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Research paper

Paving the way for low-carbon hydrogen supply chain deployment by exploring the potential of renewable energies and multisectoral hydrogen demand: Case study of France

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ABSTRACT

France has set ambitious targets for hydrogen production in its National Roadmap, aiming to install at least 6.5 GW of electrolyzer capacity and produce 700,000 tons of hydrogen annually by 2030. The country is focusing on producing renewable or low-carbon hydrogen primarily through electrolysis. However, it faces significant barriers in rapidly scaling up renewable energy infrastructure and may need to consider import strategies to address potential shortages. Addressing these challenges requires investigating whether the availability of renewable energy for the production of electrolytic hydrogen could become a limiting factor for hydrogen adoption and potentially act as a bottleneck in its market integration. The methodology merges forecasts from the public and private sectors to address both renewable and non-renewable electricity production and the energy needed for rising hydrogen demand. The approach developed involves estimating France's renewable energy supply up to 2050 and determines how much of this energy can be allocated to hydrogen production to ensure it remains carbon-free and genuinely renewable. Unlike many existing roadmaps that take a more general approach, the innovative part of this study is developing a territorial perspective to conduct a detailed analysis of potential mismatches between hydrogen supply and demand.

Three distinct sources of electricity are considered for the electrolyzers, which could be connected to the grid or directly to renewable power plants: low-carbon electricity from the French grid, renewable electricity from re-powered solar and wind farms, and renewable electricity from newly installed power plants. Total electricity demand is projected to rise from 475 TWh/y in 2020 to 754 TWh/y in 2050, with the share of renewable energy increasing from 19% in 2020 to 69% in 2050.

The study evaluates the demand for hydrogen in two key sectors, industry, which is heavily dependent on hydrogen, and mobility, which currently has a more modest contribution. Hydrogen demand is expected to increase from nearly 310 ktons per day in 2025 to over 2650 ktons per day by 2050.

Given an average specific consumption of 55 kWh of electricity per kg of hydrogen produced, the total electricity demand for electrolytic hydrogen production is projected to grow from 17 TWh/year in 2025 to 146 TWh/year in 2050.

It can be concluded that allocating the entire anticipated production from re-powered solar and on-shore wind farms in the coming years will not be sufficient to meet the electricity demand required for electrolytic hydrogen production. To prevent renewable energy from becoming a bottleneck for hydrogen market integration and to avoid the need for hydrogen imports, it is crucial to allocate 5% to 10% of the projected renewable output from newly installed plants to address the increasing hydrogen demand. This result is key to creating an optimal design model for hydrogen supply chains.

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Nomenclature		Abbreviations	
CO_2	Carbon Dioxide	CSPE	Contribution to the electricity public service
CO	Carbon Monoxide	DROM	Départements et régions d'outre-mer
°C	Celsius	EDF	Électricité de France
c€	Euro cent	EIFER	European institut for energy research
H_2	Hydrogen	GIS	Geographic Information System
kWp	kW pick	ICPE	Installations Classified as Environmental Protection
CH_4	Methane	ODRE	Open Data Réseaux Énergies
Mton	Milion tons	PPE	Plan for Energy and Climate
H_2O	Water	PNIEC	Plan national intégré en matière d'énergie et de climat (National energy and climate plan)
		PPA	Power Purchase Agreement
		RES	Renewable energy source
		RTE	Réseau de Transport d'Electricité
		SIRET	Système d'identification du répertoire des établissements
		WE	Wind Europe
		WP	Wind Power
		ZDE	Zone de développement éolien

1. Introduction

In recent years, there has been a global push to decarbonize the energy sector to mitigate the effects of climate change.

This effort has necessitated the reduction of greenhouse gas emissions and the goal of keeping global warming below 2 °C above pre-industrial levels. The primary objective is to achieve net-zero global energy-related carbon dioxide emissions by 2050. To reach this target, several key strategies have been implemented, including increasing renewable energy production, electrifying energy systems, improving energy efficiency, redesigning industrial processes, and renovating buildings [1].

Hydrogen, with its versatile applications and potential to serve as a clean and efficient energy carrier, has emerged as a promising solution to meet the pressing demand for sustainable energy systems. France, recognizing this potential, has embarked on an ambitious path to harness hydrogen as a crucial element of its energy transition strategy [2].

The European energy demand is projected to be around 11,500 TWh in 2030, decreasing to 9300 TWh in 2050. According to different scenarios, hydrogen could play a central role, covering 4%–6% of the final European energy demand by 2030 and potentially increasing to 8%–24% by 2050. In the latter case, if hydrogen is free of CO_2 emissions, it would contribute to an annual abatement of roughly 700 CO_2 Mtons, which corresponds to half of the emissions required by the 2 °C plan [3,4].

However, planning the renewable hydrogen supply chain is complex due to its operational characteristics and the variety of technical solutions. Despite these options, the development of renewable hydrogen supply chains remains immature and challenging. Additionally, the various renewable feedstocks used for hydrogen production exhibit high uncertainty in terms of their availability and performance [5,6].

Currently, hydrogen production primarily relies on natural gas through steam methane reforming, resulting in what is commonly referred to as grey hydrogen. To achieve low-carbon emissions, various hydrogen production pathways are being explored. Although many involve fossil fuel-based methods, such as steam methane reforming or coal gasification coupled with carbon capture and sequestration, an alternative approach involves biomass gasification. However, the only technically feasible solution, independent of fossil fuels and without overlooking local CO_2, is water electrolysis. It is crucial to note that for this electrolysis process, the electricity source must be derived from renewable energy sources [7,8]. Given the substantial electricity requirements for hydrogen production, concerns arise regarding the potential shortage of renewable resources for electrolytic hydrogen production, leading to an escalating demand [9].

The methodology developed in this work is based on merging forecasts from both public and private entities for the France case study [10]. The country is prioritizing the production of renewable or low-carbon hydrogen mainly via electrolysis. However, it encounters substantial challenges in swiftly expanding renewable energy infrastructure and may need to explore import strategies to mitigate potential shortages [10]. This approach bridges the gap between renewable and non-renewable electricity production on the one hand, and the energy required to meet the growing hydrogen demand over time on the other. The innovative and crucial aspect of this approach is its projection of the future supply of renewable electricity in France from the present through 2050. This methodology aims to determine the portion of renewable energy specifically allocated to hydrogen production, thereby ensuring that the hydrogen is carbon-free and genuinely renewable. This approach is essential to develop an optimal design model for hydrogen production chains.

This study, specifically focused on France, leverages the strategic framework developed by *"France Hydrogen"* [2]. This plan outlines a comprehensive strategy for decarbonizing the French energy system, with an ambitious target for France to produce and consume approximately 1,070,000 tons of renewable or low-carbon hydrogen annually by 2030.

A notable contribution of this manuscript is its rigorous assessment of hydrogen roadmaps. While numerous existing roadmaps tend to adopt a broader perspective, this investigation transcends the generalized assessment of energy resources and hydrogen demand by incorporating a territorial framework, undertaking a meticulous examination of potential discrepancies between hydrogen supply and demand.

This paper is divided into four sections following this introduction (Section 1).

Section 2 focuses on the study of renewable energy sources (RES) and presents the currently predictable available energy generated from solar and wind farms. It also considers the expiration of tariff agreements for these energy sources in the coming decades and aggregates these values with the projected production from new installations of each technology based on renewable energy sources.

Section 3 delineates the anticipated expansion in the demand for low-carbon and renewable hydrogen spanning the years 2025 to 2050. The focal sectors under scrutiny include the industrial sector, which presently stands as the predominant consumer of hydrogen, and the transportation sector, which is projected to experience significant growth in the upcoming decades.

Section 4 discusses the existing nexus between renewable energy availability and electrolytic hydrogen production.

Finally, Section 5 concludes and suggests how this approach will be useful in feeding prospective energy models for the deployment of hydrogen supply chains.

2. Assessment of the renewable energy potential for hydrogen production

2.1. Methodology

To perform a consistent analysis of the electricity market in relation to renewable energy, various parameters have been considered. These include the primary energy sources of electricity and their associated CO_2 emissions, the availability of electricity from renewable energy sources (RES), and the potential for acquiring renewable electricity through purchase agreements from the grid.

To better characterize the energy vector, a general classification of electricity has been adopted in this work:

- **RES re-powering:** 100% renewable electricity generated from existing photovoltaic panels and wind turbines, which have reached the end of their contract terms (going out of tariff).
- **RES new installations:** 100% renewable electricity generated from newly installed power plants (not limited to wind and solar technologies).
- **NO RES:** Low-carbon electricity derived from the French electricity mix and supplied through the electrical grid.

