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

4
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11

12 **Abstract**

13 This article identifies the factors that, according to international experts, will have substantial effects on the
14 future development and commercialisation of carbon capture and utilisation (CCU) technologies. A two-
15 round online Delphi study with 15 international experts in the field of CCU enabled us to explore the main
16 items within five impact categories: (1) benefits, (2) risks, (3) future developments, (4) demand, and (5)
17 supply constraints. Based on the results of the Delphi study, we constructed 4 future scenarios that represent
18 how the CCU sector could develop within 10 years, using a local scenario development workshop with 9
19 experts from within Flanders (Belgium) and the Netherlands. We used a deductive, explorative scenario
20 development method, which resulted in a two-by-two scenario matrix. We find that the local experts
21 consider the role of the government and the development of CCU costs to be the most uncertain factors and
22 could have the highest impact on the development of the sector within the next 10 years. Our insights can
23 be instructive for facilitating the process of scenario planning for CCU development activities. Finally,
24 although we work with a regionally specific case study, the same method could be implemented in other
25 regions, using the general findings from our Delphi study as a starting point for the scenario development.
26

27 **Keywords**

28 Technological foresight; Futures study; CCU; CDU; Delphi method; Scenario development
29

30 **Highlights**

- 31
- 32 • A Delphi study lists the main factors influencing CCU sector development
 - 33 • A local scenario development workshop elicits its possible future states
 - 34 • The government and CCU costs are considered the most uncertain and impactful
 - 35 • The developed scenarios provide the foundation for consequent scenario planning
 - 36 • We advocate for transparency and provide detailed insights into the protocol used

37 **Declaration of interests**

38 Declarations of interests: none
39

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41 8351 words for the main body
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43 1. Introduction

44 Carbon capture and utilisation (CCU), also known as carbon dioxide utilisation (CDU), is the
45 process of converting CO₂ emissions into building blocks for new products, like plastics and fuels [1, 2].
46 Even though such technologies have been around for decades, they have only recently started to gain
47 widespread global attention [3, 4]. CCU has been brought to the forefront in relation to carbon capture and
48 storage (CCS) as a complementary technology [5]. However, while the two concepts are technologically
49 intertwined by the step of carbon capture, they follow very different basic motivations and logics. Whereas
50 CCU is likely to help increase resource security, be it materials or energy, CCS was developed against the
51 background of direct climate mitigation. In practice, however, the terms are often commingled [6].

52 Previous research on CCU has focused on technological development and on improving process
53 efficiency [7-13]. This emphasis on technological advancement aims to enable CCU to compete with current
54 conventional, fossil-fuel-based products at the same time as lowering CO₂ emissions during the production
55 process. Besides the question of how much of the current CO₂ emissions can actually be mitigated – which
56 existing literature is already addressing [14] – other research priorities need to be addressed and investigated.
57 Various factors can influence the development and commercialisation process. These need to be explored
58 in order to be able to foresee both the drivers and barriers of technological change [15-17]. As such,
59 companies can better anticipate events in a complex and uncertain world, which might significantly improve
60 their competitive position [18, 19].

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

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

80 The results of the Delphi study are the foundation for the second step, which is scenario
81 development. This step targets the construction of different images for the future of the CCU sector and will
82 allow organisations to focus on long-term strategic thinking, enhancing their ability to be more proactive
83 and, thus, acquire an important advantage over their competitors [19]. Using an explorative, deductive
84 scenario development method, we construct four diverging scenarios in an expert workshop. More
85 specifically, we use a combination of scenario tools including the impact/uncertainty matrix, influence-
86 diagrams and scenario axis, to structure discussions and to map participant's opinions and thoughts [28].
87 We used a case-study approach for this step, involving experts within Flanders (Belgium) and the
88 Netherlands. Both regions are considered favourable regions for the development of CCU activities, both in

89 terms of CO₂ availability and the potential for CO₂ utilisation [29]. Besides, these regions have a long history
90 of fruitful cooperation taking the form of a cross-border industrial cluster for the chemistry sector.

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

98 2. Overview of CCU and the relevant literature

99 The CCU process consists of three main steps: (1) the capturing of CO₂, (2) the purification and
100 conversion of CO₂ to useful ground material, and (3) the utilisation of the converted CO₂. Step (1) focuses
101 on the capturing of CO₂ from either flue gases, for example from existing power plants, or directly from the
102 air [30]. Where the former has a cost advantage, since CO₂ is present with a higher concentration in flue
103 gases, an advantage of the latter is that it can also target mobile emission sources, such as cars and airplanes.
104 In step (2), the CO₂ will be transformed by breaking the bonds between carbon and oxygen atoms and by
105 forming new bonds with certain reactants, thereby forming new ground materials [31]. For the last step (3),
106 the transformed CO₂ is used as a building block in various end applications, such as the production of
107 polymers, fuels, building materials, chemical intermediates, etc. [32]. Note that we do not aim to provide a
108 technical overview of all the different CCU pathways; we merely want to show the diversity.

109 Previous research on CCU has focused on developing and enhancing specific parts of the
110 technological processes [5, 7-13]. Besides the focus on technological innovations, past literature has tried
111 to gather a comprehensive overview of the different CCU routes and their corresponding environmental
112 impact, with the main focus being on the amount of CO₂ emissions being mitigated, although other
113 environmental impacts such as acidification potential and human toxicity potential have also been included
114 [2, 33-35].

115 Additionally, research efforts have been made to elucidate other non-environmental impacts
116 that CCU technologies might have on society; these elements can act as important driving forces behind its
117 development. As mentioned above, CCU can provide an economic benefit to companies, given that CO₂
118 can be used to produce saleable products [9, 36]. Furthermore, employing CCU technologies would present
119 new job opportunities [37, 38] and could possibly actuate a lower reliance on (imported) fossil fuels for
120 energy needs as well as grid balancing [38, 39]. Some applications could help lower the carbon footprint of
121 end-products, even if the overall impact to CO₂ mitigation is limited [40].

122 Although the commercialisation of CCU technologies could produce a considerable amount of
123 benefits, there are still various challenges and risks that need to be overcome before large-scale
124 implementation can be achieved. Most risks considered in the literature focus on possible negative
125 environmental impacts and technological risks [6, 33, 41, 42]. The main technological challenge originates
126 from the high thermodynamic stability of CO₂, which requires high energy levels to overcome [43]. To
127 manage this issue, catalysts such as zinc (Zn) and cobalt (Co) are being used, although this can form an
128 obstacle considering the limited performance and lifetime of many catalysts and the fact that they are often
129 sourced from geo-politically unstable regions, which can possibly cause supply security issues [39, 44-46].
130 Other risks include the high costs associated with CO₂ capture and the overall poor economic viability, due
131 to the low price of the end products [38, 39, 47-49], the large dependence on hydrogen [50] and the limited
132 sequestration [41, 51, 52].

133 Research regarding the future of CCU technologies and their potential end-applications has
134 been limited. Most of the important future developments indicated by the literature involve the improvement

135 of process efficiencies and reduction of investment costs, both of which will be necessary to establish
136 economically feasible CCU routes. Large-scale applications of CCU capturing and processing are expected,
137 with a current need for more demonstration units [5].

