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Planning a Notable CCS Pilot-Scale Project: A Case Study in France, Paris Basin—Ile-de-France

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Abstract: Few commercial-scale carbon capture and storage (CCS) projects are currently operating in the world, with almost all in the USA and China. Despite a high number of CCS pilot-scale projects achieved in Europe, only two commercial-scale projects are operating today. The goal of this study is to present a case study in France to select a promising location to deploy a notable CCS pilot-scale project based on a multicriteria regional-scale approach. The methodology applied in this case study describes and assesses different aspects involved in CCS technology at the regional scale, and then an evaluation of economic key performance indicators (KPI) of CCS is carried out. The assessment at the regional scale gives an overview of where CCS could be applied, when CCS could be deployed and how to launch CCS considering the needs and concerns of stakeholders in the region. Technical aspects were mapped, such as the location of irreducible CO_2 sources and long-lasting emissions and the location of storage resources and existing potential transport infrastructures. We identified the waste-to-energy and chemical sectors as the main CO_2 sources in the region. An economic analysis of a hypothetical scenario of CCS deployment was elaborated considering three of the higher emitters in the region. A CCS scenario in the Paris Basin region with a deployment between 2027 and 2050 indicates a low CO_2 cost per ton avoided between 43 EUR/t and 70 EUR/t for a cumulated total of 25 Mt and 16 Mt, respectively, of CO_2 captured and stored for 26 years, including 7.7 Mt of CO_2 from biomass (potential negative emissions). Storage maturity and availability of the resource are the most uncertain parameters of the scenario, although they are the key elements to push investment in capture facilities and transport. Geological storage pilot projects are mandatory to prove storage resource and should be located in strategic locations close to potential CO_2 sources in case of confirmation of proven resources. Well-perceived pilot-scale projects are the first step to start engaging in deciding and investing in commercial-scale CCS projects.

Keywords: CCS pilot-scale; CO_2 reduction; Ile-de-France; regional scale; waste to energy; decarbonizing industry; Paris Basin; key performance indicators; economic evaluation

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1. Introduction

The development of carbon capture and storage (CCS) has been slow in the last decade in Europe. Only two CCS projects are currently operating within the European Economic Area, mainly off the Norwegian coast. The main reasons include a low CO_2 price on the EU Emissions Trading System (EU ETS). Well below 10 EUR/tCO_2 prior to 2017, the CO_2 ETS price has increased since 2018, reaching the highest ETS price of 95 EUR/tCO_2 on 13 February 2022 [1]. Negative perceptions of CCS projects in several nations also contributed to delaying CCS deployment [2,3]. Projects were set on hold or even cancelled due to reasons such as financing gaps, resistance of the local populations, or lack of political support [4,5]. CO_2 sources would partly influence social acceptance of CCS technology [6]. Adapting the identity of a project to local factors such as the presence of industry, transport network, or benefit from the exploitation of underground resources should play a key role in public opinion about these projects [7].

Today, few commercial-scale CCS projects are operating in the world, with almost all in the USA and China. Commercial-scale projects are those capturing, transporting and storing at least 500,000 tons of CO_2 per year. Enhanced hydrocarbon recovery (EHR) is the dominant type of project, injecting more than 500 kt of CO_2 per year [8,9]. The Global CCS Institute [8] proposes a new CCS facility classification to differentiate large-scale CCS projects and pilot-demonstration-scale projects. The proposed classification considers smaller capture facilities, which can be commercially viable. In that respect, CCS hubs are regarded as opportunities to create economies of scale that lower costs of transport and storage to multiple smaller CO_2 sources. Thus, CCS facilities must support a commercial return while operating and meeting the national regulatory requirement. Pilot and demonstration facilities capture CO_2 for testing, enhancing or demonstrating CCS technology or processes without the obligation to store CO_2 permanently.

Looking at current CCS operating and in-development projects in Europe using the proposed classification of the Global CCS Institute (Figure 1A), all CCS large-scale facilities operating and in development are located around the North Sea. Other countries in Southern and Eastern Europe completed or are operating pilot-scale projects, with approximatively half of them without CO_2 storage (Figure 1B).

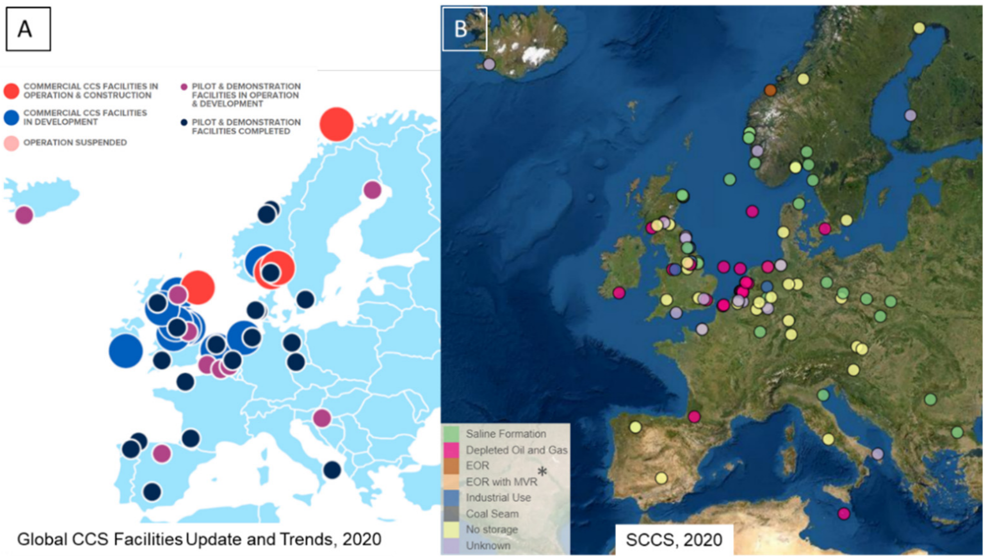

Figure 1. European map of CCS facilities completed, in development and ongoing. In (**A**), the overview of Global CCS facilities in 2020 classified by size of the project: commercial (large) scale or pilot scale. The status of these projects is represented by the color bubble. Map (**B**) indicates the storage status of all CCS projects regardless of their size. Yellow circles are projects without geological storage of CO_2. (* EOR = enhanced oil recovery; MVR = monitoring, verification and reporting).

Countries with a policy to create a business case for investment in CCS projects, such as Norway, UK, the Netherlands and the USA, are leading ongoing and in-development CCS commercial-scale projects, but other technical aspects pushed these regions up to leading in the field CCS deployment technology. These countries have a good knowledge of their storage resources from oil and gas history and government support. An atlas of CO_2 storage resources, such as the CO_2 Storage Evaluation Database (CO_2 Stored) in the UK or the Norwegian CO_2 Storage Atlas [10,11], are accurate public information based on seismic coverage, data wells and published research. The knowledge and maturity of storage resources seems to be a crucial element for the development of commercial-scale CCS facilities.

The goal of this study is to present a case study in France to select a promising location to deploy a notable CCS pilot-scale project based on technical, economic and societal aspects. This study explains and justifies the choice to locate a pilot-scale CCS project focusing on the storage element of the CCS chain and the optimization of transport for regional

CO_2 sources. Before investing in a capture facility, the emitter plant needs guarantees on where the CO_2 would be stored and how it would be transported. The technology of CO_2 capture has improved in the last 20 years, with costs depending on the gas stream and CO_2 concentration. In a wide range of industry sectors (refinery, cement, iron and steel), the cost of capture is between USD 40 and USD 120 per ton of CO_2 [12].

