Master's Thesis – master Innovation Sciences

The potential of carbon capture, utilization and storage (CCUS) to decarbonize the industry sector in Europe

A multidisciplinary three-country comparison

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Abstract

Introduction

Carbon Capture, Utilization and Storage is a technology aiming at mitigating climate change by capturing and either permanently storing CO_2 (CCS) or using it as a feedstock (CCU). This research answered the following research question: *"What role could CCUS play for European countries to decarbonize the industry sector?"*. Based on three perspectives, this research question is answered: the policy mix, technical potential, and socio-political acceptance studied in each of the three following countries: France, Spain, and the Netherlands. Subsequently, this research focussed on the alignment of these three perspectives within each of the respective countries and a cross-country comparison.

Theory

The policy mix framework is used to identify what role industrial CCUS plays in the respective national decarbonisation strategy. Subsequently, the CCUS technology process-chain have been used to research the known technical potential of industrial CCUS in the three respective countries. Lastly, the technology acceptance framework provided the concepts to identify which of these concepts influence the socio-political acceptance of industrial CCUS in the three respective countries.

Methodology

The research followed a qualitative research design to answer the main- and sub-questions. First, desk research has been executed, substantiated by nine interviews with researchers and industry respondents.

Results

In France, the lacking industrial CCU goal and instrument mix resulted in a weak alignment between the policy mix with the technical potential and the socio-political acceptance. However, there is a strong alignment between the latter two. In Spain, the lacking industrial CCUS goals are compensated by the highly consistent instrument mix and the first steps to significantly increase socio-political acceptance, resulting in a medium to strong alignment between the three perspectives. In the Netherlands, there is a strong alignment between all three perspectives due to the strong policy mix, substantiated by a large technical potential and a socio-political acceptance that is addressed.

Conclusion and discussion

The potential role for industrial CCS is large and relatively certain, and the potential role for industrial CCU is medium and rather unsure. A consistent instrument mix combined with addressing the socio-political acceptance nationally and especially on a local level is critical to further industrial CCUS developments. Also, to fully tap the industrial CCUS potential, the transportation system needs to be addressed soon as this is a long-term and essential process. The role of industrial CCUS in Europe requires further research concerning various economic aspects and international CO_2 transportation.

1. Introduction

Since the industrial revolution from around 1760 onwards, greenhouse gas (GHG) emissions on earth have increased to an all-time high, causing the average temperature on earth to rise by one degree in 2014 (IPCC, 2014). Carbon dioxide (CO_2) is emitted from burning fossil fuels, resulting in being a significant contributor to global warming (Selma et al., 2014). One of the possibilities to significantly reduce GHG emissions being released into atmosphere, is though the adoption of carbon capture, utilization and storage (CCUS) technologies. With the use of CCUS technologies, CO_2 emissions are captured from fuel combustion or industrial processes and are permanently stored or used as a feedstock.

CCUS consists of two parts: 1) carbon capture and storage and 2) carbon capture and utilization. Firstly, carbon capture and storage (CCS) allows CO_2 emissions from fossil fuel use to be transported to a geological storage, rather than being emitted to the atmosphere (Gibbins & Chalmers, 2008). CCS is broadly recognised as having the potential to play a role in meeting climate change targets by the ability to facilitate the net removal of CO_2 from the atmosphere (Bui et al., 2018). The International Energy Agency (IEA) estimates that CCS will greatly contribute to reduce CO_2 emissions in power generation and industrial applications (IEA, 2011).

Secondly, carbon capture and utilization (CCU). CCU is based on utilizing the captured of CO_2 as a feedstock to produce chemicals, materials, and transportation fuels (Al-Mamoori et al., 2017). The captured CO_2 can be used as a feedstock in different sectors and processes, e.g., food industry, agriculture, water treatment, metal fabrication or fuels (Aresta, 2007; Arning et al., 2019). When the CO_2 is used as a resource to replace fossil fuel-based products and further reduce GHG emissions, it can be considered as a renewable resource and a key process for a circular economy (Centre for Low Carbon Futures, 2011; Nocito & Dibenedetto, 2020). Possible CCUS pathways can be seen in figure 1.

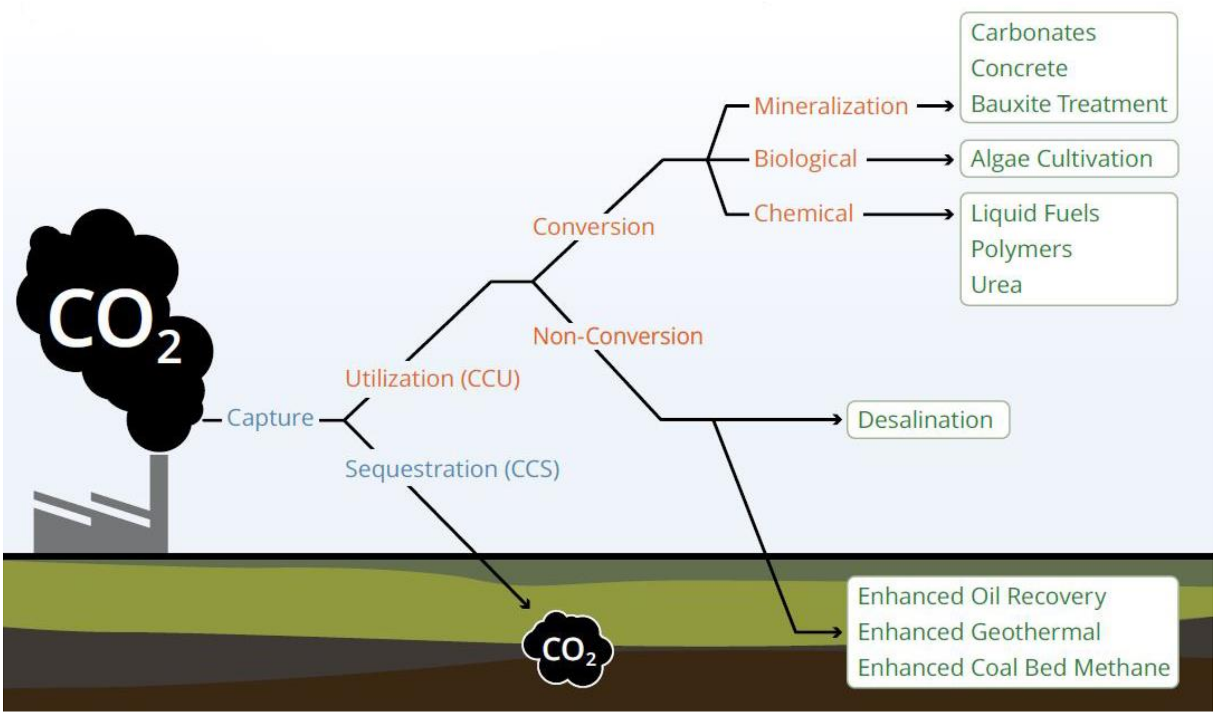

Figure 1; Carbon dioxide storage and utilization options (Global CCS institute, 2015).
Note: sequestration and storage for CCS are synonyms.

Despite not being tested extensively on a large commercial scale, CCUS is currently a seen as a useful technology in the fight against climate change and it is growing momentum (Orr Jr, 2018; Smit et al., 2014; IEA, 2020a). Some argue that reaching net zero will be virtually impossible without CCUS (IEA, 2020e; IEA, 2021). This perspective is shared by the European Union as the Horizon 2020 project funds multiple CCUS projects (IEA, 2020d). The Horizon 2020 project is, with nearly €80 billion of funding, the biggest European Union research and innovation programme ever (European Union, 2017d). Part of its funds go into supporting the further development of CCUS, including the Strategy CCUS and the Align CCUS projects.

1.1 Literature gap

As for other technologies, the deployment of CCUS unfolds as part of a socio-technical system. This term captures the interplay between human, social, organizational and technical factors (Baxter & Sommerville, 2011). Besides the broad aim of research projects and peer-reviewed literature concerning CCUS, the focus on a cross-country comparison of these identified promising areas for CCUS and a multi-disciplinary approach was insufficiently researched. Differences between countries in terms of policy strategies, technical potential and socio-political acceptance potentially influence the national implementation of CCUS were not studied in combination with each other yet. Discouraging policies, a relatively low technical potential or less socio-political acceptance could result in setbacks or unfavourable conditions for the deployment of industrial CCUS.

Policy studies towards CCUS have been executed on a small scale and primarily focussed on a single country (e.g., China) or on European-wide policies (e.g., Jiang et al., 2020; Rodrigues et al., 2015). However, a cross-country comparison concerning policies on industrial CCUS and to what extent this is part of national strategies, has not been researched yet. The potential for industrial CCUS to be implemented in the short and long term, based on a policy analysis, shed light on the role CCUS could play in national strategies. The European technical potential to implement CCUS has previously been studied by the Strategy CCUS and Align CCUS projects. However, this research shifted the focus in two ways: 1) to what extent the storage and utilization options were reflected into policy instruments and 2) the extent to which countries were participating in research projects to discover new storage and utilization potential. The latter includes the expansion of the knowledge base and the participation of researchers in new projects. In addition, the technical potential identified by previous literature, building on two projects namely Strategy CCUS and Align CCUS, were evaluated to create an overview of current CCUS implementation potential in the respective countries.

Socio-political acceptance towards a new technology is recognized as a crucial factor for further development and roll-out for such innovation (Batel et al,. 2013; Jones et al., 2017; Mikova et al., 2019). Industrial CCUS is no exception, and the socio-political acceptance is crucial for successful future deployment (Arning et al., 2019). Previous research has already studied the public acceptance of CCS and compared this to CCU (in Germany) (Dütschke et al., 2014; Sun et al., 2020; Arning et al., 2019). However, existing literature did not include an in-depth research into the three selected countries (section 1.2) to identify country specific influencing concepts.

Besides the aforementioned insufficiently researched perspectives, a literature gap concerning the multi-disciplinary approach focusing on CCUS remained. After the initial analysis on each of the three perspectives within the countries, the perspectives were combined to identify how well they aligned to each other. E.g., how did national political strategies fit together with the respective technical potential? And how did this combination align with societal and stakeholders' perceptions? Subsequently, a cross-country comparison of these results gave insight into bottlenecks, which can be avoided by other countries and lessons for successful industrial CCUS implementation were extracted.

To allow accurate country comparison, the distinction between carbon capture from the power and from the industry sector was necessary. If not, all aspects were less suitable to compare as the focus of, for example policy strategies, differs. This research focussed on CCUS in the industry sector, as renewable or less emitting alternatives for the power sector were widely researched and available, e.g., solar PV, wind energy or switching from coal-fired to natural gas-fired power plants. Concerning the latter, despite still emitting CO_2, the fuel switch from coal- to natural gas-fired power plants lead to lower CO_2 emissions, as natural gas has a lower carbon content compared to coal (Delarue & D'haeseleer, 2008). As emission-reducing alternatives were available, there was less need for CCUS in the power sector (Yu et al., 2019).

Alternatives for the industry sector were generally less available due to unavoidable process-related emissions in some sectors, theoretical limits of efficiency being reached and many differences in the used technologies and processes between industry sectors (European Union, 2017b). For example, substantial reductions in CO_2 emissions in the iron and steel industry will be impossible using conventional technologies (Kundak et al., 2009). Significant emission decreases thus critically depend on adopting a couple of key technologies (e.g., energy efficiency, fuel switching towards green energy) alongside the decarbonisation of electricity supply (Griffin & Hammond, 2019). This emission reduction was heavily needed as one-quarter of the CO_2 emissions worldwide are attributable to industrial activities which are not in the power generation sector (IEA, 2011). Thus, depending heavily on emission saving technologies, which were still uncertain or insufficiently researched, the decarbonization of the industry sector was still uncertain and could rely on carbon capture, compared to the power sector with many alternatives already available. Carbon capture may be the only available option to reduce direct emissions from industrial processes on the scale which is needed in the long term (European Union, 2017b). The combination of the three aspects, combined with the industry focus of CCUS, created a new area of research.

1.2 Research aim

This research aimed to identify the potential role of CCUS in Europe to decarbonize the industry sector. In doing so, policy strategies, technical potential and socio-political acceptance of the national implementation of industrial CCUS were studied. Afterwards, the alignment of the three perspectives was researched and subsequently, a cross-country comparison was executed. All components are explained below in more detail. From this, the following research question was derived:

"What role could CCUS play for European countries to decarbonize the industry sector?"

To answer this research question, three countries have been researched: France, Spain, and the Netherlands. There was a high potential identified to reduce CO2 emissions within the industrial regions in the respective countries, which indicated a high national potential for industrial CCUS (Strategy CCUS. (n.d.-c; European Union, 2019b). Besides the high potential, data was available in open access, which allowed pursuing data saturation. Combining both aspects resulted in valuable countries to research as industrial CCUS was likely to play a role in the decarbonization strategy in each of the countries.

Strategy CCUS has identified two industrial clusters with CCUS potential within France: Paris Basin and Rhone Valley (Strategy CCUS, n.d.-c). It was the only country with multiple clusters and included the cluster with the most CO_2 sources within the Strategy CCUS project scope (Strategy CCUS, n.d.-c; Strategy CCUS, 2020a). Besides this, France was indicated as one of the most favourable countries for implementing CCU projects and had the potential to modify its energy scenario to achieve the European targets of 2050 (Patricio et al., 2017; Mikova et al., 2019). Within the Paris Basin and Rhone Valley, potential high CO_2 industrial emission clusters were identified by the European Union: Le Havre and Marseille (figure 2).

Industrial cluster	CO_2 emitted (Mtpa)
Yorkshire	60
Marseille	35.5
Teesside	26
Antwerpen	18
Rotterdam	17.5
Le Havre	14.5
Skagerrak/Kattegat	14
Firth of Forth	7.6
Ruhr region	No data available

Figure 2; Potential industrial emission clusters in Europe (European Union, 2019b).

Strategy CCUS did identify one industrial cluster (Ebro Basin) in Spain as with a high potential for early CCS, combined with opportunities for commercial CCU and the availability of pipelines for transportation (Strategy CCUS, n.d.-a). Despite not being recognized as a high emitting CO_2 cluster by the European Union, the industrial cluster seemed to present the most complete set of conditions to deploy CCUS of all researched regions (Strategy CCUS, 2020a).

As the Strategy CCUS project focused on Southern and Eastern Europe, the Netherlands was outside the scope. The Netherlands, with Rotterdam as the focus area, was identified as having a high CCUS potential by the Align CCUS project and European Union (Align CCUS, n.d.; figure 2). This area was a large CO_2 emitter, as over ten per cent of the countries' total CO_2 emissions is generated in this area (Align CCUS, 2020c). The CCU potential was underlined by the already existing use of CO_2 for greenhouses, which is a boundary condition for a higher productivity of crop growth (Mikunda et al., 2015; TNO, 2019). Additionally, the Netherlands also has the potential to modify its energy scenario to achieve the European targets of 2050 (Mikova et al., 2019). Due to the inclusion of the Netherlands, the generalizability to Europe increases as it is outside the scope of the Strategy CCUS project.

1.3 Sub-questions

The research question was answered based on four sub-questions. The first perspective, the policy strategies, aimed to identify to what extent industrial CCUS is part of national strategies to shed light on the potential implementation of CCUS in a country in the short and long term. From this, concrete first steps in the direction of CCUS have been identified, which revealed if the policy strategy already has taken steps towards the proposed pathway. From this, the following sub-question (SQ) was derived:
SQ1: "What role does industrial CCUS play in the respective national decarbonisation strategy?"

The second perspective, the technical potential, focussed on the possibility to store or utilize the captured CO_2 in one of the respective countries. The analysis was based on Strategy CCUS and Align CCUS data, peer-reviewed literature towards CCUS potential and the participation in research projects for new CCUS potential. The aim was to create an overview of the current state to pursue national CCUS implementation and how the knowledge base expanded. From this, the following sub-question was derived:
SQ2: "What is the known technical potential of industrial CCUS in the three respective countries?"

The last perspective, the socio-political acceptance, aimed to identify which concepts influenced the national societal and stakeholder support of CCUS within the three selected countries. This involved identifying the status quo and the influencing concepts towards the socio-political acceptance concerning industrial CCUS. Generally, there are three key dimensions of acceptance for renewable

energy innovation: community, market and socio-political acceptance (Wüstenhagen et al., 2007; Jones et al., 2017). The community acceptance refers to, among other things, local stakeholders and local authorities (Wüstenhagen et al., 2007). This focus requires in-depth research and small-scale scope, which was not the aimed approach for this research. The market acceptance dimension is helpful to research for smaller-scale renewable technologies, such as solar thermal collectors (Wüstenhagen et al., 2007). Industrial CCUS is pre-eminently large-scale, which excludes the market acceptance dimension. Thus, this research only focused on the socio-political acceptance, which involved the general acceptance of technologies and policies by the public, key stakeholders and policy makers (Wüstenhagen et al., 2007). From this, the following sub-question was derived:
SQ3: "Which concepts influence socio-political acceptance of industrial CCUS?"

Figure 3; The triangle of social acceptance of renewable energy innovation (Wüstenhagen et al., 2007).

After answering the first three sub-questions for each of the selected countries, the research shifted towards the potential alignment of the three perspectives within a country. A higher alignment resulted in a higher potential for national industrial CCUS. On the other hand, if there was, for example, a contradiction due to a potentially significant role for industrial CCUS in SQ1 but there was a low technical potential in SQ2, the respective country was in trouble to pursue the strategy indicated in SQ1. From this, the following sub-question was derived:
SQ4: To what extent do the three perspectives align in a respective country?

Finally, the degree of alignment, substantiated by all previous sub-questions, created the basis for the cross-country comparison. Lessons can be learnt as it pointed out the bottlenecks and accelerating factors for the implementation of CCUS. Thus, the potential role of CCUS to decarbonize the industry sector in Europe subsequently has become visible.

1.4 Relevance

Many cross-country studies were executed concerning CCS and its relation to culture, public perception or the politics, policy and regulation, but the utilization aspect was lacking in scientific attention (Karimi & Toikka, 2018; Tcvetkov et al., 2019; Bäckstrand et al., 2011). Concerning CCUS, a cross-country comparison was executed on the knowledge spillover efficiency and many studies researched certain aspects (life cycle analysis) (Bae et al., 2020; Cuéllar-Franca & Azapagic, 2015; Sun et al., 2018). This research combined three major aspects of CCUS with a cross-country comparison, filling in a literature gap. The research on three frameworks, elaborated on in section 2, contributed to the existing literature as they were tested into new research areas. Besides filling the gap in the literature, the country comparison created a reliable foundation for future identification of potential industry areas for CCUS. This research additionally opened up the debate on expanding industrial CCUS projects throughout Europe or eventually globally.

Industrial CCUS has the potential to not only act as a CO_2 emission reducer but also as a feedstock to contribute to a circular economy. This contributed by solving a societal problem as it decarbonizes the industry sector to lower GHG emissions. Also, industrial CCUS can act as an intermediary solution for processes that were heavily emitting CO_2 and have unavoidable process-related emissions (European Union, 2017b). Future innovations might come up with solutions to decarbonize these processes, but industrial CCUS facilitated by transforming them into carbon-neutral processes until then. Besides acting as an intermediary technology, industrial CCUS was necessary to achieve net-zero goals as it will be virtually impossible without it (IEA, 2021). Industrial CCUS technologies were among the cheapest abatement options or the only option (IEA, 2021). Not focussing on CCUS increased the cost and complexity of the energy transition by an increasing reliance on technologies that are currently more expensive and at earlier stages of development (IEA, 2021).

The remainder of the research is structured as follows: the policy mix framework (section 2.1), CCUS technology process chain framework (section 2.2), socio-political acceptance concepts (section 2.3), research design (section 3.1), literature research (section 3.2), data collection (section 3.3) and the quality indicators (section 3.4). Further, concerning the results: the policy mix (section 4.1), technical potential (section 4.2), socio-political acceptance (section 4.3), alignment of the three perspectives (section 4.4), conclusion and discussion (section 5).

2. Theory

For a consistent analysis throughout the research, a framework is used to analyse the policies in national strategies and respectively its reflection into policy instruments (SQ1). Firstly, the policy mix framework of Rogge & Reichardt (2016) provided an extended concept and framework for analysis for policy mixes in sustainability transitions (section 2.1). The framework increases the understanding of the complex link between policy and technological change. The framework is created to analyse the impact of the policy mix on technological change, which corresponds with the aim of SQ1. Secondly, in section 2.2, the technology process-chain steps are used as a guideline for answering sub-question 2 regarding the technical potential. Thirdly, the socio-political acceptance analysis was based on the technology acceptance framework and the respective concepts of Huijts et al. (2012) (section 2.3). All three frameworks were used as a starting point, which indicates a deductive research. The empirical approach resulted in recommendations, adjustments or insufficiently reflected concepts in theories, which will be covered in the discussion section. The remainder of the theory section consists of the following: the policy mix framework (section 2.1), CCUS technology process-chain (section 2.2) and socio-political acceptance concepts (section 2.3).

2.1 Policy mix framework

The research of Rogge & Reichardt (2016) is used as the main reference for section 2.1. The policy mix framework is defined as a combination of three building blocks: elements, policy processes and characteristics. The three building blocks subsequently consist of multiple components and sub-components (figure 4). Alongside the building blocks, the policy mix can be specified using different dimensions.

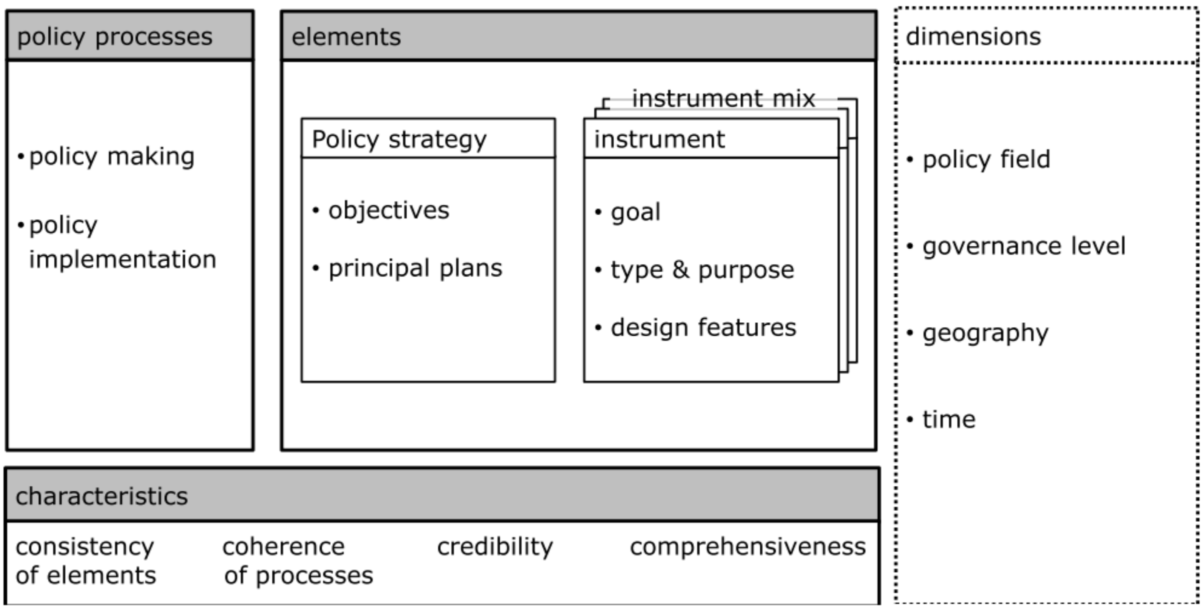

Figure 4; Building blocks of the extended policy mix concept (Rogge & Reichardt, 2016).

Firstly, the elements of the policy mix comprise the policy strategy and instrument (mix). The policy strategy is defined as a combination of policy objectives and the principal plans for achieving them. Tuominen & Himanen (2007) define the policy objective as what the policy is trying to achieve, the overall goal or target, e.g., a certain per cent reduction of CO_2 emissions due to CCUS in France. Additionally, the principal plans outline the general path that governments propose to take for the attainment of their objectives, e.g., frameworks, guidelines and roadmaps (Rogge & Reichardt, 2016). The policy strategy can play a vital role by providing guidance of the search for actors towards a technological change. In relation to this research, it aided by identifying the national strategy concerning decarbonization of the respective industry sector. Guidance of the search is, as one of the seven functions of an innovation system, one of the dynamics for technological change (Hekkert et al., 2007).

Secondly, the policy instrument (mix) is defined by the policy instruments which constitute the concrete tools to achieve policy objectives or to address policy problems, e.g., the European Emission Trading System (Rogge & Reichardt, 2016; Tuominen & Himanen, 2007). Multiple policy instruments (i.e., instrument mix) can be used to accomplish policy objectives. Despite the number of instruments, all instruments are characterized by three attributes: the goal, type & purpose and design features (Rogge & Reichardt, 2016). The goal of an instrument refers to the intended effect of instruments to achieve the overarching policy objectives (e.g., incentive for CCUS investments). The type (economic instruments, regulation and information) and purpose (technology push, demand pull and systemic concerns) of an instrument refer to the primary attributes of a certain instrument (e.g., tax incentives as an economic instrument for technology push). At last, the design features refer to multiple features, which summarize the content of an instrument. Descriptive design features indicate aspects, such as an instruments' legal form, its target actors and its duration. Abstract design features in the context of sustainability transition refer to six features: stringency, level of support, predictability, flexibility, differentiation and depth (Rogge & Reichardt, 2016).

The second building block of the policy mix, the policy processes, refers to the policy making processes, which are divided into policy making and policy implementation. The policy processes not only influence the elements of the policy mix but also its characteristics (Rogge & Reichardt, 2016). As this research focussed on the processes after policy implementation, this building block is excluded from the research.

The final building block of the policy mix by Rogge & Reichardt (2016) consists of four characteristics: consistency of elements, coherence of processes, credibility and comprehensiveness. Firstly, the consistency of the elements of a policy mix depends on how well the elements (building block one) are aligned with each other to achieve policy objectives. To pursue a high consistency, the policy mix at least needs to be free of contradictions or conflicts and preferable have a high synergy between the elements. Difficulties, which might arise through vested interest or political resistance, may result in unfavourable conditions to fully unleash all the potential of a policy instrument. Secondly, the coherence of processes refers to synergistic and systematic policy making and implementation processes. Due to the scope of this research, this characteristic was excluded. Thirdly, the credibility characteristic depends on whether a policy mix is believable and reliable, in general and regarding the previous two building blocks: elements and policy processes. This research only covered the element building block as the latter is excluded. Lastly, the comprehensiveness of a policy mix depends on the degree to which market, system and institutional failures are addressed by the instrument mix (Rogge & Reichardt, 2016). All four characteristics gave valuable insights into the potential to become an effective policy mix towards industrial CCUS implementation.