138 More general visions of the future of CCU and the implementation in a larger energy mix can
139 be found within project reports from industry and governmental organisations. There, the main focus is on
140 examining the CO₂ emission removal potential of CCU technology options. In particular, the CCU option
141 to make fuels, under names such as CO₂ derived fuels, synthetic fuels, liquid hydrocarbon fuels and
142 electrofuels is often cited [50, 53]. It is argued that this route would provide a way of reducing CO₂ emissions
143 from mobile emissions sources that are otherwise hard to decarbonise [54]. However, for the system to be
144 environmentally feasible it needs to be fed with renewable energy to remain a low-carbon application, since
145 the conversion of CO₂ into fuels is energy-intensive, generating additional carbon emissions when using
146 fossil fuels as energy source. Moreover, a system for direct air capture needs to be put in place to make the
147 process carbon-neutral, which will create a carbon loop. Otherwise, a large amount of CO₂ will still be
148 emitted into the atmosphere, which does not solve the transportation emission problem [31].

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

154 3. Methodology

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

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

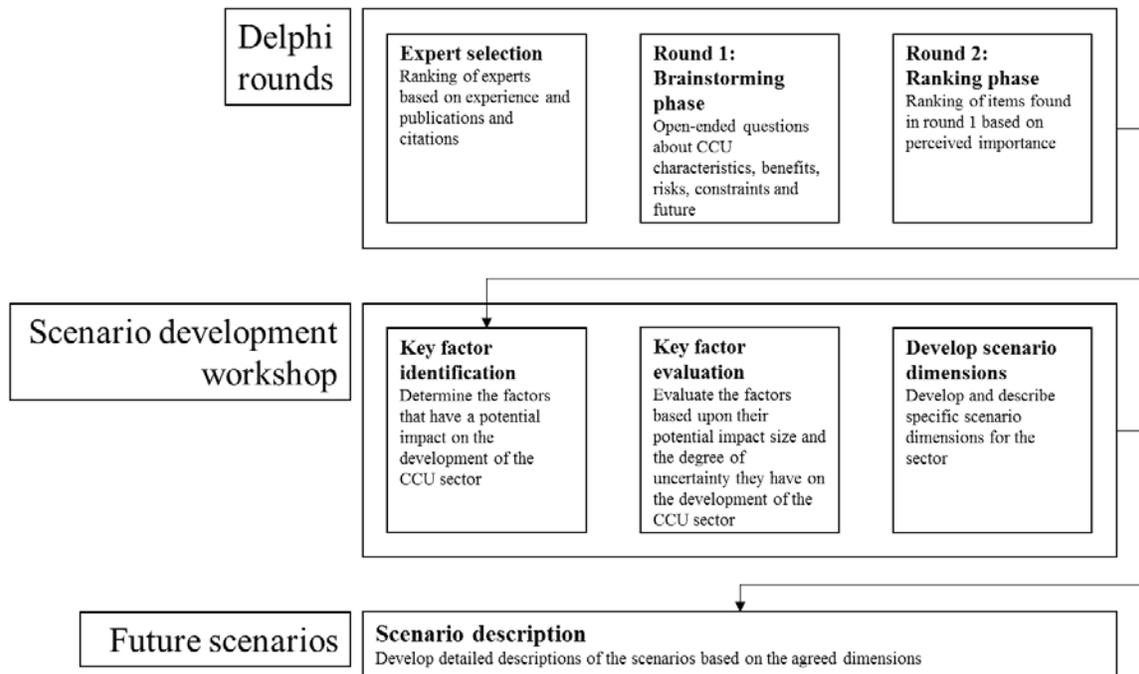
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Figure 1: Methodology

180 **4. Results**

181 This section will give an overview of the results of both the Delphi study and the following scenario
 182 development exercise. Direct, yet anonymised, quotes from the participants translated into English can be
 183 found in italics below as an illustration. The quotes in section 4.1 are from the Delphi process and in section
 184 4.2 from the scenario development workshops. Table 1 provides a summary of the five items that were
 185 ranked the highest in the Delphi study; a full list of the rankings can be found in Appendix B. For the
 186 impact/uncertainty exercise, the axis of each individual factor can be found in Appendix C.

187 **4.1. Delphi**

188 **4.1.1. Benefits of CCU technologies**

189 The literature indicates that the amount of CO₂ emissions that can be mitigated using CCU
 190 technologies as a whole is limited, and it was also mentioned by a few experts in the Delphi study [85];
 191 nevertheless, it is still considered the most important benefit by overall vote. Thus, CCU can provide an
 192 opportunity to close the anthropocentric carbon cycle and allow countries or regions to reach global carbon
 193 goals. A few experts even touched upon the possibility of reversing climate change, bringing the CO₂
 194 concentration in the atmosphere back to pre-industrial levels, albeit in the distant future with large-scale
 195 implementation of CCU.

196 Further benefits often presented within literature, such as the economic benefits [9, 36-38] and the
 197 possibility that CCU can enhance the energy independence for nations and regions [38, 39], were also
 198 mentioned but did not receive a top ranking in the Delphi. The experts brought forward a range of alternative
 199 benefits. CCU can contribute to the transition towards the circular economy. Kirchherr, Reike, and Hekkert
 200 (2017) [94] recently performed a systematic analysis of circular economy (CE) definitions being used in the
 201 current scholarly and practitioner discourse. Based on such an analysis they propose the following
 202 definition: “A circular economy describes an economic system that is based on business models which
 203 replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in

204 production/distribution and consumption processes, thus operating at the micro level (products, companies,
205 consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the
206 aim to accomplish sustainable development, which implies creating environmental quality, economic
207 prosperity and social equity, to the benefit of current and future generations.”. Seminal was the definition
208 by the Ellen MacArthur Foundation (2012) [95] which reads: “[CE is] an industrial system that is restorative
209 or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards
210 the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the
211 elimination of waste through the superior design of materials, products, systems, and, within this, business
212 models.”. The experts brought forward benefits that match elements captured by these CE definitions. For
213 instance, CCU can contribute to the transition towards the CE by using existing synergies due to the coupling
214 of different sectors. It can act as a replacement for carbon sources such as fossil fuels and biomass-based
215 feedstocks, which makes it possible to minimize the extraction of finite natural resources and eliminate the
216 debate on fuel versus food. Furthermore, CCU can provide a storage option for renewable energy,
217 supporting the transition of the energy system to a system with high penetration of renewable energy
218 sources. CCU development can also supply many technological opportunities adaptable for small- and large-
219 scale applications and numerous product possibilities. Moreover, under the condition that atmospheric
220 carbon can be captured, CCU can provide an abundantly available, almost endless reserve of carbon.

221
222 *“CCU can help enable a circular economy that holds the possibility to create economic, social and health*
223 *benefits. Until a circular economy is reality, CCU can provide an important storage option for renewable*
224 *energy. As long as we are not able to fully close the carbon cycle, CCU is an important way to provide a*
225 *source of carbon and to replace fossil carbon sources. I don’t consider the mitigation effect of CCU as too*
226 *high; volumes of CO₂ that can be fixated through CCU are far too small compared to the emissions*
227 *produced, mainly by power generation.” [participant X]*

228
229 In addition, several benefits comparing CCU technologies to CCS practices were expressed, such
230 as the possibility of CCU to overcome social and technical issues of CCS. Contradictorily, CCU was also
231 mentioned as a means of providing a learning opportunity to get to CCS.