The maturity and confidence of storage resources in Europe are low, except around the North Sea [13], which seems to be the driver of CCS operational projects. The significant lead time for the development and permitting of CO_2 geological storage sites is in the order of 7–10 years, which implies a selection of potential sites to be developed well in advance of when they are predicted to be needed. Today, CCS pilot-scale projects would play a key role in enabling CCS commercial-scale projects around Europe. Through pilot projects, storage capacity could be proven, ensuring availability of storage resources to the trajectory of investment in capture facilities.

2. Materials and Methods

A notable CCS pilot-scale project should demonstrate the technical feasibility of the technology to engage regional and national stakeholders in further developments. Today, in Europe, the maturity and confidence of storage resources seem to be the major challenge to elaborate plans for the deployment of CCS outside the North Sea. Indeed, policy also plays a key role in accelerating the technology, as well as the societal engagement to deploy it. The methodology applied in this case study in France describes and assesses different aspects involved in CCS technology at the regional scale and carries out an evaluation of economic key performance indicators (KPIs) of CCS. The assessment at the regional scale gives an overview on where CCS could be applied, when CCS could be deployed and how to launch CCS considering the needs and concerns of stakeholders in the region.

The proposed methodology is based on the mapping of technical aspects at the regional scale to define the most promising industrial clusters and hubs which would benefit from CCS technology. After this first screening of emission sources, transport infrastructures and storage site options, a second step of economic evaluation assessed the economical key performance indicators (KPIs) of deploying CCUS at the regional scale. The societal perception of some regional stakeholders is also considered as part of the mapping aspects (Figure 2) in this early exercise of planning CCS.

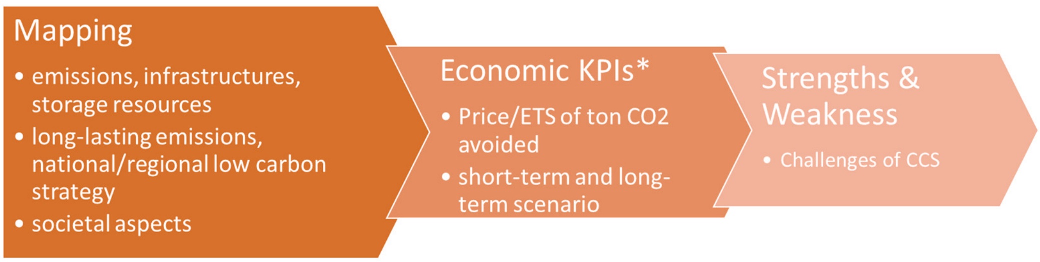

Figure 2. Schematic methodology chart illustrating the workflow to select potential areas to deploy a notable pilot-scale CCS project. * KPI: key performance indicators.

2.1. Mapping CCUS Aspects

Technical and societal aspects involved in the CCS technology were mapped in the frame of STRATEGY CCUS project (H2020, grant agreement: No 837754) for the Paris Basin region, mainly inside the Ile-de-France Department. The data gathered in STRATEGY CCUS aimed at providing the technical basis on capture, transport, and storage conditions for assessing the viability of defining and implementing CCUS clusters and hubs. Storage capacity maturity and its confidence level was assessed for two preliminary candidates. The mapping of spatial conditions for network development considers the geographic distribution of the source, sinks and transport opportunities.

The technical potential for implementing CCUS in the Paris Basin region was assessed on the basic premise that industrial CCUS clusters provide synergies, either in the capture facilities, at the transport networks or at injection and storage facilities, that result in decreasing costs for implementing the technology [14].

The mapping of emissions sources determines what CO_2 may be captured to develop an understanding of the CO_2 as part of an industrial emissions reduction program using CCUS. The starting point was the definition of current CO_2 emission quantities in the area, the locations of emitters and related details. Distinctions between the fossil fuel combustion emissions, biomass emissions and process emissions were conducted whenever there was sufficient information. Once this inventory of the CO_2 emissions was established, it was necessary to consider what portion of that would be appropriate to address using CCUS [15].

The mapping of a CO_2 transport infrastructure is the identification and planning of a CO_2 transport network within the cluster to send the CO_2 from each capture facility to a consolidation point, a hub. The transport network can be composed of a pipeline system, but for very small-capacity sources, the collection network can be composed of a modular system including road truck, rail tank-car, shipping or barge transport on inland waterways. Captured CO_2 is collected in the cluster, then conditioning facilities (e.g., compressing, liquefaction, etc.) prepare the CO_2 for transportation by truck, pipeline or ship to the injection and storage site where further reconditioning of the stream may be necessary. The available geological storage capacity and its distribution with respect to the sources result in scenarios to assess the optimal transport network development.

The storage capacities reported here were calculated using a volumetric approach for the Dogger Fm. and reservoir simulation approach for the Trias Fm. [16]. Capacity estimated by volumetric approach is dependent on standard parameters (bulk volume, porosity, net-to-gross and CO_2 density) and a modifying term, the storage efficiency factor (SEF). Storage efficiency values also reflect general geologic characteristics and boundary conditions. For example, carbonates and open systems have a higher efficiency than clastic reservoirs and closed systems. Capacity estimates were ranked using a quantitative resource pyramid approach (Table 1). Based on four tiers, the classification captures the maturity level of existing data and the understanding of the potential storage capacity. Each tier introduces gradual knowledge of the reservoir—i.e., influencing the accuracy of the storage estimate —starting from regional approximations to the evaluation of specific targeted sites. The requirements for each tier reflect this maturation. The described tiers are compatible with existing schemes, allowing outcomes to be transferred to equivalent classifications if required [13].

The CO_2 utilization opportunities are here regarded as those uses with a clear mitigation impact, either with a greenhouse gas contribution or that clearly enable other low-carbon actions, leaving out those technologies that have a negligible impact [13].

The diffusion of a technology is also a social challenge. A dedicated work package within the STRATEGY CCUS project focuses on—all kinds of—actors involved in CCUS applications. Mapping societal aspects of CCUS technology in the Paris Basin region provides a first statement of the actor structure in the innovation system for CCUS [6] at the national and regional levels. Stakeholders are defined as individuals (e.g., employee, customer and citizen) who can be concerned by the development of a CCUS project, either with respect to demands or responsibilities towards it. A mapping of stakeholders' perceptions, attitudes and interests led to defining the scope of relevant issues and specific needs to be considered locally. Following the identification of relevant actors, semistructured interviews were conducted. These interviews and broadly based discussions around CCUS, involving both representatives of the stakeholder group from the Paris Basin region and some stakeholders at the national level [17].

Table 1. Tier classification/definition and suitability criteria defining the maturity of geological CO_2 storage resource capacities.

Tiers	Classification	Suitability Criteria
Tier 1	Regional assessment; equivalent to prospective (theoretical)	Generic SEFs (storage efficiency factor). Formation and storage unit estimate. First approximation. Low data burden and global storage efficiency values where boundary conditions are poorly constrained or uncertain.
Tier 2	Discovery assessment; equivalent to low contingent (effective)	Tailored SEFs. Daughter unit estimates. Second approximation. Moderate data burden and lithology-specific regional storage efficiency factors. Distinction between deep saline aquifers, depleted hydrocarbon fields and coal beds. Boundary conditions are established.
Tier 3	Prospect assessment; equivalent to pending/on hold (practical)	Detailed data prospective candidates. Third approximation with a more taxing data burden, including subattributes of the main factors used to estimate capacity and lithology-specific local SEFs. Each candidate prospect requires either existing or targeted data acquisition sufficient to build a simple geomodel for first-pass simulation and well location consideration.
Tier 4	Site assessment; equivalent to justified/approved/on injection (matched), project.	Targeted storage sites. The final approximation prior to operation. This has the highest data burden and requires a detailed geomodel for reservoir simulation studies. Outcomes from the simulations test the accuracy of the storage efficiency factors and provide scenarios for maximizing capacity based on well planning and scheduling.