The policy mix is specified along four dimensions to capture the space in which interactions can occur: the policy field, governance level, geography and time (Rogge & Reichardt, 2016). The policy field represents the domain of the policy mix, such as energy, environmental or science, which allowed a more accurate comparison in this research. The governance level encompasses a difference between vertical (e.g., EU and member states) and horizontal (e.g., political entities at the same governance level) governance of a policy mix. The geography represents the space from which the policy mix originates, e.g., regions or cities. At last, the time dimension captures whether the policy mix develops over time in terms of the building blocks (Rogge & Reichardt, 2016). This final dimension was excluded from further research as it is already included in the descriptive design feature "duration".

2.2 CCUS technology process-chain

The CCUS technology process-chain (TPC) of Arning et al. (2019) was used as a guideline for SQ2, the technical potential. Even though the TPC was used for research into the socio-political acceptance of CCUS by Arning et al. (2019), the TPC provides a detailed breakdown of all the individual steps in the CCUS process. The CCUS TPC is built on seven individual steps, of which one is purely focussed on CCS, four on CCU and the remaining three steps on both CCS and CCU (table 1). This division shredded light on the specific step which has limitations for further national industrial CCUS developments, thus identifying the maximum technical potential. As this paper also researched to expansion of the knowledge base, this step is added to the industrial CCUS TPC.

Industrial CCUS technology process-chain	Focus (CCS and/or CCU)
CO_2-capturing	CCS and CCU
Infrastructure (transport)	CCS and CCU
Storage site	CCS
Temporary CO_2-storage	CCU
Production	CCU
Product usage	CCU
Product disposal	CCU
Knowledge base	CCS and CCU

Table 1; Technology process-chain for CCUS (Arning et al., 2019).

2.3 Socio-political acceptance

Socio-political acceptance is on the most general and broadest level of acceptance. To what extent CCUS is accepted at the socio-political level is a key determinant for investment decisions and public support (Jones et al., 2017). The socio-political acceptance analysis (SQ3) was based on the concepts of the technology acceptance framework (TAF) of Huijts et al. (2012) to understand citizen and consumer acceptance of new energy technologies, industrial CCUS in this case (table 2). Several individual (e.g., values, worldviews) and situational (e.g., fossil fuel prices) concepts are outside the scope of this framework (Huijts et al., 2012). However, these concepts are likely to influence the socio-political acceptance through the existing variables in the framework (Huijts et al., 2012). The definitions concerning the concepts of the TAF were provided by Selma et al. (2014). The definitions were slightly adapted to industrial CCUS as the scope of Selma et al. (2014) was on CCS.

Concept	Definition (Selma et al., 2014)
Knowledge	Awareness of industrial CCUS, self-assessed knowledge and objectively assessed knowledge
Experience	Direct experience with industrial CCUS, but also with related technologies (e.g., fossil fuel extraction, underground gas storage)
Trust	Trust in stakeholders. In the case of industrial CCUS typically project developers, government, NGOs
Fairness	Two types: Procedural fairness (fairness of decision processes) and distributive fairness (distribution of costs, risks, benefits)
Perceived costs	Financial costs for individuals and society, and psychological costs (e.g., effort)
Perceived risks	Potential risks to the health and safety of both humans and nature
Perceived benefits	All potential benefits attributed to industrial CCUS: for oneself, society and the environment
Outcome efficacy	Belief that someone's own behaviour affects the implementation of industrial CCUS
Problem perception	Awareness of climate change and consequences if no new technologies are implemented

Energy context	Weighing up against alternatives, consideration of the availability of other technologies that might yield equal benefits

Table 2; Adapted technology acceptance framework (Huijts et al., 2012; Selma et al., 2014).

Selma et al. (2014) excluded one and introduced two concepts from the TAF. The concept *'norms'* was excluded from the TAF as CCS was in early development and quite unknown, thus resulting in no established norms yet (Selma et al., 2014). Despite the CCS acceleration, CCU is still quite new for the creation of norms. Thus, the "norms" concept was excluded in this research as well. Besides the excluded concept, two concepts are included in the research of Selma et al. (2014). The first included concept, the *'energy context',* describes that people do not evaluate a technology in isolation but consider the availability of other technologies that might yield equal benefits (Selma et al., 2014). This concept has also been included in this research as alternatives for CCUS to decarbonize are available, which could result in an important concept for the socio-political acceptance. The second included concept by Selma et al. (2014) is the '*interface with nature'.* This concept seems to be important predictor for risk perception, benefit perception and acceptance (Selma et al., 2014). Thus, this concept seems to be an important predictor for other concepts which are already included in this research, besides that more research is needed to clarify its actual role (Selma et al., 2014). To conclude, it was superfluous to include this concept to the research.

In relation to the scope of this research, two concepts were excluded. The concept *'acceptance/attitude'* was described as both expressed acceptance ("I would accept CCUS") and revealed acceptance (whether people engage in activities for or against industrial CCUS) (Selma et al., 2014). This concept in fact described the socio-political acceptance in general. Thus, it is not seen as a concept but as the outcome because all the other concepts are researched concerning their influence of the final socio-political acceptance. To conclude, the "acceptance/attitude" concept was excluded from the TAF in this research. The second excluded concept is *'affect'*, the feeling towards industrial CCUS, with positive and negative affect being two distinct dimensions (Selma et al., 2014). This concept has a direct relation with the *perceived risks* concepts, whereas negative *affect* increases the *perceived risks* and positive affect decreases the *perceived risks* (Selma et al., 2014).

3. Methodology

Section 3 presents the methodology of the study in terms of research design (section 3.1), literature research (section 3.2), data collection (section 3.3) and quality indicators (section 3.4). The methodology concerning desk research and interviews are described in detail to provide the basis for further analysis.

3.1 Research design

The research followed a qualitative research design to answer the main- and sub-questions. As mentioned before, this research followed a deductive approach as both frameworks have been used as a starting point in new empirical settings. Although the qualitative approach leaves room for inductive results, the analysis was based on the factors derived from peer-reviewed literature. All sub-questions were first answered based on desk research and supplemented by interviews to cover any uncertainties or untraceable data. Concerning desk research, all data was acquired from either peer-reviewed literature (e.g., Google Scholar, Scopus) or from official websites and reports of governments, research institutes and other official bodies (e.g., *Planbureau voor de Leefomgeving* (Netherlands), Strategy CCUS project).

3.2 Literature research

The first sub-question was answered based on a document analysis on a national level, combined with European documents which affect the respective country and the policy mix framework and other official documents. The data was based on European but primarily governmental documents to identify decarbonization strategies (e.g., *Ministère de la transition écologique* for France). From this, more specific searches were able to fill in the components of the policy mix framework, e.g., sector specific decarbonization strategies. The second sub-question (technical potential) was answered based on peer-reviewed literature, project outputs and official documents concerning industrial CCUS potential. The strategy CCUS and Align CCUS projects provided a clear basis to start with, followed by a more detailed search into, among other things, ready-to-use infrastructures or CO_2 utilization projects. Additionally, the participation in research projects to expand the knowledge base on industrial CCUS and explore new storage and utilization potential was analysed, alongside the national research, development and demonstration budgets for CCS. Both aspects were based on desk research and supplemented by interviews to create an overview of the current state to pursue industrial CCUS implementation. Thirdly, the socio-political acceptance perspective (SQ3) was answered based on the concepts of the TAF. Project outputs and peer-reviewed literature, for example the Strategy CCUS stakeholder engagement project outputs or Eurobarometer data, was used to identify the influencing concepts on the socio-political acceptance. The fourth and final sub-question, concerning the alignment, was a qualitative analysis, based on the subtracted data from the previous three sub-questions, substantiated with interviews.

3.3 Data collection

Nine interviews were conducted with researchers and respondents from the industry with a certain degree of knowledge on industrial CCUS to pursue data saturation. The interviews were semi-structured, which left open space for broader answers; more information, but also the flexibility to steer the interview; adding questions or altering formulation to ensure a higher research saturation. All interviews were recorded with respondents' permission, fully transcribed and afterwards analysed using a coding process explained below (section 3.3.1).

The conducted interviews followed the interview guide (appendix A). Prior to an interview, a short summary of the research, combined with the main topics of the interview, were sent to the respondents as preparation to conduct a fluent interview. The interview started with a short general introduction about the research topic. The interviews were concluded by asking for any unmentioned topics and probing if the respondent knew of anyone who might was interesting to interview. This enabled snowball sampling and the data-driven additions to the interview. Table 3 provides an overview of the respondents' respective focus country, job type or industry sector, and how each respondent is referred to for quotations.

Respondent	Country	Job type or industry sector	Referring in text as
1	France	Geology	Researcher 1
2	France	Risk governance, socio-political acceptance	Researcher 2
3	France	Oil and gas industry	Industry 1
4	Spain	Geology and mining	Researcher 3
5	Spain	Technological	Industry/researcher 1
6	The Netherlands	Socio-political acceptance	Researcher 4
7	The Netherlands	Geology	Researcher 5
8	The Netherlands	CO_2 storage industry	Industry 2
9	Global	Climate Change Policy	Researcher 6

Table 3; Overview of the respondents' characteristics.
Note: Respondent 5 has experience in the industry as well as experience as a researcher.

3.3.1 Coding process

As interviews were be conducted, full transcripts and subsequently a coding process was required to identify relations between concepts and create a more in-depth understanding of the relations. Theoretical driven coding, also called thematic coding or concept coding, was applied by using the programme NVivo. "Thematic analysis is a method for identifying, analysing and reporting patterns (themes) within data" (Braun & Clarke, 2006, p. 79). This process started with a set of concepts to code, which are derived from literature and were the foundation for the interview scheme (e.g., section 2.2; appendix A). Text sections, sentences or even words were labelled as codes and attached to these concepts. The use of thematic coding did not exclude the option of finding new codes (Gibbs, 2007). Finding new codes (concepts) was highly valuable for this research as this led to some theoretical implications (section 5). This extended the current scientific knowledge which gave new insights that are relevant for future research.

During the research, several ethical issues related to data collection, handling and storage were excluded before they could appear. Firstly, no harm to respondents or subjects in any form occured during any point in time of this research. All acquired data, from both desk research and respondents, was handled with care and the privacy is in line with the GDPR regulations. Interview data was made anonymous and untraceable to a single respondent. Also, respondents were asked to fill in the informed consent form for participation in this research (appendix B). Besides this, ethical issues concerning external sources, deception, fraud and plagiarism from the researcher were in no form allowed or tolerated.

3.4 Quality indicators

The quality indicators consisted of four components: internal reliability, external reliability, internal validity and external validity. In quantitative research, reliability refers to exact replicability of the processes and the results (Leung, 2015). The essence of reliability for qualitative research lies with consistency throughout the research (Leung, 2015). The internal reliability, if the test is measuring the constructs adequately, was ensured due to the detailed methodology in this research, which was based on peer-reviewed literature and other official documents. Additionally, the internal reliability was increased due to numerous peer-feedback moments with the university. The external reliability, if the research is replicable, was ensured by standardizing the research. This was achieved by creating a methodology, following an interview scheme, accurately record-keeping of all steps involved in selecting respondents, interview transcripts and data analysis steps (Bryman, 2016; Appendix A). As a result, conducting this research again will lead to the same conclusions.

To ensure the internal and external validity of the study, systemic errors (bias) were avoided. Bryman (2016) and LeCompte & Goetz (1982) state that internal validity, to ensure causality, is one of the strengths of qualitative research. Data acquiring for this research was solely focused on this research. As a result, the data obtained was rich in relevant data for the research, which led to a high internal validity. For example, specific relevant concepts were searched for during desk research and during the preparation of the interview scheme. Besides this, unclear findings were fed back to the respondents after an interview to exclude misinterpretation. External validity, the generalizability, was ensured due to respondents and desk research into multiple perspectives and countries.

4. Results

In this section, the results of the four sub-questions are expelled in the following structure: firstly, SQ1 concerning the policy strategies (section 4.1), secondly, SQ2 concerning the technical potential (section 4.2), thirdly, SQ3 concerning the socio-political acceptance (section 4.3) and fourthly, SQ4 concerning the alignment of the three perspectives (section 4.4).

4.1 Policy mix

This section answers the first sub-question: *"What role does CCUS play in the respective national decarbonisation strategy?"*. Before looking into the three countries, the general goals and objectives of the European Union are presented, as these are likely to influence the policy mix and act as a guideline for its member states, thus the three respective countries. The European Union has set a main objective to be climate-neutral by 2050, which is the starting point for SQ1 and seen as the main objective (European Union, 2017a). This objective is in line with the Paris Agreement and at the heart of the European Green Deal (European Union, 2017a). The decarbonisation and modernisation of energy-intensive industries, such as steel and cement, is essential for achieving climate neutrality in 2050 (European Union, 2019a). The European Union has set a cap of total emissions each year by all its member states, which is called the Emission Trading System (ETS) (European Union, 2017c). The ETS limits the total emissions of over 11.000 heavy energy-using installations, which are partially industrial plants (European Union, 2017c). The covered industry sectors include oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals (European Union, 2017c). Carbon pricing can play a key role in decarbonizing the industry by creating more cost-effective energy efficiency improvements and in the longer-term investments in technologies such as CCUS (IEA, 2020b). Focussing on CCUS, the European Commission acknowledges the role of CCS and CCU in reaching this long-term emission reduction goal in a report which focuses on the potential of CCUS in Europe (European Union, 2019b). Both technologies should be seen as cost-effective options for emission reductions (European Union, 2019b).

Compared to 2019, the European CCUS capacity needs to increase by a factor of between 181 and 391 by 2050 to achieve the beforementioned objectives, although focussing on both the power sector and the industry sector (European Union, 2019b). Considering the large scale-up towards 2050, member states are required to develop integrated National Energy and Climate Plans (NECPs) in a way that aligns with the objectives of the European Union (European Union, 2019b). This resulted into the following policy recommendation towards the European Union in 2019: "Ensure Member States consider concrete deployment strategies and supportive policies for CCS and CCU nationally and in the NECPs, in order to achieve the EU 2050 climate ambitions." (European Union, 2019b, p. 6). The massive scale-up and the previous policy recommendation underline the importance of sufficient national policy mixes for CCUS to be carbon neutral in 2050. This is translated into a governance regulation, thus policy instrument, in which required member states to submit long-term national strategies by the beginning of 2020 and every ten years thereafter (European Union, n.d.-b).

A second policy instrument created by the European Union is the CCS Directive, aimed to ensure safe CO_2 capture, transport and storage and in place since 2009 (European Union, n.d.-a). The goal is to establish a legal framework for environmentally safe CO_2 storage while allowing sufficient flexibility for the member states (European Union, n.d.-a). Due to this directive, no geological CO_2 storage is possible without a permit, it is a systemic regulation. This environmental policy instrument is binding to all member states, which results in a vertical governance level, and has a permanent duration (European Union, n.d.-a). Concerning CCU, such European policies are not in place yet.

Another policy instrument concerning CCUS, implemented by the European Union, is an economic instrument which aims to provide an economic incentive for research projects: the Horizon 2020 project. The policy instrument is indicated as an economical technology push type and purpose. As mentioned before, the Strategy CCUS and Align CCUS projects are, among other projects, funded from this project with the goal to further develop CCUS in Europe. To provide some indications of the magnitude of the budgets funded by this project, the 114 million euro is available for energy projects, of which 33 million euro is allocated to low carbon industrial production using CCUS (European Union, 2019d).

Comparable to the Horizon 2020 project, the European Commission has launched the Innovation Fund. The Innovation Fund supports small- and large-scale projects on, among other things, CCS and CCU technologies in energy-intensive industries (European Union, 2019c). The difference lies within the scope of both financing instruments. The Horizon 2020 project focuses on an earlier phase of the development: the research and early innovation phase (European Union, 2017d). On the other hand, the Innovation Fund fills in the gap after the initial research and early development (European Union, 2019c). The abstract design features of both funds, with a focus on CCUS, are relatively good. There is a high ambition level and grants a high level of support due to a large number of positive economic incentives. Also, the predictability is high as the funds are certainly granted after approval, which results in some positive abstract design features.

The European Union also has implemented the European Strategic Energy Technology Plan (SET-Plan), which launched in 2007 (CCUS-SET-Plan, 2020). The goal of the SET-Plan is to bring down costs through coordinated national research efforts and by promoting cooperation between European countries, companies and research institutions (European Union, 2021). The SET-Plan identifies ten priority actions, of which CCUS is one, that could serve to help accelerate the energy system transformation and realisation (CCUS-SET-Plan, 2020). The European's aim is to become the global leader in the deployment and use of renewable energy and to meet key performance indicators for 2030 (CCUS-SET-Plan, 2020).

The above-mentioned policy instruments of the European Union concerning CCUS affect its member states industrial sectors and could influence their policy mixes. The European-wide policy instruments not necessarily influence a certain industry, but on a national level, this is more common. The following distinction is created by the IEA: 1) iron and steel, 2) cement, 3) chemicals and petrochemicals (includes oil refineries), 4) pulp and paper, 5) aluminium, and 6) other industries (IEA, 2020c).

4.1.1 France

France has created a National Low-Carbon Strategy (NLCS), which essentially is a roadmap for reducing greenhouse gas emissions up to 2050, which is binding for all citizens and companies (Ministère de la transition écologique [MTE], 2020b). The two main objectives are to achieve carbon neutrality by 2050 and to reduce the carbon footprint of French consumption (MTE, 2020b). The roadmap is seen as the outline of the general path; thus the principal plans of the policy mix framework, to achieve the overall objectives. Within the roadmap, different policy objectives towards CCUS are presented. One of the four pillars to achieve carbon neutrality is to increase and safeguard carbon sinks in, among other methods, CCUS technologies (MTE, 2020a). Also, CO_2 emissions by industrial processes should be reduced by 81% of the nonenergy emissions until 2050, compared to 2015, partially facilitated by CCUS technologies (MTE, 2020a). The report describes that CCS-technologies could capture up to 6 Mt CO_2/y by 2050 in the industry, which is ~9% of the total necessary industrial emission reduction (MTE, 2020b; figure 5). The reuse of CO_2 emissions is considered, but no concrete goals are given (MTE, 2020a).

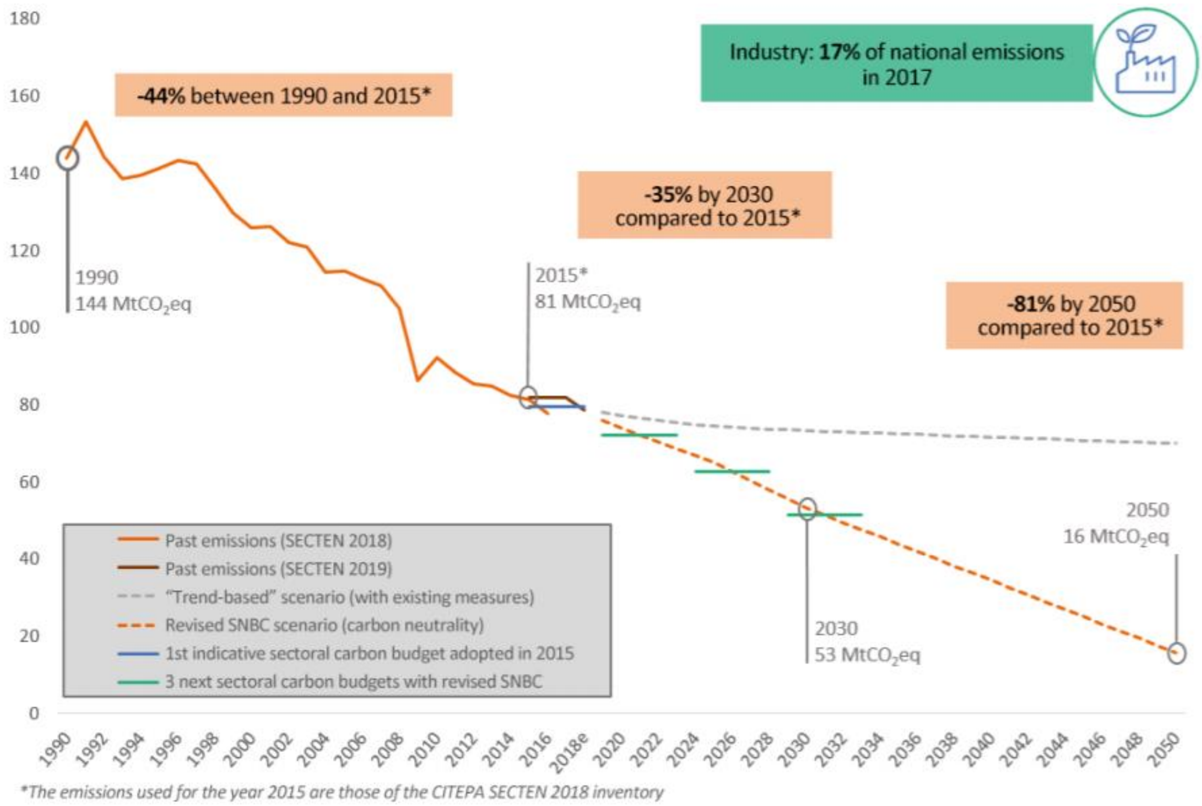

*Figure 5; Past and projected emissions of France in the industrial sector between 1990 and 2050 (in Mt CO_2eq) (*MTE*, 2020a).*

To achieve this goal, certain principal plans are presented. Companies within different industrial sectors must be supported in their transition towards low-carbon production systems (MTE, 2020a). This should be realised by providing roadmaps, financing tools and supporting the key technologies in the transition, such as CCUS (MTE, 2020b). To reach the presented policy strategy objective in the NLCS, policy instruments are necessary. The NLCS includes guidelines on governance, implementation at the national and territorial level, certain issues related to, for example, economic policies, and on sector-specific activities, such as the industry sector (MTE, 2020b). However, these guidelines have yet to be transformed into policy instruments for CCUS on investments, subsidies and more (MTE, 2020b). Despite not going into detail on policy instruments, the European CCS Directive is adopted, which results in a ready to use a legislative framework (MTE, 2020a). The French national decree on the geological storage of CO_2 came into force in late 2011, which was strongly affected by the development of the European CCS Directive (Zero CO_2, n.d.-a). This related to the rights for the exploring and grating of storage permits, alongside the monitoring, closure and post-closure of storage sites together with transferring the responsibility procedures (Zero CO_2, n.d.-a).

Apart from the European CCS Directive, the NLCS rapport indicates the support for innovation in the industry sector, provided by the Investing for the Future Programme (PIA) [Programme des Investissements d'Avenir]. This €57 billion programme subsidies throughout the innovation life cycle in France, also for industrial CCUS projects (ADEME, 2018). However, exact subsidies or the number of funded CCUS projects are not mentioned. The PIA project is an economic instrument with a technology push purpose over the duration from 2010 until 2020 (ANR, n.d.). Alongside the PIA program, France implemented the carbon tax, although indirectly focussing on industrial CCUS. The results of the tax are comparable to the demand-pull purpose of the ETS, which creates an incentive to lower CO_2 emissions and invest in innovative technologies to decarbonize processes. Despite not being directly targeting CCUS technologies, the incentive could indirectly and in the long-term increase the investments and research to push industrial CCUS. It has a binding character and targets, among other sectors, the industry sector with an endless duration.

Despite the three mentioned policy instruments, a clear instrument mix is lacking concerning industrial CCUS. The NLCS report, quite recently created in 2020, aims at "supporting the development of pilots and possible commercial CCS and CCU […]" (MTE, 2020b, p101). However, there are currently no operating industrial CCS, apart from one demonstration project which should be operating in 2022 and only a few (future) CCU projects in France (Global CCS institute, n.d.). The three CCU projects: the IGAR, Cryocap and Jupiter 1000 projects, will be elaborated further in relation to the technical potential in France (SQ2). The project status is not in line with the perspectives for CCS in France in 2015, as the research of Ricci (2015) assumed "that technologies for carbon capture and geological storage will be available from 2020" (p19). The report of the centre d'analyse stratégique (2011), concerning pathways from 2020 to 2050 towards a low-carbon economy in France, also indicated that CCS technologies should spread throughout some industrial sectors as early as 2020. Also, the yearly presented economic prospect report of 2020 in France did not mention any industrial CCS or CCU financial measurements (Ministère de l'Économie et des Finances de la République française, 2020). All the above-mentioned aspects indicate an immature stage for industrial CCUS in France concerning policy instruments to accelerate CCUS development, demonstration projects and commercial projects.

France has set a large ambition by following the European Union to be carbon neutral in 2050. However, this is a logical step as the proposal for the climate law has been submitted, which legally forces the European Union member states to be climate neutral in 2050. This converts political commitment to climate neutrality into a legal obligation (Global CCS institute, 2020). With just economic policy instruments, which only partly or indirectly affect the CCUS implementation, and the European CCS Directive in place, sufficient policy instruments towards industrial CCUS currently lack in France. Despite a high consistency throughout the policy strategy, it is not consistent with the current instrument mix. This is in line with the findings of the Norwegian Ministry of Petroleum and Energy [NMPE] (2020), even though focussing only on CCS.

4.1.2 Spain

Spain has created a National Energy and Climate Plan, which includes a roadmap for the period of 2021 until 2030 and a long-term strategy until 2050 to create a modern, competitive and climate neutral economy (Ministerio para la Transición Ecológica y el Reto Demográfico [MTERD], 2020a). The roadmap, or objectives if referring to the police mix framework, align with the main European objective to be climate neutral in 2050. The report acknowledges the importance of a carbon-free industry to achieve its objectives by modernizing the industrial sector. The main objectives described in the decarbonization strategy is to reduce the industrial CO_2 emissions by ~14% in 2030 and ~90% in 2050, compared to 2020 (MTERD, 2020a). One of the five mentioned actions points to achieve these objectives is with the use of CCUS technologies, without mentioning specific CCS or CCU goals for 2050 (MTERD, 2020a).

> Industry/researcher 1: "*No, nobody thinks in the long term, and this is a problem. […] We do not have very clear objectives in the industry. We don't know what's going to happen with the cement industry, with the steel industry, with a paper pulp, all these industries do not have a very clear objective in the national strategy.*"

CCUS is likely to play a role in industrial processes for which decarbonization modification is not feasible (MTERD, 2020a). A comprehensive review of academic and professional literature has been carried out, from which the main emission reduction options have been identified to identify the strategy of Spain (figure 6).