232
233 *“I think that the close link between CCU and CCS is not helpful. CCU has unique opportunities and it*
234 *shouldn’t be named in the same breath as CCS all the time.”[participant Y]*

235

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

236

237

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

238

239 4.1.2. Risks of CCU technologies

240 The costs of CCU technologies were viewed as the biggest risk for CCU technologies, which was
241 also confirmed in the literature [38, 47-49]. Regulatory risks were ranked second. These results could stem
242 from a large number of factors, such as a lack of support measures, legislation that would prevent the use of
243 CO₂ for CCU or the slow development of regulatory law. Technological risks, which are often the main
244 focus in current literature [43], were ranked third, with the mention of the high energy requirements of the
245 CCU process. Further factors mentioned were the strategic behaviour of competitors, as CCU could lack
246 lobbying power due to a large amount of small, geographically scattered technology development efforts,
247 and the risk of an increased reliance on fossil fuels due to the expected environmental benefits. CCU may
248 give policymakers and laypeople a false sense of security, leading to a misplaced reliance on fossil fuels,
249 possibly even a rebound effect where the use of fossil fuels actually increases. This could also slow down
250 the push for cleaner and renewable energy sources. Additional risks supplied by the experts consisted of the
251 risk of overestimating CCU potential, which could lead to greenwashing and other social risks with a focus
252 on the acceptance by consumers, industry and researchers of CCU technologies.

253

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

256 4.1.3. Future developments

257 Answers to this topic consisted of both specific technological developments and more generic trends
258 applicable to all technologies. Several experts supplied suggestions about which capturing and utilisation
259 options would be further developed in the future. With regard to the capturing methods, developments of
260 direct air capturing processes and methods to capture CO₂ from industrial plants were mentioned. The latter
261 was almost unanimously voted to be the technology that would capture the most CO₂ in the next 10 years
262 and be the most beneficial for companies to invest in. The utilisation options ranged from fuels, microalgae,
263 chemicals, mineralisation and polymers to combinations with hydrogen and energy storage plants.
264 Polymers, combinations with hydrogen and mineralisation were deemed to most likely be commercialised
265 on a large scale within the next 10 years. The most important global trends consisted of the optimisation
266 and improvements of CCU processes. A wide range of statements were provided regarding increasing the
267 efficiency of CCU processes by, for example, new solvents, better reactors, new technologies and improved
268 capturing and conversion processes. A second important future development is a predicted reduction in the
269 costs with respect to the different steps in the capturing, conversion and utilisation of CO₂ over the next 10
270 years. This indicates that experts expect the estimated economic risks to decrease in the future. Other future
271 developments, such as the commercialisation of the first large-scale processes and an increased integration,
272 are also deemed important. This integration was mentioned as the integration of the carbon capture step and
273 the utilisation step into one process, the integration with renewable energy generation and the industrial
274 integration of CCU technologies into manufacturing processes.

275
276 *“A flagship project showcasing the abilities of CCU will be a door opener for many industries. Further
277 advances and integration of different industry sectors are key to enabling CCU.”[participant A]*

278
279 Additionally, a number of regulatory actions are predicted to take place in the next 10 years; for
280 example, CCU will be accepted as part of the circular economy and products made from CO₂ will be
281 officially recognized as being renewable.

282 4.1.4. Demand constraints

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

287 Unsurprisingly, a high product price and low prices of substitutes were deemed as the most
288 important demand constraints. The high cost of CCU technologies, mentioned previously, can lead to a high
289 product price. However, it has also been predicted that costs will be reduced in the next 10 years, reducing
290 the impact of this constraint. Poor communication about CCU technologies, its processes and its end-
291 products also ranked high. For example, while there are no health risks involved with using captured CO₂
292 in the production of mattresses, consumers still perceive a certain risk level, which could be countered by
293 supplying them with extra information about CO₂ and its properties [86]. Other demand constraints were
294 the prospect that many products would have CO₂ binding or fixation time that was too short for consumers
295 to see them as CO₂ emission mitigation, and a lack of differentiation instruments to separate them from
296 fossil-fuel-derived commodities. CCU products have no guaranteed unique selling proposition, no certified
297 label on the horizon, and there is currently no financial incentive to purchase them.

298
299 *“Low prices for fossil resources are by far the most important constraint in my view – this one goes hand
300 in hand with a rather high product price compared to non CCU alternatives.”[participant B]*

301 4.1.5. Supply constraints

302 Many similarities can be found between the risks and the supply constraints of CCU technologies.
303 The top ranked items are the same, with financial, regulatory and technological constraints, respectively.
304 Likewise, the supply of CCU technologies and its end-products could be hindered by competition with
305 substitutes like fossil fuels, CCS and solar energy, depending on the strategic behaviour of competitors.
306 Other supply constraints were a lack of consumer demand, due to the factors mentioned above, a lack of
307 integration with industrial parks, and macro-economic constraints such as the delocalisation of CO₂
308 intensive industry to other countries with fewer restrictions. Considering that most of these factors resemble
309 their counterparts in the risk section, we opted to merge the two into one list for the scenario development
310 exercise.

311 4.2. Scenario development

312 4.2.1. Impact/uncertainty exercise

313 4.2.1.1. Benefits/drivers

314 The participating experts found that the premise of CCU contributing to CO₂ emission mitigation
315 could greatly impact the development of the sector. However, only the large-scale implementation of CO₂
316 as an energy storage system can effectively bring about significant reductions in CO₂ emissions, ideally
317 with a cyclical process. This means that while CO₂ can be used to store excess renewable energy by
318 transforming it into fuels, the CO₂ emissions from fuel combustion would need to be captured afterwards
319 from the air to close the carbon cycle. By using CO₂ in combination with excess renewable energy, it can
320 be employed as a means to counter fluctuations in the energy system, preventing a fossil backup.
321 Nevertheless, the participants believed that the amount of renewable energy available would be insufficient
322 for the system to make sense in the imposed time limit of 10 years. A 20-year period was deemed more
323 realistic for CO₂ as an energy storage mechanism to be commercially ready, which makes the next 10 years
324 crucial for its development and scaling up. Experts indicated a large degree of uncertainty regarding the role
325 of CCU as CO₂ mitigation system because of influencing factors such as government regulations concerning
326 CCU and renewable energy developments.

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

331 *“As long as you talk about the use of CO₂ as an input for plastics, organic compounds, it means nothing in*
332 *terms of mitigation. It only starts to mean something when you are going to use it for energy storage, so*
333 *transforming it to fuels, liquid chemical energy storage.” [participant D]*

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

344 The fact that CCU can replace current carbon feedstocks will impact the development of the sector,
345 but not significantly in the next 10 years. On a low R&D level, a lot can happen and is happening. However,

346 looking at the market, no major changes will occur in the short term. Nevertheless, uncertainty was deemed
347 to be high because CCU could, under the right conditions, replace a large amount of current carbon feedstock
348 due to the energy storage application. If the circumstances for development are right, or if fossil fuels are
349 removed from the energy sector at a fast pace, it can speed up technological advancements. This could make
350 the option of using CCU for energy storage viable in a shorter amount of time.

