Green OAT Evaluation Report

Environmental impact of the different subsidies used to promote renewable energy sources

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Executive summary

Context

The IPCC[1] emphasizes that "*climate change is a threat to human well-being and planetary health. […] Continued emissions will further affect all major climate system components, and many changes will be irreversible on centennial to millennial time scales and become larger with increasing global warming.*" The panel draws attention on the urgency to undertake climate resilient actions as "***there is a rapidly closing window of opportunity to secure a liveable and sustainable future for all.***" The IPCC stresses that *"deep, rapid, and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce projected losses and damages for humans and ecosystems."* Mitigation actions include the decarbonization of energy supply.

The European Union and France aim to achieve carbon neutrality by 2050 to fight climate change. These commitments are in line with the Paris Agreement, in which signatory countries pledged to limit the increase in global average temperature compared to pre-industrial levels to below 2°C, and preferably 1.5°C.

In order to finance expenditures from the State budget that contribute to address environmental challenges, France launched in 2017 the first French sovereign green bond, the Green OAT. Following a reorganization of the French State budget in 2021, support to renewable energy in France have been included in the eligible expenditures to green OATs. Thanks to this integration, a **significant increase of the total eligible expenditures occurred in 2021 compared to 2020 (€15 vs €8 billion), where support to renewable energy accounted for 34% of the eligible expenditures**.

Objective of the study

The **objective of this study is to provide qualitative and quantitative indicators on the key environmental impacts of expenditures allocated to supporting renewable energies in France**. This report focuses on the environmental impact of subsidized renewable energies, both in mainland France and in non-interconnected zones (Corsica and Overseas Territories). The aim is to **provide an overview of the impacts of subsidized[2] renewable production systems**. Following the classification of the French support to renewable generation, the renewables studied in this report are:

- **In mainland France: onshore and offshore wind, photovoltaic, small hydropower and biomethane.**

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[1] Intergovernmental Panel on Climate Change (IPCC), AR6 Synthesis Report, 2023

[2] In this report, the term *subsidized* renewable energies refers to productions that benefit from state support (subsidies). The term *incentives* could also have been relevant to emphasize that the financial cost of renewable facilities is offset in markets only through the sale of energy and carbon credits, which likely do not fully take into account the positive externalities of renewables (on climate, health, etc.).

- In non-interconnected zones (NIZs), all renewables for electricity production are subsidized (except bagasse when co-fired with coal).

As the primary impact of renewable energies is the reduction of greenhouse gas emissions, this subject forms the core of this study. Other types of impacts included in the analysis are: the reduction of air pollutant emissions and associated avoided costs, water and soil pollution, the use of raw materials and recycling, land use, preservation of biodiversity and naturel areas, and climate change adaptation.

Methodology

The study follows a mixed quantitative and qualitative approach. The major impacts (especially greenhouse gases emissions, but also air pollutant emissions, raw materials use and land-use) have been quantified based on a dedicated methodology comparing a reference and a counterfactual scenario. This quantitative analysis is completed by qualitative elements from a literature review covering all environmental impacts of renewable generation (biodiversity, water and soil pollution, climate change adaptation, etc.).

The quantitative assessment is based on a comparison of reference scenarios with counterfactual scenarios, both for the historical period of the support to renewable (from 2000 to 2021), and for the decades to come, using prospective scenarios (up to 2040). This prospective approach makes it possible to analyze the potential impacts that the renewable capacities currently installed and subsidized will have in the future. The "reference scenarios" assume a renewable energy development identical to historical data and in line with the considered prospective scenarios[3] for the future. The "counterfactual scenarios" are similar in all respects to the reference scenarios, except that they do not include additional renewables compared to the start of the period. In order to simulate the inclusion of renewables within the power grid in mainland France, also considering interconnections with neighbouring countries, the European electricity system of the different scenarios have been simulated using Artelys Crystal Super Grid[4]. This software **models the production of the European power system at an hourly level, taking into account various constraints such as climate variability of renewable, exchanges between different European countries and the optimization of storage assets**.

This methodology allows to estimate both which type of power source generation is replaced by power renewable generation, and where it is replaced (in France or elsewhere in Europe). Greenhouse gases emissions are then estimated **based on life-cycle emission factors**, in order to take into account the whole value-chain of the different power generation technologies. Finally, a dedicated

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[3] Two scenarios were used from ADEME Transition(s) 2050 scenarios: S2 and S3Nuc. These are two reference and contrasted scenarios built by the French ecological transition agency.

[4] https://www.artelys.com/crystal/super-grid/

methodology is used to take into account emissions savings over the entire lifespan of the renewable assets and allocate this impact equally over the duration of subsidies. Other factors are used to estimate air pollution, raw materials needs and land-use.

Key results

Climate change mitigation

In recent years, **renewable electricity in mainland France has almost exclusively replaced thermal generation, most of it in neighboring countries** (between 75% and 86%). In the considered prospective scenarios, additional renewable electricity is found to replace mostly gas-fired generation, and to enable a higher hydrogen generation by electrolysis (therefore replacing a fossil fuel-based hydrogen production via steam methane reforming).

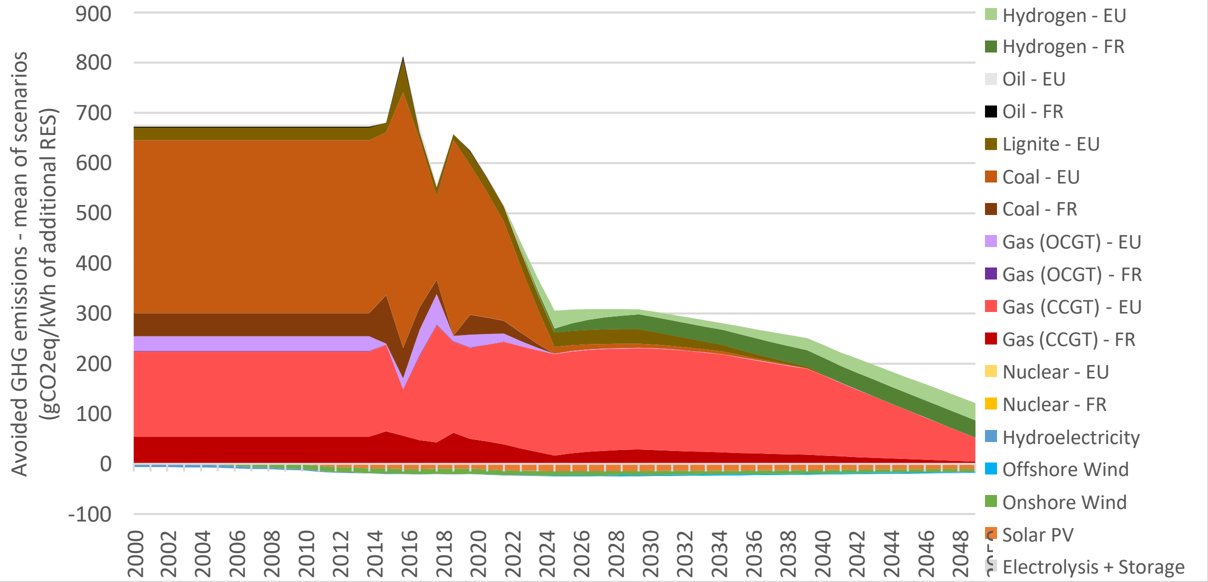

Figure 1: Avoided GHG emissions by replaced generation source, in gCO2eq/kWh of additional renewables

In Non-interconnected areas, renewable electricity subsidized and financed by Green OATs was found to replace thermal generation only, and more specifically oil, except in “La Réunion” and “Guadeloupe” where the remaining coal capacities are phased-out as well. Some limitation could nonetheless appear in the future with a rising share of renewables, which would require additional means of flexibility (*e.g.* storage) to cope with the variability of renewable generation.

In 2021, on a life cycle analysis basis, the following **avoided greenhouse gases emissions** are estimated:

- 24.3 MtCO2eq (with annualization) for subsidized renewable electricity production in mainland France (49.8 TWh production), with 85% of these emissions being avoided in neighboring countries
- 0.7 MtCO2eq for subsidized biomethane production in mainland France (4.3 TWh)
- 2.7 MtCO2eq for renewable electricity production in the non-interconnected zones (3 TWh)

The avoided emissions for all subsidized renewables represent around 4,5% of the total carbon footprint of France in 2019 (605 MtCO2eq). It should be emphasized that the quantification of avoided emissions only concerns the power system itself. Taking into account the reduction of indirect emissions thanks to increased production enabling the electrification of emitting end-uses (heating, industry, transport) would increase the benefits.

In average, 180€ of subsidies for renewable electricity in mainland France were spent for each ton of CO2eq avoided annually since 2014. There is a significant disparity between solar energy on the one hand, and wind and hydropower on the other hand, due to the high 2008-2011 feed-in tariffs for solar rooftop panels (€546/MWh in 2010). From the moratorium on photovoltaics at the end of 2010 (to allow the government and industry players to discuss subsidy levels), feed-in tariffs decreased leading to a lower difference between solar PV and other technologies.

Air, water and soil pollution reduction[5]

Air pollutant emissions (PM2.5, SO2, NOx, NMVOC) avoided by renewable generation have the same order of magnitude than the current emissions from the whole power sector in France[6]. The sum of these avoided emissions represents a small fraction of the total emissions in France (lower than 1% for all pollutant considered), but taking into account indirect reduction in emissions thanks to electrification would also increase the benefits.

With a direct impact on health, and more marginally on crops, forests and building materials, the impact of local pollutants can be converted in equivalent damage costs to these sectors. Depending on the methodology used to assess these costs, **avoided damage costs of air pollution could range between €0.9 to €7.6 billion (in both France and Europe) for the 2000-2021 period, which can be compared to total subsidies to renewables amounting to €39 billion over the same period**.

For water and soil pollution, most of the benefits are directly correlated to the replacement of fossil fuels that generate pollution hazards throughout the value chain, from production to use. Renewables can also have negative impacts on local pollution, mainly linked to the extraction of raw materials to build the different components of solar panels and wind turbines, but also at the installation stage.

Raw materials use and recycling[7]

The development of renewables will significantly increase the consumption of raw materials for the power generation, since material intensity is significantly higher for wind and solar than other low-carbon production technologies (hydroelectric, nuclear) or fossil fuels. By 2050, raw material consumption for the energy transition will be particularly high, especially for electric vehicles, power grids and renewable generation systems. Renewables will account for about 10% of current French aluminium production and about 5% of copper consumption and steel production. Batteries for electric vehicles, whose storage capacities will be useful in the future to facilitate the integration of

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[5] See section 6.1 for the study on air, water and soil pollution

[6] Keeping in mind that most of the reduction are located in neighboring countries, and not in France.

[7] See section 6.2 for the study on raw materials use and recycling

increasing share of variable renewables in the energy mix, will need significant quantities of lithium, nickel and cobalt, but less so on rare earth elements.

Metals used in renewable energy systems could be reused or recycled to meet the needs of other industries. For **solar energy, approximately 95% of the mass of resources can be recycled**, but there is still room for progress to improve the separation of glass and semiconductor films, according to the EEA. **For wind energy, approximately 90% of the materials can be recycled or reused**, but recycling the composite materials used in wind turbine blades remains a challenge that requires additional research. Raw material needs could be reduced through energy sufficiency and improved energy efficiency.

Preservation of biodiversity and natural areas[8]

Climate change and biodiversity loss are interconnected challenges, and climate change is one of the five direct drivers of biodiversity and ecosystem change, according to the IPBES. **Renewable power generation, by contributing to climate change mitigation, also proves important for biodiversity conservation.**

On the other hand, land use change due to renewables is one of the main drivers of biodiversity loss associated to renewables. **In the considered prospective scenarios in 2050, the surface area co-used by renewables for power generation would represent around 2-3% of France's total area, and renewables would account for about 0,6% of French artificialized surfaces.** In addition to the mobilization of brownfields, different solutions can help to mitigate this impact of renewables, such as agrivoltaics, a greater development of rooftop solar panels (even if they are associated to a higher cost), or installing floating panels on artificial lakes.

In their operation phase, renewable energies are associated to negative impacts for biodiversity, especially **wind turbines regarding the increased mortality of birds and chiropters. This impact is in average relatively limited compared to other threats to birds**. Impact assessments are conducted for every project to mitigate its environmental impacts, protect locally endangered species and limit the disturbance on the vicinity of the wind farms.

Climate change adaptation[9]

Solar and wind renewable generation in France will not be significantly affected in the future due to climate change. Hydroelectric power generation will be slightly more impacted, with a variation in hydrological cycles, but the average annual precipitation volume is not expected to change significantly, according to RTE.

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[8] See section 6.3 for the study on the impacts on biodiversity and the preservation of natural areas

[9] See section 6.4 for the study on climate change adaptation

Renewable energies can also, to a limited extend, contribute directly to the adaptation to climate change, thanks to possible synergies with photovoltaic production, through agrivoltaics and solar installations on water bodies to limit evaporation.

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Glossary of acronyms

ADEME: *Agence de la transition écologique (*,Ecological transition agency)

CCGT: Combined cycle gas turbine

CHP: Combined Heat and Power

CITEPA: *Centre interprofessionnel technique d'études de la pollution atmosphérique*, interprofessional technical center commissioned by the French Ministry of Ecological Transition and Territorial Cohesion to produce the French national inventories of atmospheric pollutant and greenhouse gas emissions

CRE: *Commission de Régulation de l'Énergie* (independent body that regulates the French electricity and gas markets)

EDF-SEI: EDF-SEI is a division of EDF (*Électricité de France*, the main French electricity generation and supply company, that is state-owned) that operates in most non-interconnected zones (NIZ)

EEA: European Environment Agency

EU: Depending on the specific context of this report, EU can stand either for the European Union, or for neighbouring countries modelled in the study (including non-EU countries such as the United-Kingdom and Switzerland, and excluding EU countries far away from France).

FRB: *Fondation pour la recherche sur la biodiversité* (Foundation for Biodiversity Research)

GHG: Greenhouse Gases

H2: Hydrogen

IEA: International Energy Agency

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC: Intergovernmental Panel on Climate Change

LCA: Life cycle assessment

NH3: Ammonia

NIZ: Non-Interconnected Zone (Corsica, Guadeloupe, Réunion Island, Mayotte, Martinique, Guyane, Saint-Martin, Saint-Barthélemy, Saint-Pierre-et-Miquelon, Walls et Futuna, and Ponant Islands)

NO_2: Nitrogen dioxide

NOx: Nitrogen oxide

NMVOC: Non-methane volatile organic compounds

OCGT: Open cycle gas turbine

OTEC: Ocean Thermal Energy Conversion

PM2.5: fine particles whose size is inferior to 2,5 microns

PV: Solar photovoltaics

RES: Renewable Energy System

RTE: Réseau de Transport d'Électricité (french Transmission System Operator)

SPM: Saint-Pierre-et-Miquelon

SO_2 : Sulfur dioxide

St. Barth.: Saint Barthélemy

VOLY and VSL: "value of a life year" and "value of statistical life". Approaches used to give an economic evaluation of the cost of years of life lost.

WF: Wallis-et-Futuna

1 Introduction

In January 2017, the French Treasury Agency (AFT) launched the first French sovereign green bond, the OAT 1.75% 25 June 2039, for an issuance amount of 7 billion euros. Since then, two more green bonds have been issued by the AFT: the OAT 0.50% 25 June 2044, for an amount of €7 billion in March2021, and the OAT 0.10% 25 July 2038, for an amount of €4 billion in May 2022. These OATs reinforceFrance's leading role in fulfilling the objectives of the Paris Agreement on Climate Change, signed in December 2015. The Green OATs are regularly replenished based on market demand and within the limits of green eligible expenditures. As of January 2023, the total amount of the three green OATs stood at €52 billion[10].

The purpose of these OATs is to finance expenditures from the State budget that contribute to address environmental challenges. The objectives of French green OATs include climate change mitigation, climate change adaptation, biodiversity protection, and air, soil and water pollution reduction[11].

Since 2021, subsidies for renewable energy have been integrated within the eligible expenditures financed by Green OATs. This follows a reorganization of the French State budget, as support for renewable energies was previously financed through earmarked taxes. In 2021, a total of €5,148 million was allocated to the support of renewables, accounting for 34% of the funds raised through OATs in that year.

In addition to the annual publication of a report on the allocation and performance of OATs, France has committed to reporting on the environmental impacts of public expenditures linked to green debt emissions. As part of this commitment, *ex-post* evaluations of the environmental impacts of eligible expenditures linked to Green OATs are conducted, and overseen by the Green OATs Evaluation Council. Given the recent integration of support to renewable in the green eligible expenditures, it is important to assess the extent to which renewable energies contribute to France's environmental objectives.

The objective of this evaluation is to provide qualitative and quantitative data on the main environmental impacts of expenditures allocated to support renewable energies in France. This report focuses on the environmental impact of subsidized renewable energies, both in mainland France and in non-interconnected zones (Corsica and Overseas Territories). The aim is to provide an overview of the impacts of subsidized renewable production systems. The main impact of renewable energies is the reduction of greenhouse gas emissions, and this topic thus forms the core of this study. Other topics covered include the reduction of air pollutant emissions and associated avoided costs, water and soil pollution, the use of raw materials and recycling, land use, preservation of biodiversity and naturel areas, and climate change adaptation.

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[10] Green OATs website: https://www.aft.gouv.fr/en/green-oat

[11] Framework for Green OATs [Link]

2 Subsidy mechanisms for renewables in France

2.1 Description of the different mechanisms

Presentation of the Different Support Mechanisms

The French government supports the development of renewable energies through various mechanisms. This support takes place both upstream in the field of research and development, as well as during the industrialization phase, to support offer (for example, through feed-in tariffs, calls for tender) and commercial deployment (*e.g.* through fiscal incentives).

The scope of this study includes, according to the French budgetary classification, various actions of Program 345 *"Service public de l'énergie"* (Public Energy Service) of the general budget :

- Support for renewable energies in mainland France (Action 9, excluding bioenergy)
- Support for biomethane injection (Action 10)
- Support for energy transition in overseas territories (Action 11.01)

This support for renewable energies is implemented through two subsidy mechanisms: feed-in tariffs *("obligation d'achat", in french*) and premiums (*"complément de remuneration", in french*). These are typically 20-year contracts, but this duration can vary across the different types of renewable.

- With feed-in tariffs, every kilowatt-hour injected into the public grid is purchased by an obligated buyer (*e.g.* EDF) at a predetermined price. The government then makes up the difference with the market prices. These are often linked to Purchase Obligation Contracts, and reserved to small scale installations (below 500 kW).
- With premiums, renewable energy producers sell their production directly on the markets. The difference between the revenue from this sale and a reference remuneration level is then calculated. When this difference is positive (*i.e.* when market prices are higher than the reference remuneration), the premium mechanism generates revenue for public finances. When this difference is negative, a premium is paid by the French State (through the obligated buyer) to make up for this difference. These contracts are often linked to larger renewable projects, and part of these contracts are the results of competitive tenders organised by the French Government.

We emphasize that in this report, the term *subsidized renewable energies* refers to productions that benefit from state support (subsidies). The term *incentives* instead of *subsidies* could also have been relevant. It emphasizes that the financial cost of renewable facilities, which would be borne solely by producers without support mechanisms, is offset in markets only through the sale of energy and carbon credits, which likely do not fully take into account the positive externalities of renewables. These positive externalities (on climate, health, etc.) are thus an additional justification for this support, which is not only explained by *a priori* lower economic profitability.

Renewable Energies Studied

For the sake of clarity, *renewable energies* terms in this report will refer to the energy sources that benefit from a support from the French State *and* are included in the scope of the expenditures eligible to the Green OATs. The renewable energy sources studied are the following:

- In mainland France:
    - Electricity production: onshore and offshore wind, photovoltaic solar energy, and small hydropower
    - Gas production: biomethane injection
- In non-interconnected zones (NIZs), all renewables for electricity production are subsidized (except bagasse from sugar cane when co-fired with coal).

Therefore, some renewables, such as biomass, are excluded from the scope of the study (except in the NIZs).

Specificities in Non-Interconnected Zones (NIZs)

In non-interconnected zones, there are additional support mechanisms to compensate for the production costs, which are significantly higher than in mainland France[12]. These support mechanisms are divided into two categories, as shown in Figure 2: support for energy transition (including renewable energies) and solidarity mechanisms (support to electricity production from fossil fuels).

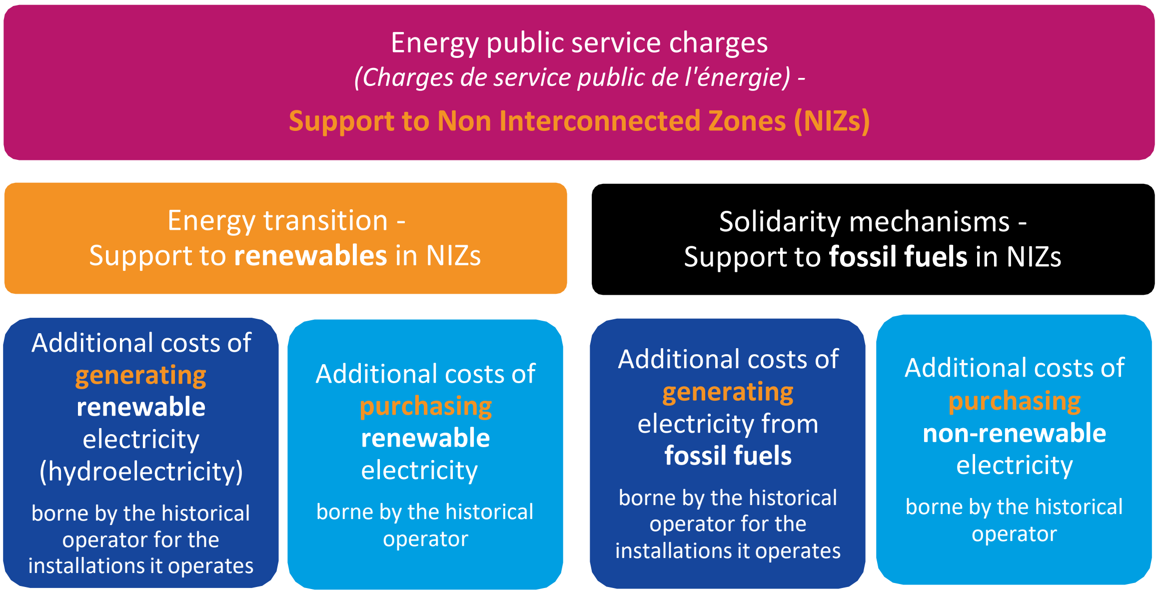

Figure 2 : Diagram of support mechanisms to electricity production in NIZs

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[12] According to the *Commission de régulation de l'énergie* (CRE), the cost of production is about 5 times higher in the NIZs than in mainland France. Support mechanisms aim to allow consumers to be charged at the same level as in mainland France (principle of tariff equalization). [CRE presentation of RES support financing] [FR]

Only subsidies related to the support mechanisms for energy transition are included in this study. These subsidies for renewables are divided into two categories: subsidies to make up for production costs of large historic hydropower installations on the one hand, and subsidies to make up for the costs of purchasing renewable electricity (similar to feed-in tariffs in mainland France, and mainly covering purchasing costs for photovoltaic solar energy, onshore wind and biomass).

2.2 Subsidies in the current energy price crisis

Europe has faced from the end of 2021, and so far still in 2023, an energy crisis marked by particularly high electricity prices in the market[13]. The start of this price increase dates back to mid-2021, and is partly linked with the increase of fossil fuel prices following the post-Covid economic recovery, in particular gas. The situation has also been exacerbated by low stocks availability (both for gas and hydropower) after the winter of 2020-2021, and geopolitical factors (interruption of the commissioning of the Nordstream2 gas pipeline, global competition for access to liquefied natural gas resources). The increase in gas prices, followed by coal and CO2 prices in the Emissions Trading System (EU - ETS) market, has led to a sharp increase in electricity prices in European markets. The lower wind power production in France in 2021 and the low availability of nuclear power plants have also exacerbated the energy crisis. The invasion of Ukraine by Russia in early 2022 has further heightened tensions and caused price increases.

In this exceptional context of particularly high electricity market prices, the support mechanism for additional remuneration for renewables is no longer a burden for the state but a source of revenue. The French Energy Regulatory Commission (CRE) estimates that the charges for public energy services (covering all support mechanisms) for 2023 will overall generate €1549 million for the state[14].

2.3 Historical subsidies

This section presents data on subsidies for renewables from 2000 to 2021, for mainland France and non-interconnected zones. It presents the volumes and capacities that were subsidized, as well as the associated expenses. This data has been reconstructed from various sources, primarily the annual reports of the CRE on the evaluation of public service charges for energy from 2005 to 2022,

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[13] CGCSPE, *Rapport annuel du Comité de gestion des charges de service public de l'électricité n°4* [Link][FR]
[14] CRE, *Délibération de la CRE du 13 juillet 2023 relative à l'évaluation des charges de service public de l'énergie pour 2024 et à la réévaluation des charges de service public de l'énergie pour 2023* [Link][FR]

supplemented by data from a report of the same institution detailing the contribution to public electricity service[15].

2.3.1 Mainland France

Subsidized renewable electricity production in mainland France deals mainly with solar power, wind power, and small hydropower (especially run-of-river hydropower).[16]

Photovoltaic production only really began in the 2010s, and reached 12.4 TWh for the subsidized portion in 2021, with a capacity of nearly 13 GW supported. Over the past 10 years, approximately 90% of the production has been subsidized. The photovoltaic sector has represented the majority of subsidies, with a total of €24.6 billion over the period 2000-2021 (compared to €11.5 billion for wind energy). This is mainly due to historical purchase obligation contracts concluded at over €500/MWh in 2010. A moratorium was implemented at the end of 2010 to reduce the costs of supporting photovoltaics, following the plunge of PV panels installation costs. The CGCSPE[17] indicates that pre-moratorium solar represented 3.7 GW of support in 2021, compared to 8.1 GW for post-moratorium solar. However, subsidies paid for pre-moratorium solar amount to €20.1 billion, compared to €4.6 billion for post-moratorium solar. The feed-in tariff of pre-moratorium solar was of order €450/MWh, compared to between €33 and €62/MWh for post-moratorium solar. It is important to have in mind that these important purchase costs are still paid today, since obligation contracts for solar last 20 years, and the feed-in tariff is fixed at the signature of the contract.

Wind power production emerged at large scale earlier than photovoltaic power, as early as in the 2000s. Subsidized wind power production reached 36.2 TWh in 2020. However, the production was significantly lower in 2021 due to less favourable wind conditions, despite an increase of the total capacity of 700 MW. The subsidized installed capacity in 2021 was 16.3 GW. The yearly increase in subsidized production typically ranges from 1 to 4 TWh and approximately 90-95% of the total production is subsidized. The average feed in-tariff for wind power is €42/MWh over the period 2000-2021, with no major inter-annual disparity, contrary to solar photovoltaic. In 2020, subsidies reached their peak at €1.95 billion, before falling down to €200 million in 2021 in the context of the energy crisis. According to the CRE[18], this sector will be the main source of revenue for the state in 2022 and 2023 through the premium mechanism.

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[15] Annual reports are, for example, the 2022 one introduced right above. The report that present support mechanisms is available there: [Link][FR]

[16] The amounts of subsidies considered here correspond to those validated by the *Commission de régulation de l'énergie* (CRE). They are usually not exactly tracked in budgetary amounts of net cash flows, as the State procedes with advances and successive adjustments which tend to smooth out expenditure over time.

[17] Electricity Public Service Charge Management Committee (*Comité de gestion des charges de service public de l'électricité*), annual report n°4 [Link][FR]

[18] CRE, *Délibération de la CRE du 13 juillet 2022 relative à l'évaluation des charges de service public de l'énergie pour 2023* [Link][FR]

Run-of-river hydroelectricity represents production volumes ranging from 3.2 to 6.7 TWh per year over the period 2000-2021. These variations are mainly due to weather conditions (more or less rainfall in a given year) and changes in installed capacities. Approximately 10% of hydroelectric productions are subsidized, the historical large dams already being financed. A cumulated capacity of about 2 GW has been subsidized in 20 years, with no significant increase since 2004 (as the French hydroelectric potential is already largely exploited). This sector is particularly cost-effective in terms of subsidies, averaging €111 million per year over the period 2000-2021, i.e. in average 21€ of public subsidy per MWh generated.

Biomethane subsidised injected production reached 4.3 TWh in 2021. The increase in injected biomethane is rapid, as less than 0.1 TWh was subsidised in 2015. The subsidies amounted to €222 million in 2021.

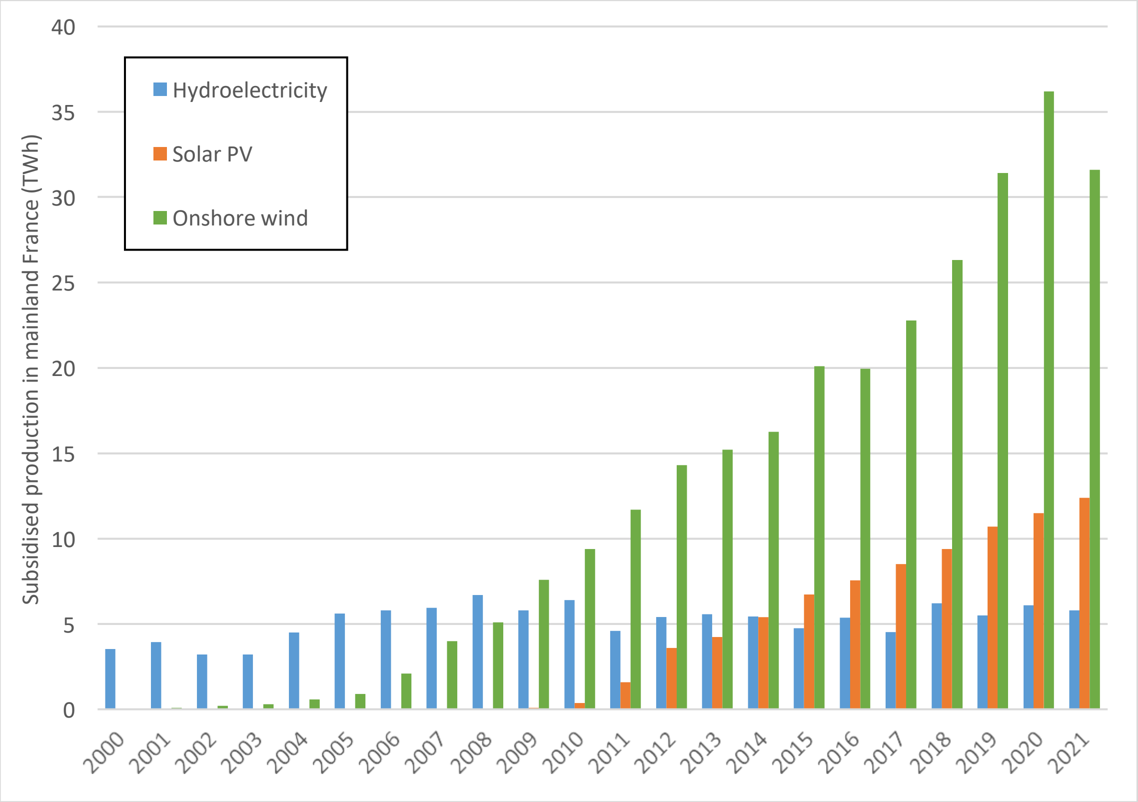

Figure 3: Annual subsidized production in mainland France (TWh)

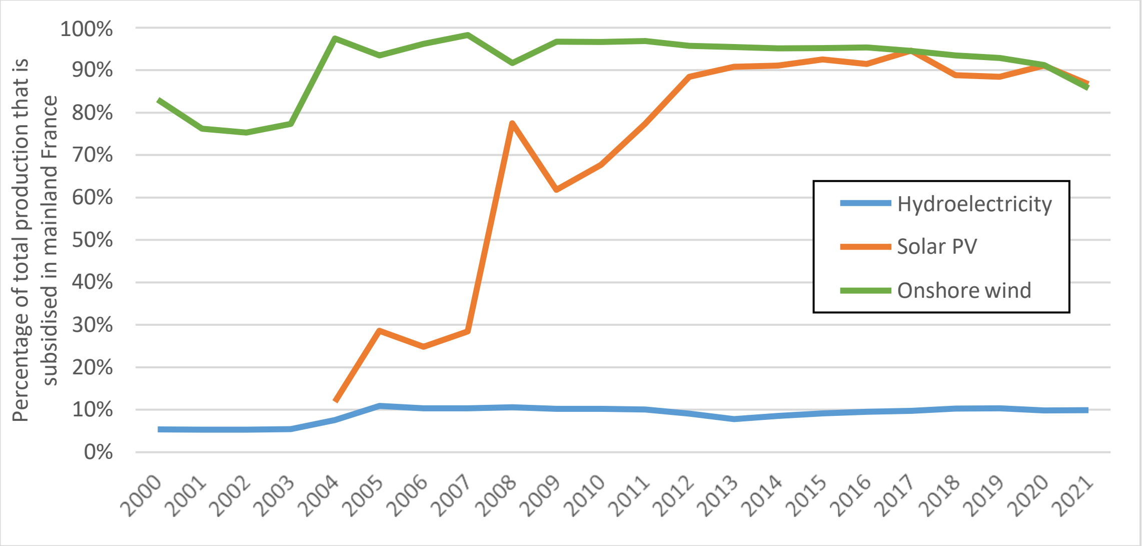

Figure 4: Percentage of total production (per energy source) that is subsidized in mainland France

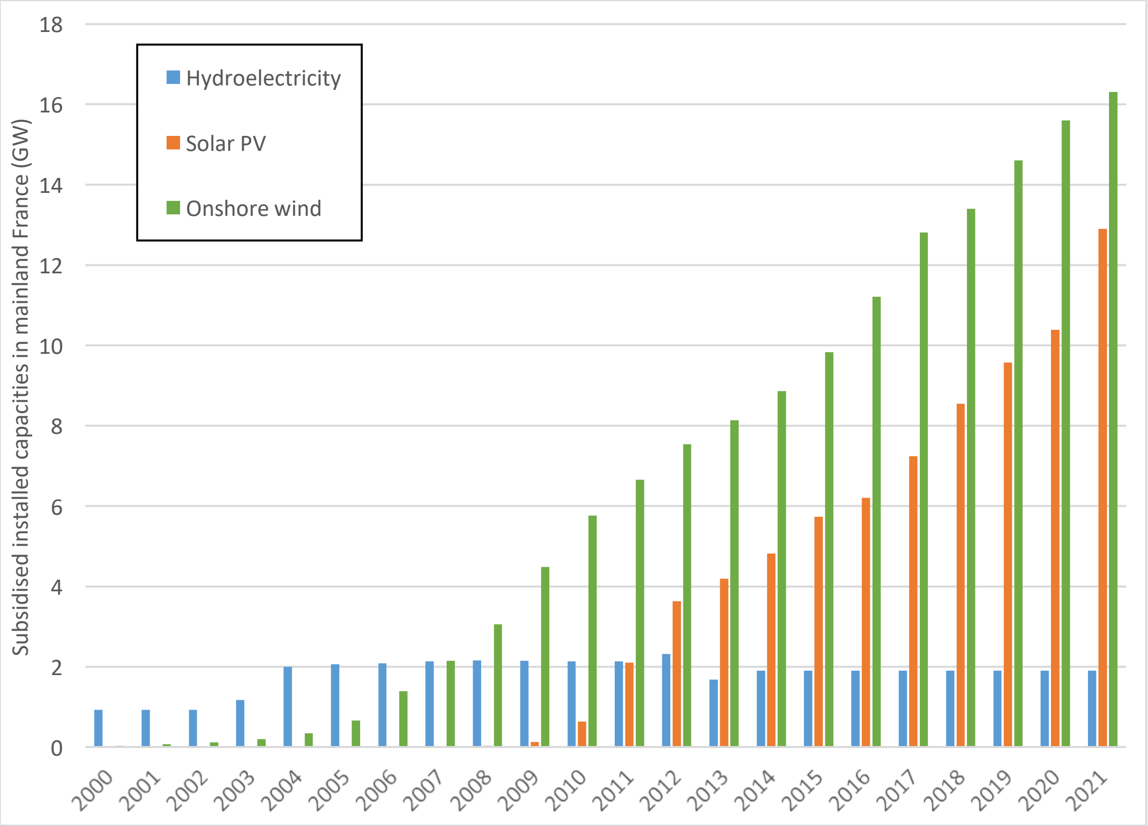

Figure 5: Annual subsidised installed capacities in mainland France (GW)

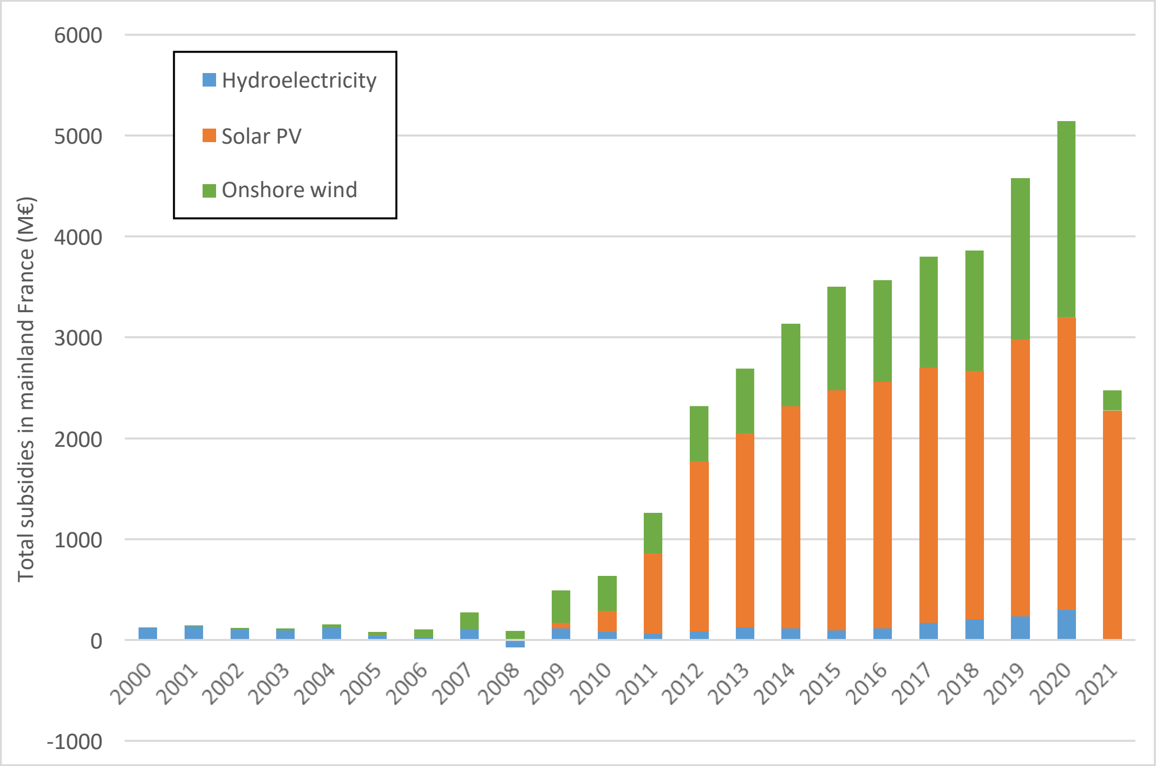

Figure 6: Total annual subsidies in mainland France (M€)

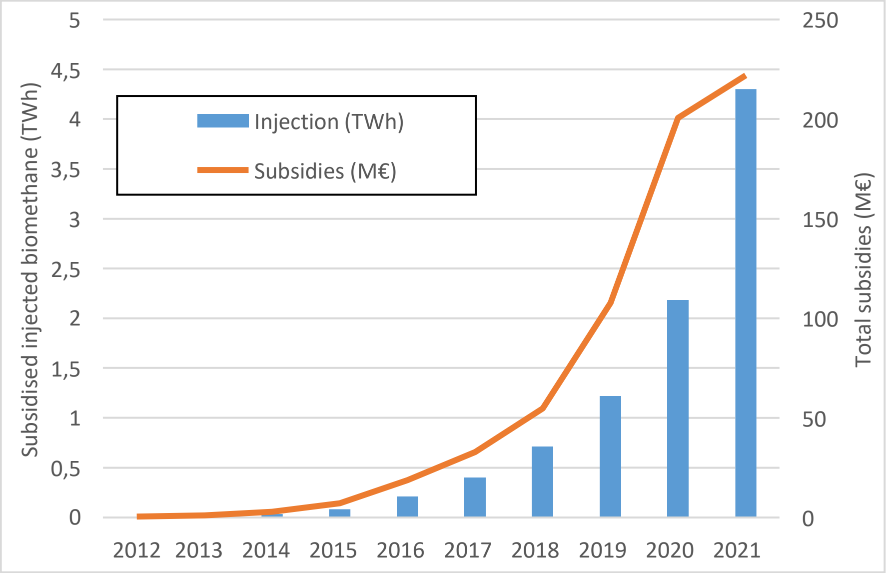

Figure 7: Subsidised biomethane production (TWh) and associated subsidies (M€)

2.3.2 Non-Interconnected Zones (NIZs)

Renewable energy subsidies in the non-interconnected zones (NIZs) depend largely on local context, as the energy mix varies greatly from one NIZ to another. The historical production by renewable energy sources and by NIZ for the period 2000-2021 is presented in Appendix 7.1.

It is noteworthy that until the 2010s, the majority of subsidized renewable energy production in the NIZs was from historical hydroelectricity (dams in Reunion, French Guiana, and Corsica), with an average annual production of around 1,3 TWh. Other renewables have also been developed, mainly in Guadeloupe, Martinique, Corsica, French Guiana, and La Reunion. This development of renewables in these territories is primarily linked to photovoltaic solar energy since the 2010s (which was particularly expensive), and to a lesser extent to electricity production from bioenergy (biomass, bagasse, biogas), wind, small hydro and geothermal sources. Almost 3 TWh were subsidised overall in 2021 for all these regions.

Almost all of the renewable electricity production in the NIZ is subsidized, totalling €428 million in 2021. As in mainland France, historical hydroelectricity appears to be significantly less costly, especially compared to photovoltaic solar energy. In fact, in 2021, historical hydroelectricity accounted for nearly half of the renewable energy production, but only 4% of the total subsidies.

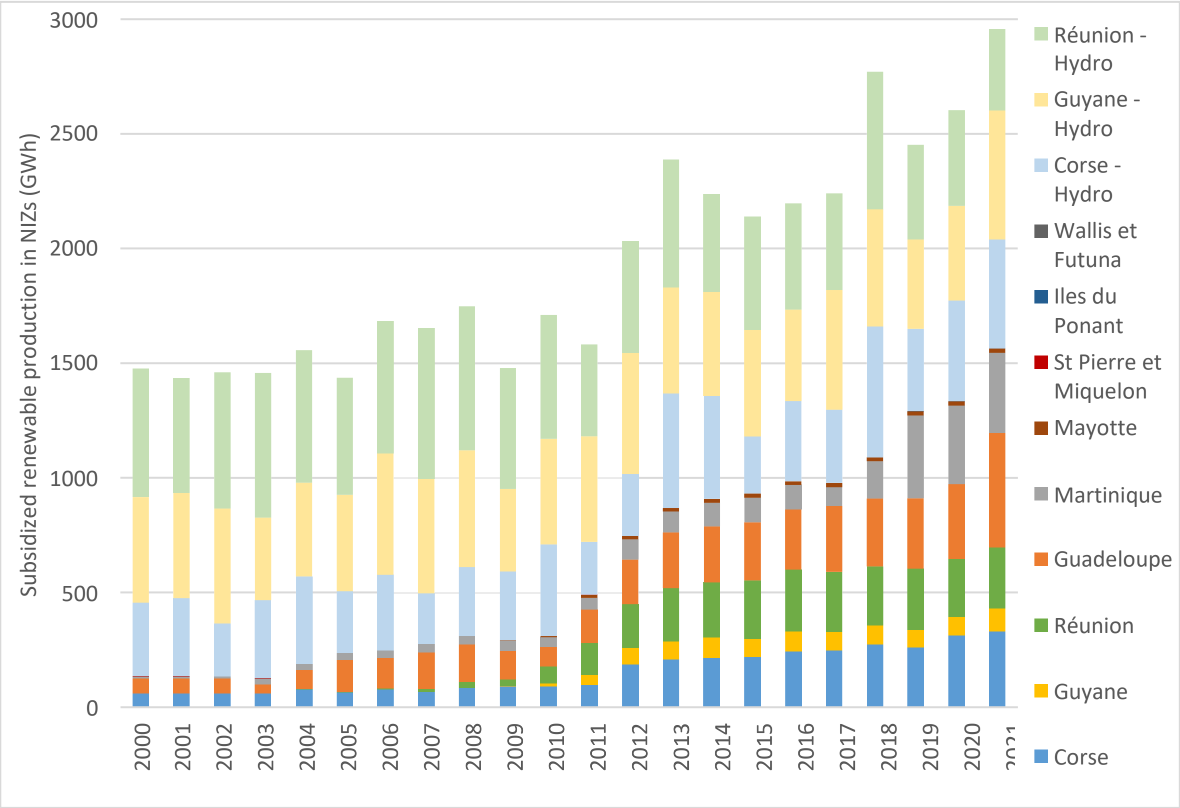

Figure 8: Historical annual subsidized renewable production per NIZs (GWh)

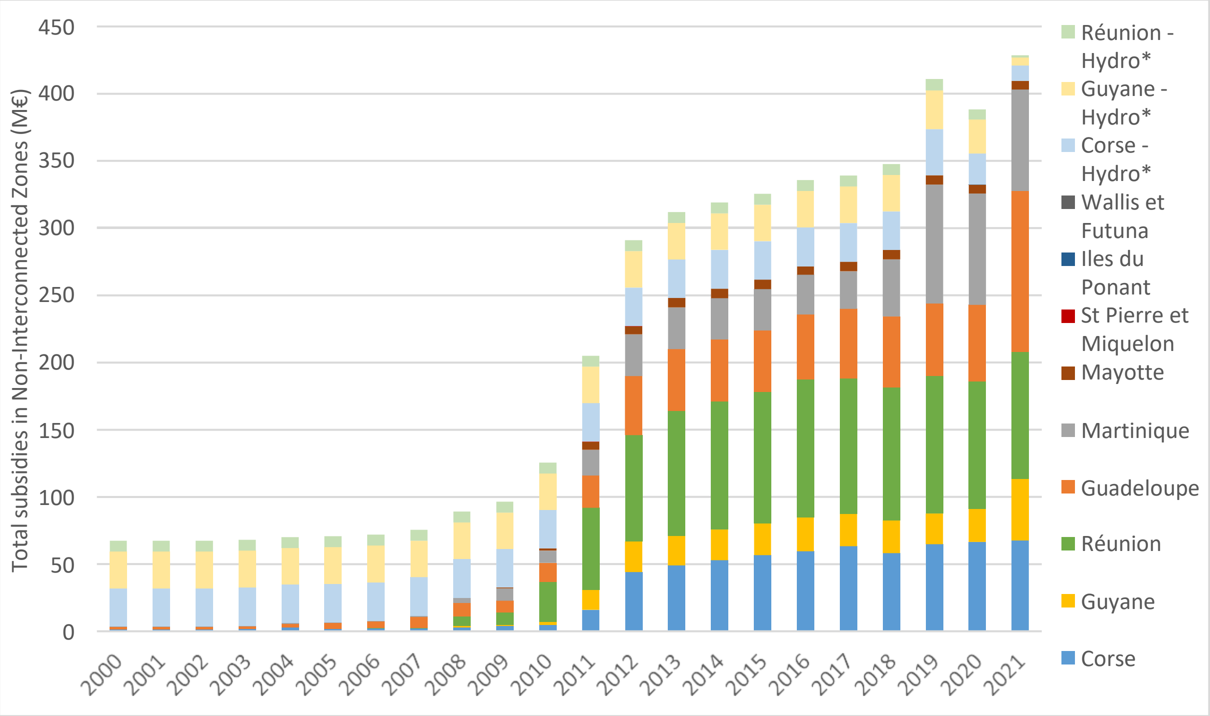

Figure 9: Total annual subsidies for renewable production in NIZs (M€)

2.4 Alignment of subsidies with the EU Taxonomy

2.4.1 Definition

The EU taxonomy[19] is a classification system created by the European Commission, establishing a list of environmentally sustainable economic activities. The goal of this taxonomy is to identify criteria defining the conditions for economic activities to be considered as environmentally sustainable.