The initiative of "RES re-powering" is exclusively concentrated on existing photovoltaic panels and wind turbines. This focus is justified by the suitability of these technologies for impactful re-powering, enhancing their energy efficiency while minimizing environmental impacts through the replacement of components such as rotors, wind turbine blades, and panels [11]. In addition, these technologies have historically received incentives and are projected to continue to benefit from this financial support in the coming years [12,13].

For the first type of energy, a database has been constructed by extrapolating data from public and private data sets on renewable electricity production plants, particularly using the *Open Data Réseaux Énergies* (ODRE [14]). Within this database, only two technologies have been identified as potentially suitable for electrolyzer supply: solar panels and offshore wind turbines. The data pertain to existing plants that could potentially be re-powered in the upcoming years, and their position is already known. This crucial information has enabled the identification of primary locations at a regional level from which the renewable power of these re-powered plants is expected to originate.

The contribution of other RES technologies, including offshore turbines and hydroelectric power plants, will only be considered in the category "RES new installations". This assumption is based on the premise that existing installations are already meeting the current demand and cannot provide electricity for future hydrogen production. In the case of RES re-powering, only farms that are coming out of contracts for incentives are considered. This approach facilitates the establishment of new power purchase agreements (PPAs) or similar arrangements, specifically tailored for electrolytic hydrogen production.

The availability of the remaining electricity, classified as "RES new installations" and "NO RES", has been extrapolated from the "Futurs énergétiques 2050" report by "Réseau de Transport d'Électricité" (RTE) and its various partners [15–17]. This report provides information on the total demand for electricity in France, the current share of renewables (19.1%–24.5%), and the projected share by 2050 (46%–69%).

2.2. Assessing the RES re-powering: Evaluating post-incentive potential for renewable hydrogen production

2.2.1. Assessment of the plants available for re-powering

The first step in building the database involved consulting the Open Data platform called *"Registre national des installations de production et de stockage d'électricité"* [14], which was established in 2017 by gas and electricity network stakeholders. This platform provides various information on energy production, storage and use in France on different scales. According to this database, there are approximately **1845 wind farms** and around **45,000 solar installations** in France.

It is important to highlight that occasionally, a single entry in the database pertains not to a whole site but to a particular component within a wind or solar park. These components were aggregated if they were part of the same wind or solar park.

Furthermore, very small productions (that is, less than 36 kW) were aggregated by city from the Open Data source [14]. Consequently, specific information for the individual site was missing. Therefore, also due to the small size of the facilities, these are not included in this study. The smallest electrolyzer considered in this work has a nominal capacity of 1 MW, so only farms with a peak power (nominal, installed, or injected, depending on the available information) above 1 MW are considered in this study.

To complete the database, additional sources were integrated. For wind power plants, supplementary information was obtained from the following databases: Wind Europe (WE) [18], Wind Power (WP) [19], and CEREMA Eoliennes en mer [20]. Table A.9 in Appendix details the sources used for each parameter.

2.2.2. On-shore wind farms

Eole 2005 was the first program launched by the French state to support the wind sector [21]. From 1996 to 2000, calls for projects in which competitors had to propose the electricity selling tariffs led to the construction of several wind farms. In 2000, the system was completely modified and the purchasing obligation mechanism was introduced. When planning a wind farm, the developer could ask the French public utility EDF to buy, for a 15-year contract, all the produced electricity at a fixed price, decided by the State. The goal was to cover building costs. The final consumers paid to EDF the CSPE (Contribution to the Electricity Public Service).

That scheme went through several changes, the main one being about the electricity tariffs, from 2008: the price was fixed (8,2 c€/kWh) for the first ten years from the commissioning date, then could fluctuate (2,8 to 8,2 c€/kWh), depending on the site's productivity. The administrative processes are slowly facilitated: in 2013, the minimal number of turbines per site (5) and the ZDE (areas for the development of wind power) are removed from official texts and getting an official authorization becomes easier.

In 2016, the state strategy was revised to introduce contracts with additional remuneration instead of purchasing obligation: electricity is sold on markets, and for 15 years, EDF pays the difference between the market price and a reference price, determined at the beginning of the project and financed by CSPE. This affects all projects launched in 2016. Starting in 2017, a distinction was made between small-scale wind farms (comprising fewer than 6 wind turbines, each with a power capacity below 3 MW) and large-scale farms (exceeding the aforementioned criteria). To ensure the economic viability of smaller sites, they receive additional remuneration for twenty years from the commissioning date. However, large-scale sites are planned through biannual projects calls, during which potential developers propose electricity sales prices. The contracts signed with the selected consortiums span 20 years. A summary of incentives for offshore wind farms in France is provided in Table A.10 in Appendix.

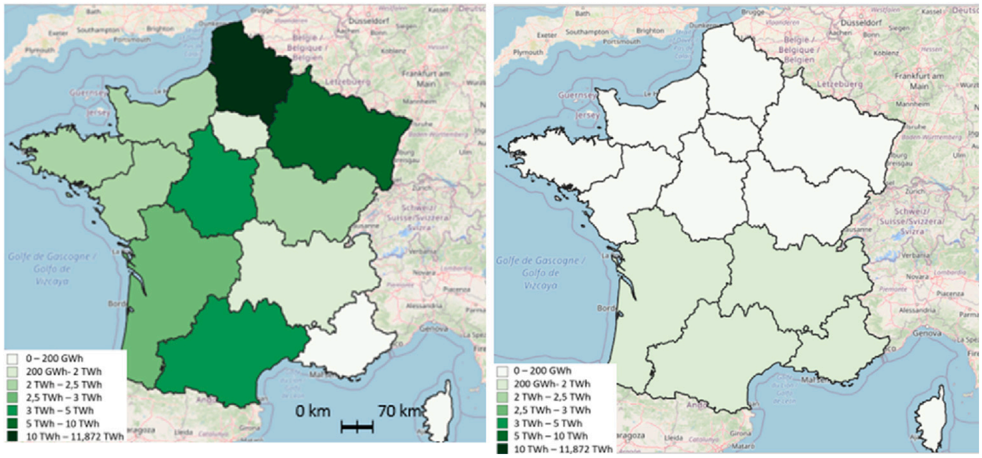

Fig. 1. Yearly energy production from on-shore wind farms in French regions (GWh) (left side); yearly energy production from solar farms in French regions (GWh) (right side).

2.2.3. Solar farms

As already explained, this study does not consider installations with a total farm power capacity less than 1 MW; thus, the schemes presented here are only valid for sites large enough to guarantee a certain hydrogen production, although there are other mechanisms for smaller solar panels. The first measures supporting the development of solar energy in France were launched in 2002, to offer twenty-year-long feed-in contracts for the installation of solar panels [22]. The electricity selling prices could vary by region (for example, metropolis, Corsica, and DROM, overseas departments and regions of France) and there were limits on maximum power capacity, depending on the type of supporting buildings. This was applied to structures with commissioning dates after 15 March 2002, and in some situations with commissioning dates between 10 February 2000 and 15 March 2002. Until 2004, the power capacity had to be under 1 MW for collective housing and professional buildings, but this barrier was then removed [23,24]. In 2006, lawmakers introduced a premium for the integration of solar panels into buildings while maintaining feed-in tariffs. It was abandoned in 2018. Since 2010, selling prices have been dropping. The current system, in place since 2017, consists of calls for projects for large installations (more than 100 kWp) either in buildings or on the ground. For those with a power capacity above 500 kWp, there is no feed-in tariff but an additional remuneration, with contracts signed for twenty years, from the commissioning date. The submitted projects must make a sale price proposal and are partly evaluated on economic competitiveness [23].

2.2.4. Electricity coming out of contracts

According to the stipulated contracts, in the next decade, a total wind power capacity of around 1 GW per year will be coming out of tariffs, even though the turbines are still able to maintain a high level of production for at least five years [25]. The majority of solar farms instead will not come out of tariffs until at least 2025 in France; it is only possible to make hypotheses about their future. In fact, the legal framework could change by then. From 2025, around 1 GW will see their contract end each year, with a rise from 2028. For both technologies, three options exist currently once the contract has expired [26]:

- **Stop production:** This option involves dismantling the turbines/solar panels and rehabilitating the site.
- **Continue farm operation:** In this case, generated electricity can be sold on the market, to aggregators or to companies.
- **Initiate a re-powering operation:** This option entails replacing some of the equipment to modernize and improve productivity.

Auto consumption is considered in some cases when it could be financially interesting, but most likely for small installations. Re-powering and removing functioning panels to implant them elsewhere are other potential options.

Wind farms

The power and energy production of large wind farms on-shore that have reached the end of their incentives each year, covering the period from 2015 to 2040 for the entire of France, have been calculated. Table A.11 (Appendix) displays those values in detail. It should be noted that there are no values for the years between 2032 and 2036 (inclusive) due to a change in contract lengths in 2017. This change extended the contract duration from fifteen years to twenty years, resulting in no wind farms reaching the end of their incentives during these five years.

