Appendix 1: 1112-00004A - Mission CCUS – a roadmap for Carbon Capture, Utilisation and Storage

Roadmaps for mission-driven green research and innovation partnerships (Innomission-roadmaps)

Innomission partnerships: Translating mission roadmaps into sustained actions

The call for mission-driven green research and innovation partnerships is the second phase in Innovation Fund Denmark's (IFD) Innomission program. Phase one generated roadmaps for each of the four missions (https://innovationsfonden.dk/da/programmer/groenne-missioner). Phase two now asks for proposals to form Innomission partnerships to drive action based on the directions outlined in the roadmaps.

During phase one Innovation Fund Denmark received 12 roadmaps within the four mission areas. Of these 12 roadmaps, six roadmaps were selected by the IFD Board of Directors to provide direction to the partnerships in designing action plans. The six roadmaps are described in the call for innomission-partnerships and shown in its full length in these appendices.

The Green CCUS Roadmap

- Towards a fossil free future

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1 Partnership and roadmap interaction

The "green" Carbon Capture, Utilisation and Storage (CCUS) roadmap we present here, envisions to deliver crucial solutions to the CO_2-driven climate challenge. Its key approach is to store CO_2, and to use CO_2 derived from the atmosphere instead of fossil sources. This approach takes the form of an ambitious and complex strategy aimed at a fundamental transformation of the carbon economy as well as societal activities. It depends on a broad and all-embracing collaboration between many stakeholders. Therefore, our CCUS roadmap was developed by a wide range of players: The main drivers being 6 universities (AU, KU, AAU, CBS, SDU and RUC), 3 technological service institutes (Danish Technological Institute, Force Technology and the Alexandra Institute), Energy Cluster Denmark and NIRAS, while NGOs, other universities and research institutes (DTU & GEUS), regulation advisers (Bureau Veritas) and industries (Food&Bio Cluster, CLEAN, Nature Energy, AquaGreen, Aalborg Portland, AffaldVarmeAarhus, Ørsted) also provided input. It is a fundamental requirement for the solution to the massive CO_2 challenge and the CCUS strategy, that the all-embracing and collaborative approach demonstrated by this roadmap, will also become the basis for the future implementation.

In addition, it is worth noting that the CCUS roadmap cannot be viewed in isolation. The CCUS challenge started out as a relatively straight-forward challenge of removing fossil carbon from industrial point sources. However, as this roadmap demonstrates, the implementation of CCUS has strong impacts far beyond the fossil-based point sources, and major overlaps can be identified with the other missions focused on "Green fuels", "Agriculture and food" and "Circular economy". Obvious overlaps are identified with the mission on green fuels as carbon capture from the CCUS roadmap will feed the Power-to-X activities, with the mission on climate friendly agriculture because biological storage will involve and possibly impact agricultural activities, and finally with circular economy of plastics and textiles because CCU will feed future use of plastics and materials. A coordinated effort across the roadmaps is therefore essential. Such coordination has been beyond the development of the CCUS roadmap but is a central requirement for the success of the four missions.

2 Vision

CCUS is critical for reaching the goals of 70% emission reduction in 2030 and net-zero emissions in 2050. It is also critical, as pointed out by the IPCC, to reduce atmospheric CO_2-concentrations through net-negative emissions in decades to centuries after 2050 in order to prevent long-term global warming beyond 1,5-2°C.

The vision for the present roadmap is thus to achieve a fundamental change in the way we view, value, and use carbon resources. We envision to capture and store current fossil CO_2 emissions, while simultaneously implementing a complete switch from fossil-based to "green" supplies derived from the atmosphere. We strive to demonstrate how our green CCUS-track balances the short-term urgent CCS needs with the long-term CCUS-plan that delivers globally scalable and innovative solutions to the carbon needs of the society. The roadmap focuses especially on avoiding that the solution to the 2030 goal of 70% emission reduction creates a technological "lock in", with massive short-term investments in technology and infrastructure becoming obstacles to the long-term goal. Finally, through integration of business-, human- and social-sciences and a focus on the final goals, our vision is to outline solutions that generate a wealth of new industries, export opportunities, growth, and jobs.

Key deliveries of the green-track CCUS roadmap

- Crucial contributions to the goal of 70% CO_2-reduction by 2030, carbon neutrality by 2050, and long-term negative emissions beyond 2050, while still ensuring the necessary carbon supply to society. The technical potential in 2030 is up to 8 ton CO_2 captured per year in 2030 (50-80% of the emission gap to reach the 70% target) and in 2050 up to 6 ton CO_2 can be captured and supplied to the production of green fuels and products.
- Technologies, tools and pathways to limit emissions to the atmosphere in both short and long term by gradual, but fast, switching from the current fossil-based carbon supply to a green supply based on the atmosphere to deliver the carbon needed in the society, combining permanent storage and smart utilisation of carbon resources.
- Multiple green pathways for atmospheric CO_2 to enter the societal carbon streams through a combination of large, small and scalable innovative solutions and the build-up of new technologies and companies with a significant national and international business potential.
- Outlines and timelines of the research and development needed for the individual technologies, as well as the systems integration based on existing knowledge, Danish strongholds and strong partnerships between universities, technological service providers, large and small companies, and societal stakeholders.

- Awareness and solutions to urgent societal readiness steps needed at the legal, regulating, economic and political level as well as externalities necessary to implement the changes without compromising key sustainability, environmental, biodiversity and human conditions.

Long-term strategies without short-term "lock in"

The implementation of the CCSU roadmap must facilitate both the short-term 70% CO2 emission reduction by 2030 and the next and even more challenging step to reduce to net-zero and below by and after 2050. Therefore, the here-and-now actions based on high-TRL technologies must be urgently brought into play at the unavoidable fossil-based emission sources, while also allowing for the onset of the longer, more visionary, and innovative perspectives of green CCSU. Importantly, we must avoid making high investments in technologies and infrastructures with limited long-term perspectives that become obstacles to the long-term solutions.

Therefore, by bridging the short-term (2030) and long-term (2050) perspectives, this CCSU roadmap facilitates a relatively short way to a fossil-free CO2 future and to business and technology innovation beyond what we know today. Furthermore, the roadmap addresses how a sustainable implementation of technological solutions can be achieved by (1) obtaining the necessary levels of societal readiness, e.g. through regulatory and financial instruments, as well as (2) protecting biodiversity and the environment. A systems-based, technology-agnostic approach, in which sector coupling and scalability play vital roles, is of key importance to the implementation of our roadmap.

Taking carbon from black to green

Currently, fossil hydrocarbons are used to cover the societal needs for energy and chemicals. These hydrocarbons flow linearly from subsurface extraction through societal utilization into CO_2 emissions to the atmosphere. We have to end this linear flow in a foreseeable future, and start viewing CO_2 as a valuable, and limited, resource in a circular carbon economy. There is no way we can continue current fossil carbon extraction and use, while maintaining a stable atmospheric CO_2 concentration through CCS only. We therefore have to limit fossil-based carbon sources to a minimum and allow atmospheric CO_2 to become the main supply for societal carbon needs in fuels, chemicals and materials.