		Siderurgia	Petroquímica	Cemento	Papel y pasta	Cerámica	Vidrio	Alimentación
Más mencionado	1	Hornos	Procesos catalíticos	Materia prima alternativa	Hornos	Hornos	Hornos	Provisión tratamiento por calentamiento
	2	Electrólisis	Recuperación de calor	Residuos de base biológica y biomasa	Recuperación de calor	Recuperación de calor	Recuperación de calor	Hornos
	3	Reciclaje de gases de combustión	Separación con membrana	CCUS	CCUS	CHP	Precalentador	CHP
	4	CCUS	CHP	Hornos	Residuos de base biológica y biomasa	Residuos de base biológica y biomasa	Oxicombustión	Residuos de base biológica y biomasa
Menos mencionado	5	Recuperación de calor	CCUS	Recuperación de calor	Provisión tratamiento por calentamiento	Materia prima alternativa	Materiales primarios reciclados	Separación con membrana

Figure 6; Main identified areas of emission reduction per industry sector in Spain (MTERD, 2020a).
Note 1: Translations industries and Y-axis: Siderurgia = iron and steel; Petroquímica = chemicals and petrochemicals; Cemento = cement; Papel y pasta = pulp and paper; Cerámica = ceramics; Vidrio = glass; Alimentación = food; Más mencionado (Y-axis) = more mentioned; Menos mencionado (Y-axis) = less mentioned.
Note 2: Translations technologies: Hornos = ovens.; Electrólisis = electrolysis; Reciclaje de gases de combustión = flue gas recycling; Recuperación de calor = heat recovery; Procesos catalíticos = catalytic processes; Recuperación de calor = heat recovery; Separación con membrana = membrane seperation; CHP = combined heat and power; Materia prima alternativa = alternative raw material; Residuos de base biológica y biomasa = bio-based waste and biomass; Provisión tratamiento por calentamiento = provision for heat treatment; Precalentador = preheater; Oxicombustión = oxyfuel.

Referring to the IEA industry sectors, CCUS could play a role in decarbonizing the iron and steel (siderurgia), chemicals and petrochemicals (petroquimica), cement (cemento) and pulp and paper industries (Papel y pasta). Despite being less mentioned (menos mencionado), as seen on the Y-axis, compared to other emission reduction technologies, CCUS is still seen as a feasible option in these industries. This is because the quantity of being mentioned in this research does not necessarily relate to the potential net savings by a technology. This is underlined in figure 7 by the potential CO_2 reduction per industrial sector and by the following respondent.

> Industry/researcher 1: *"65, 70% [of the emissions in the cement industry] is what we call process emissions. […] For these process emissions, carbon capture is the main tool."*

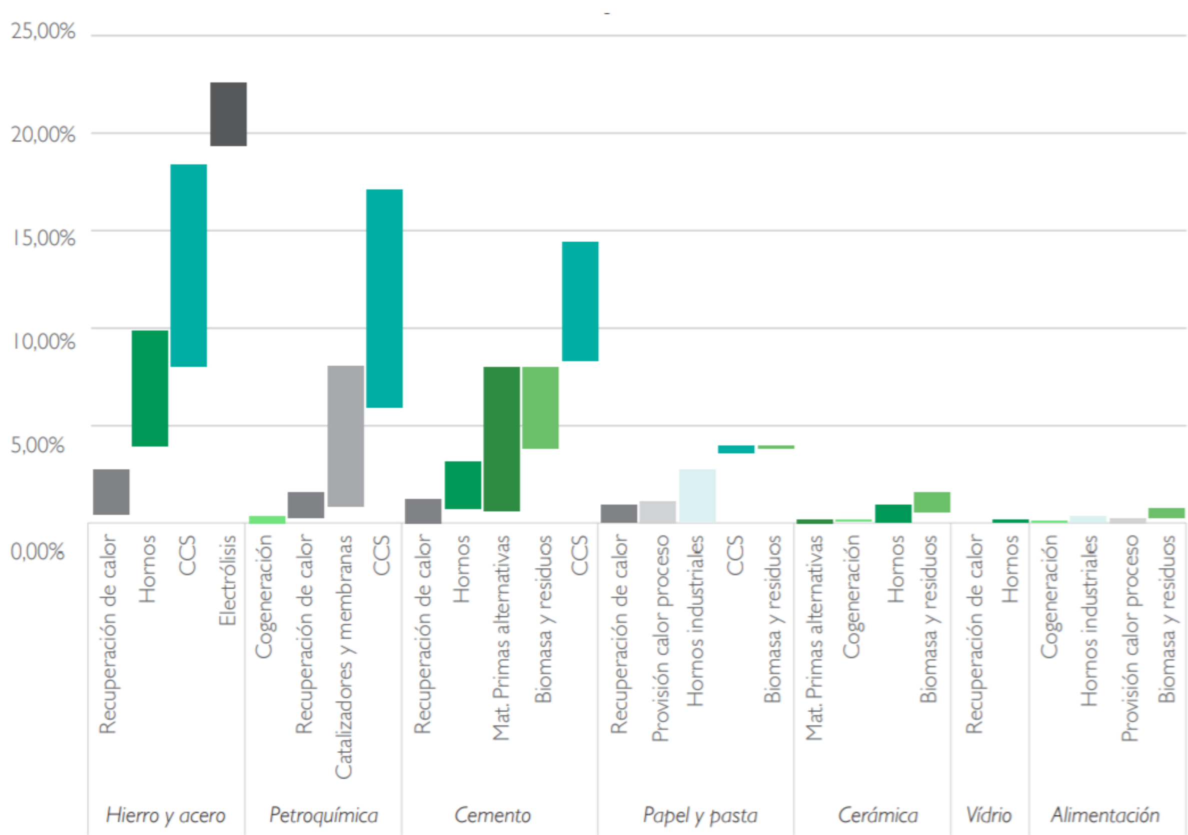

Figure 7; Potential CO2 reduction per industry sector in Spain (MTERD, 2020a).

Despite being indicated as CCS in figure 7, the in-text references are related to CCUS. To achieve the CCUS developments or objectives of figure 6 and 7, certain policy instruments must be implemented to support the technological transition towards a decarbonized industry. The high costs and unresolved questions regarding storage or the lack of realistic alternatives for the sustainable use of captured carbon on a large scale have hindered and continue to hinder the commercialisation of CCUS technologies in Spain (MTERD, 2020a). Consequently, very little progress has been seen to date in the introduction of CCUS on a large scale. Spain is, as a member of the European Union, affected by the ETS. Despite not being specifically focussed on CCUS, this results in an economic incentive for heavily emitting industries to invest in technologies to reduce CO_2 emissions, such as CCUS.

The European CCS directive, concerning safe geological CO_2 storage, has been implemented into domestic law in Spain in 2010, which was *"a very quick implementation of the CCS directive into the Spanish legislation"* (Researcher 3; Spanish CO2 Technology Platform, n.d.-a). The CCS Directive provides a legal framework, which is based on exploration licences and storage permits granted by ministries (Spanish CO2 Technology Platform, n.d.-a). The exploration licence is granted to determine the storage capacity for a period of nine years maximum. The storage permit entitles its holder to exclusively operate the storage site for fifty years (Spanish CO2 Technology Platform, n.d.-a). The permit firstly involves a declaration of public interest in respect of the overlying land, which is required for the installation of injection facilities and secondly, a plan for continuous monitoring of the injection facilities and storage complex (also from the Spanish government) (Spanish CO2 Technology Platform, n.d.-a). By adopting and implementing the CCS directive, Spain has created a permanent systemic regulative policy instrument, which is legally binding for all CO_2 storage projects. The instrument has a high degree of predictability and a low degree of flexibility, as the licences and permits are evaluated by a predetermined approach which will be identical for all evaluations.

Referring to the unresolve questions regarding the storage and usage of carbon, Spanish research and development (R&D) projects are necessary to answer these questions and lay a reliable basis for further CCUS development (MTERD, 2020b). Instruments should address the needs of the technological development necessary to fight climate change (MTERD, 2020b). Concerning industrial CCUS in Spain, storage or the use of CO2 in the manufacture of durable materials are alternatives that need to be the subject of long-term feasibility studies (MTERD, 2020a). Preliminary analyses of possible storage alternatives are currently being carried out by the Spanish Geological and Mining Institute (Instituto Geológico y Minero de España) (MTERD, 2020a). In terms of uses in durable materials, relevant advances are not expected for at least two decades (MTERD, 2020a). Industrial CCUS is thus expected not to be implemented in the short term. The current research on the storage and utilization potential is in contrast with the potential indicated in figure 6 and 7, where CCUS is likely to play a role. Also, the Strategy CCUS project has already identified CCUS potential in Spain. Despite the discrepancy, research on industrial CCUS in Spain is necessary as CCS projects only have been implemented on a pilot scale (MTERD, 2020a). Operational costs and uncertainty concerning storage create problems for economies of scale (MTERD, 2020a). Between 2010 and 2015, only four pilot and demonstration CCS projects have been executed in Spain, which was mainly focused on the power generation sector (Global CCS institute, n.d.). Concerning CO_2 utilization, only three demonstration projects have recently been executed (Spanish CO2 Technology Platform, n.d.-b).

The Spanish government has created multiple instruments to aid national CCUS developments, although these are also focussed on the power generation sector. The CIUDEN project, developed in 2006, is a policy instrument to boost the development of efficient, cost-effective and reliable CCS technologies (ENOS, n.d.). The project's goal is to develop several research infrastructures on all aspects of CCS and contribute to the creation of a favourable environment for onshore CO_2 storage (ENOS, n.d.). This informative instrument with a systemic purpose does not have a binding character but has a high level of support and decreases uncertainties where possible for all potential actors. Research on CCS transportation and storage aspects are similar to the industrial counterpart, e.g., injection strategies or monitoring stations. Thus, some developments resulting from this could be adopted for industrial CCS.

Another policy instrument in Spain is the State Incentives and Aid. This economic instrument's goal is to offer companies and a broad range of financial aid and incentives to foster investments in, among three other sectors, specific industrial sectors (ICEX, n.d.). These incentives are designed to foster productive investment, research, development and innovation (ICEX, n.d.). However, exact subsidies are unclear and (industrial) CCUS projects are also not specifically mentioned. This creates uncertainty, although industrial CCUS projects assumably could apply for financial aid. The instrument has a technology push purpose, which targets many companies and sectors without having a binding character. It has a high level of support, as the incentives are high, which could result in highly innovative outcomes. Besides the national instruments, Spanish companies can also benefit from various European Union funding programs, such as Horizon 2020 and Innovation fund, but are also affected by the ETS.

The fourth and final Spanish policy instrument is a variation on a national carbon tax. Although mentioning that Spain does not have a carbon tax, the Spanish government priced about 84% of its carbon emissions from energy use (OECD, 2019). The energy taxes are levied within the European Energy Tax Directive from 2003 (OECD, 2019). From 2018, the main taxes on energy use in Spain are implemented into this framework, which resulted in different tax rates across energy products and users (OECD, 2019). This instrument has a binding character and influences the industry, alongside its endless duration.

Following the National Energy and Climate Plan, Spain follows the goals of the European Union to be carbon neutral in 2050, and industrial CCUS is likely to play a role in four industry sectors to achieve this goal. Predictions of CO_2 emission reductions expect that in three of these four industrial sectors, CCUS technologies are likely to play a larger role than other technologies (figure 7). In the other industry sector, only one technology has been predicted to play a larger role than CCUS. Despite mentioning these progressive goals, no clear CCUS targets are set. Besides this, the principal plans (e.g., guidelines, roadmaps) to achieve these goals are lacking, which results in a potential low consistency of the policy strategy. Concerning the instrument mix, research on certain aspects of CCUS is supported, combined with economic incentives. However, the focus is primarily on CCS and not on the whole industrial CCUS-chain. Thus, the policy strategy is not in line with the instrument mix for Spain, resulting in a low consistency.

4.1.3 The Netherlands

Due to the European climate law from 2019, the Netherlands is obligated to create a long-term strategy climate plan to reduce GHG emissions in 2050. The Netherland set the long-term goal to reduce GHG emissions by 95% in 2050, compared to 1990 (Rijksoverheid, 2019; figure 8). This 95% reduction should result in a carbon-neutral country. The long-term goal for the industry is to have net climate-neutral raw materials, products and processes (Ministerie van Economische Zaken en Klimaat, 2019). The principal plans, the general path of how to achieve these goals within the industry, is focused on process efficiency, energy-saving, CCS, electrification, use of blue and green hydrogen (which requires CCS) and the acceleration of circularity (Rijksoverheid, 2020). The transition requires the use of at least two of the following options: biomass, nuclear power or CCS (Planbureau voor de Leefomgeving, 2017). The favourable CCS policies in the Netherlands create a large potential for this technology, which is necessary as the 95% reduction cannot be achieved without CCS technologies (Rijksoverheid, 2018; Rijksoverheid, 2019). Besides this, the captured CO_2 could be used as a feedstock and result in negative emissions (Rijksoverheid, 2019). CCS in the Netherlands is particularly useful in the industry instead of in the power generation sector (Rijksoverheid, 2018). Apart from the long-term goal, intermediate and target levels for 2030 are created in the ‘climate plan 2021 – 2030’ (Rijksoverheid, 2020). The main goal for 2030 is a GHG reduction of 49% compared to 1990, which is above the European goal of 40% (Rijksoverheid, 2019; figure 8). In 2017, the industry was responsible for 57,7% of the GHG emissions, and for 2030, a reduction of 14.3 Mt CO_2 should be realised in the industry in total (Rijksoverheid, 2020; Clean Energy Solutions Center, 2020). Eventually, the goal for 2025 onwards is to realise a CCS capacity of 7 Mt CO_2 /year (Topsector energie, n.d.). For CCU, no clear quantitative goals have been formulated in the Integrated Knowledge and Innovation Agenda (IKIA) (Topsector energie, n.d.). The IKIA is part of the climate agreement and gives an indication of what knowledge and innovations will be necessary to achieve the climate targets of 2050 (Topsector energie, n.d.).

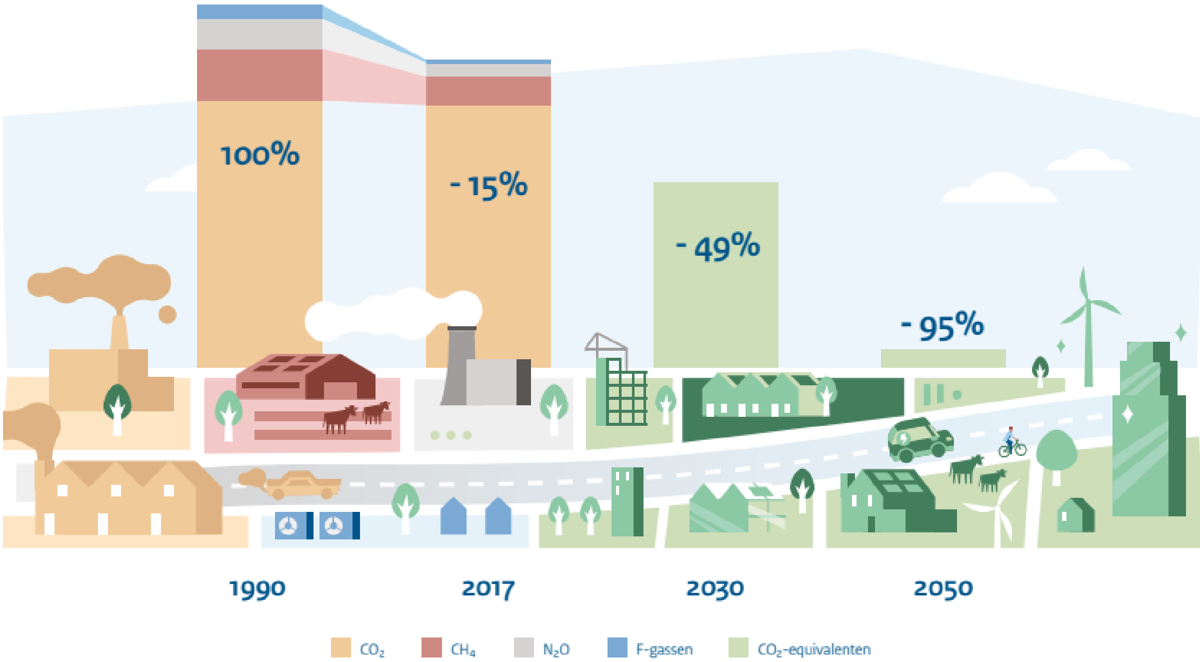

Figure 8; Emissions 1990, 2017 and goals 2030 – 2050 in the Netherlands (Rijksoverheid, 2020).

To achieve the climate and CCUS goals in the Netherlands, four policy instruments that affect industrial CCUS are implemented. Firstly, the CCS-directive is almost directly implemented into the Dutch legislation and regulations (Mining Act) (Rijksoverheid, 2018). The CCS-directive does not differ between CO_2 storage in aquifers and empty gas fields, which results in superfluous and too conservative requirements for the Dutch empty gas field storage (Rijksoverheid, 2018). Examples are the exploration licence and long monitoring requirements, which are both unnecessary for depleted gas fields (Rijksoverheid, 2018). The former is unnecessary as on the depleted Dutch gas fields, there will, in general, be sufficient information available so that the exploration phase is superfluous, and CO_2 storage permits can be applied for immediately (CMS, n.d.). For the latter, the financial consequences are also considerable, as monitoring costs that cannot be estimated at present have to be considered for longer periods of time: twenty years for the operator and subsequently an additional thirty years by the government (Rijksoverheid, 2018). Despite some differences in its implementation of the CCS Directive, the Dutch government has, as far as possible, following the structure and the licensing system of the existing mining legislation (CMS, n.d.). With the implementation of the CCS Directive, provisions, specifically pertaining to the storage of CO_2, have been included in the Mining Act (CMS, n.d.). Among other aspects, the contents of the permit (application) and regulations concerning the transfer to the Dutch government of responsibility for stored CO_2, after it has been verified that it is safely and permanently stored (CMS, n.d.).

The second policy instrument in the CATO research programme, funded by the Dutch government. The CATO project was divided into the CATO-1 and CATO-2 projects, which respectively were in operation from 2004 – 2009 and 2010 and 2014 (CATO, n.d.). Currently, the CATO programme operates as a CCS network to ensure cooperation for CCS projects. The CATO project has provided several innovations in the CO_2 capture, transportation and storage sectors, which resulted in a leading position in the international CCS community for the Netherlands (CATO, n.d.). This research, development and demonstration (RD&D) programme has a systemic purpose and has been developed to generate new knowledge. It provides a high level of support for the CCS industry and has a non-binding character, although the actual research activities were ended in 2014.

The third policy instrument is the subsidy for carbon-reducing measures. The subsidies are provided by the SDE++ program, which will be released in 2021 to stimulate sustainable energy production, CO_2

reduction technologies and the climate transition (Rijksoverheid, 2020; Rijksoverheid, 2018). Subsidies for CCS are limited by the Dutch government to technologies, processes and sectors without a cost-effective alternative, combined with a limit subsidy level of 7,2 Mt CO_2 for industrial CCS (Rijksoverheid, 2020). The limit is to ensure that the development of CCS does not come at the expense of technologies that are necessary for the long-term transition (Rijksoverheid, 2020). This economic policy instrument has a technology push purpose and targets all actors within the industry sector without any binding character. The ambition level, level of support and the incentives to pursue CCS is high due to the aid which removes economic uncertainties. The SDE++ subsidy took away an important economic barrier:

> Industry 2: *"The first hurdle was the expansion of the subsidy system, which meant that CCS was not included in the SDE scheme until 2020. That was the main reason why no market player wanted to venture into CCS, and now, I think, the biggest hurdle has been taken."*

Despite the CCS subsidies resulting from this policy instrument, the utilization part is not targeted. However, the Netherlands does have a policy instrument in place to cover this. The Dutch Enterprise Agency (RVO) is a governmental body that helps citizens and companies to invest in, develop and expand towards a sustainable and economically strong society (Rijksdienst voor Ondernemend Nederland, n.d.-b). It supports the Ministry of Economic Affairs and Climate Change, represents the Netherlands in several international CCUS related groups and provides subsidies to national CCUS projects (Rijksdienst voor Ondernemend Nederland, n.d.-a). Thus, despite not being mentioned in the long-term national strategy, economic instruments targeted both CCS and CCU are in place. This policy instrument has the same aspects within the policy mix framework as the subsidy for CCS. Besides these national instruments, Dutch companies can also benefit from European funding programs, such as the Horizon 2020 and the Innovation Fund.

At last, a national carbon tax is implemented in 2021, which should result in an emission reduction of 14.3 Mt CO_2 within ten years (Rijksoverheid, 2018). The purpose of the tax is not to generate revenue but to encourage companies to make investments. If there are any revenues due to the tax, these will be used to decarbonize the industry (Rijksoverheid, 2018). The tax is an economic instrument that has a demand-pull purpose by creating decarbonization incentives, such as CCUS technologies. As revenues are not the main purpose, this will be excluded from the analysis within the policy mix framework. The carbon tax has a legally binding character for all companies within the industry until a new emission reduction value has been established.

The favourable policy conditions, as indicated by the Dutch government, are reflected in the policy characteristics. There is a high consistency within the Dutch policy strategy regarding CCS, but no clear CCU goals are given. The CCS instrument mix, which focuses on decarbonizing the industry by the carbon tax and financial aid, is consistent with the policy strategy. Combining both aspects results in these favourable conditions for industrial CCS. This is underlined by the NMPE (2020) as the overall significance of CCS is "high" (p. 108) and by the European Union (2019b) as the Netherlands has a "favourable" (p. 41) government attitude. The favourable conditions are reflected in the number of industrial CCUS projects within the Netherlands. R&D programs for industrial CCUS technologies, although primarily on CCS, have been developed alongside multiple CCS and CCU projects. CCS projects are currently well developed within the Netherlands, as multiple demonstration projects have been completed (Global CCS institute, n.d.). Commercial, industrial CCS projects and CCS hubs, such as the Porthos project, are currently in early or advanced development, which indicates a more mature status (Global CCS institute, n.d.). Concerning CCU, smaller demonstration projects (e.g., as a feedstock for greenhouses) are in operation, and a 'CO_2 Smart Grid' is developed, but a clear goal for 2050 is lacking (OCAP, n.d.-b).

4.1.4 Overview policy mix

This section provides an overview of the results of SQ1 regarding the national policy strategies and the policy mix framework (table 4; table 5; table 6).

Building block	Components	Sub-components	France
Elements	Policy strategy	Objectives	6 Mt CO_2/y CCS by 2050, no specific CCU goals.
		Principal plans	Roadmaps, financing tools, supporting the key technologies.
	Instrument (mix)	Goals	Safe geological storage; incentive for CCUS investments; discourage CO_2 emissions.
		Type & purpose	Regulation; economic (twice).
			Systemic (twice); technology push.
		Design features (Descriptive and abstract)	*Descriptive:* *CCS directive:* Legally binding, industry and power generation sectors, 2011 – endless duration; *PIA:* Voluntary, many sectors, 2010 – 2020; *Carbon tax:* Legally binding, all sectors, 2014 – endless duration.
			Abstract: *CCS directive:* High stringency, low level of support, high predictability, low flexibility, low differentiation, high depth; *PIA:* High stringency, high level of support, high predictability, high flexibility, high differentiation, high depth; *Carbon tax:* High stringency, low level of support, high predictability, low flexibility, high differentiation, low depth.
Characteristics	Consistency of elements	Of policy strategy	High (CCS), low (CCU)
		Of instrument mix	High
		Of instrument mix with policy strategy	Medium (CCS), low (CCU)
	Credibility		Medium (CCS), low (CCU)
	Comprehensiveness		Medium
Dimensions	Policy field		*CCS directive:* Energy and industry; *PIA:* higher education and training, research, industry and SMEs, innovation, sustainable development and digitization; *Carbon tax:* Energy, industry and climate.
	Governance level		*CCS directive:* Vertical; *PIA:* Vertical; *Carbon tax:* Vertical.
	Geography		*CCS directive:* Nationally; *PIA:* Nationally; *Carbon tax:* Nationally.

Table 4; Overview policy strategies in the policy mix framework of France.
Note 1: PIA [Programme des Investissements d'Avenir] refers to Investing for the Future Programme.
Note 2: If no indication of (CCS) or (CCU) is given, it refers to both.

In France, the CCS goal is substantiated by regulative and economic policy instruments, but the informative instruments are lacking. This results in a medium consistency of the policy mix with the policy strategy and subsequently a medium CCS credibility. Due to the lacking CCU goal, there is a low consistency within the CCU policy strategy and between the policy strategy and the instrument mix. Subsequently, there is low credibility, indicating that it is not believable and reliable. The economic policy instruments which fund research and innovation are the first step towards large scale industrial CCUS. Projects are still dependent on such financial injections. Also, the small scale and eventually larger scale (demonstration) industrial CCUS projects are not economically viable, thus reliable on such economic contributions.

In the table below, table 5, the overview of the Spanish policy strategy in the policy mix framework is given.

Building block	Components	Sub-components	Spain
Elements	Policy strategy	Objectives	No specific CCS or CCU goals. To fully decarbonize the industry in general.
		Principal plans	Action points, financing tools, research projects to provide roadmaps.
	Instrument (mix)	Goals	Safe geological storage; boost CCS development; incentive for CCUS investments; discourage CO_2 emissions.
		Type & purpose	Regulation; informative; economic (twice).
			Systemic (thrice); technology push.
		Design features (Descriptive and abstract)	*Descriptive:* *CCS directive:* Legally binding, industry and power generation sectors, 2010 – endless duration; *CIUDEN:* Non-binding, CCS industry and power generation sectors, 2006 – endless duration; *SIA:* Voluntary, all industry sectors, duration unknown; *Carbon tax:* Legally binding, all sectors, 2014 – endless duration.
			Abstract: *CCS directive:* High stringency, low level of support, high predictability, low flexibility, differentiation, high depth; *CIUDEN:* High stringency, high level of support, high predictability, low flexibility, low differentiation, high depth; *SIA:* High stringency, high level of support, high predictability, high flexibility, high differentiation, high depth; *Carbon tax:* High stringency, low level of support, high predictability, low flexibility, high differentiation, low depth.
Characteristics	Consistency of elements	Of policy strategy	Low
		Of instrument mix	High
		Of instrument mix with policy strategy	Low
	Credibility		Low
	Comprehensiveness		Medium (CCS), low (CCU)
Dimensions	Policy field		*CCS directive:* Energy and industry; *CIUDEN:* Research, climate and innovation; *SIA:* Research, industry, sustainable development and technology; *Carbon tax:* Energy, industry and climate.
	Governance level		*CCS directive:* Vertical; *CIUDEN:* Horizontal;

			SIA: Vertical; *Carbon tax:* Vertical.
	Geography		*CCS directive:* Nationally; *CIUDEN:* Nationally; *SIA:* Nationally; *Carbon tax:* Nationally.