Offshore wind farms have not been considered in this initial phase of the study focused on re-powering due to a lack of information on the re-powering process for offshore farms. Further investigations could be conducted to assess the feasibility of transporting electricity from offshore platforms to the mainland for electrolytic hydrogen production or the possibility of installing electrolyzers on offshore platforms and subsequently transporting hydrogen to the mainland via pipelines.

Solar farms

The power and energy outputs from solar farms with an installed capacity of no less than 1 MW, post-incentive period, have been calculated for each year between 2027 and 2040. Table A.12 (see Appendix), provides these detailed values. These figures represent the aggregate data for the entirety of France.

2.2.5. Graphical representation of the main results

To facilitate interpretation, the main outcomes of these studies are presented through visually informative maps, utilizing QGIS (Quantum Geographic Information System) software. These maps illustrate the distribution of farms clusterized on a regional scale producing renewable energy in the French territory from wind and solar energy.

The first two maps depict the **yearly energy production** for each French region, coming from on-shore wind and solar farms in 2020 (data processed from [27]).

The maps in Fig. 1 illustrate that wind farms generally produce more energy than solar farms. However, in certain Southeast regions of France, this trend is reversed due to limited wind resources or space for wind turbines, coupled with higher solar resources compared to the North. The Eastern regions are particularly favorable for wind farms, with the Atlantic coast also showing some potential.

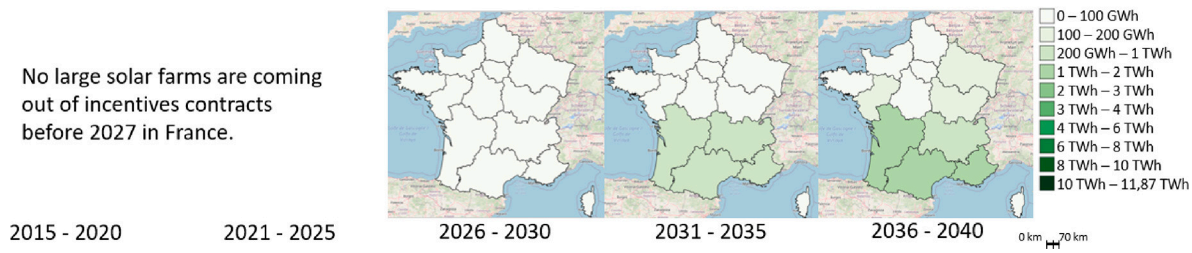

Fig. 2. Evolution of the cumulative yearly energy production of solar farms coming out of incentives in French regions (GWh).

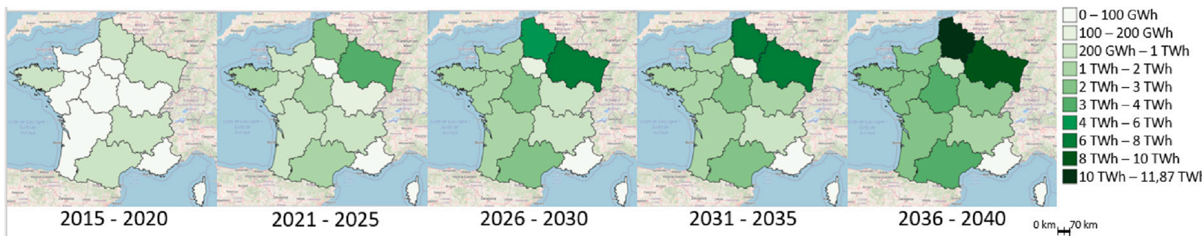

Fig. 3. Evolution of the cumulative yearly energy production of wind farms coming out of incentives in French regions (GWh).

In a second step, following the work presented in the previous section, a group of maps has been created. These maps illustrate the **evolution over time of sites that leave incentives** at the regional scale for both solar and wind farms. The analysis starts from 2015 and moves on a 5-year basis. Figs. 2 and 3 show that the cumulative energy production that goes out of incentives in each French region during the represented timeframe.

Regarding the evolution of energy production from farms exiting incentives, it is noteworthy that wind farms will be the first to reach the end of their contracts, starting in 2015 (3), while the first solar farms will only reach this point in 2027 (2). Another important observation is the gap between 2032 and 2036 for wind farms. Prior to 2017, wind farms had fifteen-year long-term contracts, but there was a change in 2017 that extended the contracts to twenty years. As a result, no wind farms will reach the end of their contracts between 2032 and 2036 (both inclusive), as shown in Appendix Table A.11.

2.2.6. Re-powering

In this first part of the study, only two sources of energy, namely **offshore wind farms and solar farms**, have been considered to be likely to provide electricity for hydrogen electrolysis. However, farms with a power capacity below 1 MW have been excluded from the study, as they would not generate enough energy to produce large volumes of hydrogen, making the process excessively expensive [28]. It is important to note that only farms that have already come out of contracts for incentives or will do so in the future have been included in the analysis. This allows for the establishment of new Power Purchase Agreements (PPAs) or equivalent arrangements.

By adding the energy production of the past and present years, the total free of incentives can be determined (see Tables A.11 and A.12). However, there is a limitation to the energy produced by re-powered plants. The calculations also take into account the remaining lifetime of the farms once they have come out of contracts. Therefore, only the sites that could still be operational before decommissioning are included in the calculation. Table 1 summarizes the lifetime of solar and wind installations [26,29], as well as the contract duration, depending on their start year [30]. This information helps determine which productions should be added when assessing the cumulative energy accessible during a given year.

Table 1
Lifespan and contract duration for solar and on-shore wind farms.

Types of farms	On-shore wind farms	Solar farms
Re-powering for solar farms exists for equipment commissioned before 2017	20y	30y
Approximate lifetime for equipment commissioned after 2017	25y	30y
Duration of feed-in contracts signed before 2017	15y	20y
Duration of feed-in contracts signed from 2017	20y	20y
Remaining lifetime after re-powering	10y	10y

Once a wind or solar farm's feed-in tariff contract expires, it faces several options: dismantling, selling electricity on the spot market, to aggregators, or to the industry via a Power Purchase Agreement (PPA), or, potentially, re-powering. In this study, only wind farms are considered for re-powering. While re-powering is also possible for solar farms, it is typically less significant and occurs throughout the infrastructure's lifespan. Specific components of solar installations have shorter lifespans and require regular replacement, which helps avoid reductions in electricity production and breakdown issues. Subsequently, one could consider that keeping the energy production constant, if not even increasing it, over the years for a solar farm that is already more than twenty years old includes small re-powering procedures [31,32].

No major adjustments are needed to transition from France as a whole to the regional scale, as the database already provides the energy production coming out of incentives from wind and solar farms for each region.

Different re-powering processes

Because of legal and technical factors restraining their development, re-powering operations can be classified into three main categories:

- **Almost identical:** There are no variations in the height or number of turbines, and there is no significant increase in their power capacity. The re-powering process involves replacing the existing equipment with newer and more efficient versions, with little change in the location;

Table 2
Wind farm probabilities for re-powering.

Re-powering type	Overall probability for re-powering	Yearly energy production
Impossible	9,55%	x 0,00
Almost identical	39,50%	x 1,15
Limited in height	28,05%	x 3,00
Unlimited	22,90%	x 5,00

Table 3
Delays for re-powering processes, Ademe [25].

Re-powering type	Delay between end incentives contract and post-re-powering commissioning	Remaining lifespan after re-powering
Impossible	–	5 years
Almost identical	3 years	10 years
Limited in height	4 years	10 years
Unlimited	5 years	10 years

- **Limited in height:** it is similar to the previous re-powering process described, but with a slight improvement in energy production and longer administrative procedures. Turbines can get more powerful or higher, but up to a certain point;
- **Unlimited:** the re-powering processes are not subject to any restriction;

The Ademe study [25] has proposed some estimations of different parameters to predict the patterns in re-powering in the coming decades. Averages were calculated from this document and the yearly energy production, in case of re-powering, is modified as follows:

- Almost identical: x 1,15
- Limited in height: x 3
- Unlimited: x 5

According to the analysis of limitations, 35% of wind farms are not subject to any constraints, while the remaining 65% of them have to address at least one constraint. These constraints can be related to the proximity of radars, airports, military installations, protected natural areas and landscapes, or inhabited zones. The constraints influence the probabilities related to different types of re-powering operations, which have been calculated starting from [25] as shown in Table 2.

In addition, the remaining lifespan of re-powered sites is assumed to be ten years, thanks to the technical improvements achieved through the re-powering process. However, it is important to note that the duration of the entire re-powering process, from initial studies to the commissioning of the new site, can vary significantly. Although the dismantling of old equipment and installation of new equipment typically takes about a year, administrative procedures can often be lengthy, particularly in the face of local opposition. In France, the longest duration identified for the re-powering process was six years.