2.2. Economic Key Performance Indicators (KPIs)

The CCUS scenario deployment at the Paris Basin described the business case of CCUS technology until 2050 based on technoeconomic modelling and hypothesis. The regional CCUS scenarios are based on both the performances of local industries in operation and for which CCUS is a relevant mitigation alternative, as well as the regional storage capacities known to date. For each of the regional scenarios evaluated, the cost difference between investing in CCUS or paying the carbon penalties to remain in compliance with the EU ETS is calculated to estimate the CCUS costs in terms of CO_2 avoided for each of the scenarios deployed [18].

A scenario evaluation tool was developed in the STRATEGY CCUS project to evaluate future CCUS value chains [19], where CO_2 is captured from point emissions and transported to utilization industries or for permanent storage. The tool uses the data gathered from the mapping aspects at the regional level and the key technological and economical parameters for implementing the CCUS technology related to:

1. Energy consumption.
2. Net present costs for the capture, transport and storage.
3. Amount of CO_2 emissions avoided and negative emissions.
4. Revenue created by the down-stream utilization industries.

Scenario analysis examines the results of how future events are laid out in time. Despite the inherent uncertainty in the predictions, regional evaluations provide a first glance at possible future decision paths. A better planning of the project development enables proactive actions to be taken (e.g., with regards to total energy consumption) and allows decision makers to avoid foreseeable risks.

3. Results

The Paris Basin—Ile-de-France (IDF), as studied in the STRATEGY CCUS project (EU H2020 project, grant agreement: 837754) and showed in Figure 3, is located in the center-northern part of France around the French capital—Paris—and it covers the administrative region of Ile-de-France and the Loiret department (storage option). It is the most populated region of France with more than 12 million inhabitants (20% of the French population). The Paris Basin IDF is still largely rural: nearly 11 million people live in the Paris agglomeration, which represents 24% of the Ile-de-France surface area, the rest of the region is made up of agricultural land, forest and natural spaces. The Ile-de-France department is an economically active region, producing nearly 30% of the French gross domestic product (GDP).

Figure 3. Geographic location of the Ile-de-France department and Paris Basin region as studied in STRATEGY CCUS project. Copyright: Google images @2022. Geographic National Institute of France.

Demography and land occupation is the first concern of the Paris Basin region, with CO_2 emissions mainly related to waste from energy plants, heat (power) plants and the chemical industry, which corresponded to 54%, 23% and 12%, respectively, of the total CO_2 emission of this region in 2019 (Appendix A).

3.1. Mapping Results

3.1.1. Emissions Sources

Emissions of CO_2 in the Paris Basin amounted to 5.5 Mt in 2019 [20]. This places the region well behind the French port regions (Dunkirk, Le Havre and Marseille-Fos), despite its high population rate. The emissions pattern is also very different, as the 5.5 Mt of CO_2 is split into 39 emitters, with almost 40% of these facilities emitting less than 50 kt of CO_2 in 2019 (Figure 4 and Appendix A). Only about 10% of facilities emitted more than 300 kt of CO_2 in 2019 and around 30% of facilities emitted between 100–300 kt of CO_2 (Figure 5A).

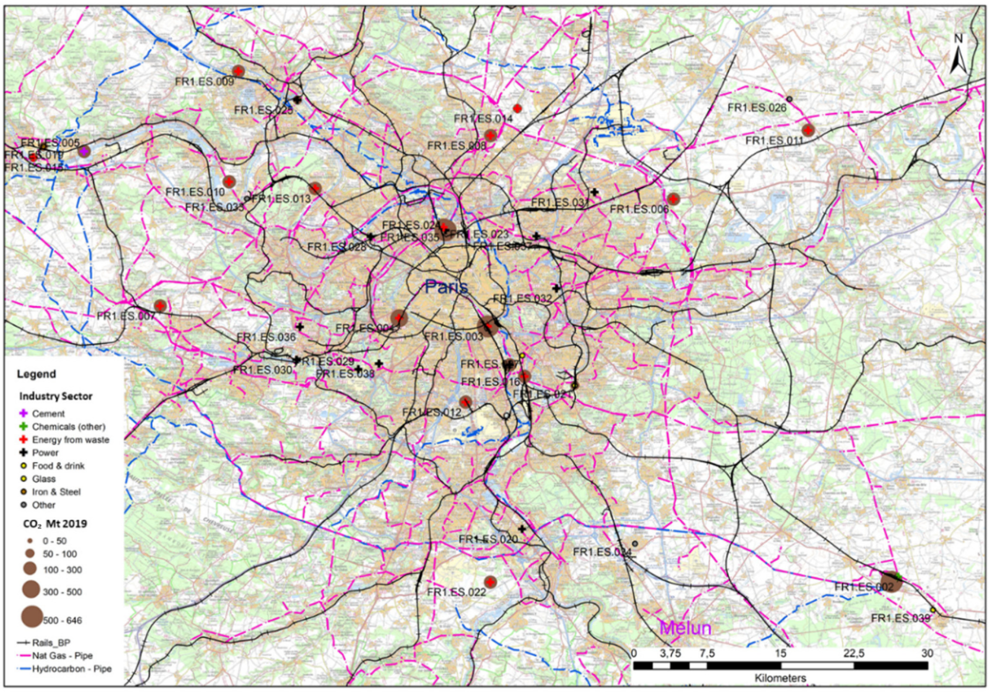

Figure 4. Geographical location of emission sources of the Paris Basin region. Color of symbol indicates the industrial sector and the size of symbols (in brown) the CO_2 emission in Mt in 2019 (data from [20]). The railways and existing natural gas and hydrocarbon pipelines are also indicated in the map (pipeline data from: GRTgaz and Data Gouv.).

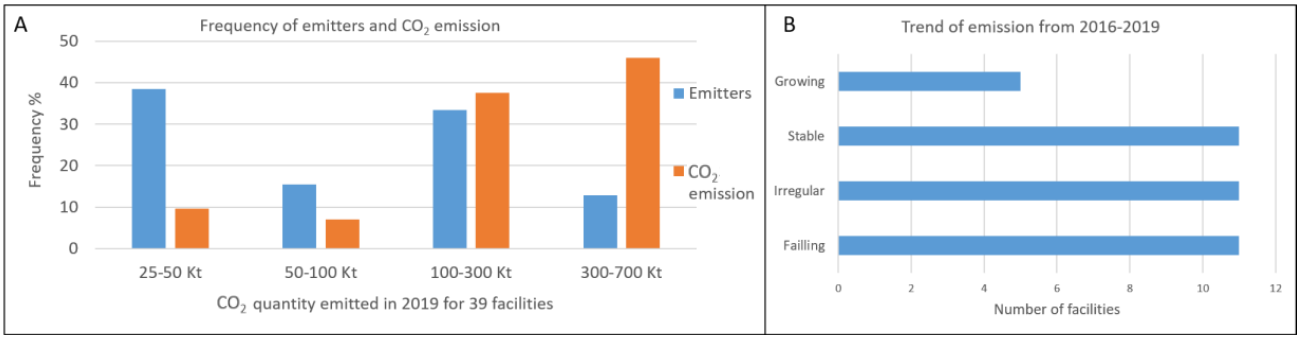

Figure 5. (**A**) CO_2 emitter facilities and CO_2 emissions frequency classed by CO_2 quantity ranges for 39 industrial facilities in the Paris Basin region. (**B**) Emission trend of these 39 facilities between 2016 and 2019. Data from [20].