Table 5; Overview policy strategies in the policy mix framework of Spain.
Note 1: SIA refers to the State Incentives and Aid programme.
Note 2: SIA duration unknown.

Despite having regulative, informative and two economic policy instruments regarding CCUS developments, a clear policy strategy is missing in Spain. The Spanish government has not provided specific CCS or CCU goals for 2050, which results in a low consistency throughout this strategy as no indication can be given whether certain goals can be achieved without any significant trade-offs or not. The four Spanish policy instruments are, on the other hand, highly consistent as they rather reinforce than undermine each other. However, due to the lacking national policy strategy, the consistency of the policy strategy with the instrument mix is low. These two aspects cannot reinforce each other without providing specific goals to work towards, which also results in a less credible policy mix. Besides this, the comprehensiveness of the policy mix lacks regarding industrial CCU. This is due that only two of the four policy instruments also focus on industrial CCU, which are both economically.

The last table of this section, table 6, provides the overview of the Dutch policy strategy in the policy mix framework.

Building block	**Components**	**Sub-components**	**The Netherlands**
Elements	Policy strategy	Objectives	7 Mt CO_2/y CCS from 2025 onwards, no specific CCU goals.
		Principal plans	Financing tools, roadmaps, targets, research projects.
	Instrument (mix)	Goals	Safe geological storage; boost CCS development; incentive for CCUS investments; discourage CO_2 emissions.
		Type & purpose	Regulation; informative; economic (twice).
			Systemic (thrice); technology push.
		Design features (Descriptive and abstract)	*Descriptive:* *CCS directive:* Legally binding, industry sectors, 2011 – endless duration; *CATO:* non-binding, CCS industry, 2004 – 2014 *SDE++:* Voluntary, sectors without a cost-effective alternative, 2021 – 2036; *Carbon tax:* Legally binding, all sectors, 2021 – endless duration.
			Abstract: *CCS directive:* High stringency, low level of support, high predictability, low flexibility, differentiation, high depth; *CATO:* High stringency, high level of support, high predictability, low flexibility, low differentiation, high depth; *SDE++:* High stringency, high level of support, high predictability, high flexibility, high differentiation, high depth; *Carbon tax:* High stringency, low level of support, high predictability, low flexibility, high differentiation, low depth.
Characteristics	Consistency of elements	Of policy strategy	High (CCS), low (CCU)

		Of instrument mix	High
		Of instrument mix with policy strategy	High (CCS), low (CCU)
	Credibility		High (CCS), low (CCU)
	Comprehensiveness		Medium (CCS), low (CCU)
Dimensions	Policy field		*CCS directive:* Energy and industry; *CATO:* Research, climate and innovation; *SDE++:* Research, industry, sustainable development and technology; *Carbon tax:* Energy, industry and climate.
	Governance level		*CCS directive:* Vertical; *CATO:* Horizontal; *SDE++:* Vertical; *Carbon tax:* Vertical.
	Geography		*CCS directive:* Nationally; *CATO:* Nationally; *SDE++:* Nationally; *Carbon tax:* Nationally.

Table 6; Overview policy strategies in the policy mix framework of the Netherlands.

The Netherlands is doing very well on their industrial CCS policy mix. Clear goals and high consistency in the policy strategy and instrument mix are provided, which results in high credibility. The instrument mix covers regulative, informative and economic aspects which reinforce each other when pursuing the mutual CCS goal. However, the CCU policy mix is lacking in the Netherlands. Only half of the policies affect industrial CCU, which is both economically oriented, and no specific CCU goal for 2050 is indicated. This results in a low consistency throughout the policy strategy and low ability of the policy strategy and the instrument mix to work together. Consequently, this results in low credibility when referring to the Dutch industrial CCU policy mix.

4.2 Technical potential

This section answers the second sub-question: *"What is the known technical potential of CCUS in the respective countries?"*. This provides an overview of the current state to pursue national industrial CCUS implementation and gives insight into developments concerning the national knowledge base. Referring to the technology process-chain (TPC) in table 1, seven aspects of CCUS are researched: 1) CO_2-capturing (CCS and CCU), 2) infrastructure (CCS and CCU), 3) storage site (CCS), 4) temporary CO_2-storage (CCU), 5) production facility (CCU), 6) product usage (CCU) and 7) product disposal (CCU). After analysing the TPC steps, the national bottlenecks for CCUS are identified, and research to overcome these bottlenecks is evaluated. Subsequently, the IEA data on the to identify the knowledge base.

The current infrastructure in the respective countries is partly dependent on the reusability of existing pipelines. Multiple research projects studied these differences, but these did not mention significant technical limitations in the transportation aspect (Svensson et al., 2004; European Union, 2019; Benson et al., 2012; Grant et al., 2018). The only limitation concerning transportation that could arise is the distance from capture to storage sites, as different diameters and multiple pipelines could vary the total capacity. However, this is primarily an economic issue and not necessarily technological as studies up to 1000 km have been executed without mentioning technical limitations (Svensson et al, 2004; Grant et al., 2018).

The reuse of an existing oil or gas pipeline may cost 1 – 10% of the cost of building and installing a new pipeline, which could help overcome the initial cost hurdle faced by many CCS projects to date (European Union, 2019). There are a couple of conditions that affect the suitability to reuse the pipelines, excluding storage site conditions: location, size, age, condition and the availability of data (ERA NET-ACT, 2019; Department for Business, Energy & Industrial Strategy, 2019; Rabindran, 2011).

The European Union (2019b) identified a knowledge gap in the offshore transport infrastructure as studies are encouraged to identify the infrastructure which is suitable for reuse. This indicates that the abovementioned conditions are not fully developed, which hinders the reuse of these pipelines. Besides the necessary further research on and immaturity knowledge on the conditions, CO_2 transportations occur under different circumstances compared to oil and gas transportation. In principle, CO_2 pipelines operate at higher pressure than natural gas pipelines, and consequently, CO_2 pipelines require a thicker pipeline wall (Knoope, 2015).

4.2.1 France

In France, the Strategy CCUS project and the European Union have identified two industrial clusters with CCUS potential: Paris Basin (Le Havre) and the Rhone Valley (Marseille) (Strategy CCUS, n.d.-c; European Union, 2019b). This potential is created due to early onshore storage development, a large storage capacity potential and the possibility for developing small to medium CCUS hub and clusters (Rhone Valley) (Strategy CCUS, n.d.-d; Strategy CCUS, n.d.-b).

CO_2-capturing (CCUS)

Most of the industrial CO_2 emissions in France, 50 Mt CO_2/y (2019) of the total 81 Mt CO_2/y (2015), are originated from the large industrial clusters in the Paris Basin and Rhone Valley (European Union, 2019b; MTE, 2020a). The capturable industrial emissions in France are 10% of the French emissions in 2017, which represents ~31,0 Mt CO_2/y (NMPE, 2020). As mentioned before, France has the goal to capture up to 6 Mt CO2/y for industrial CCS purposes, alongside considering the CCU option without mentioning specific goals (MTE, 2020b). As the capturable industrial emissions exceed the 2050 goal for industrial CCS, no limitations are found within this step of the industrial CCUS technology-chain.

Infrastructure (CCUS)
The previously identified two industry clusters in France are well connected to the national natural gas network (Commission de Régulation de l'Energie, 2019). After further research on the specific conditions, this network might be reused for the transportation of CO_2, as the industrial clusters with CCUS potential are connected. There is, however, a condition that hampers this development. The French oil and gas network primarily transports imported oil and gas as more than 98% of the total national consumption is imported (Global legal group, 2021). However, France imports about five times more natural gas than it exports (Global legal group, 2021; IEA, n.d.-d). The natural gas import-export ratio is explained mainly due to the geological location of France, which results in being a transit centre between northern and southern Europe (Global legal group, 2021). As natural gas and oil use is primarily dependent on import, the infrastructure cannot be used for the transportation of CO_2 as the phase-out of natural gas and oil does not have occurred yet. Also, the pipelines do not necessarily connect to potential storage sites. However, researcher 1 is positive for the future: *"I think that most of the pipelines could be reused to transport CO2"*. As this view is not shared by the European Union (2019b), potentially, a new infrastructure must be built to facilitate the connection between the CO_2 emitting industries and potential storage or utilization sites. The first developments have been made, as in the Rhone Valley, a pipeline to collect CO_2 from different sources and supply different applications is being planned (Strategy CCUS, n.d.-d). Smaller parts of the pipeline network, which are connected to the oil and gas field, might be reused after further research on its conditions. The magnitude of such an infrastructure must not be underestimated.

> Industry 1: *"This is a very big infrastructure project. I mean, today, you begin with one project, and you do point to point transport."*

Despite being indicated for only having onshore storage potential, international transportation of CO_2, especially for the Paris Basin, might be a viable option as the North Sea offers a large storage potential (NMPE, 2020; European Union, 2019b; Strategy CCUS, n.d.-b). However, as international industrial CCUS activities are outside the scope of this research, follow-up studies are needed.

Storage site (CCS)
Estimations of the storage capacity of France vary quite a bit. The report of GeoCapacity (2009) estimated the total storage capacity in France at 8,7 Gt CO_2, the NMPE (2020) estimated 1 – 1,5 Gt CO_2, although mentioning the lack of available knowledge, and ADEME (2019) has set an estimation of around 27 Gt CO_2. The storage potential indicated by the Strategy CCUS project for both the Paris Basin and Rhone Valley add up to 415 Mt CO_2 storage capacity (Strategy CCUS, 2021). The differences between the calculations can be explained by the scale and available information from, among other aspects, injection wells.

> Researcher 1: *"It is not a problem that this number is not real, it is just another scale. If you want to reach the capacity at the basis scale, of course, we need many wells at different places."*

As the French CCUS goal is set on 6 Mt CO_2/y in the industry and 10 Mt CO_2/y in the energy production, a total of 16 Mt CO_2/y should be operational in 2050 (NMPE, 2020). If the goal of 16 Mt CO_2/y is established anytime soon, the NMPE research of 1 – 1,5 Gt CO_2 storage capacity will not be reached in 2050. This does not result in a potential barrier as the CCUS activities do not outweigh the storage capacity. As the storage will be focussed onshore, other aspects can become important to consider, such as the stability of the surface in urban areas or socio-political acceptance. The former is outside the scope of this research, on which follow-up studies can proceed. The latter will be discussed in section 4.3.

Temporary storage (CCU)
A few industrial CCU projects are under development in France, which could require temporary storage (ADEME, 2019). However, not every CCU project needs temporary storage as the CO_2 could be directly transported and reused after being captured. For example, the IGAR project aims to capture waste CO_2, convert it and subsequently reinject it to reduce iron ore in the steelmaking industry (ArceloreMittal, n.d.). The Cryocap installation, which has a capture capacity of 0,1 Mt CO_2/y, temporarily stores liquid CO_2 before delivering it by truck to customers (Air Liquide, 2015). The storage is only accessible and used by this project and does not involve a larger network connection, limiting the practical use of this storage for other CCU projects. For the Jupiter 1000 project, the captured CO_2 is used to create methane which can be reinjected into the gas network (Jupiter 1000). During the methanation process, the CO_2 is continuously injected and, at the most for a short time stored. However, the exact effects on the storage are still unsure as the end of the trials is planned for 2023 (Jupiter 1000). All these projects do not have temporary storage, which is accessible for other CCU projects. This could be a limitation for the industrial CCUS potential in France.

Production (CCU)
Despite not being connected to each other, all previously mentioned CCU projects in France contribute to the reduction of CO_2. Apart from the individual process steps or funds, the IGAR project does not indicate a specific CO_2 reduction (ArceloreMittal, n.d.; ADEME, n.d.). The Cryocap installation has a capture capacity of 0,1 Mt CO_2/y, which all will be used for utilization purposes to meet the need for continuous supply in, for example, beverage carbonation or agricultural uses (Air Liquide, 2015). However, this constant demand for CO_2 is not reflected in the government's plans, as there is no indication given of the level of demand in the future (MTE, 2020a). The Jupiter 1000 project aims to end the trials in 2023, but eventually, a total of 0,380 kt CO2/y is expected to be used to produce methane (Jupiter 1000, n.d.). The demand could rise in the future as the CO_2 could be transported by trucks, like the Cryocap project. However, a clear overview of the French CO_2 demand for production and the actual CO_2 saving due to current projects is lacking.

Product usage (CCU)
The usage of the captured CO_2 in France occurs in different sectors. Firstly, in the steelmaking industry, the IGAR projects save iron ore after the CO_2 is being processed in the blast furnace (ArceloreMittal, n.d.). This process creates a large potential for France as it was the 16th producer of steel in the world in 2019, based on production volumes (World Steel Association, 2020). Also, France consumed 16,0 Mt iron ore in 2018, which significantly could be reduced by utilizing the captured CO_2 (World Steel Association, 2020). The Cryocapt project does not specify its potential consumers, apart from the potential sectors in which CO_2 can be used (Air Liquide, 2015). Despite this, it underlines the broad potential of French CCU projects.

On the other hand, the usage of processed CO_2 in the Jupiter 1000 project is clear as it provides methane to the national grid (Jupiter 1000, n.d.). This process is valuable in twofold: 1) it saves fossil fuels, which otherwise would be used to produce natural gas and 2) it provides a large potential for CO_2 usage, as the French industry alone has a final annual consumption of ~450 PJ natural gas (IEA, n.d.-a). However, this process requires hydrogen, which could become a barrier to CO_2 savings during its production.

Product disposal (CCU)
After the actual usage of CO_2 as a feedstock, the question remains whether the products store it permanently or not. In the steelmaking industry, the added CO_2 is permanently stored in its products and thus not emitted into the atmosphere again. In the case of the Cryocapt project, this remains unclear as the end consumers are not mentioned specifically. The Jupiter 1000 project saves the use of fossil fuels by reusing the captured CO_2 partially. Without this project, the produced methane would otherwise be created with fossil fuels, thus saving emissions. However, as the methane is eventually

used after transportation in the national gas network, the captured CO_2 will be released back into the atmosphere. Despite not being mentioned before, the FastCarb project, which is currently under development in France, is worth mentioning. The project is still in the research and trial phase but reuses captured CO_2 in cement production (CPI, 2020). The CO_2 will eventually be permanently stored in concrete as the final product, although it can affect the performance on which safety rules have been established (CPI, 2020). If safety aspects are guaranteed, a large potential for France will become available as there are 52 cement plants in operation (Cemnet, n.d.).

Knowledge base (CCUS)

According to the IEA (n.d.-e), France had a varying total energy technology research, development and demonstration (RD&D) [total RD&D] budget between 2000 and 2019. However, for France, the period from 2002 to 2019 is taken, as the former is the first year of a CCS RD&D budget and the latter is the last available year that provides this information. The total RD&D budget varied between 1007 and 1338 million euro (figure 9). Within the same period, the RD&D budget on CO_2 capture and storage is extracted, which varies between three and 73 million euro. It must be noted that the IEA did not provide a detailed RD&D budgets for CCU and only focussed on CCS for both the industry as the power generation sector. To compare the RD&D CCS budgets of the three countries in SQ4 and research the knowledge base expansion, a few steps have been taken. First, the average of the RD&D CCS budgets is taken, which is percentage-wise calculated, compared by the average total RD&D budget in the same period. The average budget between 2002 and 2019 for CCS RD&D in France is a bit less than 27 million euro per year, and the average of the total RD&D budget was around 1168 million euro per year. This results in an average of 2,29% of the total RD&D budget spend on CCS RD&D in France in the period 2002 – 2019. One of the potential causes of these budget variations is that *“it may happen that in the first year, we spent 70% of the money on this pilot and the second year we only spend 30% of the money. So, you can see some variation because we cannot build a pilot every year.”* (Industry 1).

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0.000	0.000	3.325	3.754	6.981	11.436	29.571	31.313	33.478	73.540	46.493	57.014	41.867	34.801	26.398	21.169	15.074	12.556	15.392	18.303
755.726	557.668	1,049.498	1,046.259	1,007.109	1,012.809	1,008.922	1,055.414	1,136.312	1,253.071	1,207.250	1,338.224	1,333.049	1,333.781	1,278.128	1,244.932	1,146.744	1,153.097	1,190.502	1,236.687

Figure 9; Total RD&D in Million Euro (2019 prices and exch. rates) and CO2 Capture and Storage budget in France (IEA, n.d.-e).

Note: The rows represent the respective year (above), RD&D budget CO2 capture and storage (middle) and total energy technology RD&D budget (below). 2019 prices and exch. rates.

Besides the average CCS RD&D percentage, it is also interesting to research how this percentage evolved. Figure 10 shows the year-by-year averages, which gives a good overview of the past developments. From 2006 until 2013, a relatively large percentage was allocated to CCS RD&D. The decline from 2011 until 2017 could indicate a shift towards other, might more promising, decarbonization technologies. In the last two recorded years, 2018 and 2019, an increase is seen.

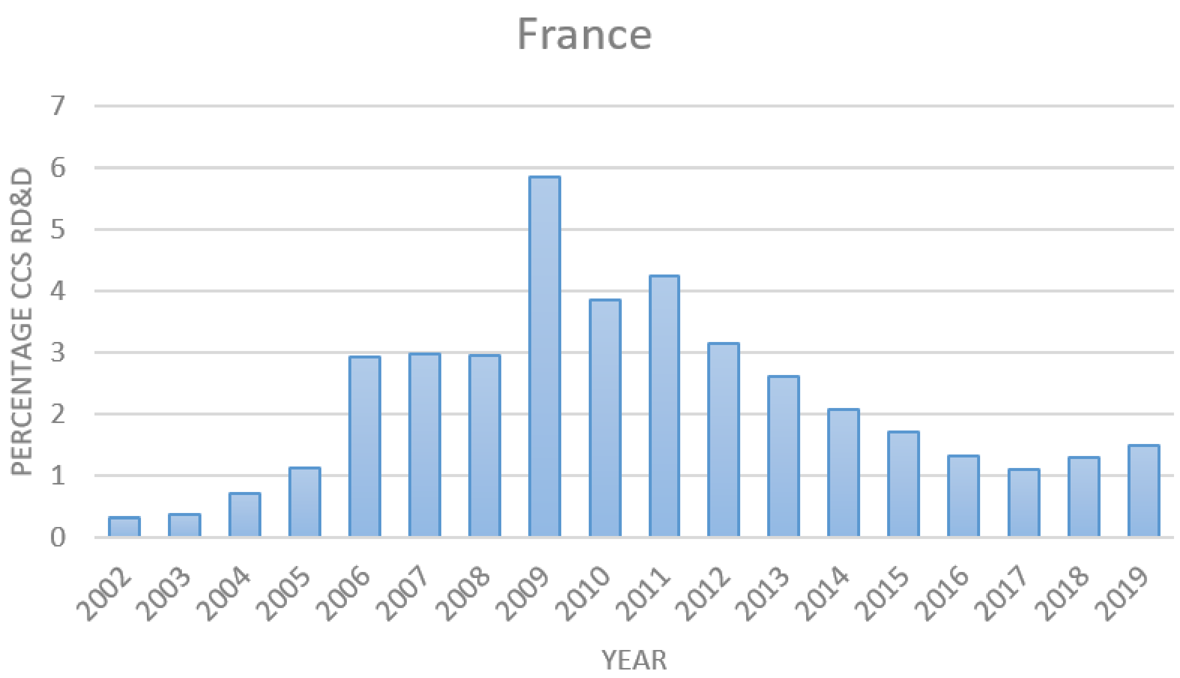

Figure 10; Annual CCS RD&D budgets as a percentage of the total energy technology RD&D budgets in France.

4.2.2 Spain

In Spain, the Strategy CCUS project has identified industrial CCUS potential for the Ebro Basin cluster (Strategy CCUS, n.d.-a). This potential is created by the potential for early onshore storage development and opportunities for several commercial CCU technologies (Strategy CCUS, n.d.-a). Also, the availability of a transportation network of gas pipelines could link emitting industry sources with CCUS sites (Strategy CCUS, n.d.-a).

CO_2-capturing (CCUS)

The industry in Spain emitted 34,0 Mt CO_2 in 2018, which was around 14% of the total emissions (IEA, n.d.-b). These emissions are partially emitted in the Tarragona, North Castellón and North Teruel industrial areas, located in the Ebra Basin cluster (Strategy CCUS, n.d.-a). As the national goal is to reduce CO_2 emissions by 90% in 2050, compared to 2020, the reduction should be around 30,6 Mt CO_2/y [if compared to 2018] (MTERD, 2020a). Despite being indicated as important in four industry sectors, no specific goals are given for CCS and CCU (figure 7; MTERD, 2020a). Also, the NMPE (2020) report does not cover Spain and thus not indicate its capturable emissions. Due to both missing aspects, no indication can be given whether the capturable emissions exceed the potential industrial CCUS use in Spain. Thus, a potential limitation remains unclear.

Infrastructure (CCUS)

The industry cluster in the Ebra Basin is well connected to a transportation network from the port of Barcelona, which includes the potential access to around 2000 km of gas pipelines (Strategy CCUS, n.d.-a). However, Spain is for almost all its gas consumption dependent on import (IEA, n.d.-c). This results in the same barrier that applied for France, as this infrastructure does not necessarily connect to a storage site, and the import of natural gas and oil is still essential. Currently, no large-scale CO2 transportation infrastructure projects are being developed, apart from small infrastructure networks for a specific project.

Storage site (CCS)

The Spanish Geological Survey carried out a detailed study on the storage capacity in Spain which resulted in an estimated capacity of 12 Gt CO_2 (Zero CO2, n.d.-b). This is comparable to the report of the European Union (2019b), which was estimated to be between 12,9 – 14 Gt CO_2. The Strategy CCUS report (2021), which only focussed on the Ebra Basin area, calculated a local storage potential of 229 Mt CO_2. Despite not mentioning an overall industrial CCUS goal for 2050, the Spanish cement industry calculated that from the 0,729 t CO2/t produced cement in 2018, a total of 0,272 t CO2/t produced cement relies on breakthrough technologies such as CCUS by 2050 (Sanjuán et al., 2020). Combining this with 12,76 Mt cement production (2016) results in around 4,76 Mt CO_2/y, which should be reduced by technologies such as industrial CCUS (Statista, 2020). This, however, cannot be projected to other industry sectors, which results in having no indication of whether the storage capacity outweighs the capturable CO_2 emissions.

Temporary storage (CCU)

Within Spain, there are a few CCU projects which could be affected by the temporary storage of CO_2. The first project is the CENIT SOST-CO_2 project, which is currently completed and aimed to address the complete CO_2 life cycle, seeking sustainable alternatives to CCS (CENIT SOST-CO_2, 2012). The project created a newly built storage tank for project-specific purposes only (CENIT SOST-CO_2, 2012). The current storage is not connected to a larger transportation network and can thus not serve as temporary storage for other CCU projects, which generally would result in a barrier. However, due to this project, a saving in the material cost reduction and a weight reduction of the steel is required (CENIT SOST-CO_2, 2012). This could serve as a big step towards affordable temporary CO_2 storage for other projects.

Secondly, the CO_2 Funnels project, launched in 2010 and is currently completed (Repsol, n.d.). This project aimed to demonstrate the possibility of capturing industrial CO_2 through CO_2 fertilisation of energy crops to obtain biomass, which may be used to generate energy (Repsol, n.d.). Energy crops grow solely to provide a feedstock for the energy industries and are low-cost and low-maintenance crops (Basu, 2018). During this process, the captured CO_2 does not require separate temporary storage as the captured CO_2 is directly added to the CO_2 fluxes in the greenhouses. The greenhouses involved in this project might not have a connection to a larger CO_2 network, but it opens the potential to reuse CO_2 for the purpose of crop growth (for energy) in Spain. Thirdly, the CCU Lighthouse project aims to be operational in 2022 and capture CO_2 during the cement production process to be reused locally (Carbon Clean, 2020). Comparable to the CO_2 Funnels project, the captured CO_2 will accelerate crop growth in the agricultural industry (Carbon Clean, 2020). No indications of temporary storage are given, and the captured CO_2 could directly be reused in the greenhouses[1].

Production (CCU)

The products which can be created from these projects vary a lot. The CENIT SOST-CO_2 project created 25 significant commercial products in multiple sectors (CENIT SOST-CO2, 2012). Some examples are optimising new materials for a more efficient CO2 capture, water (pools) treatment and the registration of a new PET tray (CENIT SOST-CO2, 2012). Also, developments in several industries, such as the chemical, agricultural and food industries, have been made (CENIT SOST-CO_2, 2012). The project primarily focussed on research goals and not on large industrial CO_2 reductions immediately. This results in no direct large-scale production, but it creates many opportunities for further developments of CCU (production) activities in and outside Spain by expanding the knowledge base.

The CO_2 Funnels project also does not indicate a specific amount of reused CO_2 during the project, comparable to the CENIT SOST-CO2 project. Around 3000 m^2 and multiple greenhouses were affiliated to the project, which indicates quite a large project (Energy12, 2012). However, no indication of the

[1] It is assumed that the CO_2 is permanently stored or removed from the atmosphere in greenhouses. However, as greenhouses might use superfluous amounts of CO_2 above the saturation level to increase the crop production even further, there might be a spill-over, resulting in CO_2 released back into the atmosphere and a lower net CO_2 savings.

(expected future) demand of CO_2 for greenhouses in Spain has not been given yet, nor indicated by the government. Due to the lack of indications on reused CO_2 volumes, exact conclusions cannot be drawn. However, due to the research and demonstration project, a large potential for future projects has been created within and outside Spain.

At last, the Lighthouse project indicates that around 0,07 Mt CO_2/y will be utilized from 2020, which is around ten per cent of the cement plant's total CO_2 emissions (PTECO2, 2021). Eventually, the goal is to fully decarbonize and reduce all the 0,7 Mt CO_2/y emissions at the respective plant (PTECO2, 2021). Although no specific indications (future) demand volumes of captured CO_2 are indicated, the project is seen as a first step to revolutionize the cement and agricultural sectors (Carbon Clean, 2020). This indicates the large potential for future CCU projects in these sectors, thus resulting in no limitation.