Based on the earlier calculations, it is determined that certain sites will undergo either almost identical, limited-in-height, or unlimited re-powering. Following the re-powering process, the yearly energy production is increased, and the remaining lifespan of the sites is extended to ten years. However, it is important to consider the duration of the re-powering processes, which can range from three to five years, and incorporate it into the calendar. Fig. 4 shows the timeline for the lifespan of renewable energy sites.

For solar farms, after the twenty-year contract for incentives expires, the farm continues to operate for an additional approximately ten years.

In contrast, wind farms face several potential scenarios: shutting down the site, continuing production for five years without modifications, re-powering without changes (identical), or upgrading the farms with varying levels of modification (nearly identical, limited, or extensive). The duration for these processes are summarized in Table 3, and the remaining operational lifespan post-re-powering is estimated to be around ten years.

Table 4
Different RTE scenarios - Energy Future.

Scenario [TWh/y]	2020	2025	2030	2035	2040	2045	2050
Sobriety	475	501	527	568.5	610	662	714
Electrification -	475	484	493	510	527	553	578
Reference	475	492	508	537.5	567	606	645
Electrification +	475	511	546	591	636	668	700
Energy efficiency -	475	501	527	568.5	610	662	714
Reindustrialization	475	500	525	580	635	695	754
Hydrogen+	475	500	525	580	635	695	754

2.2.7. Results for re-powering processes

Based on the data provided in Section 2.2.4 and the assumptions made for the re-powering processes described in Table 2, the availability of renewable energy sources in France, specifically from on-shore wind and solar farms without tariff, is illustrated in Fig. 5.

It can be seen that the peak of available energy that exits tariffs from 2015 to 2050 (blue line) will occur in 2042, reaching 10 TWh. Meanwhile, the total cumulative renewable energy exiting tariffs over the same period (orange line) will reach 56 TWh in 2035.

Another key point highlighted in Fig. 5 is that it shows the total energy from French on-shore wind and solar farms exiting tariffs. However, it is difficult to pinpoint the exact portion of this energy that will be allocated to electrolytic hydrogen production.

In conclusion, the geographical representation of the results using QGIS has been adopted, as demonstrated in Figs. 2 and 3. In this case, the renewable electricity production coming from re-powered wind and solar plants is represented on a regional scale in Fig. 6.

2.3. RES new installation and NO RES low-carbon: assessment of electricity demand and renewable penetration in the french energy market

The second part of the study analyzed the evolution of the electricity mix in France to understand how electrolytic hydrogen production might impact overall energy demand and availability. Insights from the RTE report [15] were instrumental in exploring various scenarios. Table 4 summarizes these scenarios, offering an overview of France's total energy demand from 2020 to 2050.

It should be noted that the black numbers in the table represent the data found in the report, while the blue numbers were linearly interpolated for the years where information was not provided (i.e., 2025, 2035, and 2045).

While linear interpolation may introduce some simplification and potential inaccuracies, the trends across the various scenarios are consistent with this approach. Furthermore, as presented in what follows, the total amount of electricity will not be a limiting factor in meeting the electricity demand associated with hydrogen production.

A total of seven scenarios were considered in the analysis of RTE [15]: all scenarios result in increased consumption of electricity, ranging from 20% ("Electrification-") to 60% ("Reindustrialization" and "Hydrogen+"). This means that the French power system must accommodate a likely rise in electricity demand as transformations for carbon neutrality begin, despite improvements in energy efficiency and sufficiency. Furthermore, new European and national targets – specifically a 55% reduction by 2030 for Europe and a 40% reduction for France- – require more rapid action than the baseline scenario, with hydrogen emerging as a key solution. Consequently, the "Hydrogen+" scenario has been selected as the reference scenario for this study.

To finally calculate the amount of energy available from the energy vector "RES new installation", a further study has been conducted to determine the share of energy that would be produced from renewable sources. The main sources considered were the Plan for Energy and Climate (PPE) [33] and Ademe [17]. Since neither of these sources provided a complete forecast from 2020 to 2050, it was necessary to merge the data and interpolate a few values. The results are shown in Table 5.

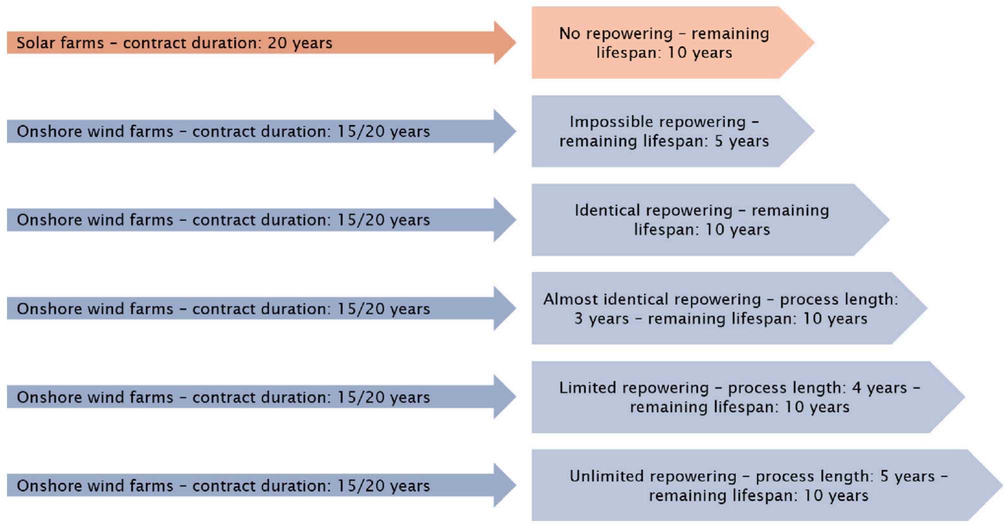

Fig. 4. General calendar of re-powering options.

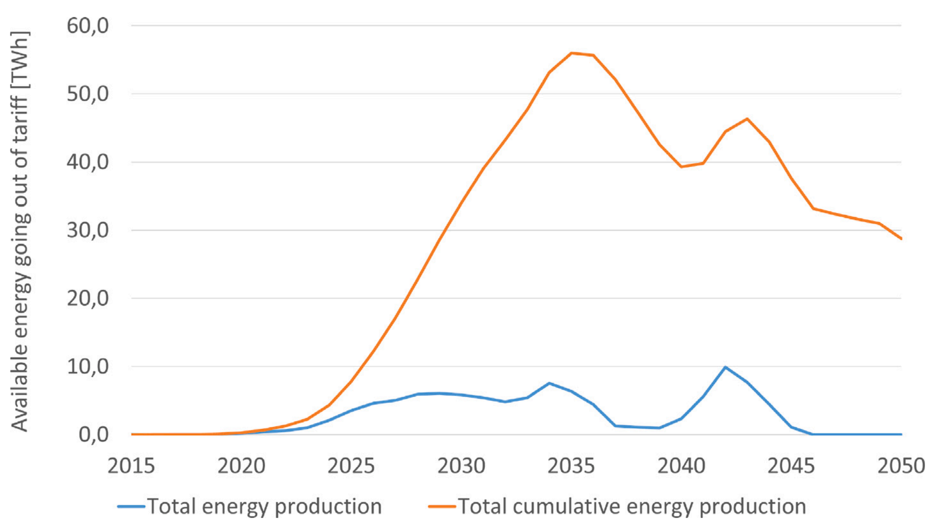

Fig. 5. Available energy going out of tariff from 2015 until 2050.

Table 5
Renewable penetration in French energy market.

Renewable penetration in French energy market	2025	2030	2035	2040	2045	2050
Share of RES	31.6%	40.0%	45.0%	50.0%	60.0%	69.0%

Referring to the nomenclature adopted in this work, it is then possible to split the renewable energy in two main categories: the first category referring to the electricity coming from re-powered plant already operating nowadays (i.e. RES re-powered), the second category referring to the electricity coming from the future new installations of renewable plants (i.e. RES new installations). Using the values from the "Hydrogen+" scenario as a baseline, the "RES re-powered", "RES new installations", and "NO RES" scenarios were calculated, as illustrated in Fig. 7.

It is worth noting that, while a location has been defined for "RES re-powered" power plants, the same cannot be said for "RES new installations". Therefore, this type of electricity, along with "NO RES" electricity, will be considered available in the grid but will not be geographically represented as illustrated in Fig. 6.

3. Estimation of hydrogen demand

3.1. General considerations

In the existing literature, various scenarios outline diverse levels of hydrogen penetration and its impact on the energy market. A significant contribution is the RTE report [15], which introduces two primary scenarios: the "Reference" scenario and the "Hydrogen+" scenario. For this study, the "Hydrogen+" scenario is selected as the base scenario for in-depth analysis. This choice is based on the assumption of a significant and robust integration of hydrogen within the French energy market.