The Taxonomy Regulation is based on six environmental objectives:

1. Climate change mitigation
2. Climate change adaptation
3. The sustainable use and protection of water and marine resources
4. The transition to a circular economy
5. Pollution prevention and control
6. The protection and restoration of biodiversity and ecosystems

The Taxonomy sets out three cumulative conditions that an economic activity has to meet to be recognised as Taxonomy-aligned:

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[19] Source: European Commission website on EU Taxonomy

- making a substantial contribution to at least one environmental objective
- doing no significant harm to any other environmental objective (DNSH)
- complying with minimum social safeguards

2.4.2 Alignment of the subsidised projects

In order to verify that the subsidised projects are aligned with the EU taxonomy, a specific analysis would have been required to verify that each project respects the conditions of the EU taxonomy, as done by companies subject to Taxonomy Regulation.

Because of the number of projects involved, and the lack of associated detailed data, a per-project analysis would have not been possible within the scope of this study. To overcome this difficulty, we have decided to provide an overview of the EU taxonomy criteria related to the economic activities of the projects subsidised, with the aim to estimate what might be the limiting criteria in the French context.

This analysis has been limited to the electricity generation of solar photovoltaic, wind power and hydropower, that represent most of the subsidised generation considered in this study. The three corresponding activities in the taxonomy Climate Delegated Act[20] are:

- 4.1: Electricity generation using solar photovoltaic technology
- 4.3: Electricity generation from wind power
- 4.5: Electricity generation from hydropower

Substantial contribution

The substantial contribution criteria for electricity renewable generation defined in the Taxonomy climate Delegated Act is the electricity generation itself, that contributes to climate mitigation. Additional criteria for hydropower are required for non run-of-river plants (which do not dispose of artificial reservoirs)[21], which only applies to some historic hydro damns in NIZs since all other subsidies in mainland French and new hydropower plants are run-of-river.

Do no significant harm criteria

- Climate change adaptation: generic criteria (appendix A) are required Part 6.4 of this report provides some elements showing how renewable energy plants could satisfy these criteria, using an average approach (no specific location chosen).
- Sustainable use and protection of water and marine resources:
  - for hydropower, specific measures have to be implemented to mitigate the impact on the water bodies (biodiversity, important variation of water flows), which is already required in the French regulation.

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[20] Regulation (EU) 2021/2139 [Link]

[21] life-cycle GHG emissions lower than 100 gCO_2e/kWh, or power density of the electricity generation facility above 5 W/m^2

  - for offshore wind, appropriate measures have to be taken to mitigate impact on maritime waters, which is required in the impact assessment study that has to be conducted before a new project approval.
- Transition to a circular economy: for solar and wind, an assessment of the recyclability and durability of the used materials has to be performed, with minimum recyclability targets, and evolution planned for the future for even higher recyclability requirement for new projects. In particular, equipment that are easy to dismantle and refurbish are mandatory for new projects.
- Pollution prevention and control: not applicable (no DNSH criteria are required for wind, solar and hydroelectricity production activities).
- Protection and restoration of biodiversity and ecosystems: An Environmental Impact Assessment (EIA) at the scale of the site or project has to be performed, which is the case in the European, and in particular French regulation, for large-scale projects (not applicable for solar rooftop panels).

Compliance with minimum social safeguards

As mentioned in the EU taxonomy regulation, minimum social safeguards refer to procedures implemented by the different actors to ensure the compliance with the OECD Guidelines for Multinational Enterprises and the UN Guiding Principles on Business and Human Rights, including the principles and rights set out in the eight fundamental conventions identified in the Declaration of the International Labour Organisation on Fundamental Principles and Rights at Work and the International Bill of Human Rights.

Since all the renewable generation is by definition associated to renewable installations located in France, the minimum social safeguards at the installation and electricity production stages are assumed to be met, in accordance with the different laws and regulations present in France.

However**,** minimum social safeguards may not be respected in some countries where some key components materials are extracted. This analysis of the technology manufacturing stage would in any case require more detailed and specific data, and a high degree of traceability of the origin of the different components and materials, on a project basis.

3 Evolution of the French energy mix and decarbonisation

3.1 Renewable energy in the energy mix

While public discussions about renewable energy often focus on wind and solar power, these two sources of energy represent currently only a limited fraction of renewable *primary energy* production. Wood is the leading renewable energy source in France, and is mainly dedicated to the production of heat. Renewable power generation accounts for about a third of total renewable primary energy production. Around half of this renewable electricity comes from hydroelectricity, with solar photovoltaic and wind together accounting for slightly less than hydroelectric production in 2021, but their production is expected to increase and exceed the one from hydro in the coming years.

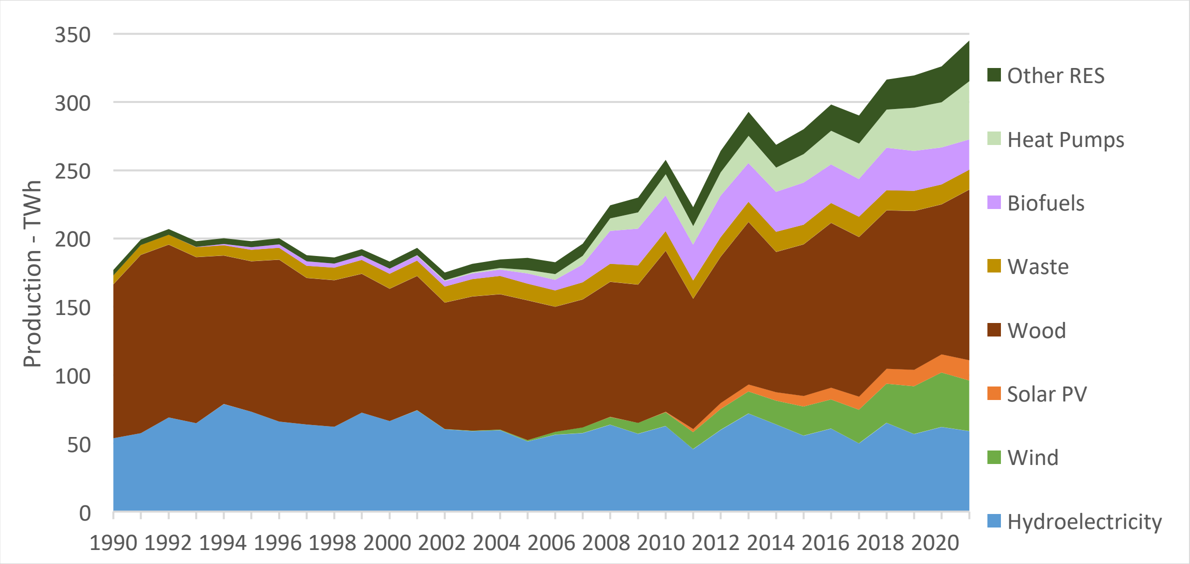

Figure 10: Primary production of renewable energy in France (source: SDES, *Chiffres clés de l'énergie, 2022*)

As mentioned in section 2.1, this study focuses only on a fraction of the total renewable in France, which corresponds to what is subsidized in the Program 345 of the French State budget[22]. This corresponds in mainland France to solar photovoltaic, wind, small hydropower, and biomethane (included in the figure above in "Other RES" category). In non-interconnected zones, all renewable energies (except bagasse generation when co-fired with coal) are subsidized by the budgetary expense under study.

For the rest of this report, for the sake of clarity, any mention of "renewable energy", or "renewable production" will only refer to the above-mentioned technologies.

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[22] Presentation of Program 345 [Link][FR]

3.2 Historical production and scenarios for the evolution of the French electricity mix

Studying the environmental impact of renewable energies requires analyzing both the historical and future French electricity mix in order to take into account the fact that subsidized installations producing decarbonized energy today will also do so in the future. This study aims to assess their impact over their entire lifespan and shed light on the environmental impact of renewable energy production that will still be subsidized in the future.

The French electricity mix historically relies mainly on nuclear (especially since the 1980s), then hydropower, and to a lower extent fossil fuels. Since the 2000s, significant wind and photovoltaic production have emerged, and these technologies are set to play an increasing role in the French electricity mix in the future.

3.2.1 Electricity production in mainland France

The historical production of the French electricity mix has been reconstructed since 2000, with a breakdown by means of production[23]. For the future, two prospective scenarios from the *Transition(s) 2050* (ADEME)[24] reference study have been studied. These are the S2 and S3-Nuclear (S3Nuc) scenarios, which have been chosen to depict two contrasted energy systems, particularly in terms of levels of electricity demand, nuclear and renewable production, and demand for hydrogen (produced by electrolysis).

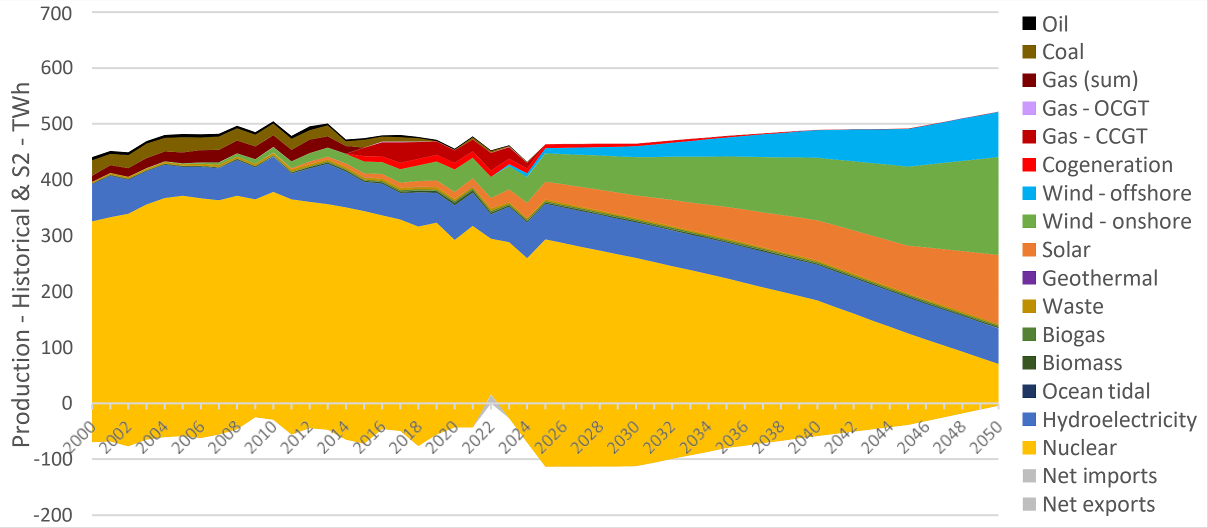

Figure 11: Electricity production in France, historical (2000-2022) and S2 scenario (2023-2050), in TWh. Negative value corresponds to electricity exports: therefore production (from all sources) is counted from negative values

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[23] Mostly using open data from network operators (ODRÉ) and the "*Chiffres clés de l'énergie"* publications from SDES (Statistical Service of Ministries responsible for the environment, energy, construction, housing, and transportation).

[24] ADEME, *Transition(s) 2050*, Feuilleton *Mix électrique* [Link][FR]

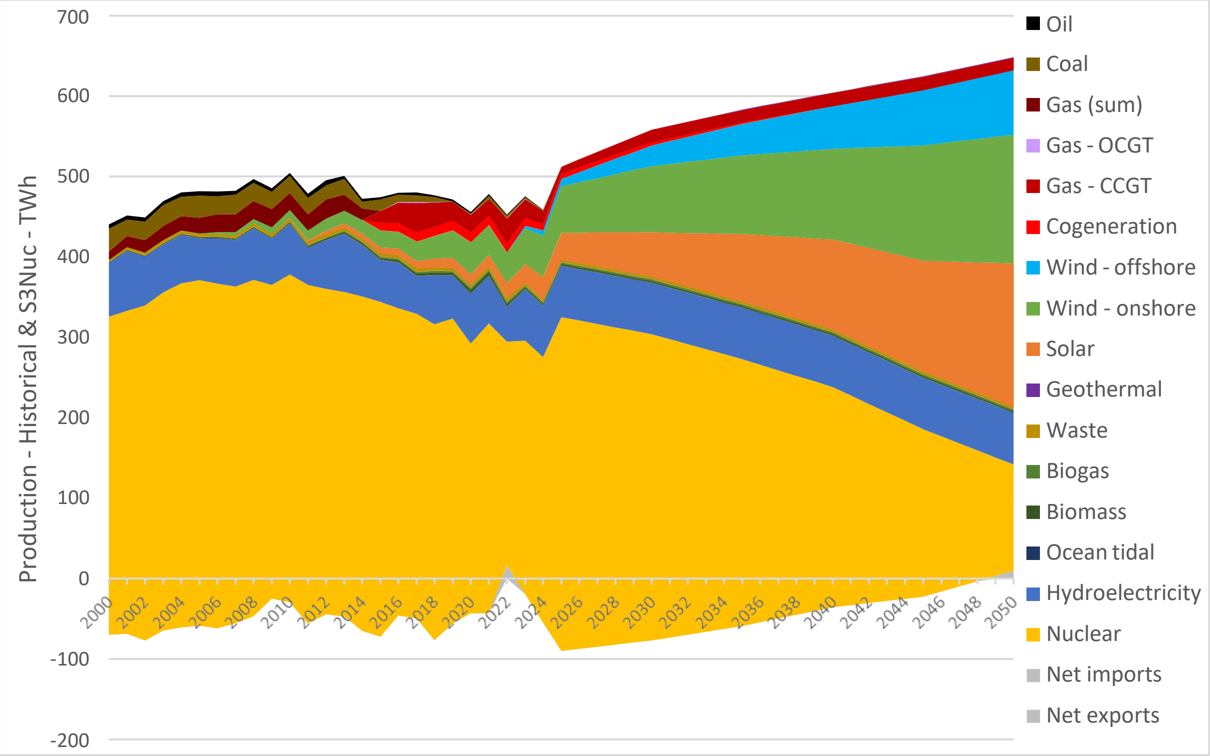

Figure 12: Electricity production in France, historical (2000-2022) and S3Nuc scenario (2023-2050), in TWh. Negative value corresponds to electricity exports: therefore production (from all sources) is counted from negative values

3.2.2 Electricity production in non-interconnected zones (NIZs)

The historical electricity production in the non-interconnected zones (NIZs) has been reconstructed, with a breakdown by means of production for each of the territories, from 2000 to 2021[25]. The historical production by territory is presented in detail in Appendix 7.1.

For the future, the productions were calculated from the data in the adequacy reports and PPEs (Pluriannual Energy Programming) of the different territories[26]. For the five most populated territories (La Réunion, Corsica, Guadeloupe, Martinique, and French Guiana), thermal production is assumed to be decarbonized by 2038, in line with objectives stated in the different strategic documents. Electricity production in thermal power plants is currently mainly based on oil in the NIZs (and partly on coal in Réunion and Guadeloupe); it is assumed for the five main territories that oil is progressively replaced by biodiesel in the different scenarios (see Figure 13).

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[25] Main sources: EDF SEI open data, adequacy report, regional agencies, CRE, PPE. This work of reconstructing production since 2000 for all NIZs has not been found in public reports and had to be created for this study.
[26] Calculation methodology is detailed in Annex 7.5.

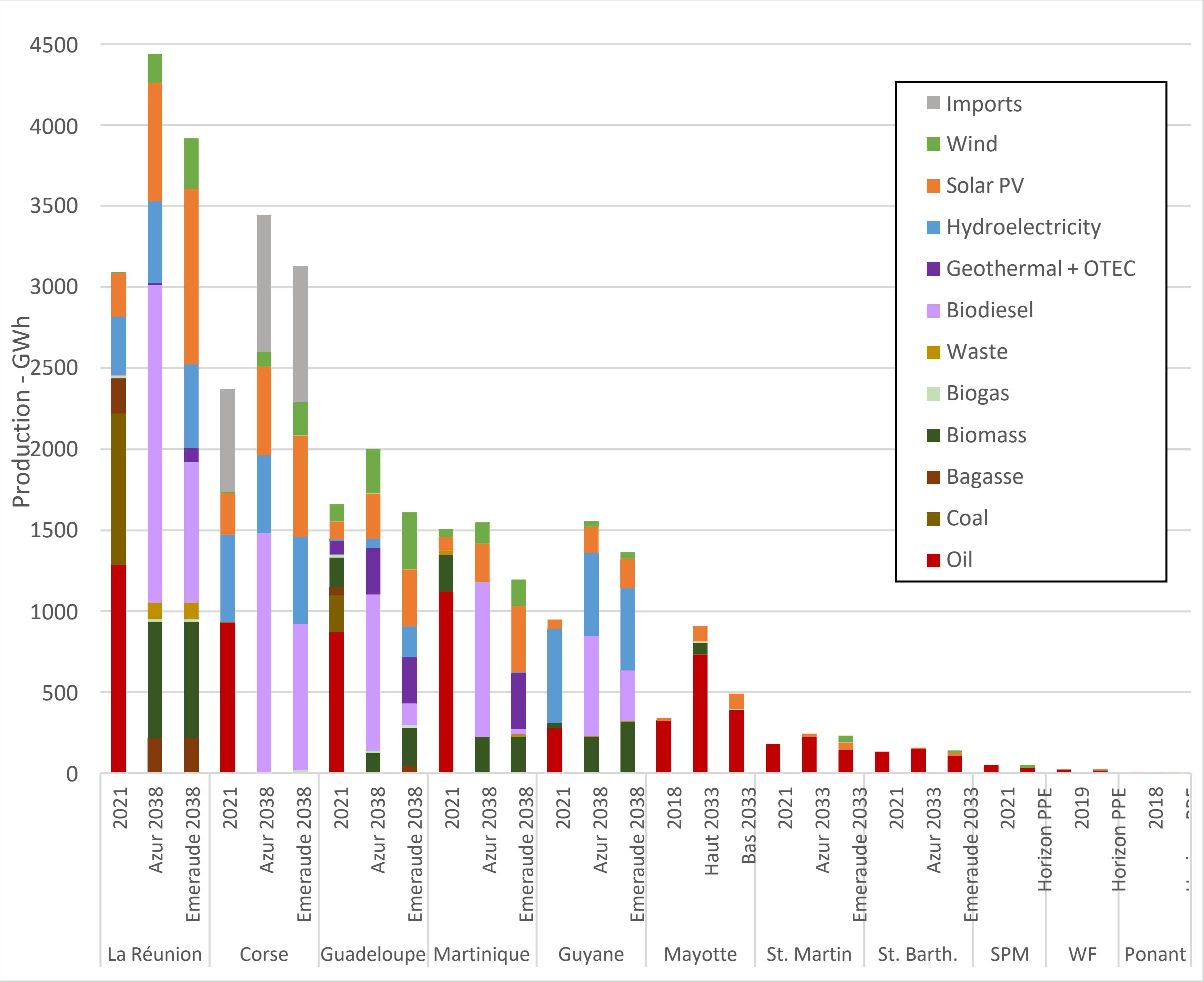


Figure 13: Electricity production (GWh) in NIZs, in 2021 and at a prospective horizon in two scenarios (2038 or 2033)

3.3 Overall contribution of electric renewables to the decarbonisation of the French energy mix

3.3.1 French and European Decarbonization Strategy

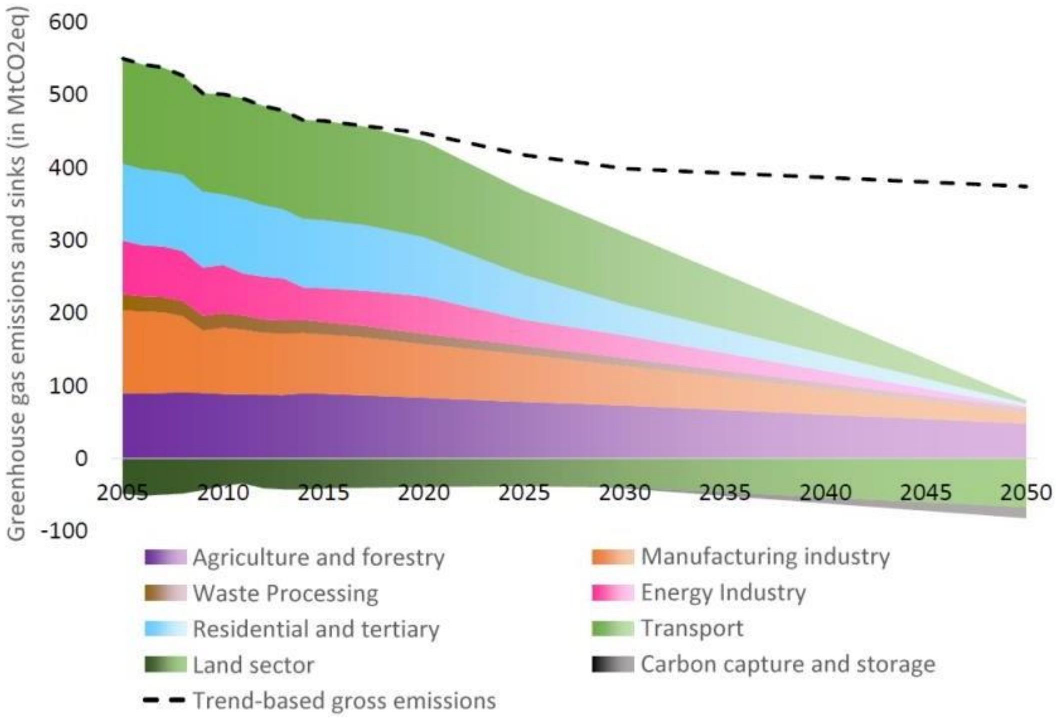
The European Union and France aim to achieve carbon neutrality by 2050 to fight climate change. These commitments are in line with the Paris Agreement, in which signatory countries pledged to limit the increase in average temperature to below 2°C, and preferably 1.5°C.

In 2019, the European Parliament declared a climate emergency asking the European Commission to adapt all its proposals in line with a 1.5°C target for limiting global warming and ensure that greenhouse gas emissions (GHG) are significantly reduced. The Commission then proposed the *European Green Deal*, which is a roadmap and framework to facilitate the achievement of European climate objectives. In 2021, the European Parliament adopted the EU Climate Law, which makes legally binding a target of reducing emissions 55% by 2030, and climate neutrality by 2050. To achieve the

2030 target, the Commission proposed the legislative package Fit for 55, which includes, among others, rules on GHG emissions trading, national GHG emissions reduction targets, carbon removal in the land use sector[27].

In France, the implementation of climate objectives is reflected in the energy-climate law and the National Low Carbon Strategy (SNBC)[28]. The SNBC is France's roadmap to fight climate change. It provides guidance for implementing the transition to a low-carbon economy in all economic sectors. It defines a trajectory for reducing greenhouse gas emissions by 2050 and sets short- to medium-term objectives, known as carbon budgets. It has two ambitions: to achieve carbon neutrality by 2050 and reduce the carbon footprint of French consumption. French energy policy is also guided by the Multiannual Energy Plans[29], which set energy objectives on a 10-year horizon for mainland France and non-interconnected zones.

Carbon neutrality is legally defined in France as a balance, on national territory, between anthropogenic emissions by sources of greenhouse gases (GHG), and anthropogenic removals by GHG sinks. The SNBC thus displays a trajectory of emissions reduction to reach emissions of 80 MtCO2eq by 2050, with equivalent absorption in carbon sinks. This trajectory is sectoral, as presented in Figure 14. The SNBC strategy and PPE plan are currently being updated.



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[27] European Parliament, *Green Deal: key to a climate-neutral and sustainable EU* [Link]

[28] Ministère de la Transition écologique et solidaire (Ministry of Ecological Transition and Solidarity), *Stratégie Nationale Bas Carbone,* 2020 [Link]

[29] Named PPE in French (*Programmations pluriannuelles de l'énergie*)

Figure 14: Trajectory of greenhouse gas emissions and sinks evolution in France (source: SNBC)

Recently, two major prospective studies have been published on the evolution of the French energy mix by 2050. These are the *Energy Pathways to 2050* (*Futurs Énergétiques*) study by RTE[30], the operator of the French electricity transmission network, and the *Transition(s) 2050* study by ADEME[31], the ecological transition agency (this study also covers other aspects of the ecological transition). These two studies have been major references for the completion of this work. Two scenarios of the ADEME study for the electricity mix have been used, and both studies have been sources of inspiration and data for the environmental analysis.

Both the SNBC and the detailed prospective studies by RTE and ADEME foresee a significant decrease in energy consumption and a strong electrification of uses to replace fossil fuels. As a result, most scenarios project an increase in electricity consumption in France. Therefore, it is necessary to develop low-carbon electricity production systems. Since not all uses can be electrified, other energy sources, particularly biomass, are expected to develop. To decarbonize the gas sector, the development of biomethane production is also an important element in most scenarios.

3.3.2 Contribution of Electrification and Development of Renewable Energies

The French National Low-Carbon Strategy (SNBC) plans that the electricity sector will represent 55% of France's final energy consumption by 2050, amounting to 580 TWh. RTE indicates that in its prospective scenarios, the electricity sector will contribute for about 55% of the reduction of energy-related GHG emissions, mostly through transfers to electricity (50% - 156 MtCO2eq) and more marginally thanks to the closure of the last fossil thermal power plants (5%). The electrification of transport represents the main lever (97 MtCO2eq). The electrification of heating and industry will also lead to significant reductions in GHG emissions. Some scenarios also envision the reindustrialization of France, which could serve as a significant lever for reducing the nation's carbon footprint, given the currently much lower carbon intensity of the electricity mix compared to most other countries. RTE estimates that if industrial goods currently imported were manufactured in France, the national carbon footprint would be reduced by 75 MtCO2eq emissions annually.

It is worth noting that France has a unique feature among major industrialized countries: its electricity mix has been largely decarbonized since the 1980s, thanks mostly to nuclear energy, and secondly to hydropower. Since the 2000s, wind and solar power have also provided decarbonized electricity. Direct emissions from the electricity sector amounted to 20 MtCO2eq in France in 2019 (source: CITEPA), compared to 222 MtCO2eq in Germany (source: European Environment Agency).

Therefore, the challenge for the French electricity system is not so much to decarbonize its current production, but rather to increase the volume of low-carbon energy produced to enable electrification of other sectors. This challenge is particularly crucial as the French nuclear fleet was largely developed

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[30] RTE, *Futurs Énergétiques* [Link]

[31] ADEME, *Transition(s) 2050* [Link]

in the 1980s within a narrow timeframe. Most French reactors are now around 40 years old, and while there are plans to extend their lifespan to 60 years or even more, most of these reactors will be phased out by 2060.

3.3.3 Assessment of the environmental impact of subsidized renewables in the French and European decarbonization context

The objective of this study is to assess the environmental impact of subsidized renewable energies (for electricity production and biomethane) in France. This evaluation takes into account the specificities of the French and European energy context. A major focus of this analysis is the quantitative evaluation of the volumes of greenhouse gas emissions avoided by subsidized renewables, as presented in sections 4 and 5.

Note that the impacts of renewable energies in terms of avoided GHG emissions largely depend on the system in which they are integrated and what other means of production they replace. The integration of significant shares of intermittent renewable energies (solar, wind) into the electricity mix requires the development of flexibility means (storage, flexibility of production and demand). This issue is particularly important for insular regions (NIZs). Finally, the impact of renewables will be greater when they replace fossil fuels. Since the French electricity mix itself is already largely decarbonized, the impact of French renewables depends greatly on the electricity mix of neighbouring countries.

4 Description of the study methodology and modelling of counterfactual scenarios

This study focuses on the environmental impacts of subsidized renewable energies in mainland France and in the NIZs. Environmental impacts cover a very wide range of topics, such as climate change, pollution, material use, etc., for which it is not always possible to define quantitative methods to estimate the impacts. In order to circumvent this difficulty, the approach adopted in this study mixes quantitative and qualitative analyses.

The most structuring environmental impacts have thus been quantified, based on a dedicated modelling work carried out in this study and using assumptions from reference studies (RTE *Energy Pathways to 2050* study, ADEME, etc.). The **quantification of greenhouse gas emissions avoided by subsidized renewable energies** has thus been the central work of this study. The methodology used for greenhouse gases has also been extended to assess avoided emissions of air pollutants, and their associated costs have also been quantified. The impact of renewable installations in terms of materials required and surface area have also been quantified.

Other impacts, for which it appeared more difficult to carry out quantifications, have also been studied but with a qualitative approach, through a literature review. The impact of the development of renewable energies on water and soil pollution, recycling, the preservation of biodiversity and natural areas, and climate change adaptation are thus based on a literature review.

The following subsections are dedicated to a description of the methodology used to assess the quantification of greenhouse gases emissions and local pollutants avoided by subsidized electric renewable energies[32].

4.1 Impact assessment principle: counterfactual scenarios

In order to study the impact of subsidized renewable energy, two scenarios are compared: a scenario with renewable energy development identical to historical data and in line with the considered prospective scenarios ("reference scenario"), and one without additional renewables from a given reference year ("counterfactual scenario"), all else being equal. This counterfactual principle is applied both for the study of the mainland France energy system and of non-interconnected zones.

The counterfactual scenarios are separated in two periods, the historical period (from 2000 to 2021) and the prospective period (since 2021). For the past, the counterfactual presents renewable production capacities fixed at their 2000 level. Similarly, for the future, they are fixed at their 2021

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[32] The methodology used to assess the impact of biomethane on greenhouse gases emissions is directly presented in the section 5.5.

level. The rest of the system (demand, installed capacities of other means of production) is kept identical.

The differences of electricity production by technology between the two scenarios allow to deduce which productions are avoided by renewable energy, and then to deduce other impacts (GHG, local pollutant, etc.) by using appropriate emission factors.

Table 1 - Definition of the counterfactual and reference scenarios

	Metropolitan France		**Non-Interconnected Zones** (NIZ)	
	Reference	Counterfactual	Reference	Counterfactual
Past (2000 – 2021)	**Historical** installed capacities *(RTE)*	**2000** installed Renewable Energy Systems (RES) capacities *(RTE)*	**Historical** production by NIZ *(reconstructed)*	**2000** RES production *(reconstructed)*
Future (from 2021)	**ADEME *Transition(s) 2050*** S2 & S3Nuc scenarios	**2021** installed RES capacities *(RTE)*	**Prospective scenarios** by NIZ *(reconstructed)*	**2021** RES production *(reconstructed)*

The graphs below show the production differences between the reference scenarios and the counterfactual scenarios for metropolitan France, for the historical period, the S2 scenario, and the S3Nuc scenario. Productions in the future scenarios and in the past counterfactual are obtained by a dedicated model of the power system, as described in subsection 4.2.

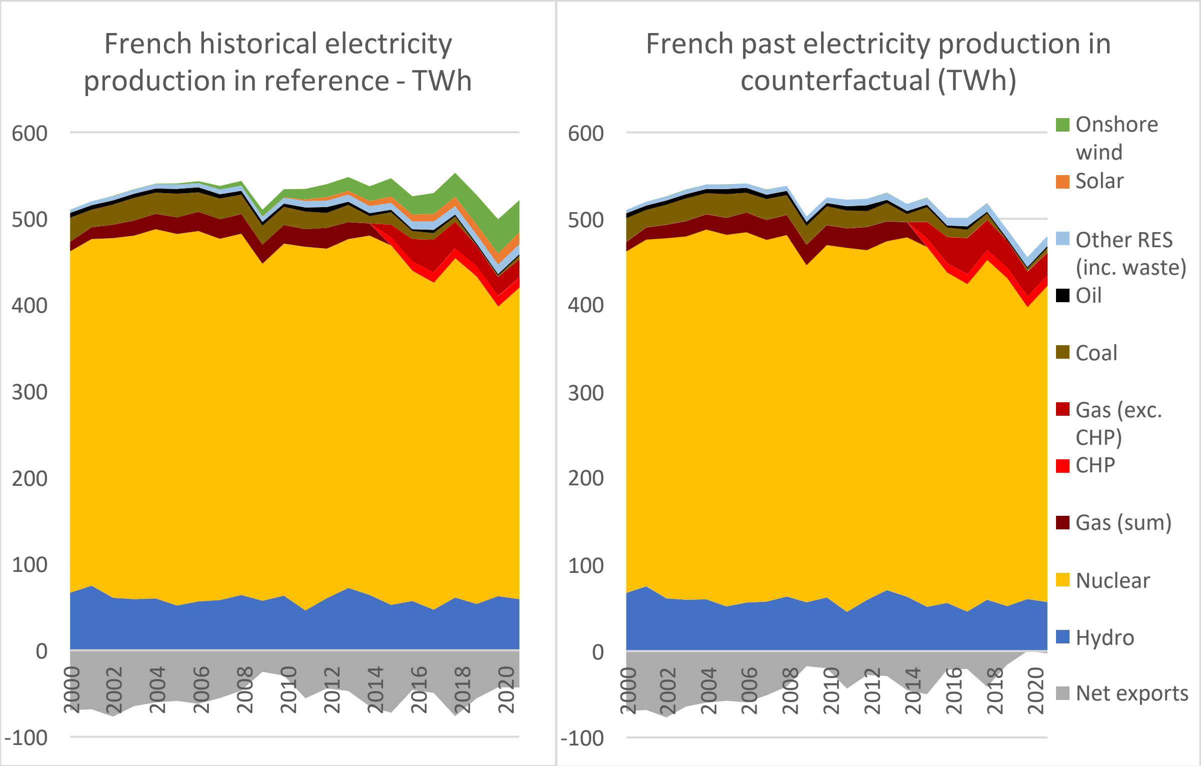

Figure 15: Electricity production in past scenarios (reference and counterfactual) for mainland France (TWh)

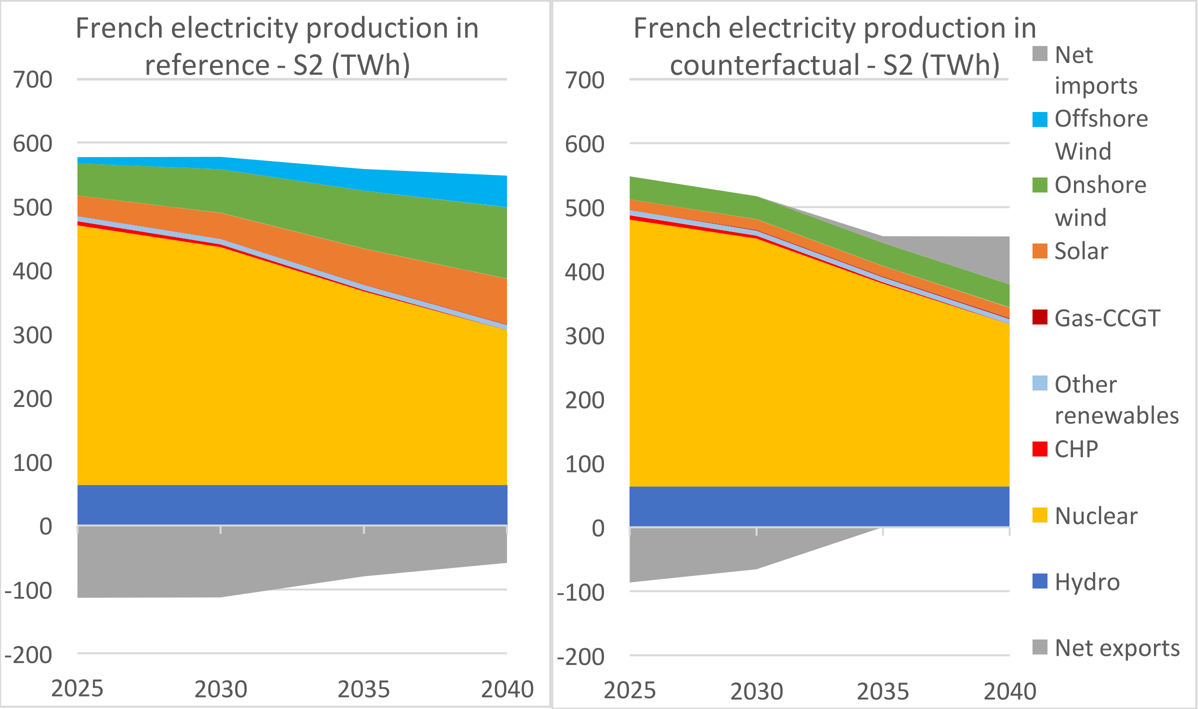

Figure 16: Electricity production in S2 prospective scenarios (reference and counterfactual, mainland France) (TWh)[33]

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[33] For imports and exports, the difference between both in a given year is presented ("net exports/imports"). For example, when the difference is negative, it means that there are more exports than imports.

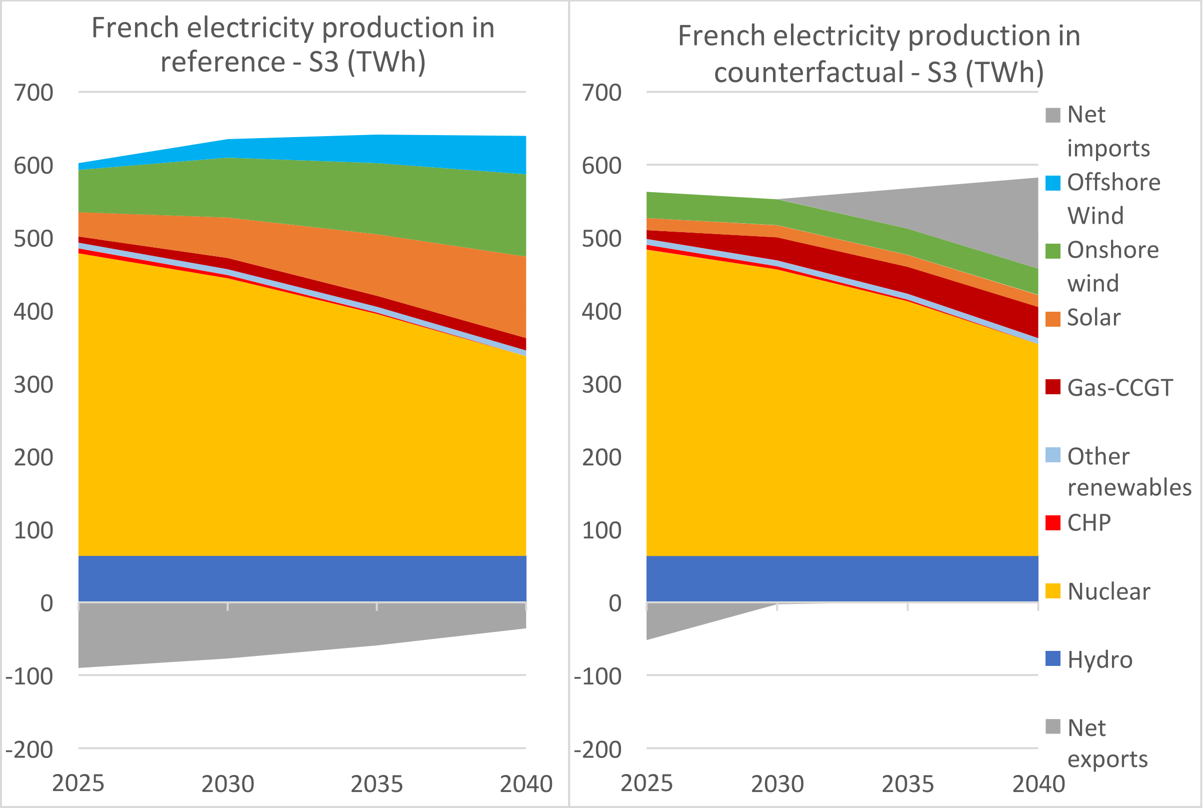

Figure 17: Electricity production in S3Nuc prospective scenarios (reference and counterfactual, mainland France) (TWh)[34]

4.2 Modelling methodology

4.2.1 Modelling methodology for mainland France

The European electricity system is modelled using the Artelys Crystal Super Grid software[35]. The software allows for a detailed simulation of the energy system.

The production mix is determined on an hourly basis by optimizing the generation plan in order to minimize generation costs, while maintaining the supply-demand balance. Many other constraints are taken into account in the modelling, including:

- Climate variability (renewable production and demand) through historical curves.
- The varying level of flexibility of the demand depending on the time horizon and electricity uses (non-flexible demand, electric vehicles, heating, industry, electrolysis, etc.).

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[34] See note 33 for the interpretation of net imports / exports.
[35] A short description of the tool and its functioning is available in Annex 7.2.

- Electrolysis (for the future) is partially controlled by a price signal[36].

In this study, neighbouring countries are modelled to take into account the impact of French renewable development in the generation plan of thermal plants in other European countries. Installed *capacities* in countries other than France are identical in both reference and counterfactual scenarios, but their *production* (generation plan) is optimized by the model and can change between counterfactual and reference scenarios. In this report, neighbouring countries are often aggregated and referred to as "EU". It should be noted that this does not reflect the exact perimeter of the European Union, and includes the United Kingdom and Switzerland which are interconnected with the French electricity network. Conversely, some European Union countries (the most distant) are not modelled, as the impact of the evolution of the French electricity mix plays only marginally on them.

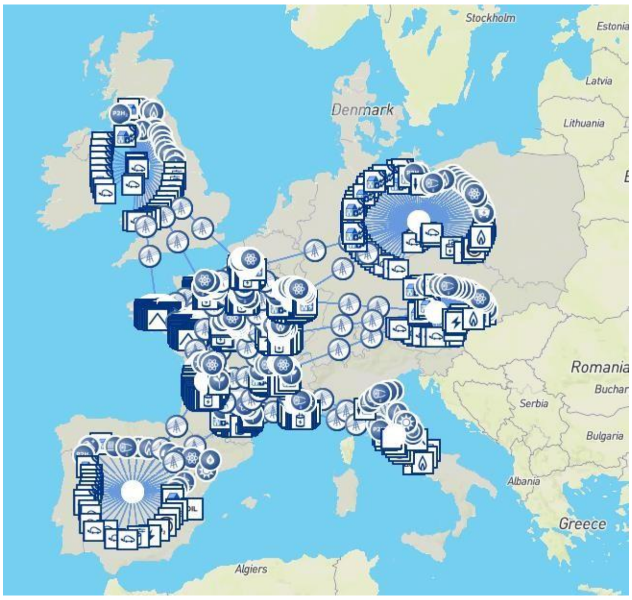

Figure 18: Representation of the European energy system in Artelys Crystal Super Grid (prospective scenarios)

The modeling of the electrical system provides relevant indicators for comparing systems with and without additional renewables, particularly on electricity production by technology.

It is important to note that the power generation in scenarios with and without additional renewables is optimized at an hourly level, with detail by technology and by country. In the counterfactual scenario, this representation allows to represent which generation plants will have to adapt their generation plan to cope with the lower renewable generation in France. For example, with less renewable the power system can adapt in various ways: higher thermal generation in France, higher import volumes and additional generation from neighboring countries, lower exports, lower hydrogengeneration by electrolysis (only in the future), etc.

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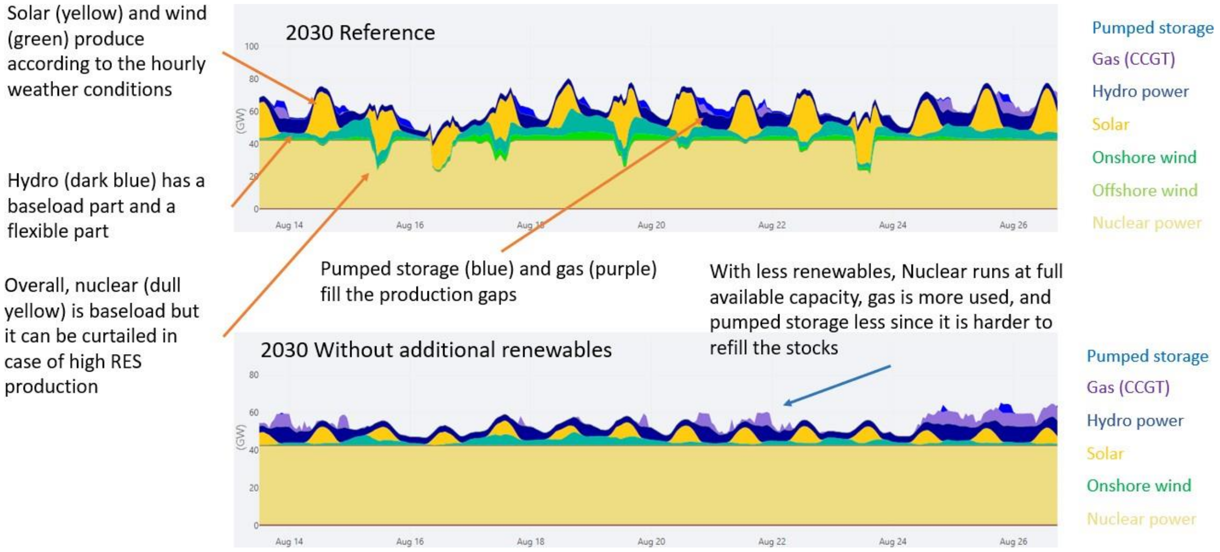
[36] Some of the electrolyzers operate only when electricity prices are sufficiently low. Other electrolyzers produce continuously as base load units, with an exception in winter, when they can also provide downward flexibility to the power system.