Phasing out extraction of fossil-based carbon will in itself reduce the emissions to the atmosphere. At the same time, it makes atmospheric CO_2 the only CO_2 source, thereby creating a pull for atmospheric CO_2 for capture and utilization. In the short term, this will be an important steppingstone to a CO_2-neutral future with little or no extraction of fossil carbon. In the longer term, it will lead to a net-negative state based on utilization and storage of atmospheric CO_2. Consequently, over the course of the roadmap, carbon will switch from fossil sources (current state) to atmospheric sources (future green state) in a circular utilization that recycles atmospheric carbon to industry and fuels, but continuously captures more than is recycled.

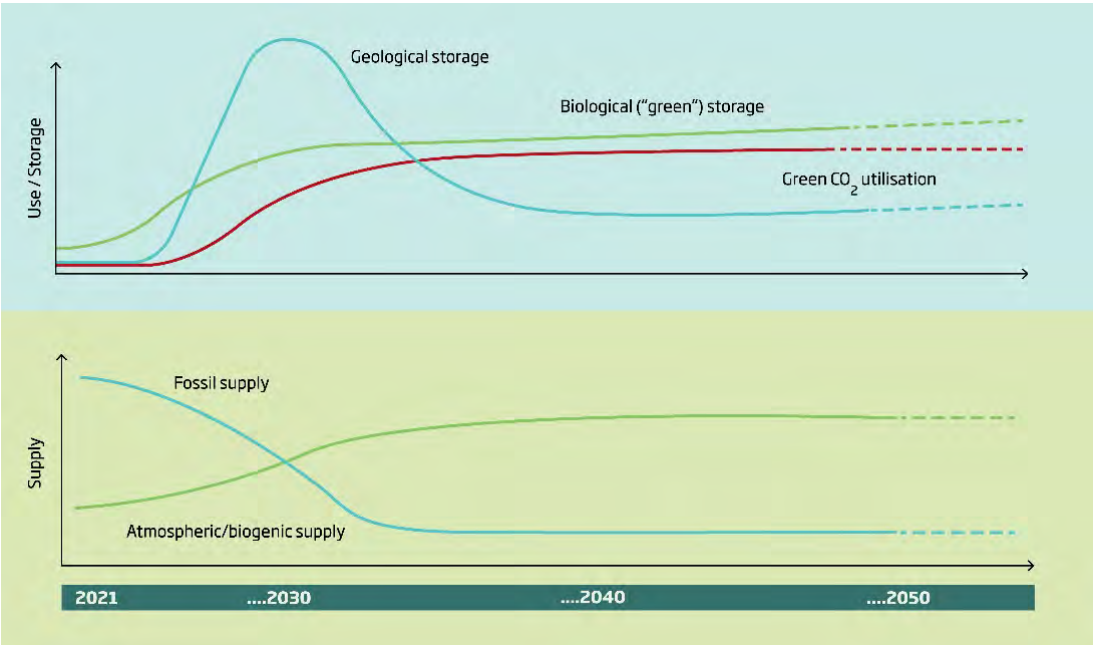

Fig. 2.1: Future annual CO2 flow rates of CCS and CCU

Combining storage and utilization of carbon with targeted impact

The switch from black (fossil-based) to green carbon tracks involves two simultaneous and complementary strategies regarding CCS and CCU. Our current high fossil-based CO_2 emissions calls for immediate CCS action focused on a few large emission sources. Meanwhile, a complementary green strategy is needed, developing smart technologies and pathways to capture and use the atmospheric CO_2 as the main CO_2 source. These strategies have to be pursued side by side and share a number of features and technologies, especially geological storage, which is continuously needed for providing short-term emission reduction in 2030 and net-negative emissions in 2050 and beyond. The two approaches will switch importance in the coming few decades, with a pre-dominant but eventually retracting role of CCS and fossil-based sources, and a steadily growing significance of CCSU based on atmospheric sources (Fig. 2.1).

The green path in this CCUS roadmap is the only way to provide the carbon needed for societal activities in a fossil-free CO_2 future. It builds on a wide range of carbon-capture technologies, from nature's own mechanisms in biomass (photosynthesis) and minerals, to direct capture from industrial point sources and from the atmosphere (Fig. 2.2). The balance between storage and utilization of CO_2 will develop over time as technologies and industries mature and grow. The early phase (2020-2030) has a strong focus on combining capture from industrial point sources with geological storage, but it also involves natural CO_2-storing processes by photosynthesis in biomass and soils (including biochar), as well as innovative CCU projects and utilization for fuels (Power-to-X) or chemicals. The early phase will gradually transfer into the long-term phase (2030-2050) where the society's need for carbon will be reduced, as energy is increasingly supplied by wind, solar and geothermal sources. Then fossil carbon sources will be replaced by new and innovative technologies extracting carbon directly from the atmosphere (using sustainable biogenic sources or direct air capture) to provide chemicals, materials, and some fuels.

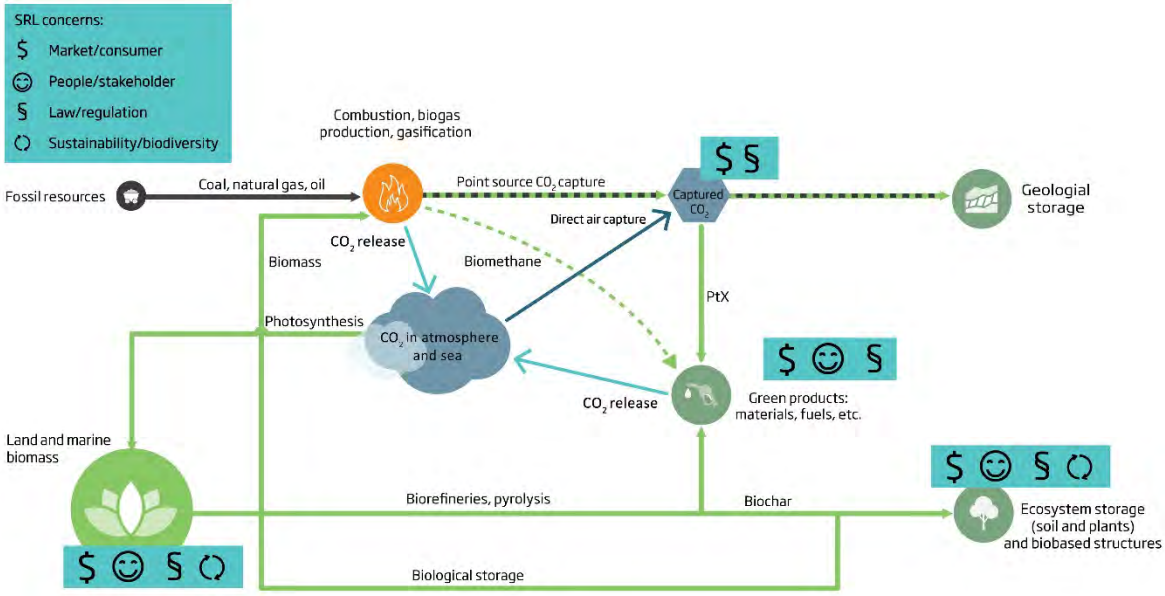

Fig. 2.2: The future CO_2 streams (2050 scenario)

For the CCUS roadmap, several challenges related to basic geological, chemical and biological understanding, systems integration, as well as assuring societal readiness to adopt the new solutions and sustaining environment and biodiversity remain. In particular, legislation and valorization of CO_2 and economic incentives for different sectors are currently main barriers. Overall, solutions must be found by combining technical aspects with sector coupling and economics, social sciences, and humanities in a holistic approach. It is worth pointing out, that the main obstacle for a CO_2-neutral future is likely not lack of technology, but lack of economic drivers.