The key sectors expected to dominate the hydrogen market in the coming decades are identified as the industrial and mobility sectors. Currently reliant on grey hydrogen, the industrial sector is anticipated to progressively transition towards a higher proportion of low CO_2

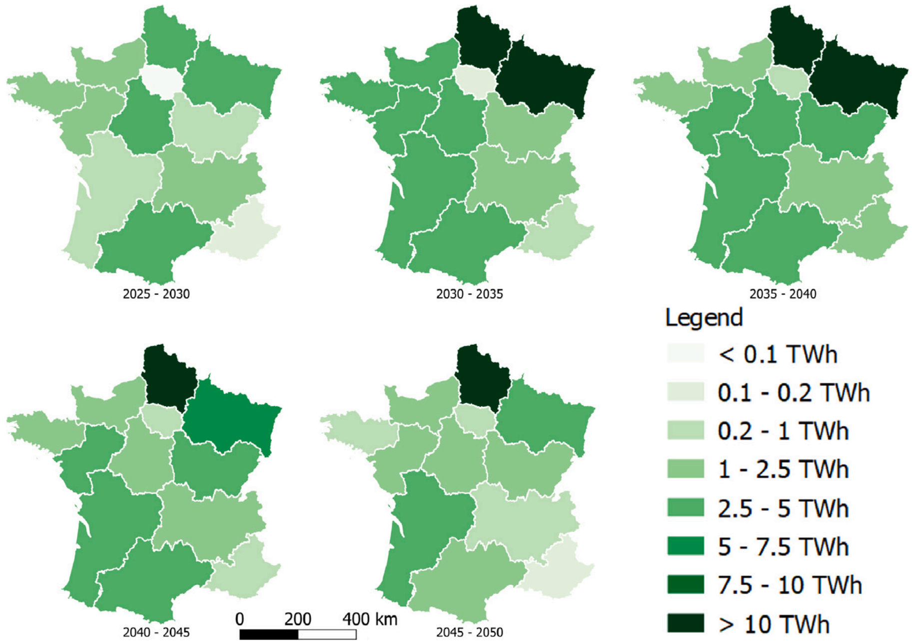

Fig. 6. Evolution of the yearly electricity production from re-powered solar and wind farms in French regions [TWh/year].

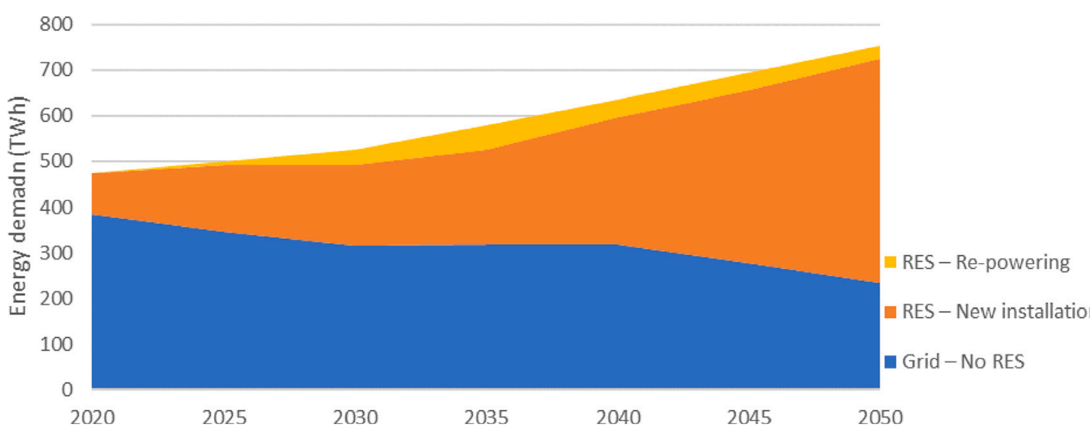

Fig. 7. French electricity mix 2020–2050 [TWh].

hydrogen. Concurrently, the mobility sector is experiencing a surge in demand due to the increasing adoption of electric vehicles. The assessment of hydrogen demand will explore various scenarios, using the following approach: industrial demand will gradually shift towards a larger share of low CO_2 hydrogen, while initial demand in the mobility sector will also be met with low CO_2 hydrogen. Notably, sectors such as residential heating, although projected to contribute to future hydrogen demand, are excluded from the scope of this study.

3.2. Hydrogen demand estimation for the industrial sector

Various industries rely on hydrogen for their processes, including fine chemistry, metallurgy, glass manufacturing, food production, and other activities. Consequently, companies have established hydrogen production plants, often utilizing steam methane reforming, as well as infrastructure to store and condition the gas prior to sale. In France, it is mandatory to declare the possession of hydrogen when it exceeds 100 kg due to safety regulations. Many sites choose to declare even if the quantity is below that threshold. This information can be accessed online through the "Géorisques" website [34].

The infrastructures declarations are organized using three Installations Classified as Environmental Protection (ICPE) codes. Although the nomenclature and reference codes related to hydrogen production, usage, and storage infrastructures changed in 2015, both old and new codes can still be found:

- **IC 1415 (prior to 2015):** industrial production of hydrogen
- **IC 1416 (prior to 2015):** storage or use of hydrogen
- **IC 4715 (since 2015):** sites containing hydrogen

The "Géorisques" website offers various filters to identify relevant sites. For this analysis, only infrastructures with the IC 4715 code were selected. After applying the filters and conducting the search, the website displayed a list of infrastructures with basic data. This search identified a total of 227 infrastructures. The company's SIRET (identification number) was provided, and the geographical information

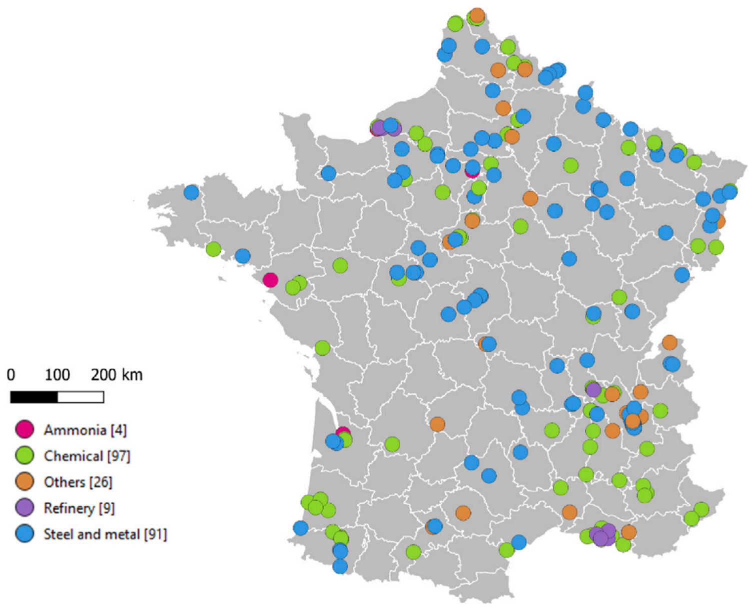

Fig. 8. Industrial plants identified as hydrogen users.

Table 6
Clusterization to macro-sectors.

Sectors from RTE [15]	Macro-sectors
Refinery Transport (maritime + aviation) Methanation H_2 injection (mixing)	Refineries
Ammonia and fertilizer	Ammonia production plants
Chemical	Chemical plants
Steel making	Steel and metal plants
Industrial heat Industrial miscellaneous	Others

Table 7
Renewable/low-carbon industrial hydrogen demand [kton/y].

EIfER scenario - Disruptive	2020	2025	2030	2035	2040	2045	2050
Share of renewable/ low-carbon hydrogen	1.50%	2.90%	4.00%	5.50%	7%	9.00%	11%
Refineries	5.85	11.14	15.12	37.87	69.94	118.00	178.55
Ammonia plants	3.56	6.87	9.48	13.04	16.59	21.33	26.07
Chemical plants	0.72	7.66	9.72	13.04	16.17	19.85	23.10
Steel and metal plants	0.00	1.31	3.60	5.78	8.40	18.90	33.00
Others	3.69	9.14	15.36	23.51	32.97	59.14	92.74
Total	13.82	36.11	53.29	93.23	144.07	237.22	353.47

included the address, department, region, and Lambert coordinates. Each line in the list presented the name of the infrastructure and its administrative status. Moreover, each plant could be classified into a specific "sector" category. For the purpose of this study, the industrial plants were clustered in four macro-sectors: Refineries (9 plants), Ammonia production plants (4 plants), Chemical plants (97, not including ammonia production plants), Steel and metal plants (91 plants) and Others (26 plants), as shown in Fig. 8.

The current hydrogen demand and predictions until 2050 were extrapolated from the RTE study [15]. As not all the categories align with the four macro-sectors mentioned earlier, a clusterization process was conducted, resulting in the following categorization, as presented in Table 6.