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

354

355 4.2.1.2. Risks/barriers

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

362

363 *“Some people say that the price for electricity will become very cheap, while others say that’s not going to*
364 *happen at all.” [participant E]*

365

366 Regulation was the most commonly mentioned factor during the discussion, but it was quickly
367 redefined by our expert group to the role of the government, considering that they are in fact deciding the
368 extent to which certain regulations will be put in place. The group of experts voiced the opinion that
369 government actions will significantly influence the future development of the CCU sector, but it is very
370 uncertain how policy measures will evolve in the future. On one hand, the policies that the government
371 instils can have a very positive impact. For example, regulations about CO₂ mitigation, combined with
372 guidelines and policies to stimulate innovation, can accelerate the development of the sector. On the other
373 hand, overly strict regulations or a lack of higher-level coordination (on a European level, for example) can
374 act counterproductive. A high amount of uncertainty was noted on the grounds that a lot of external trends
375 can influence policy makers. For example, policy measures in other parts of the world and in other
376 industries, market prices of energy, and lobby groups can all affect the way regulations are put in place.

377

378 *“It’s a global problem [cfr. CO₂ mitigation], trans-boundary, where governments, local, national,*
379 *European and even on a world level, are involved. That provides a large amount of uncertainty because*
380 *you don’t know what exactly which government can or must do.” [participant F]*

381

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

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

390

391 4.2.1.3. Future developments

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

397
398 *“The optimization will be there and it will have a high impact with very large certainty.” [participant X]*
399

400 4.2.1.4. Demand constraints

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

405 The experts did not agree on the impact and uncertainty regarding communication about CCU
406 technologies. Some were of the opinion that it will have a very high impact on the sector and pointed to the
407 issues with onshore CCS applications that were quickly deemed to be unfavourable as a CO₂-mitigating
408 strategy and to the case of CCU mattresses, which certain consumer groups were reluctant to buy after
409 finding out they were made with CO₂ [86, 87]. The parallel with the public reluctance towards windmills
410 was also mentioned. A clear link was made between the government and the opinion of the general public;
411 the latter partly determines how the former sets up its policies, which in turn influences the direction of the
412 industry.

413
414 *“The crowd will steer policy makers, the policies will steer the industry, the technology; it’s the determining
415 link.”[participant Y]*
416

417 With regard to the sequestration, in parallel to the discussion on CO₂ mitigation and the circular
418 economy, the point was made that if the carbon cycle is restored, it is not relevant how long the CO₂ is
419 stored in a product. Hence, experts were very certain that this factor would not play a large role in the
420 development of the sector.

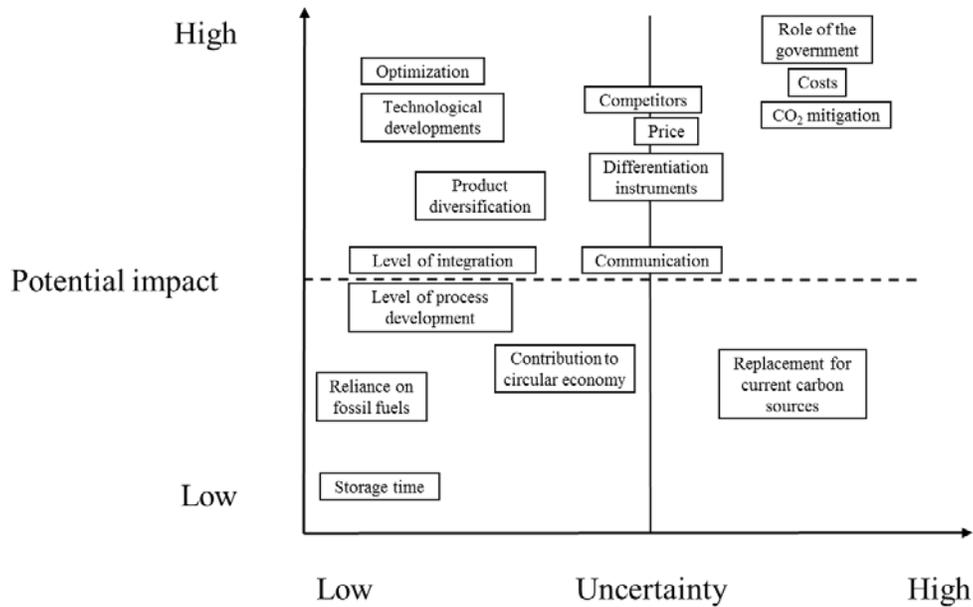
421 Differentiation instruments can have a high impact on the development of the sector, but the experts
422 were not certain about how those instruments would evolve over the next 10 years. The experts did not have
423 a clear vision of how to include a label for CCU products, considering that products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

427
428 *“I think it will only count for a certain percentage [of the population], I think that there are undoubtedly
429 studies available for various products and that one can draw a parallel to CCU products. A certain
430 percentage of the population is willing to pay more if there is a certain label on it and I don’t think that
431 percentage will differ from that for other products.” [participant Z]*
432

433 4.2.2. Future scenarios

434 Figure 2 displays the central tendency for each factor of the impact/uncertainty exercise for the sake of
435 legibility. The size of the boxes in Figure 2 is irrelevant as they reflect the length of the label attributed to
436 the factor inside the box, only their relative position matters. The original plots, as obtained by expert vote,
437 are given in Appendix C. The bigger the cloud displayed therein, the more the experts’ opinions varied.
438 Based upon this plot, two factors were chosen as the framework for the scenario building. The experts

439 thought the role of the government, the development of the costs and the CO₂ mitigation potential were the
 440 most uncertain factors and could have the highest impact on the development of the sector. The experts
 441 choose the role of the government and the development of the costs as the two factors for the scenario axis
 442 because the factor CO₂ mitigation potential was deemed to be closely related to the role of the government.
 443 The extreme values that were chosen to form four distinct scenarios were: stimulating government–
 444 unstimulating government, and high costs–low costs. Below are the four scenarios with the description
 445 based on the elements raised by the experts during this exercise, followed by some illustrative, anonymised
 446 quotes in italics.
 447



448 **Figure 2: Impact/uncertainty matrix**
 449

450 4.2.2.1. Scenario 1: Stimulating government–High costs: “CCU purgatory”

451 This scenario represents a world where international, national and local governments are highly
 452 supportive of the CCU sector and take initiative by subsidising the sector and by creating a stable investment
 453 climate. However, the support measures prove to be insufficient due to a lack of R&D results and industry
 454 take-up. Simultaneously, cost developments in the energy market (such as oil, renewable energy) are
 455 unsupportive of CCU sector development. Consequently, technology costs remain high and the industries
 456 are reluctant to choose CCU related production methods above their conventional alternatives.
 457

458 *“Only subsidizing isn’t sustainable; at a given moment the subsidies are withdrawn and we can again end
 459 up with a scenario of high costs.” [participant A]*

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

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

464 4.2.2.2. Scenario 2: Stimulating government–Low costs: “CCU paradise”
 465

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

472
473 *“Communication, awareness and differentiation are important to get the crowd going and the government
474 can definitely play a role there.” [participant D]*

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

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

479 *“A cooperative industry leads to lower costs, but it can also be the lower costs that will convince the industry
480 to cooperate.” [participant X]*

481

482 4.2.2.3. Scenario 3: Unstimulating government–High costs: “CCU hell”

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

489

490 *“Standing still is going backwards.” [participant Y]*

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

493 *“The industry can hinder development by not doing anything themselves, or by only buying [CO₂] rights
494 abroad.” [participant A]*

495 *“The consumer will disengage because of the high costs and the government will reflect their movement.”
496 [participant B]*

497

498 4.2.2.4. Scenario 4: Unstimulating government–Low costs: “Saint industry”

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

506

507 *“This could only happen with an enormous amount of luck.” [participant C]*

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

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

513 5. Discussion

514 The CO₂ mitigation potential of CCU technologies remains one of the most important themes to
515 discuss and examine. Although the experts of the Delphi indicated this as one of the most important benefits
516 for CCU technologies, it became clear from the workshop that a whole series of conditions needs to be met
517 in order to reach a viable end-concept. Ideally, in the product design phase the process would be set up in
518 such a way that a carbon loop would emerge; otherwise, only a very limited amount of CO₂ would be
519 mitigated [88]. We noted that another important benefit would be the replacement of current fossil carbon
520 feedstock, which could, ultimately, affect the environment positively. If these rather taxing preconditions
521 are not met, the viability of the CCU concept would suffer, reducing the chances of CCU being taken up in
522 the portfolio of environmentally friendly production techniques.

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

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

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

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

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

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

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

597 6. Conclusion

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

603 The Delphi results show that the main selling point for CCU technologies remains the potential CO₂
604 emission reduction, although the scenario exercises and the literature review do mention stringent
605 preconditions that need to be met for this benefit to be reaped. Other benefits, such as CCU replacing current
606 carbon feedstocks while providing an abundantly available source of carbon, will help avoid the depletion
607 of finite natural resources.

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

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

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

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

638 Building on the results, a more extended forecasting exercise can be made that focuses on the long-
639 term development of CCU technologies, considering that we limited the time period to 10 years for the
640 impact uncertainty exercise and to 2030 for the scenarios. Certain trends will not have a significant impact
641 within this timeframe, but may have a large influence in 20 or 30 years' time, thus providing a great starting
642 point for follow-up futures studies. Similarly, the exercise can also be made for different promising
643 development regions. Finally, we would like to note that the study can be extended to include wider

644 stakeholders, such as proponents of alternative solutions for CO₂ reduction, as a larger perspective might be
645 gained on the future of CCU from an even more heterogeneous group of experts. Moreover, an alternative
646 format to developing the scenarios can be used leading to less extreme potential future states.

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859 Appendices

860 A. Methodology

861 A.1. Delphi

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

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

867 The process is managed by using consecutive questionnaires, also known as ‘rounds’, each aiming
868 to get a larger amount of consensus on a certain topic. A further characterisation of different Delphi-types
869 is given by Pare et al. (2013) [62], who divided the Delphi method into four categories: (1) The Classical
870 Delphi, where the goal is to create consensus; (2) the Policy Delphi, which aims to define and differentiate
871 views; (3) the Decision Delphi, used to prepare and support decisions; and (4) the Ranking-type Delphi,
872 which identifies and ranks key issues. Given that the aim of the present research was to determine the key
873 factors that will influence the development of the CCU sector, it falls into the last category (Ranking-type
874 Delphi) [59, 60]. Figure 1 provides an overview of the consecutive phases we followed to identify the
875 different impact factors and to move towards a final ranking; these phases were (1) participant selection, (2)
876 a brainstorming phase and (3) a ranking phase. Note that these stages can be different depending on the
877 research objectives; for example, although the brainstorming phase was present originally, it is often
878 replaced by a literature review to form the list of items necessary for ranking. For supplementary information
879 on the other methodological options, we refer to the vast amount of literature dedicated to this subject [22,
880 23, 26, 61-65].

881 A.1.1. Expert selection

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

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

898 The initial list of experts consisted of 132 professionals distributed over the four established
899 categories. Within the invitation we asked participants to identify other specialists who would be able to
900 provide insightful knowledge on the subject of CCU technology, a form of snowball sampling [67]. After
901 the first list, we were able to put together a second list of 108 professionals, based upon further research and

902 experts' suggestions. In total we contacted 240 experts for participation in the first round, with a response
 903 rate of 15 per cent (36 experts). In the invitation we mentioned that if they participated in all rounds they
 904 would be able to win one of three €50 gift cards from Amazon; such financial incentives are often used to
 905 raise response rates [68]. The second round was sent out to the participants of the first round and resulted in
 906 a response rate of 42 per cent. We find that 15 respondents is within what is considered acceptable in terms
 907 of panel size based on numbers proposed in e.g. Loo (2002) [100] and Rowe and Wright (2001) [97] for
 908 heterogeneous panels. 15 is a small, yet acceptable number in terms of Delphi panel size given that the
 909 quality of the obtained data is ensured via a proper protocol. Participants' characteristics, such as gender,
 910 work organisation and years of experience, can be found in Table A.1. Looking at the participants of both
 911 rounds, we see that the most prominent regions developing CCU technologies are accounted for with
 912 participants from large players such as Germany and the United States [5, 29]. Furthermore, all four
 913 categories that we set out to include in the study are represented. This heterogeneity leads to having a wider
 914 scope [97] and hence facilitates both a more systemic evaluation and a fairer balance between being
 915 knowledgeable and impartial compared to a more homogenous panel. Exposure to subject bias cannot,
 916 however, be fully avoided, which is considered a strength in consensus building, yet restricts the findings
 917 to what a group of participants considers important in relation to that topic [74].
 918

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

919
 920 **Table A.1: Participants' characteristics**
 921

922 A.1.2. Design of Round 1

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

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

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

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

942 A.1.3. Design Round 2

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

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

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

962 Once an initial ranking of the items has been received, a Delphi study can end or there can be another
963 ranking round with additional information about the different items, such as the mean, the previous choice
964 of the participant or comments given by the different experts concerning their ranking [62]. The goal of
965 performing another round would be to reach a higher amount of consensus, which is often measured with
966 Kendall’s W coefficient of concordance [26, 62, 73]. Stopping criteria for the Delphi process have also been
967 developed; these include stopping when Kendall’s W reaches a value higher than 0.7, stopping after three

968 rounds, or stopping when the mean rankings for two successive rounds have not shown a significant
969 improvement based on the McNemar test [74].

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

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

989 A.2. Scenario development

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

993
994 *“Descriptions of journeys to possible futures. They reflect different assumptions about how current*
995 *trends will unfold, how critical uncertainties will play out and what new factors will come into play.”* (UNEP
996 2002, p. 320) [75]
997

998 There are different ways to categorise scenario building approaches [20, 76-79]. Two of the main
999 distinctions that are made within scientific literature are the categorisation into exploratory and normative
1000 scenarios and the categorisation into deductive and inductive approaches. Exploratory scenarios, also called
1001 descriptive scenarios, start from the current situation. Assumptions are made about factors that lead to
1002 different pictures of possible futures. Normative scenarios start with various images of the future and paths
1003 are constructed regarding how to arrive to these futures, starting from the future and working backwards
1004 towards the present [80, 81]. Inductive methods allow the scenarios to emerge by themselves, building step
1005 by step on the available data; no overall framework is imposed. With deductive methods, an overall
1006 framework is used to start the exercise and data is fitted into the framework [78]. In this classification
1007 scheme, our scenario exercise can be considered an exploratory, deductive scenario building approach in
1008 which we aim to see how the present situation can change, what factors will be important and how they will
1009 behave, within a predetermined framework of possible futures.