Denmark as a global CCSU demonstration platform

Denmark has significant strongholds in the CCUS transition, which will provide solutions to the global CO_2-challenge. Innovations within utilization of CO_2 for fuels, chemicals and materials are currently booming, and enormous potentials exist for building a future Danish industry delivering non-fossil and green solutions globally, while creating jobs and growth in Denmark. Likewise, Denmark has huge potentials for large-scale geological storage, not only due to the many promising reservoirs in and around the North Sea area, but also due to the

extensive knowhow gained over decades with advanced oil- and gas-exploration. By pairing university-based research with open-science platforms for innovation with industries, our CCUS roadmap focusses on the full value chain and brings world-leading research in capture-and-storage technologies, chemical CO_2 conversion, biorefinery and life sciences into play.

The transformational journey of CO_2, from being a global problem to becoming a global opportunity, requires a strong and very dense collaboration between industry, RTOs, universities, public agencies and other authorities. Being a global CCUS demonstrator strengthens Danish industry competitiveness and enhances the impact of science. It paves the way for systemically re-thinking the regulatory **regimes** and framework conditions, transfers the challenges of scaling into a common ambition and guides a broad, yet tangible capability of all stakeholders. It is a key vision of our roadmap to tackle these fundamental challenges and provide the important coupling between short-term (2030) and long-term (2050) goals.

3 CCUS Potentials

CCUS covers several technologies for fetching CO_2 from carbon sources and storing them permanently underground or in minerals or utilising the CO_2 for the production of materials or fuels, thereby substituting fossil sources. In conjunction with other CO_2-emission reduction initiatives CCUS is a relevant tool in Denmark to abate emissions from hard-to-reduce processes and either provide permanent CO_2 storage (CCS) or provide non-fossil carbon-based fuels and products (CCU).

The greenhouse gas emission reduction goals set by the Danish government aim at reducing the greenhouse gas emission by 70 % in 2030 compared to 1990 emission levels and reaching net-zero emissions by 2050. The current status is shown in Fig. 3.1.

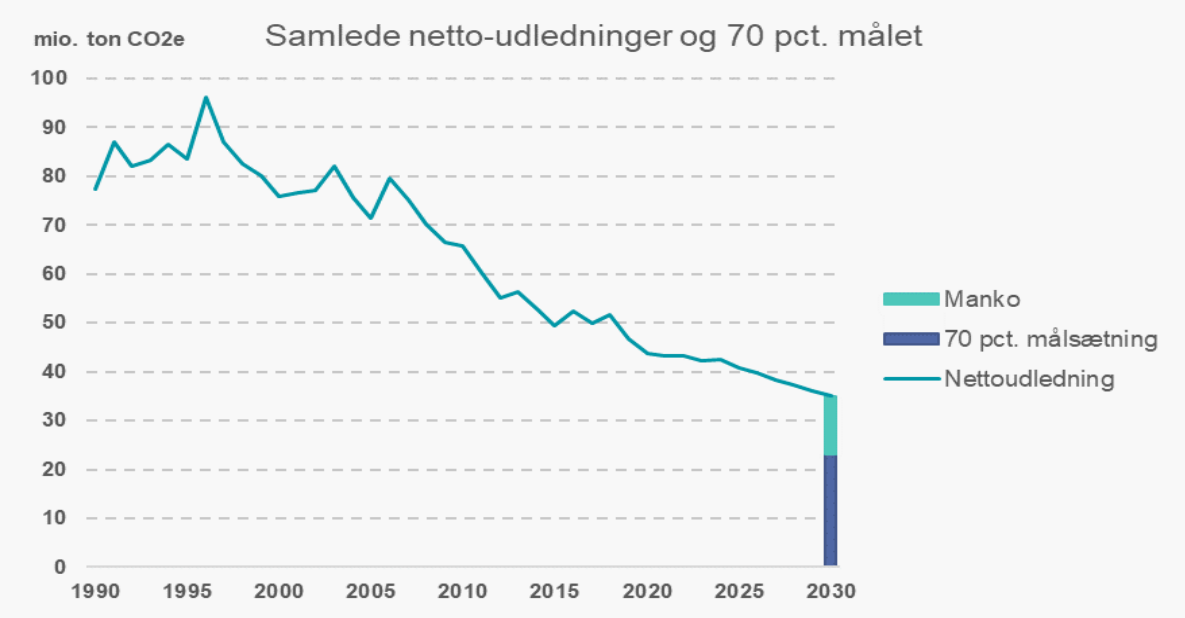

Fig. 3.1: Current status of 70% goal. Source: ENS Klimastatus og fremskrivninger, April 2021

3.1 Carbon sources

The source of CO_2 and the subsequent use has a large impact on the resulting net emissions. For an atmospheric carbon source (aka. non-fossil) such as biomass, the collected CO_2 has just recently been removed from the atmosphere and storing of the collected CO_2 will thus result in a net removal of CO_2 from the atmosphere. Accordingly, sequestration of fossil CO_2 can facilitate carbon emission reductions, but in order to remove CO_2 from the atmosphere, the CO_2 must originate from a source that absorbed the CO_2 from the atmosphere. Long-term storage can also include e.g. storage in ecosystems and sediments or uptake in concrete. The impact of the source and use of the CO_2 is depicted in Fig. 3.2.

The CO_2-source must be verifiably sustainable. This means, for example, that biomass must be harvested sustainably, which ensures that a similar amount of biomass is being regrown. This must furthermore be verifiable through regulation structures and certificates.

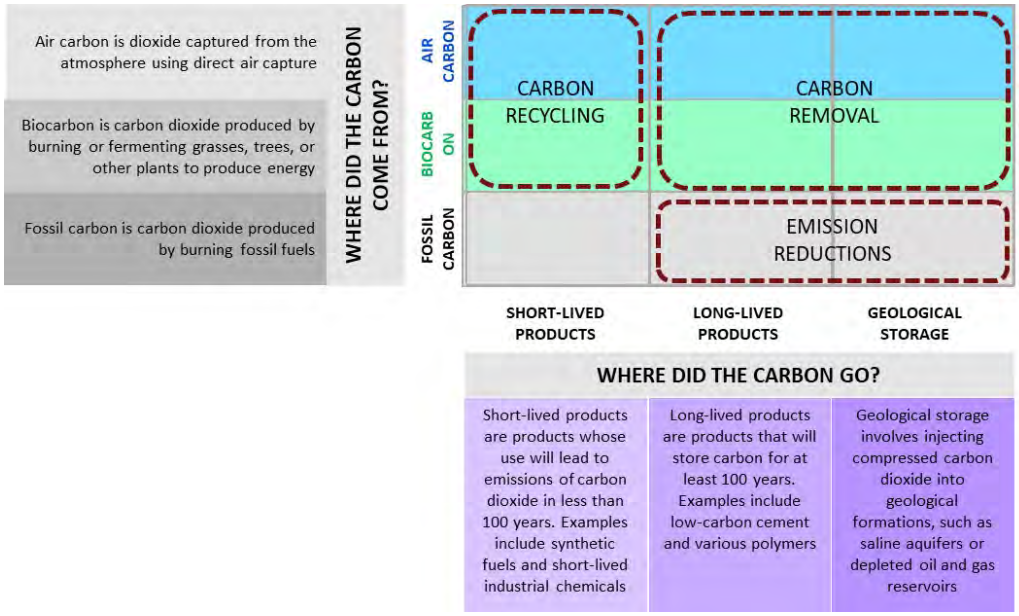

Fig. 3.2: Reduce, Remove, Recycle: Clarifying the Overlap between Carbon Removal and CCUS, American University, 2020

3.1.1 Large CO_2 point sources

CO_2 is most feasibly collected from the largest point sources being power plants, waste incineration plants and cement plants. The relatively low cost per unit of mass of CO_2 means that logistics and easy transport of CO_2 are also relevant parameters to consider, which would favour large plants with direct access to ship transport.

The potential point sources are listed in Fig. 3.3 showing the expected maximum feasible volumes. Most of these point sources have access to the sea. The most feasible sources for initial projects will be newer waste incineration plants and biomass CHPs, where remaining technical lifetime is long and there is a steady annual emission volume, thereby giving rise to high capture plant utilisation, but noticeably the expected CO_2 emissions from waste incineration are expected to decrease with increased amounts of recycling in the future. With the increased electrification and use of renewable energy towards 2050, the point sources for CO_2 will be fewer and smaller.

The increased use of biomass in the Danish energy sector does per definition provide CO_2-neutral energy services and contributes significantly to the attained national CO_2-reductions, while biomass-based combined heat and power plants remain relevant point sources for carbon capture. Accordingly, there will still be relevant sites for carbon capture, even though the energy sector is expected to be almost CO_2-neutral by 2050 (Fig. 3.4).

CO_2 emissions from point sources (Mt CO_2e/year)	2017 emissions	2030 emission	2030 CC potentials	2050 emissions	2050 CC potentials
Waste incineration (fossil)	1,4	0,6	0,6	0,2	0,2
Waste incineration (renewable)	3,5	1,7	1,7	0,9	0,9
Large biomass power plants	2,9	3,3	2,5	1,7	1,5
Cement production	2,3	1,33	1,1	1,0	0,8
Refineries	2,7	2,3	1,1	0,7	0,4
Other heavy industry	1,6	1,6	0,4	0,8	0,2
Total large point source potentials			**7,4**		**3,9**
- of which is fossil CO_2			2,1		1,2

Fig. 3.3 Point sources for Carbon Capture. Data derived from Basisfremskrivningen and CO_2 neutral affaldsenergi 2030 and data from NIRAS/Danish Council on Climate Change. "Other heavy industry" covers the 20 largest industrial CO_2 emitters in Denmark except refineries. The 2050 data are best guesses based on expected electrification and efficiency improvement of the relevant sectors.

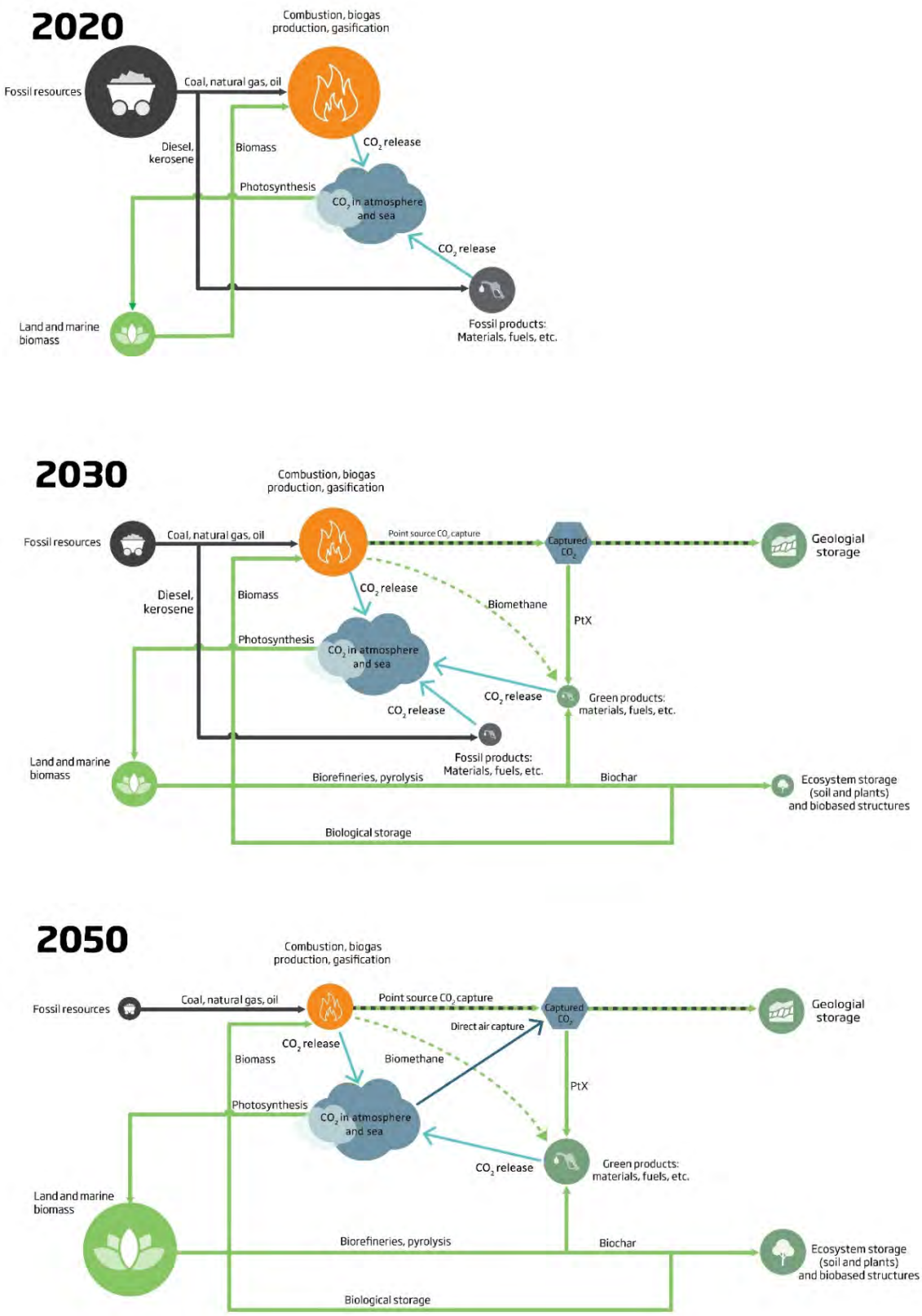

Fig. 3.4: The change of CO_2 flow from fossil to atmospheric CO_2. The size of the icons depicts the increase/decrease in yearly amounts

3.1.2 Alternative CO_2-sources

Other future alternative sources of CO_2 or other forms of carbon will come from smaller sources. The price of capturing CO_2 will be higher for smaller sources because of the lack of economy-of-scale and the increased unit cost for transport of CO_2. Smaller CO_2 point sources include district heating plants mainly running on biomass or biogas as well as emissions from medium size industries with own production of process heat. These types of CO_2-sources are also expected to decline as the energy services become electrified.

A significant alternative CO_2 source is from biogas, which is expected to be an increasingly important energy source for industry process heat as well as a building block for future carbon-based products. Raw biogas consists of roughly 60% methane and 40% CO_2. For now, a large part of this CO_2 is emitted through upgrading (i.e. purifying to CH_4 and releasing the CO_2) of biogas for injection of methane in the national natural-gas grid. However, this CO_2 source may also be collected and stored or utilised, or the biogas can be methanised through the addition of hydrogen. In this way the emission of CO_2 to the atmosphere is captured and the carbon is available as methane for direct use or further processing. The estimated amounts of possible methanation of biogas are estimated at 15 PJ/yr in 2030 and 17 PJ/yr in 2050 (Grøn Gas Denmark). This equals 0,9 Mt CO_2/yr and 1,0 Mt CO_2/yr, respectively.

The future demand for atmospheric carbon does not necessarily come in the form of CO_2, but could also be in other non-oxidized forms, depending on the use. An example is the aforementioned biogas upgrading where the biogenic carbon is collected as methane with the aid of hydrogen. Another route of long-term storage of carbon is in the form of biochar from pyrolysis, which Danish Council on Climate Change estimates at a 4 Mt/year potential in 2030 and which the Danish government suggest as >25% of the initiative for the agricultural emission reductions in 2030. Atmospheric CO_2 can also be captured directly from the air for example by the direct use of technology or by enhancement of the CO_2 uptake capabilities ecosystems (Fig 3.4).

3.2 Future demand for carbon

A main focus point for reaching the climate goals is naturally ending the use of fossil fuels. This is well underway in the energy sector and in households but is expected to be difficult in the transport sector, for example in shipping and aviation, where requirements for energy density makes it challenging to utilize battery-electric or hydrogen solutions. Moreover, it is also expected that demands for carbon in other sectors will continue to exist in the future (Fig. 3.4.). The predominant future fuels for maritime and aerial transport are not yet known, as several options are available such as e-methanol, DME, hydrogen, ammonia, ethanol-based fuels and more. Other areas where renewable CO_2 can substitute fossil carbon is depicted in Fig. 3.5.

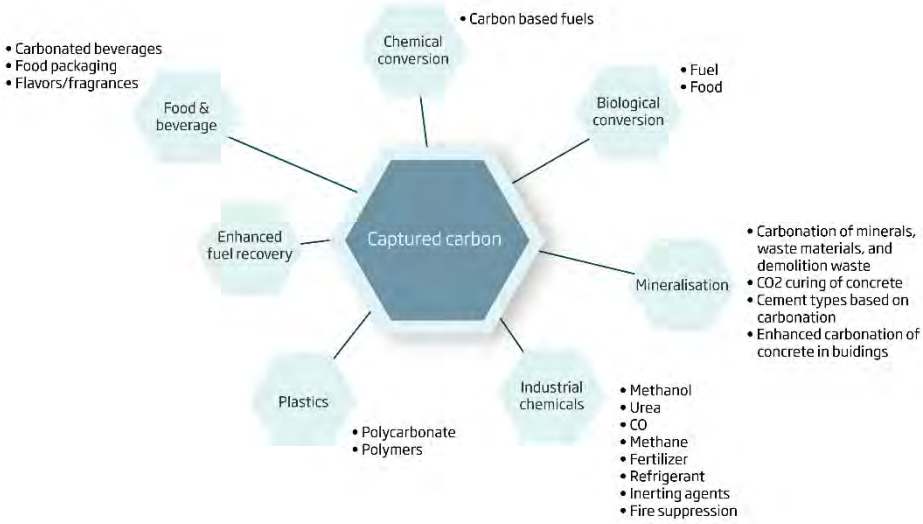

Fig. 3.5: Uses of captured carbon.

This shift towards renewable fuels in the maritime and aerial transport sectors will give rise to large international market needs for such fuels, again giving rise to a demand for CO_2 and other building blocks for drop-in fuels. Energy consumption for maritime and arial transport in Denmark including both domestic and international transport is expected to demand approx. 1,8 Mt green CO_2 in 2030 and approx. 7,2 Mt green CO_2 in 2050 (https://www.danskenergi.dk/udgivelser/potentialet-CO2-fangst-danmark-til-groenne-omstilling).

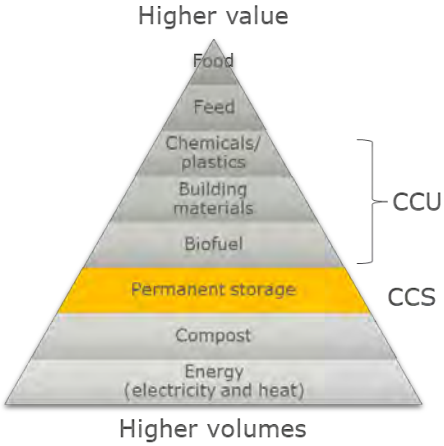

Fig. 3.6: Hierarchy of value of biomass

will become a scarce resource as the fossil carbon source extraction is minimized, while carbon to produce products such as chemicals and plastics is still needed, and some process emissions of CO_2 are unavoidable. Today approx. 7% of the global fossil oil and gas is used for products, not fuels. This demand is not expected to decrease at the same rate as the need for fossil fuels for power and fuels, but biogenic sources of carbon must meet this demand in combination with carbon harvested by direct air capture. The biogenic carbon will thus have many uses and the value of biomass and biogenic sources for various uses must therefore be considered carefully.

The highest value of biomass resources is human food and animal feed, while the lowest value is the production of heat and electricity or only heat, which should be avoided in the fossil free future (see Fig. 3.6). In between are the uses related to CCU and CCS. In a market-based approach, the balancing of biomass use will self-regulate, but that will require a proper valuation of the climate effect of CCU and CCS.

In order to achieve net negative emissions, which is required according to the IPCC if global warming should not exceed 1.5-2 °C, and in order to compensate fossil carbon use, there is an additional demand for green carbon for storage purposes.

3.3 Danish CO_2-balance

During the period from 1990 to 2019 the greenhouse gas emissions have been reduced by 40 %, from 77 Mt per year in 1990 to 47 Mt per year in 2019. These numbers do not include the biogenic CO_2 emission, which accounted for additional 17 Mt per year excl. bioethanol and biodiesel (https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf21_hovedrapport.pd). The biogenic CO_2 emissions are primarily due to phasing out of coal and an intensified use of bioresources in the Danish energy sector, which in 2019 amounted to 166 PJ per year excl. bioethanol and biodiesel, and out of this 66 PJ per year was from imported biomass (primarily wood pellets), 17 PJ per year was biogas and 19 PJ per year was from incineration of biodegradable waste.

Considering that the future recycling initiatives will reduce the amount of waste available for waste incineration plants, and that the biogas will be used for purposes where CO_2 point capture is not possible/feasible, for example for maritime or arial transportation, the potential of point source capture of biogenic CO_2 was less than 17 Mt per year in 2019. Moreover, in a global context, it is important to consider the global limitations on how much sustainable biomass the world can produce. The demand for biomass is increasing globally, and according to the Danish Council on Climate Change, the use of bioenergy per person in Denmark is almost three times as high as the global potential for sustainable biomass production per person (https://klimaraadet.dk/da/rapporter/biomassens-betydning-groen-omstilling). At the same time, the use of land for biomass production also needs to be considered in relation to alternative land-use options, for example food production and reforestation. It is therefore important to ensure that the use of biomass in a Danish context considers the global limitations, and basically achieves a national balance.