Solar (yellow) and wind (green) produce according to the hourly weather conditions

Hydro (dark blue) has a baseload part and a flexible part

Overall, nuclear (dull yellow) is baseload but it can be curtailed in case of high RES production

Pumped storage (blue) and gas (purple) fill the production gaps

With less renewables, Nuclear runs at full available capacity, gas is more used, and pumped storage less since it is harder to refill the stocks

Figure 19: Comparison of the cumulative production indicator (August 2030, S3Nuc)

By calculating the production differences between scenarios with and without additional renewables, it is possible to determine which production substitutions are made following the development of renewable energy, notably in terms of thermal production (nuclear and various fossil technologies), imports and exports, use of storage systems, and (in prospective scenarios) production of hydrogen by electrolysis.

Once production differences are obtained, it is possible to quantify several environmental impacts using emission factors from the literature. This work was carried out as part of this study to quantity avoided greenhouse gas and air pollutants emissions between the two scenarios.

The modeling specificities for the past and future are detailed in Annex 7.3.

4.2.2 Modelling for non-interconnected zones (NIZs)

General principles

The study of the impact of renewables in non-interconnected areas follows the same rationale as in metropolitan areas both for historical and prospective scenarios, comparing reference scenarios (historical production for 2000-2021, adequacy reports and PPE after 2021) with respect to counterfactual scenarios (production fixed at its level of 2000, and 2021 respectively).

The prospective study horizon depends on the reference document (see Annex 7.5.2). For the most populated NIZs (La Réunion, Corsica, Guadeloupe, Martinique, Guiana), the horizon of the adequacy reports is 2038; for Mayotte, Saint-Martin, and Saint-Barthélemy, the horizon of the adequacy reports is 2033. For the smallest NIZs (Saint-Pierre-et-Miquelon, Wallis-et-Futuna, and the Ponant islands), the reference documents are the PPE with a 2023 horizon. Since the renewable energy development targets in these PPEs have not been achieved to date, and these documents are the only references available, we consider that the targets constitute the reference system for the horizon of 2033 (in order to study the same horizon as the intermediate-sized NIZs).

Modeling issues and replacement assumptions

For the historical period, the past production was reconstructed based on various sources; the methodology is described in Annex 7.5.1. For the prospective period, the estimation of the composition of the electricity mix for each NIZ is based on adequacy report and PPE; the methodology is described in Annex 7.5.2. The two contrasted scenarios, Azur and Emeraude, from the system operator's (EDF-SEI) adequacy reports were retained.

Contrarily to the approach adopted for mainland France, a simplified rationale has been selected to model the replacement of renewable production in NIZs, based on *annual* volume replacements rather than a modelling at the hourly level. Indeed, fossil-fuel local power generation is often the only alternative in regions without (or with limited) interconnections with the mainland, which is the case for NIZs. The study thus assumes for both the past and the future that the energy replaced is fuel oil: each renewable quantity of electricity (MWh) produced is supposed to have allowed and will allow to avoid one MWh of fuel oil electricity production[37]. This assumption is justified in Annex 7.5.3.

It is important to bear in mind that this methodology is a simplification of the reality, especially in a future context of large renewable integration that can threaten grid stability. Some islands have currently a disconnection threshold for production facilities, when variable renewable energy production reaches about 35% to 45% of the total electricity production. Then, different assumptions related to demand flexibility (particularly through electric vehicle charging), energy demand management, installed battery capacities, and technologies providing reserve capacities (batteries, diesel groups, etc.) could influence the integration of renewable, and then their impact on the electricity mix. These issues are discussed in more detail in Annex 7.5.4.

4.3 Results of the modelling of renewables impact on electricity production

4.3.1 Modelling of production changes in mainland France

The operation of the European power system is simulated for the past (2015-2019) and future (2025, 2030, 2035, 2040) periods, under scenarios with and without additional renewables (compared to installed capacities in 2000 and 2021 respectively). To cover the entire period (2000-2050), production changes are interpolated for the years not explicitly modelled. For the period 2000-2014, the effect of

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[37] Except for Réunion and Guadeloupe, during the prospective period, as explained in Annex 7.5.3.

renewables production in France on the interconnected European power system is considered to be the average of the period 2015-2019 (renormalized by historical renewable production).

From the simulations, the production gaps between the reference and counterfactual scenarios, corresponding to the impact of additional renewables on the operation of the power system, are derived. The avoided fossil fuel production (gas, coal, oil), modulated nuclear production, additional electrolysis generation for the future (low-carbon hydrogen), and additional losses incurred (curtailment and losses in pumped hydro storage and battery cycles, grouped under "others*") due to the additional renewables can thus be quantified. The analysis separates production differences (in the two compared scenarios) in France and in neighbouring interconnected countries (which are aggregated under the acronym "EU" in the graphics).

The graphs below show the impact of additional renewables in terms of energy production (historical period, S2 and S3 scenarios). Given that the impact of renewable development is studied relatively to fixed years (2000 and 2021), a "volume effect" is observed on the changes in production, corresponding to the additional volumes of produced renewable energy. Other graphics providing different visualizations of changes in production by sector are available in Annex 7.4.1.

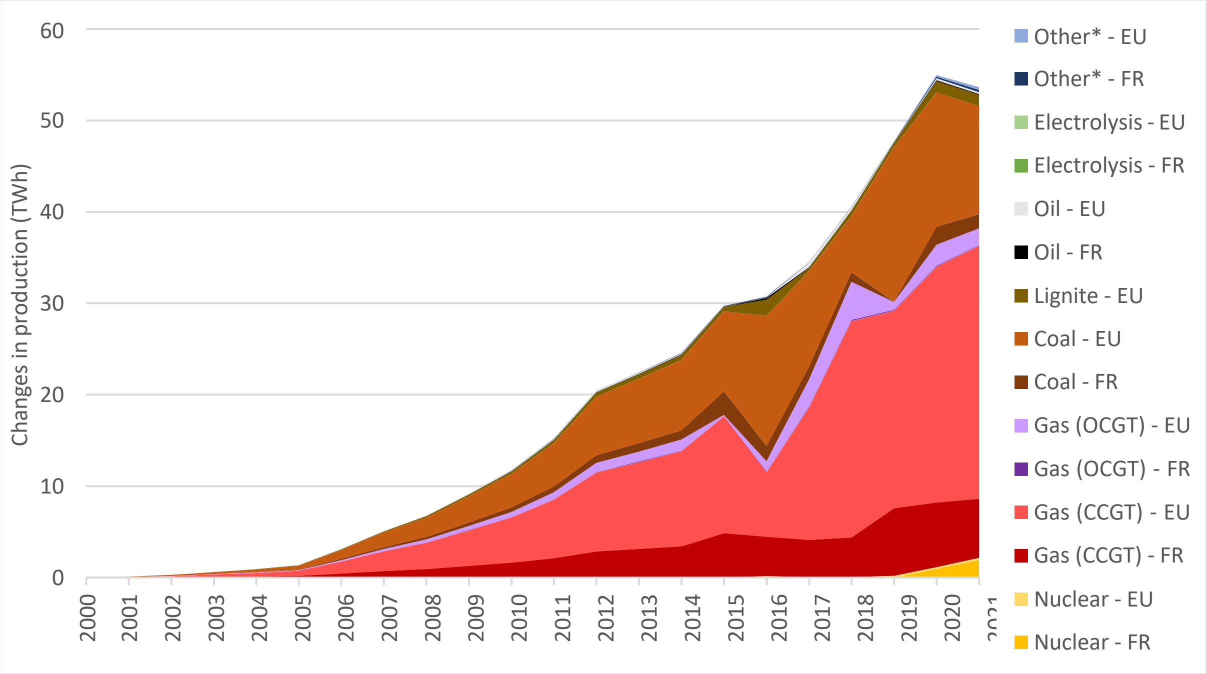

Figure 20: Electricity production replaced by additional renewables for the historical period (TWh)

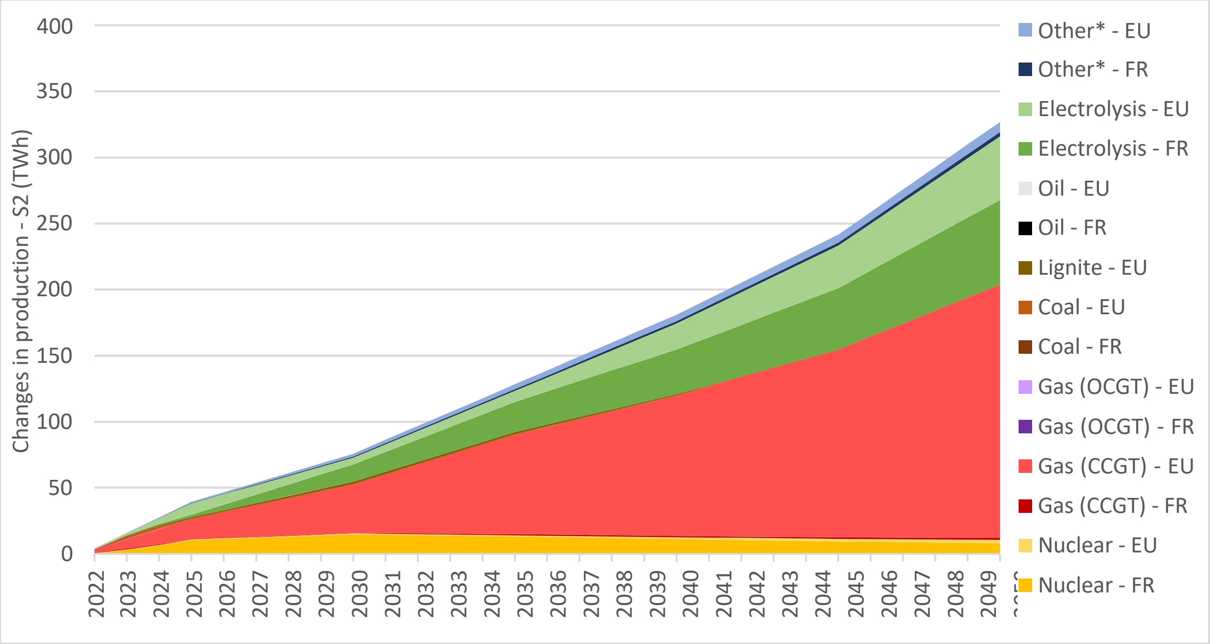

Figure 21: Thermal electricity production replaced and additional electrolysis allowed by additional renewables in the prospective period, scenario S2 (TWh)

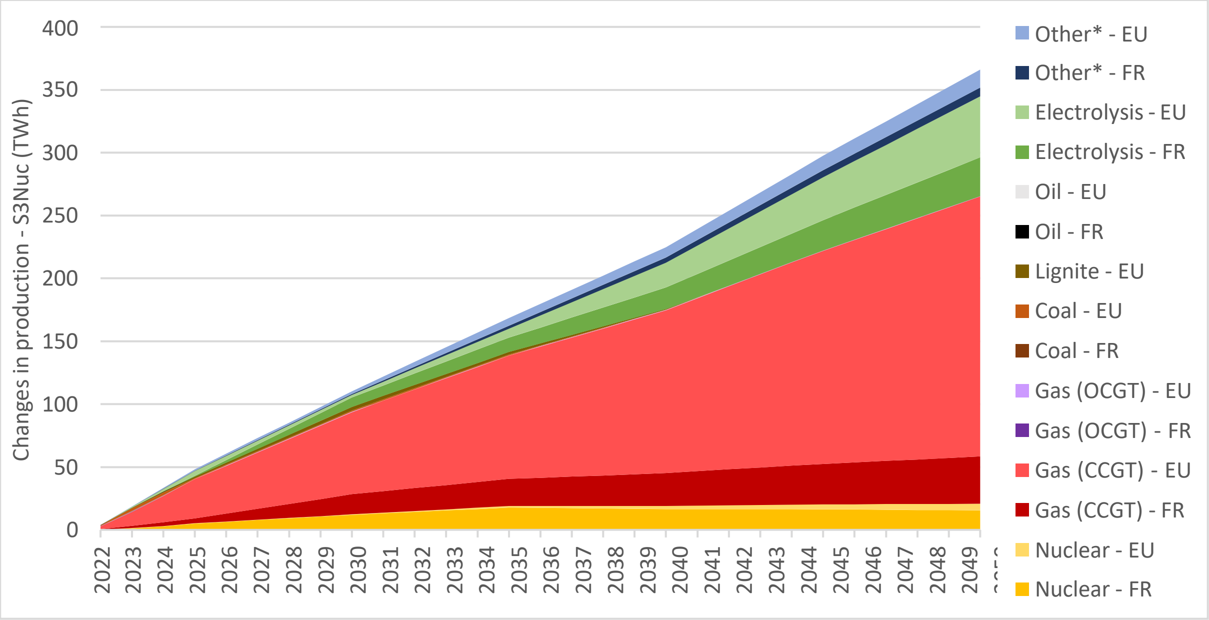

Figure 22: Thermal electricity production replaced and additional electrolysis allowed by additional renewables in the prospective period, scenario S3Nuc (TWh)

The "volume" graphs make it possible to represent the overall impact of renewables on total production. It is also interesting to look at the evolution of the distribution of the changes in production by means of production, by representing these graphs in percentage (see below Figures 21 and 22) to visualize what an additional MWh of renewable energy replaces (in proportion), on average over the year, for a given year.

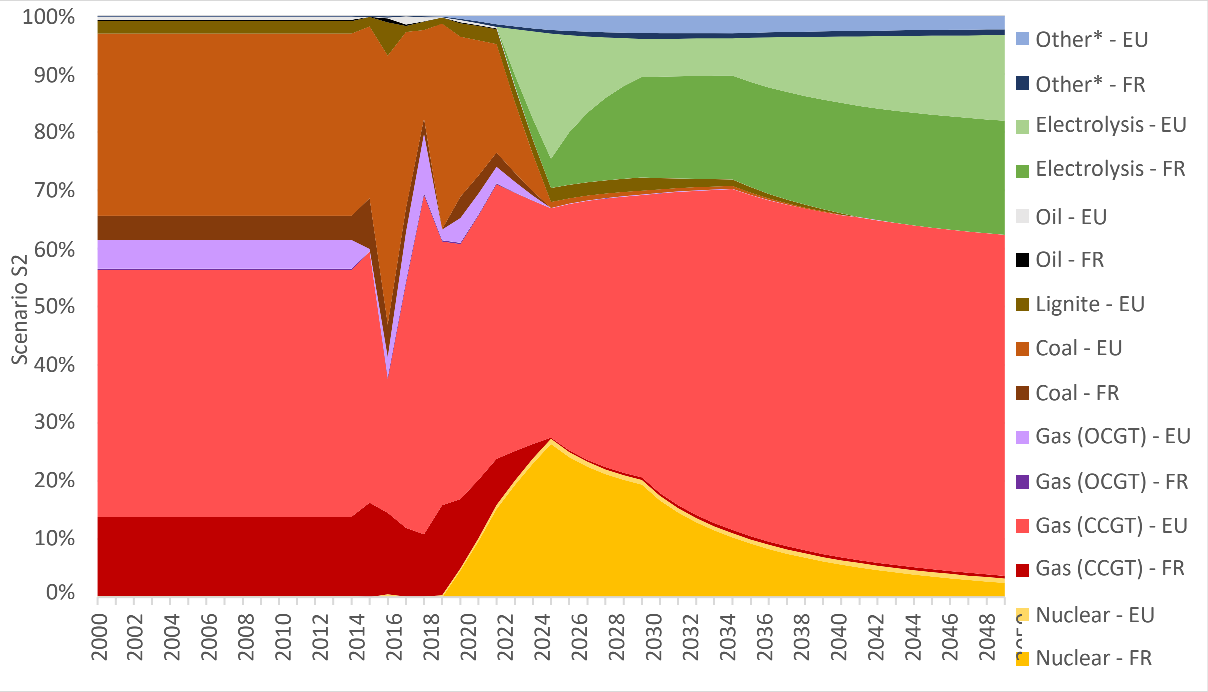

Figure 23: Production changes in proportion of replaced electricity, scenario S2

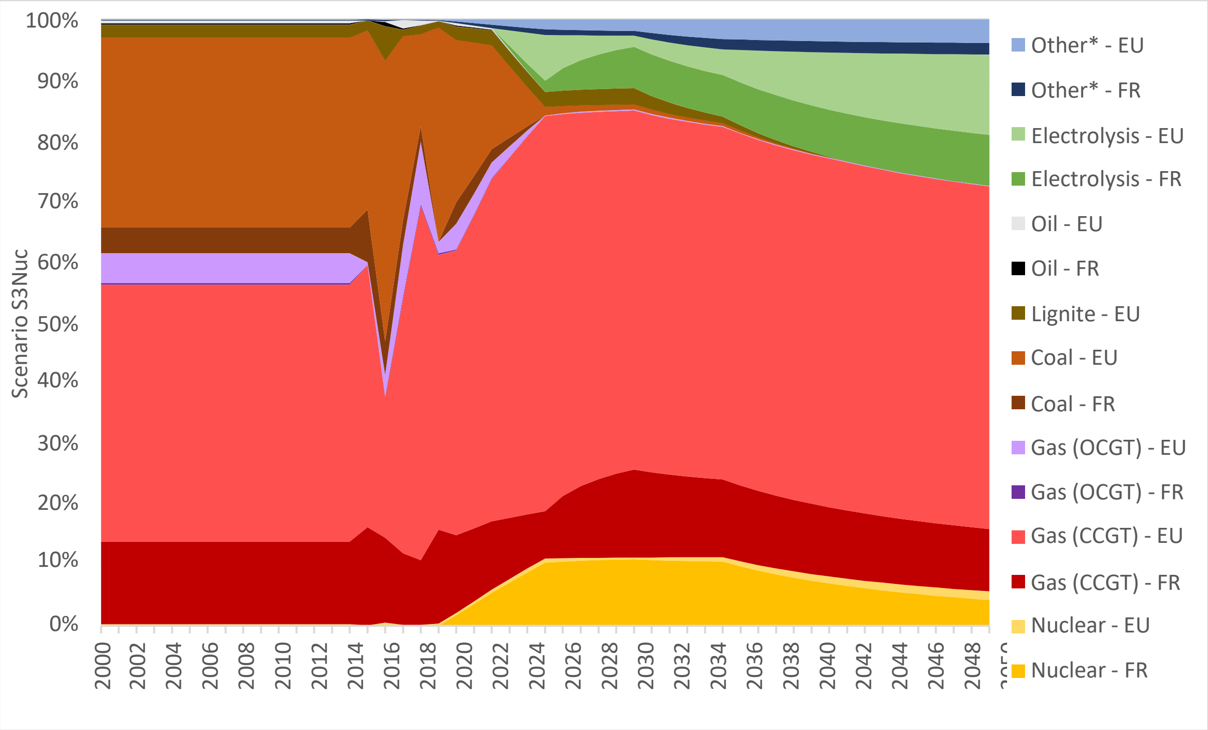

Figure 24: Production changes in proportion of replaced electricity, scenario S3Nuc

Briefly said, additional renewables primarily replace fossil fuels (both in France and abroad), then allow for more hydrogen production (in France and abroad), and finally, if electricity cannot be exported, replace nuclear power production.

4.3.1.1 Analysis on the historical period

Over the historical period, additional renewables replaced mainly thermal production[38], with the majority of the production (between 75% and 86%) replaced originating from neighbouring countries. Approximately 60% of the replaced production corresponded to gas (including approximately 14% in France) and 40% to coal (including approximately 4% in France).

The years from 2015 to 2019 (explicitly modelled from historical data) present significant inter-annual variability, which can be attributed to the variability of market prices. This variability affects the *marginal production* (and therefore the production replaced by additional renewables), which is mostly composed of gas or coal. Market prices depend mainly on consumption, and thus on climatic conditions (more or less heating needs).

Due to the unavailability of data for modelling, this study considers that the impact of renewables over the 2000-2014 period corresponds to the 2015-2019 average: this represents a significant approximation for a given year, but the results for the trajectory as a whole are likely to give a reasonable view of what happened in the past. Indeed, renewable production volumes for the 2000-2014 period represent less than 30% of the total renewable production from 2000 to 2021.

4.3.1.2 Analysis on the prospective period

For the prospective period, there is a clear difference between S2 and S3Nuc scenarios (which were chosen on purpose as contrasted scenarios).

Electricity production from fossil energy (excluding cogeneration) in France amounts to less than 1 TWh in 2025 in S2 scenario, compared to about 15 TWh in S3Nuc scenario (which can be explained by the higher domestic consumption in S3Nuc compared to S2: the difference amounts to around 45 TWh in 2025 and 110 TWh in 2040). This explains why in scenario S3Nuc, 1 MWh of additional renewable energy replaces on average 0.1 MWh of gas production in France, compared to nearly 0 in scenario S2.

In neighbouring countries, the electricity production from fossil fuels that is replaced by renewables will become predominantly gas-based in the future, rather than a mix of gas and coal. This can be explained mainly by the fact that gas is occupying a growing share of thermal production in the European mix, replacing coal capacities in most of European countries, in the prospective scenarios which are used for this study. The scenarios used to represent the energy mix of the different countries were created before the energy crisis that started in 2021 and whose effects are already mentioned in section 2.2. As a result of this crisis, it is likely that the importance of gas in the electricity system will be lower in the future than that considered in this study, which could affect the results obtained here in the short term. However, the development of biogas and synthetic methane should reduce the importance of natural gas in the gas mix in the 2040-2050 period.

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[38] By modeling assumption, the annual nuclear production is not modified by renewables. This is justified in Annex 7.3.2.3, and is in line with other studies (notably RTE's 2019 adequacy report).

Renewables also replace (but in a much lower extent than fossil fuels) nuclear production, mainly in France. Replacing nuclear energy production accounts for about 5 to 10% of production changes in scenario S3Nuc. In scenario S2, nuclear accounts for a higher share of the replaced production at the beginning, peaking at 26% in 2025, and then decreases more rapidly than in S3Nuc down to 2% in 2050. This can be explained by the fact that the installed nuclear capacity in 2025 and 2030 is identical in both scenarios, while domestic consumption is much lower in S2, and that nuclear capacity decreases more rapidly in S2 than in S3Nuc afterwards (there is no new nuclear in S2). Figure 19 illustrates nuclear power curtailment (in an hourly basis) when renewable production is significant compared to demand.

Electricity used for hydrogen production by water electrolysis plays a larger role in scenario S2 than in scenario S3Nuc. Specifically, in 2050, electrolysis accounts for 27% of electricity consumption in France in scenario S2, compared to 11% in S3Nuc. This partly explains why the additional hydrogen production by electrolysis (and the associated needed electricity) in France is proportionally more significant in S2 than in S3Nuc. Concerning the additional hydrogen production in Europe, the two scenarios are very similar at the end of the period, but at the beginning of the period this additional production is proportionally more important in S2 than in S3Nuc. This can be explained by the fact that with lower consumption in France and relatively similar installed low-carbon production capacities in 2025, more electricity can be exported and used for hydrogen production by water electrolysis in neighbouring countries (since there are relatively few electrolysis capacities in France at this horizon to consume electricity surplus).

The "others" category in Figures 21 and 22 above includes curtailment and losses related to storage efficiency (batteries and pumped hydro storage – PHS). Differences between scenarios are due to the fact that the higher the variable renewable production (solar, wind), the more storage means are used, and therefore the higher the losses associated with a storage cycle. Up to 6% of additional renewable production is thus lost (the maximum is reached at the end of the period in scenario S3Nuc).

4.3.2 Modelling of production changes in NIZs

4.3.2.1 Production changes on the historical period in NIZs

For the NIZs, as explained earlier and detailed in annex 7.5.3, it is assumed that every MWh of renewable energy produced replaces one MWh of oil-fired electricity. The avoided oil-fired electricity production is therefore equal to the subsidized renewable production in each NIZ. This production was reconstructed from the annual reports of the CRE (the French Energy Regulatory Commission) and is shown in Figure 25 (see annex 7.5.1).

Until the early 2010s, it was mainly historical hydraulic installations in Reunion, French Guiana, and Corsica that avoided electricity production from oil. Other productions were also developed over the period, mainly in Guadeloupe, Corsica, Martinique, French Guiana, and Reunion. These include solar photovoltaic, wind, geothermal, and biomass-based production, as presented in Figure 26. The details of electricity production by NIZ are given in Annex 7.1, and almost all renewable productions are subsidized in the NIZs (with the notable exception of power plants combining coal and bagasse).

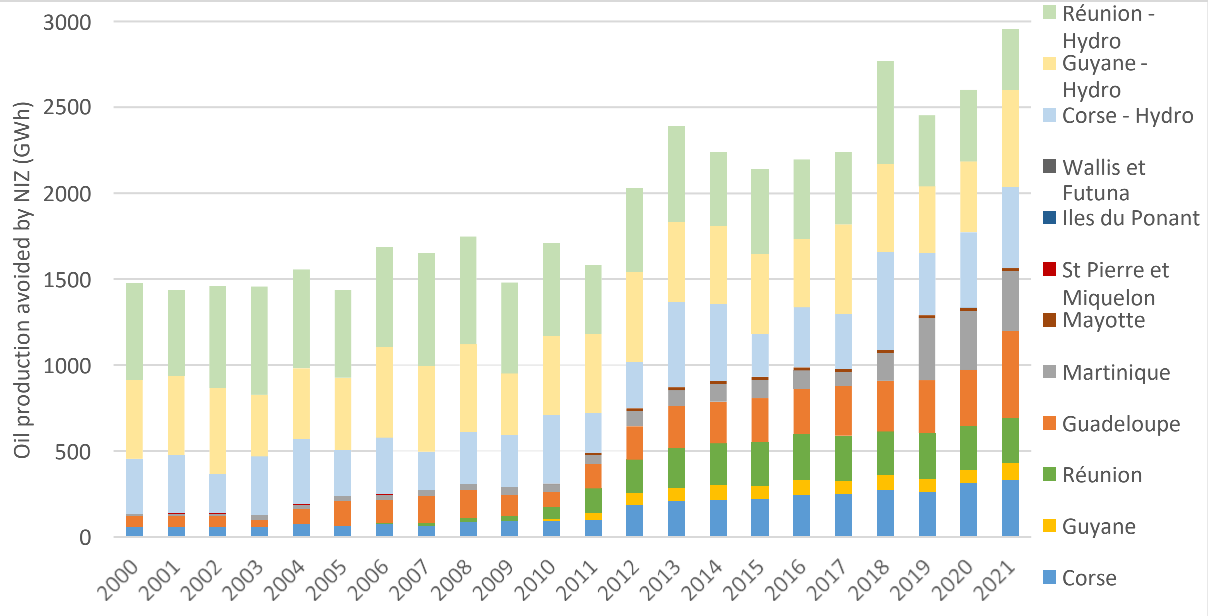

Figure 25: Avoided oil-fired production in each NIZ, historical period (GWh)

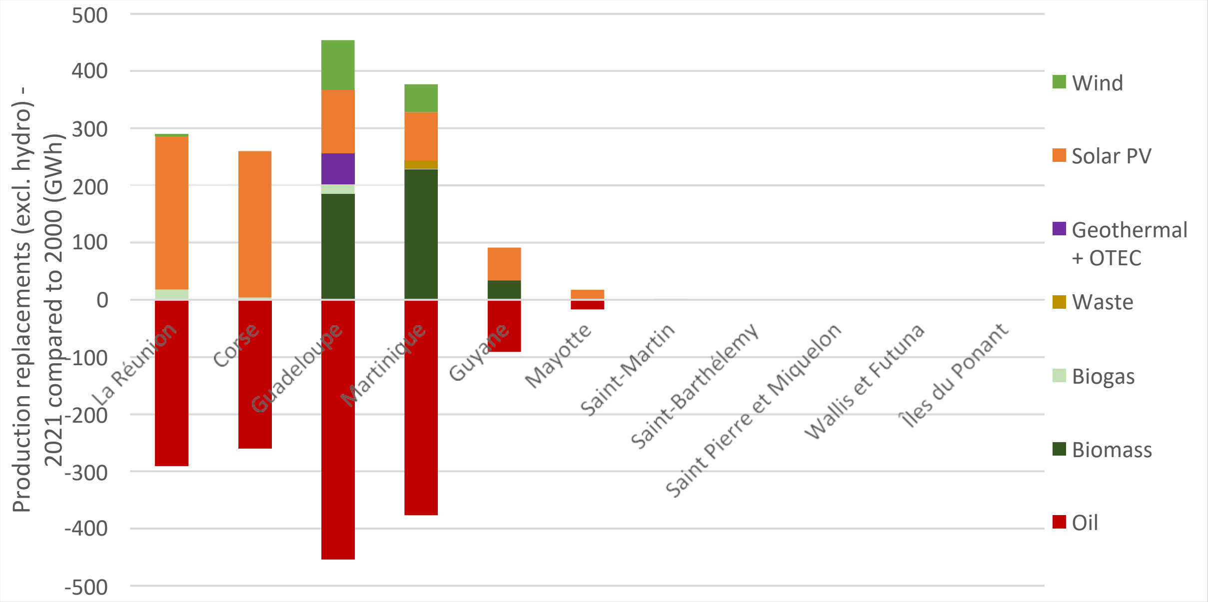

Figure 26: Changes in production due to additional renewables in 2021 compared to 2000 (excluding hydroelectricity and non-subsidized bagasse) – *OTEC stands for Ocean Thermal Energy Conversion*

4.3.2.2 Production changes on the historical period in NIZs

For the prospective period (horizons 2038, 2033 and PPE of the Azur and Emeraude scenarios), we also assume that every additional MWh of renewable production (compared to 2021) replaces one MWh of fossil production[39].

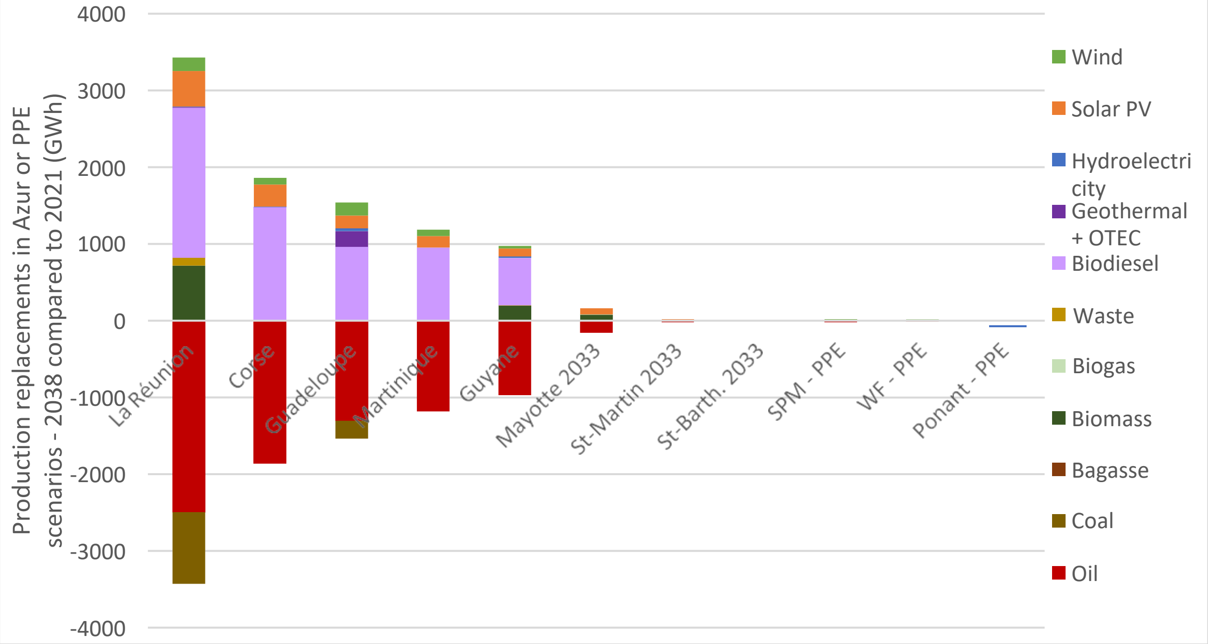

Figure 27: Changes in production due to additional renewables compared to 2021, Azur and PPE prospective scenarios.

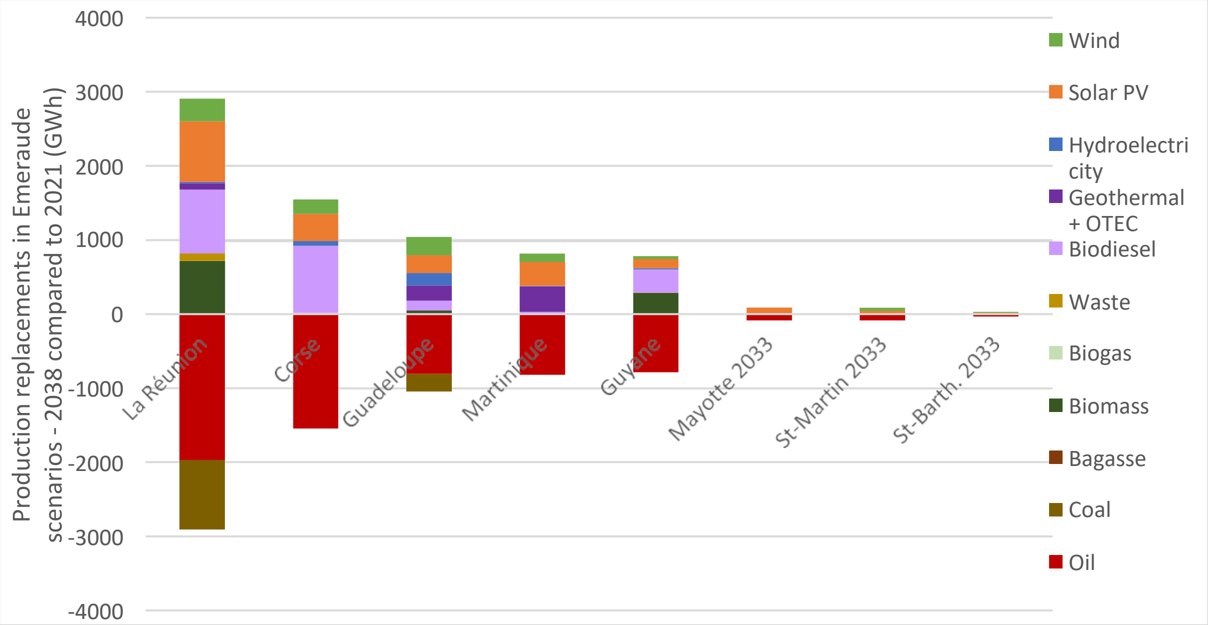

Figure 28: Changes in production due to additional renewables compared to 2021, Emeraude prospective scenarios.

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[39] The assumptions are detailed in Annex 7.5.3. Replaced coal is equal to 2021 production.

The Azur and Emeraude scenarios differ notably in their energy demand management (lower consumption in Emeraude) and level of renewable production (higher in Emeraude). By design, the scenarios assume a phase-out of fossil fuels in the five main non-interconnected zones, with the use of biodiesel to meet demand. As a result, the changes in production assured by the additional renewables rely more heavily on biodiesel in the Azur scenarios than in the Emeraude scenarios.

5 Climate change mitigation

The primary objective of developing renewable energies is to reduce greenhouse gases (GHG) emissions, by decarbonizing energy production (electricity and hydrogen in particular), and also by allowing a switch from fossil fuel to electricity for various end-uses (heating, electric vehicles, electrification in industry, etc.). The overall contribution of renewable energies to the decarbonization of the French economy is discussed in section 3.3.

While the metropolitan power system is already largely decarbonized thanks to historical nuclear and hydraulic production capacities, the development of renewables allows for further decarbonization of the French mix as well as that of neighbouring countries. Non-interconnected zones (NIZs) still have a largely carbon-intensive mix, and development of renewable have a direct impact on fossil-fuel power generation.

The objective of this section is to estimate the GHG emissions reductions allowed by the development of renewable in mainland France and in NIZs, based on the production replacement described in the previous section, and using reference GHG emission factors.

5.1 Emission factors used

In order to assess greenhouse gas emissions from electricity production, life cycle assessment (LCA) factors for GHG emissions are used. LCA enables the comprehensive consideration of both direct and indirect emissions throughout the entire life cycle of the production process, including raw material extraction, manufacturing, transformation, transportation, construction, decommissioning, waste management, and combustion.

Where available, we used the GHG emission factors used by RTE in the *Energy Pathways to 2050* study, which are derived from a modelling effort adapted to the French context. The factors from the RTE study also incorporate a prospective vision, up to 2050. These factors provide emissions reported per unit of energy produced, in grams of CO2 equivalent per kWh of electricity produced. The emission factors provided are interpolated between 2020 and 2050 in this study.

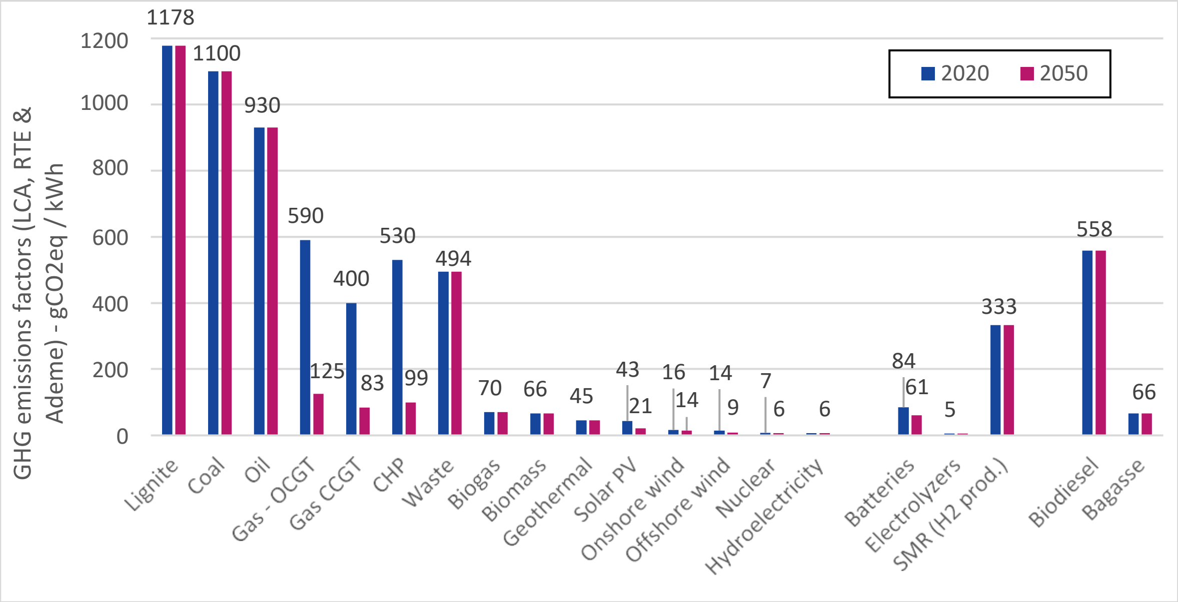

Figure 29 : Greenhouse gas emission factors in life cycle analysis for the power system (gCO2e/kWh)

The **details of the sources used and additional analysis on the factors are available in Annex 7.6.1**. We draw particular attention to the following points:

- Prospective emissions from gas-fired power plants take into account the transition to 100% biomethane in the networks by 2050.
- To account for emissions avoided through hydrogen production enabled by renewables (water electrolysis), we assume that the alternative means of production would have been steam methane reforming (SMR). The hydrogen produced "in addition" in the reference scenario compared to the counterfactual thus counts, by assumption, as avoiding emissions equivalent to those associated with steam methane reforming.
- Emission factors for biodiesel greatly vary among sources, since they rely mainly on assumptions regarding changes in land use for its production in LCA. The factor used in this study takes a medium hypothesis regarding land use impact, and more information regarding this assumption can be found in annex 7.6.2.

5.2 GHG emissions from electricity production in life cycle analysis

To give an idea of the magnitude of emissions avoided by subsidized renewables in France, we provide below the total greenhouse gas emissions (in life cycle analysis) from the mix of electricity production in mainland France and the NIZs. For comparison with neighboring countries, electricity production in 2019 emitted: 222 MtCO2eq in Germany, 81 MtCO2eq in Italy, 59 MtCO2eq in Spain, and 57 MtCO2eq in the United Kingdom, compared to 20 MtCO2eq in France[40]. The carbon intensities of the French electricity mix is also available in Appendix 7.6.3.

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[40] Source: *Energy Pathways to 2050*, RTE. The scope includes only direct emissions (not in LCA) in France.

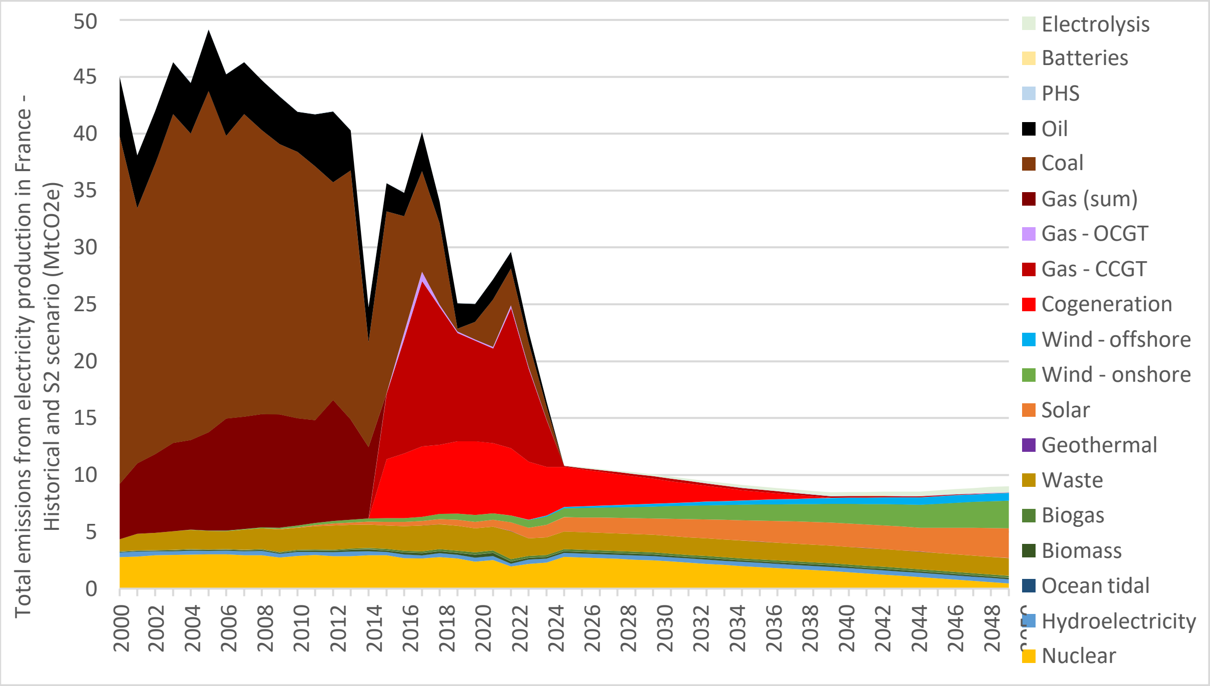

Figure 30: GHG emissions related to electricity production in mainland France, historical and scenario S2 (MtCO2e)

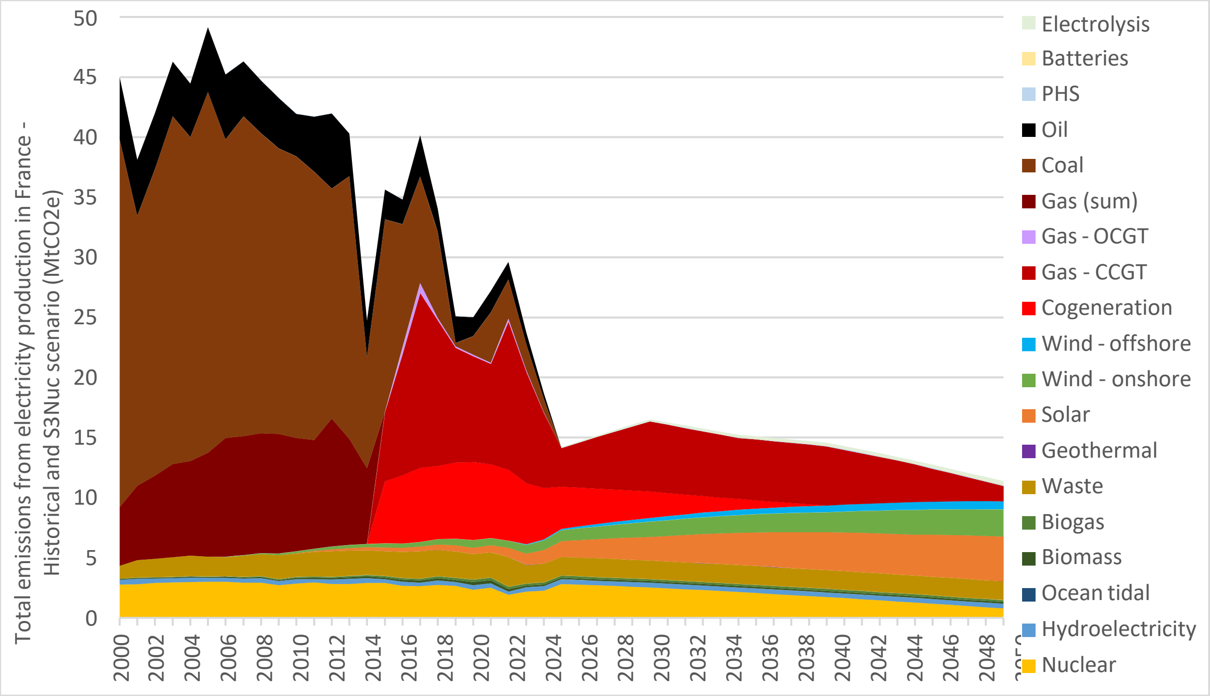

Figure 31: GHG emissions related to electricity production in mainland France, historical and scenario S3Nuc (MtCO2e)

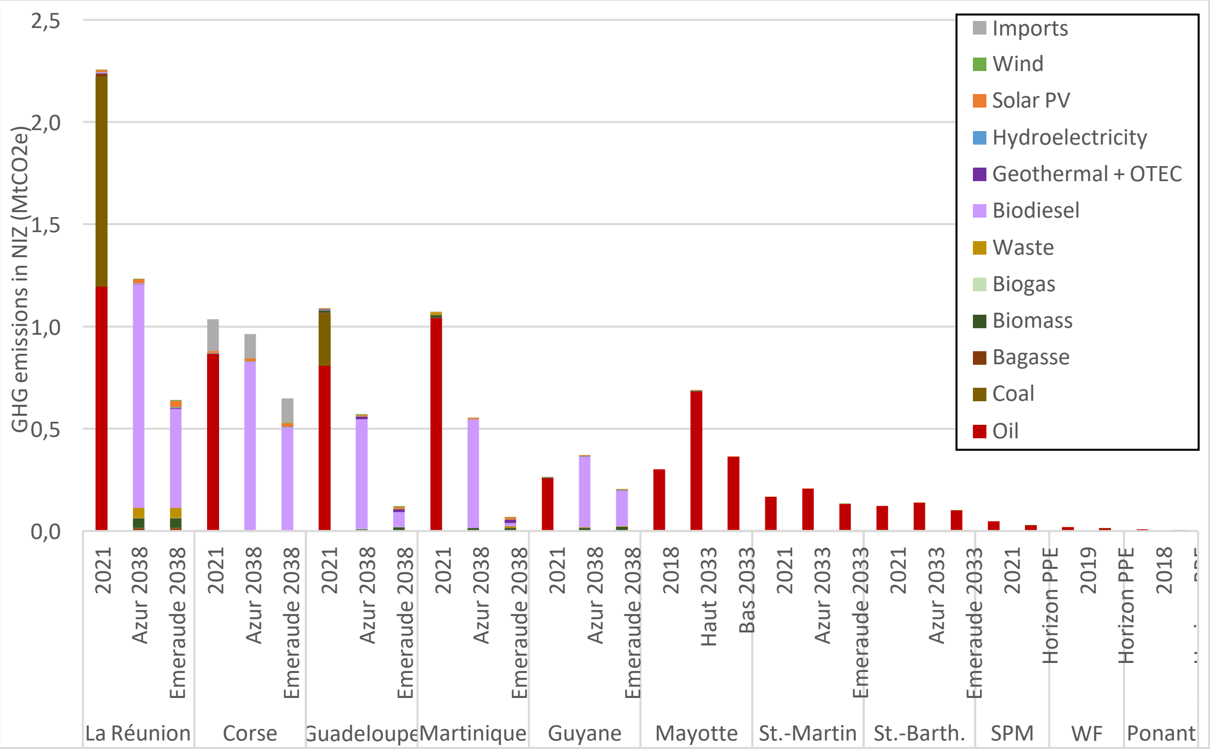

Figure 32: GHG emissions related to electricity production in the NIZs, in 2021 and projected in the future (MtCO2e)

5.3 Quantification of GHG emissions gains

Results presented in this section are the average impacts between S2 and S3Nuc scenarios. Results per scenario are available in Appendix 7.4.2.