1010 More specifically, building on the result of the Delphi, which consisted of a list of critical issues
1011 essential for the integration of CCU technologies in existing and new industries, we investigate how the
1012 CCU sector could transform. We use a case study approach to develop possible scenarios that the CCU
1013 sector in Flanders/the Netherlands can face by 2030, using a workshop setting to develop the scenarios. The
1014 workshop is based on workshop designs of Wulf et al. (2010) and Siebelink et al. (2016) [28, 82]. The

1015 scenario development process followed during the workshop consisted of the four steps listed below (see
1016 Figure 1):

1017
1018 Step 1. Determine the factors that have a potential impact on the development of the CCU sector in
1019 the case study region.

1020 Step 2. Evaluate the factors based upon their potential impact size and the degree of uncertainty
1021 they have on the development of the CCU sector in this region.

1022 Step 3. Develop and describe specific scenario dimensions.

1023 Step 4. Develop detailed descriptions of the scenarios based on the agreed dimensions.

1024
1025 The established scenarios describe what the industry could look like in the future and provide an
1026 exploration of the external environment in which companies would operate [21]. This allows organisations
1027 to better prepare for plausible future scenarios by evaluating whether their strategies, capabilities, resources
1028 and products are able to stand up to the challenges that will arise in the next decade. Organisations starting
1029 in or working with CCU technologies can use these scenarios for creating strategy and evaluating their
1030 current resources.

1031 A.2.1. Workshop design – Before the workshop

1032 The aim of the workshop was to construct four scenarios for the development of the CCU sector in
1033 Flanders and the Netherlands. Before the official workshop we had two trial workshops; one, with fellow
1034 researchers, focused on testing the methodology and the tools for the scenario development exercise. For
1035 the second trial workshop we asked several CCU experts to establish if everything was clear and meaningful
1036 content-wise. These experts were selected from within the authors' organisations but not involved in this
1037 project. These trial versions gave us the opportunity to fine-tune the methodology of scenario development,
1038 providing information on, for example, how to best explain the Delphi results, which wording to use and
1039 how to incorporate it into the scenario tools. For the actual workshop, we deliberately selected a group of
1040 experts from within the case study area to participate in the scenario exercise, starting from the author's
1041 personal network of CCU experts. In total, nine experts from both Flanders and the Netherlands participated
1042 in the workshop, two from industry organisations, one from a research institution, two from academia, two
1043 from the government and two from consultancy agencies.

1044 Participants were informed about the workshop in person and were sent an e-mail invitation to the
1045 workshop, called '*The realisation of CCU in the Flemish-Netherlandish context*'. It was indicated that the
1046 total duration of the workshop would be four hours. Attached to the invitation they received an overview of
1047 the four most important factors per topic examined in the Delphi survey.

1048 A.2.2. Workshop process – During the workshop

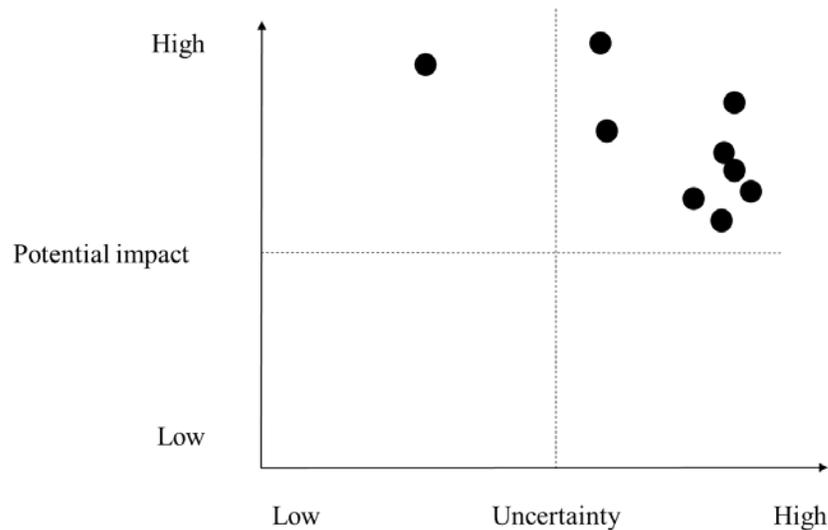
1049 A team of four researchers was present at the actual workshop, which consisted of two moderators
1050 and two note-takers. The moderators, whose role was to guide the workshop and the discussions, started
1051 with an explanation of the different process steps, the tools that would be used for each step, and the result
1052 that could be expected at the end of the workshop. Before starting with the scenario development process,
1053 there was an introduction round in which respondents stated their name and affiliated organisations. During
1054 this introduction, participants were also asked to sign a consent form, which stated the purpose of the
1055 workshop and advised that the workshop would be audio-recorded.

1056 Following the introduction, we (the moderators) continued with Step 1, where we elaborated on the
1057 results of the Delphi study. We selected 16 items from the Delphi study that were ranked highest among the
1058 different topics. For simplicity reasons we grouped the results into four categories: (1) drivers, (2) barriers
1059 containing both risk and supply constraints, (3) future developments and (4) factors that can constrain the
1060 demand for CCU technologies. For each of the categories we discussed the four most important factors,

1061 based on those indicated in the Delphi study. Items that were mentioned in more than one category were
1062 only included under the first category it was mentioned in; for the other categories, the fifth item on the list
1063 was included. We supplied participants with both the items and the explanation given by the experts in the
1064 Delphi. The experts then had the opportunity to supply other important factors or trends that had not been
1065 mentioned.

1066 After presenting the results of the Delphi and the subsequent discussion of extra factors, we moved
1067 on to Step 2, for which we used the impact/uncertainty matrix [28, 83, 84] that consists of two axes. The
1068 vertical axis ranged from low potential impact to high potential impact, for which we asked participants
1069 how much a certain factor could possibly impact the development of the CCU sector in the next 10 years,
1070 keeping in mind that this impact could be positive or negative. If the impact on the development could
1071 potentially be high, the factor would be placed in the upper half; if the impact would be low, it would be
1072 placed in the lower half of the axis. On the horizontal axis, we asked the participants to indicate how
1073 uncertain they were about the potential impact. Similar to the potential impact axis, high uncertainty on the
1074 horizontal axis would mean the expert was not at all sure about whether the expected impact would
1075 materialize, while low uncertainty would mean the expert was very sure.