Product usage (CCU)
The first project, the CENIT SOST-CO_2 project, uses the captured CO_2 in multiple sectors. The latter creates a barrier by determining the product usage as 25 commercial products were made due to the knowledge gained by this project. Besides this, the lack of current large-scale production for these products leads to the conclusion that, for this project, no product usage of the captured CO_2 can be determined. On the other hand, the CO_2 Funnels and Lighthouse projects both reuse the captured CO_2 in the agricultural sector. The crops transform the CO_2 together with water into glucose and oxygen, after catalysation by light or chlorophyll, to provide energy to grow (Bassham & Lambers, 2021). By doing so, natural gas is saved with otherwise would be burned to create CO_2.

Product disposal (CCU)
After the reuse of CO_2, the remaining lifecycle of the products remains a question. As mentioned before, the CENIT SOST-CO_2 project is too broad and primarily focussed on knowledge production, which results in not being considered in this TPC step. The CO_2 Funnels project utilize the captured CO_2 at greenhouses, which results in permanently removed CO_2. The use of CO_2 for crop growth provides a large potential to decarbonize the industry as this utilization method directly reduces the total CO_2 emissions due to photosynthesis. On the other hand, the Lighthouse project is based on using the grown crops for biomass, which is still questionable in terms of sustainability as the crops will be burned and thus release CO_2 eventually.

Knowledge base (CCUS)
The IEA (n.d.-e), which has monitored the allocation of energy technology RD&D budgets in Spain, noted that the first allocation of CCS RD&D originates from 2007 and the last from 2018 (figure 11). Within this period, Spain's total RD&D budget varied between around 75 and 288 million euro. The total CCS RD&D budgets varied between zero and a bit under seven million euro annually. First, the average CCS RD&D budget between 2007 and 2018 was a bit over 1,5 million euro, and the average total RD&D was around 124 million euro during the same period. This results in an average of 1,33% of the total RD&D budget spend on CCS RD&D in Spain in the period 2007 – 2018.

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.292	2.421	4.686	0.000	0.000	2.314	0.000	2.143	6.891	..	0.000	0.111	..
69.476	67.192	59.472	69.357	52.923	57.535	65.687	79.887	91.680	146.760	153.006	288.409	170.623	75.725	100.290	111.703	90.731	77.960	103.127	..

Figure 11; Total RD&D in Million Euro (2019 prices and exch. rates) and CO2 Capture and Storage budget in Spain (IEA, n.d.-e).
Note 1: The rows represent the respective year (above), RD&D budget CO2 capture and storage (middle) and total energy technology RD&D budget (below). 2019 prices and exch. rates.
Note 2: Due to missing information in 2016, the CCS RD&D budget is set on zero for this year.

The annual percentual differences for the allocated CCS RD&D budgets in Spain are visible in figure 12. The figure highlights the large differences during this period and even multiple years without any CCS RD&D budgets.

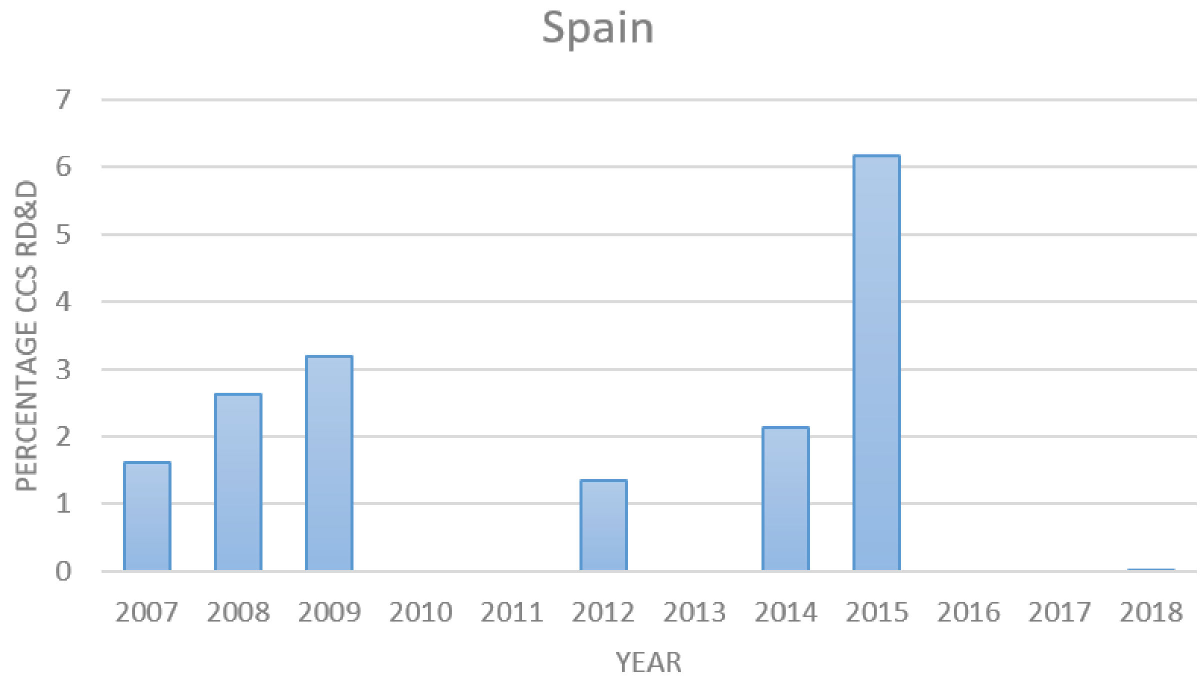

Figure 12; Annual CCS RD&D budgets as a percentage of the total energy technology RD&D budgets in Spain.

4.2.3 Netherlands

In the Netherlands, the Align CCUS project and the European Union have identified the area of Rotterdam as a high CO_2 emitting cluster with industrial CCUS potential (Align CCUS, n.d.). This potential is created by the combination of centralized facilities and the nearby offshore storage facilities (Align CCUS, n.d.). Also, relatively nearby CCU potential is available in the area, for example, as a feedstock for greenhouses.

CO_2-capturing (CCUS)

A large part of the industrial CO_2 emissions occurs in five regional clusters: Rotterdam/Moerdijk, Zeeland, North Sea Canal area, Northers Netherlands (Eemshaven-Delfzijl and Emmen) and Chemelot (Rijksoverheid, 2020). The twelve large energy-intensive companies, which together are responsible for over 60% of industrial CO2 emissions in the Netherlands, have key positions in these five industrial clusters (Rijksoverheid, 2020). The capturable emissions in the Netherlands are about 24 Mt CO_2/y, which represents about 15% of the Dutch emissions in 2017 and exclude the emissions from the power generation sector (NMPE, 2020). However, not all the capturable emissions can be captured, stored or utilized. As mentioned before, the Netherlands has the goal to realise a primarily industrial CCS capacity of 7 Mt CO_2/y from 2025 onwards, without quantifying the national CCU goal (Rijksoverheid, 2018). As the capturable emissions exceed the potential CCUS use in the Netherlands, no limitations are found within this step of the CCUS technology-chain.

Infrastructure (CCUS)

Within the Netherlands, a large infrastructure network is in place for the transportation of oil and natural gas, which is, under certain conditions, also suitable for CO_2 transportation. As previously mentioned, the conditions for reuse of this infrastructure still depends on future research, also with a local focus. This is no exception for the Netherlands, as currently, two of the largest industrial CCUS projects need further research or use newly build pipeline for transportation. The first project is the Athos project located in the North Sea Canal area (Athos, n.d.). This project has, apart from a feasibility study in 2019, various follow-up studies to draw up a more concrete project plan for the CCUS infrastructure (Athos, n.d.). The expectation is that some of these will have to be laid again, but some existing pipes can also be used again for future CCS and CCU purposes (Athos, n.d.). It is also being investigated whether the captured CO_2 can be delivered by ship. The liquid CO_2 would then be taken by pumps from the ship to a temporary storage facility onshore and subsequently be transported via the underground sea pipeline to the storage field under the North Sea (Athos, n.d.). To increase the useability of the project, the connection to the previously mentioned CO_2 network, "CO_2 Smart Grid", is also planned (Athos, n.d.).

The second large CCUS Dutch project, the Porthos project, is further developed and expected to be operational in 2024, compared to 2026 for the Athos project (Porthos, n.d.-b; Athos, n.d.). This CCS project creates a new pipeline infrastructure of 50 – 55 kilometres on both land and at sea, instead of reusing the available infrastructure (Porthos, n.d.-a). The platform which has been used for the extraction of gas will be reused for the injection of CO_2 (Porthos, n.d.-a). Building a new pipeline network is in contrast with the research of the Align CCUS project regarding infrastructure reuse for a typical site in the Dutch North Sea sector. The research concludes that the infrastructure of pipelines and platforms were regularly suitable for reuse (Align CCUS, 2019a). However, project-specific research is still necessary as there are changing conditions, such as long project lifetimes and temperature changes due to larger distances (Align CCUS, 2019a). To conclude, the large oil and gas infrastructure network in the Netherlands creates opportunities for future CCUS projects, but further research on the reusability is needed to identify its potential.

Apart from these two projects, a large CO_2 transportation network in the Netherlands is the "CO_2 Smart Grid" network (OCAP, n.d.-a). Currently, the grid transports "hundreds of kilotons CO_2 a year" to greenhouses in North- and South Holland in the Netherlands (OCAP, n.d.-a). The grid has the potential to reduce around 8 Mt CO_2/y by utilization projects (OCAP, n.d.-a). Interestingly, greenhouses are willing to decarbonize, which resulted in demand is too large for sufficient security of supply (OCAP, n.d.-b). More sources are needed to supply this sector with sufficient CO2 and to offer this security of supply (OCAP, n.d.-b). The government also has a role to play here because, for the time being, these initiatives will not be profitable enough (OCAP, n.d.-b).

Storage site (CCS)
The Netherlands has both onshore and offshore CO_2 storage sites, mainly in depleted gas fields (NMPE, 2020). However, the assumption is that there only will be offshore industrial CO_2 storage (Rijksoverheid, 2018). The offshore storage capacity is estimated at around 1400 Mt, of which 600 Mt should be available by 2028 (NMPE, 2020). As the Dutch CCUS capacity goal is set at 7 Mt CO_2/year from 2025 onwards, the offshore storage capacity should be sufficient for 2050. This is contractionary with the general view on CCS limitations by Benson et al. (2012) and Muratori et al. (2020), as they mention that the primary technical limitation for CCS is the storage capacity, and the deployment ultimately is limited by carbon storage limitations. So, this is not similar for the Netherlands as the limitation for national CCUS developments is not depending on the storage capacity.

Temporary storage (CCU)
Within the Netherlands, there are a few CCU projects which could be affected by the temporary storage of CO_2. One of the consumers of the "CO_2 Smart Grid" is the greenhouses, with has a varying demand which is higher in the summer compared to the winter (CE Delft, 2018). This varying demand results in the need for the temporary storage of CO_2. There are two potential alternatives for the grid, with or without a CO_2 buffer, which both have their strong and weaker points (CE Delft, 2018). The temporary storage for CO_2 will only be created if a CO_2 buffer is built-in (CE Delft, 2018). Without a buffer, the fact that there might be a supply shortage must be accepted by the customers of CCU projects, which is seen as a CCU network. (CE Delft, 2018). Besides this, any superfluous CO_2 will be emitted into the atmosphere (CE Delft, 2018). If a combined CCU and CCS smart grid will be created,

with includes a CO_2 buffer, the temporary storage results in the requirement of a larger pressure, and thus larger energy use, to allow offshore storage (CE Delft, 2018). Despite the extra energy usage, no limitations can be found in the temporary storage potential.

Production (CCU)

In the Netherlands, around 1,62 Mt CO_2/y in total is used for greenhouses, the soft drinks industry, and to produce urea, whereby the greenhouse sector indicates that it could use about 1,4 Mt CO_2/y extra to become climate neutral (Topsector energie, n.d.). Future demands of CO_2 are expected to be construction companies or to produce, for example, formic acid and methanol, as well as follow-up routes from methanol to olefins and gasoline (CE Delft, 2018). The demand for the usage of CO_2 is thus expected to increase in the (near) future, in addition to the fact that it is already higher than the supply for greenhouses. The CO_2 Smart Grid has the potential to reuse about 8 Mt CO_2/y, thus significantly higher than the current product usage. Despite the expected rising demands, the grid has the potential to deliver the necessary CO_2 until demands are rising, resulting in no limitation for CCU development.

Product usage (CCU)

The three Dutch CCU production sectors use the captured CO_2 in different forms. Firstly, in the greenhouses, CO_2 is necessary for crop growth, which was initially produced by burning natural gas (TNO, 2019). By reusing captured CO_2, natural gas and thus fossil fuels are saved. Secondly, the soft drinks industry uses CO_2 for beverage carbonation, which results in sparkling beverages (Thambimuthu et al., 2002). This indicates a large potential for CCU in the Netherlands with large beverage producers which require CO_2 in their production processes. At last, to produce urea, which is a fertiliser for the agriculture sector, CO_2 is required (Planbureau voor de Leefomgeving, 2019). The reuse of CO_2 can be doubled in the production of urea if the indicated costs and long lead times must be reckoned with (Planbureau voor de Leefomgeving, 2019).

Product disposal (CCU)

In the greenhouses, CO_2 is added, which consequently reduces the burning of natural gas. Also, after photosynthesis, the CO_2 is permanently transformed into harmless molecules. This utilization path directly reduces CO_2, and the reused CO_2 is not emitted into the atmosphere, which indicates an effective potential for CCU. This is, however, not the same for the soft drinks industry. Even if reused CO_2 originates from captured industrial sources, the CO_2 will partly be released into the atmosphere during opening and consuming the beverage, usually within days (Thambimuthu et al., 2002). However, CO_2 emissions are partly still saved, as these otherwise would be acquired differently, for example, by burning fossil fuels. During the production of urea, CO_2 is reused, and the urea itself and water are the end products. This seems quite harmless, as the CO_2 is fully used as a feedstock. However, as urea will be used on soils, new chemical reactions occur. Due to these reactions, 98% of the carbon in urea, which includes the reused carbon, will be emitted into the atmosphere (Yara, 2016). Thus, despite that the CO_2 emissions are saved in the initial production process, these will be emitted into the atmosphere eventually as well, resulting in less net emission savings. This is comparable to the utilization in the soft drink industry, as some CO_2 emissions are still saved in the production, which would otherwise be acquired by, for example, burning fossil fuels.

Knowledge base (CCUS)

For the Netherlands, the CCS RD&D budgets arose in 2005, and the last information monitored by the IEA (n.d.-e) is from 2018. During this period, the annual total energy technology RD&D budget of the Netherlands varied between 145 and 391 million euro (figure 13). For CCS RD&D, the annual budget varied between zero and over 40 million euro between 2005 and 2018 (figure 13). In the Netherlands, the average annual CCS RD&D budget is a bit over 9 million euros, compared to the average annual total RD&D budget of around 203 million euro. This results in an average of 4,61% of the total RD&D budget spend on CCS RD&D in Spain in the period 2005 – 2018.

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0.000	0.000	0.000	0.000	..	9.436	3.537	40.541	6.551	14.187	31.889	3.864	2.965	2.193	0.000	2.182	1.202	11.172	10.625	..
174.317	210.705	178.674	159.992	..	145.768	157.413	240.010	166.823	233.853	390.811	167.981	216.379	201.034	165.469	203.905	160.337	159.004	232.023	..

Figure 13; Total RD&D in Million euro (2019 prices and exch. rates) and CO2 Capture and Storage budget in the Netherlands (IEA, n.d.-e).
Note: The rows represent the respective year (above), RD&D budget CO2 capture and storage (middle) and total energy technology RD&D budget (below). 2019 prices and exch. rates.

The annual differences between the percentage CCS RD&D budgets, compared to the total RD&D budget, differ quite a bit (figure 14). For example, one of the differences might rely upon the process of research:

> Industry 2: *"It is not as if you do certain studies every year for four years, but there are just big chunks in between. I think that is the most logical explanation."*

In 2007, a significant increase is noticed, even though the total RD&D budget increased (figure 13; figure 14). This indicates that a substantial part of the increased total RD&D budget from 2006 to 2007 was allocated to CCS RD&D. However, from 2011 to 2016, the percentages decreased drastically, even to zero in 2014 (figure 14).

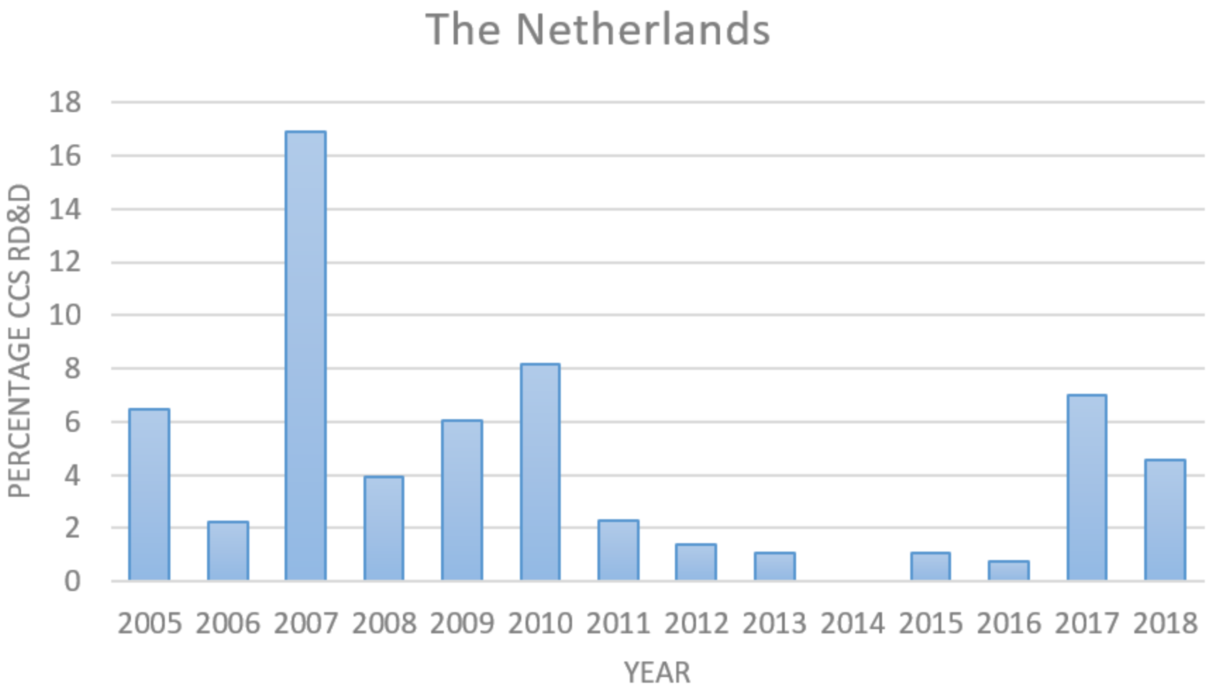

Figure 14; Annual CCS RD&D budgets as a percentage of the total energy technology RD&D budgets in the Netherlands.

4.2.4 Overview technical potential

In this section, an overview is given of the technical potential in France, Spain and the Netherlands (table

Technical potential	France	Spain	The Netherlands
CO_2-capturing (CCUS)	Capture potential > capture goal (CCS). Lacking CCU goal thus unclear for CCU.	Unclear due to lacking CCUS goals	Capture potential > capture goal (CCS). Lacking CCU goal thus unclear for CCU.
Infrastructure (CCUS)	First developments planned	Project specific only, no large-scale developments	Project specific and the creation of an open access network. Potential to transport 8 Mt CO_2/y
Storage site (CCS)	Storage potential > capture goal	Unclear due to lacking CCUS goals. Assumably the storage potential outweighs the capture potential/goal due to the large storage potential.	Storage potential > capture goal
Temporary storage (CCU)	Project specific only, no open access	Project specific only, no open access	Project specific only but open access
Production (CCU)	(Very) small scale (~0,1 Mt CO_2/y in total)	(Very) small scale, research into 25 commercial products can accelerate this (unknown total CO_2 savings)	Medium scale (1,62 Mt CO_2/y in total)
Product usage (CCU)	(Very) small scale	(Very) small scale, research into 25 commercial products can accelerate this	Medium scale, multiple usages
Product disposal (CCU	CO_2 storage temporary (methane production) and permanently (cement)	CO_2 storage permanently (greenhouses), although used for energy production eventually	CO_2 storage temporary (soft drinks industry, urea production) and permanently (greenhouses)
Knowledge base (CCUS)	Relatively stable	Very unstable but expansion of the knowledge base for CCU products	Unstable, but multiple arising projects recently

Table 7; Overview technical potential France, Spain and the Netherlands.

4.3 Socio-political acceptance

This section answers the third sub-question: *"Which concepts influence socio-political acceptance of industrial CCUS?"*. This provides an overview of the current state of the socio-political acceptance in the three respective countries. The socio-political acceptance refers to the general acceptance of technologies and policies by the public, key stakeholders, policy makers. Referring to the technology acceptance framework (TAF) in table 2, ten concepts of CCUS socio-political acceptance are analysed: 1) knowledge, 2) experience, 3) trust, 4) fairness (procedural and distributive), 5) perceived costs, 6) perceived risks, 7) perceived benefits, 8) outcome efficacy, 9) problem perception and 10) energy context. The socio-political acceptance can change in a relatively short amount of time by, for example, an accident (negatively) or public information campaigns (positively). Thus, research from ten or fifteen years ago can already be outdated.

There are several European studies that focussed on certain aspects of the socio-political acceptance. For example, the European Commission has introduced the Eurobarometer surveys in 1973 to monitor the public opinion in the European Union towards its actions (Gesis, n.d.). These surveys also partially focussed on the social-political acceptance of CCUS in the three respective countries and serve as an input for other researchers. The first Barometer survey results on CCS were published in 2011 and was studied in twelve European countries, among whom France, Spain and the Netherlands (European Commission, 2011). Although the research is a bit outdated, some highlights are worth mentioning to give an indication of the socio-political acceptance in the three countries. Only ten per cent of the European respondents said they had heard of CCS and knew what it was (European Commission, 2011). This is relatively low compared to solar photovoltaic energy (59%), nuclear fusion (51%), geothermal energy (47%) or algae biofuels (24%) (European Commission, 2011). The Netherlands is an exception, with over 52% indicating to have heard of CCS and know what it is, but France and Spain are below the ten per cent average (European Commission, 2011). Also, almost half (47%) of the respondents in all twelve countries thought that CCS could help to combat climate change (European Commission, 2011).

Besides the Eurobarometer surveys, several other research projects on a European level have been executed. The research of Jones et al. (2017) focussed on the social acceptance of CCU and indicated that the research into the socio-political acceptance of CCU is quite sparse, which subsequently reflects into a low awareness level of CCU technologies. This is underlined by Perdan et al. (2017), as only 9% of the respondents knew what CCU was, although only focussing on the United Kingdom. The low awareness does not necessarily indicate an unfavourable attitude towards CCU as most of the people (51%) are in favour of CCU deployment (Perdan et al., 2017).

Although there are some similarities, the socio-political acceptance of CCS and CCU have significant differences (Arning et al., 2019). CCU was perceived more positively than CCS in Germany, which indicates that these results on the socio-political acceptance of CCS in France, Spain and the Netherlands cannot directly be reflected in the potential concepts which influence the socio-political acceptance of CCU. The difference is underlined by the Strategy CCUS project (2019; 2020b) as the CCU potential was evaluated more positively and with a higher future potential than CCS.

> Researcher 1 *"The general public is more comfortable, they can accept CCU utilization easier because it is like adding value for a waste [compared to CCS]."*

4.3.1 France

First, an overview of the mainly used scientific articles is created to present relevant information about the year, studies, countries or areas and type of respondents (table 7).

Article	Year	Focus country/area	Type of respondents
Ha-Duong et al.	2009	France	A representative sample of French residents aged 15 years and above.
Ha-Duong et al.	2011a	France	A representative sample of the French national population.
Strategy CCUS	2019	Eight project regions in France, Spain, Portugal, Croatia, Romania, Greece, Poland	National and regional stakeholders found with the support from partners from the consortium in the eight dedicated focus regions.
Strategy CCUS	2020b	Eighth project regions in France, Spain, Portugal, Croatia, Romania, Greece, Poland	In the field of politics and policies, research and education, industry (demand side and supply system), support organizations, Influencer (NGO's, experts, etc.).

Table 8; Overview of the relevant information of the main articles used for the socio-political acceptance in France.

The influence of the different concepts on the socio-political acceptance of industrial CCUS is studied throughout France, although primarily focussing on CCS. In France, 79% recognized the seriousness of climate change and mentioned that action should be undertaken, thus having a *general understanding of climate change* (Ha-Duong et al., 2009). However, this dropped to 62% three years later in 2010 (Ha-Duong et al., 2011a). Even though the research is a bit outdated, the *awareness* of CCS was between 27% and 34% in 2007 and remained around one third in 2010, which is rather low compared to other low carbon energy technologies (Ha-Duong et al., 2009). In comparison, wind energy has a 97% awareness, biofuels 93% and hydrogen vehicle 71% (Ha-Duong et al., 2009). Even though around one third indicated to have heard of CCS, only 6% was able to *describe its principle correctly* (Ha-Duong et al., 2009). Due to more emerging CCS project in France, a (failed) carbon tax and more debates on climate change, this rate increased to 17% in 2010 (Ha-Duong et al., 2011a).

The research of Ha-Doung et al. (2009) also highlights the influence of *knowledge* on the degree of approval, which can be interpreted as socio-political acceptance. Initially, before providing information, 59% of the respondents approved the use of CCS, which decreased to 38% after providing information (Ha-Duong et al., 2009). This indicates three aspects. At first, an increased *knowledge* influences the socio-political acceptance as the approval rate changed, although negatively. Secondly, the opinions of respondents are not firmly anchored from the start. As third, the socio-political acceptance rate is initially quite high, and the public is willing to engage with the technology. While the approval rate dropped after information provision, a bias has potentially occurred (Ha-Duong et al., 2009). People tend to pay more attention to what they have heard last and were influenced by risk considerations and subsequently being oriented towards a negative view of CCS (Ha-Duong et al., 2009). Resultingly, the 38% and 59% might only be interpreted as a range when being compared to other studies (Ha-Duong et al., 2009). This bias is underlined three years later as the research shows a significant and positive correlation between the degree of *provided information* and a favourable opinion about the use of CCS in France (Ha-Duong et al., 2011a). Although this opinion remains fragile, the *knowledge of a specific project* in France reduces the volatility of opinion (Ha-Duong et al., 2011a). It must be noted that the research of Ha-Duong et al. (2009) and Ha-Duong et al. (2011a) are both a bit outdated and differences could have been occurred in the meantime, especially given the observed volatility.