It is important to note that hydrogen transport for the maritime and aviation sectors has been categorized under refinery demand. The refinery macro-sector was selected as the most appropriate category for addressing the production of e-fuels for these sectors. This categorization was made because the hydrogen demand in the mobility sector only covers terrestrial transportation, including light and heavy-duty vehicles, buses, and trains (see Section 3.3).

The two main scenarios considered from RTE study [15] are depicted in Fig. 9. For the 'Hydrogen+' scenario, which is the focus here, various proportions have been examined to represent the segment of industrial hydrogen demand that will be fulfilled with a low CO_2 footprint. The breakdown of the local industrial demand satisfied by renewable and/or low-carbon hydrogen is detailed in Table 7. These values are derived from a combination of results obtained from the "Hydrogen+" scenario developed by FCH JU [3] and internal research conducted at EIfER.

After evaluating the low CO_2 footprint hydrogen demand for each macro-sector from 2020 to 2050, we allocated a portion of this hydrogen demand to each plant identified in the Géorisques database [34]. The demand was distributed equally among plants within the same macro-sector.

Once the demand for low CO_2 footprint hydrogen was evaluated for each macro-sector from 2020 to 2050, a specific hydrogen demand was allocated to each plant identified in the Géorisques database [34]. The demand was evenly distributed among the plants within the same macro-sector.

3.3. Hydrogen demand estimation for the mobility sector

Unlike the industrial demand, the entire hydrogen demand for this sector has been assumed to be met with either renewable or low-carbon emission hydrogen.

The categories identified in the RTE report [15] include "Road transport" and "Rail transport". The two main scenarios analyzed in this context are the "Reference" and "Hydrogen+" scenarios, both depicted in Fig. 10. Similar to the hydrogen demand for the industrial sector, the "Hydrogen+" scenario will also be considered for the mobility sector.

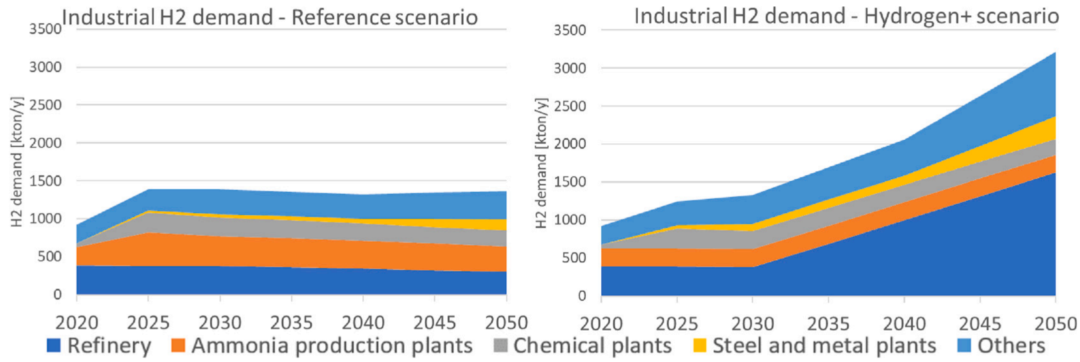

Fig. 9. Industrial hydrogen demand - “Reference” scenario (left side); Industrial hydrogen demand - “Hydrogen+” scenario (right side).

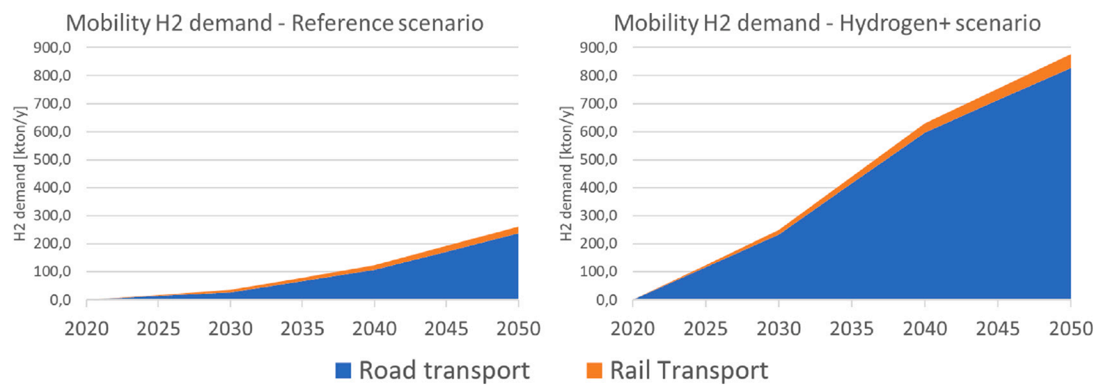

Fig. 10. Mobility hydrogen demand - “Reference” scenario (left side); Mobility hydrogen demand - “Hydrogen+” scenario (right side).

To allocate the total mobility demand to each French region, we calculated the proportion of vehicles registered in each region. The database used for this analysis [35] includes data for four vehicle categories: heavy goods, light commercial vehicles, passenger cars, and public transit. By aggregating the total number of vehicles in each category, we determined the regional shares of the vehicle fleet (see Table A.13 in Appendix). Hydrogen demand was then allocated to each region based on these shares.

In summary, by aggregating hydrogen demand from both the mobility and industrial sectors, we identified regions with notably high hydrogen demand during the analyzed period, as depicted in Fig. 11.

4. Exploring the nexus: renewable energy availability and electrolytic hydrogen production

From the preceding sections, the availability of renewable electricity generated in France and the demand for low-/zero-carbon hydrogen from 2025 to 2050 can now be contextualized.

The specific electricity consumption for producing 1 kg of electrolytic hydrogen depends on several factors, including operating temperature and current density. Overall, the loading factor and the type of electrolyzer play a central role in the total energy efficiency of the system. Given the focus of this study on assessing the feasibility of the electrical system to supply sufficient electricity for electrolytic hydrogen production, a standardized average value of 55 kWh per kg of hydrogen produced has been used [36,37].

Table 8 consolidates the cumulative values obtained thus far for total electricity production in France, renewable electricity, and the electricity demand if the entire hydrogen production were to rely on electrolysis.

Table 8
French electricity production vs. hydrogen demand [TWh/y].

	2020	2025	2030	2035	2040	2045	2050
French total electricity production	475.0	500.0	525.0	580.0	635.0	695.0	754.0
Renewable French electricity production	90.7	153	210	261	317.5	417	520.3
Electricity demand for hydrogen production	0.8	8.8	16.6	29.3	42.6	54.5	67.6

The data presented in Table 8 indicates that the share of electricity for electrolytic hydrogen production does not exceed 9% of the total French electricity production or 13.5% of the renewable production. However, a more detailed analysis is needed to fully understand the implications for the electricity available for electrolytic hydrogen production.

While the data suggests that the availability of renewable energy may not be a limiting factor for low-/zero-carbon electrolytic hydrogen production in France, two key considerations must be addressed. First, it is unrealistic to assume that all renewable energy will be allocated to electrolytic hydrogen production, as renewable energy also supports various other applications. Second, uncertainties in the hydrogen plan indicate that assuming hydrogen generation will occur exclusively through electrolysis is impractical.

To account for these factors, three scenarios were examined in which 50%, 75%, and 100% of the hydrogen demand is met with

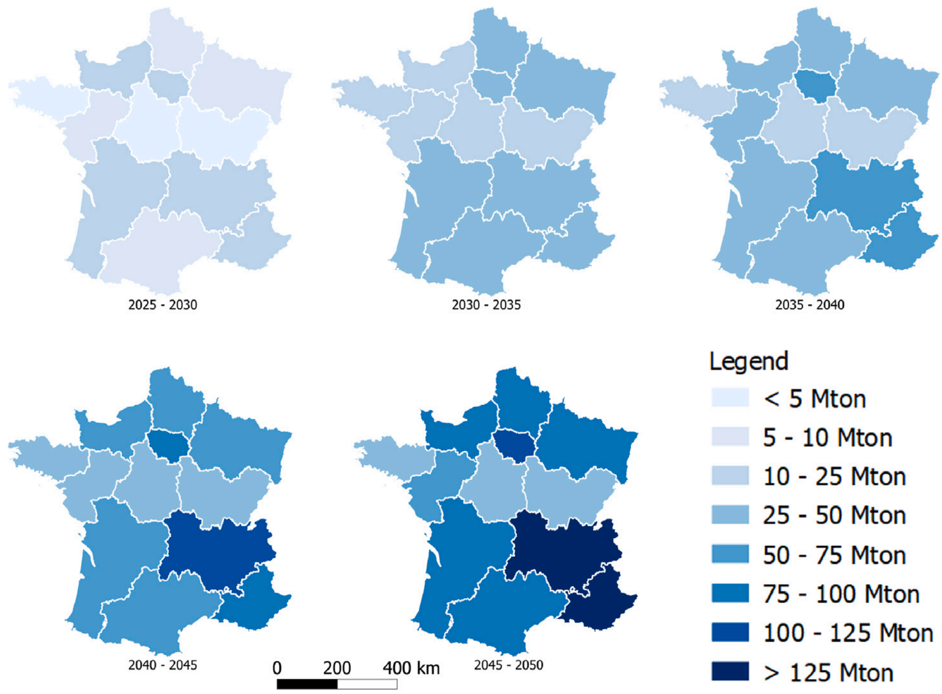

Fig. 11. Evolution of the annual hydrogen demand in industrial and mobility sectors across French regions(Mton/year).