1076 For each factor, participants first debated the position they would give to the factor by arguing why
1077 they thought it belonged in a certain quadrant. They were all then asked to locate the factor on the matrix
1078 with a token indicating their final view on the impact and uncertainty of that factor. It was not necessary to
1079 reach consensus in this step, so multiple quadrants could contain tokens. However, the quadrant containing
1080 the most tokens was picked as the final placement; see Figure A.1 for an illustration of the axis.
1081



1082 **Figure A.1 impact/uncertainty axis for cost development**
1083

1084 Step 3 was the formation of scenario dimensions, the goal of which was to form the framework for
1085 four distinct future scenarios. For the scenario dimensions, two factors from the 'high-impact-high-
1086 uncertainty' quadrant are chosen, considering that these factors need further investigation before a company
1087 can begin to form a plan on how to deal with them. Both factors are given two extreme values (for example,
1088 for the 'cost development' factor this could be: high costs versus low costs). This enabled us to draw a two-
1089 by-two matrix, which is commonly used in scenario building to visualise significantly different alternative
1090 future business environments that can arise [78]. The experts decided which two factors they wanted to use
1091 as scenario dimensions and the extreme values assigned to them.
1092

1093 The final part of the workshop, Step 4, consisted of describing and narrating the different scenarios.
1094 This was done by generally asking which factors could lead the sector to this situation in 2030 and what the
1095 consequences would be for the CCU sector if we did arrive at this scenario in 2030. To allow the participants
1096 to structure their ideas, we introduced the influence-diagram as a method to visualise the connections
1097 between the various factors and trends that had been brought forward. Despite the introduction, the tool was
1098 not used by the experts themselves; instead, for each of the scenarios they presented influencing factors,
1099 while one of the moderators then grouped them together by topic and built the influence diagram and
1100 narrative based on the connections verbally indicated by the experts. Afterwards, the moderators verified
1101 that they all agreed with the results and made the necessary adjustments.

1102 In this process participants could fall back on the factors and the previous discussions from Step 2.
1103 As a starting point we used the scenario in which the sector was located at the moment, what factors would
1104 cause the sector to still be in this scenario by 2030 and the accompanying implications. By doing this,
1105 participants explored which factors play a role in shaping the future of CCU, and this provided a baseline
1106 for the influence diagrams of the other scenarios.

1107 A.2.3. Workshop analysis – After the workshop

1108 After the workshop, we sent a follow-up e-mail to all the participants, thanking them for their
1109 contribution and explaining to them what the next steps are. For the analysis of the workshop, we first started
1110 by transcribing the audio recording. We recorded the whole workshop and had note-takers present as a back-
1111 up, providing us with an abridged transcript in case something went wrong with the audio recording. For
1112 the impact/uncertainty exercise, all statements made regarding a single factor (such as the cost development)
1113 were gathered. For each factor, we then divided the statements into statements related to the potential impact
1114 and statements related to the uncertainty. Finally, a general description was formed for each item, based on
1115 the location of the item and the arguments made by the experts. For the scenario building exercise, the
1116 influence diagrams from the workshop were used to narrate the different scenario descriptions. These were
1117 then extended with explanatory information from the transcript and checked for internal inconsistencies
1118 [19].

1119
1120

1121 A.3. Lessons learned from implementing the proposed protocol

1122 Based on our experience, we would like to provide the following practical lessons learned. Firstly,
1123 it is challenging to establish the credibility of the researcher and by consequence of the research. This is
1124 even more the case without a prior track record or reputation in the knowledge area - here this was CCU- to
1125 which the Delphi or scenario development method will be applied. Therefore, we advise research teams to
1126 devote considerable effort to gaining access to a network within the knowledge area and incentivize
1127 participation to the Delphi and/or scenario development by means of for example: (a) truthful and detailed
1128 revelation of the protocol and as such the expected effort from the respondents, but also of the fact that they
1129 will be receiving input from an expert group with similar, yet not identical expertise; (b) a personal invitation
1130 on the phone followed up by an e-mail, instead of only sending out email invitations to participate to the
1131 research; (c) asking for commitment prior to sending out the invitation to participate [98]; or (d) providing
1132 other stimuli like gift cards, first-hand insight into the study's results, or by already describing ways for the
1133 participants to use the outcomes of the study to which they participate.

1134 Secondly, quality control is strongly recommended and running a pilot test of the Delphi survey and
1135 the scenario development workshop is indispensable. We suggest separate, consecutive pilot tests with
1136 experts in the methodology and with experts in the knowledge area to verify the perceived appropriateness
1137 and duration of the protocol. This judgement will at least help to increase the face validity of the research.

1138 Thirdly, be prepared to invest in the timely follow-up of non-respondents and in not letting
1139 respondents that have answered to the first round(s) of the Delphi go cold by sending out reminders and by
1140 providing fast feedback. We could have improved our drop-out rate by converting the traditional Delphi
1141 into a real-time Delphi [99]. Also here we want to stress that e-mail reminders are easier to ignore than a
1142 phone call followed up by an email.

1143 Fourthly, to successfully organize a scenario development workshop a date should be fixed well in
1144 advance. To facilitate doing so, the following routine can be used. Call potential participants to find a couple
1145 of dates suitable to a critical mass. Create a doodle (or similar planning tool) with limited options. Send it
1146 out to the full list of purposefully selected potential participants. Take attrition into account when deciding
1147 upon the number of people that you invite.

1148 Finally, make sure the moderator(s) is (are) sufficiently supported during the workshop to enable
1149 them to focus on the content and not on the logistics such as having the supporting material to present the
1150 format (e.g. the beamer, the clicker, a flip chart, ...) and to develop and save the results of the workshop
1151 (e.g. an audio-recorder, a camera, a flip chart, ...) or the coffee break. Make sure the moderator is trained
1152 in facilitating group discussions and as such is impartial, constructive and able to open up and close the
1153 dialogue.

1154

1155

1156 B. Full rankings of Delphi exercise based on perceived importance

1157

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

1158

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	Macro-economic risks
9	Climate risks
10	Overproduction risk
11	No need risk
12	Health risks

1159

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

1160

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

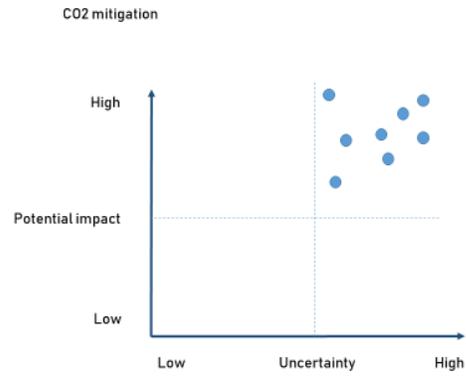
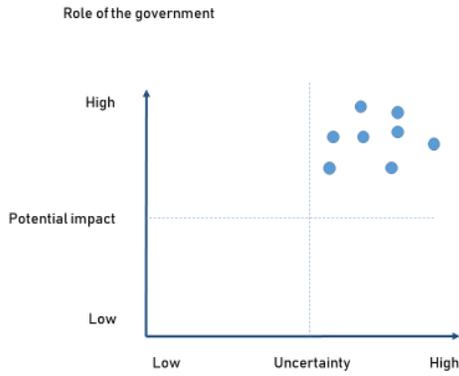
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Rank	Supply constraints
1	Financial constraints
2	Regulatory constraints
3	Technological constraints
4	Competition with other (emerging technologies)
5	Lack of consumer demand
6	Lack of integration
7	Macro-economic constraints
8	Resistance from fossil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