In terms of the emission trends of CO_2 between 2016 and 2019 (Figure 5B), sources in the area show a decreasing trend in the emissions in recent years for eleven facilities, the other eleven facilities showed an irregular tendency and eleven others had a stable trend; only five facilities have increased their emissions (waste to energy and power). Twenty-eight facilities representing almost 80% of region's emissions (Figure 6A,B) are energy-from-waste and power (heat) facilities, which is consistent with the high-population pattern of the region. Another large part of the emissions come from one chemical facility (12%). CO_2 emissions from non-fossil-fuel combustion are an important proportion of the total emissions in the region, being estimated at up to 2.1 Mt/y, with 38% of the total emissions related to biomass combustion possibly raising the case for bioenergy with carbon capture and storage (BECCS). This alternative may be particularly interesting for the two large energy-from-waste plants south-west of Paris, FR1.ES.003 and FR1.ES.004, where CO_2 emissions from biomass are estimated, respectively, at 0.34 Mt/y and 0.28 Mt/y.

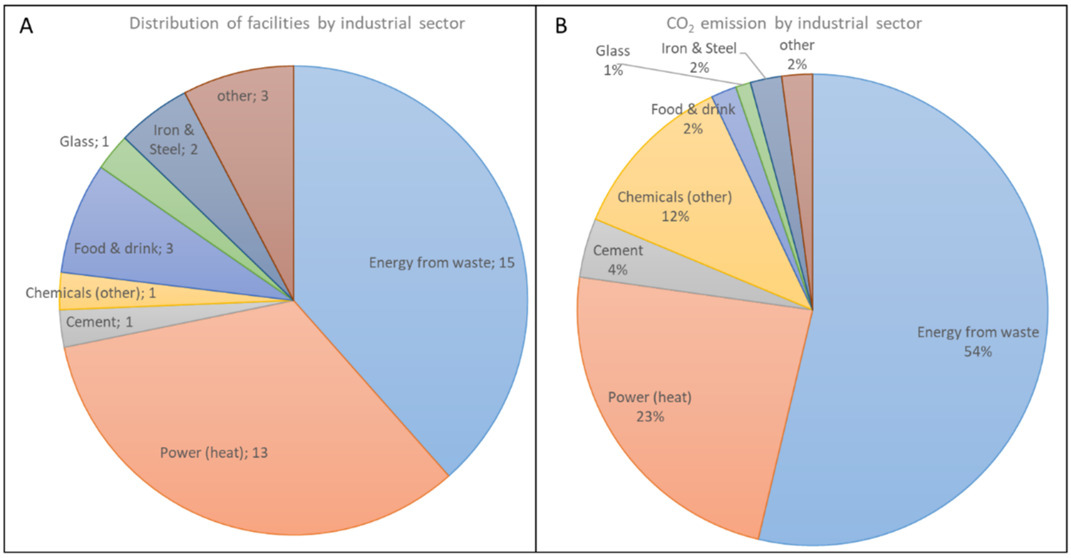

Figure 6. (**A**) Number of facilities by industrial sector and (**B**) the respective percentage of these sectors in the global amount of CO_2 emission of the region in 2019.

3.1.2. Storage Options

The Paris Basin in France is the largest onshore French sedimentary basin. First volumetric estimations of CO_2 storage capacity in the Paris Basin ranged from 800 Mt up to 27 Gt of CO_2. Two sedimentary formations, the Dogger Fm. of the Middle Jurassic and the Keuper Fm. of the Triassic, have known and good reservoir levels in the Paris Basin region [21].

The France Nord project (2013) [16] carried out detailed modeling of Keuper Fm., including the Donnemarie, Chaunoy and Boissy sedimentary members, which are mainly composed of silici-clastic sediments. Capacity estimates resulted in an assessment of the effective storage capacity, appropriate to the Tier 2 definition (Table 1). The resulting estimates relied on (i) refined geological and dynamic models in the investigated injection areas, (ii) scenarios for the commissioning of CO_2 injectors and (iii) preassessment of the long-term behavior and fate of the CO_2. The overall main objective was to reach 200 Mt of injected CO_2 in the reservoir over 40 years. Two areas of the Paris Basin were evaluated for storage in the Keuper Fm., one in the North of Paris—Keuper Nord—and another in the South of Paris—Keuper Sud (Figure 7). The effective storage capacity for Keuper Sud and Keuper Nord were, respectively, estimated to be up to 140 Mt and 81 Mt of CO_2 through dynamic modelling, after a 40 year period of injection in the—optimized combination of—injector wells. Water production was considered among the optimization scenarios but was finally dismissed for the estimates of the effective storage capacity, mostly due to the limited knowledge of the hydraulic connectivity in the deep sandstone formations.

The Dogger reservoir has been an important oil-reservoir target since the 1950s. Since the 1970s, the Dogger Fm. has progressively become the main geothermal aquifer exploited in the Paris region, with up to forty geothermal plants currently in operation. As a deep and productive aquifer (1500–2000 m depth), the hot groundwater (55 °C to 85 °C) is locally extracted from the Dogger Fm. to supply heat for up to 210,000 housing units. However, the performance of some wells has been affected by corrosion processes and the deposition of scale (i.e., secondary mineral precipitates). Moreover, the geothermal exploitation of the Dogger Fm. over decades has led to a gradual development of "cold bubbles" in the aquifer around and nearby the re-injection wells, progressively reducing the heat productivity over time.

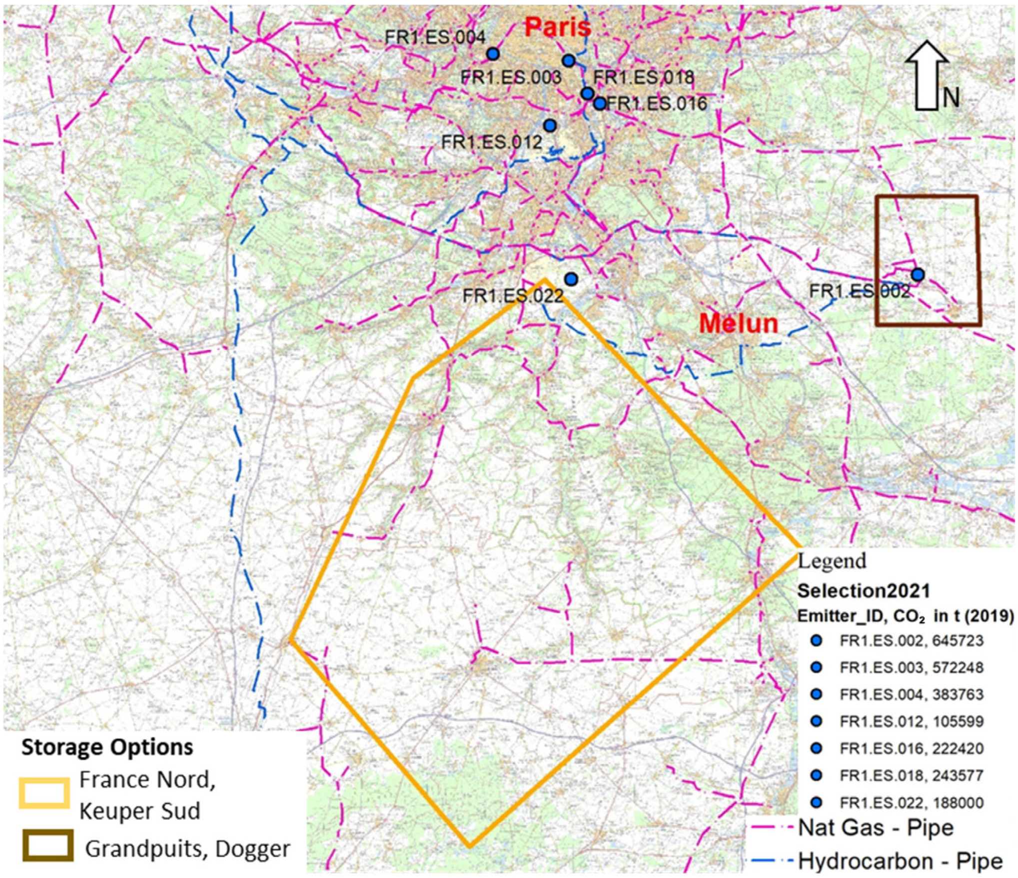

Figure 7. Storage options in both potential geological formations of the Paris Basin: the Keuper Fm. studied in the France Nord project and the Dogger Fm. at Grandpuits around the biggest CO_2 emitter of the region. Other CO_2 emission sources are also indicated by blue dots. These other sources are waste-to-energy facilities.