Although there might be a positive correlation between providing information and an increased socio-political acceptance, it must be provided early on during a project to succeed. Being late to reach out to the public can be fatal to a planned CCS project (Ha-Duong et al., 2009). People form opinions through dialogues and these opinions are diverse, volatile and historically and situation-dependent (Ha-Duong et al., 2009). Thus, a distinction between local and national socio-political acceptance must be made:

> *Researcher 6: "Tackling the public perception is local because there is no one size fits all".*

This was visible during a CCS-project which was around winemakers in France:

> *Researcher 2: "[The winemakers] are afraid that when customers learn that there is underground carbon dioxide stored, they might not like it anymore. So, it is a case of stigmatization or fear of stigmatization. […] I would not say that they are resistant to the technology, it are more the fears or being concerned about the steam that it might spoil a little into the area."*

The local distinction was also seen during the Lacq CCS project by Total between 2010 and 2013. The local socio-political acceptance was likely to be high from the beginning of the project as Total had generated *economic development* and *local needs* for decades, alongside to have proven to control higher risks (Ha-Duong et al., 2011b). The latter is also indicated by the Strategy CCUS project (2019), as the respondents generally *trusted* the technical capability of the local industry to implement CCUS. Besides Total having a relatively high initial *trust* from the local society, they released an information campaign to provide information and hired experts to answer questions (Ha-Duong et al., 2011b). One of the consequences was that concerned citizens created an association of opponents, which asked pointed questions (Ha-Duong et al., 2011b). This, however, improved the quality of the local debates and is not seen as a negative but rather a positive effect on the final socio-political acceptance (Ha-Duong et al., 2011b). This is confirmed as:

> *Researcher 5: "I am very much in favour of a good discussion, so I also see opponents as parties who can sharpen your own image and analyses".*

The role of the *media* is highlighted in both the research of Ha-Duong et al. (2011b) and the more recent Strategy CCUS (2019) research. A *multi-faceted communication strategy* is essential to disseminate information that is still vague or erroneous and prevent the risk that false information will confuse or block the public debate (Ha-Duong et al., 2011b). The multi-faceted communication includes the internet, information meetings and word of mouth and traditional media, although CCUS does not seem to be a major topic in the local media in France (Ha-Duong et al., 2011b; Strategy CCUS, 2019). Besides the lack of CCUS attention in the local media in France, there is no ongoing discourse around potential CCUS developments (Strategy CCUS, 2019). Even after executing experiments to create attention, the desired outcome has not been reached:

> *Researcher 2: "It is not discussed at national level"*, although *"We have put it out to attract attention locally, but it didn't make the national news"*. This makes it *"difficult to talk about social acceptance for something which people do not [know] about."* And *"I think there is a need for a good narrative".*

The Strategy CCUS (2020b) report indicates that respondents were, in general, somehow positive about the use of CCS along with *other low carbon technologies*, although mentioning that CCUS investments cannot compromise with investments in other technologies (Strategy CCUS, 2020b). Also, industrial CCUS development have a low initial socio-political acceptance and could face local opposition (mainly regarding CCS) (Strategy CCUS, 2020b). The latter resulted in a more negative view towards CCUS technologies and considered that CCUS should play a limited role in the solution towards climate change (Strategy CCUS, 2020b). Several concerns were raised, although being relatively positive about CCUS and indicating that CCUS technologies will have a relevant role to reduce CO_2 emissions in the industry sector (Strategy CCUS, 2020b). The study highlights the issues of respondents for potential *environmental risks*, *potential costs* and *social impacts* (Strategy CCUS, 2020b). These raised and potentially unresolved issues could influence the (local) socio-political acceptance. To address these issues and positively influence the local socio-political acceptance, *transparency* and *involvement* of the local society is necessary (Strategy CCUS, 2020b).

Besides these potentially negative effects on the socio-political acceptance of CCUS technologies in France, several benefits were highlighted. In contrast to the potential environmental risks, the *environmental benefits*, in terms of CO_2 emission reduction and climate change mitigation, are indicated as a benefit, which is associated with the development of CCUS technologies (Strategy CCUS, 2020b). Also, *(local) economic benefits* and other benefits related to companies and the promotion of a circular economy are mentioned (Strategy CCUS, 2020b). Ha-Duong et al. (2011b) mentioned that the locally generated economic development during the Lacq project influenced the socio-political acceptance positively. However, these *economic developments* were not related to economic benefits from CCUS developments but to previous activities in the area. Thus, the influence on the socio-political acceptance in France on industrial CCUS remains unclear.

Influence of concepts
The factors which influence the socio-political acceptance of industrial CCUS in France are not thoroughly researched. The two research projects of Ha-Duong et al. (2009; 2011a) on the socio-political acceptance of CCS are a bit outdated but analysed multiple concepts in a repetitive survey to identify trends and increase the quality of results. The Strategy CCUS project researched this more recently with studies published in 2019 and 2020. However, these aimed to provide a first identification of the actor structure in the innovation system for CCUS, with a focus on different levels (2019) and to map stakeholders' views on CCUS technologies (2020b) (Strategy CCUS, 2019; Strategy CCUS, 2020b). Thus, they provided an overview of stakeholders' views but did not primarily focus on the influence of certain views or concepts on the socio-political acceptance.

Currently, France is lacking a public debate or *media* attention concerning industrial CCUS which negatively influenced the socio-political acceptance. The *awareness* of CCS remained quite stable between 2007 and 2010 but the *knowledge* within this group increased as the group who described the principle correctly was multiplied by three. Thus, a higher *awareness*, for example by more *media* attention, does not necessarily indicates a higher level of *knowledge*. However, if a higher *knowledge* level would be achieved by an information campaign such as during the Lacq project, a significant and positive correlation with the socio-political acceptance in found in France. Such information campaigns are currently developing in France.

> Industry 1: *"They [the industry] try to explain what CCS is."* and *"We [industrial company] probably could do like a video on YouTube to talk about CCUS. And not only us, I think a lot of other companies as well. We can also see that they [the industry] publish this kind of videos to try to educate the big public."*

The direct *experience* with industrial CCUS or related technologies has proven to influence the socio-political acceptance in France. Total's Lacq project showed that the local industry has proven to be able to cope with higher risks and generally *trusted* the technical capability of the local industry to implement CCUS. This *experience* eventually resulted in a higher level of trust in the local industry, thus the concept *experience is seen as a predictor for the level of trust.* Although there is a positive influence of *experience* and *trust* on the socio-political acceptance, it only has been proven on a local scale in France, not nationally. The *perceived costs* and *perceived risks* are indicated as potential issues by the

Strategy CCUS (2020b) project. There is no elaboration on the magnitude or direction of the influence of both concepts on the socio-political acceptance within this research. However, without resolving these issues, there assumably are negative correlations. The influence of the *outcome efficacy*, the belief that someone's own behaviour affects the implementation of CCUS, is indirectly mentioned. After the information campaign of Total's Lacq project, an association of opponents emerged. This indicates that these people had the belief that their behaviour, by creating an opposition, could affect the CCS implementation. As mentioned before, this eventually resulted in a positive effect on the socio-political acceptance.

There are also several concepts that have not been proven to affect the French socio-political acceptance. *Fairness*, procedural and distributive, was not indicated as one of the influencing concepts on the socio-political acceptance in France. The *perceived benefits*, economically and environmental, does not influences the socio-political acceptance in France. The benefits from previous industrial activities in the region are seen as trust in the industry stakeholders as these benefits are not related to the (future) industrial CCUS projects. The *problem perception* of climate change and its consequences decreased from 79% in 2007 to 62% in 2010. However, the direct influence on the socio-political acceptance of industrial CCUS in France has not been researched nor mentioned as a barrier. Thus, no correlation is found. The influence of the *energy context*, weighing up against alternative CO_2 reducing technologies, is also rather unclear. Industrial CCUS is indicated to play a role as one among the many options, although this should not interfere with investments in other technologies. However, the direct influence of the energy context on the socio-political acceptance of industrial CCUS in France has not been researched yet.

4.3.2 Spain

First, an overview of the mainly used scientific articles is created to present relevant information about the year, studies countries or areas and type of respondents (table 8).

Article	**Year**	**Focus country/area**	**Type of respondents**
Upham & Roberts	2011	United Kingdom, Belgium, the Netherlands, Germany, Spain and Poland	Six focus groups with the general public, one held in each country.
Lupion et al.	2013	Spain	The public: two sites in the Castilla y Léon region, onshore, but different innterms of population, size, educational level and employment ratio.
PTECO2	2017	Spain	A sample of the general population residing in Spain (n=963), Asturias (n=352) and Castilla y León (n=377).
Oltra & Sala	2017	Spain	Survey study with members of the general population. General sample (n=963). Two regional samples (n=800).
Tcvetkov et al	2019	Twenty countries among which France, Spain and the Netherlands	A review of 135 articles to create a state-of-the-art overview.
Strategy CCUS	2019	Eight project regions in France, Spain, Portugal, Croatia, Romania, Greece, Poland	National and regional stakeholders found with the support from partners from the consortium in the eight dedicated focus regions.

Strategy CCUS	2020b	Eighth project regions in France, Spain, Portugal, Croatia, Romania, Greece, Poland	In the field of politics and policies, research and education, industry (demand side and supply system), support organizations, Influencer (NGO's, experts, etc.).

Table 9; Overview of the relevant information of the main articles used for the socio-political acceptance in Spain.

Several research projects have been executed recently in Spain to research and stimulate industrial CCUS developments, e.g., CIUDEN, Strategy CCUS and PTECO2. The CIUDEN project started in 2006 and was founded with the involvement of three ministries: environment, industry and economics (Bellona, 2015). Although the focus was on the technical side of CCS, the project accelerated the development of CCS in Spain and resulted in a bright future for CCS (Bellona, 2015). However, one crucial aspect still relies in the social awareness and public communication of CCS as all previous efforts will be invalid if the public opinion is not brought into the debate and feels comfortable with CCS technologies (Bellona, 2015). CCUS is according to the Strategy CCUS (2019) project not a topic that is frequently discussed in national or regional *media* so far. However, on higher level between researchers and politicians, *"there are important debates"* (Industry/researcher 1). Upham & Roberts (2011) highlight the importance of the currently missing public debate in Spain on industrial CCUS in relation to the knowledge about CCS as there are generally misconceptions and multiple interpretations of information which is released 'in the wild'.

The concerns in Spain about *climate change* are at a higher level than average as Spain experienced hot summers and drought which affected their lives (Upham & Roberts, 2011). Water restrictions and other measurements have given the public an insight into the reality of climate change (Upham & Roberts, 2011). This is contradicted by PTECO2 (2017) the level of public familiarity with climate change can be considered medium as half of the populations says they know something about it. Even though the *problem perception* of climate change seems medium to high, it has had a limited impact on the socio-political acceptance of CCS (Upham & Roberts, 2011). The level of *knowledge* about CCS on the other hand seems to have a positive correlation with the socio-political acceptance of CCS in Spain, even though the familiarity with CCS is only 14% in Spain (Upham & Roberts, 2011; PTECO2, 2017). If *knowledge* about CCS lacks, respondents tent to prefer other existing and more familiar technologies, although there is a link with the local context (Upham & Roberts, 2011). However, this view is not shared by the research of Oltra & Sala (2017). The attitude towards CCS in Spain decreased after additional information has been evaluated by respondents, such as specific information about CCS, stakeholders' views and potential negative consequences (Oltra & Sala, 2017).

Although a negative correlation is suggested between *knowledge* and the socio-political acceptance in Spain, Oltra & Sala (2017) did not execute a similar research where information about potential positive consequences is provided. Thus, the relation between providing potential positive consequences of CCS and the socio-political acceptance is still unsure when referring to the Oltra & Sala (2017) research. Upham & Roberts (2011) on the other hand provided an overview of CCS, its rationale and arguments for and against CCS. Thus, as Upham & Roberts (2011) have researched this correlation two-sided, these results suggesting a positive correlation in Spain between knowledge and the socio-political acceptance, although mentioning the local context.

> Industry/researcher 1: *"They [the companies from the CCS project] made a very good social information campaign. They had a lot of meetings with local authorities, neighbours, even local media, universities, everything around. And they had a very good acceptance at that point."*

The local context or *experience* with technologies which are similar to CCUS is an important aspect. Accidents or positive examples influence the local perception and thus socio-political acceptance of

CCUS (Tcvetkov et al., 2019). In Spain, the Castor project in 2012 aimed to create a large-scale artificial deposit of natural gas in the Mediterranean Sea for the event of there being a scarcity or stopped imports (Strategy CCUS, 2019; The Corner, 2017). Eventually, the project had to be halted after one year due to series of seism's in the region (The Corner, 2017). The socio-political acceptance of CCS has been *"determined by the accident we had years ago […] as people think that storage of CO_2 is the same as the storage of natural gas"* (Industry/researcher 1). This accident eventually resulted in a lower socio-political acceptance, partially due to that this occurred *"in front of them",* thus suggesting that it had the most effect on the local socio-political acceptance (Industry/researcher 1). However, on a national level, there is a significant level of trust in the industrial sector to implement CCUS technologies in the future in Spain (Strategy CCUS, 2020b).

Apart from *trust* in technologies causing no accidents, building *trust* on several aspects seems to be a major factor to enable public engagement in local areas in Spain (Lupion et al., 2013). Subsequently, public engagement is an enabler to achieve a high level of public acceptance (Tcvetkov et al., 2019). There is a distinction between *trust* on a *national level*, primarily concerning the government and other related institutions and trust on a *local level* concerning local authorities and other stakeholders (Lupion et al., 2013). On a national level, there tend to be a low level of *trust* in the government to promote CCUS technologies (Strategy CCUS, 2020b). The lack of political and regulatory support is also indicated as one of the main barriers for future industrial CCUS implementations (Strategy CCUS, 2020b). However, around 50% is in favour of public support for CCS R&D and 43% are in favour of the government providing financial incentives for CCS implementation, thus indicating a medium socio-political acceptance for government interventions towards CCS (PTECO2, 2017). In general, there is a low level of *trust* in the ability of different actors to make good decisions regarding CCS (2.61 points on a scale of 1 to 5) (PTECO2, 2017). The actor for which participants report the lowest level of confidence is the government (2.12), followed by industry (2.60) and environmental associations (3.13) (PTECO2, 2017).

On a *local level*, the results on *trust* are more positive. Compared to the national level, regional governments are perceived as more supportive to CCUS technologies (Strategy CCUS, 2020b). Also, beneficial results have been observed towards CCS after following a clear communication plan during a CCS-project (Lupion et al., 2013). There was a very close interaction with the local stakeholders and authorities, which eventually resulted in a high socio-political acceptance as it felt as their own project for the local public (Lupion et al., 2013). Besides the communication, locally trusted parties, which can be all sorts of stakeholders, need to moderate and respond to concerns as they arise (Upham & Roberts, 2011). Some other factors to build trust in local areas are a high transparency, create a dialogue instead of a monologue, engage instead of convincing, take early actions, and more (Lupion et al., 2013). All the build-up *trust* will eventually result in a higher local socio-political acceptance, which is critical for the implementation of a particular project (Lupion et al., 2013).

Although *procedural and distributive fairness* are not mentioned directly, these are incorporated in the trust concept. Identifying the local public's diverse needs is seen as a key factor to achieve a high level of support (Tcvetkov et al., 2019). The local public will not be satisfied, thus not supportive, if they experience unfairness during the project development or in the costs and risks. However, both concepts are not directly mentioned but incorporated in the concept of trust. Thus, the direct influence of *procedural and distributive fairness* on the socio-political acceptance is hard to determine.

The feeling towards industrial CCUS is relatively positive in Spain as 62% consider it as a good solution to reduce CO_2 emissions (PTECO2, 2017). However, fear and aversion are also mentioned as feelings which are generated but into a lesser extent (PTECO2, 2017). Stakeholders in Spain indicated that CCUS technologies will play a relevant role in the decarbonization of the industry sector and be critical in this sector in the long term (Strategy CCUS, 2020b). However, this view is not nationally shared as Tcvetkov et al. (2019) mentioned that CCUS technologies are perceived favourable but as an intermediate step in solving the global warming issues. Besides these differences, CCS and CCU are also seen as separate. On the one hand, CCS was perceived more problematic than CCU in the long term, but on the other hand, CCU is seen as insufficient to result in significant CO_2 reductions in the short term and only a promising technology for the long term (Strategy CCUS, 2020b). Lupion et al. (2013) partly agree with this statement towards CCS as these technologies are seen as a viable option towards climate change mitigations, even though its future is depending on several factors such as optimization of the technical aspects and the existence of favourable regulatory, political and financial frameworks. Although there are some differences between future CCS and CCU developments, there still is a favourable attitude towards CCUS technologies in general as only a minority rejected or were sceptical (Strategy CCUS, 2020b). Thus, to conclude, there generally is a positive *feeling* towards CCUS technologies in the future.

The *perceived costs* are not seen as the most important factor in determining which electricity production methods should be used in Spain as respondents rather chose preventing climate change as most important (Upham & Roberts, 2011). This can be directly linked to the cost aspect of CCS when choosing between energy saving technologies, thus preferring the prevention of climate change over the costs (Upham & Roberts, 2011). These respondents also indicated that the financial risks associated with CCS are probably significantly greater compared to other renewable technologies (Upham & Roberts, 2011). Tcvetkov et al. (2019) underline that stakeholders are seeing the perceived costs only as a slightly concern. However, after the failure of the Castor project, the costs of the project were partly recovered by billing gas consumers in the region, which affected the socio-political acceptance in the region (Strategy CCUS, 2019; The Corner, 2017). Thus, the *perceived costs* of the CCUS technologies itself does not seem to influence the socio-political acceptance largely, but it cannot be neglected if the costs increase for the (local) society.

The *perceived risks* or CCS are considered medium or medium-high and the negative potential effects on the environment are mentioned often (PTECO2, 2017). The most common feeling generated by possible CCS is concern (55% of respondents), followed by interest (49%) and fear (39%) (PTECO2, 2017). These concerns and fears indicate that there are certain *perceived risks* among the respondents which influence the socio-political acceptance in Spain (PTECO2, 2017). The feelings of concern are related to safety (leaks and releases) and possible impacts on the health of the population and the local environment (PTECO2, 2017). Other areas of concern are linked to the project management (not a *perceived risk* in this case) or the belief that it is not a sufficiently proven technology (PTECO2, 2017). Also, for the perceived risks there is a difference between the national and local context. In the local context, there is a belief that a storage facility would have a negative rather than a positive impact on their locality (PTECO2, 2017). At the same time, there is some agreement among participants that a storage facility could have a positive impact on the local economy (PTECO2, 2017). In general, the participants' evaluation of the different consequences of CCS has a *significant predictive power* on the final socio-political acceptance towards CCS (PTECO2, 2017).

Most participants (75%) consider CCS technologies as personally relevant, which can be interpret as a personal *perceived benefit (PTECO2, 2017)*. Concerning CCU, the usefulness of reducing emissions and the possibility of using local CO_2 are the main perceived benefits (PTECO2, 2017). The possible existence of economic benefits for the local society is the most positively rated consequence (47%).

> Industry/researcher 1: *"Especially in the areas with an industrial tradition, it is very common that there is a close link between these large industries and the population. There are many areas or industrial hubs in which a lot of the people has worked for these companies and thus have had a lot of local benefits. […] So, they see the benefits of having an industry in the area and they are keen to see new projects that will keep these activities there for the future."*

Identifying the needs of the local society and subsequently translate these needs into perceived benefits on forehand or early on during a project is one of the key factors which enable a high level of local socio-political acceptance (Tcvetkov et al., 2019). Local stakeholders perceive benefits in the form of the preservation of the local industry, new socio-economic opportunities and technological development (Strategy CCUS, 2020b).

Industrial CCUS technologies are placed in the *energy context* by weighing up against alternatives. There is not a clear consensus about which role industrial CCUS should play for the future in Spain and subsequently how this influences the socio-political acceptance. CCUS technologies could compete with alternative decarbonization options and complement with existing and future renewable technologies (Strategy CCUS, 2020b). These alternative technologies could also hamper the CCUS development as these limits the value of implementing CCUS technologies (Strategy CCUS, 2020b). Tcvetkov et al. (2019) partially agreed as CCS technologies, thus not CCU, are seen as an intermediate step and thus not as the final solution, complementary or not. In the research of PTECO2 (2017), CCS technologies do not have the preference compared to other CO_2 saving technologies. However, a prominent role is given to CCS if there is a focus purely on emission reductions (PTECO2, 2017). Although some differences about the potential role of CCUS, the extent to which the energy context influences the socio-political acceptance cannot be neglected.

Influence of concepts
The socio-political acceptance of industrial CCUS technologies is critical when implementing a certain project. However, the degree to which certain concepts influence the socio-political acceptance of industrial CCUS in Spain differs. Also, especially the more older research projects seem to have focussed on CCS instead of CCUS, thus the results primarily reflect on CCS. The correlation between *knowledge* about CCS and the socio-political acceptance is positive, although the local context still influences this correlation. If there is a lack of CCS knowledge, existing and more familiar technologies are preferred, thus also referring to the *energy context*. The *knowledge* concept is thus seen as an predictor for the energy context. Important (media) debates about CCUS are currently lacking for the public, which does not favour any CCUS developments, although the correlation between awareness and knowledge is unsure. Any negative *experience* with CCUS influences the socio-political acceptance of CCUS in Spain in the local context. The influence on a national scale is uncertain and the influence of positive experience is still unsure.

The differentiation between the national and local context is important when referring to the *trust* in stakeholders. National stakeholders tent to gain a low level of trust, especially towards the government, although the trust for financial incentives (43%) and public support (50%) for CCS R&D and implementation are accepted. A low level of trust is seen as a barrier towards CCS implementation but not directly as an influencing factor on the socio-political acceptance of CCS. On a local level on the other hand, trust ca be built through clear communication, involvement and creating a dialogue. If there is a local trust in the (local) stakeholders, the socio-political acceptance of CCS will increase, thus indicating a positive correlation.

The general feeling towards CCS in Spain is quite good as 62% consider CCS as a good solution to reduce CO_2 emissions (PTECO2, 2017). However, negative feelings such as fear and aversion towards CCS are common. The generally positive feeling towards CCUS technologies resulted in a positive future prospect, although complementary with other technologies. This suggests a positive correlation between the socio-political acceptance by the public, key stakeholders, policy makers and their feeling towards CCS technologies.

The *problem perception* of climate change seems to have a limited influence on the socio-political acceptance of CCUS, although there are some discrepancies between several researchers. There are some *perceived risks* concerning CCS technologies for the environment and human health. Concerns are fears are related to the safety and the potential (local) impact. The correlation of this concept to the socio-political acceptance is negative and the concept is also a strong predictive power on the final socio-political acceptance towards CCS in Spain. The last concept which has a positive correlation is the *perceived benefits*. Especially the local socio-political acceptance can be highly increased if the local needs are identified and addressed. Also, new local developments and opportunities which arise due to CCUS developments are indicates as having a positive influence on the socio-political acceptance.

Apart from the influencing factors, there are also a couple of factors for which no direct correlation has been seen. The *procedural and distributive fairness* seem not to influence the socio-political acceptance directly. Also, the *perceived costs* of activities related to CCUS project seem not to influence the socio-political acceptance as long as the costs are not directly affecting the (local) public. At last, also the *outcome efficacy* did not influence the socio-political acceptance in France.

4.3.3 The Netherlands

First, an overview of the mainly used scientific articles is created to present relevant information about the year, studies countries or areas and type of respondents (table 9).

Article	**Year**	**Focus country/area**	**Type of respondents**
CATO	2011	The Netherlands	Four surveys were administrated in 2004, 2005, 2007 and 2008. The samples contained respectively 333, 300, 327 and 240 respondents of the general Dutch population, with distributions of age, gender, location and education reflecting the distributions in that population.
Terwel et al.	2012	Barendrecht, the Netherlands	811 local residents.
CATO	2015	The Netherlands	936 representative samples of Dutch population and 15 in-depth interviews with lay people.
Terwel & Ter Mors	2015	The Netherlands	Residents and local government authorities of small and medium-sized cities (by Dutch standards; populations <100,000 inhabitants). Residents and LGAs of the town of Barendrecht were not approached to participate in the study.
Align CCUS	2019b	The Netherlands	General public, details unknown.
Align CCUS	2020a	Germany, the Netherlands, United Kingdom, and Romania	Media and website analysis.

Table 10; Overview of the relevant information of the main articles used for the socio-political acceptance in the Netherlands.

The socio-political acceptance in the Netherlands was studied by the CATO projects between 2004 and 2014 (CCS) and is currently studied by the Align CCUS project from 2017 onwards (CATO, n.d.; Align CCUS, 2019b). Between 2004 and 2008, the awareness and knowledge of CCS developments was researched with four surveys (CATO, 2011). Around 25% of the Dutch respondents seemed *aware* of CCS, compared to almost 50% by the end of 2008 (CATO, 2011). This increase continued and resulted in an 66% *awareness* of CCS developments in 2011 (Align CCUS, 2019b). The *general understanding of global warming* in the Netherlands is increased a bit between 2004 and 2008 as the group of respondents which know 'a bit' was declining and shifted towards the group which indicated to understand it (CATO, 2015).