5.3.1 Mainland France

5.3.1.1 Annualization principle

One of the main objectives of this study is to quantify the impact on European greenhouse gas (GHG) emissions of electric renewable energies which are subsidized in France . Since French subsidies for renewable energies are associated with contracts that mostly last for 20 years, renewable capacities producing in 2021 were also largely subsidized in the past. Most of them will also continue to produce electricity and remain subsidized in the future.

There is therefore a methodological issue regarding how to take into account the impact of subsidized renewable energies over their entire lifespan. The choice made hereby is to *annualize* the impacts for mainland France: the impact of installed capacity is evaluated over its entire lifespan (by summing the annual impacts of avoided and additional productions) and is equally distributed over the duration of subsidies (20 years). The methodology is described in Annex 7.8.

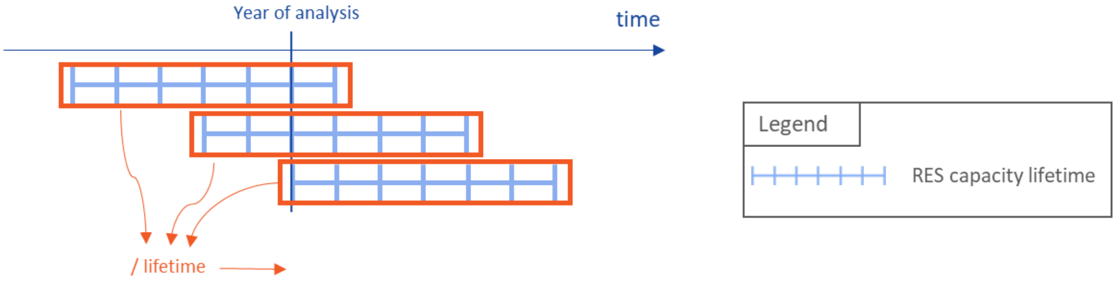

Figure 33: Annualization principle for the impact of subsidized renewables

5.3.1.2 Avoided emissions in mainland France

In section 4.3.1 we calculated the reduction of fossil and thermal productions as well as the increase of hydrogen production. By applying the emission factors presented in section 5.1 to these results, we calculate the emissions avoided by these additional renewables (Figure 34). Three types of emissions are considered:

- The reduced emissions associated with additional renewable electricity production, which would have been produced by thermal means otherwise (mostly fossil-fired).
- The reduced emissions associated with additional hydrogen production (by water electrolysis with renewable electricity), which would have been produced through steam methane reforming otherwise.
- The additional emissions associated with renewables, electrolysis, and storage means (in LCA).

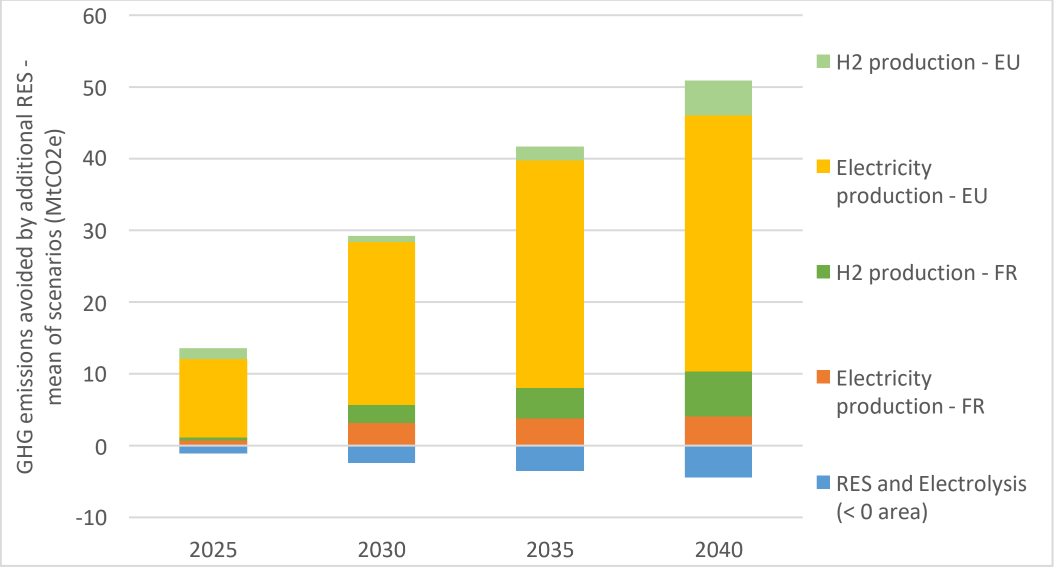

Figure 34: Emissions avoided by additional renewables compared to 2021 (average of prospective scenarios), in MtCO2eq

Avoided emissions can be expressed per MWh of additional renewable generation, including non-subsidized generation. The details of the avoided emissions per sector are given in Figure 35 below.

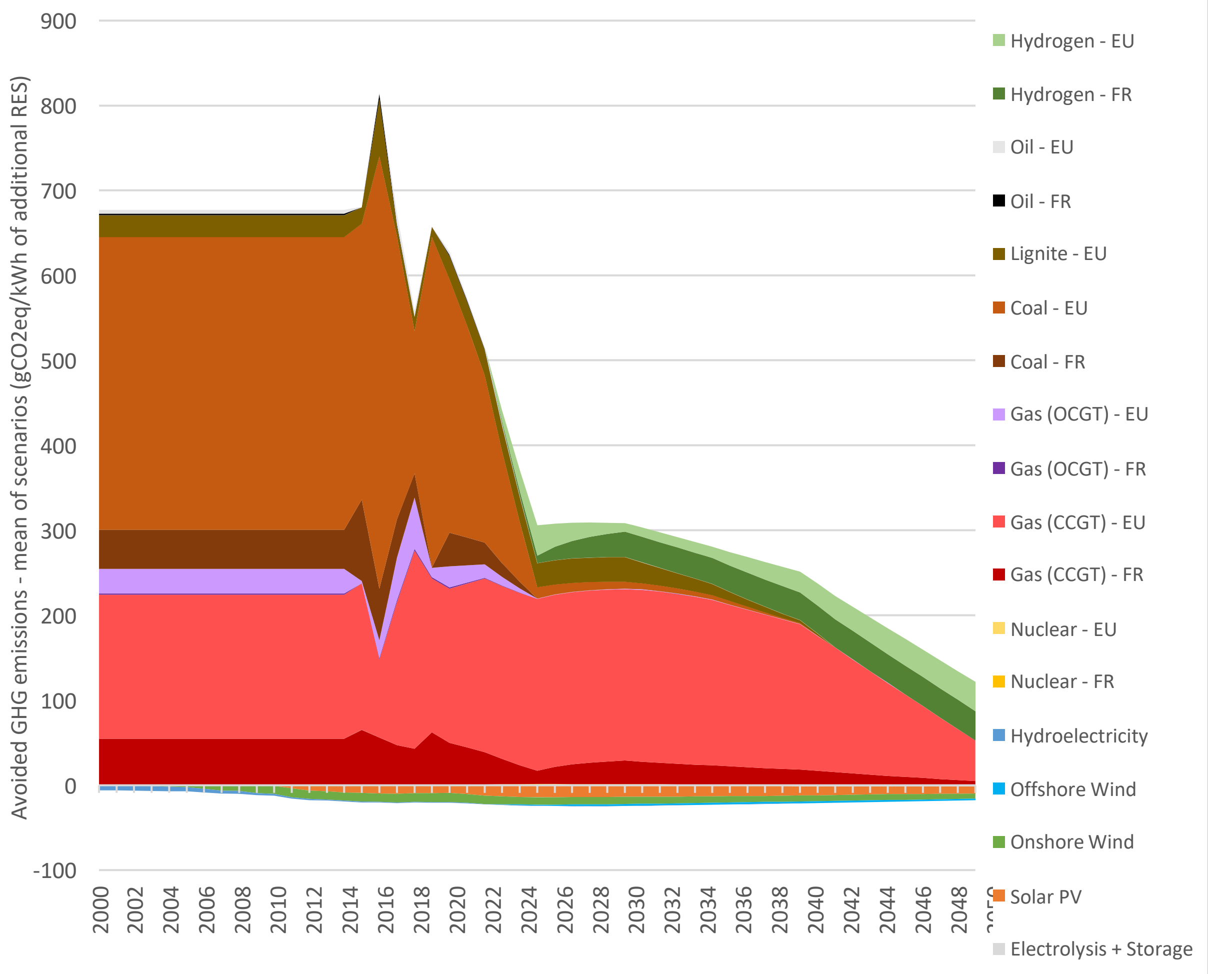

Figure 35: Avoided emissions (average between scenarios), in gCO2eq/kWh of additional renewables

Results are quite similar to those on production replacements, as they only reflect a distortion by emission factors. Coal occupies a more significant share for the historical period (as it is more emitting than gas). The share of gas in emissions strongly decreases between 2040 and 2050, notably due to the sharp increase in the share of biomethane in the gas mix (while the alternative to water electrolysis - steam reforming - is assumed to still use fossil gas). For comparison, the carbon intensity of the reference mix (Figure 81, in Annex 7.6.3) is globally decreasing with a maximum of 90gCO2e/kWh for the historical period, and about 20 gCO2e/kWh for the prospective period.

Then, the annualization methodology is applied to calculate the average carbon impact of subsidized renewable productions. Results are given in Figure 36 below.

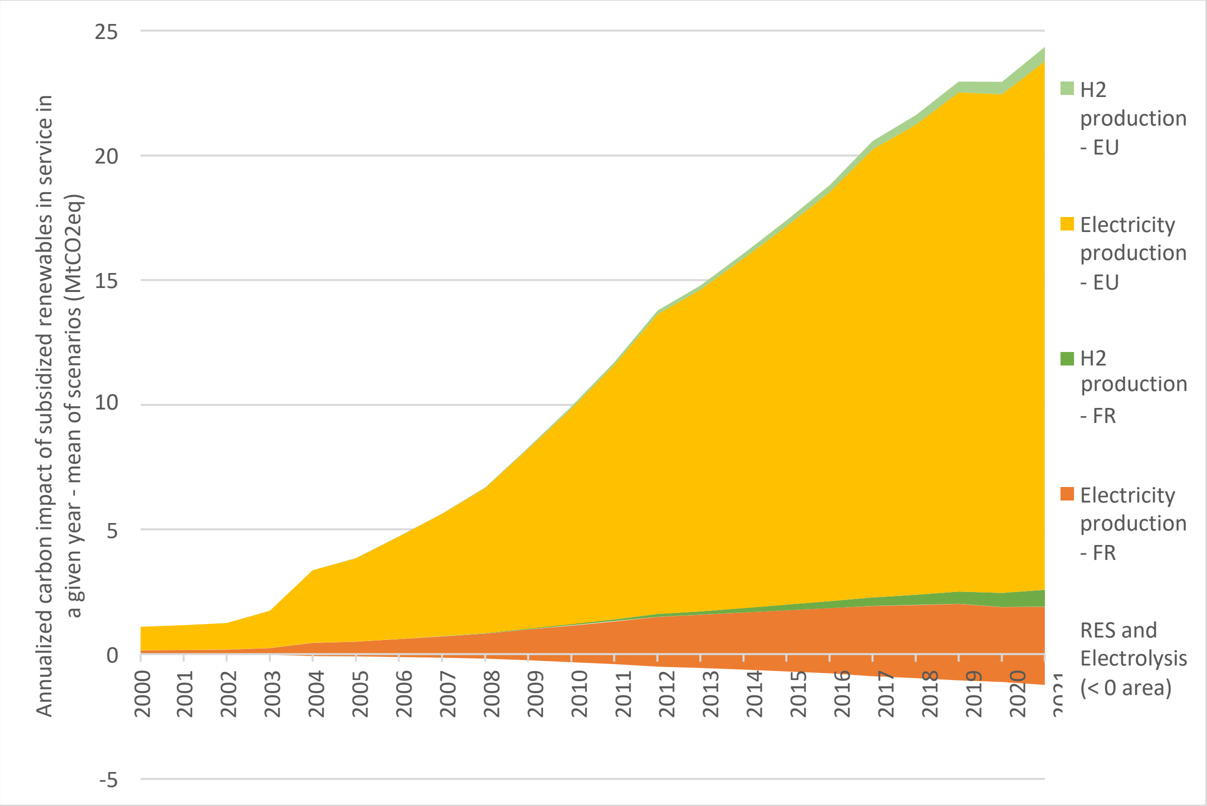

Figure 36: Annualized carbon impact of subsidized renewable capacities in service in the given year, in MtCO2eq

We therefore obtain the average carbon impact of subsidies, taking into account the evolution of the electricity mix over the entire duration of the subsidy for the production means. This impact is calculated using a life cycle analysis and is based on a detailed model of the operation of the European electricity system.

For example, the annualized avoided emissions associated with renewables which were subsidized in 2021 are 24 MtCO2eq, approximately the total emissions of electricity production in France. Around 85% of the emissions avoided by renewable subsidies in France are in neighboring countries[41].

If the avoided emissions related to hydrogen production may seem surprising in Figure 36, given that there is currently no significant electrolysis-based hydrogen production in France, this can be explained by the annualization methodology. Indeed, the renewables installed in 2021 will allow hydrogen production in the future, and since the average impact over the duration of the subsidy is considered, this hydrogen-related impact is already taken into account in 2021.

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[41] These results are consistent with RTE's work performed in the 2019 Generation Adequacy Report, which estimated the emissions avoided by wind and solar generation in France at 22 MtCO2 in 2019, including 17 MtCO2 abroad (77%). It is important to note that the modeling scope is different between the two studies, notably due to the annualization of the impact of renewables.

5.3.2 Non interconnected zones (NIZs)

For each NIZ, the emissions avoided historically and at the prospective horizon (2038, 2033) by the renewable productions are calculated. The avoided emissions are interpolated for the intermediate years. The calculation of the avoided emissions is based on a life cycle analysis of the impact of subsidized renewables, some of which have a relatively high carbon content (waste and biodiesel in particular). The avoided emissions are then divided by the quantity of additional renewable generation. The results are presented in Figure 37.

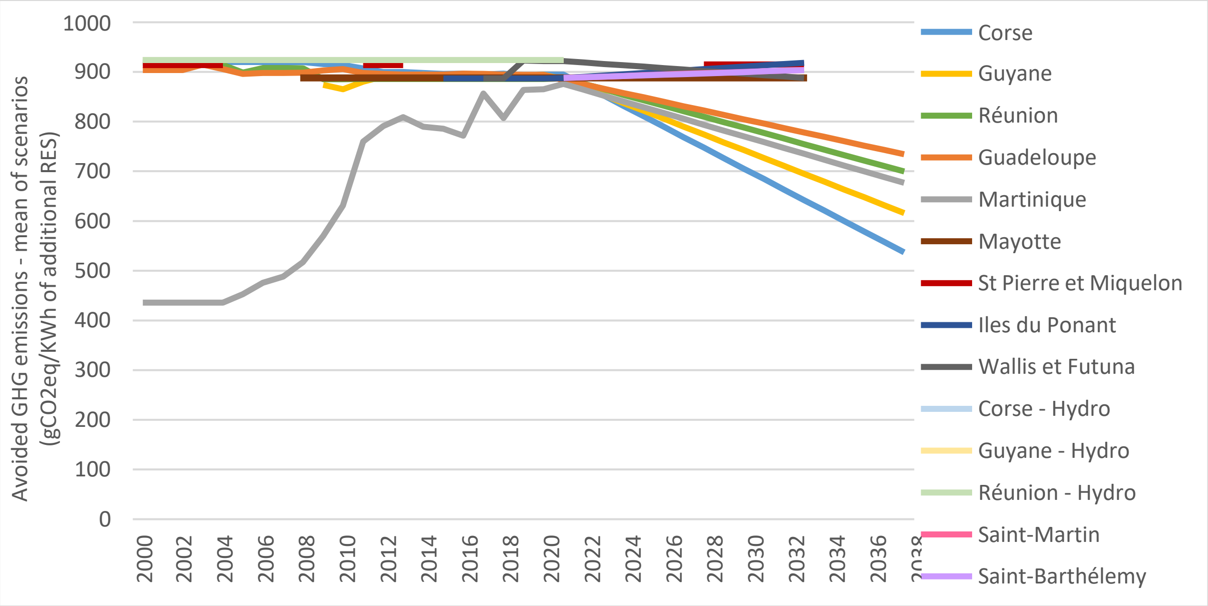

Figure 37: Avoided GHG emissions per kWh of additional renewable production in NIZs, in life cycle assessment (in gCO2eq/kWh)[42]

During the historical period, the carbon impact (in terms of avoided emissions) of renewables is around 900 gCO2eq/kWh, which corresponds to the carbon intensity of oil-based electricity production, reduced by the impact of renewables in life cycle analysis. Only Martinique, with a significant proportion of subsidized production from waste, has a significantly less favorable benefit in the early historical period. For the prospective period, avoided GHG emissions per renewable kWh become less important due to the increasing share of biodiesel used in fuel oil power plants (which has a higher a GHG emission factor than other renewables).

The emissions avoided by subsidized renewables over the historical period in the NIZs are presented in Figure 38 below. The emission of 2.7 MtCO2eq was thus avoided in 2021 and nearly 39 MtCO2eq over the period 2000-2021. Historical hydroelectric production accounts for an average of 1.2 MtCO2eq avoided per year, representing nearly 70% of the total emissions avoided during the period 2000-2021.

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[42] For some NIZs, no renewables were installed on given years (*e.g.* before 2008 in Mayotte, or since 2014 in Saint-Pierre-et-Miquelon)

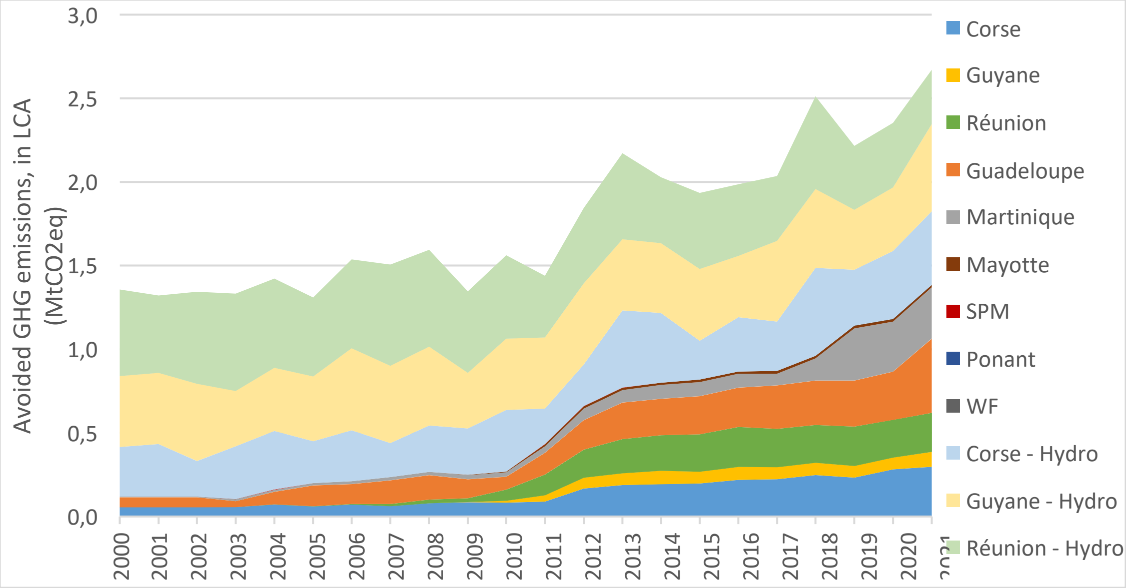

Figure 38: Total voided GHG emissions in NIZs, in life cycle assessment (in MtCO2eq)

5.4 Comparison of GHG emissions to subsidies

An interesting indicator for assessing the effectiveness of subsidies in decarbonization is the ratio of government subsidies for renewables to avoided greenhouse gas emissions. Figure 39 and Figure 40 show this indicator.

5.4.1 Mainland France

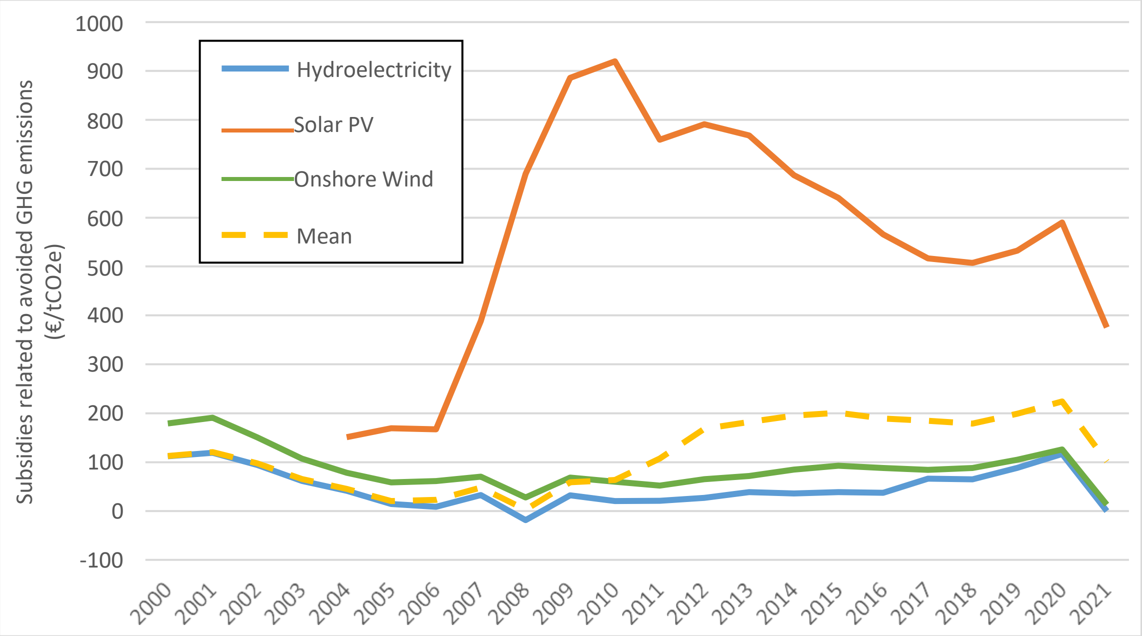

Figure 39: Avoided GHG emissions compared to subsidies to renewable in mainland France (€/tCO2eq)

The ratio between subsidies and avoided emissions (which is an indicator of the efficiency of subsidies from the perspective of reduced greenhouse gas emissions) largely depends on the technology used in mainland France[43]. This is because subsidy contracts are differentiated based on the production technology. Specifically, subsidies for photovoltaics (compared to production) are higher than for the other technologies. This is mainly due to the fact that subsidies for photovoltaic production were significantly higher when the sector emerged (the purchase cost peaked at €546/MWh in 2010) than they are today (typical new purchase contracts are signed at around €55-75/MWh). The inter-annual variability can be explained by the evolution of the purchase contracts, the variability of the market prices (contracts for difference mechanisms), and the variations of the carbon impact of the same production.

Across all sectors, the average cost of subsidies paid to avoid one ton of CO2eq is around €180 over the 2014-2021 period (and €200 without 2021), for renewable electricity production in mainland France. We emphasize that the indicator given here is not sufficient on its own to study the effectiveness of public spending. To do so, it should be compared with the share of public subsidies in the total production cost per MWh, and with the additionality of public spending (how much €1 of public spending has actually triggered of private spending).

5.4.2 Non interconnected zones (NIZs)

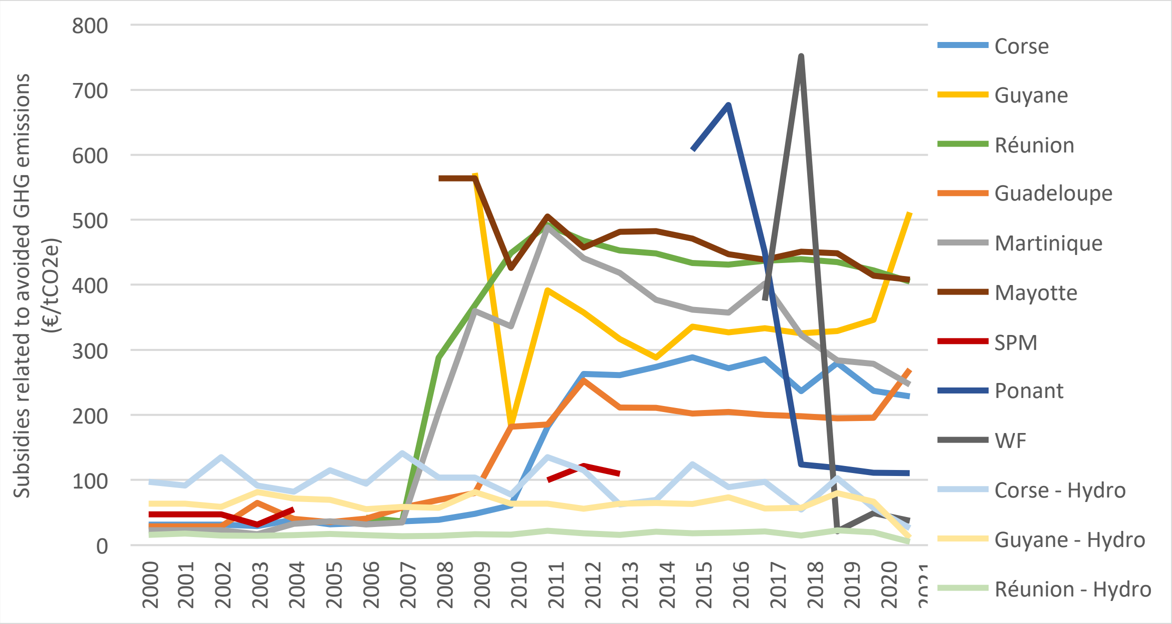

Figure 40: Avoided GHG emissions compared to subsidies to renewable in NIZs (€/tCO2eq)

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[43] It should also be noted that this study considers that one renewable MWh avoids the same emissions regardless of the production technology. This is an approximation, since the emissions avoided increasingly depend on the production profile compared to the demand (depending on the season or the time of day in particular). The curves presented in Figure 39therefore do not exactly represent the subsidy cost per ton of avoided GHG emissions of each technology, although they are a good approximation.

For the 2000-2007 period, most of the subsidies for renewable energy in the NIZs were directed to hydroelectric power generation, but between 2007 and 2011 the strong development of solar photovoltaics associated to important feed-in tariffs led to an important increase of the amount of subsidy per MWh of renewable produced.

For Wallis and Futuna, the plunge of subsidies per tCO2e is directly linked to the commissioning of a new hydro power plant, with a low feed-in tariff. For Ponant islands, the important decrease in 2018 is linked to the new subscription of rooftop solar PV contracts, with significantly lower feed-in tariffs that the one subscribed a few years before.

5.4.3 Difference with abatement costs

It should be noted that this indicator is not a CO2 abatement cost[44]. Firstly, subsidies do not necessarily match total investment expenses in renewable production means (private and public expenses, for purchase and operation). Secondly, an abatement cost is calculated for a specific decarbonization action (such as the development of electric vehicles) with respect to a reference carbon asset and therefore depends on its choice (which sources of electricity production would have been used without the development of renewables). Moreover, abatement costs are often established for a given use, which is not always the case here (would the same amount of consumption have occurred?). Finally, as emphasized by RTE[45], the calculation of the abatement cost of a decarbonization action in the power generation system requires considering simultaneously the evolution of the whole European power system (to internalize system costs) and of the consumption (particularly to account for the electrification of uses).

RTE has thus calculated the abatement costs of decarbonation options enabled by low-carbon electricity production (by studying the adaptation of the electricity mix following the development of different electric uses), rather than the cost of reducing CO2 emissions from electricity production (which is produced to match a demand). A study by *France Stratégie*[46], which adopts a different methodology, estimates the abatement cost for electricity production only (including storage but not the end uses of electricity) at about 370 €/tCO2e (in 2050).

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[44] An abatement cost represents the cost of actions that allow to avoid greenhouse gas emissions. For a socioeconomic abatement cost, the cost and gains associated to the different actions are calculated from the perspective of the society. It can be compared to the "value for climate action" (shadow price of carbon for the evaluation of investments and public policies), adopted by public authorities following the Quinet report [Link]. This value is €250/tCO2e avoided in 2025, €500/tCO2e in 2040, and €775/tCO2e in 2050.

[45] RTE, *Futurs Energétiques* [FR], Chapter 11 (section 11.9 notably regarding abatement costs)

[46] France Stratégie, Abatement costs, part 3 - electricity. Report of the commission chaired by Patrick Criqui [Link][FR]

5.5 Biomethane

Calculating the emissions avoided by subsidized biomethane production consists in multiplying injected production by natural gas emission factors (to calculate emissions avoided) and biomethane emission factors (to take into account emissions in LCA)[47].

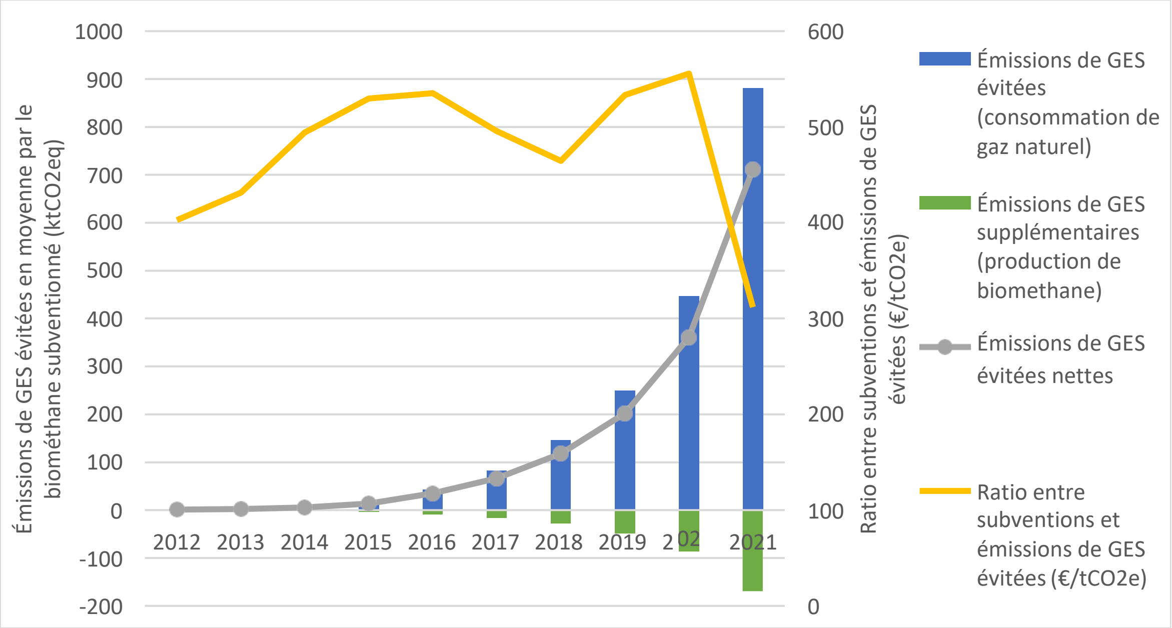

Figure 41 : Greenhouse gas emissions from biomethane (ktCO2eq), avoided emissions in replaced natural gas (ktCO2eq) and comparison to subsidies (€/tCO2eq avoided)

The emissions avoided by biomethane production strongly increased, in line with the development of the sector. In 2021, biomethane production allowed for the avoidance of 700 ktCO2eq. The cost ratio of subsidies to emissions avoided is around €500/tCO2eq, with significant interannual variability (linked notably to the variability of natural gas prices). This ratio is higher than the one depicted in Figure 39 for renewable electricity productions (around €180/tCO2eq avoided in mainland France).

5.6 Avoided GHG emissions compared to French total emissions

The subsidized renewable energies studied in this work have abated significant amounts of greenhouse gas emissions. In 2021, on a life cycle analysis basis, the following avoided emissions are estimated:

- 24.3 MtCO2eq (with annualization) for renewable electricity production in mainland France
- 0.7 MtCO2eq for biomethane production in mainland France
- 2.7 MtCO2eq for renewable electricity production in the NIZs

Over the period 2000-2021, the cumulative avoided emissions are as follows:

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[47] Source ADEME, see Annex 7.6.1.

- 253 MtCO2eq (with annualization) for renewable electricity production in mainland France
- 1.5 MtCO2eq for biomethane production
- 39 MtCO2eq for renewable electricity production in the NIZs

It is interesting to compare these avoided emissions to total French greenhouse gas emissions. In 2021, French emissions amounted to 418 MtCO2eq excluding LULUCF[48] (land use, land use change and forestry – this sector represented the net capture of 14 MtCO2eq in 2020[49]). Avoided emissions for all renewable subsidized represent then around 7% of France net emissions.

It is also interesting to compare the emissions avoided by subsidized renewables with France's carbon footprint, which in 2021 was 604 MtCO2eq (corresponding to 8.9tCO2eq per person)[50]. The carbon footprint is an evaluation of greenhouse gas emissions including emissions related to imported goods and excluding that of exported ones. Since most of the emissions avoided by French renewables are avoided in neighboring countries, it is a particularly relevant indicator. The share of imports and exports in the French carbon footprint and emissions inventory is presented in Figure 42 below.

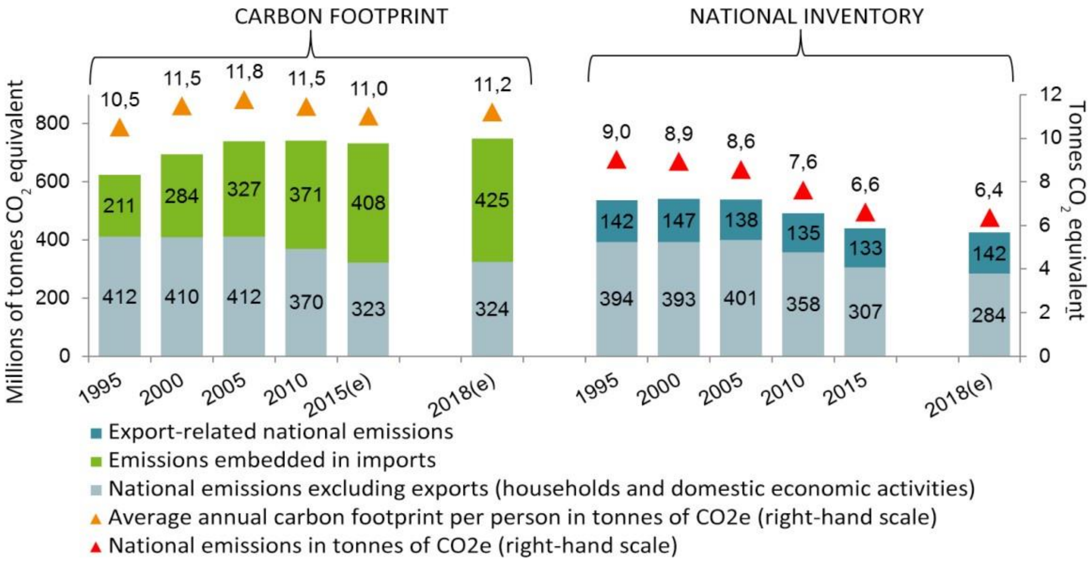

Figure 42: Comparison of the carbon footprint with the national emissions inventory (source: SNBC[51])

The avoided emissions for all subsidized renewables represent around 4,5% of the total carbon footprint of France.

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[48] Ministère de la Transition écologique et solidaire (Ministry of Ecological Transition and Solidarity), *Emissions de gaz à effet de serre : la France atteint ses objectifs* [Link][FR]

[49] Ministère de la Transition écologique et solidaire (Ministry of Ecological Transition and Solidarity), *Chiffres clés du climat, edition 2022* [Link][FR]

[50] Ministère de la Transition écologique et solidaire (Ministry of Ecological Transition and Solidarity), *L'empreinte carbone de la France de 1995 à 2021* [Link][FR]

[51] Ministère de la Transition écologique et solidaire (Ministry of Ecological Transition and Solidarity), *Stratégie Nationale Bas Carbone,* 2020 [Link]

6 Environmental impacts other than climate change mitigation

The impact of renewables goes beyond the reduction of emissions of GHG. Various other environmental aspects (such as pollution, land use, waste management, biodiversity and natural areas, and climate change adaptation) have yet to be considered to get a full picture of the environmental impact of renewables.

The goal of this section is to cover them. Both the positive impacts (mainly linked to the replacement of fossil-fuel generation) and the negative impacts of renewables (such as land use and raw material needs) are covered in the different sub-sections.

6.1 Air, water, and soil pollution

This section presents several types of pollution: air pollution avoided thanks to renewables and pollution of soils and water caused by them. The pollution is considered as much as possible over the whole life-cycle of renewables (mining, construction, etc.). The quantification of avoided air pollution follows the same methodology as for avoided greenhouse gas emissions (Section 5.3). The costs associated with air pollution are then estimated using a study by the European Environment Agency (Section 6.1.2). Section 6.1.3 presents an overview of the other types of pollution caused by renewables.

6.1.1 Avoided air pollution

Summary:

Air pollutant emissions (PM2.5, SO2, NOx, NMVOC) avoided by renewable generation have the same order of magnitude as the current emissions from the entire power sector in France, but only 6% to 20% are avoided in France, the rest being avoided in neighbouring European countries. The sum of these avoided emissions represents a small fraction of the total emissions in France (less than 1% for all pollutant considered), but the benefits would be greater if the indirect emission reductions due to the electrification of various end uses using this additional renewable generation were taken into account.

Air pollution avoided by renewables is not the primary objective of their development but constitutes an important co-benefit. This subject is particularly interesting as it is estimated that 40,000 deaths in France are attributable each year to fine particulate matter (PM2.5), and around 7,000 to nitrogen dioxide emissions (NO_2)[52]. This section quantifies the pollution avoided by renewables in operational phase in mainland France.

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[52] Santé Publique France [Link][FR]

The quantification of atmospheric pollution avoided by renewables follows the same methodology as the one used for GHG emissions. Pollutant emission factors are applied to the results of the modelling of production replacement to estimate the pollutant emissions avoided per MWh of renewable production. The latter are then annualized to estimate the emissions avoided by subsidized renewables.

6.1.1.1 Emission factors used

The quantitative analysis proposed here focuses on the direct emissions of four primary pollutants (PM2.5, SO2, NOx, NMVOC) which are studied by RTE in its study *Energy Pathways to 2050* for the electricity production sector. This section draws on this work and presents some results of that study. In particular, the same emission factors of air pollutants for electricity production are used[53].

PM2.5 are fine particles, mainly induced by wood heating in France. They can either be emitted directly or result from physicochemical transformations of other pollutants (NOx, NH3, SO2, NMVOC in particular). Emission factors hereby considered relate to direct emissions only. Nitrogen oxides (Nox) come mainly from road transport (especially diesel vehicles) in France. Sulfur dioxide (SO2) comes mainly from industrial emissions and maritime transport in France. Non-methane volatile organic compounds (NMVOC) are more related to the use of solvents for domestic or industrial purposes and to the combustion of wood in France.

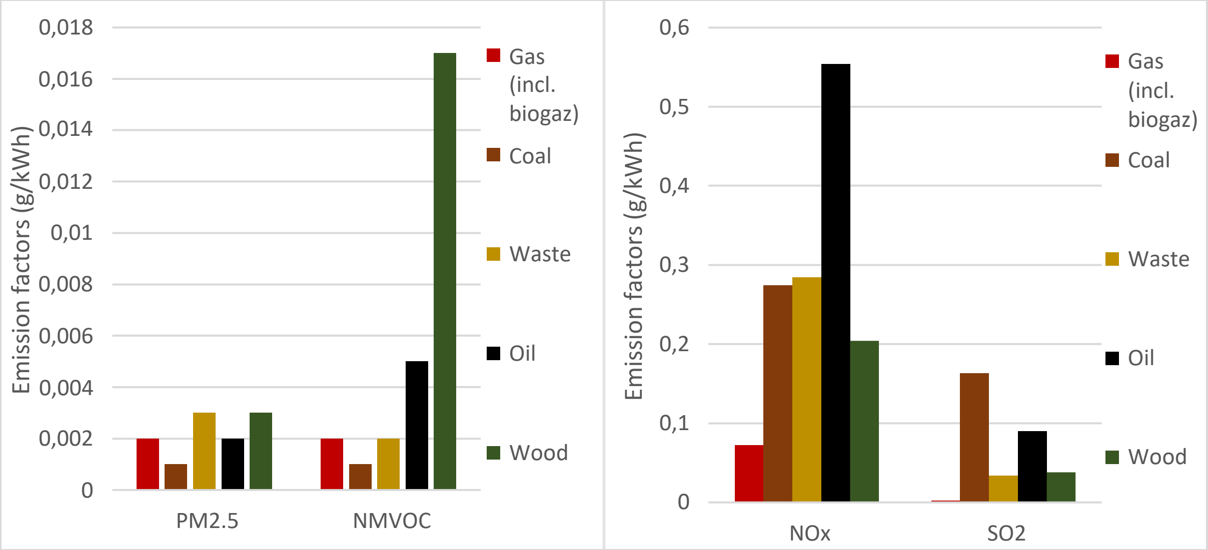

Figure 43: Emission factors of air pollutants (g/kWh, RTE emission factors from CITEPA)

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[53] The scope and factors used are discussed in Appendix 7.7.1. The factors used were determined for France and for 2019. They are used for the whole period and for neighboring countries, which represents a major approximation. However, the key messages derived from the associated calculation would not be largely impacted by changes of these parameters except for the quantification of avoided emissions in the past, underestimated by this methodology.

6.1.1.2 Avoided emissions in mainland France

Avoided emissions of atmospheric pollutants are calculated by multiplying the emission factors by the modeling results of the replacements in electricity production induced by renewables (cf. Section 4.3.1). The avoided emissions for each of the four pollutant studied (PM2.5, NMVOC, NOx, SO2) per additional MWh of renewable production (between reference and counterfactual scenarios) are then obtained. The results are presented below in Figure 44 and Figure 45 (average of S2 and S3Nuc scenarios).

For PM2.5 and NMVOC, most of the avoided emissions are related to renewable production replacing electricity production from gas. For NOx, coal represents a proportionally larger share of avoided emissions. For SO2, almost all of the avoided emissions are related to electricity production from coal. This is mostly due to the fact that most of renewable energy replaces gas (and not a mix of coal and gas as in the past) in the future, and to the higher PM2.5 and NMWVOC (respectively lower for NOx and SO2) emission factors of gas than coal.