Apart from oil and gas and geothermal energy, the Dogger Fm. was previously studied with respect to the CO_2 storage capacity in a different research project. Within the France Nord project, the carbonates (limestones) of the Dogger Fm. displayed a limited thickness (<30 m) and a likely cemented primary porosity in the investigated areas [16]. In the GESTCO [22] and Geocapacity [23] projects, the theoretical capacity (Tier 1) of carbonate rocks was estimated to be up to 4320 Mt for a storage efficiency factor (SEF) of 6% and up to 1440 Mt for a SEF of 2%. As a result, the storage efficiencies were calculated to 6% and 2% (conservative approach) for each respective estimate. The density of CO_2 used for calculation was 400 kg/m^3, which corresponds to an approximate depth of 1400 m and a temperature of 70 °C. The significant discrepancy of the storage capacity between the identified structural traps, and the broad aquifer taken as a whole, illustrates the required necessity for large suitable geological structures in front of the CO_2 productions.

In order to study an alternative option for storage, and taking into account the very good potential of the Paris Basin in providing storage resources, a screening of the Grandpuits area (Figure 7) close to the emission source already capturing CO_2 (Emitter ID: FR1.ES.002 in Figure 4) explored possibilities to optimize and reduce CO_2 transport. This screening concerned technical geological aspects and a gap analysis of available data [24].

The Keuper Fm. in the Grandpuits area is deeper and is being exploited currently for oil-field production in the boundaries of the selected area (Figure 7). Oil fields are likely compartmentalized by sedimentary heterogeneity linked to the fluvial system or by faults. Seven old wellbores in the area reached the Keuper Fm. with few cores available. Keuper reservoirs are more than 2500 m deep in the Grandpuits area (Figure 7). The Dogger Fm. is also known as a good reservoir in this area. The top of the (Bathonian) Dogger reservoir around the emitter FR1.ES.002 is around 1700–1800 m deep. The geothermal potential linked to the high permeability and porosity of the Bathonian (Middle Dogger) is well known around Paris and Melun, which are located at 100 km and 20 km from the Grandpuits area, respectively. Nine old wellbores are available in the area, and many cores were drilled close to the investigated area.

The CO_2 storage capacity of the Dogger Fm. in the Grandpuits area using an analytical formula was estimated using the Equation (1).

$$\begin{gathered} M_{CO_2} = 1 \times 10^{-9} \times [(A \times 1 \times 10^6) \times h \times Phi] \times \rho_{CO_2} \times SEF \\ \text{With} \\ [(A \times 1 \times 10^6) \times h \times Phi] = \text{Reservoir Pore volume} \end{gathered} \quad (1)$$

where:
$\mathbf{M_{CO_2}}$ is the CO_2 storage capacity of a prospect field as a mass (Mega ton). **A** is the total area of prospect reservoir (km^2).
h is the gross reservoir thickness (m).
Phi is the average porosity (decimal).
$\boldsymbol{\rho_{CO_2}}$ is the CO_2 density at reservoir storage conditions (kg/m^3).
SEF is the storage efficiency factor (decimal).

The total area (A), the gross reservoir thickness (h) and the average porosity (Phi) of the prospect reservoir for the Dogger Fm. in this area was obtained from the volume calculation of the reservoir pore volume using a porosity value of 10%. The geological model of the Dogger Fm. elaborated in the ANR project SHPCO2 (2010) [25] at the regional scale was used to calculate reservoir pore volume. The resolution of the model is low, therefore, a SEF of 2% was used as the efficiency factor. The capacity estimate as Tier 2 using the regional-scale geomodel of the Dogger is 165 Mt of CO_2 for a reservoir pore volume of 1.61×10^{10} rm^3.

3.1.3. Spatial Condition for Cluster and Network

The proximity of the French capital, Paris, makes the area well served by natural gas and hydrocarbon pipelines, rails and important road axes (Figure 4). Despite the good possibility of a transport network, two aspects should be considered: pipeline availability and railway connection and availability. The CO_2 sources are spread across the whole promising region (Figure 4); however, only at Grandpuits, with the chemical plant (FR1.ES.002) and at the south-western part of Paris, with the two largest energy-from-waste plants (FR1.ES.003 and FR1.ES.004), does there seem to exist the locus for the onset of an industrial CCS cluster based on large emitters aggregating other minor sources to build a common network at the south of Paris (Figure 8).

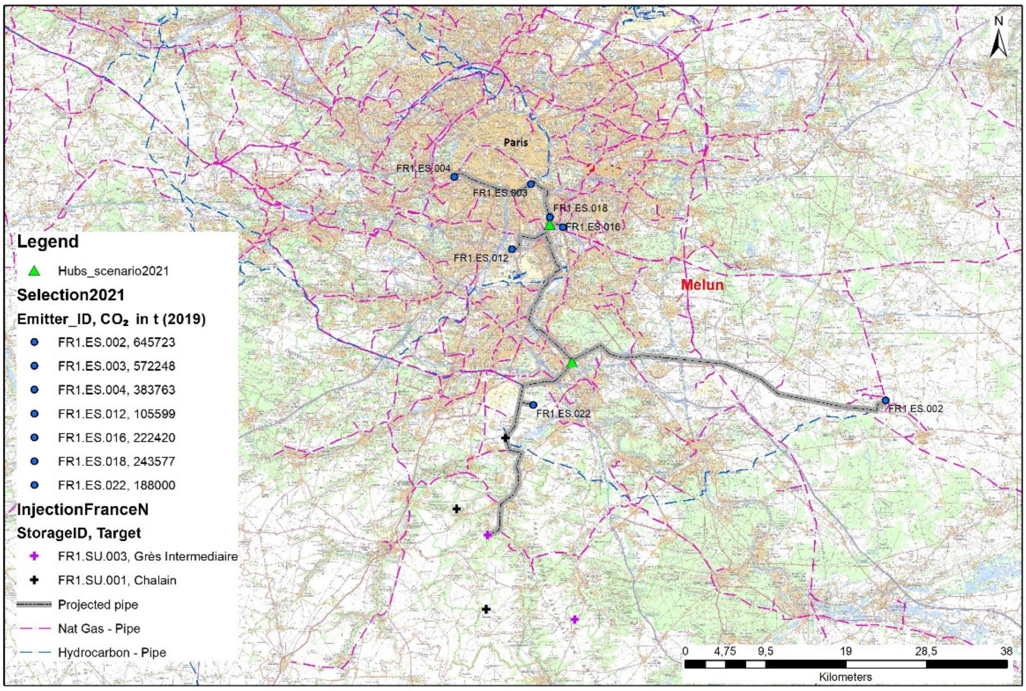

Figure 8. Spatial conditions for clusters and the transport network of CO_2. New pipelines following existing ones are considered "projected pipelines". Storage locations are represented by simulation injection points carried out in the France Nord project (FR1.SU.003 and FR1.SU.001) for the Keuper Fm. and for the Dogger Fm.; storage location is on the emission point FR1. ES.002.