The Dutch CCS development have got a lot of media attention between 2004 and 2008 due to the plans for storage in Barendrecht (CATO, 2011). Despite all the *media* attention for CCS, the *unawareness* was still quite high in the Netherlands. This indicates that presence of CCS in the media is *not a predictor* for the socio-political awareness of CCS developments (CATO, 2011). Thus, the relatively high media coverage of CCUS recently in the Netherlands, for example due to the Porthos project, is still no indication of a high awareness on this topic nowadays (NOS, 2021; RTL Nieuws, 2021; Align CCUS, 2020a). Industrial CCUS in the media is not always projected positively:

> Industry 2: *"You quickly get the sense that you are spending a lot of money to cover up CO2 that is emitted without doing anything at the source. So, it just lends itself very easily to this kind of [negative] short-sighted one-liners."*

The Align CCUS project published two reports so far on the socio-political acceptance which involved the Netherlands, one in 2019 (CCUS) and the other in 2020 (CCS) (Align CCUS, 2019b; Align CCUS, 2020b). The findings suggest that the future of industrial CCS development is hopeful, although the *knowledge* in the Netherlands about CCS was perceived low on average (Align CCUS, 2020b). The group of people who had never heard of CCS is decreasing over the years, but this not necessarily resulted in an increased *knowledge* about CCS (CATO, 2015; Align CCUS, 2019b). Apart from this, there is a *slightly positive feeling* towards the implementation of industrial CCS in the Netherlands (Align CCUS, 2020b). Communication is proven to be key in the overall opinion towards industrial CCS in the Netherlands (Align CCUS, 2020b). *Providing information* to citizens about the outcomes of industrial CCS implementations, both positively and negatively, had a slight positive influence on the overall opinion (Align CCUS, 2020b). Even though this could positively influence the overall opinion, a general *knowledge* increase about CCS does not necessarily result in a higher socio-political acceptance rate:

> *Researcher 4: "We do not see a significant correlation between knowledge and acceptance"* due to that *"there are positive and negative misunderstandings [which level out]".*

Thus, although providing project specific outputs could positively influence the socio-political acceptance, the influence of general knowledge about CCS in the Netherlands seems not to correlate with a higher socio-political acceptance.

Providing knowledge is still just one of the many factors which influence the socio-political acceptance on industrial CCUS in the Netherlands (Align CCUS, 2019b). The *credibility or trust* of the stakeholders and the message itself influence the outcome of the provided information (Align CCUS, 2019b). Multiple stakeholders providing knowledge could lead to a multiplicity of (conflicting) messages. These conflicting messages could arise due to the use of similar arguments for and against CCS by proponents and opponents (Align CCUS, 2020a). For example, presenting CCS as a sustainable technology by proponents and as not sustainable by opponents (Align CCUS, 2020a). The concerns of the society were primarily focussed on the CO_2 transport and storage, thus information provision on these aspects could positively influence the *perceived risks* (Align CCUS, 2020a). The socio-political acceptance towards CCS is affected by the perceived risk as the higher the *perceived risks* to the health and safety of both humans and nature, the more negative attitude towards CCS implementation (Align CCUS, 2020a). An important indicator for the overall *attitude* towards industrial CCS was found to be the *attitude* towards the industry (Align CCUS, 2020b). Besides this, the *place attachment* at a regional level and the *proximity* to coastal areas influenced the national attitude towards industrial CCS, which implies an influence of spatial perceptions and the site placement of industrial CCS developments (Align CCUS, 2020b).

The *credibility and trust* in stakeholders are recognized by the Align CCUS (2019b) project, as the distinction between the general and local society is indicated to be important. The onshore CCS demonstration project in Barendrecht between 2007 and 2010 highlighted this as the local public felt that the less trusted parties, Shell and the national government, had too much influence in the decision-making progress, compared to the people of Barendrecht itself, referring to *procedural unfairness* (Terwel et al., 2012). In general, NGOs are found to be trusted most, the government lower and the industry is trusted the lowest (Huijts et al., 2007). The level of *trust* in these three actors depends on the perceived competence and intentions, which were found to be related to perceived similarity of goals and thinking between one of these actors and the society (Huijts et al., 2007). The high level of trust in NGOs can be both positively and negatively for industrial CCUS developments:

> Industry 2: "*There are NGOs that are against it, such as Greenpeace, which I still don't think wants to see it. But you also have NGOs that have turned, such as the one of nature and environment, which I believe was also opposed to it in the past, but now sees the benefit of it, certainly in the short term, in making those steps towards energy transition and especially in the CO2 reduction that is necessary.*"

Creating a mutual *trust* between stakeholders, including the local society, and commitment to each other is the most important lesson which can be learned from this project (Global CCS institute, 2010). This can be created by including all stakeholders in an early stage, communicate about the process, be open and transparent and define, discuss and integrate certain demands, needs, values and interests of different stakeholders (Global CCS institute, 2010). Messages which are clear, accessible and appeal to citizens' interests are key when providing information about such a project (Align CCUS, 2020a). It may be complex and time-consuming to identify the relevant society for offshore CCUS developments in the Netherlands, but it should be an important step in the project (Boomsma & Ter Mors, 2018). This was done insufficiently with the onshore CCS project in Barendrecht as it was cancelled in 2010, which was partly motivated by the lack of support for the project among the local public (Terwel et al., 2012). Although not directly mentioned by the government, the lack of socio-political acceptance for onshore CCS activities could have been important in the decision to only pursue offshore CCS activities in the Netherlands in the future.

There are several methods to influence the socio-political acceptance, for example by only providing environmental or economic information as different groups consider different benefits more important (Align CCUS, 2020a). This indicates that, although varying in importance, the *environmental and economic* aspects of CCS influence the socio-political acceptance. Another method to reduce the socio-political resistance refers to the compensation of the local area and provide economic benefits, despite not being the silver bullet that makes all difficulties disappear (Terwel & Ter Mors, 2015). For example, the perceived *procedural unfairness* and the lack of *trust*, which are strong predictors of less socio-political acceptance, will probably remain (Terwel & Ter Mors, 2015). However, a compensation can help to resolve some objections of those who perceive *distributive unfairness*, which refers to the distribution of costs, risks, benefits (Terwel & Ter Mors, 2015; Selma et al., 2014).

Influence of concepts

The research on which concepts influence the socio-political acceptance of CCS in the Netherlands has gained attention throughout the past years with large scale research project such as CATO and Align CCUS. Despite focussing on CCS and CCU, the Align CCUS project primarily researched the socio-political acceptance of CCS yet, instead of both aspects. As mentioned before, the socio-political acceptance of CCS and CCU have significant differences (Arning et al., 2019).

Whilst the socio-political acceptance of CCS is largely researched in the Netherlands, the research on the socio-political acceptance of CCU is still sparse. Resultingly, the concepts of the technology acceptance framework which influence the socio-political acceptance is only focussed on industrial CCS. The *trust* in stakeholders is indicated as a key predictor for the socio-political acceptance of CCS developments. *Trust* can be gained by, among other things, clear and early communication and involvement of the local society. An *unfairness* feeling influences the socio-political acceptance negatively, but *procedural unfairness* can be avoided by creating *trust* and *distributive unfairness* partially by providing local compensations.

The influence of the *perceived costs* on the socio-political acceptance is not fully researched. Current studies are not indicating any influence of this concept, but the respondents indicate that NGOs are afraid for a *"lock-in" (Researcher 4)* of industrial CCS due to provided subsidies by the government. This can be linked to the perceived costs as NGOs use the following argument: *"All that money going to CCS could have gone to other applications."* (Industry 2). Thus, the costs of the CCS technologies create a barrier for accepting the deployment for NGOs. However, the subsidy (SDE++) is only provided in a certain time frame and with a limit of 7,2 Mt CO2. Researcher 4 indicated to *"not know"* how NGOs such as Greenpeace would respond to this argument. Thus, the magnitude of the influence of the *perceived costs* is quite unclear, although it is likely to play a role for the socio-political acceptance of NGOs. This also refers to the *energy context* concept, weighing up against alternatives, as the focus and funds should be allocated to other renewable energy technologies, according to some NGOs.

Besides the *perceived costs*, the *perceived risks* also influence the socio-political acceptance in the Netherlands as higher perceived risks results in a lower socio-political acceptance. The *perceived benefits* are not specifically mentioned but overlap a bit with the *distributive fairness* as a compensation, thus benefits, will influence the socio-political acceptance in the Netherlands. However, the magnitude of influence still unknown in a broader view as this only covered the personal and society benefits and not the *environmental benefits*. This is similar for the *problem perception* concept as the understanding of global warming is sufficient but the effects on the socio-political acceptance are unsure.

Apart from the concepts which affect the socio-political acceptance of industrial CCS, a few concepts are not proven to have any effect. The awareness or *knowledge* of industrial CCS developments in the Netherlands was increasing over the years until at least 2011. More studies are necessary to identify the recent developments as the current media coverage is not indicator for a higher *knowledge*. Thus, no correlation is seen between an increased general *knowledge* about industrial CCS and an increased socio-political acceptance. The *experience* with previous CCUS developments or related technologies also did not affect the socio-political acceptance in the Netherlands much as, for example, multiple CCS projects have been emerged after the failed Barendrecht project. However, project specific outcomes could slightly increase the overall socio-political acceptance. At last, the *outcome efficacy* is also not seen to influence the socio-political acceptance of industrial CCS in the Netherlands.

4.3.4 Overview socio-political acceptance

- Table to give an overview: High, medium, low or unknown influence on the socio-political acceptance of industrial CCS.

Table 11 provides an overview of level of influence all researched concepts have on the socio-political acceptance in France, Spain and the Netherlands.

Socio-political acceptance	**France**	**Spain**	**The Netherlands**
Knowledge	High	High, predictor for the energy context	None
Experience	High, predictor for trust	High	None, potentially on a local scale
Trust	High	High	High

Fairness	None	Low to medium, intertwined with trust concept	High
Perceived costs	High	None, only a larger influence if the costs are directly reflected to the (local) society	High
Perceived risks	High	High	High
Perceived benefits	None, only in relation to other activities in the past	High	High
Outcome efficacy	High	None	None
Problem perception	None, is chaining but no influence	Medium	High
Energy context	Low, if it does not interfere with investments in other technologies	Medium, but many discrepancies between researchers	High

Table 11; Overview of the level of influence of the concepts on the socio-political acceptance in France, Spain and the Netherlands.

4.4 Alignment three perspectives

This section answers the fourth sub-question: "*To what extent do the three perspectives align in a respective country?"*. The three previous sub-questions concerning the policy mix, technical potential and socio-political acceptance are researched for France, Spain and the Netherlands. However, a high alignment between these perspectives within of the three countries results in a larger potential for industrial CCUS. This section thus gives an overview of how well the previous results are aligned in the same direction for future industrial CCUS in the respective country. First, a short summary of the results from the previous sub-questions is provided, followed by the alignments between the policy mix – technical potential; policy mix – socio-political acceptance; technical potential – socio-political acceptance.

4.4.1 France

The French government has set ambitious goals for the industry to pursue with CCS, compared to the current developments. The lacking instrument mix does not support the policy strategy, which is underlined by ADEME (2020) as financial and regulatory support measures should be considered for the industries wishing to implement CCS as part of their decarbonisation strategy. The annual funds for CCS RD&D in France are relatively stable, thus indicating that CCS is on the agenda for the future.

> *Researcher 2: "[Industrial CCS] is not part of the political debate [as during] the election in France, […] nobody talks about CCS."*
>
> Researcher 1: "*They [the politicians] do not speak about the storage because it is going to be dangerous to speak about that. So, they just do not speak about it. It is like it doesn't exist."*

In France, there is a large potential for industrial CCUS. The storage and capture potential outweigh the goals for industrial CCS and for CCU there are several reuse purposes, for example in the steelmaking or cement industries. However, the high potential is not reflected in the developments of projects, which thus are lacking in France: *"Here in France we don't have the practical cases. […] It is missing more practical operations."* (Researcher 1). Due to the lacking policy instruments to pursue the policy strategy goals, not many industrial CCUS projects have emerged. *As the large potential is not supported by the instruments, it indicates a weak alignment between the policy mix and technical potential in France.*

Besides the lack of the political debate, the national media attention in France *"is not there yet"* (Researcher 2) and *"there is a need for narratives"* (Researcher 2). Although the awareness on a national level is not seen as a predictor for an increased knowledge and thus a higher socio-political acceptance, national attention for industrial CCUS could stimulate the (local) debate which subsequently influences the (local) socio-political acceptance positively. The lack of political attention or debates and stimulating policy instruments resulting in less CCUS projects thus do not help to increase the socio-political acceptance of industrial CCUS in France but rather decreases it. Even though the political debates are missing, the French industry considers to only pursue offshore CCUS.

> Industry 1: *"It has much less political pressure. And I also think that there is a public lack of common education sense, because if you are talking with the public, the people, very often they say it is better to do CCU to convert CO2 into some valued product than to do CCS, to just store it and we do not valorise them, but they are not aware about the cost to convert CO2 into a valuable product."*

This underlines the need for information campaigns in France to increase a high knowledge level about industrial CCUS and subsequently increase the socio-political acceptance. The people in France *"are not against the technology [but] probably they do not know much about it"* (Researcher 2). Thus, there are opportunities to cover the knowledge gap positively for industrial CCUS, as there is no large resistance to be found yet. However, the currently policy mix does not align to utilize this potential. This is also seen in the lacking industrial CCU activities which can influence the socio-political acceptance positively.

> Researcher 1: *"CCU is something that is very easy to see the results from as there is a product, and you are producing something. So, we can see the product and the product that you are create has a value."*

Thus, to conclude, the lacking policy mix weakly aligns with the socio-political acceptance in France.

The large technical potential within France for industrial CCUS, combined with the not necessarily negative socio-political acceptance indicate a strong alignment between the two perspectives. The industry in France should be able to influence the local acceptance for a project, especially if the industry has provided several (economic) benefits in the past. Also, the built up (positive) local experience and subsequently trust, alongside initiating a local debate increases the socio-political acceptance. As there are several concepts which can positively influence the socio-political acceptance of industrial CCUS in France, the ability to fully tap the technical potential can be achieved. *Thus, there is a strong alignment between the technical potential and the socio-political acceptance of industrial CCUS in France.*

4.4.2 Spain

Due to the inconsistent Spanish policy strategy, no clear directions are given for CCUS developments until 2050. The Spanish instrument mix provides the concrete tools to achieve policy objectives, but due to the lacking goals, the industry has no clear foresight on the potential CO_2 reductions in their sector by CCUS technologies. This also could create a barrier for industrial CCUS developments as clear goals or principal plans create trust in a certain chosen path for the future on which technology investments partially rely. The instruments, on the other hand, have provided incentives for the industry and research projects to proceed. This indicates that, even without clear goals or principal plans, the technical potential can be used. In Spain there is a large storage potential and there are progressive research projects concerning the potential role of industrial CCUS and potential commercial CO_2 products. Due to this, the lack of a clear policy strategy is less relevant in relation to the alignment of the policy mix and the technical potential, even though there are large concrete developments necessary in, for example, the Spanish CO_2 infrastructure. *Thus, there is a medium to strong alignment between the policy mix and technical potential of industrial CCUS in Spain.*

As there are no clear goals or principal plans presented, there is a low consistency within the Spanish policy strategy. Resulting from this, the industry is not directly encouraged or stimulated to develop CCUS technologies. If other technologies are developed instead of industrial CCUS, the familiarly to CCUS technologies does not increase. This negatively influences the socio-political acceptance in Spain as other technologies are preferred due to being more familiar. However, the strongest predictors for socio-political acceptance of industrial CCUS in Spain, the perceived risks and perceived (local) benefits, are not directly affected by the low consistency of the Spanish policy strategy. Due to the high consistency of the Spanish instrument mix, the policy mix aligns to a medium extent with the socio-political acceptance in Spain. The instruments support the research and development of industrial CCUS on, for example, the currently lacking infrastructure. This, subsequently, could increase the experience and knowledge level to increase the socio-political acceptance. *Thus, to conclude, there is a medium alignment between the policy mix and the socio-political acceptance of industrial CCUS in Spain.*

The technical potential has increased due to the research and development of 25 commercial products. The familiarity of CCU products for the broader public, due to a high visibility, is a solid way to increase the socio-political acceptance. These created products also increase the experience with reused CO_2 products and might even reduce the perceived risks as these products can serve as an example for the safe use of CCU technologies. The different CCUS projects in Spain are, however, still on a small scale. The national technical potential is not visible for the larger public and without enough incentives from the government, the public debate and large-scale developments of CCUS projects or CCU products will not evolve. This subsequently does not increase the socio-political acceptance on a national scale as the predictors such as the perceived risks are not addressed enough. On a local level, such developments can create a large difference as, for example, prototypes or small-scale examples can be shown to the public, thereby increasing the socio-political acceptance for industrial CCUS due to an increase familiarity, the experience, trust, perceived benefits and potentially less perceived risks. *To conclude, there is a medium alignment between the technical potential and the socio-political acceptance of industrial CCUS in Spain.*

4.4.3 The Netherlands

The goal to store 7 Mt CO_2/y in offshore oil and gas fields by 2025 is progressive and does require the necessary developments already. Several policy instruments are developed to stimulate and support the developments towards this goal. The technical potential for CCS in the Netherlands does align with the current CCS goal as the necessary infrastructure is being built and the storage capacities outweigh the goal until at least 2050. Also, even though there are no specific CCU goals, several projects have emerged, and the demand is expected to increase. *Thus, these developments indicate that the current policy mix strongly aligns with the technical potential in the Netherlands as the projects are emerging rapidly.*

The current policy mix in the Netherlands is constantly developing concerning industrial CCUS. The example of Barendrecht has shown that if certain policies are lacking for the current or future situation, they will be adapted. After the Barendrecht project which had a low local socio-political acceptance, the Netherlands focussed on offshore CO_2 storage only. The government has not explicitly mentioned this correlation, but this relation is indicated by Researcher 5: *"I think they have incorporated that into their policy without explicitly mentioning it. That is my impression, but I have never heard them say it explicitly."*

Besides the national changes, local changes are necessary to increase the socio-political acceptance of industrial CCUS. The policy mix sufficiently bridges the financial gap, which is necessary to address all local needs and start the local debate. *Thus, to conclude, there is a strong alignment between the policy mix and the socio-political acceptance of industrial CCUS in the Netherlands.*

The Netherlands has a few projects which are quite far developed and certainly beyond the research phase. This opens the possibility to influence several factors to increase the socio-political acceptance of industrial CCUS. Apart from using best cases and gaining more knowledge in general, trust, as a key predictor, can be built by showing the results and experience of previous projects. Also, the previous experience with similar technologies, such as the drilling and transportation of oil and natural gas, created a certain level of (local) trust that can increase the socio-political acceptance in the Netherlands. This experience, which is continuously growing, combined with the large potential in terms of infrastructure, storage and reuse of CO_2, results in many opportunities to create the ideal situation for national public debates and to build the necessary (local) trust, together with identifying and addressing local needs. *Thus, there is a strong alignment between the technical potential and the socio-political acceptance of industrial CCUS in the Netherlands.*

4.4.4 Overview alignment three perspectives

This section provides an overview of the alignments of the three perspectives in France, Spain and the Netherlands.

Alignment three perspectives	France	Spain	The Netherlands
Policy mix – technical potential	Weak	Medium to strong	Strong
Policy mix – socio-political acceptance	Weak	Medium	Strong
Technical potential – socio-political acceptance	Strong	Medium	Strong

Table 12; Overview alignment policy mix, technical potential and the socio-political acceptance in France, Spain and the Netherlands.

5. Conclusion and discussion

The final sections start by providing a summary of the previously answered four sub-questions in France, Spain and the Netherlands. The first three sub-questions are as followed: *SQ1: "What role does industrial CCUS play in the respective national decarbonisation strategy?", SQ2: "What is the known technical potential of industrial CCUS in the three respective countries?", SQ3: "Which concepts influence socio-political acceptance of industrial CCUS?"*. After the research on the three perspectives, the policy mix, technical potential and socio-political acceptance, the research focuses on the potential alignment of these three perspectives within a country by answering the fourth sub-question: *SQ4: To what extent do the three perspectives align in a respective country?*. Contradictions between the potential role industrial CCUS can play in three perspectives result in a weak alignment. On the other hand, a strong alignment between the perspectives results in a higher potential for industrial CCUS in Europe. After summarizing the four sub-questions for each country, a cross country comparison is made to identify the similarities, differences, and lessons learned from this. Similarities and differences between countries in the policy mix, technical potential and socio-political acceptance or the alignment reveal valuable lessons. Subsequently, the potential role of industrial CCUS in Europe is highlighted, based on an answer to the following main research question: *"What role could CCUS play for European countries to decarbonize the industry sector?*. At last, the discussion points and limitations of this research are identified, and theoretical implications are given, followed by recommendations from this research. Below, table 11 provides an overview of the main results of all four sub-questions.

Sub-question	**Topic**	**France**	**Spain**	**The Netherlands**
Policy mix (SQ1)	Consistency policy strategy	High (CCS), low (CCU)	Low	High (CCS), low (CCU)
	Consistency instrument mix	High	High	high
	Consistency policy strategy with instrument mix	High (CCS), low (CCU)	Low	High (CCS), low (CCU)
	Credibility	Medium (CCS), low (CCU)	Low	High (CCS), low (CCU)
Technical potential (SQ2)	Infrastructure (CCUS)	First developments planned	Project specific only, no large-scale developments	Project specific and the creation of an open access network. Potential to transport 8 Mt CO_2/y
	Storage site (CCS)	Storage potential > capture goal	Unclear due to lacking CCUS goals. Assumably the storage potential outweighs the capture potential/goal due to the large storage potential.	Storage potential > capture goal
	Production (CCU)	(Very) small scale (~0,1 Mt CO_2/y in total)	(Very) small scale, research into 25 commercial products can accelerate this (unknown total CO_2 savings)	Medium scale (1,62 Mt CO_2/y in total)
	Product disposal (CCU)	CO_2 storage temporary (methane production)	CO_2 storage permanently (greenhouses),	CO_2 storage temporary (soft drinks industry, urea production) and

		and permanently (cement)	although used for energy production eventually	permanently (greenhouses)
	Knowledge base (CCUS)	Relatively stable	Very unstable but expansion of the knowledge base for CCU products	Unstable, but multiple arising projects recently
Socio-political acceptance (SQ3)	Knowledge	High	High, predictor for the energy context	None
	Experience	High, predictor for trust	High	None, potentially on a local scale
	Trust	High	High	High
	Perceived costs	High	None, only a larger influence if the costs are directly reflected to the (local) society	High
	Perceived risks	High	High	High
	Perceived benefits	None, only in relation to other activities in the past	High	High
	Energy context	Low, if it does not interfere with investments in other technologies	Medium, but many discrepancies between researchers	High
Alignment three perspectives (SQ4)	Policy mix – technical potential	Weak	Medium to strong	Strong
	Policy mix – socio-political acceptance	Weak	Medium	Strong
	Technical potential – socio-political acceptance	Strong	Medium	Strong

Table 13; Overview main results of the four sub-questions.

France

France has set the goal to be climate neutral and store 6 Mt CO_2/y with industrial CCS technologies by 2050, without indicating a specified CCU goal. However, only the European CCS Directive and two economic policy instruments (systemic and technology push) are in place, which affects the industrial CCUS developments. Informative policy instruments are lacking, and without a CCU goal, it results in a medium consistency of the instrument mix with the policy strategy in France for CCS and low concerning CCU. All aspects of the policy mix sub-question (SQ1) combined indicate an immature stage for industrial CCUS in France in relation to the policy mix. Concerning the technical potential, around 31,0 Mt CO_2/y of the total 81 Mt CO_2/y industrial emissions in France can be captured (NMPE, 2020; MTE, 2020a). This exceeds the French CCS goal for 2050, even after considering the power generation sector CCS goal of 10 Mt CO2/y. However, to achieve the industrial CCS goal, several projects need to emerge, which are currently lacking. The thoughts and prospects that the deployment of CCS should start at the beginning of the 2020s are already delayed as CCS is still in a (very) early development stage in France. This is also seen in the CO_2 transportation infrastructure as only the first developments have been made to collect CO_2 from different sources.

The status of the socio-political acceptance of industrial CCUS in France is still unsure. The research of Ha-Duong et al. (2009; 2011a; 2011b) are a bit outdated, and the Strategy CCUS project (2019; 2020b) has a more high-level view from stakeholders and did not involve the public so far. However, some concepts are found within studies that influence the socio-political acceptance of industrial CCUS in France directly: *knowledge*, *experience,* which is a predictor for the level of *trust*, *perceived costs*, *perceived risks* and the *outcome efficacy*. In France, an increased *knowledge* level will also stimulate the debate and potentially generate opposition. Due to the rising opposition, the influence of the *outcome efficacy* is seen in, for example, a debate or discussion. General media debates do not influence the socio-political acceptance as awareness is not an indicator of the *knowledge* level. French studies on the socio-political acceptance pointed out that there is a difference between the local socio-political acceptance, which is visible when referring to the influence of *experience* and *trust*. Both concepts have a positive correlation with the socio-political acceptance level in France, although only proven on a local level. Any local *experience* with companies that can cope with higher risks and have a certain level of technical capabilities resulted in a high local *trust* level. As consequently *experience* is seen as the predictor for *trust*.

The goals for the industry to pursue with CCS are ambitious compared to the current developments in France. The alignment between the policy mix and technical potential in France is weak, primarily due to the lack of supporting policy instruments for the available large technical potential. The weak policy instruments subsequently also result in a *weak* alignment between the policy mix and the socio-political acceptance in France. On the other hand, there is a *strong* alignment between the technical potential and the socio-political acceptance in France. The French industry is likely to influence the local acceptance for a project, especially if the industry has provided several (economic) benefits in the past. To conclude, France can utilize its technical potential, as the national socio-political acceptance is currently not low, but an adequate policy mix is currently lacking.

Spain

The Spanish government has not set any CCUS goals for 2050, even though CCUS is likely to play a larger role compared to other technologies in three industry sectors when referring to emission reductions, namely the cement, petrochemicals and paper industries (MTERD, 2020a). Despite these progressive forecasts in several sectors, the principal plans to achieve this are lacking, which results in an inconsistent policy strategy. The instrument mix, on the other hand, covers the three primary instrument types: regulative, informative and economical. Several instruments are in place to pursue industrial CCUS developments. Although the instrument mix is consistent, the policy strategy is inconsistent, and there thus is a low consistency between the two aspects. Since the Castor project in 2012, *“There has been no support from national authorities to do CCS [in Spain]. […] In the last two, three years when the utilization has become more relevant, something has started to change as utilization is seen in a different way. So even if there is no active policy to support these activities, at least there is now a strong opposition [who are pro industrial CCUS] compared to as it was five or six years ago.”* (Industry/researcher 1). Thus, industrial CCUS developments are still suffering from the Castor project as there is a lack of political support, even nowadays. To successfully proceed in the future with industrial CCUS, the current policy mix is not sufficient. There are no clear goals, and without sufficient political support, industrial CCUS will face difficulties during its development.

