{2018}$ MWh^{-1}. For 2035A (r.50%), the electricity spot price varies from 47 – 64 $€_{2018}$ MWh^{-1}. For 2035W (r.35%), the electricity spot price varies from 46 – 59 $€_{2018}$ MWh^{-1}. For 2035V (r.40%), the electricity spot price varies from 45 – 56 $€_{2018}$ MWh^{-1}. These results coincide with predictions from other analyses.[12,18]

As mentioned, these results assume that the LCOE of nuclear energy remains stable, with a capacity factor of ≈75%. If a miscalculation in supply/demand (including the reduced export of energy to neighboring countries) results in the decrease of this capacity factor to 65%, this can result in an increase of 10 $€_{2018}$ MWh^{-1} to the spot price of electricity. A solution would be to decommission these nuclear power plants, however this leaves France vulnerable to potential supply shortages during peak demand. An increased reliance on foreign imports would inevitably increase the spot price on the French electricity market as well. Rather as nuclear reactors approach the end of their lifetimes, replacing their capacities with Power to X to Power alternatives can help ensure that the French base load is satisfied.

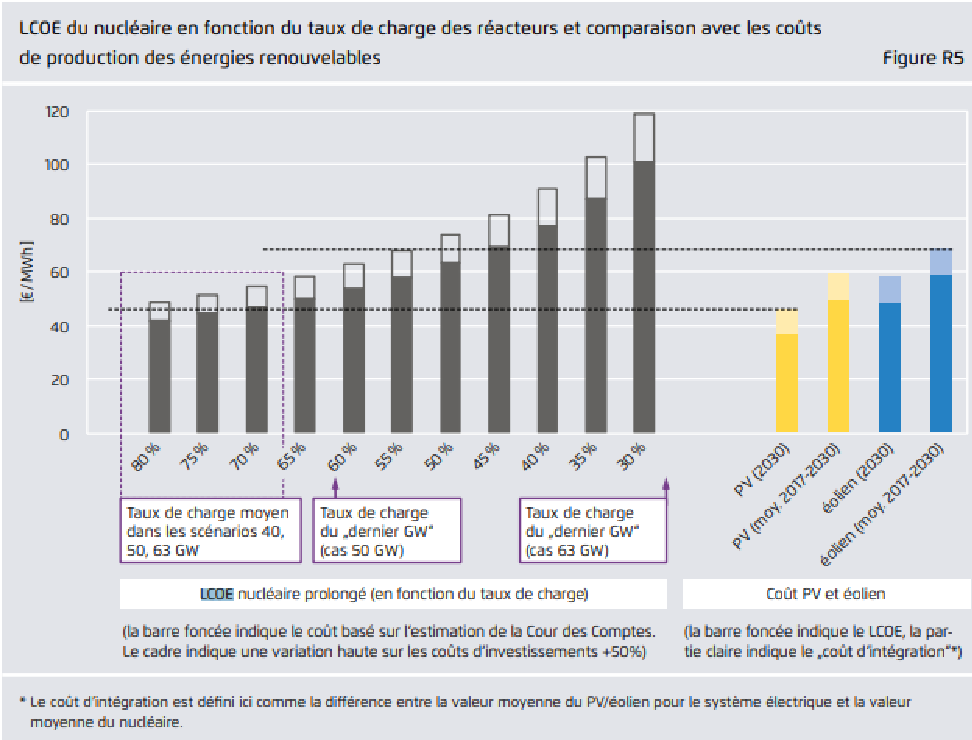


Figure 16: Levelized Cost of Electricity for Nuclear, Wind and PV (top), Source: Agora Energiewende, Iddri (2017).