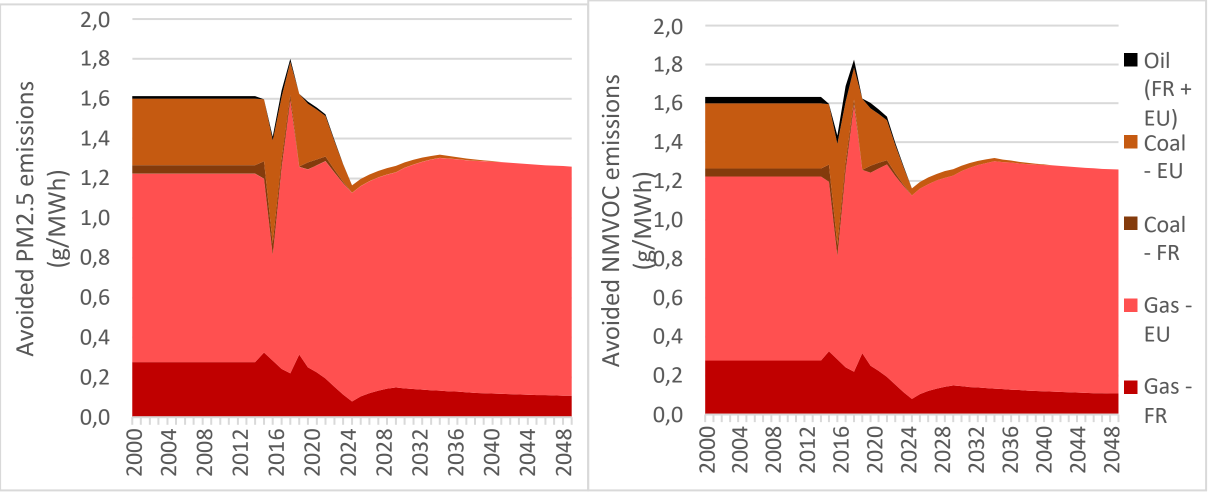

Figure 44: Avoided emissions of PM2.5 and NMVOC (in grams per additional renewable MWh)

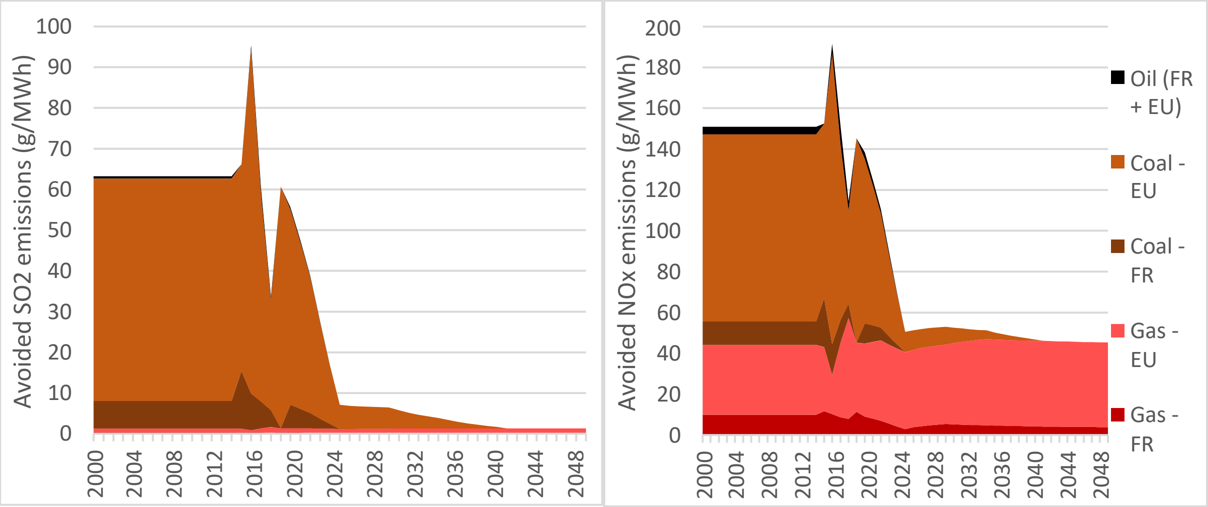

Figure 45: Avoided emissions of SO2 and NOx (in grams per additional renewable MWh)

The annualization methodology is then applied to calculate the emissions (expressed in total weight of pollutant) avoided by subsidized renewables. The results are presented below for scenarios S2 and S3Nuc.

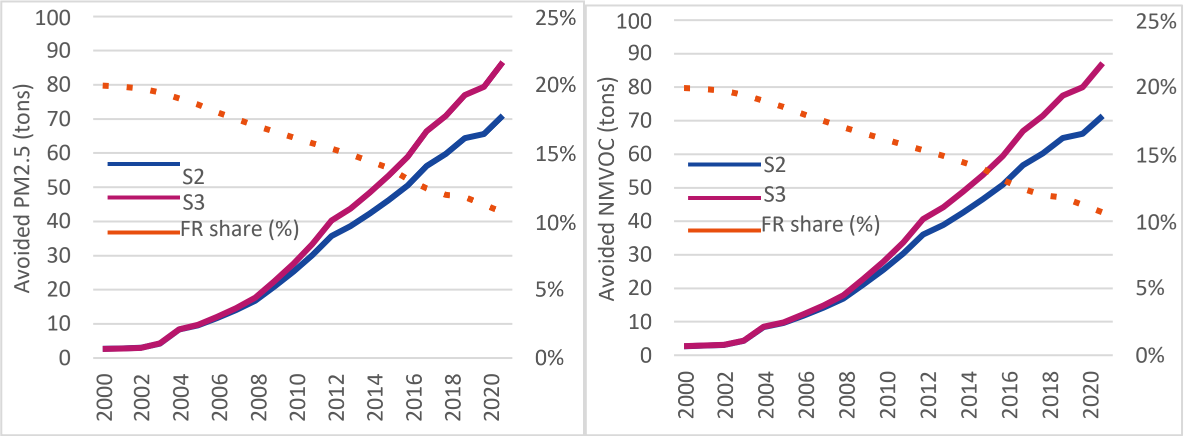

Figure 46: Total avoided PM2.5 and NMVOC emissions thanks to subsidized RES (tons)

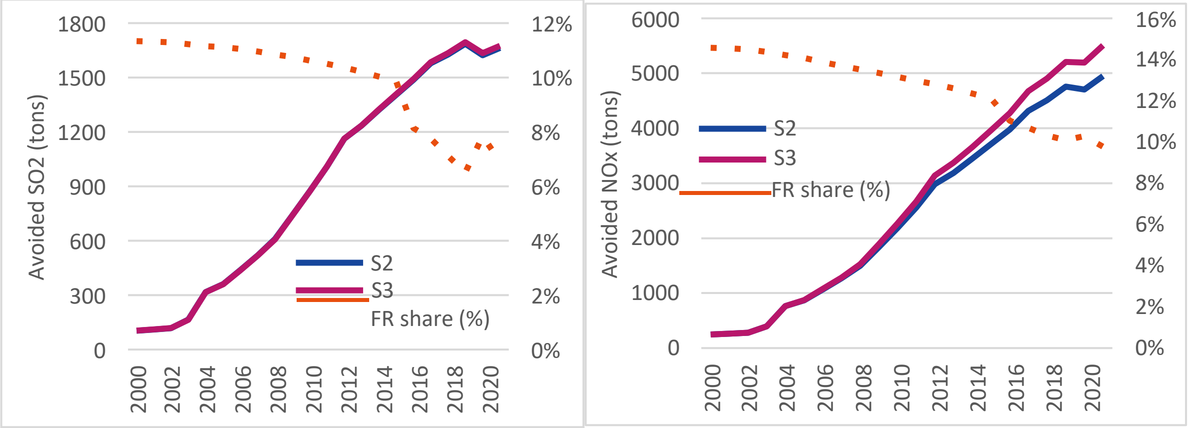

Figure 47: Total avoided SO2 and NOx emissions thanks to subsidized RES (tons)

The above graphs also provide the share of emissions avoided in mainland France over total emissions avoided, which decreases over time due to the faster phase-out of fossil fuels in France compared to neighboring countries and varies depending on the pollutant. In 2000, the share of avoided emissions was at most 20%, down to about 6% at the lowest, in 2021.

6.1.1.3 Air pollutants emissions and context

Comparison to national emissions

To give an indication of the volume of emissions avoided by renewables, they are compared to the emissions of the whole French electricity mix in Figure 48 computed with RTE emissions factors. The avoided emissions (more than 80% are avoided in neighboring countries) thus represent roughly the total current emissions of the French electricity production mix for PM2.5 (76%) and NOx (87%), half of it for NMVOC (49%) and twice for SO2 (222%).

It is important to note that atmospheric pollutant emissions from the French electricity mix are particularly low compared to neighboring countries, notably Germany, due to the low proportion of electricity production from fossil fuels[54].

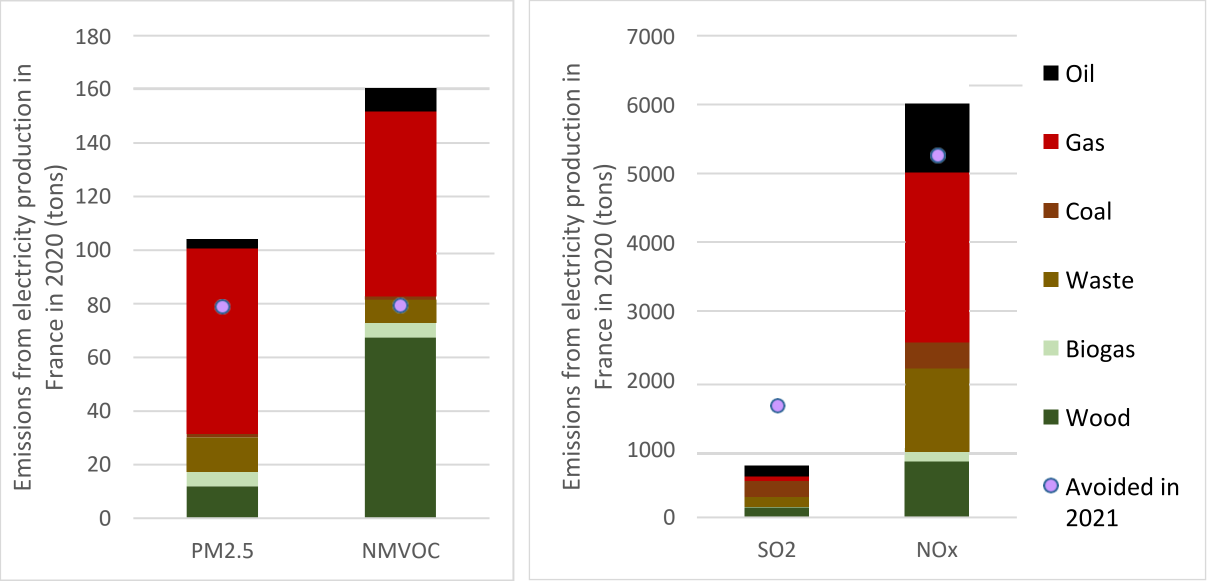

Figure 48: Air pollutant emissions from electricity production in 2020 in France, compared to avoided emissions from RES subsidized in 2021 (tons)

Comparison to national targets for emission reduction

We can also compare avoided emissions from renewables to national reduction targets. Figure 49 compares atmospheric pollutant emissions in 2005 and targets for 2020 and 2030, as well as a comparison between avoided emissions by subsidized renewables and reduction targets between 2005 and 2020[55].

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[54] RTE, translated from *Energy Pathways to 2050*, section 12.6.4.1 (FR): *"as early as 1990, electricity production accounted for only one-fifth of SO2 emissions, 5% of NOx emissions, and a minor share of PM2.5 and NMVOC emissions. Yet, since 1990, SO2 emissions from electricity production have fallen by 99%, NOx emissions by 92%, and PM2.5 emissions by 94%. [...] The electricity production sector has now become an almost negligible contributor to pollutant emissions in France, accounting for 2% of SO2 emissions, 1% of NOx emissions, and less than 1% of NMVOC and PM2.5 emissions. [...] The situation is different from that observed in other European countries. For example, in Germany in 2019, SO2 emissions from electricity production and heat networks accounted for one-third of national SO2 emissions (i.e., 99 kt), mainly due to coal-fired power plants."*

[55] The following ratio is calculated: (emissions avoided in 2020 - emissions avoided in 2005) / (2020 targets - 2005 emissions). The avoided emissions elsewhere than in France are then also counted. This does not exactly represent the contribution of renewable energies to the achievement of the targets, but it provides an interesting order of magnitude. 2020 targets are calculated from the emission reduction objectives (given in % of 2005 emissions). These objectives come from the European directive on the reduction of national emissions of certain atmospheric pollutants [Link].

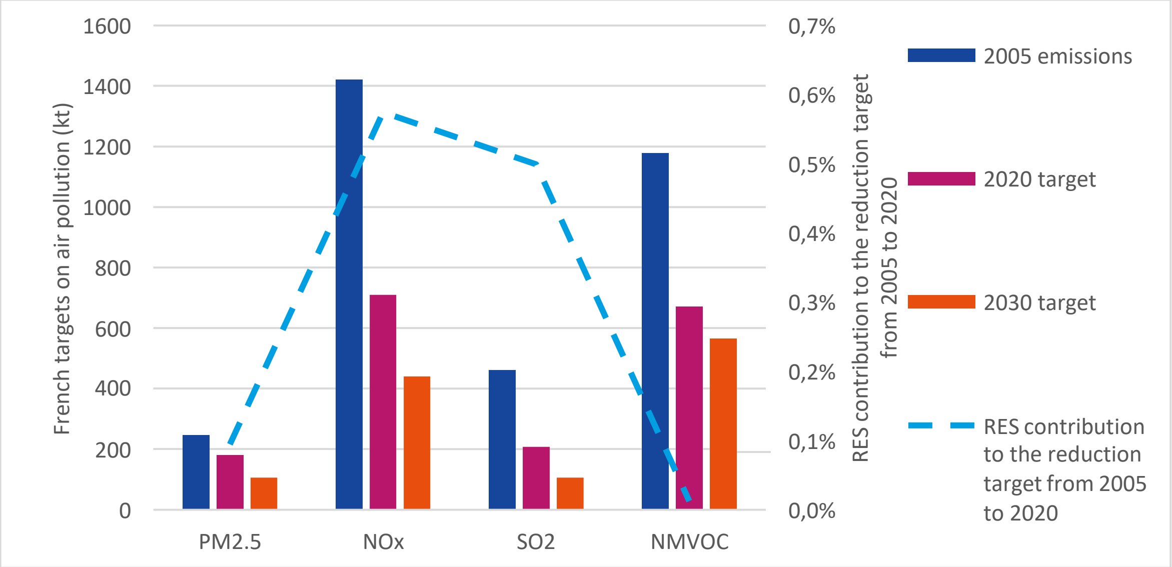

Figure 49: French targets on air pollution (kt)

The avoided emissions within the scope of electricity production therefore represent a small share of atmospheric pollutant reduction objectives, of the order of less than one percent.

Contribution of the energy transition to the reduction of air pollutant emissions

Nevertheless, the energy transition will lead to a significant reduction in atmospheric pollutant emissions, and this transition is made possible by the development of low-carbon electricity production, as discussed in section 3.3. According to RTE, the reduction in atmospheric pollutant emissions is essentially driven by the replacement of old and inefficient equipment, to which electrification of uses contributes.

The electrification of vehicles will be responsible for a reduction of 136 kt of NOx emissions between 2019 and 2030 (about 20% of emissions in 2019), according to RTE. The electrification of heating and industry will also lead to a reduction in emissions, but to a lesser extent. The electrification of industry between 2019 and 2030 will lead to a reduction of 20 kt of SO2 emissions, and the electrification of heating will lead to a reduction of 9 kt of SO2 emissions, according to RTE. This represents about 29% of current emissions.

According to RTE, direct PM2.5 emissions are currently mainly linked to individual wood heating (about half of national emissions). As RTE's scenarios do not predict a transfer of production from wood to electricity (in accordance with the SNBC – *National low carbon strategy*), it is essentially a reduction of auxiliary and leisure heating with wood, as well as the renewal of the appliances, that will allow to reduce the emissions. The electrification of vehicles (-5 kt) and industry (-2 kt) will still lead to a reduction in emissions, but to a lesser extent (about 5% of current national PM2.5 emissions).

6.1.2 Damages costs caused by air pollution

Summary:

With a direct impact on health, and more marginally on crops, forests and building materials, the impact of local pollutants can be converted in equivalent damage costs to these sectors. Depending on the methodology used to assess these costs, avoided damage costs of air pollution could range between €0.9 to €7.6 billion for the 2000-2021 period (in both France and Europe), which can be compared to total subsidies to renewables amounting to €39 billion over the same period.

Air pollution has a significant impact and particularly on human health. *Santé publique France*[56] estimates that nearly 40,000 deaths per year are attributable to exposure of people aged 30 and over to fine particles (PM2.5), resulting in an average loss of life expectancy of 8 months. According to this study, PM2.5 air pollution is responsible for 7% of mortality in France. In addition to mortality caused by air pollution, it generates considerable expenses for the healthcare system.

Air pollution (particularly NOx, SO2, NH3 and O3) also has important impacts on the environment (fauna, flora, eutrophication and acidification of water, impact on soils, etc.). For example, ozone emission leads to a degradation of agricultural yields (impact on crops and forests), and acid rain can threaten buildings by inducing a loss of limestone[57].

The aim of this section is to propose an estimation of the costs avoided by subsidized renewables thanks to avoided air pollution.

6.1.2.1 Hypotheses

The estimation of avoided costs is based on the results of avoided atmospheric pollutant emissions (section 6.1.1) and a study by the European Environment Agency (EEA)[58] that provides an assessment of the costs generated by air pollution. Most of the costs (over 90%) are related to health, and the remaining to crops, forests, and buildings. Two methods of health-cost estimation are proposed in the study: the VOLY (value of a life year) methodology provides a low evaluation and the VSL (value of statistical life) methodology provides a high estimation. The estimates of avoided costs are proposed by type of pollutant and by country.

This study quantifies avoided emissions for France on the one hand, and for neighboring countries (which are aggregated) on the other. The EU-min and EU-max cost estimates presented in this section correspond to minimum and maximum assumptions, respectively, for the costs factors of air pollution in neighboring countries. It is important to note that avoided emissions in neighboring countries also benefit the French population to a certain extent: air pollution is both a local and transboundary problem.

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[56] Santé publique France : press release [Link][FR], full study [Link][FR]
[57] Sources: RTE, *Energy Pathways to 2050*, chapter 12.6 (air pollution) [Link][FR] and EEA study below
[58] EEA – ETC/ATNI, *Costs of air pollution from European industrial facilities 2008-2017* [Link]

The methodology and assumptions are detailed in Appendix 7.7.2.

6.1.2.2 Damages costs of air pollution in mainland France

To determine the avoided costs, direct emissions avoided by subsidized renewables (annualized, as described in Section 6.1.1.2) are therefore multiplied by the costs of air pollution, using the VOLY and VSL cost methodologies, and the EU-min and EU-max estimates. The results of the costs avoided by subsidies per year are presented in Appendix 7.7.3. Figure 50 shows the results of the total costs of air pollution avoided in 2021 (left) and cumulatively over the period 2000-2021 (right) for each of the estimates.

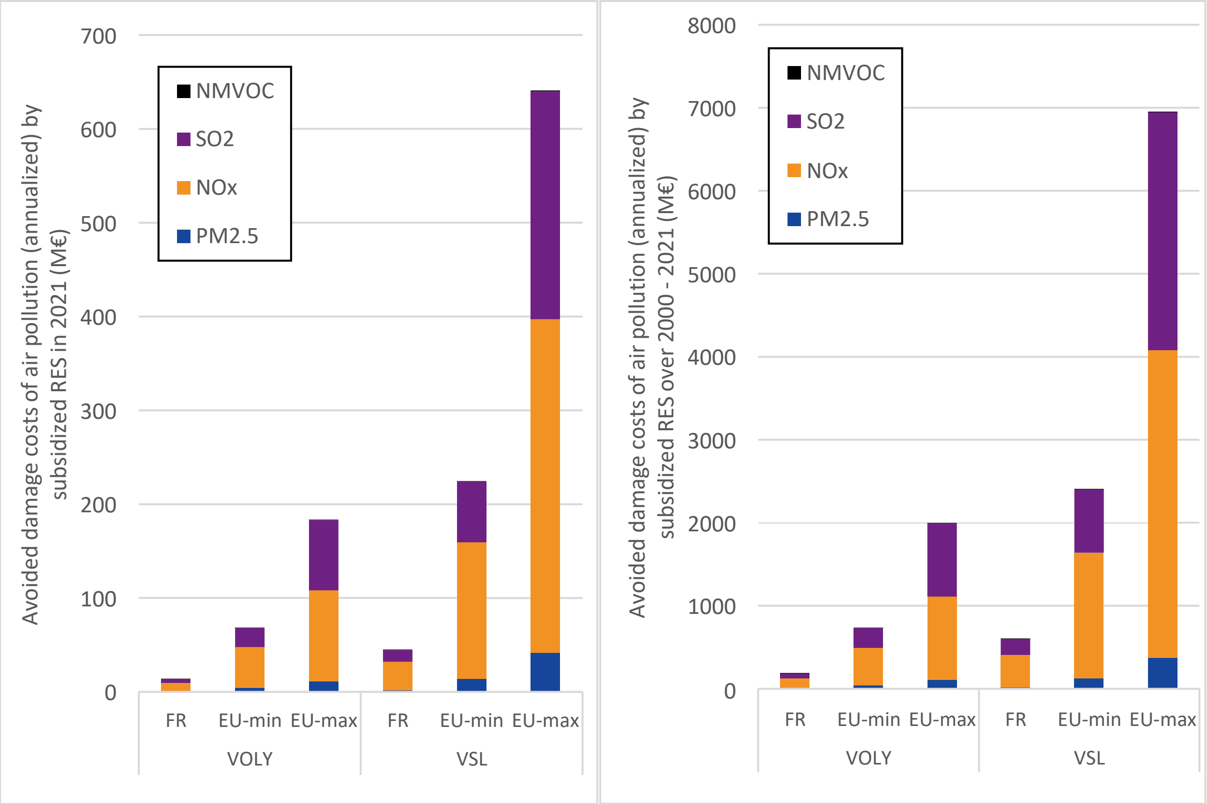

Figure 50: Avoided damage costs of air pollution (annualized) by subsidized RES in 2021 (left) and over 2000-2021 (right), in M€

Over the 2000-2021 period, the avoided costs on direct air pollution represent, in France, between 180 M€ (VOLY methodology) and 600 M€ (VSL methodology). In neighboring countries, according to the low and high estimates, the avoided costs represent between 750 and 2 000 M€ (VOLY) and between 2.4 billion€ and 7 billion€ (VSL). The avoided air pollution thus represents a significant co-benefit, in particular with the avoided emissions abroad. As a reminder, over the same period (2000-2021), the subsidies to renewables amount to €38.6 billion (see section 2.3).

6.1.3 Water and soil pollution

Summary:

In terms of water and soil pollution avoided by renewables, most of the benefits are directly related to the replacement of fossil fuels, which create pollution risks throughout the value chain, from production to use. However, renewables can have a negative impact on local pollution, mainly related to the extraction of raw materials to build the different components of solar panels and wind turbines, but also during the installation phase.

The construction of renewable energy production systems nevertheless generates pollution, particularly to water and soil. Within the framework of this study, these issues have been subject to a qualitative literature review. The main concerns identified are related to mining and the associated pollution. Other concerns have also been identified, particularly related to the construction of renewable production facilities (manufacturing, construction works, etc.).

Pollution avoided thanks to the replacement of fossil fuels

In the first hand, it is important to note that renewable energies are intended to replace fossil fuels which are also important sources of pollution to water and soil. Pollution from fossil fuels are diverse. They are related to production stages (coal mines, oil and gas wells, hydraulic fracturing, drilling and processing sludge), transport (oil spills, pipeline leaks, etc.), and use (emission of pollutants from combustion that can end up in air, water and soil, physicochemical reactions of emitted atmospheric pollutants that can have harmful effects on water and soil, etc.).

Pollution generated by extraction and mining of raw materials

Raw material needs for renewable development are studied in section 6.2. These needs are met by mining activities, which generate various types of pollution, particularly to water and soil[59]. It is nevertheless important to note that mining products are used for other purposes than renewables.

Mining is likely to pollute watercourses and groundwater resources. For example, sulphide deposits are subject to acid mine drainage that contributes to freshwater acidification, thus impacting ecosystems.

The International Energy Agency also indicates that *"water pollution is particularly worrisome in the processing stage, where grinding, milling and concentration methods generate toxic effluents loaded with heavy metals and chemicals. […] Water pollution is especially problematic in China, where REE production was conducted illegally or in unregulated small-scale activities until recently. There are numerous wastewater ponds, formerly used for leaching activities, abandoned near mining sites."*

Another important risk identified by the IEA concerns the management of mining residues, typically stored in ponds or behind dams, which present risks of downstream watercourse contamination. In

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[59] These topics are notably presented in an IEA report: *The Role of Critical Minerals in Clean Energy Transitions* [Link]

particular, tailings dam failure can cause large-scale environmental disasters, as shown by the examples of Brumadinho (2019) and Fundão (2015) in Brazil.

In addition, mining and mineral processing require significant volumes of water. However, about half of the world's copper and lithium production is concentrated in areas of high water stress. Questions thus arise about water use conflicts, typically for the "salars" industry in South America.

In addition to water and soil pollution, mining activities also generate air pollution (mine dust, etc.) as well as noise pollution, which can affect biodiversity. Biodiversity issues related to the development of renewables are addressed in section 6.3.2.

Pollution generated at the installation stage

The manufacturing of photovoltaic panels and wind turbinesis likely to generate pollution. However, fewinformation was found on this production step during the literature review.

The construction phase, to install the renewable production systems, also generates nuisances (like all construction work). A particular issue with renewables is that they are often placed in natural areas rather than in urban areas (particularly onshore and offshore wind, ground-mounted solar, etc.). Building site machinery can thus release pollutants and can induce ground levelling. In addition, renewable installations involve sealing or artificializing soil, which can disrupt water flow. This is particularly the case with the concrete base of wind turbines.

In France, impact studies conducted before construction consider these issues and lead to proposals for mitigation and compensation solutions if necessary. French law also regulates the dismantling of wind turbines and provides for the excavation, at least partial, of the foundations of onshore wind turbines.

Noise pollution

Noise pollution is under particular scrutiny for onshore wind turbines. In France, impact studies consider this issue, and French legislation requires a minimum distance of 500m between the mast of a planned wind turbine and any dwelling.

It is important to emphasize that the development of renewable energy is an essential part of the energy transition and vehicle electrification, in order to quickly increase low-carbon electricity production (see Section 3.3). One of the benefits of this electrification is the reduction in noise pollution, since electric vehicles are quieter than internal combustion engine vehicles. Therefore, wind turbines may increase noise pollution locally, but reduce it elsewhere.

6.2 Raw materials use and recycling

The energy transition, in addition to its climate benefits, will help reduce dependence on fossil fuel imports. However, the development of a decarbonized energy system requires significant quantities of mineral resources (especially for photovoltaic panels and wind turbines, networks, and electric vehicles batteries) which cannot only be met by national capacities of production. This increased demand raises new questions about mineral resource supply. The extraction conditions of these resources and the end-of-life management of energy transition equipment (notably through recycling) are major issues that are both economic, geopolitical, and environmental in nature. The aim of this section is to present the environmental issues related to raw materials arising from the development of renewable energies.

6.2.1 Raw materials impact

Summary:

The development of renewables will significantly increase the consumption of raw materials for the electricity generation, as the material intensity of wind and solar is much higher than that of other low-carbon generation technologies (hydro, nuclear) or fossil fuels. By 2050, raw material consumption for the energy transition will be particularly high, especially for electric vehicles, power grids and renewable generation systems. Renewables will account for about 10% of current French aluminium production and about 5% of copper consumption and steel production.

Solar and wind energy each account for about 30% of copper consumption, solar accounts for almost 90% of aluminium, and wind accounts for half of the steel and a third of concrete. Batteries for electric vehicles, whose storage capacity will be useful in the future to facilitate the integration of increasing share of renewables in the energy mix, will need significant quantities of lithium, nickel and cobalt, but less rare earth elements. The grid, which also needs to be developed to accommodate renewables, will also require significant amounts of copper and aluminium compared to generation means (around34% and 17% respectively).

The environmental impact of raw materials is mostly linked to mining activities and occurs abroad, as most metals are imported in France. The need for raw materials could be reduced through energy sufficiency and improved energy efficiency.

6.2.1.1 Quantification of structural resource requirements in France

In France, the needs for mineral resources related to the energy transition were studied by RTE in its *Energy Pathways to 2050* report[60], which inspired this section. Among the numerous mineral resources identified as critical for the energy transition, RTE has emphasized "structural resources" for the

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[60] RTE, *Futurs Énergétiques*, chapter 12.3 (mineral ressources) [Link][FR]

electricity sector: copper, aluminum, steel, and concrete. RTE's study provides an evaluation of resource needs in its prospective scenarios. This work has also been carried out by ADEME[61] for its prospective scenarios, including those used for this study, and the results were similar. The following section provides an evaluation of the needs for copper, aluminum, steel, and concrete in the electricity mix, divided by the lifespan of the generation facilities[62].

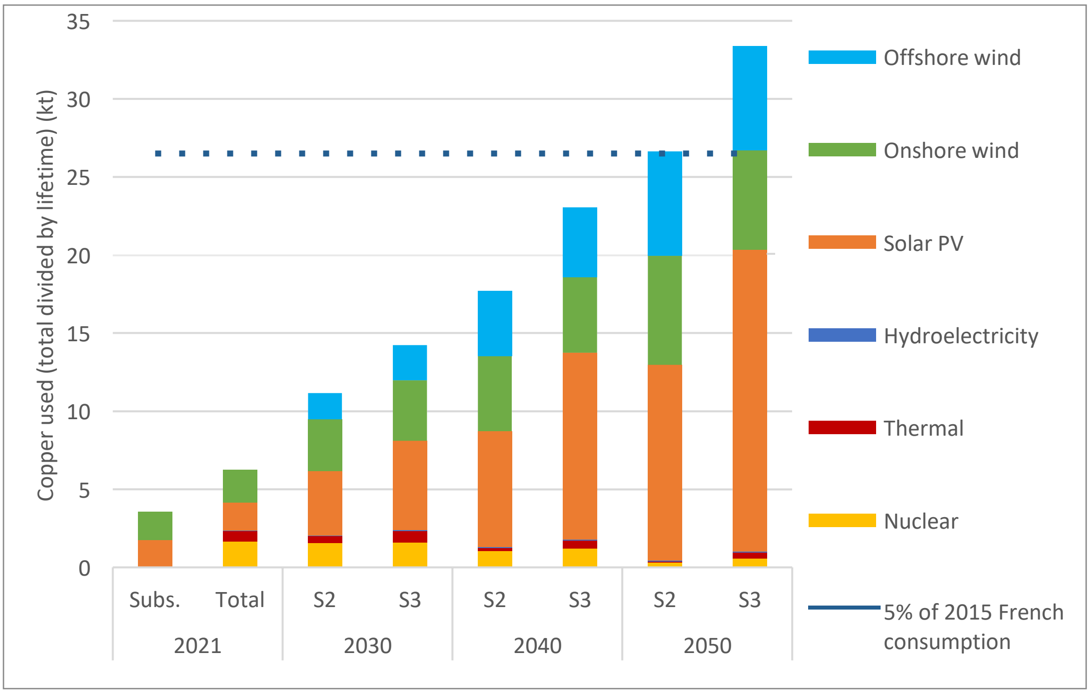

Figure 51: Copper used in electricity production mix, assuming that metal requirements are spread over the lifetime of the different assets (kt)

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[61] ADEME, *Transition(s) 2050*, Feuilleton *Les matériaux pour la transition énergétique, un sujet critique* [Link][FR]

[62] RTE and ADEME studies provide annual resource needs for different raw materials until 2050. An alternative quantification of raw material needs is proposed here, complementary to the RTE and ADEME approach, which draws inspiration from life cycle analysis. Raw material needs are not expressed according to the needs of new capacity installations, but by dividing the needs for all the installed capacities of the mix at a specific year by the lifespan of the facilities. The resulting indicator therefore takes into account the entire life of the facilities, and thus the fact that the resources locked up in electricity generation assets will serve beyond 2050. However, it does not consider the trajectory of mineral resource requirements.

The graphs presented here show the use of the "structural resources" identified by RTE in 2021, 2030, 2040, and 2050 for the two ADEME scenarios used as a reference for this study (in 2021, we present both subsidized renewables and the complete mix). The selected material usage estimates are taken from the RTE study (2020 estimates). They are comparable to those provided by ADEME (SURFER database [Link][FR]) and JRC [Link].

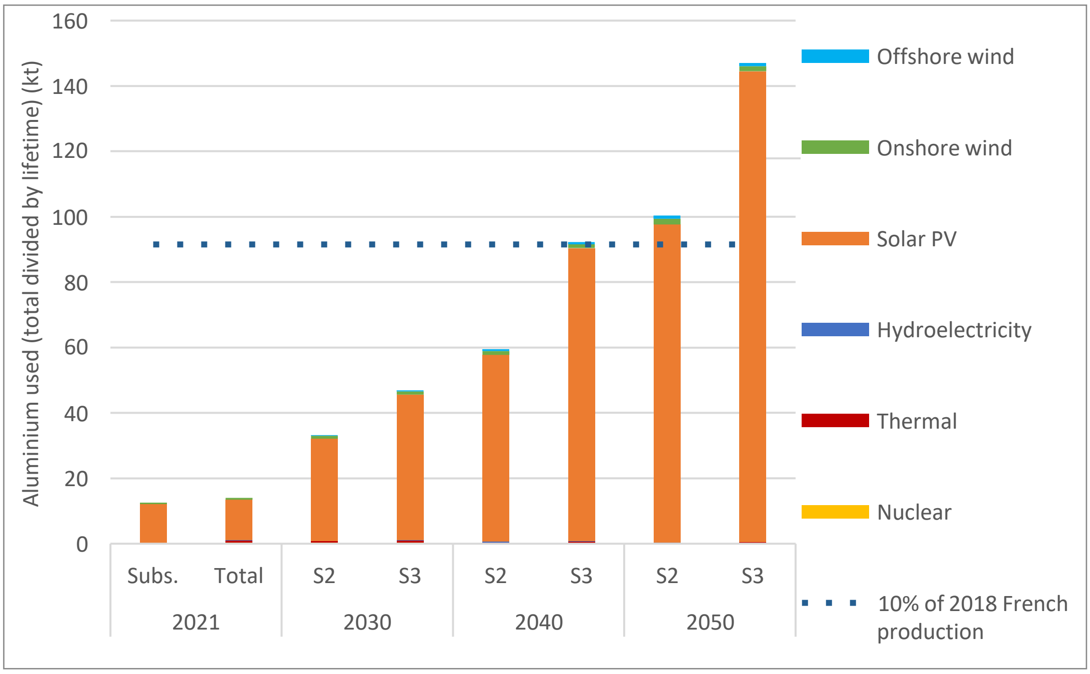

Figure 52: Aluminum used in electricity production mix, assuming that metal requirements are spread over the lifetime of the different assets (kt)

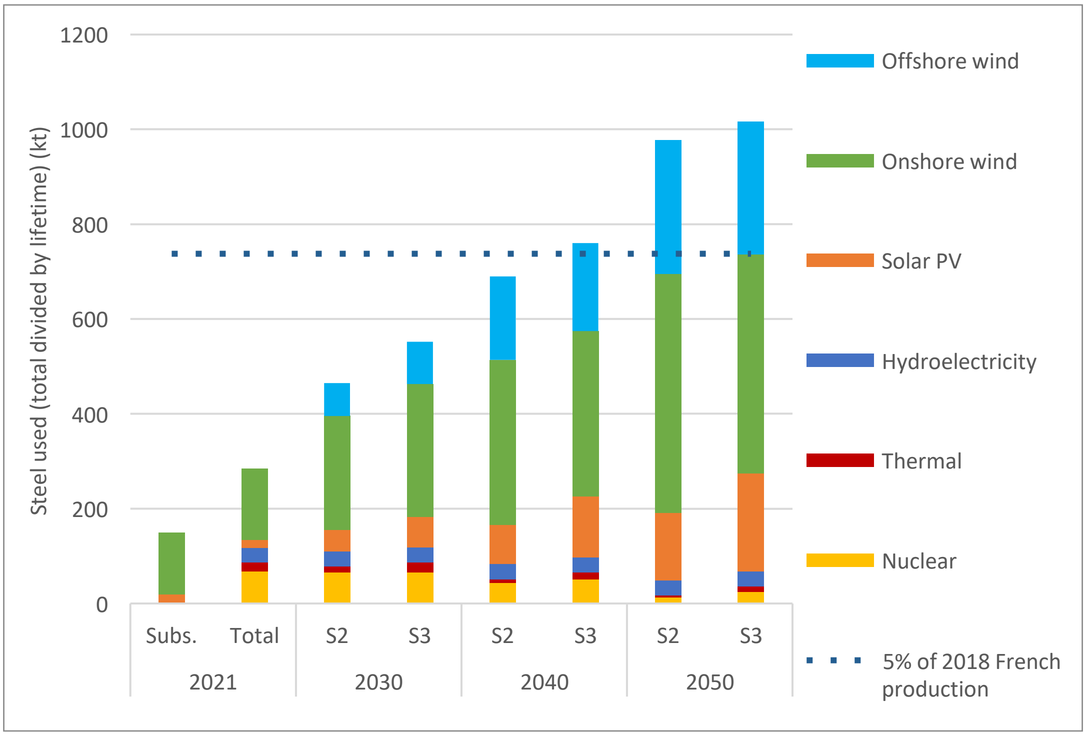

Figure 53: Steel used in electricity production mix, assuming that metal requirements are spread over the lifetime of the different assets (kt)

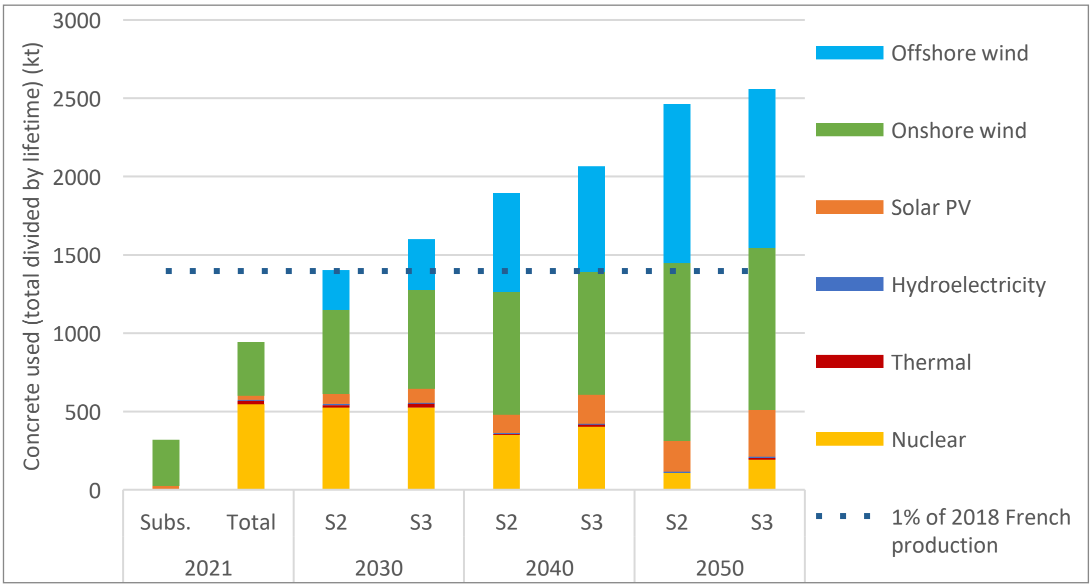

Figure 54: Concrete used in electricity production mix, assuming that mineral requirements are spread over the lifetime of the different assets (kt)

The consumption of structural raw materials in subsidized renewables represents a significant portion of the total consumption in the current production mix (2021). Solar and wind energy each account for about 30% of copper used, solar accounts for nearly 90% of aluminum, and wind accounts for half of the steel and one-third of the concrete used.

It can be observed that the material intensity (material requirement relative to production – in t/MWh) is significantly higher for wind and solar compared to other low-carbon production technologies (hydroelectric, nuclear) or fossil fuels. This constitutes a major drawback of renewables, which must be considered when assessing their environmental impact.

Furthermore, the use of mineral materials by renewables is expected to increase significantly by 2050, with a threefold increase for wind and about a tenfold increase for solar compared to current levels. Even if the total amount will be significantly higher that today, the share in the total demand for all uses in France will remain contained. By 2050, the copper used in renewable capacities, divided by their lifespan, will represent approximately 5% of 2015 French consumption. This figure (relative to 2018 French production) is around 13% for aluminum, 6% for steel, and 1.7% for concrete.

Other raw materials used by renewables and associated systems

Other mineral materials are important for the development of renewables, including silicon for photovoltaics, rare earths elements for offshore wind, and chromium and zinc in alloys.

RTE emphasizes that rare earths elements, while often mentioned in debates and raising questions about dependency on China, do not present a primary issue for the electricity system in practice. On the one hand, these metals are not particularly rare from a geological perspective, and on the other hand, the electricity system consumes very little of them, with almost all the consumption being used for the permanent magnet of synchronous generators, primarily in offshore wind turbines.

Furthermore, in order to accommodate the development of renewables, the transportation and distribution networks will require adaptations and will therefore generate consumption of metals (mostly aluminum and copper). In 2050, RTE predicts a 55% higher copper consumption for the grid in its 100% renewables scenario compared to its scenario with the highest share of nuclear power. For aluminum, the need is 80% higher in the 100% renewables scenario. In these scenarios, the aluminum used for the transmission network is equivalent to about 34% of the copper used in the generation means (average between the scenarios). For aluminum, this figure is around 17%.

The development of batteries, primarily for electric vehicles, presents more critical challenges than the electricity system, according to RTE. This is particularly the case for lithium (which also has low recycling perspectives), cobalt, and nickel. Other metals are also important for batteries, including manganese, graphite, and silver. These challenges must be taken into account with the development of renewables, as batteries (stationary and for electric vehicles) will likely provide part of the flexibility needed to integrate large shares of intermittent renewable energies (solar, wind) into the electricity mix.

Other energies

During the literature review, hydroelectric production systems and anaerobic digestion systems (for biogas generation), which are also subsidized, did not appear to have significant challenges in terms of mineral material consumption. These systems require concrete, steel, and copper, but in limited quantities compared to their production and installed capacities in prospective scenarios.

While wind and solar demand significantly more mineral materials compared to thermal production technologies, it should be noted that replacing nuclear power (in prospective scenarios) with renewables will help reduce the need for uranium and zirconium, and reduce the generation of radioactive waste.

6.2.1.2 Analysis of raw material environmental impacts worldwide

Global demand for mineral raw materials for energy transition

Many countries, like France, have committed to energy transition, particularly through the development of renewable energy and electric vehicles, which will result in a significant demand for mineral resources. In its carbon neutrality scenario, the International Energy Agency (IEA) forecasts a fourfold increase in demand for mineral raw materials (excluding aluminum and steel) for low-carbon technologies between 2020 and 2040, according to a report that serves as the basis for this section[63].

This demand will be primarily driven by batteries (for electric vehicles and energy storage) as well as the development of electric grids. In the same scenario, low-carbon technologies are projected to

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[63] IEA, *The Role of Critical Minerals in Clean Energy Transitions* [Link]. The scenario in question is the SDS, which is compliant with carbon neutrality at mid-century.

account for approximately 90% of global lithium consumption, 70% of cobalt consumption, 60% of nickel consumption, and 45% of copper consumption. In a 2°C warming scenario, the World Bank[64] has estimated the global demand for several mineral raw materials for energy transition in 2050 and compared this demand to current production. In this scenario, the consumption of lithium, graphite, and cobalt is projected to be between 4.5 and 5 times the current production.

Environmental Impacts

The demand for mineral raw materials, whether for renewable energy development in France or for global energy transition, will generate significant environmental impacts. Given the increasing demand, both in France and worldwide, recycling of metals is unlikely to be sufficient. Thus, mining activity will have to increase to enable the energy transition.

The majority of metals consumed in France are extracted elsewhere in the world, which means that the majority of environmental impacts related to mining activity occur abroad. These impacts vary depending on the metals, types of mines (underground or open-pit), extraction techniques, countries of origin, and characteristics of the subsoil, among other factors. These impacts encompass various issues, including pollution, water demand, biodiversity and changes in land use, as well as greenhouse gas emissions.

The pollution generated by mining activity is discussed in section 6.1.3. It should be noted that mining products are used in many other sectors besides renewables, and fossil fuels (which renewables are intended to replace in the context of energy transition) also generate significant pollution. The impacts on biodiversity are presented in section 6.3.2 and should also be compared to the impact of fossil fuels.

Greenhouse gas emissions associated with mining activity for renewable energy facilities are considered in life cycle analyses. While these emissions are not negligible, the electricity produced by renewables remains significantly lower in carbon intensity than that produced from fossil fuels (see Figure 29). With the rapid growth in mining demand, IEA has identified the risk that production may become more energy-intensive. However, the IEA also emphasizes that various efforts can be made to reduce emissions during the extraction and processing of mineral resources, such as the use of low-carbon electricity (depending on the local energy mix) for refining and smelting of ores, energy efficiency measures, and electrification of trucks. According to the IEA, a simulation for a copper production project showed that up to 80% of emissions could be reduced through electrification with renewable electricity.

Levers for reducing environmental impacts

To mitigate the environmental impacts of renewables, several levers can be mobilized at all levels, from mining extraction to electricity demand.

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[64] World Bank Group, *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* [Link]

Within the scope of mining activity, actions can be taken to both reduce extraction needs and improve practices. The IEA indicates that reprocessing of mining residues and extraction of multiple metals from the same ore can maximize resource recovery rates. By doing so, it is possible to increase metal production for the same amount of mining extraction, thereby reducing the risks of pollution. In addition, the IEA highlights that more sustainable mining practices, such as better waste management, can contribute to reducing the risks of pollution. Furthermore, the IEA recommends promoting higher environmental, social, and governance standards. Establishing stricter standards in the supply chain could be a tool to reduce environmental risks, as well as providing financial support to projects implementing impact mitigation measures.

Research and development activities could also help reduce the environmental impacts of renewables by improving processes. These improvements can relate to both mining processes (environmental impacts during extraction and processing phases) and the design of low-carbon systems (reducing the material intensity of renewables and batteries for the same service provided). For example, RTE estimates the aluminum material intensity for ground-mounted photovoltaic systems at 29 t/MW in 2020, compared to 17.4 t/MW in 2050 in its *Energy Pathways to 2050* study. Improved recycling can also enable better resource reuse; this topic is addressed in section 6.2.2.

Another important lever relates to consumption. Renewable production aims to meet energy needs, which could potentially be reduced through improved energy efficiency and energy sufficiency[65]. RTE has assessed the reduction in mineral resource needs for the electricity system and electromobility in a sufficiency scenario: depending on the resources, the reduction in needs ranges from 15% (steel) to 30% (lithium), and is around 25% for most metals.

6.2.2 Recycling

Summary:

Metals used in renewable energy systems could be reused or recycled to meet the needs of other industries. For solar energy, about 95% of the mass of resources can be recycled, but there is still room for progress to improve the separation of glass and semiconductor films, according to the EEA. For wind energy, about 90% of the materials can be recycled or reused, but recycling the composite materials used in wind turbine blades remains a challenge that requires further research.

Industrial-scale recycling facilities and large-scale physical collection of products will be needed in the coming decades to manage the end-of-life of renewables installed since 2000.

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[65] Energy efficiency means using less energy for the same service. It is made possible by the use of technologies with a better output (heat pumps vs. convectors for example) or by reducing losses (thermal insulation of a building for example). Energy sufficiency corresponds to a reduction in the service rendered (e.g. lowering the heating temperature or reducing the size of the vehicle). It can be voluntary, particularly with the aim of reducing environmental impacts.

Recycling of renewable energy systems addresses several issues, from mineral resource availability to end-of-life management of the facilities. By reducing the demand for primary mineral resources, recycling can help reduce the environmental impacts of renewable energy technologies.