> Industry/researcher 1: *“We need something more [more policies]. At least, we need to have a very clear definition of how this activity could be carried out. What I mean is that it needs to be clear that if there are any incentives to the implementation of these projects, it needs to be clear that these activities are not going to be stopped or blocked by the authorities when the projects come to an industrial stage. We need to clarify a lot what would be the real scenario for industrial [CCUS] projects. Because right now, this is not clear. They are like, you [the industry] can keep doing things and keep researching, but it is not very clear that we will get it to a real industrial project. […] They [the industries] are not going to invest a lot of*

money if they do not see it very clear. […] At this point, this is not clear, so they are not going to do it [invest in industrial CCUS].”

Due to the lack of specific CCUS goals, it is not possible to precisely mention whether the technical potential is larger compared to the prospect of industrial CCUS or not, although the estimated capacity of 12 Gt CO_2 is expected to be large enough. The cement sector indicated that in 2016 around 4,76 Mt CO_2/y should be reduced by breakthrough technologies such as CCUS, the 2050 forecasts are still unsure. Although this reduction also can be achieved with other measures and technologies, such as the use of alternative raw materials and fuels, it gives an indication of the scale industrial CCUS might need to have as this was only concerning the cement industry. A first start in the research and innovation phase is made as several potential CCU products have been created by the CENIT SOST-CO_2 project. 25 significant commercial products in multiple sectors resulted from this.

In Spain, the following concepts are found in studies that influence the socio-political acceptance towards industrial CCUS: *knowledge, experience, trust, perceived risks, perceived benefits, problem perception and the energy context*. In Spain, the lack of *knowledge* or familiarity among the public about industrial CCUS results in the technology being less preferred compared to other existing and more familiar carbon saving technologies. This indicates a positive correlation with the socio-political acceptance for industrial CCUS as the other way around, an increased *knowledge* thus results in being more preferred to other technologies. Besides this, *knowledge* is seen as a predictor for the *energy context* as a decreased level of knowledge results in other technologies being more preferred. The influence of the *experience* with industrial CCUS or similar technologies in the past has a positive correlation with the socio-political acceptance in Spain, although only proven on a local scale as on a national scale it is still unsure. Studies in Spain on the socio-political acceptance pointed out that the *perceived risks* concept is a strong predictor for the final socio-political acceptance in Spain. The difference between the national and local context are also seen in the *trust* concept as the local *trust* in (local) stakeholders has a positive correlation with the socio-political acceptance of industrial CCUS in Spain. The national context is rather unclear. Spanish socio-political acceptance studies also pointed out that this is also seen for the *perceived benefits* concept as, especially the local socio-political acceptance, strongly increases if the local needs are identified and addressed.

Firstly, there is a *medium to strong alignment* between the policy mix and the technical potential of industrial CCUS in Spain. This is due to the large technical potential and progressive expansion of the knowledge base because of research projects but lacking policy strategy concerning CCS and CCU goals. Secondly, the alignment between the policy mix and the socio-political acceptance is *medium*. The high consistency of the Spanish instrument mix supports the research and development of industrial CCUS, resulting in an increased knowledge and experience level, thus a higher socio-political acceptance. The low consistency of the policy strategy does not align with the socio-political acceptance as the industry is not directly encouraged or stimulated to develop CCUS technologies. If other technologies are developed instead of industrial CCUS, the familiarity with CCUS technologies does not increase.

Industry/researcher 1: *“It [the industrial CCUS goals] will only change when the politicians change, and they see that we need a country solution because sending it with a boat to North Sea is very expensive.”*

Thirdly, there also is a *medium alignment* between the technical potential and socio-political acceptance in Spain. The creation of several projects and CCU products leads to an increased socio-political acceptance, however, only on a small scale. The national technical potential is not visible for the larger public, and without sufficient top-down incentives or support from the government, the public debate and large-scale projects will not evolve, thus not resulting in an increased national socio-political acceptance. Subsequently, the local socio-political acceptance will not increase. To conclude, Spain has a large technical potential concerning industrial CCUS, but an adequate policy mix is currently lacking. The national socio-political acceptance is currently not low, but the familiarity is rather small to the wider public to fully engage with industrial CCUS.

The Netherlands

The Netherlands has a clear policy strategy concerning the offshore CCS goal of 7 Mt CO_2/y from 2025 onwards. A CCU goal, on the other hand, is lacking. The Dutch instrument mix covers regulative, informative and two economic instruments to achieve the goals. All combined, this resulted in a high consistency of the policy strategy for CCS and low for CCU. The consistency of the instrument mix has, however, a high consistency for both CCS and CCU. Further, the consistency between the policy strategy and instrument mix is, again, high for CCS but low for CCU. Concerning the technical potential, the capturable emissions exceed the potential CCUS use in the Netherlands, and the storage potential is sufficient until 2050 with the current goal for CCS. Besides this, there are several infrastructure projects in development to transport the captured CO_2, alongside the potential future opportunities provided by the extensive natural gas infrastructure. Concerning CCU, there are several projects ongoing, and the demand is expected to increase, although not on a very large level.

In the Netherlands, the following concepts are found in studies that influence the socio-political acceptance towards industrial CCUS: *trust, fairness, perceived costs, perceived risks, perceived benefits, problem perception and the energy context*. Dutch studies on the socio-political acceptance pointed out that *trust* is seen as a key predictor for the final socio-political acceptance in the Netherlands. This can be increased, for example, by clear and early communication and local involvement during a project. The *(un)fairness* experienced by the local public and subsequently *perceived benefits* are interlinked as the identification and realisation of local compensations results in a higher socio-political acceptance for industrial CCUS on both aspects. Again, the difference between the national and local context is important. The local socio-political acceptance suffers from a more clear and direct influence of certain concepts, which can be addressed well, in contrast to the national acceptance, which is harder to influence.

In the Netherlands, there is a *strong* alignment between the policy mix and the technical potential. There is a clear industrial CCS goal, although lacking a CCU goal, and the supporting policy instruments result in rapidly emerging industrial CCUS projects to tap its full technical potential. There also is a *strong* alignment between the policy mix and the socio-political acceptance in the Netherlands. Industrial CCUS policies have been adapted in the past to the socio-political acceptance status, as seen in the Barendrecht case as there was a low socio-political acceptance. Resulting from the Barendrecht case, policies were adapted as industrial CCUS would only take place offshore from them on. Also, the economic policies bridge the financial gap, resulting in an increased number of emerging projects, thus creating the potential to address the local needs for an increased socio-political acceptance. At last, there is a *strong* alignment between the large technical potential in the Netherlands and the socio-political acceptance. The rapidly evolving projects to utilize the large technical potential result in an increased local and national socio-political acceptance. To conclude, the Netherlands has a strong policy mix which resulted in many industrial CCUS projects to utilize its full potential, also due to the socio-political acceptance, which is currently medium to high. By combining all three aspects, rapid evolvements of projects are seen, in both quantity and scale.

Cross-country comparison

To start off, none of the three countries has set a clear CCU goal for 2050. In France, this eventually resulted in a weak alignment of the policy mix with the technical potential and socio-political acceptance. Interestingly, these alignments were stronger aligned in Spain and the Netherlands, even though these two countries also did not have a clear CCU goal (and no CCS goal for Spain). However, for both countries, the policy instruments compensated this as these resulted in clear progression concerning industrial CCUS projects. Thus, a clear CCS and CCU goal, supplemented with the principal plans, seems not to be necessary to pursue industrial CCUS developments. Even though it might not be necessary, clear and consistent goals can give guidance to the industry of the pursued strategy until 2050. Thus, this is not seen as superfluous and can add value to create a stronger alignment. One of the reasons that there are no CCU goals yet, might rely on the lack of research into the possibilities:

> Industry 1: *"My feeling is that we should really look into this as a specific product and need to investigate the different pathways of producing and choose the best way. If CO_2 utilization is not the best way to produce this product, then we should not set a goal to convert CO_2 into this product. So, for me, I think this is the reason that we cannot really set up a goal for the CO_2 routinization."*

The infrastructural developments in the Netherlands, in combination with the increasing demand which hardly is fulfilled yet, show that such projects are necessary to fulfil future CO_2 demands for CCU projects. Such infrastructure projects are currently not under development in France and Spain and without a sufficient supporting instrument mix, these projects are not likely to emerge due to the financial gap.

> Industry/researcher 1: *"CO_2 capture is very well recognized in the whole European Union as a tool to get the net zero emissions. The way that different countries our focused is different. There are several countries like the United Kingdom, the Netherlands and Norway that are working more in the storage systems because they know that it is a long work for more than 10 years to try to develop all the infrastructures and get the scientific knowledge for an industrial solution."*

The storage potentials within the three countries seem to be sufficient until 2050. However, the potential in Spain seems not to be fully utilized yet, when referring to the *medium* alignment between the technical potential and the socio-political acceptance. The advancements in the technical potential, for example, as new products are created, can be used to increase the socio-political acceptance. However, efforts are still not visible to the larger public.

Experience and (local) trust, combined with low perceived risks, seem to be key predictors for the final socio-political acceptance in a country or project area. If opportunities are not fully utilized to increase the socio-political acceptance, countries will eventually not be able to fully tap their technical potential. Within all three countries, *trust* and the *perceived risks* influence the socio-political acceptance. Although there are some differences between countries, *trust* can be built by including the (local) public in an early stage, informing them and create local interaction. Also, identifying the local needs and subsequently addressing these needs is an often-mentioned as important within the three countries. Apart from creating trust, previous activities by the (local) industry can serve as the foundation for a higher level of *trust* for industrial CCUS as local economic *benefits* were realised in the past or the industry has proven to be able to cope with higher *risks*. Although addressing the local socio-political acceptance might not be the silver bullet for an increased level of national socio-political acceptance, industrial CCUS projects are likely to fail if this Is not addressed well. Thus, especially for a single project, increasing the local socio-political acceptance is key for the future of the project.

Role of industrial CCUS in Europe

In this section, the following main research question will be answered: *"What role could CCUS play for European countries to decarbonize the industry sector?* This research has shown that there are large differences between CCS and CCU within the three respective countries. Industrial CCS is further developed compared to CCU in each of the three countries as there are, among other things, relatively more CCS projects being developed, there is more experience and a clearer policy mix. The role of CCS to decarbonize the industry by capturing (unavoidable) emissions in Europe is seen as a must by many. A clear instrument policy, which can also prevent a lock-in as seen in the Netherlands, combined with addressing the socio-political acceptance nationally but especially on a local level, is key to further industrial CCUS developments. The technical potential outweighs the CCUS goals for 2050 in the three respective countries, which indicates that other European countries probably also have a significant amount of storage and utilization potential. Currently, France and Spain lack a sufficient CO_2 transportation system which becomes a barrier in the future as there are currently no policy instruments to address this. Such projects are, also in other European countries, necessary to create a successful industrial CCUS system. Thus, the role of CCUS in other European countries also depends on the (future) policy instruments to support the creation of a large-scale CO_2 transportation system.

The role for industrial CCUS to decarbonize the industry sector in the future is seen as medium to large in Europe. The maturity of industrial CCS with many best cases is rolled out widely compared to industrial CCU. The role of industrial CCS is seen as large for the future in Europe as it is a proven technology, and this research has shown that if governments are willing to proceed with industrial CCS, it is possible. The role of industrial CCU to decarbonize the industry sector is seen as medium, but rather unsure. Industrial CCU is still less developed compared to industrial CCS, and without any goals, no certain indication of the potential can be given. However, based on the early developments and small-scale projects, it assumably will play a role eventually. As proven in the Netherlands, strong alignments between the policy mix, technical potential and socio-political acceptance result in strong industrial CCUS developments. Also, a supporting instrument mix has proven to be necessary for progressive industrial CCUS developments. The national but also local socio-political acceptance is very important as projects succeed or fail on this subject. This might cause a problem in other countries with a low socio-political acceptance as a low socio-political acceptance can result in less political support and thus less stimulating policy instruments. Such chain reactions can be fatal for the development of industrial CCUS in the future. There are many possibilities to solve a low (local) socio-political acceptance, as this research has proven that each country has its influencing concepts on the socio-political acceptance. Although there are many differences, trust and the perceived costs influence the socio-political acceptance for industrial CCUS in all three countries. Addressing these two concepts to a positive extent is thus seen as necessary for European countries to pursue industrial CCUS.To conclude, there are many differences between France, Spain and the Netherlands, which indicates that the role of industrial CCUS should be evaluated for each European country specifically. The pace of the industrial CCUS developments consequently differs greatly, but this highlights the importance of a good alignment between all three aspects to proceed with industrial CCUS successfully. It is thus seen as a technology with a medium to large potential to decarbonize the industry sector in Europe, although the role of CCS will probably outweigh the role of CCU until 2050.

5.1 Discussion

In this section, some limitations or discussion points that came up during this research need to be presented and are discussed. This research has been conducted by one researcher, which could decrease the reliability. To some degree, there might be a lower reliability compared to multiple researchers as all implications were subjective to the thoughts of one researcher. However, various feedback moments and the use of peer-reviewed literature and official documents have ensured that consistency throughout the research has been ensured to a certain level.

Another methodological aspect lies within the variation of respondents and their respective interviews. Out of the nine respondents, seven are researchers. Although this implies a relatively narrow background of respondents, there is a large variation between the focus and knowledge areas. Also, the variation countries and thus area of knowledge among the respondents were well divided. Even though there is a lot of variation in topics, knowledge areas and countries, all respondents were involved in the industrial CCUS area, thus resulting in being in a 'CCUS bubble'. However, to gain valuable insights usable for this research, a certain level of knowledge about the topic is necessary, thus recent involvement is required.

The industrial CCUS topic is a rapidly changing sector with many developments. Recent development might not be incorporated by the time this research is published. This is, however, unavoidable when performing research on a topic that is in development. During feedback moments and interviews, it was regularly asked whether the supervisors or respondents had any recent updates in this field. Another discussion point that arose concerns the language barriers while performing the research on France and Spain. Many documents were only available in the foreign language, which potentially resulted in information that is missing in this research. To pursue data saturation, any missing information was tried to be covered by interviews or various other methods such as sending emails.

Although this research studies various perspectives and multiple countries, some aspects which might be relevant for the potential role of industrial CCUS in Europe are excluded. The cost aspects could play a large role, especially in relation to the European Emissions Trading Scheme (ETS). Industrial CCUS projects depend for a significant part on the economic support of governments to close the financial gap. The price of ETS allowances is expected to rise significantly until 2050. This could cover the financial gap as from the industry's perspective, there is a better business case with CCUS compared to without CCUS. Industry/researcher 1: *"With the CO2 at 50 euro per tonne, these kinds of technologies [CCUS] begin to be possibly competitive."* This development has not been included due to the scope of this research. Further research could include the cost aspect.

Also, the international transport of CO_2 has not been researched. This is outside the scope of this research as this only recently has become legally possible to transport CO_2. Besides this, European countries currently do not have a project in operation that involves international CO_2 transport. Thus, the influence of international CO_2 transportation on the potential role of industrial CCUS until 2050 is still unsure. Further research needs to focus on the influence of international CO_2 transportation and how this will affect, for example, countries with a low technical potential.

Concerning the knowledge base in the technical potential sub-question (SQ2), a limitation arose. The CCS RD&D budgets of France, Spain and the Netherlands only focussed on CCS and not on CCU. Also, the data covered not only the industry but also the power generation sector. Besides this, the time frames where there were actual funds for CCS RD&D in the three respective countries were taken, which results in different time frames that are not fully comparable. Besides this, the IEA data did not include every year, e.g., Spain: 2016. However, these aspects are not seen as a limitation of this research as the CCS RD&D data is used as an indication and not to directly compare it to each other.

Concerning the socio-political acceptance (SQ3), two discussion points arose. Firstly, the socio-political acceptance yet has (almost) not been researched with a distinction between the industry and the power generation sector, thus increasing the difficulty to create this division. The Strategy CCUS project indicated the industrial CCUS potential for France, Spain and the Netherlands. Thus, if no specific indication was given in a certain paper, it was assumed to cover at least both the industry sector and the power generation sector, thus being valuable for usage during this research. Concerning the Netherlands, this division was clearer as only industrial CCUS in pursued. Secondly, a variation of wording for almost the same groups are used, e.g., the public, the community, the society, etc. These distinctions are unavoidable in such a research and have a relatively similar meaning, thus justifying the choice to use these for this research, although carefully.

Theoretical implications

A couple of theories are used to lay the basis for this research. For SQ1, the policy mix framework of Rogge & Reichardt (2016) has proven to be very useful during the analysis as it covered all aspects of the policy mix in a respective country. Apart from the second building block, the policy processes, which is excluded due to this research's scope, the three used dimensions to capture the space in which interactions can occur seem not to be relevant for this research. Especially the geography dimension turned out to be national for all researched policy instruments. However, further research can reveal whether there are regional differences between policies in the future.

The second main used theory refers to the CCUS technology process-chain (TPC) or Arning et al. (2019). This research has proven that the CCUS TPC is valuable to study the socio-political acceptance of CCUS which was the focus of Arning et al. (2019) and provides a detailed breakdown of all CCUS process steps to research other aspects in a structured manner. Although this might not be relevant in relation to Arning et al. (2019), this research has shown that the development of the knowledge base is valuable in relation to the technical potential for a technology. Further research can focus on the relation between the addition of the knowledge base and the technical potential or other research areas and different (emerging) technologies.

At last, the concepts of the technology acceptance framework (TAF) of Huijts et al. (2012) are used to research SQ3, the socio-political acceptance. Selma et al. (2014) adapted the framework with a focus on CCS, but despite this, several concepts were adjusted for the scope of this research, industrial CCUS. The concepts “norms”, “interface with nature”, and “acceptance/attitude” are excluded from this research, and the concept “energy context” is included, compared to Huijts et al. (2012). Further research can point out whether some of these decisions are also viable for other emerging energy-saving technologies in the future. Also, further research is needed to clarify the division between the national and local socio-political acceptance as this research has proven that there are significant differences.

Recommendations

For a successful industrial CCUS rollout, the difference between the local and national socio-political acceptance is key in the (future) developments. The industry itself, alongside local governments or interest and opposition groups, needs to identify the local public's needs and fulfil those needs. In many cases, the industry has a significant lifespan in the local area, need to initiate local debates, information campaign, etc. to build trust eventually. Thus, it is recommended for the industry to take the lead and play an active role in an industrial CCUS project. Besides an active role in the industry, the government also need to be a front runner to this subject. The government need to research the concepts which largely influence the socio-political acceptance in their respective country and create an overview of the best cases from which can be learned and who to contact for any help.

The future of industrial CCU is still unsure compared to industrial CCS. The demand for CO_2 and the different potential utilization pathways are rather unclear and differ between countries. Governments need to explore the national CO_2 utilization potential by performing large-scale research into their country's different products and processes, which uses CO_2. Subsequently, the connection between CO_2 emitters and the CO_2 demand must be made to provide a high-level overview of the utilization potential. Also, the differentiation between temporarily and permanent CO_2 storage need to be researched. Projects that permanently store the CO2 to a larger extent need to gain a preferred status over the projects that temporarily store the CO_2. Besides this, a clear policy strategy needs to be created to guide the industry, resulting in more industrial CCUS.

Industrial CCUS is necessary for industrial processes where emissions are unavoidable and rely on future innovation to decarbonize these processes. Besides this, industrial CCUS is necessary to achieve net-zero goals, and it is among the cheapest abatement options or even the only option. The policies are currently not always set to create enough incentives and provide a structured basis for industrial CCUS developments. National policymakers need to rethink their policy mix and create policies specifically for industrial CCUS. Industry 1: *“I think this kind of specific CCUS policy per time period can already accelerate the CCUS project developments”.* Industrial CCUS specific policies create a solid basis for any developments and provide guidance for the industry and the local policymakers, and the public, on what to expect in the future.

To conclude, industrial CCUS is in an early stage of development, but the roll-out has started. Industrial CCS is further developed in each of the three respective countries than industrial CCU, and a clear CCU policy strategy is lacking. The impact of CCS on the decarbonization of the industry is seen as strong, and the impact of CCU is seen as medium until 2050, although more unsure. To successfully develop and implement industrial CCUS projects on a large-scale in Europe, top-down national support is necessary in relation to a sufficient policy mix and how to cope with a potential lack of (local) socio-political acceptance. Industrial CCUS is one of the very useful technologies to tackle climate change and reach net-zero in 2050.

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Appendix

Appendix A – Interview guide

First, thank you for giving your time for this interview – it should last about 30 minutes. As we talked about before, the interview will be recorded, if that is fine for you. Short introduction of myself.
Agreement necessary

Further, all data will be anonymized, safely stored and not shared.

We will start. As discussed before, my thesis covers multiple aspects of CCUS in France, Spain and the Netherlands: the policies, technical potential and the socio-political acceptance. We will go through all three aspects but always feel free to skip a question.

We will start with some general questions, followed by a few abstract questions and then we continue with the evaluation and personal questions. Please keep in mind that the focus is primarily on industrial CCUS, although some aspects could also cover the power generation sector.

General background questions

1. How long have you been working in the field of CCUS and how are you involved with CCUS?
    a. *What did you do before this? (If recently started working on CCUS) (year)*
2. What projects were you involved in recently or what is your field of expertise?
    a. What is/was your role?

Sub-question 1 (policy mix):

3. *Explaining the national identified policy instruments. Overview of policies per country will be created before and explained during the interview.*
    a. *Do I miss any (local) policy instrument/documents?*
    b. Do you see any regional differences in policies?
    c. **Spain:** I have found the State Incentives and Aid programme, but I could not find the duration of this. Do you know its duration or when the programme stops?
4. *Implementation process*
    a. During this research I primarily focussed on results after the implementation process of policies which affect CCUS. However, there might were some hurdles during this process. Do you know if there were any of these barriers or hurdles?
        i. Resistance to change (vested interests), (Long lasting) political debates, etc.
    b. Did you see any drawbacks due to this?
        i. Do you think less radical but more supplemental policies are thus implemented? To overcome such barriers and 'meet in the middle'.
    c. Do you see evaluations or monitoring processes after CCUS policies are implemented?
5. *Policy potential*
    a. To what extent do you think that the CCUS policies tap its full potential, or did you see any difficulties? What further policy measures are needed?

Sub-question 2 (technical potential):

6. *CO_2 transportation by pipelines in general:*
    a. If the captured CO_2 will be transported by pipelines, these pipelines cannot be used for oil/natural gas transport. This might be an issue when aiming to reuse existing pipelines if areas are still dependent or oil and natural gas import.
        i. How do you think that this will affect the development of CCUS?
        ii. Do you know any study about this or maybe some projects which had to cope with this problem?
7. *Energy technology research, development and demonstration budgets:*

a. Each country has a specific RD&D (research, development and demonstration) budget which is aimed at CCS. This budget varies a lot during the years, do you maybe know why this is changing such a lot? *Send figure in the chat of table, not graph?*

8. ***France** total storage potential:*
    a. Storage potential to store the captured CO2 underground. There are quite some differences between estimations, what do you think can cause these differences?
        i. GeoCapacity (2009): 8,7 Gt
        ii. Norwegian Ministry of Petroleum and Energy (2020) estimated 1 – 1,5 Gt CO_2, although mentioning the lack of available knowledge
        iii. ADEME (2019): 27 Gt
9. ***France** CCU goal:*
    a. Goals for carbon capture and storage in 2050 are given but not for the utilization. There are no exact goals given for CCU in the French National Low Carbon Strategy, do you know if there are any plans to proceed with reuse CO2 until 2050?
    b. Currently there are a few utilization projects in France, but do you know what the total amount of reuse CO2 is or what the demand is in France?
10. ***Spain** CCS/CCU goals:*
    a. There are no goals given for industrial CCS or CCU to become carbon neutral in 2050, despite being indicated as highly important in 4 industry sectors (figure below). What are your thoughts on this? Do you know if there are any goals given?
        i. Iron and steel, chemicals and petrochemicals, cement and pulp and paper industries. See figure below.
11. ***Spain** CCUS infrastructure*
    a. Do you know if there are currently any infrastructure projects concerning the transportation of CO2 in Spain?
    b. CCS in geological formations may become a common attractive option to Morocco, Portugal and Spain, also because these countries share some offshore sedimentary basins that are likely to be potential suitable reservoirs for CO2. Do you see such infrastructural development internationally?
12. ***Spain** CCU projects:*
    a. Do you know if there is an overview of the current CCU projects in Spain? What are your thoughts on the current CCU projects in Spain in terms of capacity and progress?
    b. I came across the Lighthouse CCU project for the cement industry, but I cannot find any information about this project. Do you know where to search or who to approach?

Sub-question 3 (socio-political acceptance):

13. Who do you see as the 'opponents' or resisting actors of CCUS in your country? And who is driving the development?
    a. Society, existing industry, political parties, etc.
14. What is your general evaluation/view on the socio-political acceptance in your country?
    a. Did you see any developments in the past 10/15 years? Can be favourable or unfavourable for CCUS.
    b. Main barriers for the society.
15. Is it discussed in society? Or not yet? (Newspaper readings, etc.)
16. Do you know if there are any recent studies on this topic?

17. Are there any topics which we did not discuss but are maybe relevant for this research?

Thanks a lot for your time, it was very interesting and helpful! *Do you have any other contacts I can approach for an interview? Could you introduce me to him/her?*
Do you have any questions for me?
Thanks again for your time and have a good day!

Appendix B – Informed consent form

The informed consent form has been signed by all interviewees, which are in possession of the researcher and the respective respondent. Two interviewees indicated that their data only could be used for this research, after which the form was slightly adjusted.

Utrecht University

INFORMED CONSENT FORM

for participation in:

The potential of carbon capture utilization and storage (CCUS) to decarbonize the industry sector in Europe.

To be completed by the participant:

I confirm that:

- I am satisfied with the received information about the research;
- I have been given opportunity to ask questions about the research and that any questions that have been risen have been answered satisfactorily;
- I had the opportunity to think carefully about participating in the study;
- I will give an honest answer to the questions asked.

I agree that:

- the data to be collected will be obtained and stored for scientific purposes;
- the collected, completely anonymous, research data can be shared and re-used by scientists to answer other research questions;
- video and/or audio recordings may also be used for scientific purposes.

I understand that:

- I have the right to withdraw my consent to use the data;
- I have the right to see the research report afterwards.

Name of participant: ____________________

Signature: ______________________________ Date, place: ___/___/____,

____

To be completed by the investigator:

I declare that I have explained the above mentioned participant what participation means and the reasons for data collection.
I guarantee the privacy of the data.

Name: ____________________

Date: ___/___/_____(dd/mm/yyyy)

Signature: