Exploring the future of carbon capture and utilisation by combining an international Delphi study with local scenario development

Peer-reviewed author version

VREYS, Kim; LIZIN, Sebastien; VAN DAEL, Miet; Tharakan, Joe & MALINA, Robert (2019) Exploring the future of carbon capture and utilisation by combining an international Delphi study with local scenario development. In: 1942/28336, 146, p. 484-501.

DOI: 10.1016/j.resconrec.2019.01.027
Handle: http://hdl.handle.net/1942/28336

Title page

Exploring the future of carbon capture and utilisation by combining an international Delphi study with local scenario development

Kim Vreys[1,2], Sebastien Lizin[1*], Miet Van Dael[1,3], Joe Tharakan[2], Robert Malina[1]

[1] Hasselt University, Faculty of Business Economics, Centre for Environmental Sciences, Agoralaan building D, 3590, Diepenbeek, Belgium: kim.vreys@hotmail.com, robert.malina@uhasselt.be
[2] Université de Liège, HEC-Liège, Department of Economics, bd du Rectorat B31, B-4000, Liège, Belgium: j.tharakan@ulg.ac.be
[3] VITO, Unit of Separation and Conversion Technologies, Boeretang 200, 2400, Mol, Belgium: miet.vandael@vito.be
** corresponding author: email: sebastien.lizin@uhasselt.be*

Abstract

This article identifies the factors that, according to international experts, will have substantial effects on the future development and commercialisation of carbon capture and utilisation (CCU) technologies. A two-round online Delphi study with 15 international experts in the field of CCU enabled us to explore the main items within five impact categories: (1) benefits, (2) risks, (3) future developments, (4) demand, and (5) supply constraints. Based on the results of the Delphi study, we constructed 4 future scenarios that represent how the CCU sector could develop within 10 years, using a local scenario development workshop with 9 experts from within Flanders (Belgium) and the Netherlands. We used a deductive, explorative scenario development method, which resulted in a two-by-two scenario matrix. We find that the local experts consider the role of the government and the development of CCU costs to be the most uncertain factors and could have the highest impact on the development of the sector within the next 10 years. Our insights can be instructive for facilitating the process of scenario planning for CCU development activities. Finally, although we work with a regionally specific case study, the same method could be implemented in other regions, using the general findings from our Delphi study as a starting point for the scenario development.

Keywords

Technological foresight; Futures study; CCU; CDU; Delphi method; Scenario development

Highlights

- A Delphi study lists the main factors influencing CCU sector development
- A local scenario development workshop elicits its possible future states
- The government and CCU costs are considered the most uncertain and impactful
- The developed scenarios provide the foundation for consequent scenario planning
- We advocate for transparency and provide detailed insights into the protocol used

Declaration of interests

Declarations of interests: none

Word count:

8351 words for the main body

1. Introduction

Carbon capture and utilisation (CCU), also known as carbon dioxide utilisation (CDU), is the process of converting CO_2 emissions into building blocks for new products, like plastics and fuels [1, 2]. Even though such technologies have been around for decades, they have only recently started to gain widespread global attention [3, 4]. CCU has been brought to the forefront in relation to carbon capture and storage (CCS) as a complementary technology [5]. However, while the two concepts are technologically intertwined by the step of carbon capture, they follow very different basic motivations and logics. Whereas CCU is likely to help increase resource security, be it materials or energy, CCS was developed against the background of direct climate mitigation. In practice, however, the terms are often commingled [6].

Previous research on CCU has focused on technological development and on improving process efficiency [7-13]. This emphasis on technological advancement aims to enable CCU to compete with current conventional, fossil-fuel-based products at the same time as lowering CO_2 emissions during the production process. Besides the question of how much of the current CO_2 emissions can actually be mitigated – which existing literature is already addressing [14] – other research priorities need to be addressed and investigated. Various factors can influence the development and commercialisation process. These need to be explored in order to be able to foresee both the drivers and barriers of technological change [15-17]. As such, companies can better anticipate events in a complex and uncertain world, which might significantly improve their competitive position [18, 19].

By combining two technological forecasting methods – (1) the Delphi and (2) the scenario development technique [20] – we explore the various factors that need to be considered, examined and monitored to support the establishment of a CCU market in the next 10 years. By explaining how these factors behave and how they interact, we provide an exploration of the elements that will influence the success of companies and the environment in which they operate [21]. This will provide organisations with a starting point to investigate the feasibility and viability of different CCU routes, which is crucial for all stakeholders active in CCU development.

More specifically, we use the Delphi methodology in a first step to obtain more insights into the various aspects that can potentially impact the CCU sector. The Delphi methodology focuses on the gathering of experts' opinions in areas where little knowledge is available, in order to acquire a more concise view of the problems regarding the investigated topic [22-27]. CCU is an emerging field in which knowledge is spread out over a relatively small number of experts. We combine their insights to get a better understanding of the most important drivers and barriers of CCU technologies. Consequently, we provide an overview of (1) important benefits that could arise if large-scale adoption and implementation of the technology would occur in the future; (2) critical risk issues of the technology (these are scarcely mentioned and often limited to negative environmental impacts of the technologies); and (3) important future developments (the CCU market is still in its early stages and we want to examine whether there is a general consensus about what developments can be expected in the market within the next 10 years); finally, we investigate which factors will hinder these evolutions in terms of (4) demand and (5) supply.

The results of the Delphi study are the foundation for the second step, which is scenario development. This step targets the construction of different images for the future of the CCU sector and will allow organisations to focus on long-term strategic thinking, enhancing their ability to be more proactive and, thus, acquire an important advantage over their competitors [19]. Using an explorative, deductive scenario development method, we construct four diverging scenarios in an expert workshop. More specifically, we use a combination of scenario tools including the impact/uncertainty matrix, influence-diagrams and scenario axis, to structure discussions and to map participant's opinions and thoughts [28]. We used a case-study approach for this step, involving experts within Flanders (Belgium) and the Netherlands. Both regions are considered favourable regions for the development of CCU activities, both in terms of CO_2 availability and the potential for CO_2 utilisation [29]. Besides, these regions have a long history of fruitful cooperation taking the form of a cross-border industrial cluster for the chemistry sector.

We will start with a concise introduction to the CCU concept and an overview of relevant literature, bundling existing knowledge on the various factors impacting the development of CCU technologies. We then discuss the methodological implications of the combination of the Delphi study and the scenario development in more detail, because extensive outlines of the process and different steps are often missing or not well documented in the existing literature. We illustrate the process with the direct application to the topic of CCU technologies. The last part of the paper consists of the results of both parts, followed by a discussion on the business and policy implications of our findings and the general conclusion of our work.

2. Overview of CCU and the relevant literature

The CCU process consists of three main steps: (1) the capturing of CO_2, (2) the purification and conversion of CO_2 to useful ground material, and (3) the utilisation of the converted CO_2. Step (1) focuses on the capturing of CO_2 from either flue gases, for example from existing power plants, or directly from the air [30]. Where the former has a cost advantage, since CO_2 is present with a higher concentration in flue gases, an advantage of the latter is that it can also target mobile emission sources, such as cars and airplanes. In step (2), the CO_2 will be transformed by breaking the bonds between carbon and oxygen atoms and by forming new bonds with certain reactants, thereby forming new ground materials [31]. For the last step (3), the transformed CO_2 is used as a building block in various end applications, such as the production of polymers, fuels, building materials, chemical intermediates, etc. [32]. Note that we do not aim to provide a technical overview of all the different CCU pathways; we merely want to show the diversity.

Previous research on CCU has focused on developing and enhancing specific parts of the technological processes [5, 7-13]. Besides the focus on technological innovations, past literature has tried to gather a comprehensive overview of the different CCU routes and their corresponding environmental impact, with the main focus being on the amount of CO_2 emissions being mitigated, although other environmental impacts such as acidification potential and human toxicity potential have also been included [2, 33-35].

Additionally, research efforts have been made to elucidate other non-environmental impacts that CCU technologies might have on society; these elements can act as important driving forces behind its development. As mentioned above, CCU can provide an economic benefit to companies, given that CO_2 can be used to produce saleable products [9, 36]. Furthermore, employing CCU technologies would present new job opportunities [37, 38] and could possibly actuate a lower reliance on (imported) fossil fuels for energy needs as well as grid balancing [38, 39]. Some applications could help lower the carbon footprint of end-products, even if the overall impact to CO_2 mitigation is limited [40].

Although the commercialisation of CCU technologies could produce a considerable amount of benefits, there are still various challenges and risks that need to be overcome before large-scale implementation can be achieved. Most risks considered in the literature focus on possible negative environmental impacts and technological risks [6, 33, 41, 42]. The main technological challenge originates from the high thermodynamic stability of CO_2, which requires high energy levels to overcome [43]. To manage this issue, catalysts such as zinc (Zn) and cobalt (Co) are being used, although this can form an obstacle considering the limited performance and lifetime of many catalysts and the fact that they are often sourced from geo-politically unstable regions, which can possibly cause supply security issues [39, 44-46]. Other risks include the high costs associated with CO_2 capture and the overall poor economic viability, due to the low price of the end products [38, 39, 47-49], the large dependence on hydrogen [50] and the limited sequestration [41, 51, 52].

Research regarding the future of CCU technologies and their potential end-applications has been limited. Most of the important future developments indicated by the literature involve the improvement of process efficiencies and reduction of investment costs, both of which will be necessary to establish economically feasible CCU routes. Large-scale applications of CCU capturing and processing are expected, with a current need for more demonstration units [5].

More general visions of the future of CCU and the implementation in a larger energy mix can be found within project reports from industry and governmental organisations. There, the main focus is on examining the CO_2 emission removal potential of CCU technology options. In particular, the CCU option to make fuels, under names such as CO_2 derived fuels, synthetic fuels, liquid hydrocarbon fuels and electrofuels is often cited [50, 53]. It is argued that this route would provide a way of reducing CO_2 emissions from mobile emissions sources that are otherwise hard to decarbonise [54]. However, for the system to be environmentally feasible it needs to be fed with renewable energy to remain a low-carbon application, since the conversion of CO_2 into fuels is energy-intensive, generating additional carbon emissions when using fossil fuels as energy source. Moreover, a system for direct air capture needs to be put in place to make the process carbon-neutral, which will create a carbon loop. Otherwise, a large amount of CO_2 will still be emitted into the atmosphere, which does not solve the transportation emission problem [31].

With these considerations in mind, we aim to capture and reflect on existing knowledge regarding the difficulties and driving forces behind CCU technologies. A thorough questioning of experts' viewpoints on these topics will give us an overview of the issues impacting the development and commercialisation of CCU technologies and provide us with future directions in which the sector can evolve.

3. Methodology

This research has two main goals: (1) to obtain an overview of the critical issues related to CCU technologies, and (2) to establish the interrelationships of these factors in a specific case study. We have chosen two qualitative methods – the Delphi methodology and scenario development technique – as a guideline to reach this end result. These methods have been linked previously as a promising way not only of providing an isolated observation of key impact factors, but to additionally determine the interactions between these factors [20, 55-57]. This combination enhances the validity of the data by structurally identifying key factors using a pool of independent experts from different backgrounds, which decreases the possibility of overlooking important trends, increasing the credibility of the scenario exercise [55, 57].

The Delphi methodology is a qualitative research method developed by the RAND Corporation in the 1950s [58] that uses multiple questionnaires to reach consensus within a group of experts in a selected field. Other qualitative methods such as interviews and focus groups would have proven too expensive and time-consuming considering the global spread of CCU experts. The scenario development has the objective of further investigating the relationships between the different factors. Given that these relationships are very context-specific, we worked with a case study in the Flanders/Netherlands region. The actual development of the scenarios happened in a workshop format with experts on CCU technologies from within the investigated region. An overview of the methodology is given in Figure 1 and is discussed in further detail in Appendix A.

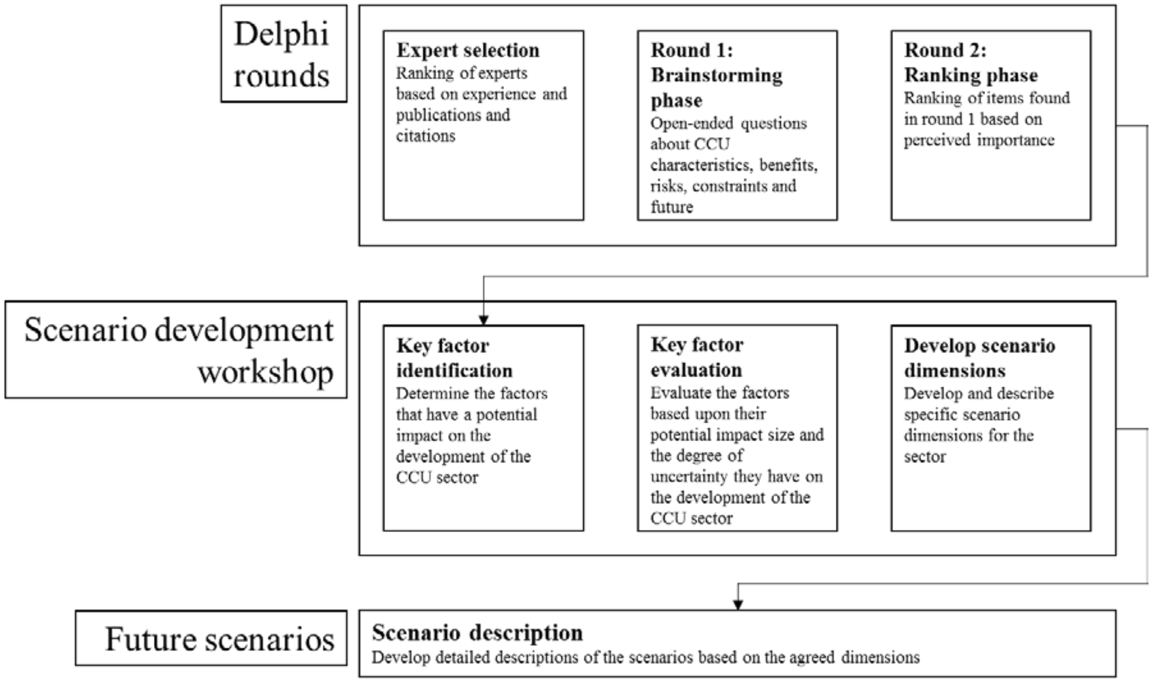


Figure 1: Methodology

4. Results

This section will give an overview of the results of both the Delphi study and the following scenario development exercise. Direct, yet anonymised, quotes from the participants translated into English can be found in italics below as an illustration. The quotes in section 4.1 are from the Delphi process and in section 4.2 from the scenario development workshops. Table 1 provides a summary of the five items that were ranked the highest in the Delphi study; a full list of the rankings can be found in Appendix B. For the impact/uncertainty exercise, the axis of each individual factor can be found in Appendix C.

4.1. Delphi

4.1.1. Benefits of CCU technologies

The literature indicates that the amount of CO_2 emissions that can be mitigated using CCU technologies as a whole is limited, and it was also mentioned by a few experts in the Delphi study [85]; nevertheless, it is still considered the most important benefit by overall vote. Thus, CCU can provide an opportunity to close the anthropocentric carbon cycle and allow countries or regions to reach global carbon goals. A few experts even touched upon the possibility of reversing climate change, bringing the CO_2 concentration in the atmosphere back to pre-industrial levels, albeit in the distant future with large-scale implementation of CCU.

Further benefits often presented within literature, such as the economic benefits [9, 36-38] and the possibility that CCU can enhance the energy independence for nations and regions [38, 39], were also mentioned but did not receive a top ranking in the Delphi. The experts brought forward a range of alternative benefits. CCU can contribute to the transition towards the circular economy. Kirchherr, Reike, and Hekkert (2017) [94] recently performed a systematic analysis of circular economy (CE) definitions being used in the current scholarly and practitioner discourse. Based on such an analysis they propose the following definition: “A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.". Seminal was the definition by the Ellen MacArthur Foundation (2012) [95] which reads: "[CE is] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.". The experts brought forward benefits that match elements captured by these CE definitions. For instance, CCU can contribute to the transition towards the CE by using existing synergies due to the coupling of different sectors. It can act as a replacement for carbon sources such as fossil fuels and biomass-based feedstocks, which makes it possible to minimize the extraction of finite natural resources and eliminate the debate on fuel versus food. Furthermore, CCU can provide a storage option for renewable energy, supporting the transition of the energy system to a system with high penetration of renewable energy sources. CCU development can also supply many technological opportunities adaptable for small- and large-scale applications and numerous product possibilities. Moreover, under the condition that atmospheric carbon can be captured, CCU can provide an abundantly available, almost endless reserve of carbon.

"CCU can help enable a circular economy that holds the possibility to create economic, social and health benefits. Until a circular economy is reality, CCU can provide an important storage option for renewable energy. As long as we are not able to fully close the carbon cycle, CCU is an important way to provide a source of carbon and to replace fossil carbon sources. I don't consider the mitigation effect of CCU as too high; volumes of CO_2 that can be fixated through CCU are far too small compared to the emissions produced, mainly by power generation." [participant X]

In addition, several benefits comparing CCU technologies to CCS practices were expressed, such as the possibility of CCU to overcome social and technical issues of CCS. Contradictorily, CCU was also mentioned as a means of providing a learning opportunity to get to CCS.

"I think that the close link between CCU and CCS is not helpful. CCU has unique opportunities and it shouldn't be named in the same breath as CCS all the time."[participant Y]

Rank	Benefits
1	CO_2 mitigation
2	Enable/contribute to the circular economy
3	Replacement for current carbon sources
4	Provide technological opportunities
5	Provide an abundantly available source of carbon

Rank	Risks
1	Micro-economic risks
2	Regulatory risks
3	Technological risks
4	Strategic behaviour risks
5	Increased reliance on fossil fuels

Rank	Future developments
1	Optimizations/improvements of CCU processes
2	Cost reduction
3	Commercialization of first large-scale processes
4	Increased integration
5	Regulatory actions supporting the implementation of CCU

Rank	Demand constraints
1	High product price
2	Low prices of substitutes
3	Poor communication about CCU technologies
4	Storage constraint
5	Lack of instruments differentiating CCU products from conventional products

Rank	Supply constraints
1	Financial constraints
2	Regulatory constraints
3	Technological constraints
4	Competition with other (emerging technologies)
5	Lack of consumer demand

Table 1: Top 5 ranking based on perceived importance (1=highest - 5=lowest)

4.1.2. Risks of CCU technologies

The costs of CCU technologies were viewed as the biggest risk for CCU technologies, which was also confirmed in the literature [38, 47-49]. Regulatory risks were ranked second. These results could stem from a large number of factors, such as a lack of support measures, legislation that would prevent the use of CO_2 for CCU or the slow development of regulatory law. Technological risks, which are often the main focus in current literature [43], were ranked third, with the mention of the high energy requirements of the CCU process. Further factors mentioned were the strategic behaviour of competitors, as CCU could lack lobbying power due to a large amount of small, geographically scattered technology development efforts, and the risk of an increased reliance on fossil fuels due to the expected environmental benefits. CCU may give policymakers and laypeople a false sense of security, leading to a misplaced reliance on fossil fuels, possibly even a rebound effect where the use of fossil fuels actually increases. This could also slow down the push for cleaner and renewable energy sources. Additional risks supplied by the experts consisted of the risk of overestimating CCU potential, which could lead to greenwashing and other social risks with a focus on the acceptance by consumers, industry and researchers of CCU technologies.

“It is necessary to get industry into action and that on a global scale; otherwise, production will move. Changes of regulations are mandatory to increase the willingness of participation.” [participant Z]

4.1.3. Future developments

Answers to this topic consisted of both specific technological developments and more generic trends applicable to all technologies. Several experts supplied suggestions about which capturing and utilisation options would be further developed in the future. With regard to the capturing methods, developments of direct air capturing processes and methods to capture CO_2 from industrial plants were mentioned. The latter was almost unanimously voted to be the technology that would capture the most CO_2 in the next 10 years and be the most beneficial for companies to invest in. The utilisation options ranged from fuels, microalgae, chemicals, mineralisation and polymers to combinations with hydrogen and energy storage plants. Polymers, combinations with hydrogen and mineralisation were deemed to most likely be commercialised on a large scale within the next 10 years. The most important global trends consisted of the optimisation and improvements of CCU processes. A wide range of statements were provided regarding increasing the efficiency of CCU processes by, for example, new solvents, better reactors, new technologies and improved capturing and conversion processes. A second important future development is a predicted reduction in the costs with respect to the different steps in the capturing, conversion and utilisation of CO_2 over the next 10 years. This indicates that experts expect the estimated economic risks to decrease in the future. Other future developments, such as the commercialisation of the first large-scale processes and an increased integration, are also deemed important. This integration was mentioned as the integration of the carbon capture step and the utilisation step into one process, the integration with renewable energy generation and the industrial integration of CCU technologies into manufacturing processes.

"A flagship project showcasing the abilities of CCU will be a door opener for many industries. Further advances and integration of different industry sectors are key to enabling CCU."[participant A]

Additionally, a number of regulatory actions are predicted to take place in the next 10 years; for example, CCU will be accepted as part of the circular economy and products made from CO_2 will be officially recognized as being renewable.

4.1.4. Demand constraints

The demand constraints provided by the experts indicated both consumer and producer demand constraints. Because the constraints related to producer demand are highly related to the supply constraints, which were also questioned, we opted to merge the producer demand constraints and the supply constraints into one list and form a separate list for consumer demand constraints.

Unsurprisingly, a high product price and low prices of substitutes were deemed as the most important demand constraints. The high cost of CCU technologies, mentioned previously, can lead to a high product price. However, it has also been predicted that costs will be reduced in the next 10 years, reducing the impact of this constraint. Poor communication about CCU technologies, its processes and its end-products also ranked high. For example, while there are no health risks involved with using captured CO_2 in the production of matrasses, consumers still perceive a certain risk level, which could be countered by supplying them with extra information about CO_2 and its properties [86]. Other demand constraints were the prospect that many products would have CO_2 binding or fixation time that was too short for consumers to see them as CO_2 emission mitigation, and a lack of differentiation instruments to separate them from fossil-fuel-derived commodities. CCU products have no guaranteed unique selling proposition, no certified label on the horizon, and there is currently no financial incentive to purchase them.

"Low prices for fossil resources are by far the most important constraint in my view – this one goes hand in hand with a rather high product price compared to non CCU alternatives."[participant B]

4.1.5. Supply constraints

Many similarities can be found between the risks and the supply constraints of CCU technologies. The top ranked items are the same, with financial, regulatory and technological constraints, respectively. Likewise, the supply of CCU technologies and its end-products could be hindered by competition with substitutes like fossil fuels, CCS and solar energy, depending on the strategic behaviour of competitors. Other supply constraints were a lack of consumer demand, due to the factors mentioned above, a lack of integration with industrial parks, and macro-economic constraints such as the delocalisation of CO_2 intensive industry to other countries with fewer restrictions. Considering that most of these factors resemble their counterparts in the risk section, we opted to merge the two into one list for the scenario development exercise.

4.2. Scenario development

4.2.1. Impact/uncertainty exercise

4.2.1.1. Benefits/drivers

The participating experts found that the premise of CCU contributing to CO_2 emission mitigation could greatly impact the development of the sector. However, only the large-scale implementation of CO_2 as an energy storage system can effectively bring about significant reductions in CO_2 emissions, ideally with a cyclical process. This means that while CO_2 can be used to store excess renewable energy by transforming it into fuels, the CO_2 emissions from fuel combustion would need to be captured afterwards from the air to close the carbon cycle. By using CO_2 in combination with excess renewable energy, it can be employed as a means to counter fluctuations in the energy system, preventing a fossil backup. Nevertheless, the participants believed that the amount of renewable energy available would be insufficient for the system to make sense in the imposed time limit of 10 years. A 20-year period was deemed more realistic for CO_2 as an energy storage mechanism to be commercially ready, which makes the next 10 years crucial for its development and scaling up. Experts indicated a large degree of uncertainty regarding the role of CCU as CO_2 mitigation system because of influencing factors such as government regulations concerning CCU and renewable energy developments.

“As long as renewable energy is scarce, CCU could be something to avoid the need for a fossil backup in winter times, for example, so this could be a form of energy storage on a large scale, but that is also immediately the precondition, that it is possible on a large scale to make it economically viable.”[participant C]

“As long as you talk about the use of CO_2 as an input for plastics, organic compounds, it means nothing in terms of mitigation. It only starts to mean something when you are going to use it for energy storage, so transforming it to fuels, liquid chemical energy storage.” [participant D]

The need for a cyclic process does not necessarily mean that CCU will make a large contribution to the advancement of the circular economy. The experts made it clear that there are two cycles to discuss: the inorganic, technical cycle and the organic, carbon cycle. The former consists of connections between metals and non-metals and points to the recycling of product materials. The latter consists largely of carbon and hydrogen compounds and points to the use and re-use of carbon dioxide as a feedstock. CCU can largely impact the latter cycle if the right process scale for energy storage is met. Conversely, CCU has less of an impact on the former cycle. However, closing the material cycle will always require additional energy and, in this, CCU will help make the total process really cyclical. The experts, valuing the technical cycle more than the carbon cycle for the circular economy, concluded with a large degree of certainty that the link to the circular economy will have a limited impact on the development of the CCU sector.

The fact that CCU can replace current carbon feedstocks will impact the development of the sector, but not significantly in the next 10 years. On a low R&D level, a lot can happen and is happening. However, looking at the market, no major changes will occur in the short term. Nevertheless, uncertainty was deemed to be high because CCU could, under the right conditions, replace a large amount of current carbon feedstock due to the energy storage application. If the circumstances for development are right, or if fossil fuels are removed from the energy sector at a fast pace, it can speed up technological advancements. This could make the option of using CCU for energy storage viable in a shorter amount of time.

Lastly, the Delphi results indicate that technological opportunities would greatly help the development of CCU technologies, which the experts predicted –with a high degree of certainty– would have a large impact on the CCU sector.

4.2.1.2. Risks/barriers

Based on the trial workshops, the economic risks were redefined to the evolution of the costs for CCU technologies, including costs related to production, input and investment; the notion economic risks was deemed to be too broad. The experts found that the costs will greatly impact the development, commercialisation and scaling-up of CCU technologies and largely depend on the price of electricity and the price of renewable energy. Since no expert could really predict how these prices will evolve in the future, the costs were consequently ranked under the category of high uncertainty.

"Some people say that the price for electricity will become very cheap, while others say that's not going to happen at all."[participant E]

Regulation was the most commonly mentioned factor during the discussion, but it was quickly redefined by our expert group to the role of the government, considering that they are in fact deciding the extent to which certain regulations will be put in place. The group of experts voiced the opinion that government actions will significantly influence the future development of the CCU sector, but it is very uncertain how policy measures will evolve in the future. On one hand, the policies that the government instils can have a very positive impact. For example, regulations about CO_2 mitigation, combined with guidelines and policies to stimulate innovation, can accelerate the development of the sector. On the other hand, overly strict regulations or a lack of higher-level coordination (on a European level, for example) can act counterproductive. A high amount of uncertainty was noted on the grounds that a lot of external trends can influence policy makers. For example, policy measures in other parts of the world and in other industries, market prices of energy, and lobby groups can all affect the way regulations are put in place.

"It's a global problem [cfr. CO_2 mitigation], trans-boundary, where governments, local, national, European and even on a world level, are involved. That provides a large amount of uncertainty because you don't know what exactly which government can or must do." [participant F]

The experts did not fully agree on the impact and uncertainty concerning the strategic behaviour of competitors. Competition could arise from numerous industrial sectors, such as fossil fuel companies, the battery sector and the bio-based economy. Some experts predicted that their behaviour would have significant impacts – both positive and negative – on the sector in the future, while others leaned more towards the lower side of the axis, noting that CCU can have an impact upon so many industries that it seems impossible for competitors to counter all the efforts the sector makes to grow.

Experts had a high degree of certainty that the risk of CCU leading to an increased reliance on fossil fuels was something that would not influence the sector.

4.2.1.3. Future developments

All of the future developments that were mentioned in the workshop were placed in the high-impact-low-uncertainty square. The participating experts all agreed that CCU processes would be further optimized, predicting a higher level of integration with renewable energy generation process development in the future and a more diverse product spectrum. The experts had no doubt that these trends will all positively impact the development of the CCU sector and occur in the next 10 years.

“The optimization will be there and it will have a high impact with very large certainty.” [participant X]

4.2.1.4. Demand constraints

The experts voted that product price will have a large impact on the development of the CCU sector and they were moderately to highly uncertain about the way this factor would develop. However, the participants were not certain about how the price will develop; this depends on various external factors such as government actions, the price of renewable energy and market fluctuations.

The experts did not agree on the impact and uncertainty regarding communication about CCU technologies. Some were of the opinion that it will have a very high impact on the sector and pointed to the issues with onshore CCS applications that were quickly deemed to be unfavourable as a CO_2-mitigating strategy and to the case of CCU mattresses, which certain consumer groups were reluctant to buy after finding out they were made with CO_2 [86, 87]. The parallel with the public reluctance towards windmills was also mentioned. A clear link was made between the government and the opinion of the general public; the latter partly determines how the former sets up its policies, which in turn influences the direction of the industry.

“The crowd will steer policy makers, the policies will steer the industry, the technology; it’s the determining link.”[participant Y]

With regard to the sequestration, in parallel to the discussion on CO_2 mitigation and the circular economy, the point was made that if the carbon cycle is restored, it is not relevant how long the CO_2 is stored in a product. Hence, experts were very certain that this factor would not play a large role in the development of the sector.

Differentiation instruments can have a high impact on the development of the sector, but the experts were not certain about how those instruments would evolve over the next 10 years. The experts did not have a clear vision of how to include a label for CCU products, considering that products would not be different from existing ones. The use of a carbon footprint was mentioned as a possible way to differentiate CCU products. However, some experts were of the opinion that it would not have much impact on CCU development since a label only appeals to a small percentage of the general public.

“I think it will only count for a certain percentage [of the population], I think that there are undoubtedly studies available for various products and that one can draw a parallel to CCU products. A certain percentage of the population is willing to pay more if there is a certain label on it and I don’t think that percentage will differ from that for other products.” [participant Z]

4.2.2. Future scenarios

Figure 2 displays the central tendency for each factor of the impact/uncertainty exercise for the sake of legibility. The size of the boxes in Figure 2 is irrelevant as they reflect the length of the label attributed to the factor inside the box, only their relative position matters. The original plots, as obtained by expert vote, are given in Appendix C. The bigger the cloud displayed therein, the more the experts’ opinions varied. Based upon this plot, two factors were chosen as the framework for the scenario building. The experts thought the role of the government, the development of the costs and the CO_2 mitigation potential were the most uncertain factors and could have the highest impact on the development of the sector. The experts choose the role of the government and the development of the costs as the two factors for the scenario axis because the factor CO_2 mitigation potential was deemed to be closely related to the role of the government. The extreme values that were chosen to form four distinct scenarios were: stimulating government–unstimulating government, and high costs–low costs. Below are the four scenarios with the description based on the elements raised by the experts during this exercise, followed by some illustrative, anonymised quotes in italics.

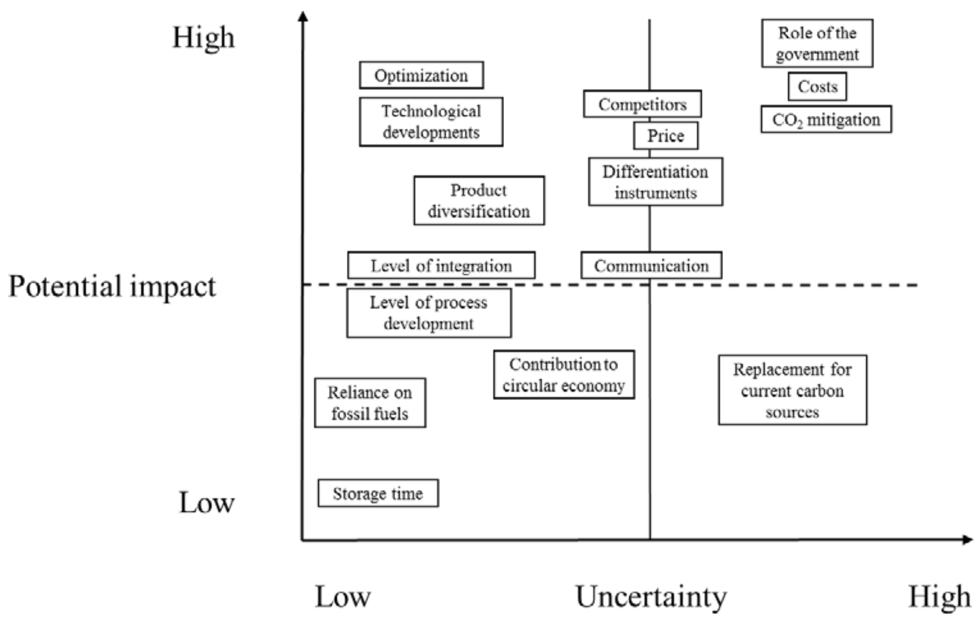


Figure 2: Impact/uncertainty matrix

4.2.2.1. Scenario 1: Stimulating government–High costs: *"CCU purgatory"*

This scenario represents a world where international, national and local governments are highly supportive of the CCU sector and take initiative by subsidising the sector and by creating a stable investment climate. However, the support measures prove to be insufficient due to a lack of R&D results and industry take-up. Simultaneously, cost developments in the energy market (such as oil, renewable energy) are unsupportive of CCU sector development. Consequently, technology costs remain high and the industries are reluctant to choose CCU related production methods above their conventional alternatives.

"Only subsidizing isn't sustainable; at a given moment the subsidies are withdrawn and we can again end up with a scenario of high costs." [participant A]

"After a certain amount of time, the industry needs to take over. The subsidies will need to gradually fade out while the industry needs to cooperate and take over." [participant B]

"Everybody expects renewable energy to become cheaper; however, it could very well be that this doesn't happen and then we are in a high cost situation." [participant C]

4.2.2.2. Scenario 2: Stimulating government–Low costs: *"CCU paradise"*

This is a world in which governments and industry work together to successfully establish the CCU sector. The government creates a well communicated, structured vision, where decisions regarding policy measures are based on a well-defined techno-economic framework. The same strategy is taken up by the industry, leading to an increase in R&D efforts, important technological breakthroughs and the development of energy efficient processes. Attention is directed towards communication to the general public and the implementation of valuable product-differentiation methods, leading to increased public take-up.

"Communication, awareness and differentiation are important to get the crowd going and the government can definitely play a role there." [participant D]

"If renewable energy becomes cheap, there is no excuse anymore against a change over, so those who stick to the old way of working could get a penalty." [participant E]

"There is a risk that the government will focus on one technology, which proves to be the wrong route; then the whole development process needs to be started over." [participant F]

"A cooperative industry leads to lower costs, but it can also be the lower costs that will convince the industry to cooperate." [participant X]

4.2.2.3. Scenario 3: Unstimulating government–High costs: *"CCU hell"*

In this scenario, the focus of governmental policies and actions lies elsewhere. Governments subsidise other technologies and other industries (fossil fuels, health industry, etc.). Industry initiatives decrease due to the lack of support measures and the lack of R&D, resulting in persisting high technology costs and price, thereby further averting possible investors. Consumers are not on board because of the high prices, which further leads governments to direct their attention elsewhere. External factors such as a (CCS) scandal and the continuing high price of renewable energy can also lead the CCU sector into this situation.

"Standing still is going backwards." [participant Y]

"If there is a change in government and the new one has a different view on CCU issues, it can work unstimulating." [participant Z]

"The industry can hinder development by not doing anything themselves, or by only buying [CO_2] rights abroad." [participant A]

"The consumer will disengage because of the high costs and the government will reflect their movement." [participant B]

4.2.2.4. Scenario 4: Unstimulating government–Low costs: *"Saint industry"*

This is a world in which the industry manages to establish a growing CCU sector despite an unstimulating government. A lack of governmental support, combined with the stimulation and protection of other existing industries, seriously hinders the development of the sector. Due to extensive efforts and perseverance from the CCU industry and technological breakthroughs, the industry succeeds in lowering the costs for CCU products, leading to consumers' take-up, which further increase the economies of scale. External events such as the fuel sector turning to CCU fuels, the rise of fusion or thorium reactors or rising petroleum prices could also allow the industry to end up in this scenario.

"This could only happen with an enormous amount of luck." [participant C]

“If the fuel sector switches to CCU, that could lead to the low costs because of economies of scale.” [participant D]

“If the industry can put a CCU product on the market on a large scale, the costs will automatically be under control and the government will then have less of a say in the interaction between companies and consumers.” [participant E]

5. Discussion

The CO_2 mitigation potential of CCU technologies remains one of the most important themes to discuss and examine. Although the experts of the Delphi indicated this as one of the most important benefits for CCU technologies, it became clear from the workshop that a whole series of conditions needs to be met in order to reach a viable end-concept. Ideally, in the product design phase the process would be set up in such a way that a carbon loop would emerge; otherwise, only a very limited amount of CO_2 would be mitigated [88]. We noted that another important benefit would be the replacement of current fossil carbon feedstock, which could, ultimately, affect the environment positively. If these rather taxing preconditions are not met, the viability of the CCU concept would suffer, reducing the chances of CCU being taken up in the portfolio of environmentally friendly production techniques.

Regarding the scenarios, our results indicate that the future of the CCU sector will largely depend on the actions of three major players: the government, the industry and the consumers. The direction in which these players focus their efforts and actions will ultimately determine how far the CCU sector will develop by 2030. Scenarios 1 and 2 represent situations where the government takes action in favour of the CCU sector, but with varying success. Scenario 2, ‘CCU paradise’, would be the dream scenario for all who take up CCU technologies in their production processes. Sufficient governmental support will provide them with opportunities to lower costs, guide technological innovations and enhance consumer acceptance. While such a future may seem unreachable right now, well-thought-out and precise actions may make it significantly more feasible within the next decades. For the sector to move towards this situation, the construction of an overarching framework for further evaluation of the different CCU routes is necessary to guide policy and industry initiatives. This framework, based on thorough techno-economic and life cycle analysis (LCA)-based assessments [89, 90], for example, will provide clarity regarding which CCU technologies are most advantageous to be implemented in the existing markets. Industries can use such frameworks to evaluate different technologies, guiding R&D efforts towards the most promising routes, which will increase the chances of technological breakthroughs and lowering technology costs. The government can further stimulate this trend by supporting R&D efforts and by providing supporting regulatory actions. Furthermore, the framework could be used in the communication towards end-consumers, by providing overarching guidelines for the environmental evaluation of the production processes, increasing the credibility of the claim that the products are more environmentally friendly.

In Scenario 1, ‘CCU purgatory’, the government fails in its attempts to establish the CCU sector. The participants of the workshop illustrated this situation with the case of biomass. There the government subsidised the technology for a certain period and did not put the right follow-up processes in place. This for instance led to the situation where many biomass power plants are no longer operational [91]. With a lack of research results, companies are unable to lower the costs of operation before the subsidies from the government disappear, leading them back to the high-cost situation and making them unable to survive in the highly competitive industries. This scenario could become reality for the sector by 2030 if the correct government and industry actions are not taken. Further research into government actions and their effects on industry efforts and extensive dialogue between the two parties will provide a more guided insight into the best way to design these supporting measures in a sustainable way. These discussions can also provide the foundation for the evaluating framework mentioned in the previous paragraph.

In Scenarios 3 and 4 the government is unsupportive of the development of a CCU sector, which has far-reaching consequences. Scenario 3, 'CCU hell', represents the worst-case scenario. Not only does the government not cooperate but the industry also appears unwilling to take the lead. The participants indicated that this scenario would mean the end of the CCU sector in the long run. To avoid ending up in this situation, actions from government and industry are necessary. A governmental shift in focus, away from the fossil fuel industry towards the renewable-energy industry, could open up funding for research efforts crucial to instigate CCU industry growth. Here, the CCU industry has the task of ensuring that it fits within the renewable energy picture, providing environmentally friendly production processes. Besides the government and the industry, the lack of consumer support was also mentioned. We saw several methods that could influence consumer behaviour, such as the use of differentiation-instruments and consumer communication efforts. Although the differentiation instruments could have a high impact on the development of the sector, we saw that there was still an average amount of uncertainty concerning this factor. Further research into the effectiveness of environmental labels and how to link them to CCU products could provide better insights into their possible implementation. Focussing on how to bring CCU products to the end-consumers could allow the sector to move from scenario 3 to one of the low-cost scenarios.

The experts considered Scenario 4, 'Saint industry', the least likely scenario. This scenario also represented a lack of governmental support. Without its support, intensive and far-reaching technological developments would need to occur in the next 10 years in order for the sector to have any chance of moving to this scenario. According to the participants, while this period may be too short for the sector to grow to this scenario, 20 or 30 years would be a more feasible time frame without having to exceed the technological and financial limits of CCU companies.

We can conclude that the participants have intuitively reaffirmed that institutional change is at the heart of the transformation process, as firms not only compete over the market but also to gain influence over the institutional framework. Such an influence seems to be a precondition for rapid take-off to occur afterwards. The conditions under which such a growth phase takes place seems to be very difficult to accurately predict [92], hence the added value of scenario development.

Given the different visions on the future of CCU, organisations involved in CCU activities can use these results and recommendations as a starting point in a subsequent scenario planning exercise, where the goal is to build and evaluate its strategic options [19, 93]. After identifying a company's desired future scenario, it can start mapping the changes it needs to make to move towards that scenario. A company must figure out what the different scenarios mean for its organisation, which strategic options are necessary to reach the desired scenario, and what option is the best given its current resources.

Methodologically, we clearly described how the Delphi methodology was merged with a scenario development workshop in order to enhance forecasting credibility. While examples can be found that use this combination of methods, we were surprised by the lack of practical details, which are important to consider when applying both methods. Thus, by providing a detailed explanation and overview of key lessons learned, see Appendix A, of the research process with all the different steps that are necessary to come to a well-founded result, supplemented with a case study, we have provided a transparent protocol for upcoming sectors and new technologies that can be used as a basis for long-term strategy thinking, enhancing the understanding of the external environment with which they will be confronted. Yet, we would like to note that our protocol is not intended to be prescriptive. We do not wish to claim that subsequent studies in which Delphi's are combined with scenario development workshop should be executed exactly like ours in all cases. There are many different 'useful' protocols for accomplishing a Delphi study [65]. We merely advocate for more transparency in this regard.

6. Conclusion

The aim of this paper was to create an overview of critical factors that can influence the development and implementation of CCU technologies in existing and emerging production streams, and also to predict how these factors will interact in the future. By using a combination of the Delphi methodology and scenario development techniques, we were able to structurally bring together knowledge on the subject gathered from global and local experts within the CCU sector.

The Delphi results show that the main selling point for CCU technologies remains the potential CO_2 emission reduction, although the scenario exercises and the literature review do mention stringent preconditions that need to be met for this benefit to be reaped. Other benefits, such as CCU replacing current carbon feedstocks while providing an abundantly available source of carbon, will help avoid the depletion of finite natural resources.

Furthermore, we discovered important risks that can seriously hinder the establishment of CCU technologies. High costs, a lack of supporting regulation and technological setbacks were indicated as barriers that could prevent CCU pathways from making it to the market successfully. However, numerous advancements are being made in the technological process. Experts predict that their development will increase at a fast pace in the next 10 years with higher levels of optimisation and commercialisation. The integration with renewable energy was also seen as an important development in the future, where CCU can, for example, act as an energy storing system.

We further explored the interaction between the Delphi factors by gathering experts' opinions on their impact and uncertainty. This allowed us to separate the factors that will have a high impact on the development of the sector – such as the government, cost development, technological developments and the behaviour of competitors – and factors that will have a low impact on the sector, such as the contribution to the circular economy, sequestration and the dependence on fossil fuels. Four possible scenarios for the CCU sector in 2030 were created based on two high-impact factors with large uncertainty: the role of the government and cost development.

The most appealing scenario 'CCU paradise' is characterised by a strong cooperation of industry and government; together they establish a structured vision about the direction in which they want the sector to evolve and about how they will manage this. This structured vision is well communicated towards consumers, instigating opportunities for economies of scale. In the least appealing scenario 'CCU hell', government efforts are stimulating other sectors, together with failing industry initiatives due to a lack of R&D results. Without these critical elements, consumers will not be on board, which eliminates the possibility of lowering production costs.

The two other scenarios, 'CCU purgatory' and 'Saint industry', are suboptimal scenarios in which either the government or the industry takes the initiative to establish the sector, with varying degrees of success. In the case of governmental support for CCU, no matter how many subsidies the sector receives, companies are still reluctant to choose CCU related production methods when initial R&D results are unfavourable, thus not successfully establishing the sector. When the industry takes the lead for CCU development, initial start-up of the sector will move slowly, but cost reduction allows companies to sell their products at a more competitive price, leading to increased consumers' take-up. Given these possible scenarios, we see that industry and governmental initiatives and cooperation are crucial elements in the establishment of the CCU sector and thus a starting point for future research and strategy planning.

Building on the results, a more extended forecasting exercise can be made that focuses on the long-term development of CCU technologies, considering that we limited the time period to 10 years for the impact uncertainty exercise and to 2030 for the scenarios. Certain trends will not have a significant impact within this timeframe, but may have a large influence in 20 or 30 years' time, thus providing a great starting point for follow-up futures studies. Similarly, the exercise can also be made for different promising development regions. Finally, we would like to note that the study can be extended to include wider stakeholders, such as proponents of alternative solutions for CO_2 reduction, as a larger perspective might be gained on the future of CCU from an even more heterogeneous group of experts. Moreover, an alternative format to developing the scenarios can be used leading to less extreme potential future states.

Acknowledgments

We would like to thank the participants of both the Delphi study and the scenario workshop for their valuable insights. Miss Vreys would like to thank the joint UHasselt-ULg special research grant and Dr Lizin would like to thank FWO for the postdoctoral grant (12G5418N) for making this work possible. Furthermore, we acknowledge financial support from the European Fund for Regional Development through the cross-border collaborative Interreg V program Flanders-the Netherlands (project EnOp).

References

1. Styring, P., E.A. Quadrelli, and K. Armstrong, *Carbon dioxide utilisation: closing the carbon cycle*. 2014: Elsevier.
2. Hunt, A.J., et al., *Generation, Capture, and Utilization of Industrial Carbon Dioxide.* ChemSusChem, 2010. **3**(3): p. 306-322.
3. Aresta, M., A. Dibenedetto, and A. Angelini, *The changing paradigm in CO_2 utilization.* Journal of CO_2 Utilization, 2013. **3–4**: p. 65-73.
4. Al-Mamoori, A., et al., *Carbon capture and utilization update.* Energy Technology, 2017.
5. Markewitz, P., et al., *Worldwide innovations in the development of carbon capture technologies and the utilization of CO_2.* Energy & environmental science, 2012. **5**(6): p. 7281-7305.
6. Bruhn, T., H. Naims, and B. Olfe-Kräutlein, *Separating the debate on CO_2 utilisation from carbon capture and storage.* Environmental Science & Policy, 2016. **60**: p. 38-43.
7. Najera, M., et al., *Carbon capture and utilization via chemical looping dry reforming.* Chemical Engineering Research and Design, 2011. **89**(9): p. 1533-1543.
8. Khoo, H.H., et al., *Carbon capture and utilization: Preliminary life cycle CO_2, energy, and cost results of potential mineral carbonation.* Energy Procedia, 2011. **4**: p. 2494-2501.
9. Yu, K.M.K., et al., *Recent Advances in CO_2 Capture and Utilization.* ChemSusChem, 2008. **1**(11): p. 893-899.
10. Sayre, R., *Microalgae: The Potential for Carbon Capture.* BioScience, 2010. **60**(9): p. 722-727.
11. Riduan, S.N. and Y. Zhang, *Recent developments in carbon dioxide utilization under mild conditions.* Dalton Transactions, 2010. **39**(14): p. 3347-3357.
12. Kang, D., et al., *Carbon capture and utilization using industrial wastewater under ambient conditions.* Chemical Engineering Journal, 2017. **308**: p. 1073-1080.
13. Blanken, W., et al., *Optimizing carbon dioxide utilization for microalgae biofilm cultivation.* Biotechnology and Bioengineering, 2017. **114**(4): p. 769-776.
14. Mac Dowell, N., et al., *The role of CO_2 capture and utilization in mitigating climate change.* Nature Climate Change, 2017. **7**(4): p. 243-249.
15. Margolis, R. and J. Zuboy, *Nontechnical barriers to solar energy use: review of recent literature*. 2006, National Renewable Energy Laboratory (NREL), Golden, CO.
16. Yaqoot, M., P. Diwan, and T.C. Kandpal, *Review of barriers to the dissemination of decentralized renewable energy systems.* Renewable and Sustainable Energy Reviews, 2016. **58**: p. 477-490.
17. Karatayev, M., et al., *Renewable energy technology uptake in Kazakhstan: Policy drivers and barriers in a transitional economy.* Renewable and Sustainable Energy Reviews, 2016. **66**: p. 120-136.
18. Lehr, T., et al., *Scenario-based strategizing: Advancing the applicability in strategists' teams.* Technological Forecasting and Social Change, 2017. **124**: p. 214-224.
19. Schoemaker, P.J., *Scenario planning: a tool for strategic thinking.* Sloan management review, 1995. **36**(2): p. 25-50.

20. Kosow, H. and R. Gaßner, *Methods of future and scenario analysis: overview, assessment, and selection criteria*. 2008.
21. Kunc, M. and F.A. O'Brien, *Exploring the development of a methodology for scenario use: Combining scenario and resource mapping approaches*. Technological Forecasting and Social Change, 2017. **124**(Supplement C): p. 150-159.
22. Okoli, C. and S.D. Pawlowski, *The Delphi method as a research tool: an example, design considerations and applications*. Information & Management, 2004. **42**(1): p. 15-29.
23. Linstone, H.A. and M. Turoff, *The Delphi method: Techniques and applications*. Vol. 29. 1975: Addison-Wesley Reading, MA.
24. Gupta, U.G. and R.E. Clarke, *Theory and applications of the Delphi technique: A bibliography (1975–1994)*. Technological forecasting and social change, 1996. **53**(2): p. 185-211.
25. Yousuf, M.I., *Using experts' opinions through Delphi technique*. Practical assessment, research & evaluation, 2007. **12**(4): p. 1-8.
26. Schmidt, R.C., *Managing Delphi surveys using nonparametric statistical techniques*. decision Sciences, 1997. **28**(3): p. 763-774.
27. Schmidt, R., K. Lyytinen, and P.C. Mark Keil, *Identifying software project risks: An international Delphi study*. Journal of management information systems, 2001. **17**(4): p. 5-36.
28. Wulf, T., P. Meissner, and S. Stubner, *A scenario-based approach to strategic planning–integrating planning and process perspective of strategy*. Leipzig Graduate School of Management, 2010.
29. Patricio, J., et al., *Region prioritization for the development of carbon capture and utilization technologies*. Journal of CO_2 Utilization, 2017. **17**: p. 50-59.
30. Keith, D.W., *Why capture CO_2 from the atmosphere?* Science, 2009. **325**(5948): p. 1654-1655.
31. Wilson, G., et al., *A VISION for Smart CO_2 Transformation in Europe (SCOT). Using CO_2 As a Resource*. 2016, Seventh Framework Programme and European Union.
32. Initiative, T.G.C., *A Roadmap for the Global Implementation of Carbon Utilization Technologies: Transforming CO_2 from a liability to an asset at significant market scale*. 2016.
33. Cuéllar-Franca, R.M. and A. Azapagic, *Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts*. Journal of CO_2 Utilization, 2015. **9**: p. 82-102.
34. Armstrong, K. and P. Styring, *Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO_2 Emissions Reduction*. Frontiers in Energy Research, 2015. **3**(8).
35. Aresta, M., *Carbon dioxide recovery and utilization*. 2013: Springer Science & Business Media.
36. Quadrelli, E.A., et al., *Carbon Dioxide Recycling: Emerging Large-Scale Technologies with Industrial Potential*. ChemSusChem, 2011. **4**(9): p. 1194-1215.
37. Jones, C.R., et al., *What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology*. Journal of CO_2 Utilization, 2014. **7**: p. 51-54.
38. Rahman, F.A., et al., *Pollution to solution: Capture and sequestration of carbon dioxide (CO_2) and its utilization as a renewable energy source for a sustainable future*. Renewable and Sustainable Energy Reviews, 2017. **71**: p. 112-126.
39. Styring, P. and D. Jansen, *Carbon Capture and Utilisation in the green economy: Using CO_2 to manufacture fuel, chemicals and materials*. 2011, Centre for Low Carbon Futures.
40. Artz, J., et al., *Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment*. Chemical reviews, 2017.
41. von der Assen, N., J. Jung, and A. Bardow, *Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls*. Energy & Environmental Science, 2013. **6**(9): p. 2721-2734.
42. von der Assen, N. and A. Bardow, *Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study*. Green Chemistry, 2014. **16**(6): p. 3272-3280.
43. Müller, K., L. Mokrushina, and W. Arlt, *Thermodynamic Constraints for the Utilization of CO_2*. Chemie Ingenieur Technik, 2014. **86**(4): p. 497-503.

44. Arakawa, H., et al., *Catalysis Research of Relevance to Carbon Management: Progress, Challenges, and Opportunities.* Chemical Reviews, 2001. **101**(4): p. 953-996.
45. Beckman, E.J., *Supercritical and near-critical CO_2 in green chemical synthesis and processing.* The Journal of Supercritical Fluids, 2004. **28**(2): p. 121-191.
46. Fraga, E.S. and M. Ng, *A framework for the analysis of the security of supply of utilising carbon dioxide as a chemical feedstock.* Faraday discussions, 2015. **183**: p. 309-326.
47. Song, C., *Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing.* Catalysis Today, 2006. **115**(1–4): p. 2-32.
48. Lainez-Aguirre, J.M., M. Pérez-Fortes, and L. Puigjaner, *Economic evaluation of bio-based supply chains with CO_2 capture and utilisation.* Computers & Chemical Engineering.
49. Zhang, X., J.-L. Fan, and Y.-M. Wei, *Technology roadmap study on carbon capture, utilization and storage in China.* Energy Policy, 2013. **59**: p. 536-550.
50. Dimitriou, I., et al., *Carbon dioxide utilisation for production of transport fuels: process and economic analysis.* Energy & Environmental Science, 2015. **8**(6): p. 1775-1789.
51. Li, L., et al., *A review of research progress on CO_2 capture, storage, and utilization in Chinese Academy of Sciences.* Fuel, 2013. **108**: p. 112-130.
52. Mikkelsen, M., M. Jørgensen, and F.C. Krebs, *The teraton challenge. A review of fixation and transformation of carbon dioxide.* Energy & Environmental Science, 2010. **3**(1): p. 43-81.
53. Abanades, J.C., et al., *On the climate change mitigation potential of CO_2 conversion to fuels.* Energy & Environmental Science, 2017. **10**(12): p. 2491-2499.
54. The Royal Society, *The Potential and Limitations of Using Carbon Dioxide*. 2017: Royal Society.
55. von der Gracht, H.A. and I.-L. Darkow, *Scenarios for the logistics services industry: A Delphi-based analysis for 2025.* International Journal of Production Economics, 2010. **127**(1): p. 46-59.
56. Nygrén, N.A., P. Tapio, and Y. Qi, *Lake management in 2030—Five future images based on an international Delphi study.* Futures, 2017. **93**: p. 1-13.
57. Nowack, M., J. Endrikat, and E. Guenther, *Review of Delphi-based scenario studies: quality and design considerations.* Technological Forecasting and Social Change, 2011. **78**(9): p. 1603-1615.
58. Dalkey, N. and O. Helmer, *An experimental application of the Delphi method to the use of experts.* Management science, 1963. **9**(3): p. 458-467.
59. Brancheau, J.C., B.D. Janz, and J.C. Wetherbe, *Key issues in information systems management: 1994-95 SIM Delphi results.* MIS quarterly, 1996: p. 225-242.
60. Dekleva, S. and J. Zupančič, *Key issues in information systems management: a Delphi study in Slovenia.* Information & Management, 1996. **31**(1): p. 1-11.
61. Kobus, J. and M. Westner. *Ranking-type delphi studies in is research: step-by-step guide and analytical extension*. in *9th Iadis international conference*.
62. Pare, G., et al., *A systematic assessment of rigor in information systems ranking-type Delphi studies.* Information & management, 2013. **50**(5): p. 207-217.
63. Rowe, G. and G. Wright, *The Delphi technique as a forecasting tool: issues and analysis.* International journal of forecasting, 1999. **15**(4): p. 353-375.
64. Hasson, F. and S. Keeney, *Enhancing rigour in the Delphi technique research.* Technological Forecasting and Social Change, 2011. **78**(9): p. 1695-1704.
65. Mullen, P.M., *Delphi: myths and reality.* Journal of health organization and management, 2003. **17**(1): p. 37-52.
66. Hall, J.K. and M.J. Martin, *Disruptive technologies, stakeholders and the innovation value-added chain: a framework for evaluating radical technology development.* R&D Management, 2005. **35**(3): p. 273-284.
67. Goodman, L.A., *Snowball sampling.* The annals of mathematical statistics, 1961: p. 148-170.
68. Gilbart, E. and N. Kreiger, *Improvement in cumulative response rates following implementation of a financial incentive.* American journal of epidemiology, 1998. **148**(1): p. 97-99.

69. Keil, M., A. Tiwana, and A. Bush, *Reconciling user and project manager perceptions of IT project risk: a Delphi study1*. Information Systems Journal, 2002. **12**(2): p. 103-119.
70. Powell, C., *The Delphi technique: myths and realities.* Journal of advanced nursing, 2003. **41**(4): p. 376-382.
71. Corbin, J. and A. Strauss, *Grounded theory research: Procedures, canons and evaluative criteria.* Zeitschrift für Soziologie, 1990. **19**(6): p. 418-427.
72. Alwin, D.F. and J.A. Krosnick, *The measurement of values in surveys: A comparison of ratings and rankings.* Public Opinion Quarterly, 1985. **49**(4): p. 535-552.
73. Kendall, M.G. and B.B. Smith, *The Problem of m Rankings.* 1939: p. 275-287.
74. von der Gracht, H.A., *Consensus measurement in Delphi studies: Review and implications for future quality assurance.* Technological Forecasting and Social Change, 2012. **79**(8): p. 1525-1536.
75. UNEP, *Global Environment Outlook 3*. 2002. p. 320.
76. Bishop, P., A. Hines, and T. Collins, *The current state of scenario development: an overview of techniques.* foresight, 2007. **9**(1): p. 5-25.
77. Mahmoud, M., et al., *A formal framework for scenario development in support of environmental decision-making.* Environmental Modelling & Software, 2009. **24**(7): p. 798-808.
78. Van der Heijden, K., *Scenarios: the art of strategic conversation*. 2011: John Wiley & Sons.
79. Amer, M., T.U. Daim, and A. Jetter, *A review of scenario planning.* Futures, 2013. **46**: p. 23-40.
80. Börjeson, L., et al., *Scenario types and techniques: Towards a user's guide.* Futures, 2006. **38**(7): p. 723-739.
81. Van Notten, P.W., et al., *An updated scenario typology.* Futures, 2003. **35**(5): p. 423-443.
82. Siebelink, R., J.I. Halman, and E. Hofman, *Scenario-Driven Roadmapping to cope with uncertainty: Its application in the construction industry.* Technological forecasting and social change, 2016. **110**: p. 226-238.
83. van 't Klooster, S.A. and M.B.A. van Asselt, *Practising the scenario-axes technique.* Futures, 2006. **38**(1): p. 15-30.
84. Copeman, C, *Picture This - A Guide to Scenario Planning for Voluntary Organisations*. 2006: NCVO Publications.
85. Mac Dowell, N., et al., *The role of CO_2 capture and utilization in mitigating climate change.* Nature Clim. Change, 2017. **7**(4): p. 243-249.
86. van Heek, J., K. Arning, and M. Ziefle, *Reduce, reuse, recycle: Acceptance of CO_2-utilization for plastic products.* Energy Policy, 2017. **105**: p. 53-66.
87. Schrag, D.P., *Storage of carbon dioxide in offshore sediments.* Science, 2009. **325**(5948): p. 1658-1659.
88. Goeppert, A., et al., *Recycling of carbon dioxide to methanol and derived products–closing the loop.* Chemical Society Reviews, 2014. **43**(23): p. 7995-8048.
89. Thomassen, G., et al., *A review of the sustainability of algal-based biorefineries: Towards an integrated assessment framework.* Renewable and Sustainable Energy Reviews, 2017. **68**: p. 876-887.
90. Carlsson Reich, M., *Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC).* Journal of Cleaner Production, 2005. **13**(3): p. 253-263.
91. Negro, S.O., R.A.A. Suurs, and M.P. Hekkert, *The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system.* Technological Forecasting and Social Change, 2008. **75**(1): p. 57-77.
92. Jacobsson, S. and V. Lauber, *The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology.* Energy Policy, 2006. **34**(3): p. 256-276.
93. O'Brien, F.A. and M. Meadows, *Scenario orientation and use to support strategy development.* Technological Forecasting and Social Change, 2013. **80**(4): p. 643-656.
94. Kirchherr, J., Reike, D. and Hekkert, M. *Conceptualizing the circular economy: An analysis of 114 definitions*. Resources, Conservation and Recycling, 2017. **127**: p. 221-232.

95. Ellen MacArthur Foundation. *Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition.* (2012) Available at https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

96. Hasson, F., Keeney, S. and McKenna, H. *Research guidelines for the Delphi survey technique.* Journal of Advanced Nursing, 2000. **32**(4): 1008-1015

97. Rowe, G. and Wright, G. (2001). Expert opinions in forecasting: the role of the Delphi technique. Principles of forecasting, Springer**:** p.125-144

98. Melander, L., Dubois, A., Hedvall, K. and Lind, F. *Future goods transport in Sweden 2050: Using a Delphi-based scenario analysis*. Technological Forecasting and Social Change, 2019. **138**: 178-189)

99. Gordon, T. and Pease, A. *RT Delphi: An efficient, "round-less" almost real time Delphi method*. Technological Forecasting and Social Change, 2006. **73**(4): 321-333.

100. Loo, R. *The Delphi method: A powerful tool for strategic management*. Policing, 2002.25(4), 762-769

Appendices

A. Methodology

A.1. Delphi

The Delphi method uses multiple questionnaires to reach a larger amount of consensus within a group of experts in an investigated field. A widely used definition is that of Linstone and Turoff (1975) [23], which describes the Delphi as:

"A method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem." (Linstone and Turoff, 1975, p. 3)

The process is managed by using consecutive questionnaires, also known as 'rounds', each aiming to get a larger amount of consensus on a certain topic. A further characterisation of different Delphi-types is given by Pare et al. (2013) [62], who divided the Delphi method into four categories: (1) The Classical Delphi, where the goal is to create consensus; (2) the Policy Delphi, which aims to define and differentiate views; (3) the Decision Delphi, used to prepare and support decisions; and (4) the Ranking-type Delphi, which identifies and ranks key issues. Given that the aim of the present research was to determine the key factors that will influence the development of the CCU sector, it falls into the last category (Ranking-type Delphi) [59, 60]. Figure 1 provides an overview of the consecutive phases we followed to identify the different impact factors and to move towards a final ranking; these phases were (1) participant selection, (2) a brainstorming phase and (3) a ranking phase. Note that these stages can be different depending on the research objectives; for example, although the brainstorming phase was present originally, it is often replaced by a literature review to form the list of items necessary for ranking. For supplementary information on the other methodological options, we refer to the vast amount of literature dedicated to this subject [22, 23, 26, 61-65].

A.1.1. Expert selection

The first phase of our Delphi study consisted of expert selection. The goal was to identify the experts who possess the largest amount of knowledge on CCU technologies. We followed a purposive sampling method, based upon the work of Okoli and Pawlowski (2004) [22], in which we personally selected the experts because it was imperative that the participants would consist of a range of experts from different sectors involved with the CCU sector. We identified four different categories of primary stakeholders wherein a large amount of expertise is concentrated: (1) experts from universities, (2) experts from government organisations, (3) experts from research centres and (4) experts from industry (both for-profit and non-profit organisations) [66]. Through a literature review that included academic research papers, conference material and institutional reports, we were able to establish a list of influential organisations and the affiliated experts involved in the CCU sector. We chose to not limit our expert range in the Delphi part to the case study region that we set out for the scenario development part; this allows the transferability of the Delphi findings as a start for scenario building in other regions.

Selection criteria for the final experts were (1) the number of publications and citations for the experts associated to universities and (2) the years of experience with CCU technology for the other categories. In order to obtain a broad range of opinions, we included experts such as engineers, scientists, project managers, CEOs and directors.

The initial list of experts consisted of 132 professionals distributed over the four established categories. Within the invitation we asked participants to identify other specialists who would be able to provide insightful knowledge on the subject of CCU technology, a form of snowball sampling [67]. After the first list, we were able to put together a second list of 108 professionals, based upon further research and experts' suggestions. In total we contacted 240 experts for participation in the first round, with a response rate of 15 per cent (36 experts). In the invitation we mentioned that if they participated in all rounds they would be able to win one of three €50 gift cards from Amazon; such financial incentives are often used to raise response rates [68]. The second round was sent out to the participants of the first round and resulted in a response rate of 42 per cent. We find that 15 respondents is within what is considered acceptable in terms of panel size based on numbers proposed in e.g. Loo (2002) [100] and Rowe and Wright (2001) [97] for heterogeneous panels. 15 is a small, yet acceptable number in terms of Delphi panel size given that the quality of the obtained data is ensured via a proper protocol. Participants' characteristics, such as gender, work organisation and years of experience, can be found in Table A.1. Looking at the participants of both rounds, we see that the most prominent regions developing CCU technologies are accounted for with participants from large players such as Germany and the United States [5, 29]. Furthermore, all four categories that we set out to include in the study are represented. This heterogeneity leads to having a wider scope [97] and hence facilitates both a more systemic evaluation and a fairer balance between being knowledgeable and impartial compared to a more homogenous panel. Exposure to subject bias cannot, however, be fully avoided, which is considered a strength in consensus building, yet restricts the findings to what a group of participants considers important in relation to that topic [74].

Participant characteristics	**Round 1 (n = 36)**	**Round 2 (n = 15)**
Gender		
Male	27	11
Female	9	4
Work organization		
Independent research institute	9	5
Educational institution	8	2
For profit organization	7	4
Non-profit organization	7	2
Government or government agency	4	2
Other (combination of above)	1	0
Country		
United States	9	3
Germany	7	4
France	4	2
Netherlands	3	2
Belgium	2	1
Finland	2	1
Canada	2	0
United Kingdom	2	0
Denmark	1	1
Norway	1	1
Greece	1	0
Spain	1	0
Singapore	1	0
Years of experience		
≤ 5	9	2
6 - 10	14	5
11 - 15	5	3
16 – 20	7	5
> 21	1	0

Table A.1: Participants' characteristics

A.1.2. Design of Round 1

The first round of a Delphi study is often a brainstorming round in which open-ended questions are used with the aim of obtaining a better view of the most important issues of a subject [26]. There have been cases where the first Delphi round consisted of a list of issues selected from the literature and participants were asked to directly rank these issues, thus skipping the brainstorming phase [69], although questions have been raised about the possible negative effect arising with the researcher selecting the items [65, 70].

Our questionnaire for Round 1 consisted of two parts. The first part contained general socio-demographic questions such as gender, age, country of residence, education level and experience with CCU technology. The second part existed of five open-ended questions targeting the most important impacts and constraints of CCU technologies:

1. What are the most important benefits of CCU technologies?
2. What are the most important risks of CCU technologies?
3. What are the most important future developments of CCU technologies?
4. What are the most important constraints that can hinder future demand of CCU technologies?
5. What are the most important constraints that can hinder future supply of CCU technologies?

Respondents were asked to provide at least three important items (for example, benefits) for each question. They were also encouraged to describe each item or to give an example with their answer to clarify their exact meaning. A definition of each investigated concept was added to the questions to ensure that each concept was interpreted the same way by all respondents (for example, “A benefit is an advantage, a helpful or good effect of something.”).

A.1.3. Design Round 2

The second round of a Delphi study is composed of a list of items, based on the statements made in the first round. The participants are asked to rank the items in terms of their perceived importance directly in which the lowest number is deemed most important [23]. Since we opted to have a brainstorming phase for the first round of our Delphi, we gathered a large amount of qualitative data. Grounded theory was used to form the items used in the second questionnaire [71]. This process involved conceptualising the different statements within one topic and then categorising them and forming distinct items from them. Two researchers were involved in the processing of the qualitative data to increase the validity of our findings.

The statements gathered in Round 1 provided us with 12 benefit items, 12 risk items, 11 future developments, 8 consumer demand constraints and 12 supply constraints. To the question of demand constraints, both answers regarding the constraint of consumer demand and the constraint of industry demand were given. Given that the statements given as industry demand constraints and industry supply constraints widely matched, we merged these statements to form the item list of supply constraints.

The second questionnaire consisted of four ranking exercises of the different item categories, as well as some additional questions, and was sent out at the end of July 2017. We selected a simple ranking exercise in which participants were asked to rank the items in terms of their importance via a drag-and-drop system. A rating scale would have led to experts only judging a certain item and could often create a situation in which every item is considered ‘very important’, which would not result in the differentiation we intended to establish between the items [72]. Following each question was a response space where participants could provide additional comments on their ranking of the items or on the meaning of individual items.

Once an initial ranking of the items has been received, a Delphi study can end or there can be another ranking round with additional information about the different items, such as the mean, the previous choice of the participant or comments given by the different experts concerning their ranking [62]. The goal of performing another round would be to reach a higher amount of consensus, which is often measured with Kendall’s W coefficient of concordance [26, 62, 73]. Stopping criteria for the Delphi process have also been developed; these include stopping when Kendalls’ W reaches a value higher than 0.7, stopping after three rounds, or stopping when the mean rankings for two successive rounds have not shown a significant improvement based on the McNemar test [74].

A low amount of consensus was noted at the end of the second round, with an average Kendall's W of 0.3. The respondents consisted of a small heterogeneous, globally distributed group of experts on a topic that still has an uncertain future, so it was expected after Round 1 that consensus would be hard to reach. Furthermore, although they were encouraged to comment, not many experts used this option to support their rankings of the different items, providing few arguments that could convince experts to change their ranking in a third round. A third round might even have decreased response rates further, so we decided to stop our Delphi survey after two rounds in spite of low consensus. Nowadays it is much less typical to aim at consensus in the Delphi process, although most of the Delphi literature focuses on it. Lately, the Delphi method is being used to increase the quality of scenario development by helping to contrast constructive disagreement among stakeholders [74]. The Delphi study was formatted using Qualtrics software (Qualtrics, Provo, UT) and distributed online. The invitation to participate in the first round of the Delphi was sent out in May 2017. Data was collected during 2 months. The invitation to participate in the second round of the Delphi was sent out in July 2017. Data was collected during 3 months. 2 reminders were sent during each round to stimulate further participation.