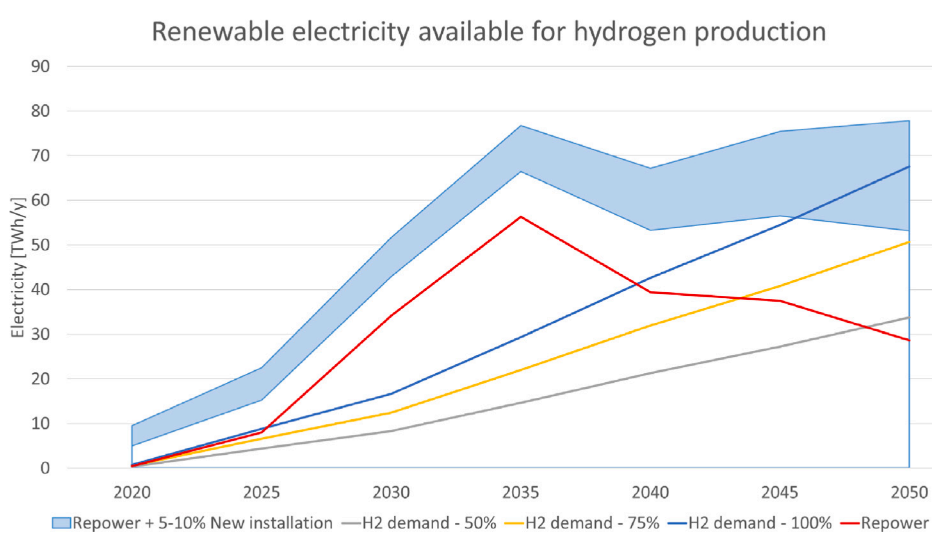

Fig. 12. Assessment of electricity availability for electrolytic hydrogen production.

renewable electricity. In these scenarios, renewable electricity from re-powered plants is prioritized and considered 100% dedicated to hydrogen production. To ensure the exclusive production of renewable hydrogen, additional renewable electricity from new installations was also considered. For covering the entire electricity demand for fully renewable hydrogen under different scenarios, a share of 5% to 10% of electricity from newly installed plants was assumed, as depicted by the blue area in Fig. 12.

In Fig. 12, due to the initially low demand for hydrogen and a substantial energy surplus from re-powered plants, there continues to be consistently an excess of electricity available for electrolytic hydrogen production in all three scenarios considered. However, a significant shift occurs between 2040 and 2045 when at least 75% of hydrogen production is assumed to come from electrolysis using renewable energy. In this scenario, the 5% energy contribution from new installations proves insufficient, requiring an increase to 10%, along with dedicating 100% of re-powered plants to electrolytic hydrogen production.

In transition from a global perspective to a local perspective, the disparity between available electricity from re-powered solar and on-shore plants and the electricity demand for electrolytic hydrogen production has been meticulously calculated. The decision to focus solely on existing plants was deliberate, as their locations and potential energy

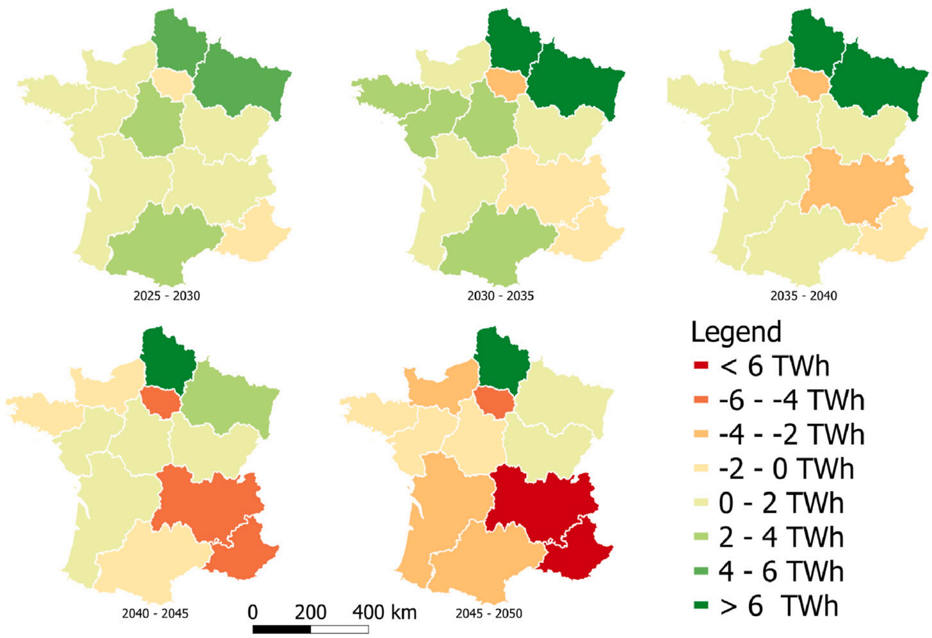

Fig. 13. Mismatch between local renewable energy from re-powered solar and on-shore wind farms and hydrogen demand [TWh].

outputs are already established. Moreover, since these plants are already operational, this mitigates the risks and uncertainties associated with obtaining permits for new production facilities.

To calculate the amount of energy for hydrogen production, the above mentioned average specific energy consumption of 55 kWh/kg has been used. Through the local approach, as depicted in Fig. 13, it can be observed that despite the abundance of renewable sources until 2040, starting from 2035, when the excess of renewable is roughly +20 TWh, several French regions are unable to meet their hydrogen demand with local renewable production (i.e. yellow and orange regions). This condition becomes more pronounced in the last period 2045–2050, when the overall mismatch exceeds −22 TWh, and only three regions produce enough renewable energy for their own local hydrogen production.

5. Conclusions and perspectives

This study aimed to determine whether the availability of renewable energy would limit the production of electrolytic hydrogen and potentially act as a bottleneck for its integration into the energy market. Specifically, the analysis focused on assessing the future supply of renewable electricity in France from the present until 2050. By evaluating hydrogen demand, the study sought to identify how much of the projected renewable energy could be allocated to hydrogen production, ensuring that the hydrogen produced remains carbon-free and renewable.

To achieve this, the study examined two main aspects: the availability of electricity for electrolytic hydrogen production and the hydrogen demand in the industrial and mobility sectors from 2025 to 2050.

Electricity was categorized into three groups: “RES re-powering”, ”RES new installations”, and “NO RES”. The “RES re-powering” category encompasses existing wind farms and solar power plants. Databases were established to monitor their energy output, and this energy was deemed available for hydrogen production once these plants exit their feed-in tariff agreements. Various scenarios were considered for re-powering, and the resulting energy production from these re-powered plants was recalculated. Given that these existing plants are already situated, the electricity from “RES re-powering” was allocated to each French department and represented geographically using QGIS.

For the “RES new installation” and “NO RES” categories, only projections for total French electricity production and demand were available. Various sources were integrated and interpolated to estimate the total electricity demand, which is expected to rise from 475 TWh/year in 2020 to 754 TWh/year by 2050. The share of total renewable energy sources (including both re-powered and new installations) is anticipated to increase from 19% in 2020 to 69% in 2050.

In terms of hydrogen demand assessment, the study concentrated on two main sectors: the industrial sector and the mobility sector.

In the industrial sector, there is an existing demand for hydrogen, with the goal of decarbonizing its production by shifting towards renewable and/or low-carbon hydrogen. It is anticipated that a growing proportion of this demand will need to be met with renewable and/or low-carbon hydrogen.

The mobility sector, though currently a smaller component of overall demand, is expected to see a significant rise in its need for low-carbon hydrogen to achieve zero emissions. For this sector, the total projected national demand has been distributed among various departments based on vehicle and population density.

After developing a comprehensive database on electricity production and hydrogen demand with projections up to 2050, various analyses were conducted. These analyses focused on identifying discrepancies between available renewable energy and the energy required to meet the growing demand for renewable hydrogen.

At the national level, it was demonstrated that even if all electricity from existing on-shore wind and solar farms, which are slated for re-powering in France, were allocated solely to hydrogen production, it would not be sufficient to meet the total electricity demand required for electrolyzers. Specifically, starting from 2040, it was observed that the energy from re-powered plants would fall short of covering the entire demand for electrolytic hydrogen production.