The above considerations suggest that the domestic biomass resources can become a bottleneck in a future net-zero CO_2 emission scenario, thus indicating a need for alternative technologies if carbon supply for green fuels, green materials, storage, etc. should be available in a relevant scale in the future. It is therefore of critical importance that the research and innovation focus is not only on the carbon value chain from biomass combustion over point source CO_2 capture to storage. Rather the focus should be broader and thereby both encompass technologies, which either do not involve biomass combustion as intermediate steps for fuels or utilize the bioresources directly in biorefineries.

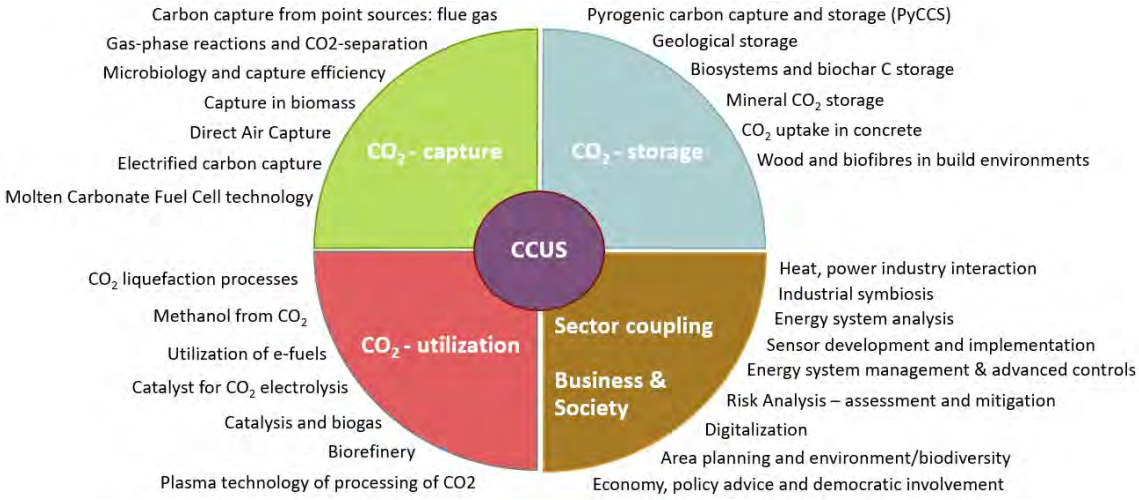

Fig. 3.7: Danish strongholds within research and innovation

3.4 Danish strongholds

Already now, the Danish universities and RTOs conduct internationally high-ranking research and development within the sectors relevant for this roadmap, ranging from agriculture over industry to digital services and including mitigation of CO_2-emissions, providing carbon for future materials, and obtaining negative emissions. Fig. 3.7 highlights the many Danish research areas and technical strongholds of relevance for CCSU, where some are at early stage of mission-driven research (low TRL), while others are close to commercialisation (high TRL). All of this technology is needed for reaching the Danish climate goals as is highlighted in the gap analysis in Section 5.

Similarly, the Danish industry has clear strongholds within key relevant areas for the green fossil-free transition such as energy, cement and building materials, biomass production, use and conversion, biotechnology, soil management and systems integration. Therefore, the industry will play an important role in CCUS, due to its innovative capabilities paired with experience in exploring green business opportunities for global commercialization, business and job creation, whilst securing high environmental standards. Consequently, Danish industries are well positioned for taking the lead within green technologies to e.g. mitigate existing large point source emissions from cement production and waste incineration, and to develop new green fossil-free solutions.

A green transition will require close collaboration between research institutions, industry, policy makers and the civil society, a cross sector collaboration being a Danish stronghold and placing Denmark with a significant potential to become an internationally recognized CCUS demonstration platform.

Companies active within CCUS see a huge potential in the green transition, given that regulative measures secure suitable conditions on the long run, and do not solely focus on 70% reduction in 2030. Therefore, this green CCUS track proposes a long-term strategy, avoiding unwanted lock-ins, and stresses the paramount importance of regulation being transparent (build on common standards), stable and long-term. The roadmap also addresses industrial needs for flexible technical solutions, business models adapted to circularity, and simplification of frameworks and regulations to ease sector coupling.

4 Technological gap analysis

4.1 Technologies: impact, readiness, challenges and business potentials

The technologies employed at various parts of the carbon value chain differ in maturity, ranging from high TRL-levels for some point-source CO_2 capture technologies to lower TRL-levels for alternative carbon value chains. In the following technological gaps for the technology groups included in the roadmap are presented. The envisioned development of TRL-levels over time is depicted in Fig. 6.7.

4.1.1 Carbon capture at point sources

Point source carbon capture is the recovery from a point source, mostly for flue gas, biogas and fermentation where the CO_2 is separated from other gases into a pure form for storage or use (PtX). Commercial technologies based on amine absorption are available also from Danish suppliers, but cost, efficiency, and energy consumption can be improved, which is also why it is mostly relevant for larger industrial plants.

Impact: Biogas is crucial in lowering the climate impact of gas both industrial and domestic use. Accordingly, the national gas grid is gradually shifted towards providing renewable biogas. The biogas production is expected to double from now 25 to c. 51 PJ by 2030. 80% of the production is expected to become upgraded and available on the gas grid. Methanisation of biogas-derived CO_2 with hydrogen has the potential to increase output by up to 40%. This is essentially a CCU Power-to-Gas process, potentially resulting in future 100% renewable gas in the grid. This further has significant potentials for sector coupling and load balancing of renewable electricity.

Readiness: Biogas upgrading is commercially available and in operation in several Danish plants. Methanisation of biogas can be achieved by a chemical catalytic or by a biological process – both depending on a source of green hydrogen – and has successfully been demonstrated in pilot and demonstration scale operation in Denmark. R&D is ongoing at universities and process suppliers.

Challenges: Key focus areas are (1) reduction of plant costs and (2) optimization of catalyst for the chemical reactor as well as hydrogen addition to the biological reactor. For the latter several process designs are being investigated and the possibility of direct injection of hydrogen in the biogas reactors could be a relevant process simplification based on an optimized biological culture.

Business potentials: Biogas upgrading is already a Danish stronghold within universities, research institutes and industry. Danish industry has the potential of developing both biological and chemical methanisation technologies with large technology export potentials.

4.1.2 Biogas upgrading and methanisation

Biogas is a key renewable energy source, essential for paving the way towards a fossil-free future in Denmark. Traditionally, biogas fuels heat and power production, yet upgrading of biogas for injection into the gas grid has become the predominant use over the last decade. Upgrading process, comprises separation of methane and CO_2, injection of purified methane into the gas grid, and releasing the CO_2.