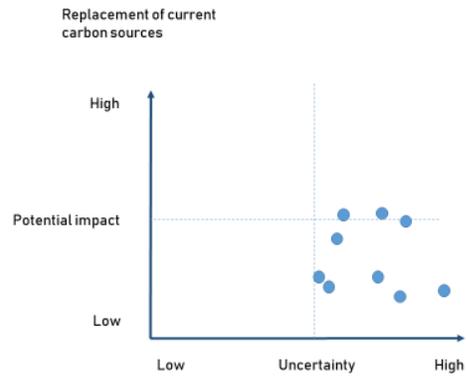
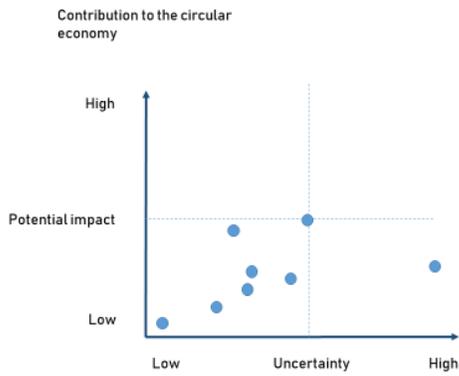
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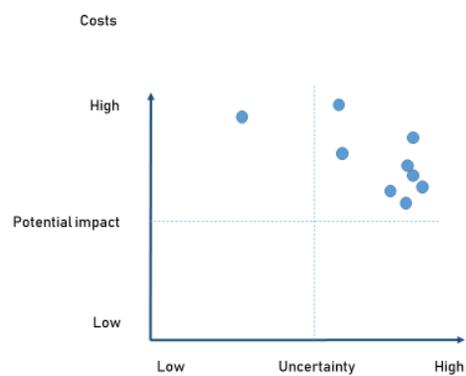
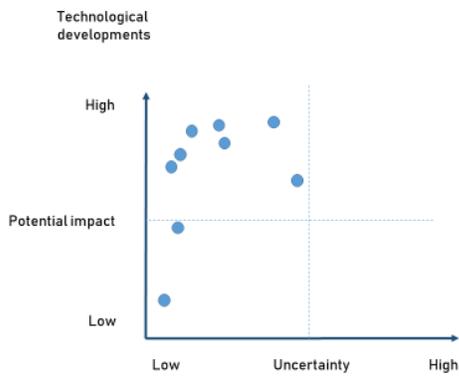
1164 C. Impact/uncertainty exercise: result of the scenario development workshop
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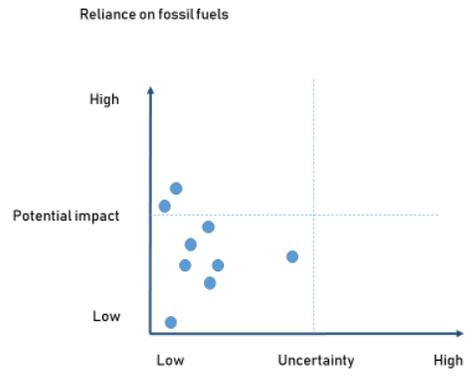
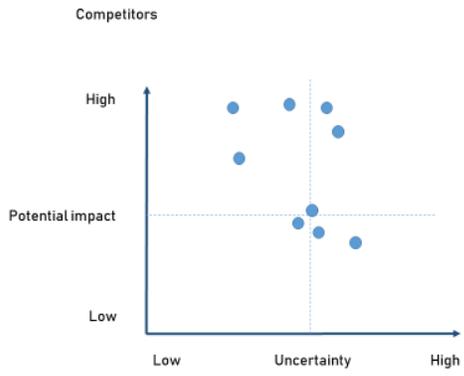
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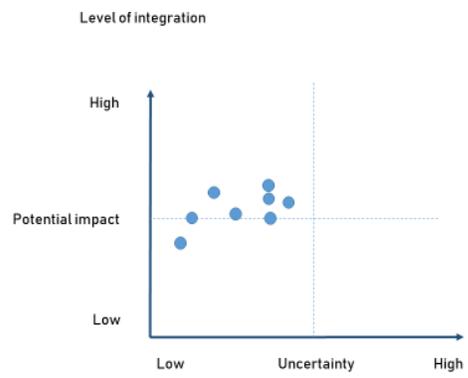
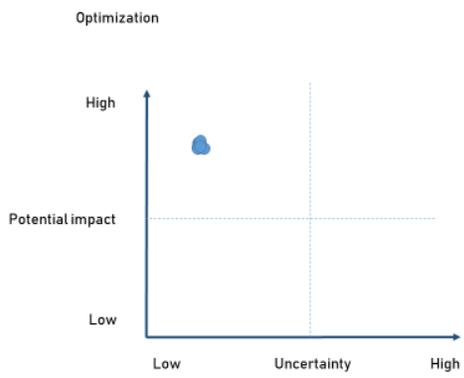
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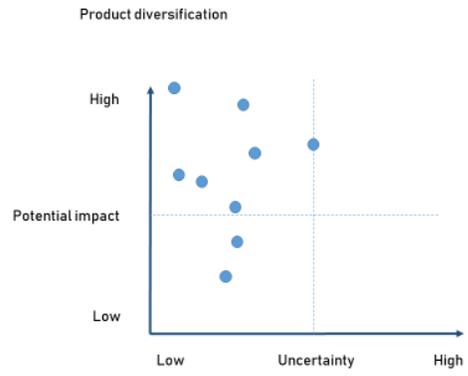
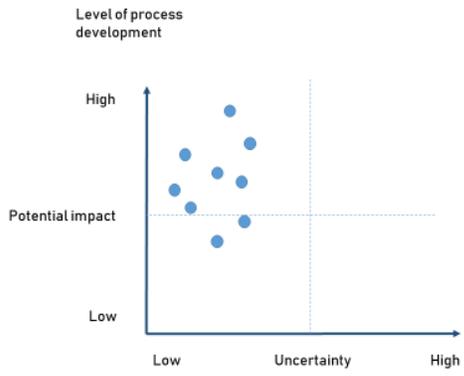
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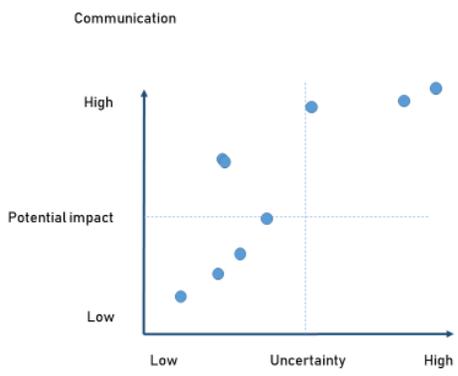
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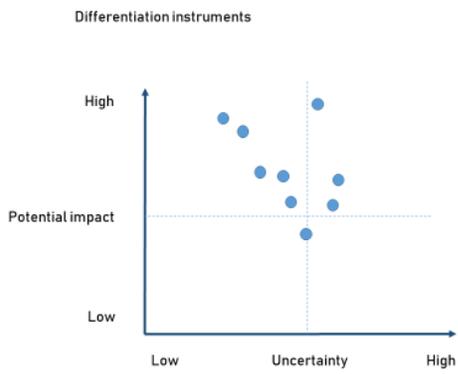
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