4.2.2 Electrical cost of hydrogen

Assuming an efficiency of 3.05 kWh Nm^{-3} of hydrogen expected for a high temperature electrolyzer, a TURPE which increases by 4% every four years – 18 $€_{2018}$ MWh^{-1} for 2018 – and renewable energy certificates whose price are inversely proportional to the amount of renewable energy – 3.16 $€_{2018}$ MWh^{-1} for 2018 – wholesale grid prices will lead to electrical costs of hydrogen in 2025 at 20 – 23 c€ Nm^{-3} (2.23 – 2.56 $€_{2018}$ kg^{-1}). For 2035A (r.50%), the production cost will be 21 – 26 $c€_{2018}$ Nm^{-3} (2.34 – 2.89 $€_{2018}$ kg^{-1}). For 2035W (r.35%), the production cost will be 21 – 25 $c€_{2018}$ Nm^{-3} (2.34 – 2.78 $€_{2018}$ kg^{-1}). For 2035V (r.40%), the production cost will be 21 – 24 $c€_{2018}$ Nm^{-3} (2.34 – 2.67 $€_{2018}$ kg^{-1}). Furthermore, if an extraneous event increases the spot price of electricity by 10 $€_{2018}$ MWh^{-1}, the production cost for hydrogen increases by 3 $c€_{2018}$ Nm^{-3} (0.33 $€_{2018}$ kg^{-1}).

These results reflect the electrical cost of hydrogen, and <u>ignore</u> the CAPEX of the electrolyser, pre-/post-processing of hydrogen, and storage expenditures. While the previous results outline costs assuming the annual average, this is most likely not how hydrogen production will operate over the year.

The 'merit-order effect' is a direct result of feed-in tariff mechanisms, whereby renewable energy <u>must</u> be bought at a fixed price and benefits from priority dispatch. As shown in Figure 17, this implies 'zero marginal cost' for renewable energy, and by displacing all other forms of energy generation up the supply curve, the market price of electricity is reduced ($P_1 \rightarrow P_2$).

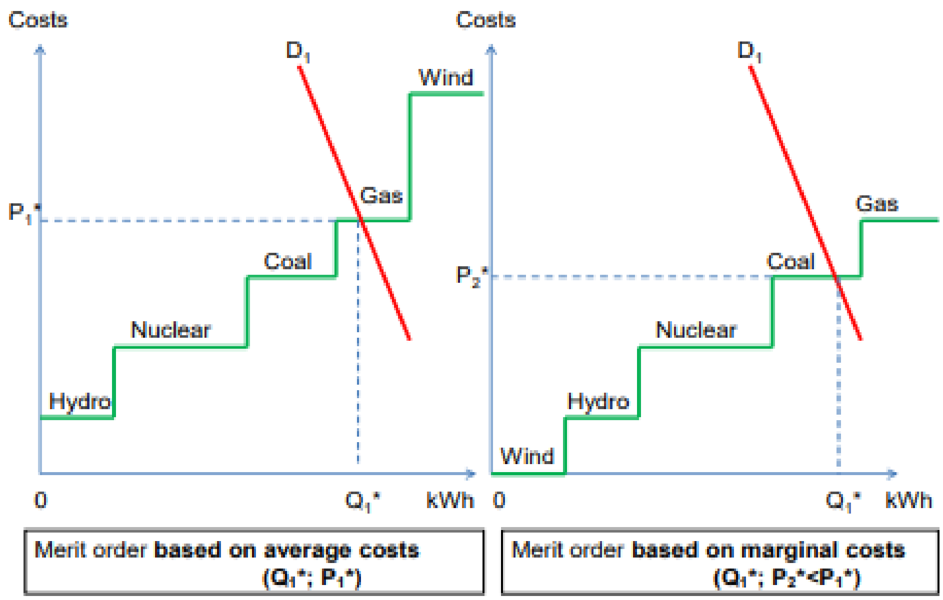
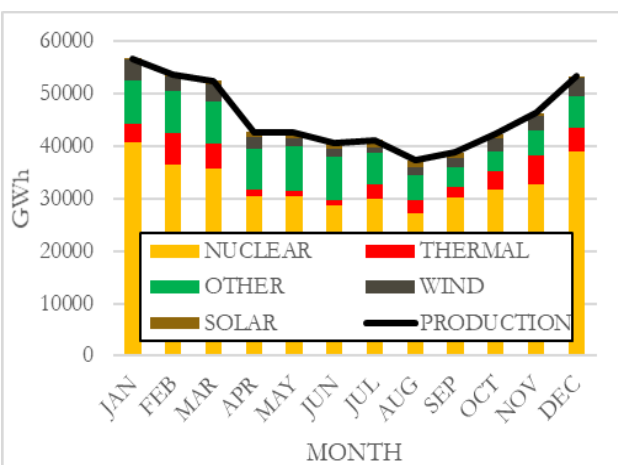


Figure 17: Merit order with and without fed-in tariff. Source: Benhmad et al. (2018)