Impact: Biogas is crucial in lowering the climate impact of gas both industrial and domestic use. Accordingly, the national gas grid is gradually shifted towards providing renewable biogas. The biogas production is expected to double from now 25 to ca. 51 PJ by 2030. 80% of the production is expected to become upgraded and available on the gas grid. Methanisation of biogas-derived CO_2 with hydrogen has the potential to increase output by up to 40%. This is essentially a CCU Power-to-Gas process, potentially resulting in future 100% renewable gas in the grid. This further has significant potentials for sector coupling and load balancing of renewable electricity.

Readiness: Biogas upgrading is commercially available and in operation in several Danish plants. Methanisation of biogas can be achieved by a chemical catalytic or by a biological process – both depending on a source of green hydrogen – and has successfully been demonstrated in pilot and demonstration scale operation in Denmark. R&D is ongoing at universities and process suppliers.

Challenges: Key focus areas are (1) reduction of plant costs and (2) optimization of catalyst for the chemical reactor as well as hydrogen addition to the biological reactor. For the latter several process designs are being investigated and the possibility of direct injection of hydrogen in the biogas reactors could be a relevant process simplification based on an optimized biological culture.

Business potentials: Biogas upgrading is already a Danish stronghold within universities, research institutes and industry. Danish industry has the potential of developing both biological and chemical methanisation technologies with large technology export potentials.

4.1.3 Uptake and storage in biomass and ecosystems

Capture of CO_2 by photosynthesis and storage in biomass and ecosystems is an ongoing natural process already contributing to storage of carbon. The further contributions from biomass storage to the 2030 and 2050 targets include both increased C-uptake (additionality) and stabilization of carbon stored in terrestrial and marine ecosystems (permanence).

Additionality is addressed by (1) increasing the productivity (NPP) of ecosystems, (2) restoration of ecosystems and their carbon storage in living biomass, deadwood, freshwater and coastal wetlands, and soil including marine sediments, (3) increasing afforestation or abandonment of drained agricultural soils, (4) establishing wetlands in low-lying areas and (5) sustainable soil amelioration using biochar from plant and algae biomass. Permanence is addressed by (1) safeguarding ecosystem carbon stores ensuring stability and resilience of terrestrial and marine ecosystems, (2) conservation of 'blue' and 'green' habitats and (3) enhanced engagement and reconnection of local communities with nature, and increased social awareness on restoration actions and their benefits.

Impact: Danish forests and wooded lands store 168 Mt C. The annual sequestration in these areas is 6.3 Mt CO_2, whereof 1.5 Mt is added to the ecosystem C stock annually. By 2030 and 2050, the sequestration in new and existing forests can reach additional 0.6 and 3.7 Mt CO_2 eq/yr, respectively (with 1.6 Mt CO_2 eq/yr as wood). On a global scale, restoration of wetlands is estimated to be able to sequester 2.5 x current C emissions. Scaling this to a Danish context indicates that there is a potential of C sequestration of 250 MtC. Agricultural land (currently 80% annual crops) store ~340 Mt C. with a potential to store additionally 0.5 Mt CO_2/yr in 2030 and 1.5 Mt by 2050 if 10% is converted into grassland. Drained organic soils emit 7-17 t/ha C annually, which can be impeded by rewetting. On a global scale, restoration of coastal ecosystems can store 234 Mt C per year. In a Danish context there is a potential of additional C sequestration of 250 MtC.

Readiness: Uptake and storage of carbon in biomass and ecosystems is not in itself technology reliant, but technology developments act as enablers of business cases and system transitions (e.g. grass biorefineries to produce protein concentrate are currently at TRL 8). Solutions that can be deployed now or within the coming five years include (1) identification and implementing of suitable restoration in relevant habitats maximizing C capture, (2) applying best practice restoration, (3) novel afforestation practices to increase NPP and C storage.

Challenges: Further developments should focus on unfolding the potential for (1) increasing biomass growth and C sequestration per area in agri- and aquaculture production through species selection, genetics and management, (2) increasing the C storage in forest and agriculture soils and marine sediments and (3) optimizing afforestation and long-term C storage in products under different growth conditions and future climates. Further, there is a strong need to (4) accurately monitor, model and forecast C sequestration, storage opportunities in ecosystems, C-recyclability in products and use of biomass products critical to climate accounting and (5) ensure that intensive biomass use does not compromise biodiversity and other environmental issues. In addition, research activities to generally understand societal aspects are needed such as (6) understanding the societal value of ecosystem services, (7) improving the spatial planning for increasing C storage in rewetted lowlands and coastal ecosystem, and (8) governance, investment and policy support on biodiversity and ecosystem service restoration.

Business potential: Sustainable biomass production has a significant business potential as it will become the foundation for material and fuels in a post-fossil society and the economy of the society will increasingly rely on biomaterials, as we phase out the use of fossil fuels and fossil intensive materials. The integration of biorefineries, CCUS etc. will increase the value not least due to tradable carbon credits. Other opportunities include establishment of a habitat restoration business sector, or industries that cultivate "blue carbon" plants.

4.1.4 Storage in geological repositories and minerals

Long-term storage in deep subsurface repositories or minerals will in the short term contribute to neutralize part of the Danish CO_2 emissions, mainly from large point sources. In the long run it will open up for negative CO_2 emission by permanently storing CO_2 captured by photosynthesis, direct air capture or at major point sources. New minerals and materials may be formed in connection with CO_2-emitting industries and/or by (bio)mineralization-capture in the marine environment (blue carbon).

Impact: Subsurface storage potentially has a capacity to store several hundred years of greenhouse gas emission (mainly CO_2).

Readiness: Solutions for subsurface storage are ready in 2025-2030, or possibly even sooner at existing offshore O&G fields. For mineral and material formation, proof of concepts exists, and solutions are ready in 2030-2050, depending on process and scale.

Challenges: A main challenge relates to (1) the current lack of legislation as it is currently not legal to store CO_2 in the deep subsurface. For large-scale geological storage, (2) an efficient environmental monitoring system is needed to ensure environmentally safe storage and to answer potential concerns in the general public and (3)

improved knowledge and understanding of interactions between injected CO_2 and reservoir bedrock as well as new methods for mitigation of potential leaks of CO_2 to the surface and better understanding of potential effects of such leaks on the environment. Further, (4) technological developments are needed to enable large-scale CO_2-capture in minerals.

Business potential: There is a huge business potential in creation of new carbon-neutral or -negative minerals and materials for the building industry (e.g. new types of concrete) and other industries. CO_2 storage in deep subsurface reservoirs can become a significant business for energy companies and the Danish society since the potential is larger than the Danish needs.

4.1.5 Pyrolysis, biochar and storage in soils and sediments

Pyrolysis of biomass produces biochar and non-fossil energy in Pyrogenic CCS systems (PyCCS) with numerous potential uses, and will potentially sink large amounts of carbon into soil, enhancing soil quality and building char reefs for soil microbes to increase soil genetic diversity, resilience and stability. Further, storage can take place in coastal and marine sediments and soils (blue carbon) or in shellfish.

Impact: Biochar and PyCCS has a potential to sequester >4 Mt CO_2-eq per year in biochar carbon and >2 Mt CO_2-eq per year from production of non-fossil energy and avoided methane emissions. In addition, biochar has an unknown extra potential for soil enhancement effects increasing crop yields, new crop production systems and increasing soil genetic diversity, resilience and stability. Coastal ecosystem restoration and conservation storing blue carbon has a huge potential (234 Tg C per year globally) which scaled to Denmark accounts for carbon sequestration of potentially 250 Mt CO_2e by 2050.