The Delphi study results provide valuable input for the scenario exercise, which requires factors that can impact the CCU sector. The factors that were ranked as most important have a large amount of uncertainty around them. Consequently, these factors demand a more detailed examination regarding their impacts on the development of CCU technologies. This provides an excellent starting point for the scenario development exercise.

A.2. Scenario development

The main goal of the scenario development exercise is to further explore the impacts of the factors uncovered in the Delphi study and map their interaction. Based on this exploration, visions of the future of the CCU sector can be made. In general, scenarios can be defined as:

"Descriptions of journeys to possible futures. They reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play." (UNEP 2002, p. 320) [75]

There are different ways to categorise scenario building approaches [20, 76-79]. Two of the main distinctions that are made within scientific literature are the categorisation into exploratory and normative scenarios and the categorisation into deductive and inductive approaches. Exploratory scenarios, also called descriptive scenarios, start from the current situation. Assumptions are made about factors that lead to different pictures of possible futures. Normative scenarios start with various images of the future and paths are constructed regarding how to arrive to these futures, starting from the future and working backwards towards the present [80, 81]. Inductive methods allow the scenarios to emerge by themselves, building step by step on the available data; no overall framework is imposed. With deductive methods, an overall framework is used to start the exercise and data is fitted into the framework [78]. In this classification scheme, our scenario exercise can be considered an exploratory, deductive scenario building approach in which we aim to see how the present situation can change, what factors will be important and how they will behave, within a predetermined framework of possible futures.

More specifically, building on the result of the Delphi, which consisted of a list of critical issues essential for the integration of CCU technologies in existing and new industries, we investigate how the CCU sector could transform. We use a case study approach to develop possible scenarios that the CCU sector in Flanders/the Netherlands can face by 2030, using a workshop setting to develop the scenarios. The workshop is based on workshop designs of Wulf et al. (2010) and Siebelink et al. (2016) [28, 82]. The scenario development process followed during the workshop consisted of the four steps listed below (see Figure 1):

Step 1. Determine the factors that have a potential impact on the development of the CCU sector in the case study region.
Step 2. Evaluate the factors based upon their potential impact size and the degree of uncertainty they have on the development of the CCU sector in this region.
Step 3. Develop and describe specific scenario dimensions.
Step 4. Develop detailed descriptions of the scenarios based on the agreed dimensions.

The established scenarios describe what the industry could look like in the future and provide an exploration of the external environment in which companies would operate [21]. This allows organisations to better prepare for plausible future scenarios by evaluating whether their strategies, capabilities, resources and products are able to stand up to the challenges that will arise in the next decade. Organisations starting in or working with CCU technologies can use these scenarios for creating strategy and evaluating their current resources.

A.2.1.Workshop design – Before the workshop

The aim of the workshop was to construct four scenarios for the development of the CCU sector in Flanders and the Netherlands. Before the official workshop we had two trial workshops; one, with fellow researchers, focused on testing the methodology and the tools for the scenario development exercise. For the second trial workshop we asked several CCU experts to establish if everything was clear and meaningful content-wise. These experts were selected from within the authors' organisations but not involved in this project. These trial versions gave us the opportunity to fine-tune the methodology of scenario development, providing information on, for example, how to best explain the Delphi results, which wording to use and how to incorporate it into the scenario tools. For the actual workshop, we deliberately selected a group of experts from within the case study area to participate in the scenario exercise, starting from the author's personal network of CCU experts. In total, nine experts from both Flanders and the Netherlands participated in the workshop, two from industry organisations, one from a research institution, two from academia, two from the government and two from consultancy agencies.

Participants were informed about the workshop in person and were sent an e-mail invitation to the workshop, called '*The realisation of CCU in the Flemish-Netherlandish context*'. It was indicated that the total duration of the workshop would be four hours. Attached to the invitation they received an overview of the four most important factors per topic examined in the Delphi survey.

A.2.2. Workshop process – During the workshop

A team of four researchers was present at the actual workshop, which consisted of two moderators and two note-takers. The moderators, whose role was to guide the workshop and the discussions, started with an explanation of the different process steps, the tools that would be used for each step, and the result that could be expected at the end of the workshop. Before starting with the scenario development process, there was an introduction round in which respondents stated their name and affiliated organisations. During this introduction, participants were also asked to sign a consent form, which stated the purpose of the workshop and advised that the workshop would be audio-recorded.

Following the introduction, we (the moderators) continued with Step 1, where we elaborated on the results of the Delphi study. We selected 16 items from the Delphi study that were ranked highest among the different topics. For simplicity reasons we grouped the results into four categories: (1) drivers, (2) barriers containing both risk and supply constraints, (3) future developments and (4) factors that can constrain the demand for CCU technologies. For each of the categories we discussed the four most important factors, based on those indicated in the Delphi study. Items that were mentioned in more than one category were only included under the first category it was mentioned in; for the other categories, the fifth item on the list was included. We supplied participants with both the items and the explanation given by the experts in the Delphi. The experts then had the opportunity to supply other important factors or trends that had not been mentioned.

After presenting the results of the Delphi and the subsequent discussion of extra factors, we moved on to Step 2, for which we used the impact/uncertainty matrix [28, 83, 84] that consists of two axes. The vertical axis ranged from low potential impact to high potential impact, for which we asked participants how much a certain factor could possibly impact the development of the CCU sector in the next 10 years, keeping in mind that this impact could be positive or negative. If the impact on the development could potentially be high, the factor would be placed in the upper half; if the impact would be low, it would be placed in the lower half of the axis. On the horizontal axis, we asked the participants to indicate how uncertain they were about the potential impact. Similar to the potential impact axis, high uncertainty on the horizontal axis would mean the expert was not at all sure about whether the expected impact would materialize, while low uncertainty would mean the expert was very sure.

For each factor, participants first debated the position they would give to the factor by arguing why they thought it belonged in a certain quadrant. They were all then asked to locate the factor on the matrix with a token indicating their final view on the impact and uncertainty of that factor. It was not necessary to reach consensus in this step, so multiple quadrants could contain tokens. However, the quadrant containing the most tokens was picked as the final placement; see Figure A.1 for an illustration of the axis.

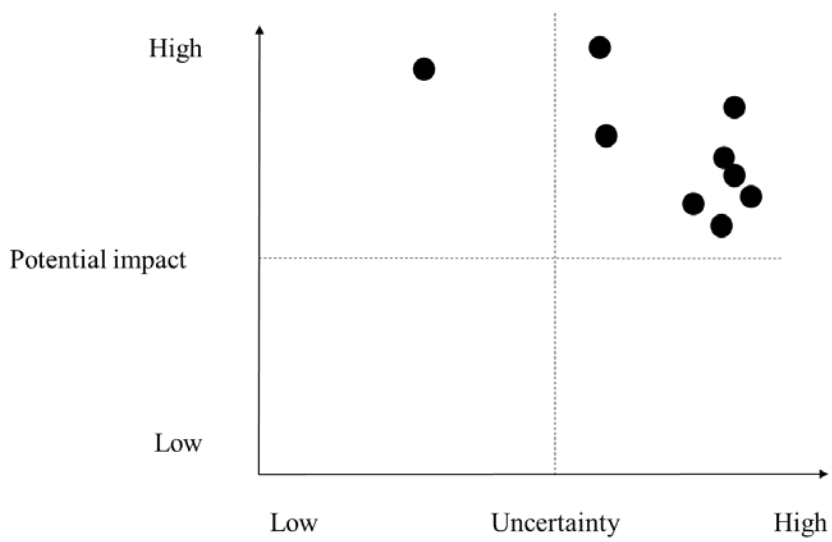


Figure A.1 impact/uncertainty axis for cost development

Step 3 was the formation of scenario dimensions, the goal of which was to form the framework for four distinct future scenarios. For the scenario dimensions, two factors from the ‘high-impact-high-uncertainty’ quadrant are chosen, considering that these factors need further investigation before a company can begin to form a plan on how to deal with them. Both factors are given two extreme values (for example, for the ‘cost development’ factor this could be: high costs versus low costs). This enabled us to draw a two-by-two matrix, which is commonly used in scenario building to visualise significantly different alternative future business environments that can arise [78]. The experts decided which two factors they wanted to use as scenario dimensions and the extreme values assigned to them.

The final part of the workshop, Step 4, consisted of describing and narrating the different scenarios. This was done by generally asking which factors could lead the sector to this situation in 2030 and what the consequences would be for the CCU sector if we did arrive at this scenario in 2030. To allow the participants to structure their ideas, we introduced the influence-diagram as a method to visualise the connections between the various factors and trends that had been brought forward. Despite the introduction, the tool was not used by the experts themselves; instead, for each of the scenarios they presented influencing factors, while one of the moderators then grouped them together by topic and built the influence diagram and narrative based on the connections verbally indicated by the experts. Afterwards, the moderators verified that they all agreed with the results and made the necessary adjustments.

In this process participants could fall back on the factors and the previous discussions from Step 2. As a starting point we used the scenario in which the sector was located at the moment, what factors would cause the sector to still be in this scenario by 2030 and the accompanying implications. By doing this, participants explored which factors play a role in shaping the future of CCU, and this provided a baseline for the influence diagrams of the other scenarios.

A.2.3. Workshop analysis – After the workshop

After the workshop, we sent a follow-up e-mail to all the participants, thanking them for their contribution and explaining to them what the next steps are. For the analysis of the workshop, we first started by transcribing the audio recording. We recorded the whole workshop and had note-takers present as a back-up, providing us with an abridged transcript in case something went wrong with the audio recording. For the impact/uncertainty exercise, all statements made regarding a single factor (such as the cost development) were gathered. For each factor, we then divided the statements into statements related to the potential impact and statements related to the uncertainty. Finally, a general description was formed for each item, based on the location of the item and the arguments made by the experts. For the scenario building exercise, the influence diagrams from the workshop were used to narrate the different scenario descriptions. These were then extended with explanatory information from the transcript and checked for internal inconsistencies [19].

A.3. Lessons learned from implementing the proposed protocol

Based on our experience, we would like to provide the following practical lessons learned. Firstly, it is challenging to establish the credibility of the researcher and by consequence of the research. This is even more the case without a prior track record or reputation in the knowledge area - here this was CCU- to which the Delphi or scenario development method will be applied. Therefore, we advise research teams to devote considerable effort to gaining access to a network within the knowledge area and incentivize participation to the Delphi and/or scenario development by means of for example: (a) truthful and detailed revelation of the protocol and as such the expected effort from the respondents, but also of the fact that they will be receiving input from an expert group with similar, yet not identical expertise; (b) a personal invitation on the phone followed up by an e-mail, instead of only sending out email invitations to participate to the research; (c) asking for commitment prior to sending out the invitation to participate [98]; or (d) providing other stimuli like gift cards, first-hand insight into the study's results, or by already describing ways for the participants to use the outcomes of the study to which they participate.

Secondly, quality control is strongly recommended and running a pilot test of the Delphi survey and the scenario development workshop is indispensable. We suggest separate, consecutive pilot tests with experts in the methodology and with experts in the knowledge area to verify the perceived appropriateness and duration of the protocol. This judgement will at least help to increase the face validity of the research.

Thirdly, be prepared to invest in the timely follow-up of non-respondents and in not letting respondents that have answered to the first round(s) of the Delphi go cold by sending out reminders and by providing fast feedback. We could have improved our drop-out rate by converting the traditional Delphi into a real-time Delphi [99]. Also here we want to stress that e-mail reminders are easier to ignore than a phone call followed up by an email.

Fourthly, to successfully organize a scenario development workshop a date should be fixed well in advance. To facilitate doing so, the following routine can be used. Call potential participants to find a couple of dates suitable to a critical mass. Create a doodle (or similar planning tool) with limited options. Send it out to the full list of purposefully selected potential participants. Take attrition into account when deciding upon the number of people that you invite.