By employing an ARMA-X-GARCH-X model, Benhmad and Percebois concluded that the day-ahead electricity spot price in Germany changes by -1 $€_{2018}$ MWh^{-1} for every injected GWh of wind or solar energy.[13] As shown in Figures 18 and 19., despite high electricity demand in the winter months (which economically should imply high prices), the strong injection of wind energy from France (and Germany, refer to Figure 10: Annual France vs. UK (left) and France vs. Belgium-Germany (right) energy exchange, 2012-2019) results in incredibly low prices. Wind energy in particular leads to high price volatility, with the increasingly prevalent phenomena of negative energy spot prices.[19] By implementing a hydrogen economy, France and Europe in general can reduce price volatility and ensure stable markets.



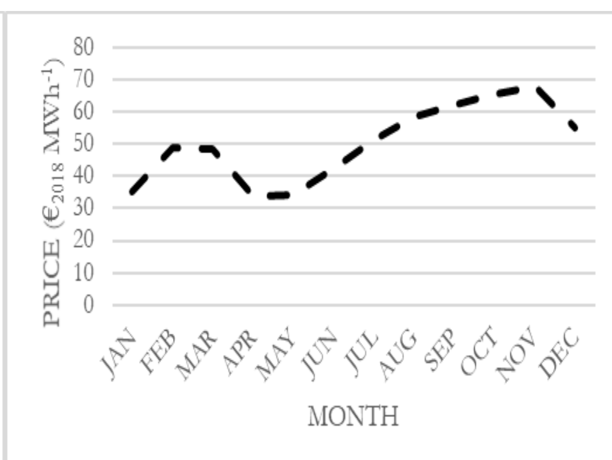


Figure 18: Monthly Energy Mix for Hauts-de-France 2018 (right), Source: RTE

Figure 19: Monthly Average Electricity Spot Prices in France 2018 (left), Source: EPEXSPOT

5 Conclusions and perspectives

Energy consumption in Hauts-de-France has stabilized since 2014 and is not expected to rise substantially in 2025 nor 2035. Electricity production in the region is comprised predominantly of nuclear and thermal energy, but exponential growth from onshore wind, along with plans to establish a 600 MW offshore wind farm near Dunkerque, indicates that production volatility will pose an issue in the region. While fortification of the transmission grid is a necessity (particularly within France) competition and uncertainty with renewable energy from the UK, Belgium and Germany means that implementation of energy storage in the form of a hydrogen economy has become a question of national security. Assuming that only 10% of all wind energy produced in Hauts-de-France is used to produce green hydrogen at a specific consumption of 3.05 kWh Nm^{-3}, this implies an annual production of 45 000 tonnes of hydrogen for 2025 and 71 000 – 122 000 tonnes of hydrogen for 2035. Curtailed wind energy potentially translates to < 35 000 tonnes of green hydrogen for 2025 and < 61 000 tonnes for 2035. It is assumed that wind production in Hauts-de-France remains at roughly 26% of national production as was the case in 2018, the latter of which is based on the PPE and forecasts provided by RTE.

According to the 2020 PPE, the LCOE of onshore wind is expected to be 54 – 59 $€_{2018}$ MWh^{-1} by 2025 and drop to 44 – 48 $€_{2018}$ MWh^{-1} by 2035. For offshore wind energy, an LCOE of 31 – 35 $€_{2018}$ MWh^{-1} is possible given current trends. The electrical cost of producing hydrogen could vary between 2.23 – 2.78 $€_{2018}$ kg^{-1} by 2025 and 2 – 2.45 $€_{2018}$ kg^{-1} by 2035.

Based on results from the sensitivity analysis and incorporating the 3 scenarios defined previously, the spot price varies between 45 – 55 $€_{2018}$ MWh^{-1} for 2025 and 45 – 64 $€_{2018}$ MWh^{-1} for 2035. The electrical cost of hydrogen then corresponds to 2.23 – 2.56 $€_{2018}$ kg^{-1} by 2025 and 2.34 – 2.89 $€_{2018}$ kg^{-1}. Furthermore, if an extraneous event increases the spot price of electricity by 10 $€_{2018}$ MWh^{-1}, the production cost for hydrogen increases by 0.33 $€_{2018}$ kg^{-1}.