6.2.2.1 Challenges related to metals

It is important to note that metals used in renewable energy systems are, at least for some, "mobilized" rather than "consumed": raw materials can be reused or recycled to renovate energy infrastructure or meet the needs of other industries.

For example, transport and distribution networks concentrate significant volumes of "mobilized" copper and aluminum (150 Mt of copper and 220 Mt of aluminum globally, according to the International Energy Agency). The fact that these are industrial facilities with large volumes of resources to be renewed is likely to facilitate the establishment of channels for reusing and recycling these metals.

On the other hand, recycling pathways for batteries are not yet mature, especially for lithium-ion batteries used in electric vehicles. However, given the volumes and the challenges related to the availability of minerals such as lithium, cobalt, and nickel, recycling appears to be crucial. Regulations can guide the development of batteries to limit their environmental impact. For example, the IEA cites a European regulation[66], which requires minimum rates of recycled metals in installations and design features that facilitate metal recovery (90% for cobalt, 90% for copper, 35% for lithium, and 90% for nickel by 2026).

The IEA indicates that key challenges for recycling include physical collection of products and physical and metallurgical separation of the different metals they contain. Recycling thus encompasses very different practices depending on the products and metals to be recycled, ranging from mining residues to end-of-life products including scrap from manufacturing activities. To improve material recycling, the IEA emphasizes the importance of supporting waste collection and research and development activities.

Current recycling rates largely depend on the metals and their uses, and are likely to evolve with the development of recycling pathways[67]. The IEA provides global recycling rates (across all uses) for several resources: approximately 60% for nickel, 45% for copper, 40% for aluminum, 35% for cobalt, and less than 1% for lithium or rare earths elements.

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[66] European Commission, regulation concerning batteries and waste batteries [Link]

[67] For example, the National Institute for the Circular Economy (INEC) has carried out a study on the resource requirements for the low-carbon transition in France: *Stratégie nationale bas carbone sous contrainte de ressources* [Link][FR]. This study proposes hypotheses on the reduction of needs, recycling rates and reuse of raw materials for energy transition technologies, for two circularity scenarios.

6.2.2.2 Specific challenges for solar panels and wind turbines recycling

The European Environment Agency studied the challenges of recycling for solar, wind, and battery technologies[68]. Below are the issues identified for solar and wind energy.

For solar energy, approximately 95% of the mass of resources can be recycled according to this study. The main resources involved are glass, copper and aluminum. The study indicates that *“apart from aluminum and glass, the remaining module scrap, including silicon, silver contacts, tin, and heavy metal containing solder (lead) usually undergoes thermal treatment in incineration plants.”* Key challenges for recycling include the separation of glass and the semiconductor film, the management of hazardous substances in photovoltaic modules, and logistical constraints associated with the maintenance of elevated installations.

For wind energy, approximately 90% of the materials can be recycled or reused, including steel, aluminum, copper, cast iron, and concrete. Critical minerals found in permanent magnets of certain types of generators, including rare earth elements, could also be valorized in the future. A major challenge is the recycling of composite materials, used in wind turbine blades: recycling infrastructure is still under development, and further research activities are necessary. The transportation of wind turbine blades (which currently have an average length of about 40 meters and may reach up to 75 meters in the future) to recycling facilities also raises logistical questions. To reuse blade materials, rather than burning or burying them, it is possible to "downcycle"[69] carbon and glass fibers (for example, to manufacture pallets, polymer concrete, noise proof barriers, etc.).

This study also presents avenues for improving circularity models, such as extending the lifespan of solar panels and wind turbines (through more resistant design, modularity, repairability, etc.), and eco-design for recycling (research and development for alternative materials or reuse of composite materials in blades), as well as repair and reuse of salvageable parts.

Solar panels and wind turbines have a lifespan of about 20 to 30 years, and their industrial-scale installation began in the 2000s-2010s. Thus, renewable energy recycling facilities need to be developed at an industrial scale in the coming years to manage the end-of-life of RES and limit the environmental impacts of the mineral materials used in renewable energy technologies. Sufficiency could be an interesting lever for limiting pressure on recycling facilities.

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[68] EEA (Oeko-Institut e.V.), *Emerging waste streams – Challenges and opportunities* [Link]

[69] Downcycling is the "recycling" of a material waste into a new material of lower quality or value.

6.3 Impacts on biodiversity and preservation of natural areas

The IPBES identifies five main direct drivers of biodiversity and ecosystem change: land-use change (or sea-use change), climate change, pollution, natural resource use and exploitation and invasive species. The purpose of this section is to quantify land use by renewables and to present the challenges of biodiversity protection and preservation of natural spaces.

6.3.1 Land use and preservation of natural areas

Summary:

In the scenarios considered, in 2050, the surface area co-used by renewables for power generation would represent around 2-3% of France’s total surface area, and renewables would account for about 0,6% of France's total artificialized surface area (the total artificial surface area linked to the electricity system would double between 2021 and 2050). According to ADEME, methanization will also generate significant pressure on land use, with more impervious surfaces associated to biomethane production in 2050 than the entire current electricity system.

In addition to the mobilization of brownfields sites (which will not be sufficient to accommodate all the capacity required), various solutions can help to mitigate this impact of renewables, such as agrivoltaics, a greater development of rooftop solar panels (even if they are more costly), or installing floating panels on artificial lakes. The preservation of natural areas is also an important issue for impact assessment studies.

This section is based on a study from RTE on the land use of electricity generation facilities[70], in particular as we used the same land use factors by technology[71]. Three types of land use are distinguished in the quantified assessment presented in the figures below: artificialized surfaces, impervious surfaces (included in artificialized surfaces), and surfaces that may restrict some co-uses. This assessment does not take into account offshore wind, hydroelectricity and biomethane production. In the graphs below, “solar PV” is equivalent to ground-mounted solar photovoltaics since roof-mounted solar is supposed not to generate any additional land use. For land occupation by the electricity network, we use RTE's assessment of the surfaces occupied in 2020[72]. Artificialization resulting from former production sites is not taken into account in the quantification either.

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[70] RTE, *Futurs Énergétiques*, chapter 12.4 (land use) [Link][FR].

[71] The following factors from RTE study were used:

Area in ha/MW	**Thermal (incl. nuclear)**	**Ground solar**	**Onshore wind**
Impervious	0,03	0,002	0.02
Artificialized	0,06	0,09	0,15
Co-uses	0	1,35	12,35

These factors are similar to those used by the ADEME for the *Transition(s) 2050* study

[72] The results on renewable land use presented in this section correspond to the surface areas directly associated with the facilities. The work of RTE (*Futurs Énergétiques 2050* in particular) has shown that systems with a higher

6.3.1.1 Artificialized areas

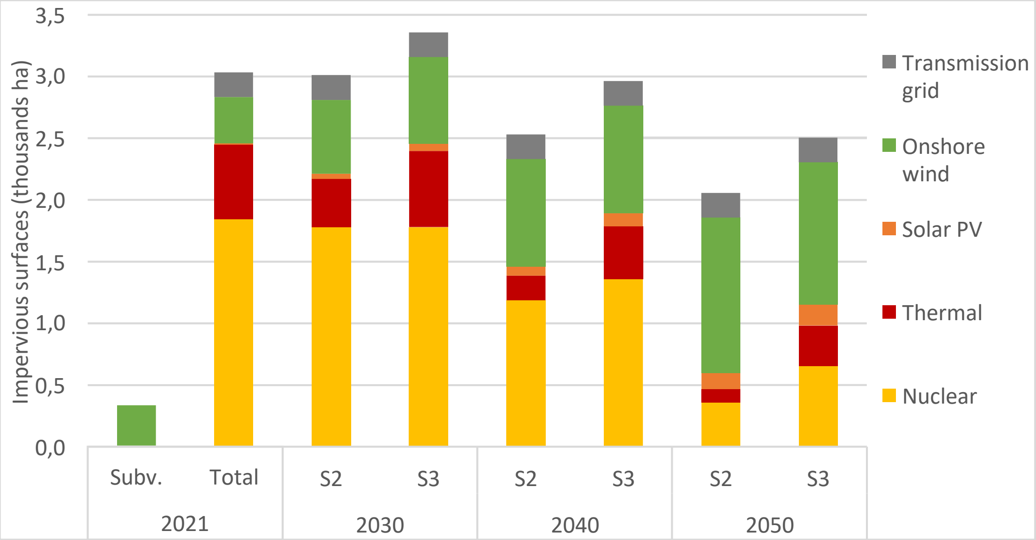

Figure 55: Impervious surfaces due to electricity mix (thousands ha)

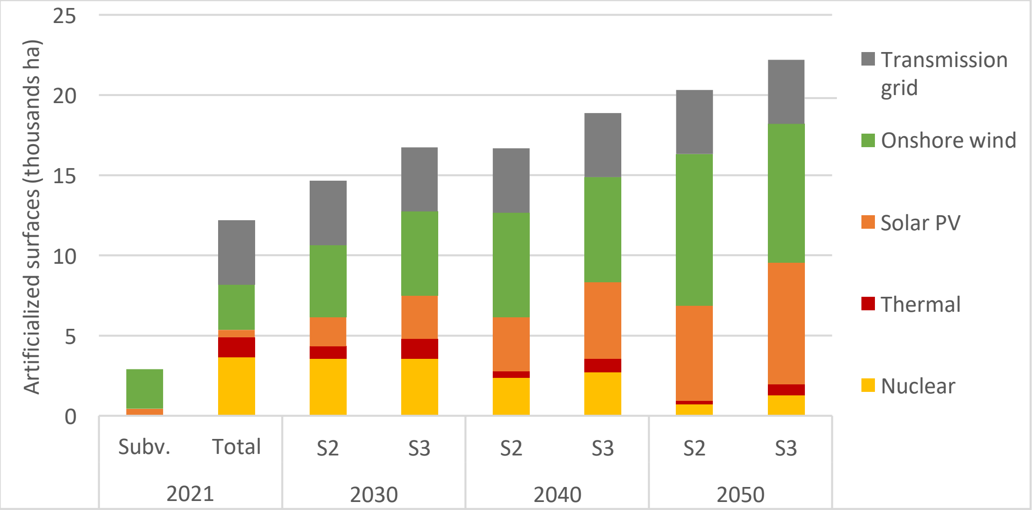

Figure 56: Artificialized surfaces due to electricity mix (thousands ha)

Artificialization refers to the alteration of the ecological functions of the soil (biological, hydrological, climatic, and agronomic functions), while impermeabilization refers specifically to the alteration of hydrological functions. Impervious surfaces, for example, include the base of wind turbines, solar panel foundations, delivery stations, and possible tanks in solar parks. Artificialized surfaces correspond to both impervious areas and access roads.

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proportion of renewables need more flexibility solutions (e.g. thermal power stations, batteries, demand flexibility, etc.) and greater development of electricity networks. The surfaces used by these flexibility solutions associated to renewables are however limited, as renewable facilities require more space than flexibilitysolutions (for example, S2 and S3 scenarios take into account flexibility needs in thermal power plants).

Currently, most impervious surfaces for the electricity system are associated with thermal production facilities (nuclear and gas in particular). Artificialized surfaces are fairly evenly distributed among thermal power plants (including nuclear), renewable facilities, and the grid. To give an order of magnitude, RTE indicates that with "*with around 12,000 hectares of artificialized surfaces and less than 3,000 hectares of impervious surfaces, the infrastructure of the entire electricity system (excluding the distribution network) represents about 0.35% of artificialized surfaces in France and 0.2% of impervious surfaces."* Excluding artificialized surfaces resulting from former production sites from the assessment, artificialization generated by the development of renewables appears to be controlled. Electricity generation capacities (renewables, nuclear and other thermal generation means) would result in twice as much artificialized surfaces in 2050 than in 2021 in these scenarios. The development of the grid (necessary to accommodate larger share of variable renewables and electrify end-uses) would also result in artificialization. By 2050, according to RTE, the electricity system would occupy less than 1% of currently artificialized surfaces in France, still much less than buildings or road transport infrastructure. To limit artificialization, it is possible to prioritize already artificialized sites (former landfills and quarries, slag heaps, industrial wastelands ...) for new renewable facilities, especially photovoltaic.

RTE indicates that a major issue is the classification of surfaces under solar panels. According to RTE's scenarios, between 70,000 and 200,000 hectares are needed for ground-mounted solar, representing between 0.1% and 0.3% of the French territory. A part of these surfaces can be considered as artificialized but the rest as allowing for co-uses. Indeed, most installations are vegetated and therefore have much smaller impacts on biodiversity compared to other artificialized areas (buildings, road transport, etc.). Moreover, these facilities generally affect the soil for a shorter time than other infrastructures, as panels are installed using stakes that can be removed at the end of the installation's lifespan. But since ground-mounted solar is very space consuming, it is still likely to compete with other uses (agriculture, buildings ...), and therefore generate indirect land use changes.

6.3.1.2 Co-uses areas

Of the total surface area occupied by the electrical system, most is accessible for co-use, particularly for agricultural and natural purposes. Most of these areas are related to onshore wind power and the electricity grid, and to a lesser extent to ground-mounted solar power.

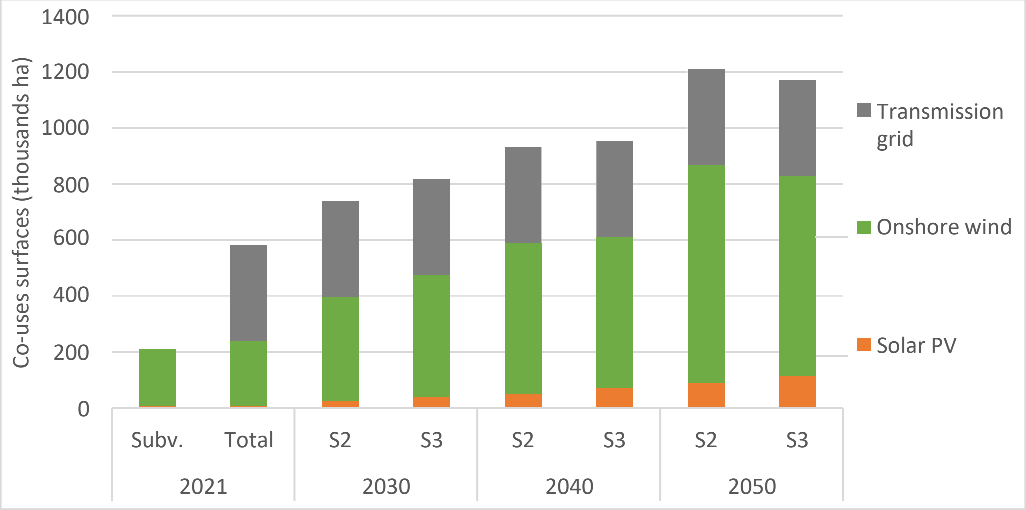

Figure 57: Surfaces of co-uses with the electricity mix (thousands ha)

RTE indicates that as of today 88% of the surfaces around wind turbines are agricultural territories, and 9% are forests. These surfaces correspond to a radius of 500 meters around the wind turbines, which is the minimum distance to a dwelling for the installation of a wind turbine in French legislation (established to limit noise pollution among others). The area around wind turbines is compatible with agricultural activities without significant issues according to the literature (excluding artificialized surfaces). Co-uses in natural areas (including forests) are also possible, but strong constraints for biodiversity protection must be taken into account through local impact studies (particularly for birds and bats).

The electric grid is expected to expand to accommodate renewable energy. The quantified evaluation of surfaces occupied by the grid corresponds to the year 2020, so these surfaces are slightly underestimated for prospective horizons. Similar to wind power, numerous co-uses are possible with the grid, particularly for agriculture or natural areas. Moreover, transmission lines can be buried to reduce land occupation.

The point of concern regarding co-use surfaces mainly focuses on photovoltaic (PV) and competition for land use. RTE emphasizes that brownfields will not be sufficient to accommodate all capacities. Agrivoltaics, the combined production of PV and agricultural activities, therefore appears as a necessity, especially considering that the conversion of agricultural lands into surfaces dedicated energy production only is prohibited. The coexistence between these uses is not straightforward and must be organized in advance to ensure that solar installations can adapt to agricultural practices without hindering them, for example by elevating or spacing out the panels to allow for mechanized agriculture. Several agricultural activities appear to be compatible with solar production, including livestock farming, viticulture, market gardening, cereal cultivation, and meadows. It appears that in some contexts, the presence of solar panels can be an asset to agricultural production, particularly by providing shade. Agrivoltaics is a new practice that still needs to be studied and regulated; recently, ADEME has published a study on this topic[73] and agrivoltaics has been defined in law[74]. To limit land occupation, a greater development of rooftop solar is possible, but it is more expensive and requires access to these surfaces. Floating PV solutions are also possible alternatives, especially on flooded quarries.

6.3.1.3 Other subsidised renewables

Offshore wind, small-scale hydropower, and biomethane production are subsidized renewable energy, but have not been quantified in terms of land use due to lack of data in the RTE study. However, ADEME has carried out a similar study[75], with a slightly different scope, including offshore wind and methanization.

For offshore wind, ADEME estimates a total footprint ranging from 142 000 ha to 475 000 ha, depending on the scenarios, with almost all of it available for co-uses (with less than 100 ha being impermeabilized). These co-uses include natural areas and fishing activities.

For methanization, ADEME estimates the current total footprint to be 1 600 hectares, of which 500 hectares are impervious. The surface area selected for the methanization site takes into account digestion, storage and energy recovery structures, traffic areas, etc. By 2050, ADEME's scenarios project a total footprint of approximately 15,000 ha, with about 4,500 ha being impervious. ADEME indicates that the activities related to methanization on these 15,000 ha are incompatible with agricultural, forestry, or natural uses. Methanization, therefore, appears to be an energy production method that requires significant land occupation. By 2050, methanization will result in more impervious surfaces than the entire current electric power system, and a significant portion of land that is incompatible with agricultural, forestry, or natural uses related to renewable energy production (between 20% and 60% depending on ADEME's scenarios). Furthermore, the cultivation of feedstocks for methanization will also require agricultural land, although the impacts appear to be less significant for biodiversity. In two of ADEME's scenarios, approximately 250 000 ha will be dedicated to feedstock cultivation for methanization by 2050. Intermediate crops can be a way to mitigate the impact on land-use, and are estimated to be around 2.6 to 3.2 million hectares in 2050 according to ADEME.

Small-scale hydropower, like offshore wind power, occupies only a marginal amount of land area, as it involves installations along rivers and not large dams with water reservoirs (which are not subsidized under the scope of this study).

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[73] ADEME, *Caractériser les projets photovoltaïques sur terrains agricoles et l'agrivoltaïsme* [Link][FR]

[74] French law, *LOI n° 2023-175 du 10 mars 2023 relative à l'accélération de la production d'énergies renouvelables* [Link][FR]

[75] ADEME, *Transition(s) 2050*, Feuilleton *Sols : quels enjeux pour une gestion durable des sols à l'horizon 2050* ? [Link][FR]

6.3.1.4 Preservation of natural areas

Given the required surface areas for renewable (including co-uses), it is interesting to compare the total footprint of the electricity system by 2050 with the available land.

To quantify the surface area occupied by an installation, RTE has used a convention defining the occupied surface as the area where it is not possible to build another installation of the same type. This convention accounts for the fact that wind turbines must be sufficiently spaced apart to avoid production disturbances from excessive turbulence. The entire electricity system (including production and transmission network) would then occupy between 1 and 1.6 million hectares by 2050 (including co-uses), representing approximately 2 to 3% of the national territory. Additionally, offshore wind energy would occupy areas ranging from 142 000 to 475 000 hectares at the 2050 horizon.

The availability of land depends on various factors, in particular legislation. For onshore wind energy, legislation imposes numerous constraints, with the most significant being a minimum distance of 500 meters from residential areas (to limit noise pollution, see end of Section 6.1.3). Other regulatory constraints are also important, such as those around airports, radars, military zones, industrial zones, etc. Environmental constraints, including the protection of biodiversity and natural spaces, also limit the development of wind energy (nature reserves, Natura 2000 sites, forests, wetlands, areas of interest for fauna and flora, etc.). Taking into account the 500-meter constraint for wind turbines, RTE estimates that approximately 14% of the French territory is suitable for wind energy installation. Considering that the surface needs for wind energy would represent a maximum of around 2% of the national territory in its scenarios, it appears technically feasible to install these quantities of wind turbines while preserving natural spaces and respecting distance from residential areas. However, the most ambitious scenarios would require very high social acceptability of wind energy in these regions, especially considering that these areas are concentrated in a few regions (Bourgogne-Franche-Comté, Grand Est, and Hauts-de-France).

The impact assessment studies of wind farms projects focus particularly on important topics for social acceptability of wind turbines. An important dimension of impact assessment studies is the preservation of landscapes and cultural heritage. Studies on the visibility of the wind farm, using on-site photographs to account for topography, are thus conducted to assess impacts. These considerations may limit the size of wind turbines (to make them less visible), and thus make it necessary to install a larger number of turbines to achieve the same installed capacity.

Offshore wind farms are, by nature, located within natural areas (the sea), although these areas are often subject to human activities, such as fishing. Environmental impact assessments prior to the installation of offshore wind farms must consider the protection of natural spaces. Moreover, France has numerous marine protected areas, which must be taken into account when defining suitable zones for offshore wind energy development (in the framework of strategic documents governing such development).

6.3.2 Biodiversity

Summary:

Climate change and biodiversity loss are interlinked challenges, and climate change is one of the five direct drivers of biodiversity and ecosystem change, according to the IPBES. By contributing to climate change mitigation, renewable energy production is also important for biodiversity conservation.

On the other hand, land use change due to renewables is one of the main drivers of biodiversity loss associated to renewables. Furthermore, in their operation phase, renewable energies are associated to negative impacts, especially wind turbines regarding the increased mortality of birds and chiropterans (although this impact is on average relatively small compared to other threats to birds). Mining and construction works can also generate pressures on biodiversity. Impact assessments are conducted for every project to mitigate the environmental impact, protect locally endangered species and limit the disturbance on the vicinity of the wind farms.

A qualitative presentation of biodiversity challenges associated with renewable energy development is provided in this section based on a literature review. This complements the quantitative approach on land used by renewables described in section 6.3.1. Land use change is indeed a major impact on biodiversity, both directly (at the renewable facility site) and indirectly (by generating land pressure).

6.3.2.1 Impact of Climate Change on Biodiversity

Climate change and biodiversity loss are interconnected challenges, as highlighted by a report from a joint workshop of IPBES and IPCC[76] which indicates that *"increased atmospheric greenhouse gas concentrations lead to increased mean temperatures, altered precipitation regimes, increased frequency of extreme weather events, and oxygen depletion and acidification of aquatic environments, most of which adversely affect biodiversity. Reciprocally, changes in biodiversity affect the climate system, especially through their impacts on the nitrogen, carbon and water cycles."*

The report explains that climate change alters environments (abiotic factors), which has a significant negative influence on biodiversity. Moreover, the report indicates that climate change often interacts with and exacerbates threats to biodiversity such as habitat degradation, emergence of diseases, spread of invasive species, and human resource extraction needs. Combating climate change is therefore crucial for biodiversity conservation, in order to avoid exceeding the adaptive capacity of ecosystems. Furthermore, the report highlights the risks posed by changes in land use, overexploitation, and pollution.

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[76] IPBES-GIEC, *Scientific outcome of the co-sponsored workshop on biodiversity and climate change* [Link][EN]. The IPBES is the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, a structure emanating from the UN whose functioning is inspired by the IPCC.

The report also emphasizes that natural and technological solutions can help mitigate and adapt to climate change while promoting biodiversity conservation. Agrivoltaics and protection of ecosystems that capture significant amounts of carbon are examples of such solutions.

Thus, by allowing the replacement of fossil fuels, renewables contribute to reduce the biodiversity loss that would have otherwise been caused by the supplementary increase in global temperature.

6.3.2.2 Upstream impacts of renewable energy production

Prior to energy production, the establishment of renewable energy systems themselves generates pressures on biodiversity, particularly during the extraction of raw materials and the construction of facilities.

Impact of mining activities on biodiversity

Mines require significant land areas to exploit resources, resulting in land use change. This change in land use leads to habitat reduction and fragmentation, resulting in local losses for fauna and flora, as well as a reduction in ecosystem services.

Moreover, mining activities generate pollution, as discussed in section 6.1.3. Water and soils, in particular, as well as air, are susceptible to pollution from mineral extraction and processing. These pollutions therefore affect biodiversity, both locally and further afield as pollutants can be transported by water. Mining accidents also impact biodiversity. However, it should be noted that mining activities serve many other purposes beyond renewables.

Given the volumes of metals required and the limitations on resource availability, some stakeholders are considering deep-sea mining. The IEA and IPBES indicate that research on biodiversity impacts is lacking, but highlight that the risks appear to be particularly significant.

Impact of construction works

The construction of renewable facilities can also impact biodiversity. In particular, the passage of building site machinery can cause damage to flora and the noise generated by the works can potentially scare away fauna. Construction works can also lead to the introduction of invasive species and generate pollution.

The land areas occupied by renewables, quantified in section 6.3.1, are also modified. The fauna and flora present at the site may lose their habitat temporarily or permanently, leading to losses and displacements.

For offshore wind, it appears that the noise generated during construction of the wind farm has a significant impact on biodiversity, as identified by FRB in their literature review (see below).

6.3.2.3 Impact of Renewable Facilities during Operation

Renewable energies can also have impacts on biodiversity during the operational phase. The "Foundation for Research on Biodiversity" (FRB) has produced a literature review on this subject, which greatly informs this section[77].

Photovoltaic Solar

The FRB indicates that the main impact of solar installations is linked to land use. Indeed, the surfaces occupied by solar power plants result in loss or fragmentation of animal habitats, leading to a reduction in feeding areas and potential isolation. Other impacts identified by the FRB are direct mortality of birds, intoxication of individuals (due to panel treatment products and herbicides), and the creation of local microclimates.

Wind Energy

A commonly highlighted effect in debates is mortality due to collision and barotrauma (pressure shock caused by blade movement). This mortality mostly concerns birds and bats, and depends on the fauna present at the installation site and the characteristics of the wind turbines. The FRB indicates that wind turbines causing the highest bird mortality are the oldest ones, installed before this issue was as well addressed as today (in particular prior to the emergence of the Natura 2000 network and the development of mitigation measures). A study by the "League for the Protection of Birds" (LPO)[78] indicates that bird mortality ranges from 0.3 to 18.3 per turbine per year. Therefore, mortality due to wind turbines is limited. This limited impact needs to be balanced since it does not reflect the fact that specific endangered species of birds can be impacted locally, where a couple of deaths can jeopardize the development of these species in the vicinity of the farm.

Other effects identified in the literature include avoidance behaviors of wildlife in the vicinity of wind farms (in particular the "barrier effect"), displacements and mortality caused by loss or modification of habitat, and disturbances related to noise or electromagnetic fields.

The literature indicates specific effects of offshore wind energy that can be positive for biodiversity. These include the "reef effect" (colonization of the base of the installation by benthic species) and the "reserve effect" (related to the limitation of fishing activities near the wind turbines). The FRB emphasizes that the reef effect is limited to about a hundred meters and largely depends on the types of installations.

Run-of-River Hydropower

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[77] *Fondation pour la recherche sur la biodiversité* (FRB), *Energies renouvelables : quels impacts des installations de production sur la biodiversité ?* [Link][FR]

[78] *Ligue pour la protection des oiseaux*, LPO-ONCFS, *Eoliennes et biodiversité, synthèse des connaissances sur les impacts et les moyens de les atténuer* [Link][FR]

The FRB indicates that the impact on biodiversity of small hydropower plants has been little studied, unlike that of large dams (which are not included in the scope of this study). One identified impact is that hydropower weirs can fragment habitats and disrupt migratory routes of certain fish species. Questions also arise regarding the effect of hydropower systems on sediment deposits, which constitute habitats for many species.

Energy Crops

Energy crops for the production of biomethane (subsidized in mainland France), biogas for electricity production (subsidized in the scope of this study in NIZs), and biodiesel (in a prospective approach in overseas territories) have impacts on biodiversity. These impacts are mainly related to competition for land occupation, which is necessary for biomass production. They largely depend on the converted surfaces and the intensity of agricultural practices (irrigation and use of fertilizers and pesticides, in particular). Birds nesting in meadows and pollinators can be affected by land use change and crop conversion. Moreover, the residues of digestate from biogas plants are an interesting natural fertilizer for agriculture but can potentially generate pollution.

6.3.2.4 Mitigation Solutions for Renewable Energy Systems Impacts

In order to limit the impact of renewables on biodiversity, several solutions can be considered.

Upstream of the installations, during the resource extraction phase, it is possible, for example, to prioritize underground mines to reduce surface occupation. However, the International Energy Agency (IEA) notes that open-pit mining has lower energy requirements than underground mining, thus generally leading to lower emissions.

As for the renewable facilities themselves, impact studies must be conducted prior to construction for authorization. These studies cover the entire lifespan of the installations: construction, operation, and decommissioning. The guide on impact studies for wind energy[79] indicates that *"the environment must be approached in its entirety: population and human health, biodiversity (fauna, flora, natural habitats...), land, soil, water, climate, material goods, cultural heritage, and landscape, as well as the interactions between these elements."*

These impact studies aim to identify the effects of renewable production plants on the environment and accordingly plan mitigation measures. The objective is first *"to avoid significant negative effects of the project on the environment or human health and reduce effects that could not be avoided.* [And then] *to compensate, when possible, for significant negative effects of the project on the environment or human health that could not be avoided or sufficiently reduced."*

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[79] *Ministère de la transition écologique* et de la Cohésion des territoires (Ministry of Ecological Transition and Territorial Cohesion), *Guide relatif à l'élaboration des études d'impacts des projets de parc éoliens terrestres* [Link]

Examples of avoidance measures include avoiding the establishment of renewable power plants in areas of high biodiversity value (rich biodiversity habitats, migratory bird corridors, etc.), or avoiding working at night and during reproductive and migratory periods. An example of reduction measure for wind turbines is to implement deterrent devices to keep wildlife away. Compensatory measures may include habitat restoration at other sites, restoration of natural environmental continuity (*e.g.,* planting hedges), or reinforcement of impacted species populations.

For wind energy, specific solutions include leaving open spaces for bird movement between parks in areas with high wind potential, slowing down or stopping turbines under certain conditions (*e.g.*, during migratory periods), or installing noise reduction devices on turbine blades.

For solar energy, developing rooftop panels rather than ground-mounted panels helps limit land use. Similarly, it is possible to install photovoltaic panels above bodies of water or on already artificialized surfaces (industrial wastelands, etc.). Agrivoltaics, if well-designed, can allow for agricultural activities to continue while producing renewable electricity. Other impact reduction measures for ground-mounted solar facilities include spacing out panels and vegetating the ground.

Depending on the river, operators of run-of-river power plants may be required to build fish ladders, which aim to allow fish to bypass obstacles created by the power plant.

Finally, for biogas and biomethane production, a solution to reduce impacts is to use by-products or multi-service environmental intermediate crops (cover crops used to produce energy), rather than crops dedicated solely to energy production.

6.4 Climate change adaptation

Summary:

Solar and wind renewable generation in France will not be significantly affected by climate change in the future. Hydroelectric power generation will be slightly more affected by changes in hydrological cycles, but average annual rainfall is not expected to change significantly, according to RTE. Renewable energies can also, to a limited extend, contribute directly to the adaptation to climate change, with possible synergies with photovoltaic production, through agrivoltaics and solar installations on water bodies to limit evaporation.

The objective set by the Paris Agreement is to keep the increase in global average temperature well below 2°C compared to pre-industrial levels, and to aim to limit the increase to 1.5°C. Even if the most ambitious targets are met, climate change is already a reality as demonstrated by the work of the Intergovernmental Panel on Climate Change (IPCC). In mainland France, temperature rise has already reached 1.7°C above pre-industrial levels (over the past decade)[80]. Therefore, it is important to study whether renewable energy systems will be resilient to climate change and if they can provide adaptation solutions.

Adaptation solutions to climate change in synergy with renewables

Renewable energy systems can be designed to provide adaptation solutions to climate change in addition to producing low-carbon electricity. In particular, the literature review conducted as part of this study identified possible synergies with photovoltaic production, through agrivoltaics and solar installations on water bodies. The IPBES study[81] states: *"grazing underneath solar panels can enhance soil carbon stocks, and grazing as well as cropping associated with solar farms could provide food. Studies also indicate that vegetation underneath the solar panels can provide pollinator habitat thereby benefiting nearby agricultural land. Solar photovoltaic cells supported on the surface of water bodies might reduce evaporation from the water bodies which could be beneficial to hydroelectric reservoirs in arid regions."*

Weather and climate change effects on the electricity system

RTE[82] has studied the impact of climate change on the electricity system by 2050. Even today, *"the effects of weather on the system are numerous and varied: temperature and sunshine variations influence the electricity consumption of households and businesses, wind power production is naturally dependent on wind conditions, photovoltaic production depends on solar radiation, but also on*

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[80] *Ministère de la Transition écologique et de la Cohésion des territoires* (Ministry of Ecological Transition and Territorial Cohesion), *La trajectoire de réchauffement de référence pour l'adaptation au changement climatique (TRACC)* [Link][FR]

[81] IPBES-IPCC, *Scientific outcome of the co-sponsored workshop on biodiversity and climate change* [Link]

[82] RTE, *Futurs énergétiques*, chapter 8 (climate) [Link][FR]

temperature which can affect panel efficiency, while the availability of hydropower and nuclear power plants depends on river flows and/or water temperature."

Climate models for 2050 indicate that heatwaves will become more frequent and intense, while cold spells will become rarer. Climate change will therefore result in decreased heating consumption in winter and increased air conditioning consumption in summer.

Resilience of the electricity system to climate change

RTE indicates that by 2050, wind and solar radiation will not change significantly, and emphasizes that "*the issue about the evolution of wind and solar production in the long term therefore lies less in the effect of climate change than in the increased dependence of the supply-demand balance on these production sources."*

Furthermore, the study highlights that the hydrological cycle will be modified and that droughts will become more frequent. According to RTE, the average annual precipitation volume is not expected to change significantly but climate change will alter the regional and seasonal distribution of precipitation, and interannual variability will remain significant, with some years being very rainy and others very dry. The management of hydropower stocks will therefore have to evolve, but subsidized hydroelectricity appears to be a resilient production source in the face of climate change.

In addition, during heatwaves and droughts, nuclear power plants located near rivers may experience decreased availability (depending on their cooling system type). This corresponds to regulatory requirements aimed at limiting water withdrawals and heating to protect the environment. Without adaptation measures or regulatory changes, climate change will increase the risk of unavailability of nuclear power plants. However, RTE notes that the average annual lost production will remain very low (from 1 to 2 TWh). The development of wind and solar power will make it possible to produce low-carbon electricity during these periods of nuclear unavailability.

Carbone4 has studied the costs induced by climate change on the electricity transmission and distribution networks. In particular, the consultancy indicates that the intensification and multiplication of extreme weather events will cost between €800 and €1,700 million in France, based on an analogy with a similar study carried out on the American power grid[83].

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[83] Carbone 4, *Le rôle des infrastructures dans la transition bas-carbone et l'adaptation au changement climatique de la France - Annexe résilience des infrastructures* [Link][FR]

7 Annexes

7.1 Electricity production by NIZ

Historical electricity production in each non interconnected zone

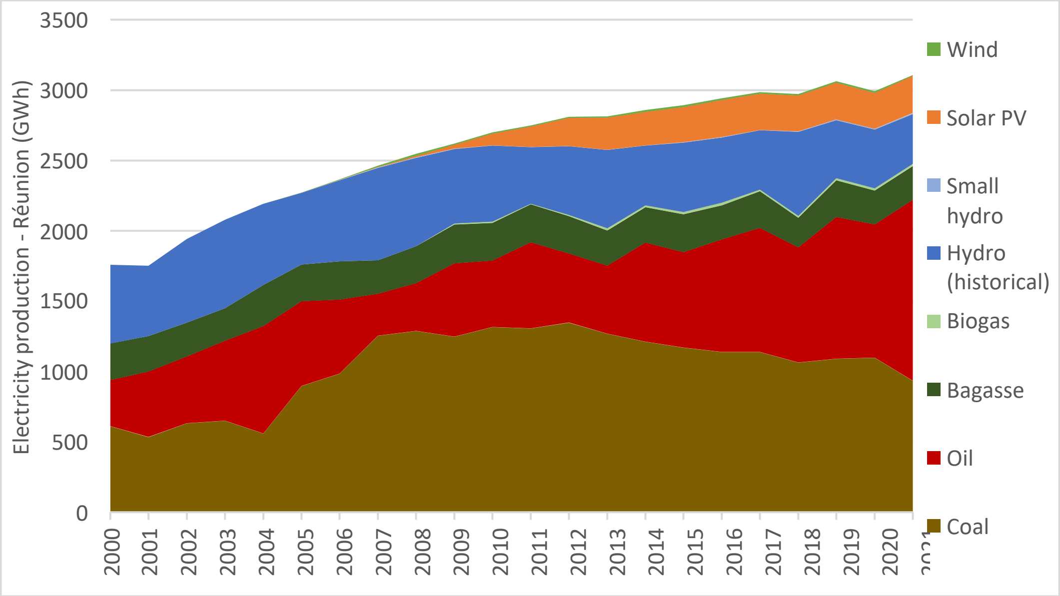

Figure 58: Historical annual electricity production in Réunion (GWh)

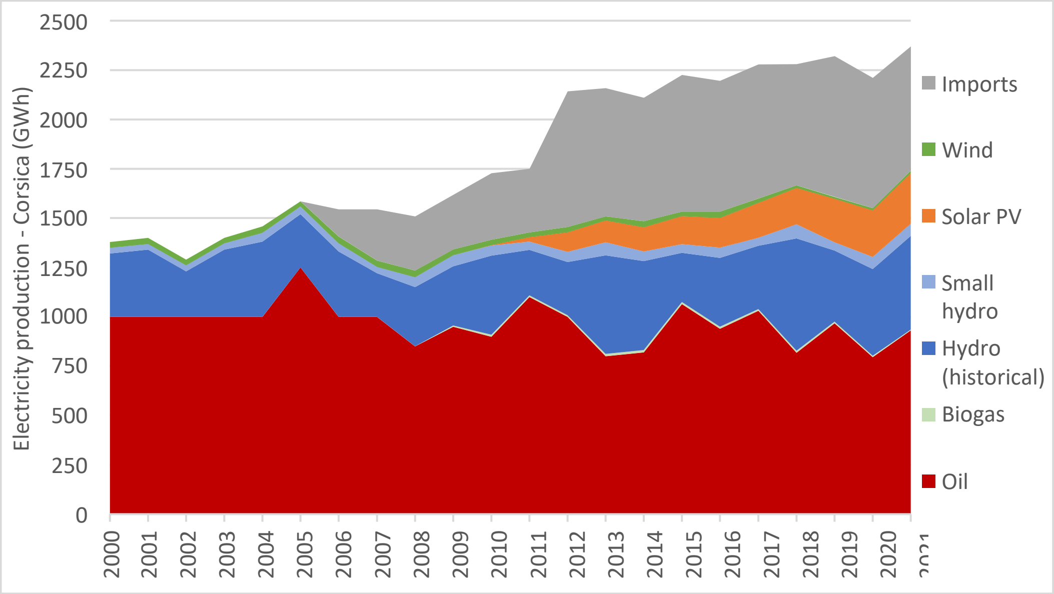

Figure 59: Historical annual electricity production in Corsica (GWh)

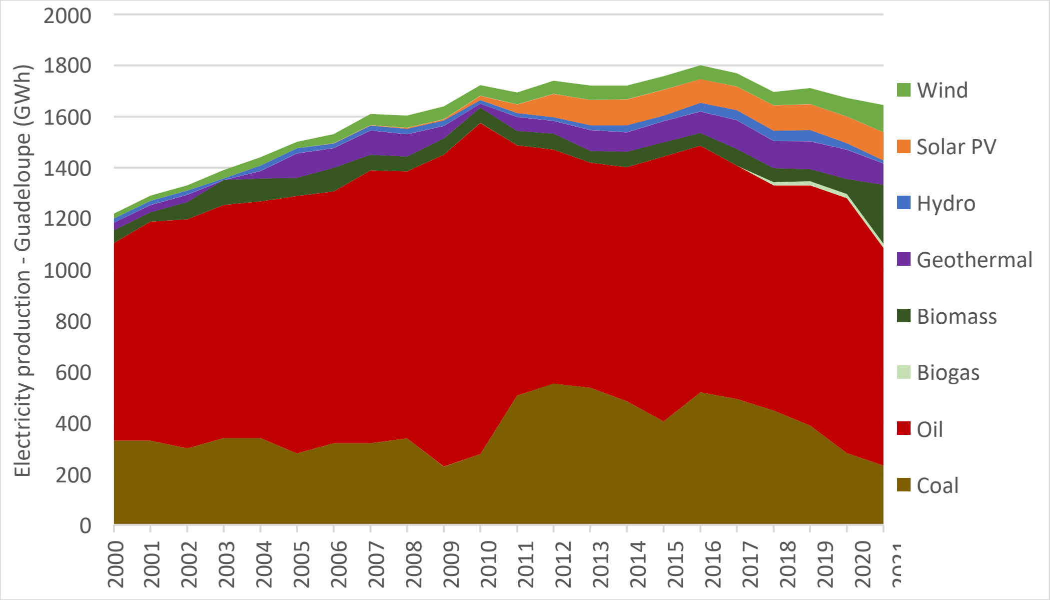

Figure 60: Historical annual electricity production in Guadeloupe (GWh)

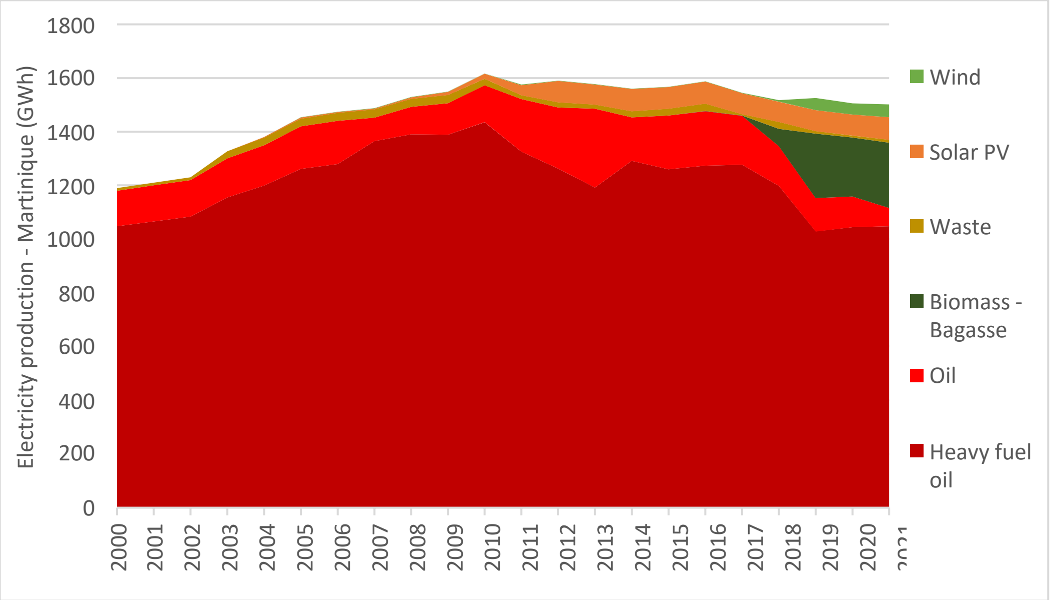

Figure 61: Historical annual electricity production in Martinique (GWh)

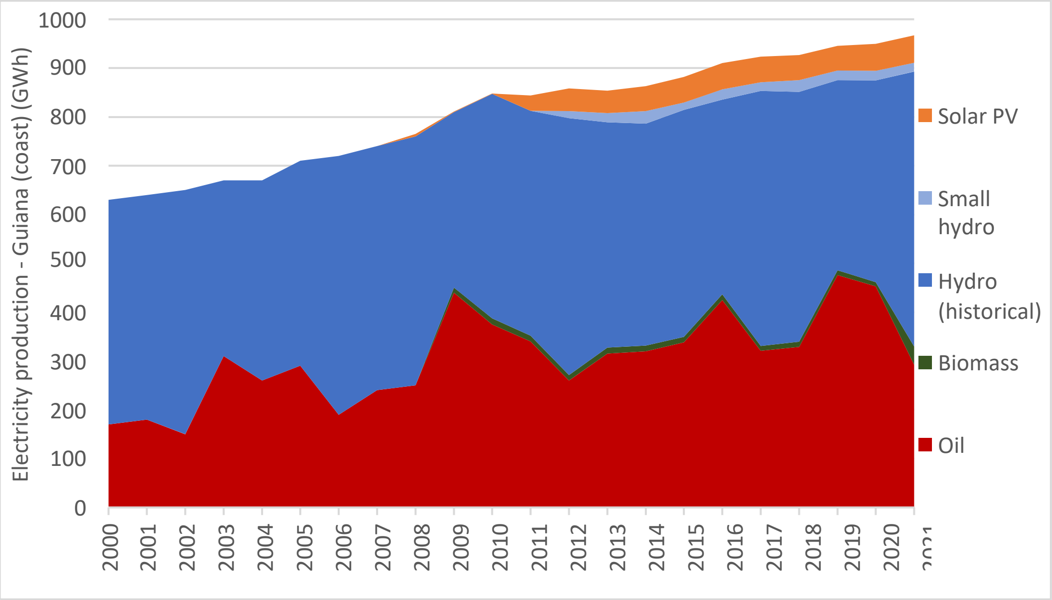

Figure 62: Historical annual electricity production in French Guiana (GWh)

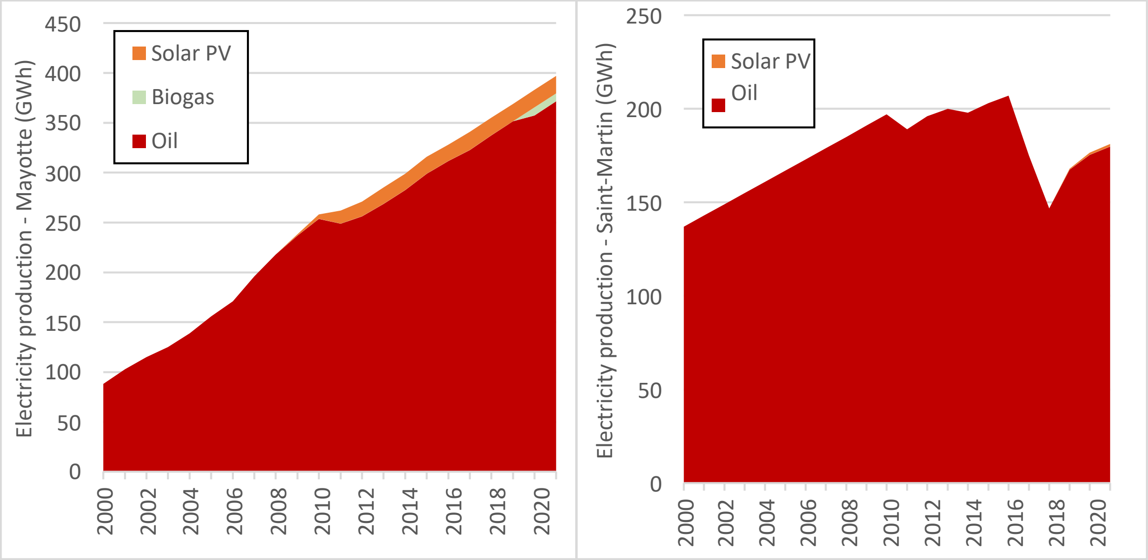

Figure 63: Historical annual electricity production in Mayotte and Saint-Martin (GWh)

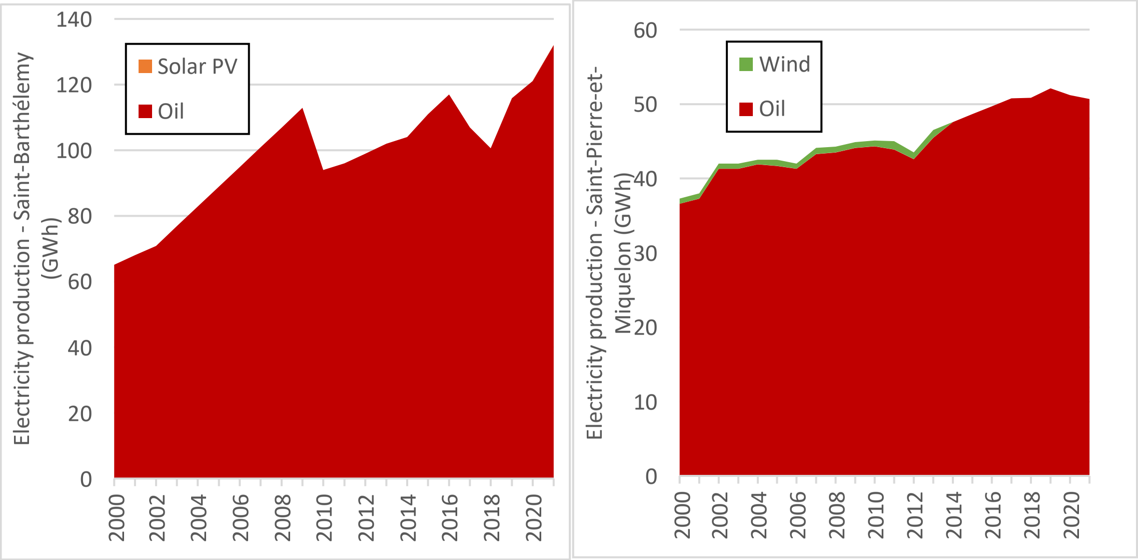

Figure 64: Historical annual electricity production in Saint-Barthélemy and Saint-Pierre-et-Miquelon (GWh)

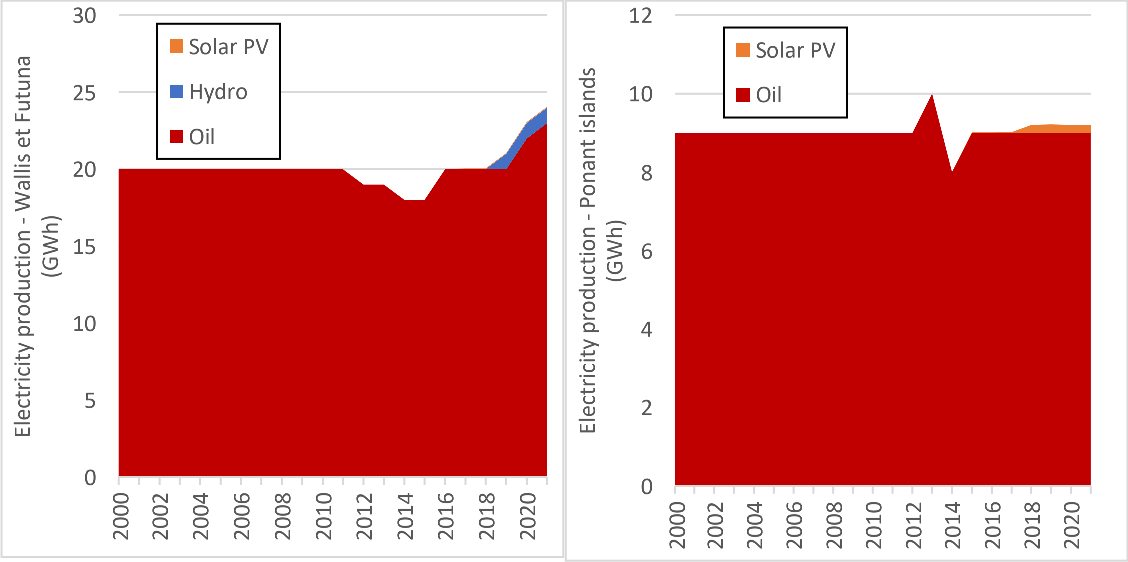

Figure 65: Historical annual electricity production in Wallis-et-Futuna and the Ponant islands (GWh)

7.2 Artelys Crystal Super Grid

For over twenty years, Artelys has been developing and continuously improving its own optimization software suite specialized in energy: the Artelys Crystal suite. Among this suite, *Artelys Crystal Super Grid* enables the simulation and optimization of interconnected energy systems from the regional to the continental scale, taking into account the links between electricity, gas, hydrogen and heat. This tool has been selected by the European Commission for its European multi-energy model METIS[84].