3.1.4. National Low-Carbon Strategy and Emission Profile

The French National Low-Carbon Strategy (SNBC) serves as France's policymaking road map in terms of climate change mitigation [26]. The SNBC roadmap considered around 80 Mt CO_2 as inevitable or irreducible emissions by 2050. The carbon neutrality for 2050 therefore involves carbon being permanently stored to compensate for these emissions. Land-sector sink (forest and agricultural land) and CO_2 capture and storage (industrial processes) are permanent storage options with an estimate of around 15% for CCS in the schema.

The industrial sector accounted for ~15% of French GHG (green house gas) emissions in 2018. Around 84% of the sector's emissions operate under the European Union Emissions Trading Scheme (EU ETS). Industrial emissions correspond mainly to the combustion of fossil fuel or biomass required to produce energy and to the industrial process itself (i.e., chemical industries). The roadmap aims to reduce emissions of the industrial sector by 2050. Taking the emission levels of the year 2015 as the basis of reference for comparison, a gradual reduction in emissions of 35% and 81% are targeted by 2030 and 2050, respectively. According to the current state of knowledge, irreducible emissions in 2050 are related to nonenergy sectors. Apart from agriculture, the mineral production, primary metallurgy, certain chemical processes and fluorinated gases represent the main targeted emitters. The energy consumption is assumed to become entirely decarbonized. The waste-to-energy sector contributed ~3% of CO_2 emissions in 2018. The SNBC roadmap accounts to reduce the sector's emissions by 37% and 66% by 2030 and 2050, respectively, taking year 2015 as the basis of reference for comparison.

CCUS technologies could contribute to avoiding 15 $MtCO_2$ per year by 2050, including around 10 $MtCO_2$ of negative emissions with energy production installations using biomass. Such technology is referred as bio-energy with carbon capture and storage (BECCS). In 2009, the adaptation of the European CCS Directive established a legislative framework to facilitate the development of the CCUS technology.

3.1.5. Mapping Societal Aspects

The mapping of societal aspects aims to study the attitude towards CCUS development and its level of acceptance of selected members of the stakeholder group. Semistructured interviews collect (i) opinions about sources of concern, (ii) perceived benefits and risks (Table 2) and (iii) conditions for acceptance and perceived barriers, each with respect to the regional development of CCUS [17]. Preferences and expectations for energy futures among stakeholders were also raised and gathered during the interviews [17].

Table 2. List of cited benefits and risks established from interviews in the Paris Basin region. At the top, the most mentioned arguments for both categories, benefits and risks are listed.

Benefits	Risks
Environmental benefits (climate change mitigation, carbon neutrality in the industries in the region and pollution reduction in the region)	Economic viability (increase in cost and decrease in competitiveness for industries)
Economic development in the region (new industries, employment, investments and allowing power plants to keep working)	Environmental risks (risk of underground storage)
Other (financial benefits for companies, beneficial for company image and promotion of a circular economy)	Social impacts (public opposition)

Twelve interviews were carried out in the Paris Basin region with regional and national stakeholders from: industry (three people); politics and policies (four people); research and education (three people); and support organization (two people). The profile of stakeholders identified for the interviews were based on the analysis of actor structures in the innovation system for CCUS [6].

Three key ideas arose from interviews in the Paris Basin:

1. The majority of interviewees considered CCUS technologies as a potential option to fight against climate change.
2. Interviewees often underline that CCUS is only one option among other solutions to reduce carbon dioxide emissions.
3. CCU is particularly well-perceived by interviewees and appears to them to offer higher potential than CCS, regardless of the current limited volumes concerned by CO_2 valorization.

3.2. Economic KPIs

The economic simulation of the region's scenario gives the main economic key performance indicators (KPIs) of CCS business cases for the period from now to the Horizon 2050. The volume of CO_2 avoided and/or removed at the regional scale and the costs associated illustrate the technoeconomic potential of the CCS technology. The regional scenarios evaluate cost differences between investing in CCUS or paying carbon penalties related to compliance with the EU ETS, giving an estimate of the breakeven price of CO_2 for each of the studied scenarios. The scenarios are elaborated for the Horizon 2050 considering the construction time for the infrastructures as capture systems, drilling wellbores for injection and monitoring and conditioning stations for transport (compressor, pumping station, etc.).

The scenario is based on the three largest carbon emitters in the south of Paris, since the storage site is located in the southern part of the region. None of the CO_2 utilization technologies were identified in the region. The fertilizer plant in Grandpuits (emitter FR1.ES.002) emitted 646 ktCO_2 in 2019. It is located in the south-eastern part of the Paris Basin region in an agricultural area, in the vicinity of the closed Grandpuits refinery. The main part of the emissions of the plant come from the SMR unit on site, which produces H_2 for an ammonia synthesis process. As methane reforming produces a H_2/CO_2 mix, the plant already has a carbon capture installation to remove CO_2 and produce pure H_2. Actually, a part of the captured CO_2 is sold to industrial gases companies, but the largest part is released into the atmosphere. Consequently, approximately 360 ktCO_2 would be already available for storage.

The installation in Ivry (emitter FR1.ES.003) is the biggest waste incineration plant of the Paris area. In 2019, 661,593 tons of waste were treated with the production of 20,393 MWh of electricity and 1,124,190 MWh of vapor injected into the Parisian heating network (CPCU). The corresponding carbon emissions amounted to 572 ktCO_2. However, the plant will be replaced by 2023–2024 by a new installation currently under construction on the same site. Anticipating the waste reduction objectives, this new plant will have half the capacity of the current one (a valorization of 350,000 tons of waste per year). The carbon emissions of this new facility should broadly amount to 300 kt/y from 2024.

The waste valorization plant in Issy-les-Moulineaux (emitter FR1.ES.004) is the most recent incineration plant in the Paris area, as it started up in 2007. It has a capacity of 510 000 tons of waste per year. In 2019, the plant incinerated 469,097 tons of waste, emitted 384 ktCO_2, produced 705,379 MWh of steam for the CPCU urban heating network and sold 34,016 MWh of electricity. The area around this emitter has high demography density. There is no physical place to install a current CO_2 capture system for this facility.

Features and carbon emissions of these three sites are gathered in the table below (Table 3). A total of 25.2 Mt of CO_2 could be captured from 2027 to 2050 with these three emitters, including 7.7 Mt of CO_2 from biomass.

Table 3. Industries considered in the scenario with their features and carbon emissions detailed after capture.

Industries	Sector	Location	Capture Start Year	Annual CO_2 Emissions Considered—MtCO_2/y	CO_2 Capture Rate (%)	Annual CO_2 Captured (Mt/y)	Total CO_2 Captured (Mt/y)	Part of CO_2 Captured from Biomass (Mt/y)
E#01 (FR1.ES.002)	Chemistry	Grandpuits	2027	0.65	*n*/a	0.36	9.7	0.0
E#02 (FR1.ES.003)	Energy from waste	Ivry-sur-Seine	2030	0.30	0.90	0.27	7.4	3.7
E#03 (FR1.ES.004)	Energy from waste	Issy-les-Moulineaux	2032	0.38	0.85	0.33	8.1	4.0

Costs related to the scenario were calculated for each stage of the chain: capture, transport and storage for the three installations. Global CCUS CAPEX and OPEX for each installation are summarized in Table 4. The excess of energy consumption for capturing CO_2 is given in TJ.