The development of flexible, dynamic demand response and energy storage is paramount to achieving the benchmarks set by the Paris Agreement. A hydrogen economy is capable of providing this synergy and security.

6 References

(1) Eco2mix Téléchargement | RTE France https://www.rte-france.com/fr/eco2mix/eco2mix-telechargement (accessed Jun 15, 2020).

(2) CLIMAT DUNKERQUE (FRANCE) https://fr.climate-data.org/europe/france/nord-pas-de-calais/dunkerque-362/ (accessed Jun 15, 2020).

(3) Bilan prévisionnel https://www.rte-france.com/fr/article/bilan-previsionnel (accessed Jun 15, 2020).

(4) Gravelines Nuclear Power Station. *Wikipedia*.

(5) Bourgeois, S. Quatre centrales gaz en Belgique pour remplacer le nucléaire, crédible ? https://www.rtbf.be/info/economie/detail_quatre-centrales-gaz-en-belgique-pour-remplacer-le-nucleaire-credible?id=10222625 (accessed Jun 30, 2020).

(6) Programmations pluriannuelles de l'énergie (PPE) https://www.ecologique-solidaire.gouv.fr/programmations-pluriannuelles-lenergie-ppe (accessed Jun 15, 2020).

(7) UK offshore wind capacity factors https://energynumbers.info/uk-offshore-wind-capacity-factors#:~:text=UK%20offshore%20wind%20capacity%20factors%20%20%20,%20%2090%20%2035%20more%20rows%20 (accessed Jun 30, 2020).

(8) Le consortium mené par le Groupe EDF remporte le projet éolien en mer de Dunkerque https://www.edf-renouvelables.com/presse/communiques-de-presse/le-consortium-mene-par-le-groupe-edf-remporte-le-projet-eolien-en-mer-de-dunkerque/ (accessed Jun 15, 2020).

(9) Fraile, D. WindEurope Views on Curtailment of Wind Power and Its Links to Priority Dispatch. June 2016.

(10) LA RÉGLEMENTATION EN FRANCE: La procédure d'autorisation d'un parc éolien https://fee.asso.fr/comprendre-leolien/la-reglementation-en-france/ (accessed Jun 15, 2020).

(11) How to extend the lifetime of wind turbines https://www.renewableenergyworld.com/2019/09/20/how-to-extend-the-lifetime-of-wind-turbines/#gref (accessed Jun 15, 2020).

(12) Vestager, M. Bruxelles, Le 26.7.2019, C(2019) 5498 Final: Décision de Tarif d'achat Pour Les Éoliennes En Mer de France. July 26, 2019.

(13) Hulshof, D.; Jepma, C.; Mulder, M. Performance of Markets for European Renewable Energy Certificates. *Energy Policy* **2019**, *128*, 697–710. https://doi.org/10.1016/j.enpol.2019.01.051.

(14) European electricity markets panorama: France https://aleasoft.com/european-electricity-markets-panorama-france/ (accessed Jun 15, 2020).

(15) Franke, A. French power grid operator RTE to invest Eur33 bil by 2035 https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/091719-french-power-grid-operator-rte-to-invest-eur33-bil-by-2035 (accessed Jun 15, 2020).

(16) Electricity Balancing https://www.entsoe.eu/network_codes/eb/ (accessed Jun 15, 2019).

(17) Märkle-Huß, J.; Feuerriegel, S.; Neumann, D. Large-Scale Demand Response and Its Implications for Spot Prices, Load and Policies: Insights from the German-Austrian Electricity Market. *Appl. Energy* **2018**, *210*, 1290–1298. https://doi.org/10.1016/j.apenergy.2017.08.039.

(18) Agora Energiewende; Iddri. L'Energiewende et La Transition Énergétique à l'horizon 2030 – Focus Sur Le Secteur Électrique. Impacts Croisés Des Choix de La France et de l'Allemagne Sur Le Nucléaire et Le Charbon Dans Le Contexte Du Développement Des Énergies Renouvelables. 2017.

(19) Benhmad, F.; Percebois, J. An Econometric Analysis of the Merit-Order Effect in Electricity Spot Price: The Germany Case. In *Time Series Analysis and Forecasting*; Rojas, I., Pomares, H., Valenzuela, O., Eds.; Contributions to Statistics; Springer International Publishing: Cham, 2018; pp 259–271. https://doi.org/10.1007/978-3-319-96944-2_18.