The Artelys Crystal Super Grid models allow for a detailed representation of each type of energy demand and production asset and their technical and economic characteristics: demand flexibility, installed capacity and investment costs of production methods, fixed and variable operating costs, minimum operating power, gradients, reserves, optimal management of hydraulic reservoirs, management of LNG imports, seasonal gas storage, variability of renewable production and the main constraints on electricity, gas and hydrogen networks between the different zones studied.

Based on all the parameters defined, Artelys Crystal Super Grid allows optimizing the installed capacity and the operating strategy of each type of energy in order to achieve an energy supply-demand balance at the lowest cost for the entire system, and according to given security of supply criteria. It istypically used at the national or supranational level and at the hourly time step. Artelys Crystal Super Grid can also model multi-energy technologies such as electrolysis, methanation or cogeneration.

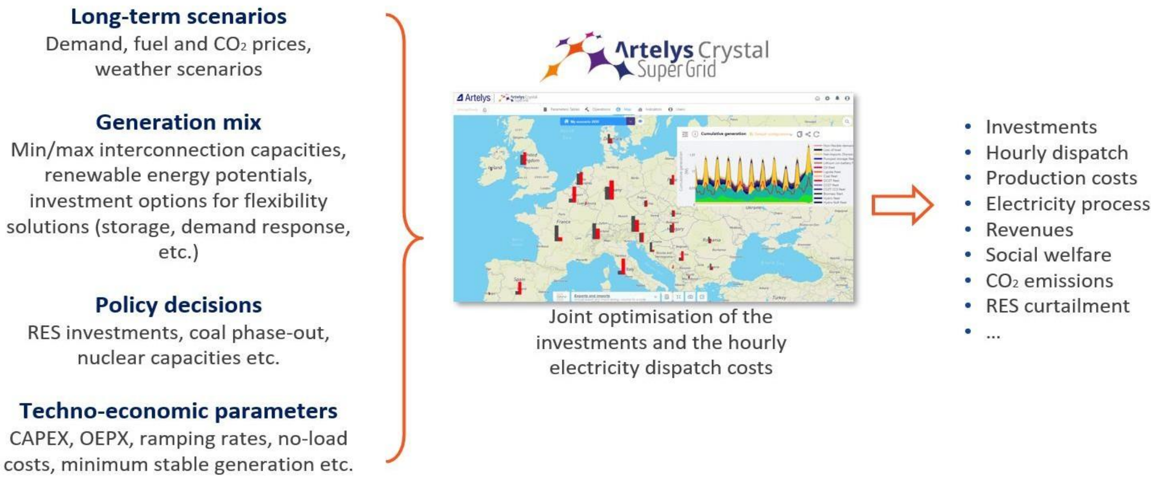

Figure 2 - High-level description of Artelys Crystal Super Grid

Artelys Crystal Super Grid is regularly used, especially by researchers and academics, to assess the social welfare impacts of infrastructure projects (e.g., interconnections, smart grid technologies, etc.), to analyze the impacts of policy measures, to perform cost-benefit analyses, or to find the optimal set of investments to ensure that a given security of supply constraint is met and/or that a given decarbonization target is achieved.

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[84] METIS presentation [Link]

7.3 Modelling specificities for past and future for mainland France

7.3.1 Modelling specificities for future

The model used for the future is the same as implemented in the study *Transition(s) 2050* for ADEME[85]. The French electricity mix was built by ADEME in its scenarios. The European power system was built using TYNDP2020 Distributed Energy scenario. The French electricity system is regionalized, and the modelled European countries are aggregated into several blocks (consistent with the interconnections at French borders): the British Isles, the Iberian Peninsula, Italy, Central Europe, and Northwest Europe (cf. Figure 18).

The years 2025, 2030, 2035, and 2040 were explicitly modeled to cover the entire period during which currently subsidized renewable installations can still receive subsidies (20-year contracts for power purchase). The intermediate years are interpolated.

The production at an hourly level, by technology and by zone, is a direct output of the model.

7.3.2 Modelling specificities for past

7.3.2.1 General approach

The modelling for the past relies on a different approach to represent the productions actually realized as faithfully as possible. The approach adopted is the same as that implemented in the study of the benefits associated with the development of renewable and recovery energies in France for ADEME[86]. Metropolitan France is explicitly modelled (as for the future), while neighbouring countries are modelled in a simplified manner through import-export capacities and historical market prices.

The explicitly modelled years replicate the historical hourly profiles of demand and availability for solar, wind, run-of-river hydroelectricity, nuclear, and several other non-flexible means of production (biomass, biogas, waste, tidal, geothermal, cogeneration). The model achieves hourly supply-demand equilibrium by optimizing import-exports (driven by historical prices), fossil thermal production (gas, coal, oil), and the remaining hydroelectric production (management of hydrological stocks calibrated to obtain annual production on the one hand and use of pumped storage on the other hand[87]).

The modelled years range from 2015 to 2019. Previous years were not modelled due to data availability constraints. Productions in the reference scenario for the past correspond to the actual history. Productions in the counterfactual scenario are calculated from the models for the years 2015 to 2019, by setting renewable capacities at their level in year 2000.

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[85] Report (FR) : [Link]

[86] Report (FR) : [Link]

[87] Contrary to the RTE figures available on the ODRÉ, the production of the STEPs is not included in the total hydroelectric production in this report, which explains potential differences.

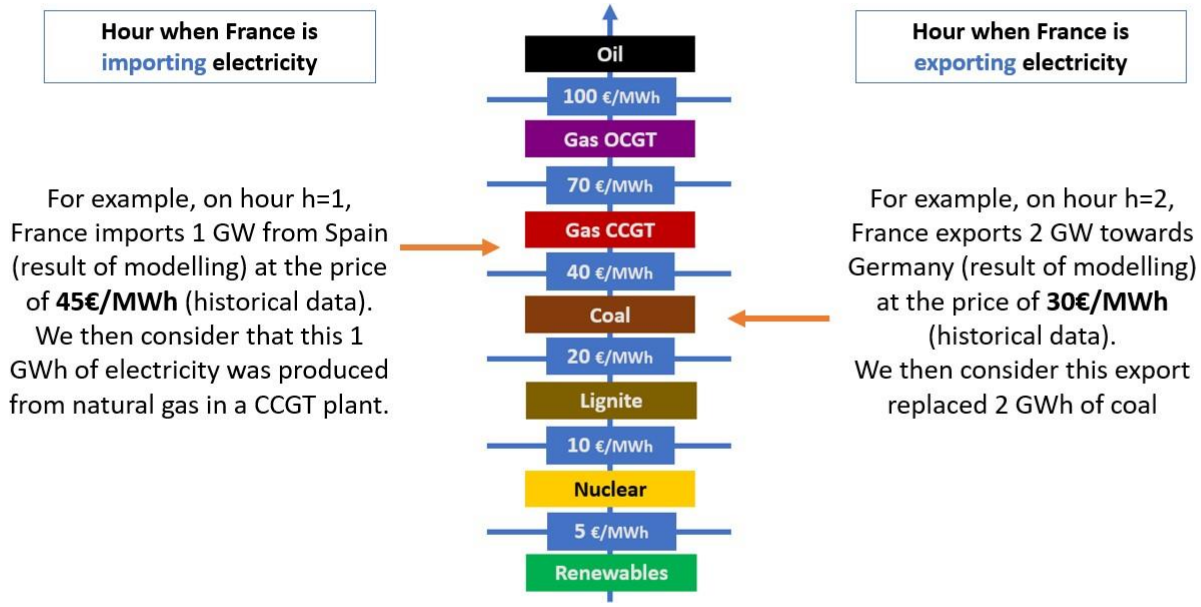
7.3.2.2 Calculation of electricity production replaced abroad

The key output of the modelling work is the production (with a breakdown by technology for France) and import-export at an hourly level. The results for France are used as such. The hourly import-export profiles are then processed to deduce the productions that additional renewables have replaced in neighbouring countries.

Imports and exports in Europe follow an economic logic: as long as interconnections are not saturated, the least costly means of production is called upon, regardless of its location in Europe (taking into account network constraints). Renewable energy (and nuclear) present low production costs (even though they have high construction costs), while fossil means of production have higher production costs (the cost depends more on the fuel than on installation costs). Therefore, non-storable renewable energies are produced first and help avoid fossil imports from neighbouring countries.

The development of renewable energy thus has a double effect abroad. On the one hand, it allows for more exports (renewable energy being cheaper to produce than fossil energy, it can be exported). On the other hand, developing renewables reduces the amount of energy imported (cheap energy is produced in France, which implies less need for imports).

A post-processing algorithm is used with the results of the simulations to determine the production technology responsible for imports as well as the avoided production due to exports, according to the principle of marginality (see Figure 66). Imported and exported volumes at each border and for each hour are allocated to a production technology based on the hourly market price. Price categories are detailed in the figure below. This algorithm is used for both reference and counterfactual scenarios, and the avoided production by renewable energies (due to both additional exports and reduced imports) is determined through comparison.



Hour when France is importing electricity

For example, on hour h=1, France imports 1 GW from Spain (result of modelling) at the price of **45€/MWh** (historical data). We then consider that this 1 GWh of electricity was produced from natural gas in a CCGT plant.

Hour when France is exporting electricity

For example, on hour h=2, France exports 2 GW towards Germany (result of modelling) at the price of **30€/MWh** (historical data). We then consider this export replaced 2 GWh of coal

Figure 66: Illustration of the principle of the algorithm used to determine marginal electricity production mean abroad

7.3.2.3 Justification of working hypotheses

Fixed Nuclear Production

A modelling assumption for the past that may appear strong is related to the use of historical nuclear production data: by construction, this implies that additional renewable energies do not replace nuclear production in France. The goal of this assumption is to take into account nuclear unavailability due to maintenance reasons.

This assumption is justified by the fact that over the modelled period (before 2019), subsidized renewable production levels remain limited (less than 10% of national electricity production), and neighbouring countries' electricity mixes are still largely carbon-based. Rather than replacing French nuclear, additional French renewable production allows for additional exports and replaces fossil fuel productions in neighbouring countries.

This is also explained by RTE (the French TSO)[88]: nuclear production modulation (which may occur on weekends of low consumption and high renewable production) follow an economic logic and relate to stock management, and it is very rare for these modulations to be linked to export capacity saturation; modulated production is therefore not "lost" but simply postponed.

Modelling of Neighbouring Countries Through Hourly Prices

The specificity of the past modelling is that only the French production system is explicitly modelled. Exchanges with neighbouring countries are simulated through interconnections whose hourly price is the actually achieved historical price. The results of the optimization performed by Artelys Crystal Super Grid on imported and exported volumes are processed afterwards, with an algorithm that determines which productions have been replaced by additional renewable energies.

This modelling method allows for a more accurate simulation of neighbouring countries' electricity mixes compared to history, where a model in which all production means of different countries would be detailed would have some difficulties to capture historical market players' behaviours.

The validity of the modelling relies on the assumption that the presence or absence of additional renewables in France does not change market prices in neighbouring countries. This is valid as long as the difference in import and export volumes represents low capacities. Indeed, electricity prices (day-ahead market) are determined by the last unit brought online (marginal price), and price differences between zones are related to interconnection saturation (if the lines are not saturated, the price is identical). Thus, as long as the hourly volume remains low, the price will not be too modified: the last production unit called upon will be of the same type.

On an annual volume basis, the impact of additional renewables represents between 14 and 35% of exports and imports in the reference case. As these variations in imports and exports are spread

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[88] In particular in the 2019 adequacy report [Link][FR], and in a note on carbon footprint [Link][FR]

throughout the year (price is formed hourly) and across all borders, the assumption appears to be justified.

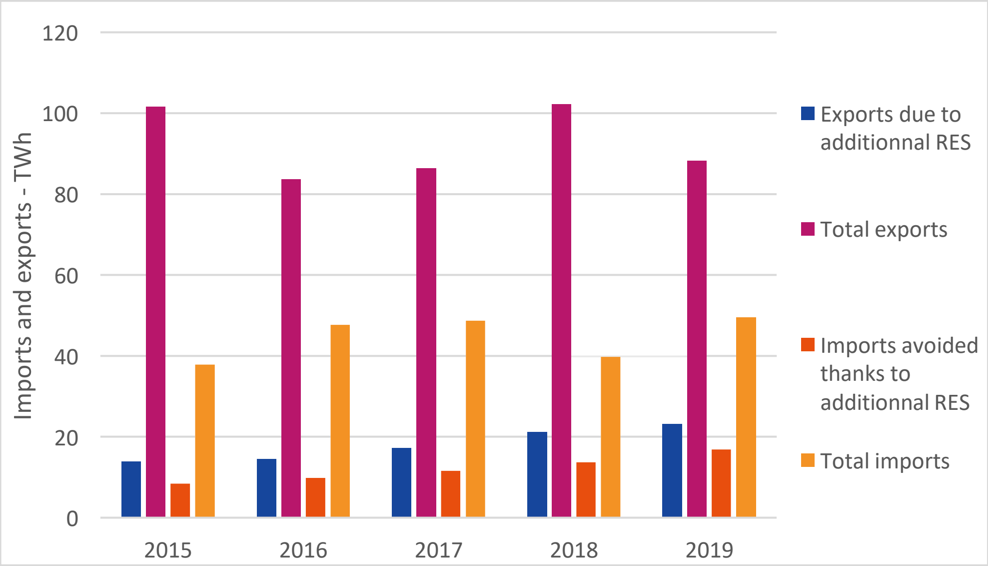

Figure 67: Share of imports and exports due to additional renewables in reference

7.4 Results per scenario

7.4.1 Representation of production change by mean of production for the modelled years

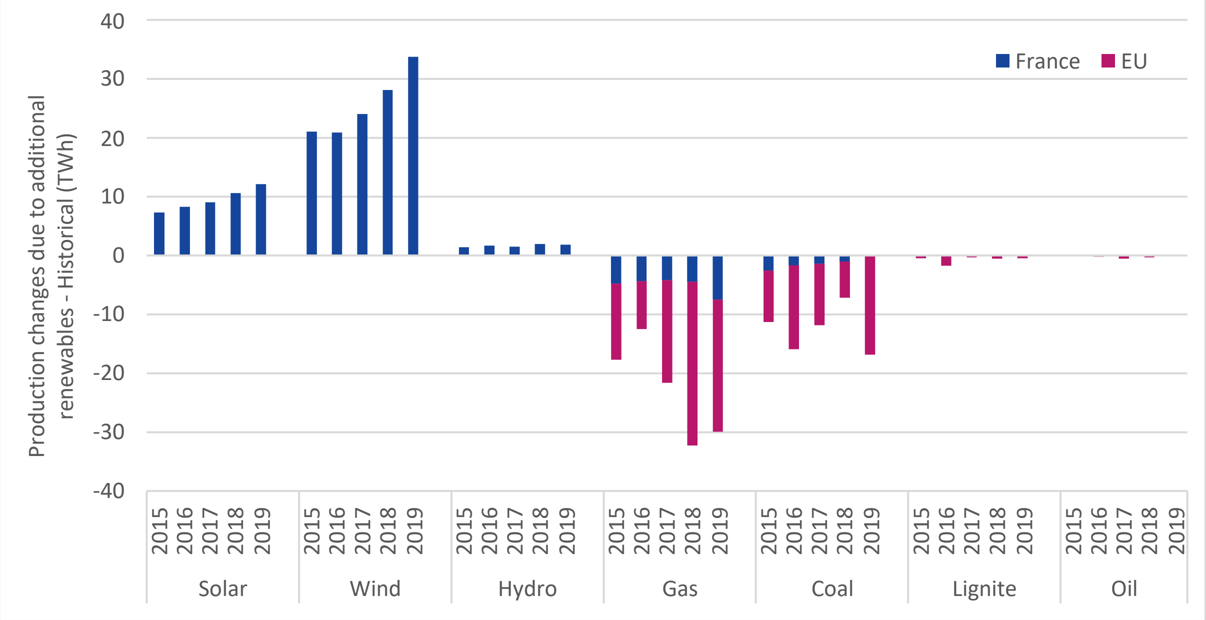

Figure 68: Differences in electricity production between reference and counterfactual scenarios for past (TWh)

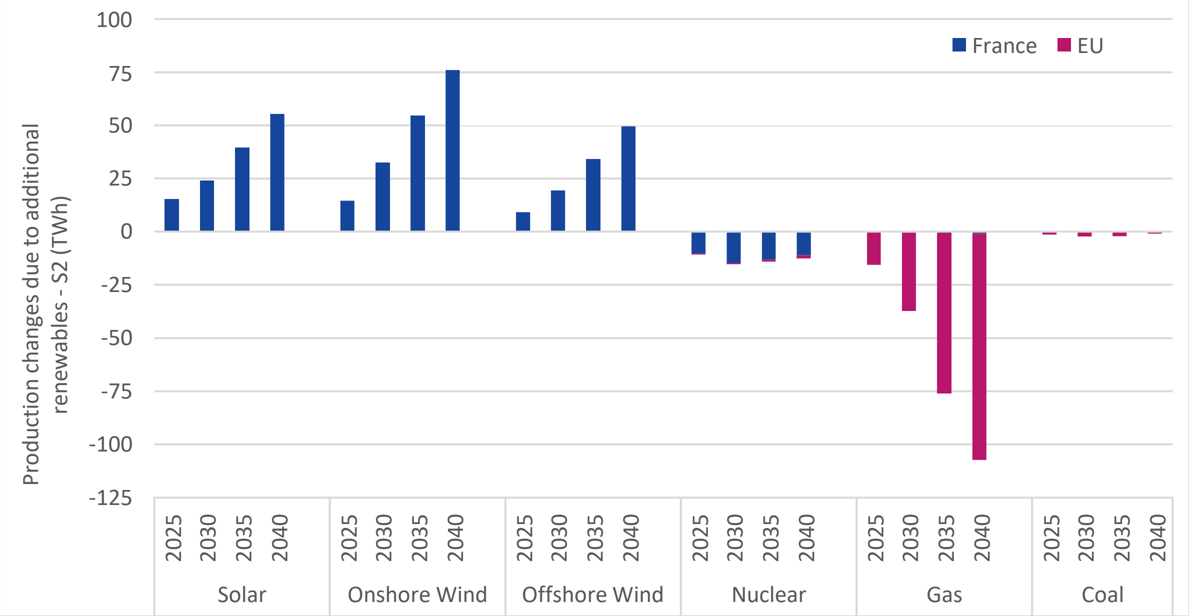

Figure 69: Differences in electricity production between reference and counterfactual scenarios for S2 (TWh)

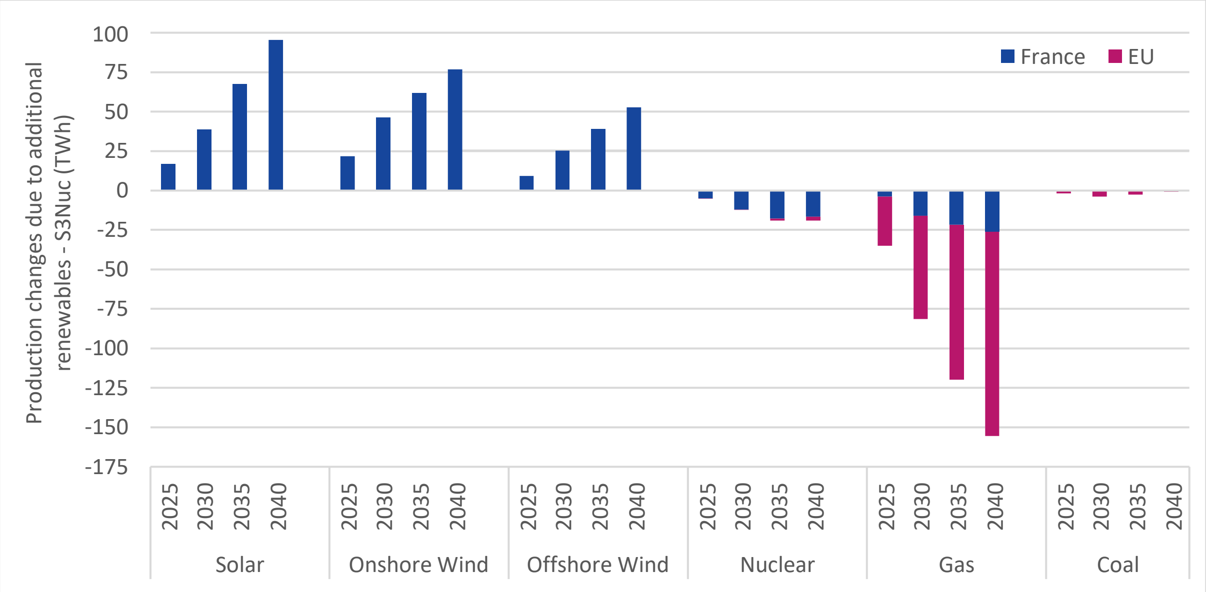

Figure 70: Differences in electricity production between reference and counterfactual scenarios for S3Nuc (TWh)

7.4.2 Results per scenario on GHG emissions

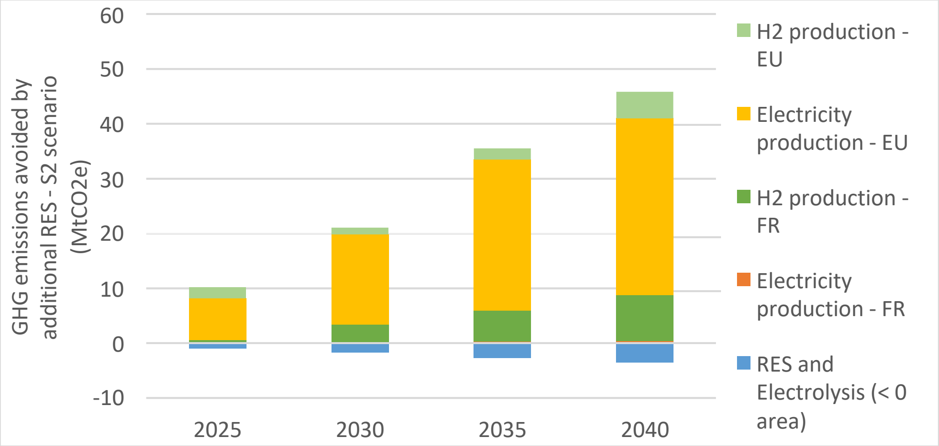

Figure 71: GHG emissions avoided by additional renewables in S2 (MtCO2eq)

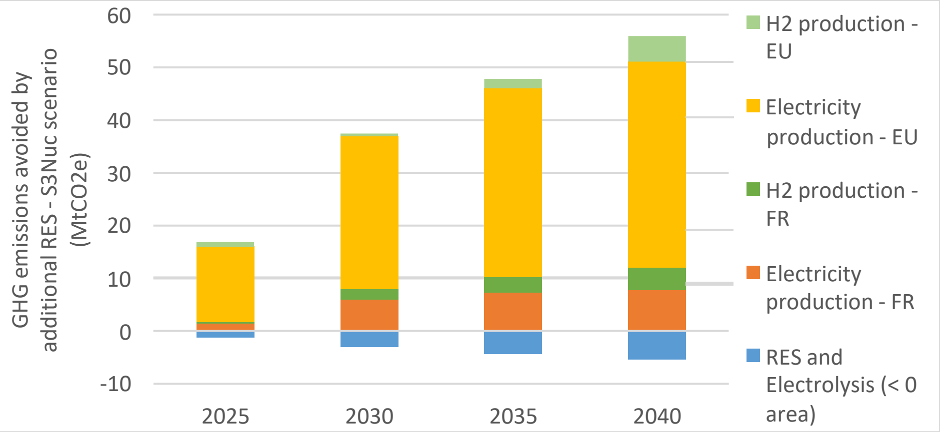

Figure 72: GHG emissions avoided by additional renewables in S3Nuc (MtCO2eq)

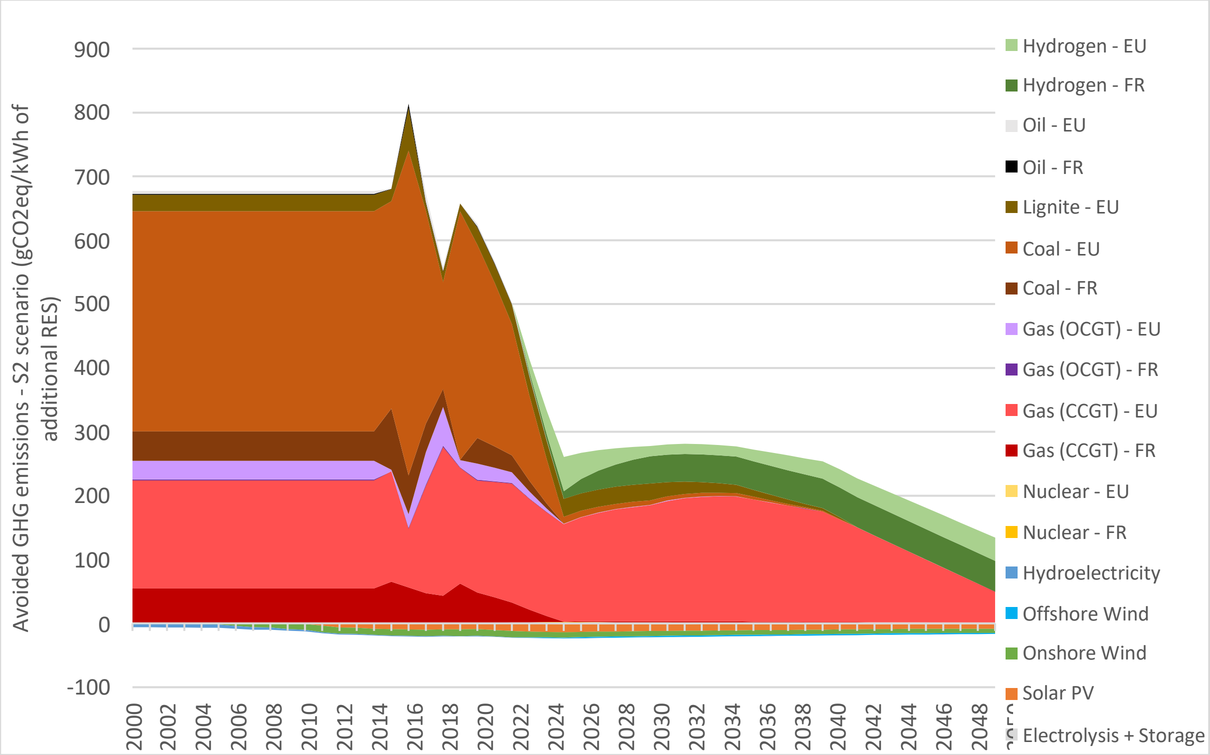

Figure 73: Avoided emissions (S2 scenario), in gCO2eq/kWh of additional renewables

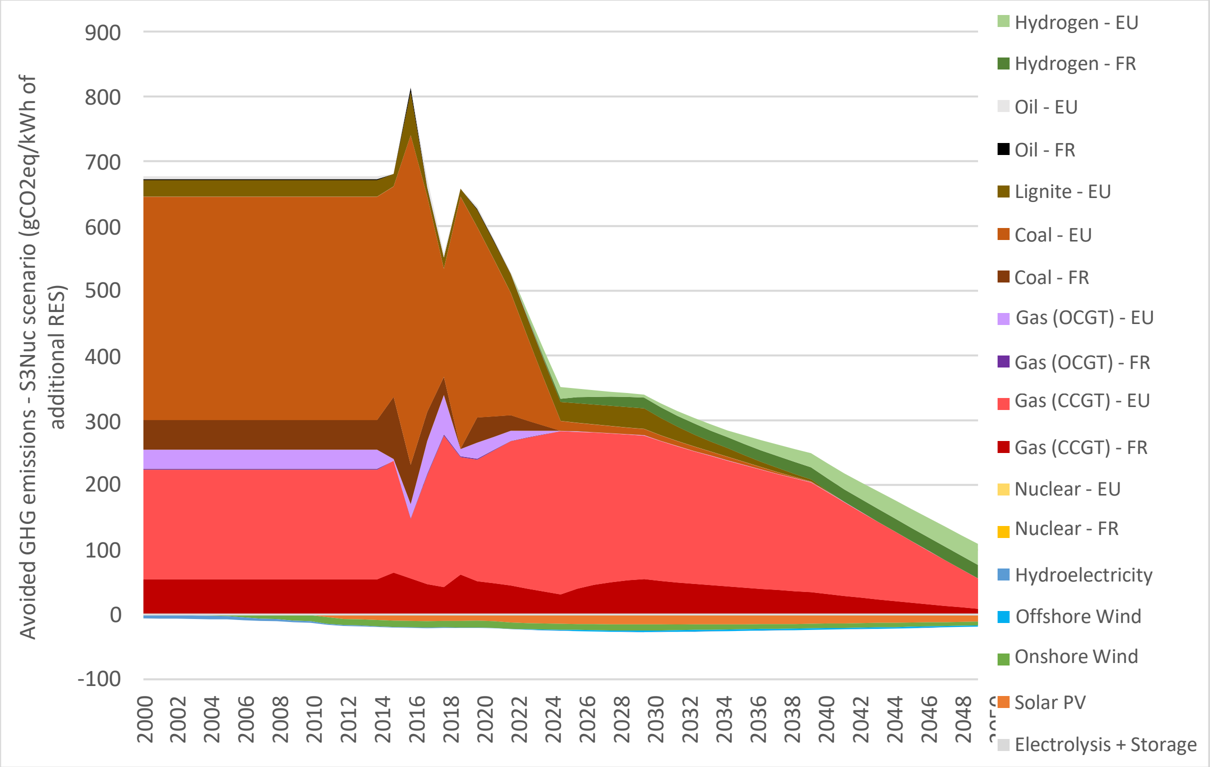

Figure 74: Avoided emissions (S3Nuc scenario), in gCO2eq/kWh of additional renewables

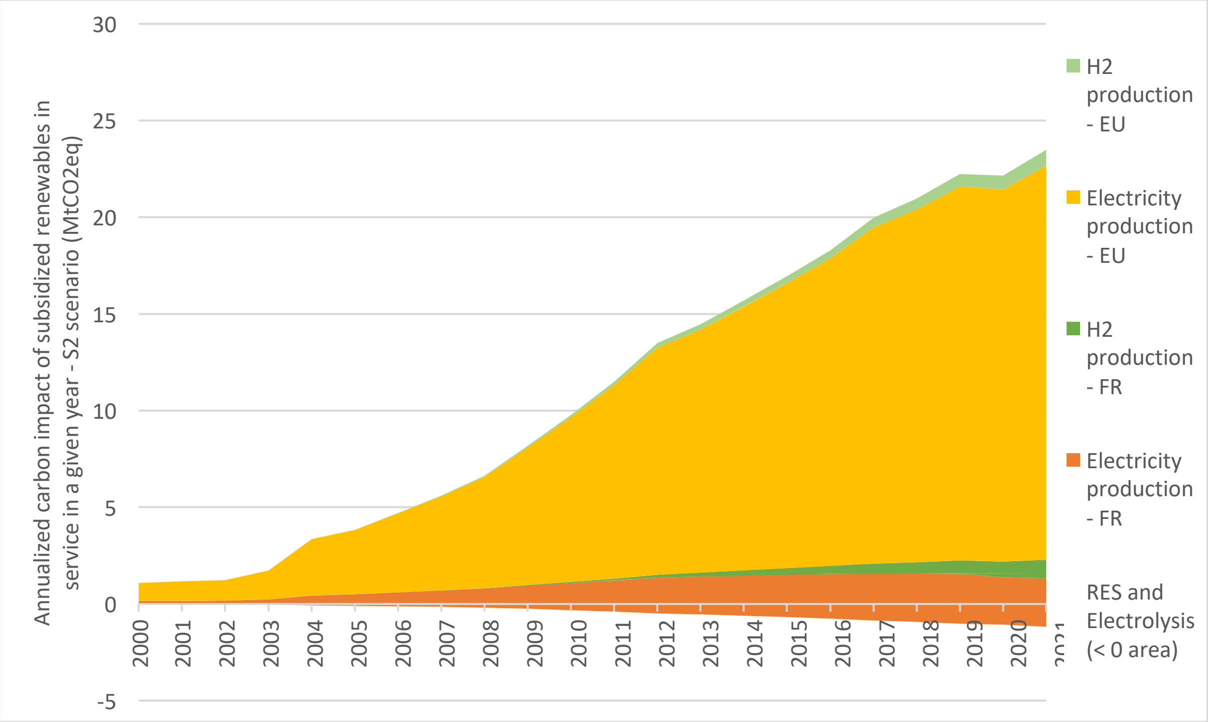

Figure 75: Annualized carbon impact of subsidized renewable capacities in service in the given year, S2 scenario, in MtCO2eq

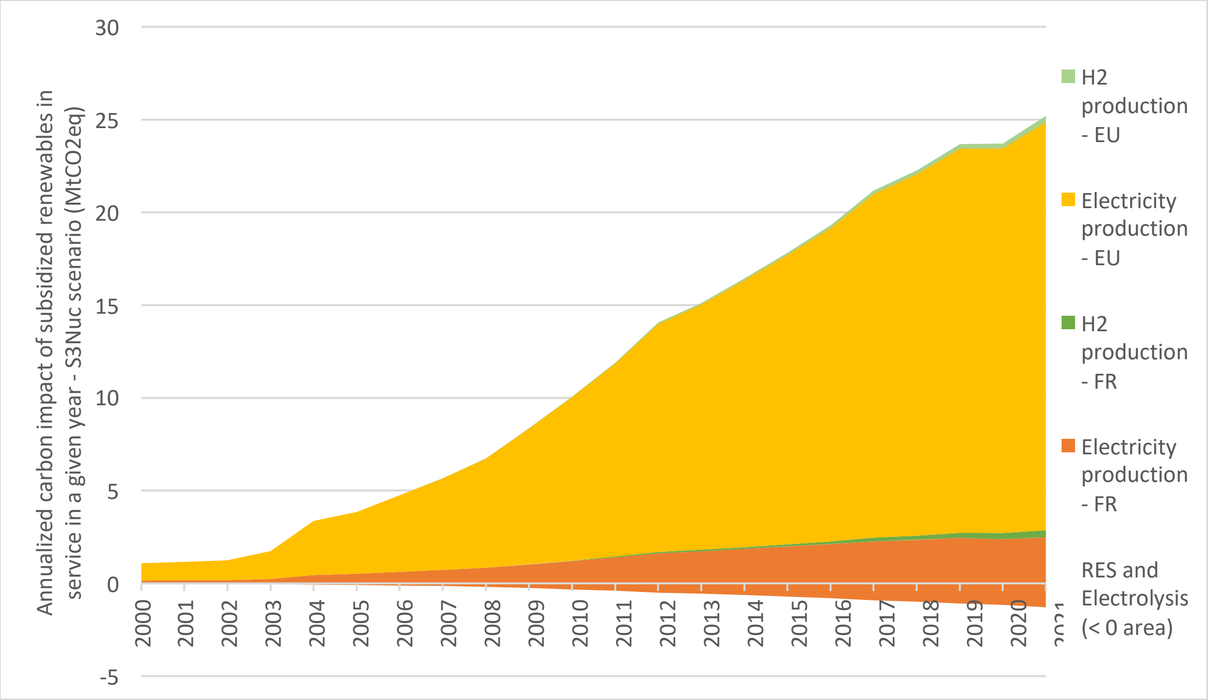

Figure 76: Annualized carbon impact of subsidized renewable capacities in service in the given year, S3Nuc scenario, in MtCO2eq

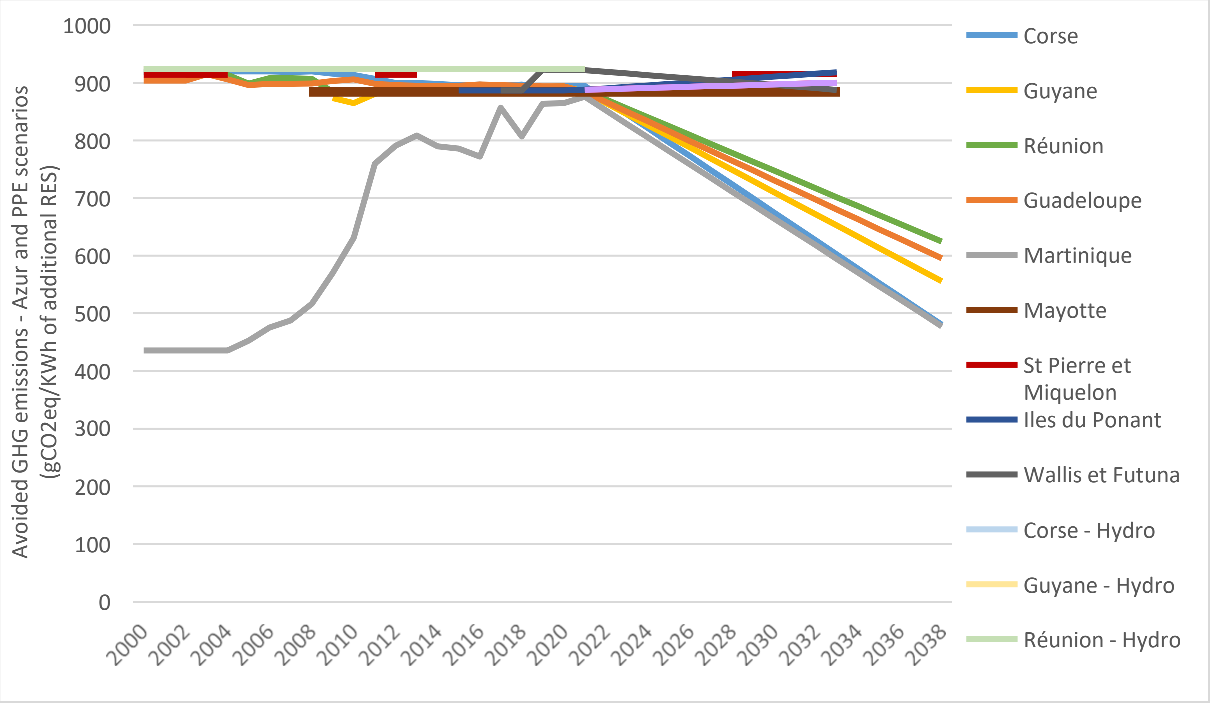

Figure 77: Avoided GHG emissions (in gCO2eq/kWh of additional renewable production), Azur and PPE scenarios

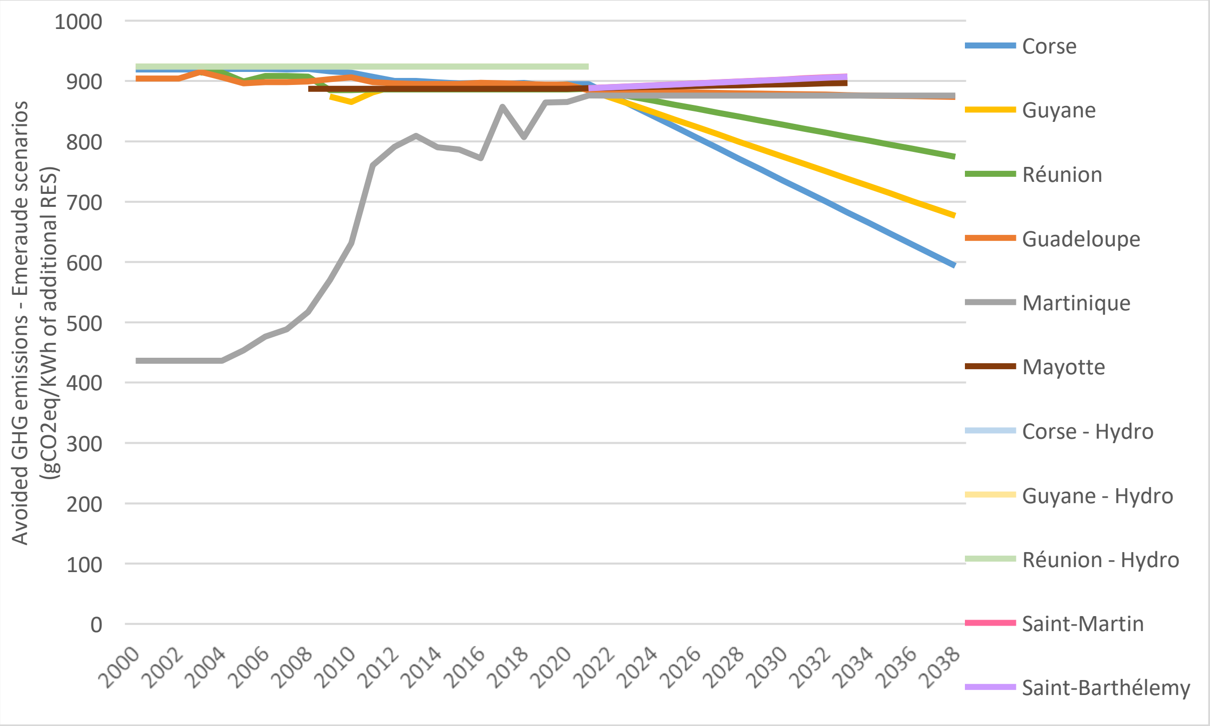

Figure 78: Avoided GHG emissions (in gCO2eq/kWh of additional renewable production), Emeraude scenarios

7.5 Production Data Reconstitution, Assumptions and Modelling Issues for the NIZs

7.5.1 Methodology for Reconstructing Historical Production in the NIZs

Historical productions in the non-interconnected zones (NIZs) have been reconstructed as part of this study, spanning from 2000 to 2021. Several sources have been used to carry out this work, where a consolidation of these generation data was not available for some of the NIZs. These sources include:

- EDF SEI open data (the electricity system operator for the majority of the NIZs) for the 2018, 2019, 2020 and 2021 productions
- Reports from the *Commission de régulation de l'énergie* (CRE), particularly annual reports on subsidies (which, depending on the year, provide the amount of subsidized energy by NIZ and production source) and a report on the functioning of subsidy mechanisms
- Reports from regional energy observatories
- Adequacy reports from network operators
- *Programmations pluriannuelles de l'énergie* (PPE) of the NIZ, which are strategic documents for steering the energy transition in France

When no data was available for a given year, production was extrapolated.