Table 4. Summary of CAPEX, OPEX and Energy consumption of CCUS for the three selected emitters of the Paris Basin region.

Industries with Capture Medium Term	CAPEX (M EUR)	Fixed OPEX (M EUR)	Variable OPEX (M EUR)	Total Costs (M EUR)	Excess of Energy Consumption for Capture (TJ)
E#01 (FR1.ES.002)	4.1	2.9	1.3	8.3	*n*/a
E#02 (FR1.ES.003)	76.4	360.1	0.3	436.8	24,413.0
E#03 (FR1.ES.004)	84.9	362.2	0.4	447.5	28,255.0

Table 5 shows the analysis of EU ETS allowance for regional expenses of the scenario with CCUS and without CCUS. The energy costs for the capture technology are taken into account in terms of TWh/year using current costs of electricity and its evolution for 2050. The regional expense in ETS allowance without CCUS is EUR 2 270 M EUR for the scenario from 2027 to 2050, whereas costs of CCUS (including remain ETS costs) are of EUR 1131 MEUR for the period. The CCUS costs represents around half of the ETS costs of allowances for the scenario without CCUS.

Table 5. Analysis of EU ETS allowance in the scenario and energy consumption.

EU ETS Parameters (EUR/tCO_2)	**Price of Allowances in 2025**	**70.1**
	Price of Allowances in 2045	**212.4**
Whole regional expense without CCUS (M EUR)	ETS costs without CCUS	2270.0
Whole region expense with CCUS (M EUR)	ETS costs with CCUS and remaining emissions	89.8
	Costs of CCUS	1041.2
	TOTAL costs with CCUS	1131.0

The CCUS value chain of the scenario is calculated in terms of EUR/t of CO_2 avoided (Table 6), taking into account the EU ETS analysis of Table 5. The breakeven CO_2 price of the scenario is 43 EUR/t of CO_2 to have a positive economic impact of CCUS in the period between 2027 and 2050. The breakeven of CO_2 price of the CCUS value chain without the emitter FR1.ES.002, which is already capturing CO_2, gives a price of around 70 EUR/t of CO_2 avoided for 16 Mt of CO_2 captured and stored.

Table 6. Analysis of CCUS system in terms of EUR/tCO_2 avoided using the EU ETS parameters of Table 5.

CCS Value Chain (EUR/tCO_2 Avoided)		−42
CAPEX (EUR/tCO_2 avoided)	Total per block	−8.3
	Cost of Capture	−2.9
	Cost of Transport	−1.1
	Cost of Storage	−4.3
OPEX (EUR/tCO_2 avoided)	OPEX per block	−33.4
	Cost of Capture	−24.7
	Cost of Transport	−0.6
	Cost of Storage	−8.1
Transport cost (EUR/tCO_2 transported)		−1.1
Utilization (income from CO_2 sales) (M EUR)		0
EU ETS credit savings in the region (M EUR)		2180

Waste-to-Energy Challenge

Although the waste-to-energy (WtE) plants are not currently included in the EU ETS in France, these facilities are important emission sources in the region, as well sources of heat energy to houses and buildings in the vicinity. Furthermore, these facilities have great potential for providing negative emissions, as part of the CO_2 emission comes from burning biomass. The emission trend of WtE facilities around high demographic zones is uncertain and could likely increase by 2030 and 2040. Most European WtE plants emit from 100 to 500 $ktCO_2$ yearly, for a production of heat and power equivalent to about 90 and 39 TWh, respectively. The WtE plants are mainly located in urban areas or in proximity, usually being the biggest CO_2 emission sources in these areas. According to carbon limits [27], emissions from the incineration of waste are irreducible once the waste streams have been created, and CCS is the abatement technology applicable. European statistics on incinerated waste showed an increase of 30% from 2006 to 2016. The European waste-to-energy association (CEWEP) analyzed the EU recycling targets for 2035 [28] and estimated a residual nonrecycled waste stream of 142 Mt/year of waste in 2035. This amount of waste at the European scale corresponds to an increase of about 40 Mt of current incineration capacities.

Regarding the perspective of CO_2 emission from waste-to-energy facilities in France, the number of incinerators decreased since 2004, passing from 131 facilities to 121 facilities in 2018, whereas the quantity of waste showed a slight increase of ~1.2 Mt, with 14.7 Mt of waste being burned in 2018 [29]. Demography in the Ile-de-France department increased by 0.4% between 2013 and 2018, passing from 11,959,807 habitants to 12,213,447. The WtE plants are currently working at 94% of their legal capacities. Landfilling options in France counted for 18 Mt of nondangerous waste in 2018 [29]. The reduction in waste quantity sent every year to WtE plants seems to be the major challenge, as WtE plants are an alternative to landfilling options which become unsustainable and uneconomic while the living standard and waste production grows [30].

CO_2 capture technology for waste-to-energy plants uses similar technology as those used for coal-fired power stations. Some examples in the Netherlands and Norway showed the feasibility of capture systems for WtE plants [30]. The WtE plant in Twence, the Netherlands, converts 1 million tons of waste to energy every year [31]. The Ministry of Economic Affairs and Climate Policy is providing a subsidy of 14.3 million for the capture system. In Norway, the WtE plant Klemetsrud is seeking to capture 400,000 Mt/year of CO_2, corresponding to 90% of the plant's emissions by 2025. The Klemetsrud plant has a capacity to process around 350 Kt of waste and emits 385 ktCO_2 per year [32]. Both of these projects demonstrate the applicability and feasibility of current CO_2 capture technologies to WtE plants with similar capacities of waste processing and CO_2 emissions as the main WtE plants of the Paris Basin region, the emitter FR.ES.003 (730 kt of waste in 2017), FR.ES.005 (650 kt of waste in 2017) and FR.ES.006 (510 kt of waste in 2017). A technoeconomic analysis of the CCS implementation for the WtE plant in Klemetsrud estimated a P50 cost of 153 EUR/t of CO_2 avoided for the capture part of CCS chain, 208 EUR/t of CO_2 avoided including different parts of the chain CCS (steam consumption, energy, conditioning, transport and storage) and 186 EUR/t of CO_2 including CCS with EOR.

In France, the WtE plants pay several taxes related to polluting activities. The inclusion of WtE facilities in EU ETS is economically unfeasible today in France without a review of the current and future taxes applied to WtE plants as a public service. The TGAP (general tax for polluting activities) is an important tax concerning the tons of incoming of nondangerous waste received for storage and incineration processing. In 2016, 86.4% of incoming waste was household and similar waste. It is important to notice an increase of incoming waste refused from the waste treatment and disposal centers. The TGAP is paid by ton-of-waste received and its amount is a function of three factors: to have an ISO 50001certificate on energy management systems; an NOx content in the emissions of less than 80 mg/Nm^3; an energy utilization higher than 0.65 of the energy outturn. This tax is increasing quickly, from 3 EUR/t to 11 EUR/t in the past two years (2021 and 2022). In 2025, the three categories defining the amount of the tax will be replaced by a fixed amount of 15 EUR/t of waste for any facility.

The CCS for French WtE plants could drastically reduce the CO_2 emissions around high demographic areas and provide negative emissions. Although, without financial compensation or government support, the inclusion of WtE facilities in the EU ETS means adding another tax to citizens related to polluting activities. The main difference between TGAP and EU ETS is the environmental benefit of installing BECCS to avoid CO_2 emissions.