Finally, make sure the moderator(s) is (are) sufficiently supported during the workshop to enable them to focus on the content and not on the logistics such as having the supporting material to present the format (e.g. the beamer, the clicker, a flip chart, …) and to develop and save the results of the workshop (e.g. an audio-recorder, a camera, a flip chart, …) or the coffee break. Make sure the moderator is trained in facilitating group discussions and as such is impartial, constructive and able to open up and close the dialogue.

B. Full rankings of Delphi exercise based on perceived importance

Rank	Benefits
1	CO_2 mitigation
2	Enable/contribute to the circular economy
3	Replacement for current carbon sources
4	Provide technological opportunities
5	Provide an abundantly available source of carbon
6	Provide a storage option for renewable energy
7	Economic benefits
8	Enhance energy independence for nations/regions
9	Overcome issues of CCS
10	Health benefits
11	Social benefits
12	Provide a learning opportunity to get to CCS

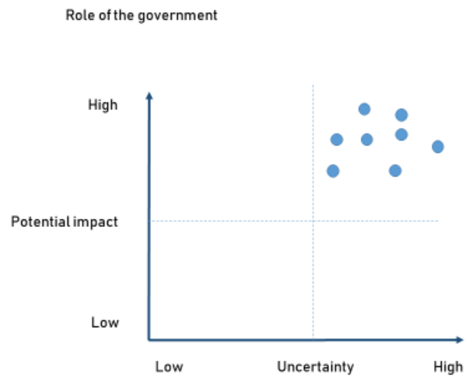
Rank	Risks
1	Economic risks
2	Regulatory risks
3	Technological risks
4	Strategic behaviour risks
5	Increased reliance on fossil fuels
6	Overestimation of CCU potential
7	Social risks
8	Marco-economic risks
9	Climate risks
10	Overproduction risk
11	No need risk
12	Health risks

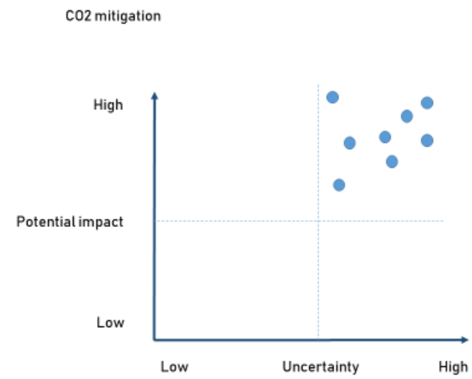
Rank	Future developments
1	Optimizations/improvements of CCU processes
2	Cost reduction
3	Commercialization of first large-scale processes
4	Increased integration
5	Regulatory actions supporting the implementation of CCU
6	Product diversification
7	Increased market demand for CCU products
8	Downgrading of fossil fuels
9	Instruments to separate low carbon-based products from conventional products
10	Better market insights
11	CCU will replace CCS

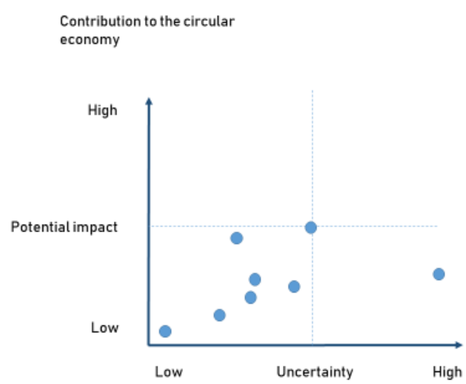
Rank	Demand constraints
1	High product price
2	Low prices of substitutes
3	Poor communication about CCU technologies
4	Storage constraint
5	Lack of instruments separating CCU products from conventional products
6	Lack of compatibility with existing applications
7	Negative technology presentation
8	Lack of public environmental consciousness

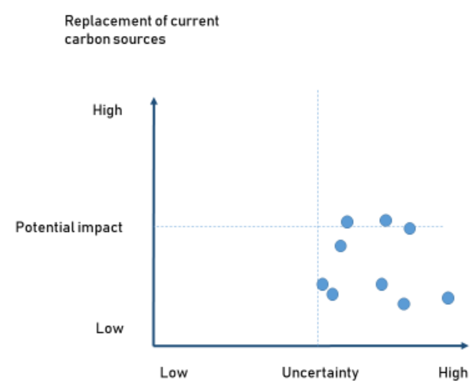
Rank	Supply constraints
1	Financial constraints
2	Regulatory constraints
3	Technological constraints
4	Competition with other (emerging technologies)
5	Lack of consumer demand
6	Lack of integration
7	Macro-economic constraints
8	Resistance from fossil producers
9	Input constraints
10	Logistics constraints
11	Storage constraint
12	Lack of communication

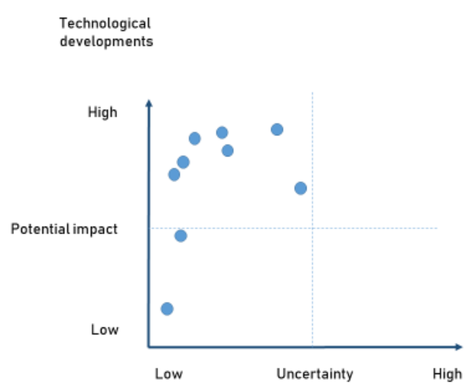
C. Impact/uncertainty exercise: result of the scenario development workshop

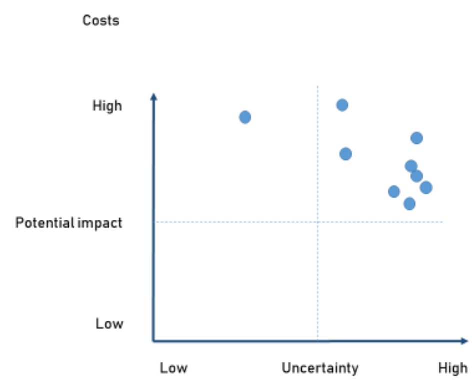


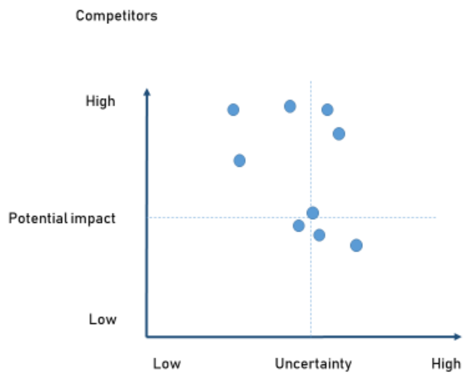


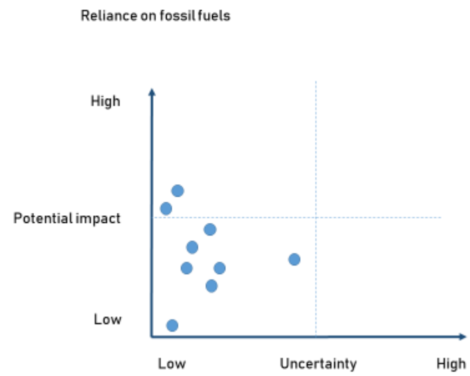


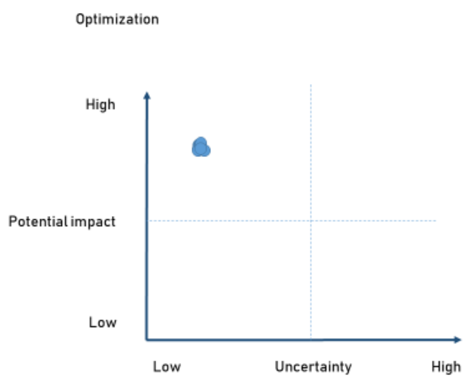


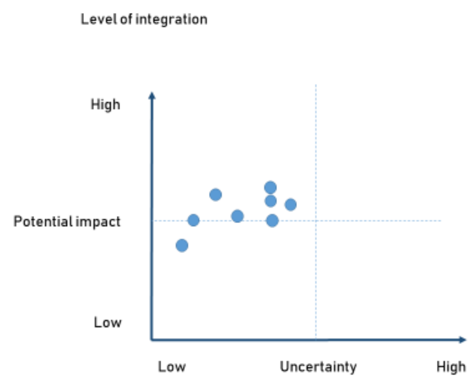


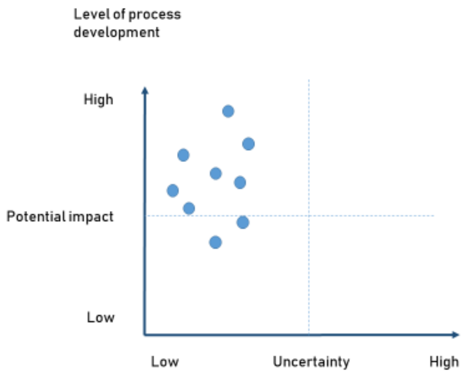


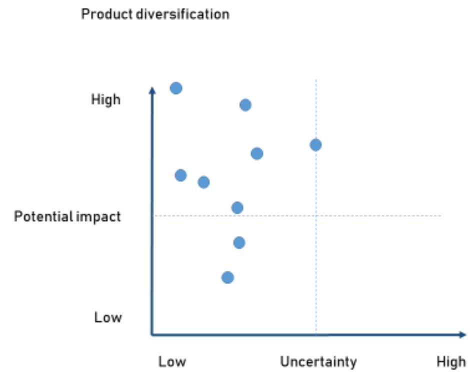

Competitors
High
Potential impact
Low
Low
Uncertainty
High


Reliance on fossil fuels
High
Potential impact
Low
Low
Uncertainty
High

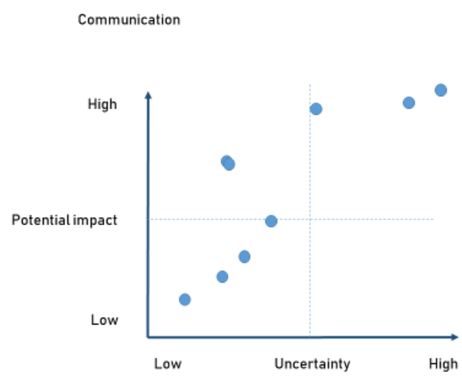

Optimization
High
Potential impact
Low
Low
Uncertainty
High

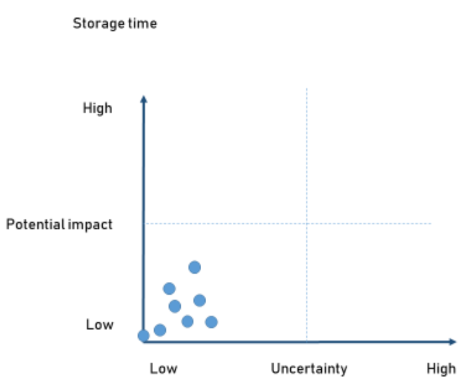

Level of integration
High
Potential impact
Low
Low
Uncertainty
High

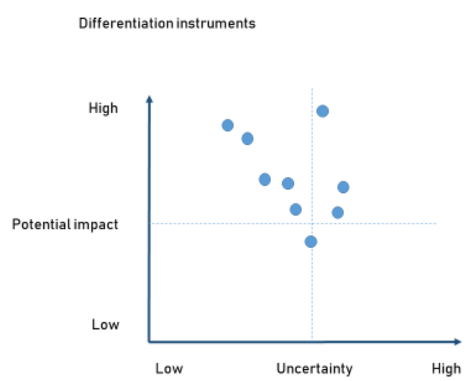

Level of process development
High
Potential impact
Low
Low
Uncertainty
High


Product diversification
High
Potential impact
Low
Low
Uncertainty
High


Product price
High
Potential impact
Low
Low
Uncertainty
High


Communication
High
Potential impact
Low
Low
Uncertainty
High


Storage time
High
Potential impact
Low
Low
Uncertainty
High


Differentiation instruments
High
Potential impact
Low
Low
Uncertainty
High