Given the uncertainties related to the origin of hydrogen in the coming decades, three scenarios were evaluated, each representing different proportions of hydrogen demand met by renewable electricity, ranging from 50% to 100%.

Assuming that all electricity from re-powered plants is dedicated to electrolytic hydrogen production, it was initially found that there is an excess of electricity available for hydrogen production across all scenarios, due to the lower hydrogen demand in the early years. However, this situation changes between 2040 and 2045 for scenarios where at least 75% of hydrogen is produced via electrolysis using renewable energy. As illustrated in Fig. 12, the available renewable electricity from re-powered plants becomes insufficient to meet the hydrogen production needs during this period.

In these cases, the renewable energy from re-powered plants alone will be insufficient to meet the demand for renewable hydrogen production. To address this shortfall, additional energy from newly installed renewable plants must be considered. The blue area in Fig. 12 represents the additional energy required if between 5% (indicated by the bottom line of the blue area) and 10% (indicated by the top line of the blue area) of the electricity from new installations is allocated to hydrogen production. For the scenario where 75% of hydrogen is produced renewably, a 5% share from new installations is sufficient. However, for the scenario with 100% renewable hydrogen, in addition to utilizing the full production capacity of re-powered plants, a 10% contribution from new installations is necessary to meet the demand.

Through the geographical methodology developed, as shown in Fig. 13, it has been possible to show the French regions that in the years will be able or not to satisfy the renewable electricity requested to supply 100% renewable hydrogen.

Adopting a local approach, the analysis reveals that despite abundant renewable energy sources, several French regions may face challenges in meeting their local hydrogen demand solely through renewable production from re-powered plants. The gap between supply and demand increases in the years, driven by an increasing hydrogen demand, which brings to the conclusion that not only the production of new renewable plants must be considered for electrolytic hydrogen production, but also the local management of renewable electricity and the logistic of the hydrogen supply chain should be further analyzed.

Despite the valuable insights gained, the methodology applied in this study has certain limitations. A primary uncertainty involves predicting the availability of electricity to meet hydrogen demand up to 2050. The scenarios for electricity demand in 2050 range from a 20% to a 60% increase compared to 2020, making the choice of the most electrified scenario a significant assumption. While this assumption is supported by other sources, it remains subject to validation through comprehensive literature review. Additionally, the study relies on unique data from Ademe regarding the re-powering of renewable energy technologies, which lacks validation from similar studies. Furthermore, while various hydrogen demand scenarios were considered, only a few were analyzed in depth. Future research could expand on this study by challenging the assumptions made and employing more dynamic models that incorporate diverse electrolyzer technologies and system efficiencies.

Finally, this approach could contribute to the implementation of various prospective energy models aimed at optimizing the hydrogen supply chain and its design. By incorporating the localization of energy sources and the potential hydrogen demand into mathematical models, it is possible to optimize supply chain logistics, reduce total costs (e.g. levelized cost of hydrogen), and mitigate emissions associated with hydrogen production, storage, and transportation.

This database represents a crucial foundation for initiating new studies and developing models to estimate more accurately national plans related to energy and hydrogen production and demand. It aids in identifying the most suitable technologies for creating a cost-effective, low-emission, and energy-efficient system, with a long-term perspective.

CRediT authorship contribution statement

Renato Luise: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Annabelle Brisse:** Supervision. **Catherine Azzaro-Pantel:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The sources of the data used in this study are listed in the references section.

Appendix

See Tables A.9–A.13.

Table A.9
Data sources for wind farms and solar panels.

Parameter	Definition	Source
Farm name	Name of the solar/wind park	ODRE
Energy Identification Code	A unique number for energy infrastructures and actors in Europe, given by ENTSO-E	ODRE
Location	City, region, country, latitude, longitude	WE/WP
Status	It can be in set-up, approved/validated, in progress (when being built), functioning, closed or abandoned	ODRE
Main actors	The owner, the developer (who managed the building project) and the operator (who currently manages the site's exploitation)	WE/WP
Calendar	Commissioning date, end of the incentives contract date, and end date	ODRE
Power and energy	Power capacity, yearly energy production	ODRE
Sources–for wind turbines	Turbines number, model and manufacturer, on-/off-shore	WE/WP
Sources–for solar panels	Panels number and type, supporting structure or building	WE/WP

Table A.10
Summary of incentives for on-shore wind farms in France.

Type of farms	Before 2000	2000–2008	2008–2013	2013–2016
Less than 6 turbines, single power capacity < 3 MW	Eole 2005, calls for projects, price fixed by the developer	Feed-in tariff contract, 15 years	Feed-in tariff contract, 15 years	Feed-in tariff contract, 15 years
6 turbines and more, single power capacity > 3 MW				
Sites in hurricane zones (Guadeloupe, La Reunion, La Martinique, Mayotte)				Feed-in tariff contracts with specific tariffs, 15 years
Type of farms	2016–2017	2017–2021	2021–	
Less than 6 turbines, single power capacity < 3 MW	Additional remuneration, 15 years	Additional remuneration, 20 years	Additional remuneration, 20 years	
6 turbines and more, single power capacity > 3 MW		Calls for projects, fixed selling price decided by the developer, 20 years	Calls for projects, fixed selling price decided by the developer, 20 years	
Sites in hurricane zones (Guadeloupe, La Reunion, La Martinique, Mayotte)	Feed-in tariff contracts with specific tariffs, 15 years	Feed-in tariff contracts with specific tariffs, 15 years	Feed-in tariff contracts with specific tariffs, 20 years	

Table A.11
Power and energy coming out of incentives per year for wind farms in France. Data generated from different sources (see Table A.9).

On-shore wind farms coming out of incentives	2015	2016	2017	2018	2019	2020	2021
Power capacity per year (MW)	23.8	22.4	91.2	93.8	150	504	868
Cumulative power capacity (MW)	23.8	46.3	137	231	381	885	1,753
Annual energy production (GWh)	19.8	17.5	165	133	287	907	1,777
Cumulative energy production (GWh)	19.8	37.3	202	336	622	1,529	3,306
On-shore wind farms coming out of incentives	2022	2023	2024	2025	2026	2027	2028
Power capacity per year (MW)	853	1,209	1,124	1,348	933	886	646
Cumulative power capacity (MW)	2,607	3,816	4,941	6,289	7,222	8,109	8,755
Annual energy production (GWh)	1,627	2,238	2,384	2,627	1,863	1,898	1,428
Cumulative energy production (GWh)	49.33	71.70	95.54	12,181	14,044	15,942	17,370
On-shore wind farms coming out of incentives	2029	2030	2031	2037	2038	2039	2040
Power capacity per year (MW)	1,153	1,216	1,402	1,714	1,667	1,374	1,096
Cumulative power capacity (MW)	9,908	11,124	12,526	14,241	15,908	17,282	18,379
Annual energy production (GWh)	2,666	2,540	3,457	4,464	4,007	3,173	970
Cumulative energy production (GWh)	20,036	22,576	26,033	30,496	34,504	37,676	38,647

Table A.12
Power and energy coming out of incentives per year for solar farms in France. Data generated from different sources, look at Table A.9.

Solar farms coming out of incentives	2027	2028	2029	2030	2031	2032	2033
Power capacity (MW)	1.4	11.0	43.1	189.7	655.0	393.9	425.6
Cumulative power capacity (MW)	1.4	12.4	55.5	245.2	900.2	1294.2	1719.7
Annual energy production (GWh)	0.0	13.0	26.9	172.6	726.6	252.7	405.7
Cumulative energy production (GWh)	0.0	13.0	39.8	212.4	939.0	1191.7	1597.4
	2034	2035	2036	2037	2038	2039	2040
Power capacity (MW)	592.1	583.2	334.3	545.3	515.7	458.9	415.7
Cumulative power capacity (MW)	2311.8	2894.9	3229.2	3774.6	4290.3	4749.1	5164.8
Annual energy production (GWh)	824.4	521.7	477.1	818.1	727.2	649.1	206.5
Cumulative energy production (GWh)	2421.8	2943.5	3420.6	4238.6	4965.8	5614.9	5821.5

Table A.13
Road vehicles share at Regional scale.

	Region	Total number of vehicles	National share
1	Auvergne-Rhône-Alpes	5'688'008	13.0%
2	Bourgogne-Franche-Comté	2'058'105	4.7%
3	Bretagne	2'470'496	5.7%
4	Centre-Val de Loire	1'890'165	4.3%
5	Grand Est	3'876'013	8.9%
6	Hauts-de-France	3'937'250	9.0%
7	Île-de-France	6'177'831	14.2%
8	Normandie	2'406'156	5.5%
9	Nouvelle-Aquitaine	4'599'121	10.5%
10	Occitanie	4'293'074	9.9%
11	Pays de la Loire	2'742'677	6.3%
12	Provence-Alpes-Côte d'Azur	3'496'518	8.0%

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