4. Discussion and Conclusions

The geographic location of sources is the first concern in the elaboration of long-term CCS scenarios. Three important emission sources are located at the south–southwest of the Paris metropolis with a low demographic area in between (Figure 4). The high demographic area around the Paris metropolis emitters would imply installing CO_2 capture systems using current technologies in a limited geographic area. Studied storage possibilities are located in the south of the Ile-de-France Department.

The key performance indicators of a CCS scenario in the Paris Basin region for a deployment between 2027 and 2050 indicates a low CO_2 cost per ton/avoided between 43 EUR/t and 70 EUR/t, for a cumulated total of 25 Mt and 16 Mt, respectively, of CO_2 captured and stored for 26 years, including 7.7 Mt of CO_2 from biomass (potential negative emissions). The low CO_2 price for the scenario would be seen as an opportunity to apply CCS in the regional scale to reach regional objectives and the ambition of CO_2 reduction for

Horizon 2050. CCS should be seen as a regional option for decarbonizing industries and not as an individual facility option.

Despite the clear statement of the SNBC (French National Low Carbon Strategy) about the benefit of CCS for irreducible emissions from industries and the benefit of deploying BECCS (negative emissions), waste-to-energy (WtE) plants are not included in the EU ETS system in France. At the perspective of reducing CO_2 emission in the Paris Basin region, the deployment of CCS and its environmental benefit for WtE installations should be considered by the French authority. Today, without the support of the government as in the Netherlands and Norway, the WtE installations are unable to consider CCS as a solution for decarbonizing the territories around big cities such as Paris, despite the low cost of about 70 EUR/t of CO_2 avoided at the regional scale.

The biggest emitter of the Paris Basin region, the fertilizers plant (FR1.ES.002), is already capturing CO_2 from its industrial process and venting it to the atmosphere. This configuration places this emitter as the candidate to launch CCS technology in the region, as CO_2 is available. The capture system represents half of the total costs of CAPEX and OPEX for CCS in this region. The geological storage capacities of Dogger Fm. around this emitter are an effective capacity (Tier 2) estimate of 165 Mt of CO_2 and seem to be enough to store its emissions of 9.7 Mt cumulated for almost 30 years. The area around the emitter is mostly rural, with the land being used for wheat crops (Figure 7). The oil and gas industry has been present for decades. Three licenses of hydrocarbon exploitation in the Keuper Fm. are being operated around the Grandpuits area, with one licensing in the Dogger Fm. Although these hydrocarbon fields are currently operating, they should stop their research and exploitation by 1 January 2040 [33]. These hydrocarbon fields being depleted would provide additional storage resources for the Horizon 2050.

In terms of infrastructures, this area is well-served by hydrocarbon pipelines, which have been exploited by the oil and gas industry since 1950. The development of a pilot-scale CCS in this area would become a notable CCS project with a perspective for large-scale development. The CCS pilot-scale project would demonstrate to local and national stakeholders the feasibility and environmental impact of the technology in terms of reducing emissions and associated risks. The reusing of oil and gas infrastructures and the high potential of geological storage for both resources, deep saline aquifers and depleted hydrocarbon reservoirs, make this location promising for further CCS development aiming to decarbonize industries around the Paris metropolis.

Although more research is needed concerning the social aspects of CCS technology and how it is perceived by national and regional stakeholders, a first overview of CCUS perception showed a positive attitude towards the technology, which was recognized as one of the tools to reduce CO_2 emissions.

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Appendix A

Table A1. Quantity reported and the emission trend between 2016 and 2019.

Emitter ID	Facility Name	Industry Sector	CO_2 from Biomass Combustion (Ton)	CO_2 Reported (Ton)	Year Reported	Emission Trend (2016–2019)
FR1.ES.002	Borealis Grandpuits	Chemicals (other)		645,723	2019	Irregular
FR1.ES.003	IVRY PARIS XIII	Energy from waste	330,683	572,248	2019	Stable
FR1.ES.004	CPCU chaufferies de ST-OUEN I et ST-OUEN II	Power	150,949	522,182	2019	Stable
FR1.ES.005	DALKIA WASTENERGY	Energy from waste	231,791	416,366	2019	
FR1.ES.006	TSI	Energy from waste	217,779	383,763	2019	Growing
FR1.ES.007	SNC Cogé VITRY	Power		243,577	2019	Stable
FR1.ES.008	Ciments Calcia usine de Gargenville	Cement	100,275	224,897	2019	Falling
FR1.ES.009	VALO'MARNE	Energy from waste	123,700	222,420	2019	Stable
FR1.ES.010	SEMARIV-CITD	Energy from waste	107,000	188,000	2018	Falling
FR1.ES.011	CPCU ST-OUEN III	Power		163,579	2019	Stable
FR1.ES.012	SIAAP Site Seine Aval	Energy from waste	143,847	144,299	2019	Falling
FR1.ES.013	SAREN	Energy from waste	81,893	143,672	2019	Growing
FR1.ES.014	Routière de l'Est Parisien (ISDND de Claye Souilly)	Energy from waste	140,933	140,933	2019	Falling
FR1.ES.015	AUROR'ENVIRONNEMENT	Energy from waste	78,501	137,944	2019	Falling
FR1.ES.016	CVD Thiverval-Grignon	Energy from waste	76,000	133,000	2018	Irregular
FR1.ES.017	AZALYS	Energy from waste	67,860	119,053	2019	Falling
FR1.ES.018	SOMOVAL	Energy from waste	60,085	106,088	2019	Stable
FR1.ES.019	GENERIS—Site de Rungis	Energy from waste	60,033	105,599	2019	Falling
FR1.ES.020	BOUQUEVAL ENERGIE	Energy from waste	86,736	86,736	2019	Falling
FR1.ES.021	SARP Industries	Energy from waste		72,764	2019	Irregular
FR1.ES.022	SAM MONTEREAU	Iron & Steel		68,948	2019	Irregular
FR1.ES.023	SGD Usine de SUCY EN BRIE	Glass		56,851	2019	Stable
FR1.ES.024	CYEL	Power	32,042	54,489	2019	Irregular
FR1.ES.025	ALPA	Iron & Steel		50,398	2019	Growing
FR1.ES.026	KNAUF Plâtres	Other		48,995	2019	Stable
FR1.ES.027	BIO SPRINGER	Food & drink		45,223	2019	Stable
FR1.ES.028	GRAND PARIS SUD ENERGIE POSITIVE	Power		44,095	2019	Growing
FR1.ES.029	ENERTHERM Noël Pons	Power		40,437	2019	Irregular
FR1.ES.030	VELIDIS Chaufferie Vélizy V3	Power		39,226	2019	Falling
FR1.ES.031	VERSEO	Power		37,512	2019	Irregular
FR1.ES.032	chaufferie zup de fontenay	Power		35,777	2019	Falling
FR1.ES.033	SAFRAN AIRCRAFT ENGINES	Other		35,666	2019	Irregular
FR1.ES.034	Chaufferie de Parly 2	Power		32,344	2019	Stable
FR1.ES.035	PEUGEOT CITROËN POISSY SNC	Other		31,713	2019	Falling
FR1.ES.036	SEMECO (et IDEX ENERGIES)	Power		30,916	2019	Stable
FR1.ES.037	chaufferie zup de sevran	Power	16,938	30,738	2019	Irregular
FR1.ES.038	LESAFFRE FRERES	Food and drink		27,850	2019	Irregular
FR1.ES.039	ENGIE Chaufferie de Meudon	Power		26,585	2019	Growing
FR1.ES.040	OUVRE FILS Sucrerie et Distillerie	Food and drink		23,812	2019	Irregular

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