7.5.2 Methodology for Evaluating Prospective Production in the NIZs

The prospective estimate of electricity production in the NIZs was based on the reference documents available for each NIZ and the data contained therein. The document used at the end depend on the NIZ:

- 2022 adequacy reports by EDF SEI (electricity system operator) for the most populous NIZ (Réunion, Corsica, Guadeloupe, Martinique, and Guyana). The prospective horizon in this case is 2038.
- 2021 adequacy reports for Saint-Martin and Saint-Barthélemy (prepared by EDF SEI) and for Mayotte (prepared by *Électricité de Mayotte*, the local operator). The prospective horizon in this case is 2033.
- Multi-year energy programming (PPE) documents for the smaller NIZ (Saint-Pierre-et- Miquelon, Wallis-et-Futuna, and the Ponant Islands). The PPEs studied had a horizon of 2023.Since the renewable energy development targets in these PPEs have not been achieved to date, and these documents are the only references available, we consider that the targets constitute the reference system for the horizon of 2033 (in order to study the same horizon as the intermediate-sized NIZs).

The adequacy reports present two contrasting scenarios. Those prepared by EDF SEI are named "Azur" and "Emeraude," and correspond to two levels of consumption and renewable production. The "Emeraude" scenarios are characterized, among other things, by significant demand-side management (reduction of electricity consumption) and a stronger development of renewable energies compared to the "Azur" scenarios. This study has taken into account both scenarios, and the results presented, when they are not detailed, correspond to the average between the scenarios.

The adequacy reports provide, for these two scenarios, the total electricity consumption, the installed capacities of different categories of energy production assets, and load factors for certain production technologies. A similar approach has been followed for the NIZ for which the only available reference documents were the PPEs.

Assumptions had to be formulated to complete the missing data, including:

- When load factors were not available, they were calculated based on current productions and installed capacities, and when this was not possible, load factors from a similar NIZ were used.
- One of the asset categories is "non-synchronous renewable energies," which gathers solar and wind energy. To break down these renewable capacities into the two assets, reference was made to the PPEs, current installed capacities, and ongoing projects, to the extent possible.
- The hydropower production used for each NIZ corresponds to the average production of recent years, to account for interannual variations in generation.

The data on installed renewable capacities and load factors allow for the calculation of theoretical annual renewable energy production, without considering any limitation on the demand/supply balance at any time, that could lead to curtailment of part of the renewable generation. This is an important simplification of this study. However, it can be justified since in order to transition to systems with a very high share of renewable energy, means of flexibility (such as energy storage systems, smart charging of electric vehicles, etc.) will need to be implemented, which will help mitigatecurtailment periods.

We then assume that the missing production (compared to the projected annual demand) will be met by thermal power generation, as it is currently the case. The adequacy reports for the five largest non-interconnected areas (Reunion, Corsica, Guadeloupe, Martinique, Guiana) indicate that, except for peak demand periods (a few hours per year), thermal power generation will be decarbonized by 2038. Therefore, we assume that for these NIZ, the calculated thermal power production will be based on biodiesel. For the other non-interconnected areas, we assume that this production will correspond to the use of fossil fuel oil, as in the current situation.

7.5.3 Production Replacement Assumptions in the NIZs

Assumption of replacement of fuel oil:

For all non-interconnected zones except for Réunion and Guadeloupe, the only source of electricity production other than renewable energy is fuel oil. Unless we assume that power plants running on other types of non-renewable fuels would have been built without the development of renewables, it appears reasonable to assume that fuel oil would have been used to cover the missing production.

Moreover, the volumes of variable renewable energy production remain limited: solar energy experienced strong growth in the early 2010s, but has since stagnated, notably to avoid too high levels of variable production on the grid. Therefore, quantifying the curtailment of renewable production is not necessary for the historical period.

We therefore assume, both for the historical and prospective parts, that one renewable MWh produced replaces one MWh of fuel oil (except for Réunion and Guadeloupe). This assumption, due to the challenges around high levels of variable renewables, is discussed in annex 7.5.3 for the prospective period.

Determining replacements in Réunion and Guadeloupe:

For Réunion and Guadeloupe, thermal electricity originates from two types of power plants: fuel oil and coal-fired power plants (the latter can also run on bagasse). Analysis of annual production histories does not allow us to determine with certainty whether additional renewables have allowed for a reduction in fuel oil or coal production. However, analysis of hourly production data suggests that coal-fired power plants operate as "base load" and that production flexibility is provided by diesel generators (cf. Figure 79 and Figure 80).

In prospective scenarios, we assume that coal will be phased out by 2038 for both islands. We then assume that additional renewables (in 2038 compared to 2021) allow for the replacement of a volume of coal production equal to the 2021 production, and that the remaining avoided productions is fuel oil.

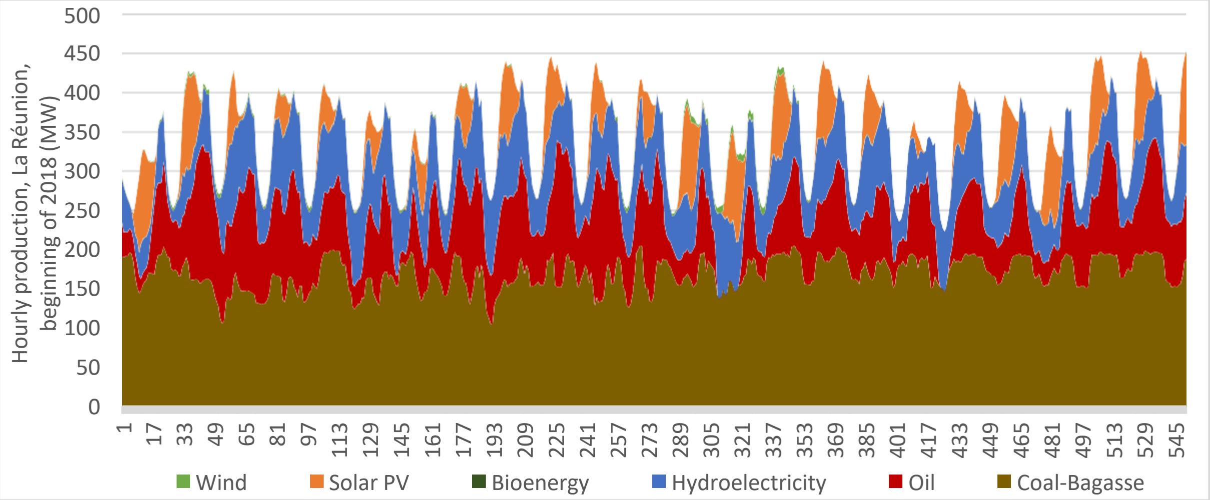

Figure 79: Hourly electricity production in Reunion Island (beginning of January 2018)

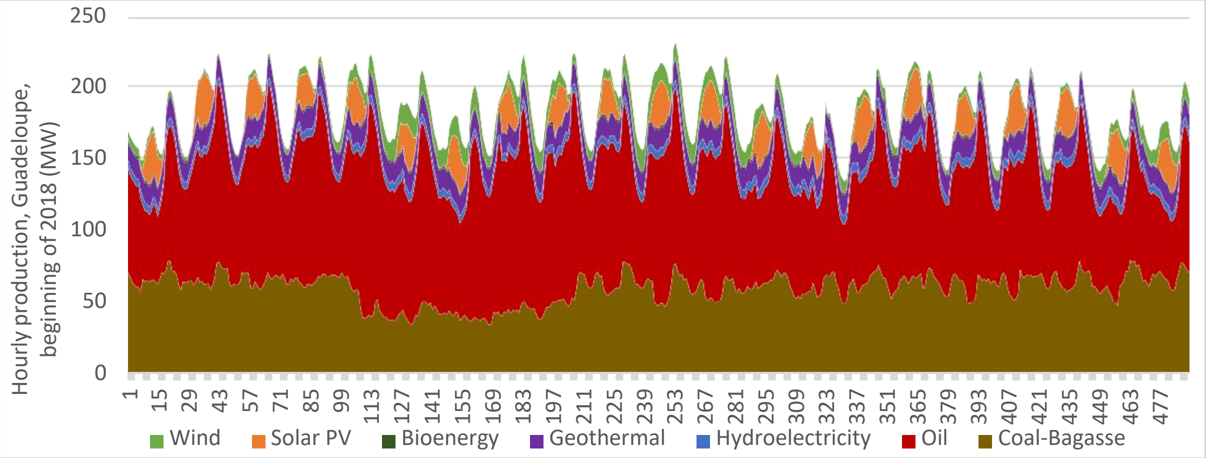

Figure 80: Hourly electricity production in Guadeloupe (beginning of January 2018)

7.5.4 Analysis of the Modelling Issues for NIZs

Differences of modelling issues with mainland France

The aim of the modeling work carried out in this study is to determine which energy production the subsidized renewable energies can replace. For metropolitan France, a detailed modelling work, at hourly level and taking into account neighboring countries, is necessary to obtain robust quantified results.

For the non-interconnected zones, the production systems are simpler, first because they are not interconnected, and second because the only thermal production source is provided by oil-fired power plants (except in Reunion and Guadeloupe). Then, there are no issues regarding the determination of the type of fossil energy avoided, nor the location where the productions are avoided. The challenge for theses isolated systems rather lies in the integration of variable renewable energies.

Issues concerning the integration of variable renewables in NIZs

Numerous questions arise regarding the feasibility of operating electrical systems with high shares of intermittent renewables, such as solar and wind, and the associated challenges have been studied by RTE and the IEA[89] for example.

A challenge concerns the constant electricity supply security, linked to the variable production profile of solar and wind. Demand-side management, large-scale storage, and the development of peak power plants are necessary for the operation of systems with high shares of variable renewables. These issues are particularly important for insular systems, as they typically have smaller size, relatively low hourly consumption, and limited production or flexibility assets. Weather conditions have a significantly stronger impact than in mainland Europe, where the highly meshed grid allow to mitigate thevariability of renewable generation across mainland Europe.

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[89] RTE – IEA, Study on the technical conditions necessary for a power system with a High Share of Renewables in France Towards 2050 [Link]

Another challenge is the stability of the electrical system, currently ensured by the synchronous rotation of alternator rotors in conventional power plants, providing the necessary inertia. Solutions for providing inertia are still relatively immature, although there is a scientific consensus on the theoretical stability of an electrical system without conventional generation capacity.

The development of electricity grids will also be necessary to accommodate renewables, particularly the distribution grid to which numerous installations will be connected (in mainland France, the transmission grid will also need to be adapted). Similarly, the operation and sizing of operational reserves will need to be revised according to RTE.

Given all these uncertainties (development of demand-side flexibility, centralized storage and peak power capacity, operation of reserves, capacity of the grid to accommodate variable renewables, inertia requirements, etc.), modeling of the operation of electrical systems in non-interconnected areas could not be conducted within the scope of this study. It should be noted that the assumption that every kWh of renewable energy will replace a kWh of fossil energy is a simplification of the reality, but still a reasonable assumption to get an order of magnitude of the production replaced by renewable. Several phenomena could however be considered to refine the analysis, including curtailment, efficiency of storage systems, production from peak power plants, conventional generation base to ensure system inertia, etc.

7.6 Appendix on GHG emissions

7.6.1 General information on the GHG emission factors used

Emission factors in LCA derived from RTE's work

The greenhouse gas emission factors used for impact calculations are primarily based on RTE's work as part of the *Energy Pathways to 2050* study, when these factors were available. RTE has studied both "direct" emissions (i.e., emissions from combustion during electricity production) and life cycle emissions. The factors used for this study are in the form of life cycle assessment (LCA). RTE obtained these greenhouse gas emission factors using parameterized models to represent the average state of installed technologies in the French energy mix at various time horizons. The factors used are presented in Figure 29.

Consideration of technological evolution and biomethane development

RTE provides emission factors for 2020 and 2050, and these data are used to account for technological evolution in the GHG impact analysis. For 2050, the average between the two estimates provided by RTE (pessimistic and trend-based evolutions) is taken. The emission factors between 2020 and 2050 are linearly interpolated (except for gas production technologies). For the period between 2000 and 2020, the emission factors from 2020 are used.

For gas production (open or combined cycle power plants, cogeneration), the evolution of emission factors is due to the use of biomethane in the gas network. The French national low-carbon strategy (*Stratégie Nationale Bas Carbone* or SNBC) aims for 100% of methane consumed from the gas network in France to be biomethane by 2050, with 11% biomethane in 2030 and 37% in 2040. The interpolation of emission factors for gas and biogas power generation is done with intermediate steps in 2030 and 2040, taking into account the reduced use of power plants in their indirect impact.

Use of emission factors adapted to the French context for Europe

The evolution of greenhouse gas emission factors in LCA for electricity production systems, provided by RTE, is adapted to the French context. Nevertheless, these factors have been used to calculate avoided emissions by French renewables in other European countries. This assumes, as a simplification, that the same type of electricity production system will emit the same amount of greenhouse gases, whether installed in France or elsewhere in Europe.

This assumption may seem strong, especially for gas production (which will be entirely based on biomethane in France by 2050). However, since Europe aims to achieve carbon neutrality by 2050, this means that electricity production will need to be almost entirely decarbonized. Thus, for gas production, this implies that European power plants will need to either use decarbonized gas (biomethane, low-carbon hydrogen and derivatives) or implement carbon capture systems. The greenhouse gas emissions from gas power plants in Europe will thus be much lower in 2050 than today, which is consistent with the assumption of transition to biomethane in France.

Clarifications on some emission factors

RTE provides greenhouse gas emission factors for hydroelectric generation without detailing the breakdown by technology. Therefore, we used the same emission factor for hydroelectricity, whether produced from dams, run-of-river, pumped hydro storage (PHS), or the tidal power plant in La Rance.

For lignite-based production, RTE only provides an estimate of direct emissions factors. To take into account other life cycle emissions (upstream, etc.), emission factors from coal are used to estimate the indirect emissions.

For waste-based production, RTE only provides an estimate of direct emissions factors, at 494 gCO2eq/kWh. This corresponds to the mean of emissions of non-renewable waste (988 gCO2eq/kWh) and renewable waste (0 gCO2eq/kWh).

Some factors were not available in RTE's study. In such cases, data from ADEME's database (*Base Empreinte*) were used. This applies to geothermal energy and hydrogen production through steam methane reforming (this factor is used to calculate avoided emissions from additional hydrogen production through renewables).

7.6.2 GHG emission factors specific to NIZs

The greenhouse gas (GHG) emission factors used for mainland France were adopted for the study of non-interconnected zones (NIZs). However, additional factors are needed, and the assumptions associated with each of them are presented below.

For bagasse, due to lack of data available in the RTE study and the ADEME database, the GHG emission factor for biomass is used as a proxy.

For imports to Corsica, the average GHG emission factor of the Italian electricity mix is used (since Corsica is connected to mainland Italy and Sardinia). For historical data, this factor is based on data from the environmental agency of the environment. For the prospective part, the projected production and consumption mix by 2040 in the National Trends scenario of the TYNDP 2022 (Ten Year Network Development Plans 2022) study by the ENTSOs (European Network of Transmission System Operators for Electricity and Gas) is used.

For biofuels, there is no value that has a clear consensus, as life cycle analysis emissions depend primarily on changes in land use for dedicated production. Thus, if dedicated biofuel crops have induced deforestation of a tropical rainforest, then the emissions will be very high. Between an "optimistic" scenario and a "maximum" scenario (deforestation of a tropical rainforest), ADEME indicates a ratio of 14 on GHG emissions per kWh of energy. To quantify GHG emissions from biofuel combustion, we referred to a study by the European Environment Agency[90]. This study, focused on the

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[90] EEA – ETC CM, *Greenhouse gas intensities of transport fuels in the EU in 2020 - Monitoring under the Fuel Quality Directive* [Link]

European transport sector, indicates a reduction in GHG emissions of around 40% through the use of biodiesel, taking into account indirect land use changes.

It should be noted that, when available, the factors from RTE were systematically compared to the factors from ADEME to ensure the validity of the data using two reference sources for France. Only one notable difference was identified, which is the emission factor for fuel oil. RTE provides an emission factor of 930 gCO2eq/kWh, while ADEME provides 730 gCO2eq/kWh. The emission factor from RTE was used for the analysis to use a single reference source as much as possible. Given that themajority of GHG emissions in NIZs come from fuel oil combustion, it is emphasized that this differencehas an important impact on the quantification of avoided emissions in NIZs.

7.6.3 Carbon intensity of the electricity mix in mainland France and the NIZs

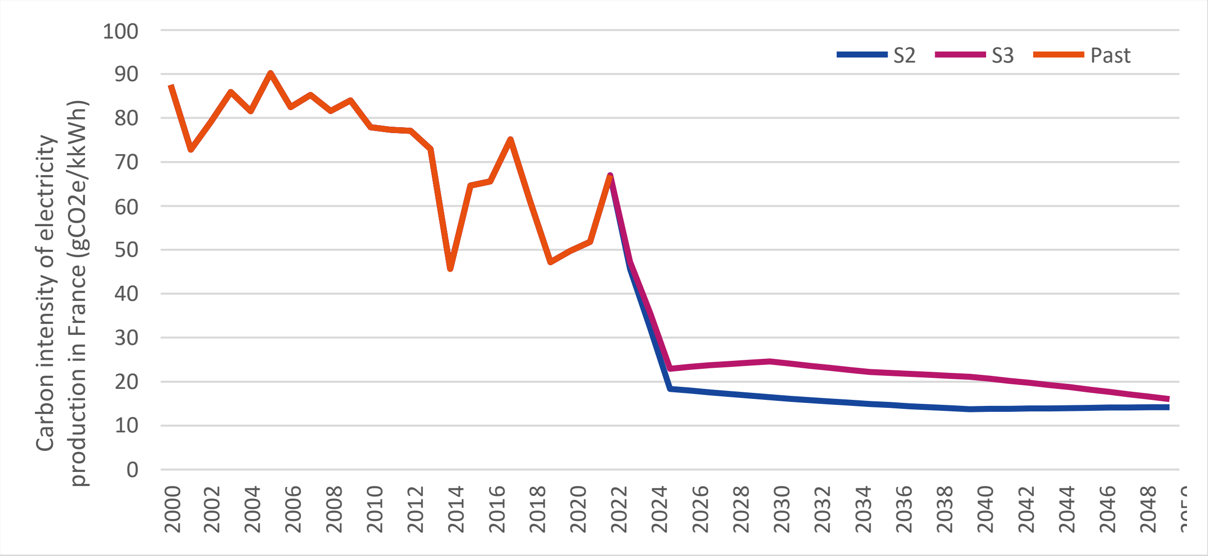

Figure 81: Carbon intensity of electricity production in mainland France (gCO2e/kWh)

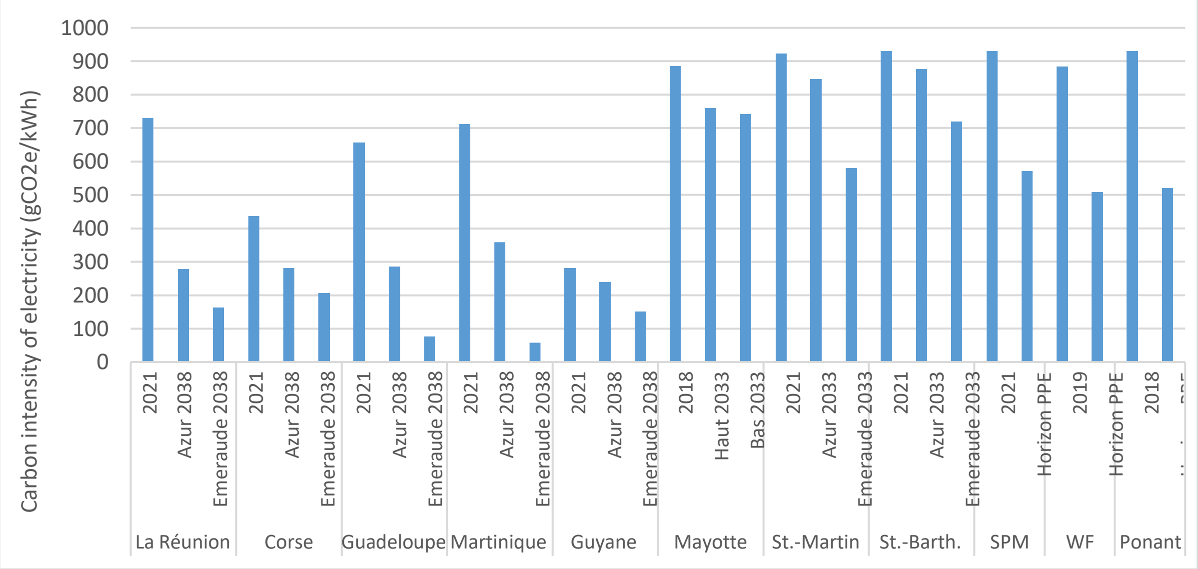

Figure 82 : Carbon intensity of electricity production in NIZs (gCO2e/kWh)

7.7 Appendix on air pollution

7.7.1 Perimeter and emission factors used

Scope of the study

The choice of the four pollutants (PM2.5, NMVOC, SO2, NOx) is identical to that of RTE[91]. RTE justifies the selection of these pollutants by stating that *"these pollutants have the greatest impact on health, are subject to national targets, and contribute directly or indirectly to the regular exceedances observed in some large urban areas."* It is also noted that ammonia (NH3), for which there are also emission reduction targets, *"was not included in the analysis because 94% of it is produced by the agricultural sector."* For particulate matters (PM), other diameters are studied in the scientific literature concerning air pollution, such as PM10. Finer particles are also sometimes studied (*e.g.* ultrafines particles PM<0.1).

Emission factors

We adopted the atmospheric pollutant emission factors for electricity production used by RTE (see below).

Table 2: Air pollutant emission factors (g/kWh)

Air pollutant emission factors, in g/kWh	Gas (incl. biogaz)	Coal	Waste	Oil	Wood
PM2.5	0,002	0,001	0,003	0,002	0,003
NOx	0,072	0,274	0,284	0,554	0,204
SO2	0,002	0,163	0,034	0,09	0,038
NMVOC	0,002	0,001	0,002	0,005	0,017

These are *direct* emission factors that do not take into account the fact that some pollutants (NOx, SO2, NMVOC) contribute to the formation of "secondary" ozone and PM2.5 through physicochemical transformations.

These factors are for France and for the year 2019. They are also used for the rest of Europe, which is an approximation (especially for coal, given the low number of active power plants in France)[92].

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[91] RTE, *Futurs Energétiques* [Link to chapter 12][Link to appendices][FR]

[92] The emission factors have significant uncertainties. In order to analyse the influence of one of the most uncertain emission factors (PM2.5 coal emission factor), a sensitivity analysis was carried out using a much higher factor (0.04 g/kWh - 40 times higher). The tested factor was based on a review of data from the US Environmental Protection Agency (EPA), which is regularly used by the European Environment Agency (EEA). This sensitivity

Moreover, in view of the downward trends in atmospheric pollutant emissions factors observed in recent decades, the use of factors for 2019 could tend to underestimate emissions avoided in the past and overestimate them for the future.

Indeed, the European Environment Agency reports a 91% reduction in SO2 emissions and a 68% reduction in NOx emissions from large combustion plants in Europe between 2004 and 2020[93]. The publication also presents the consumption of various fuels. By combining this data, this suggests a fivefold reduction in the emission factor for SO2 from coal-fired electricity production at the European level, between 2004 and 2020. This is partly due to the strengthening of emission regulations for industrial installations (IED directive), which has led power plant operators to implement more efficient processes and flue gas treatment systems, as well as to use fuels with lower sulfur content[94].

7.7.2 Hypotheses on the costs of air pollution

Methodological Differences between VOLY and VSL Assessments

The VOLY (value of life year) assessment methodology is based on the evaluation of the value of a year of life. The VSL (value of statistical life) assessment methodology is based on the statistical evaluation of the value of a life. The VSL methodology corresponds to the price that people are willing to pay to reduce their risk of death due to a health problem. The VOLY methodology takes into account the age at which a death occurs.

Explanation of Minimum and Maximum Assessments for Neighboring Countries

The European Environment Agency (EEA) study used to calculate the costs of atmospheric pollution provides costs per pollutant and per country. However, the estimate of avoided emissions does not differentiate between neighboring countries where emissions are avoided. To account for this limitation, we propose two estimates for costs: EU-min and EU-max. For each of the atmospheric pollutants considered (PM2.5, NOx, SO2, NMVOC), the EU-min estimate takes the minimum cost among neighboring countries, and the EU-max estimate takes the maximum cost. The neighboring countries considered are Germany, Belgium, the United Kingdom, Spain, and Italy.

Methodology for Calculating Avoided Costs

The costs per pollutant and country are adjusted by a sectoral correction factor[95]. The correction factor used, corresponding to electricity production, is that of the "SNAP1" sector. The correction factors

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analysis leads to an increase in the estimated avoided costs of around +30%. The general conclusions of the analysis of avoided damage costs are therefore still valid, as the order of magnitude remains the same and bearing in mind that the difference between the VOLY min estimate and the VSL max estimate is already a factor of x10.

[93] EEA, *Emissions and energy use in large combustion plants in Europe* [Link]

[94] According to RTE and EEA

[95] Sectoral correction factors are used to take account of source-receptor relationships. For example, the effects are not the same if the pollutant is emitted in a town or in the countryside, at ground level or at the top of an

provided in the study are linked to the transformations of atmospheric pollutants. Indeed, the costs taken into account in this study correspond to exposure to both primary and secondary PM2.5. Secondary PM2.5 corresponds to fine particles of this size produced by physicochemical transformations in the atmosphere. The precursors of these particles taken into account are NOx, SO2, and NMVOCs.

These correction factors are applied both in France and in neighboring countries (and are taken into account in the determination of cost factors for EU-min and EU-max). Estimates of costs for air pollution are then obtained, in euros per ton of atmospheric pollutants (for VOLY and VSL estimates, for each of the four pollutants studied), as shown in Figure 83.

These costs per ton are then multiplied by the volumes of avoided atmospheric pollutant emissions.

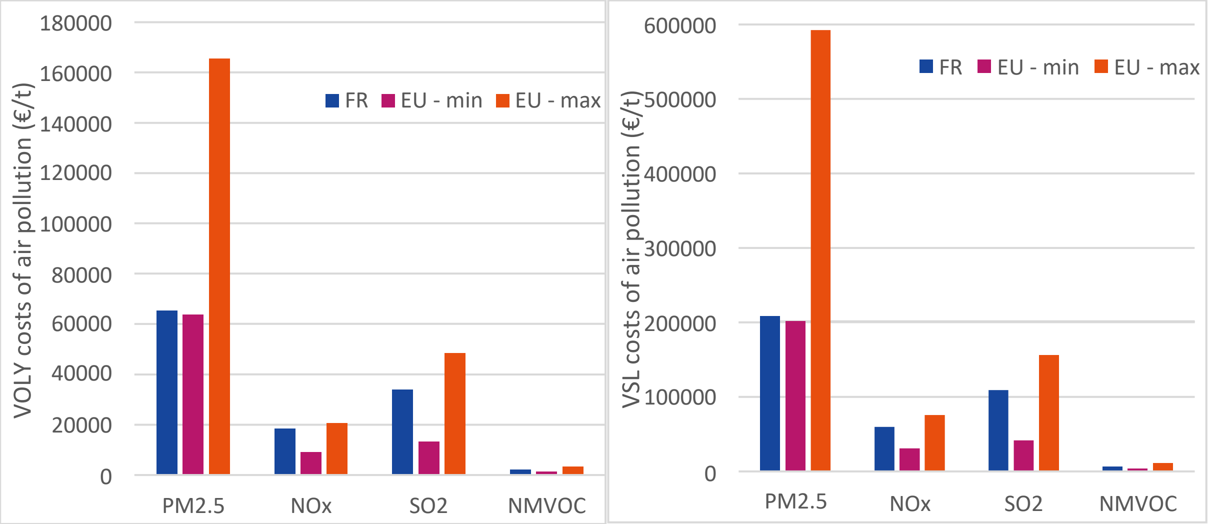

Figure 83: Cost assumptions of air pollution (VOLY and VSL, in €/t)

Types of damages considered by the European Environment Agency study

The majority of costs related to air pollution correspond to impacts on health (more than 93%). The relative shares of the different sectors (health, crops and forests, buildings) are presented in Figure 84. Unlike the EEA study, this study takes into account direct emission factors for PM2.5, and does not take into account emissions resulting from secondary transformations from PM10 (nor from NH3, as justified in section 7.7.1).

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industrial stack. These differences are taken into account by the EEA using specific sectoral factors (e.g. emissions from power plants are usually emitted from high chimneys and not at ground level in city centers as is the case with car emissions).

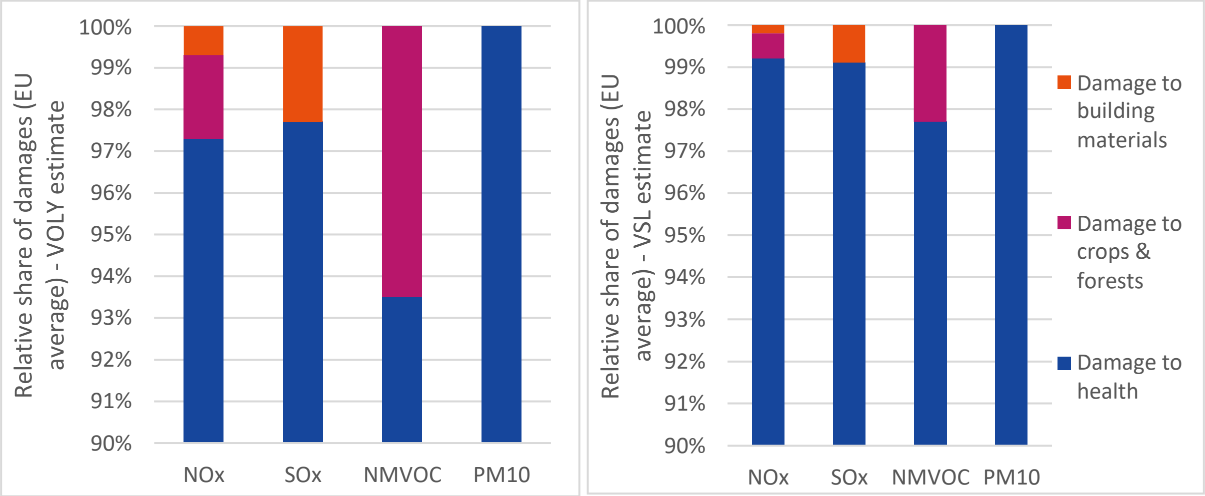

Figure 84: Relative share of damage to health, crops & forests, and building materials for the pollutants considered in this study (EU average). VOLY estimate (left) and VSL estimate (right). Note: y-axis cut-off at 90%. Source: recreated from graphs in the EEA study.

7.7.3 Avoided damage costs, annualized

As with greenhouse gas emissions, avoided atmospheric pollutant emissions due to subsidies are annualized using the method described in section 7.8. The avoided emissions are then multiplied by the costs of atmospheric pollution, for VOLY and VSL cost methodologies, and EU-min and EU-max estimates. The results of avoided costs by subsidies per year are presented in the figures below.

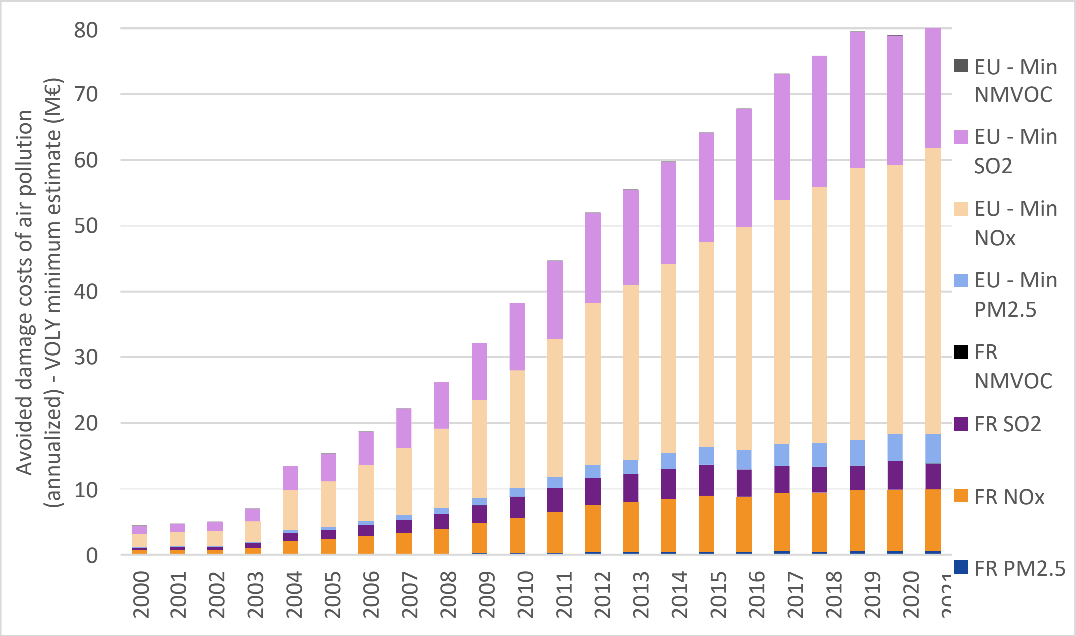

Figure 85: Avoided damage costs of air pollution (annualized) - VOLY minimum estimate (M€)

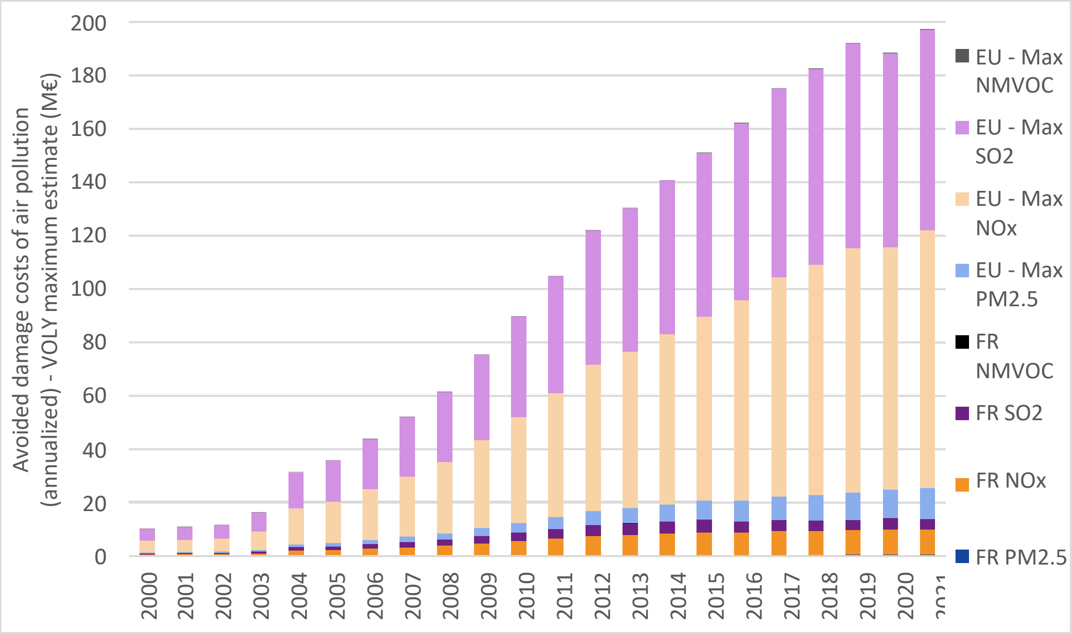

Figure 86: Avoided damage costs of air pollution (annualized) - VOLY maximum estimate (M€)

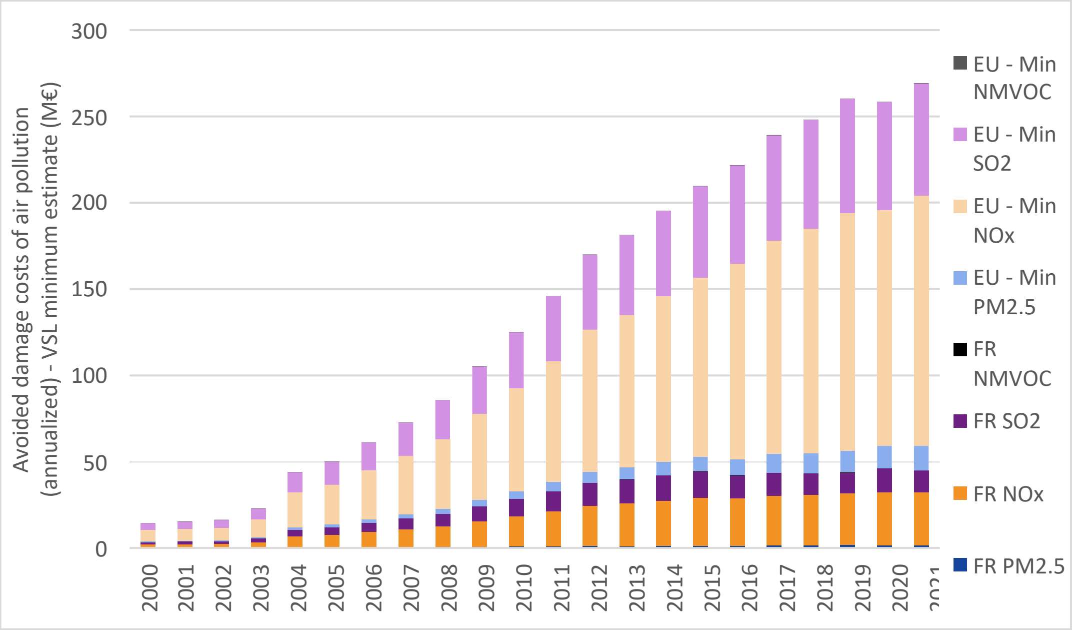

Figure 87: Avoided damage costs of air pollution (annualized) - VSL minimum estimate (M€)

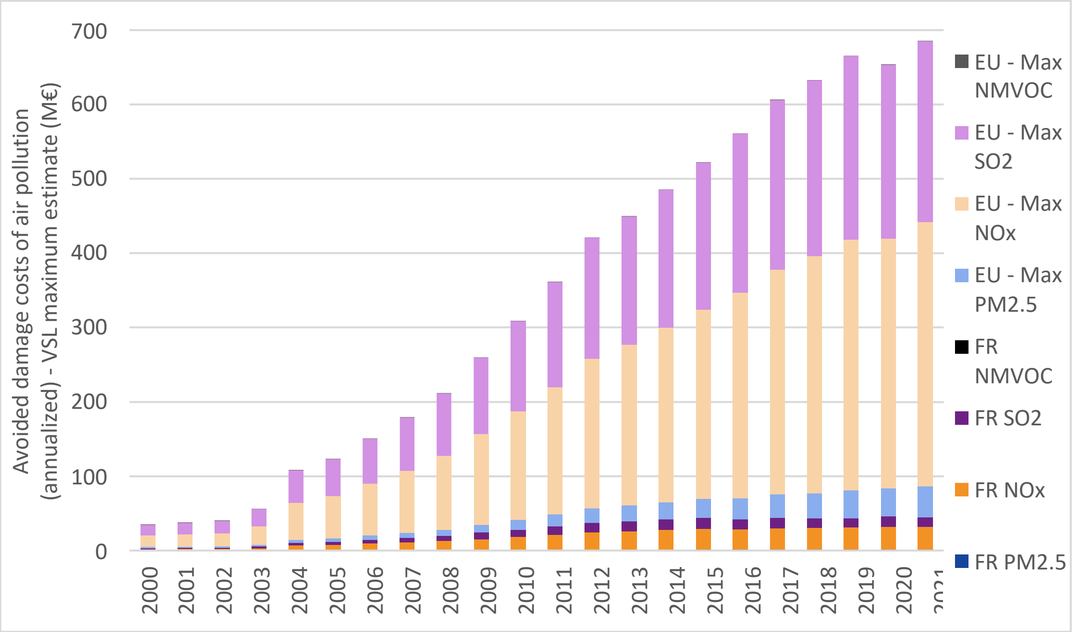

Figure 88: Avoided damage costs of air pollution (annualized) - VSL maximum estimate (M€)

7.8 Principle of annualizing the impact of renewables

7.8.1 General idea

One of the challenges of this assessment is that French subsidies for renewable energies (RES) correspond to a remuneration linked to production (feed-in tariffs or premiums), associated with long-term purchase contracts, most of the time for a duration of 20 years. Thus, the majority of subsidies spent during the year 2021 correspond to a remuneration of capacities installed before 2021.

Different methods have been considered to estimate GHG and air pollutants emission reductions. These methodologies differ in their scope: some only allow for the accounting of the current year's emissions reductions, others take into account past emission reductions from projects that are still subsidised but have been installed several years ago, as well as the emission reductions of future projects.

The methodology adopted after discussion with the Green OAT Council aims to estimate the impact of subsidised renewable energy projects over their entire lifetime. It consists of calculating the total impact of each project for its entire lifetime, and then assuming that this impact is redistributed identically for each year of its life.

The total impact in 2021 is then the sum of the average annual impacts of all projects that are currently subsidised in 2021, as illustrated in Figure 89 below. The detailed calculation steps of this methodology are explained in the next section.

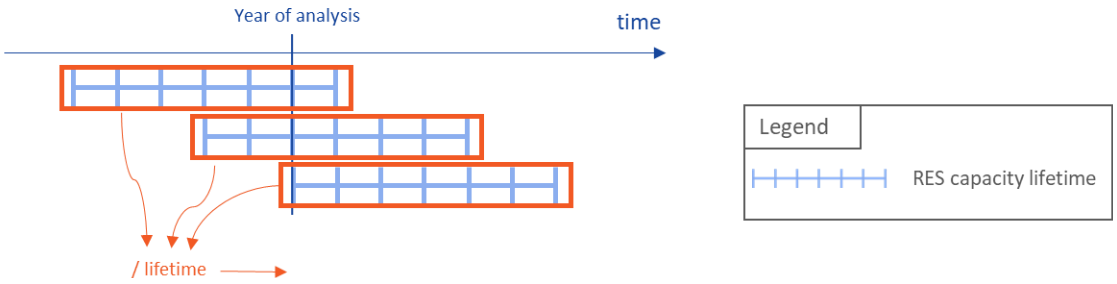

Figure 89 : Annualization principle for the impact of subsidized renewables

7.8.2 Detailed calculations for the annualization of RES impact

7.8.2.1 Estimation of the GHG and air pollutants impact of all RES for a given year

The prerequisite for calculating the impact on GHG and air pollutants emissions of a subsidised project over its lifetime is to calculate its impact for a given year. The key hypothesis for this calculation is to assume that any MWh of RES production, whether it is subsidised or not, has the same impact in terms of emissions reduction for a given year. The idea behind this choice is not to “favour” subsidised RES over non-subsidised RES. We assume here that they all have the same average impact.

Therefore, the objective is to estimate the impact on emissions of all RES for a given year. To do so, the production of the power system is simulated for a reference scenario which corresponds to the capacities actually installed for the year considered, and a counterfactual scenario where these renewable capacities are not present. These scenarios, the modelling methodology and the results are presented in section 4.

Avoided GHG and air pollutant emissions are calculated by comparing the total emissions in the baseline scenario and the counterfactual scenario. This reduction in emissions is then converted into an impact in tonnes/MWh of RES by dividing this total reduction by the difference in RES production between the reference and the counterfactual scenario.

For the following, we define:

- $impact_i$ in t/MWh of RES this impact for year I ($tCO2_{eq}$for GHG, tonnes of given pollutant for air pollution). This impact concerns all RES, not only to subsidised RES.

7.8.2.2 Reconstitution of the production of the different subsidized projects, by year of commissioning

In order to apply the methodology described in the previous section, it is necessary to have a prior reconstruction of the subsidised RES capacities and productions for each year.

For the following, and for a year i, we define:

- C_i the total subsidised RES capacity commissioned in year i,
- P_i^j its production for year j, with j ranging from i to i+19, which corresponds to the whole duration when the capacity is subsidised[96].

By definition, since subvention contracts for RES have a typical duration of 20 years, total subsidised capacity for year 2021 is equal to $\sum_{i=2002}^{2021} C_i$, and the total subsidised generation is equal to $\sum_{i=2002}^{2021} P_i^{2021}$.

7.8.2.3 Estimation of the total impact

As explained earlier in the general presentation of the methodology, the first step is to calculate the total impact of each project for its entire lifetime, and then to assume that this impact should be spread evenly over its lifetime.

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[96] In practice, for a given year of installation i, the variations in production P_i^j depend solely on the climatic conditions of year j. For future years, as the simulations are made on a predefined climatic year, this production P_i^j is independent of year j.

Thus, for all subsidised projects commissioned in year i and with capacity C_i, their average annual impact is equal to the sum over its whole lifetime of each annual impact (i.e. between years i and i+19 inclusive), divided by 20, the duration of the subsidy contract:

$$\text{annual\_impact\_C}_i = {\sum_{j=i}^{i+19} \mathrm{P}_i^j \times impact_j}/_{20}$$

To calculate the total impact of the subsidies in 2021, we need to sum up the impact of all the projects subsidised in 2021, i.e. the sum of the annual impact of all the projects commissioned between 2002 and 2021:

$$\text{total impact} = \sum_{i=2002}^{2021} \text{annual\_impact\_Ci} = \sum_{i=2002}^{2021} \frac{\sum_{j=i}^{i+19} \mathrm{P}_i^j \times impact_j}{20}$$