Readiness: For PyCCS and biochar, small-scale plants are at pilot and demonstration scale today, and large-scale plants are expected ready in 2025-2030. For blue carbon, small scale solutions are ready 2025-2030, and upscaling to full potential (national and global) is expected for 2030-2050.

Challenges: A main challenge relates to (1) new regulation and legislation around pyrolysis, storage of biochar in soil and land use is needed as well as knowledge on use, protection, and restoration of the shallow marine environment. For large-scale geological storage, (2) new biochar product value-networks need to develop and mature, and (3) new agricultural practices and crop rotation systems must be designed, tested and adopted and local and regional variations in soil enhancement effects must be evaluated. Storage in the marine environment (blue carbon) requires (4) identification of suitable restoration habitats, and restoration and conservation actions must be upscaled to national and global level.

Business potential: There are strong possibilities for new agricultural biochar industries, depending on the areal use.

4.1.6 Carbon storage in the built environment

The built environment accounts for about 39% of global CO_2 emissions, 11% from materials and construction. Thus, technologies to reduce emissions, e.g. using carbon storing materials or replacing CO_2-emitting materials in the built environment, have a significant potential for short as well as long-term goals.

Impact: Employing wood and renewable biobased materials for the built environment and using carbon for e.g. roads, concrete and plastics has a large-scale carbon storage potential and can contribute to avoid emissions from production of energy intensive materials. For wood alone, at least 1.2 mill. ton CO_2 can be stored until 2030, and at least 0.8 mill. ton CO_2/year after 2030. Similarly, applying CCS to make production of cement carbon neutral has the potential to provide CO_2 storage in concrete, amounting to at least 0.7 mill. ton CO_2/year.

Readiness: Technologies for using wood in buildings are already in place. New biobased building materials, agricultural waste products, reuse of construction wood, modularity and industrialization of the building industry and large buildings are quickly advancing. Carbon storage in concrete, asphalt binders and new composites in the build environment can be implemented from now and within a decade.

Challenges: There is a strong need for (1) improving the degree of circularity in the value chains for bio-based materials, (2) developing and applying new bio-based construction materials, (3) improving durability of wood in outdoor environments, and (4) optimizing the potential for short- and long-term storage of CO_2 in concrete structures. Furthermore, a general improvement of market perception related to the sustainability and use of forest products is needed.

Business potential: The business potentials for novel and smart CO_2-neutral technologies are considered significant. For example, building with wood enables increased pre-fabrication, speed, and quality of the built environment, as well as light transport. Methods and technologies to reduce the carbon footprint from concrete has a massive business potential.

4.1.7 Biorefinery for chemicals and materials

Biorefineries have a very high potential for providing a carbon-neutral replacement for fossil fuels, chemicals, and materials and with significant materials and energy saving advantages compared to burning and transforming all biomass into CO_2. Fuels, chemicals, materials as well as food, fibers and energy can be produced from biomass through direct extraction, enzymatic modification, fermentation, chemical catalysis, or chemical modification. Furthermore, microalgae and chemical transformations of feedstocks represent an unexploited potential for CO_2 capture from point sources.

Impact: Producing materials and chemicals by biorefinery instead of using fossil sources can reduce CO_2 emissions to zero and for some elements even to negative values. Consequently, much of today's CO_2 emissions from fossil-based chemicals and materials can be avoided.

Readiness: The basic concepts and small-scale experimental set-ups are already available. Large demonstration facilities can be implemented for microalgae, lignocellulosic biomass, and a range of green biomass/processes by 2030. Implementation at fully industrial scale is expected by 2050.

Challenges: Research and development is needed with particular focus on: (1) highly selective gas-sorptive materials and filters, (2) catalysts/enzymes operating at low temperatures and pressure for the transformation of gases to useful chemical feedstock compounds, (3) enzymatic and mechanical processes oriented towards biomasses with high CCUS abilities such as algae or perennials, (4) aqueous catalytic processes for diluted fermentation-produced platform chemicals, (5) processing and upscaling of production and harvest of microalgae and (6) general supply chain understanding and planning related to biomass availability for food as well as chemicals/materials.

Business potential: Denmark can become leading developer of biorefinery technology, including plants in Denmark. In particularly, delivering specialized, high-end biorefinery concepts, solutions, and services, bears the potential for developing new companies and industry in addition to those already in the market (e.g., Haldor Topsøe and Novozymes).

4.1.8 Direct CO_2 Air Capture

Direct Air Capture (DAC) can provide high purity CO_2 from atmospheric air for utilization and storage. DAC has the potential to overcome the potential limitation of CO_2 capture at Danish biomass-based point sources (~4.5 Mt CO_2 per annum).

Impact: DAC can contribute to deliver carbon for materials in a fossil-free future where CO_2 may be a limited resource due to constraints on land for biomass production. Further DAC will contribute to carbon neutrality in 2050 by carbon-offsetting sectors that are difficult to decarbonize. DAC is siting-flexible, and DAC facilities can be installed at potential geological storage sites. Direct air capture with storage can in the long term provide a solution for net-negative CO_2 emissions from a limitless resource. Globally, direct air capture is expected to capture 10-15 Gt CO_2/year.

Readiness: Currently pilot facilities are in operation and demonstration facilities are expected by 2030, entering full implementation by 2050.

Challenges: The main challenges relate to the high consumption of energy and water, and to the environmental effect of absorbents. Further knowledge of thermodynamics and kinetics of CO_2 absorption/desorption/diffusion is needed to assess the feasibility of this technology.

Business potential: Utilizing captured CO_2 for products such as construction material and plastics can provide long-term storage (decades or centuries) and will lead to new businesses, e.g. synthetic aggregate (limestone) for concrete with a global business potential equal to current wind turbines and solar panels. DAC will be dependent on abundant renewable electricity and a market for CO_2 or storage facilities, all of which can be offered in Denmark. The technical development as well as the societal conditions handling costs, market conditions and incentives for investments are inflection points for the development.

4.1.9 CO_2 for fuels, chemicals, and carbon-rich materials

Utilization of CO_2 for fuels, chemicals, and carbon-rich materials makes it possible to replace fossil carbon at net-zero or negative emissions, while sustaining economic activity based on carbon-rich materials and energy carriers.

Impact: The CO_2 utilization potential depends on the availability of CO_2 which will largely be restricted by (1) limited availability of biogenic (non-fossil) CO_2 from point sources and (2) the climate-driven need for storage. In the long run (2050), DAC is expected to circumvent the constraint. Further, the utilization potential depends heavily on supply of renewable electricity and the ability to scale up sustainable H_2 production from electrolysis (see later). For example, if all CO_2 from biogas in an extended biogas scenario (40 PJ) is used for utilization, it can replace c. 30 PJ natural gas and eliminate net 2.0 Mt CO_2 emissions from Denmark. Further, deploying local PtX conversion of biogas sources into liquid fuels may eliminate large and dispersed methane emission.

Readiness: Commercial solutions for PtX methanation and methanol production are ready, with green hydrogen being the main current limitation. By 2030 commercial solutions for PtX methanol and derivatives e.g. DME will be available, while technologies for processing CO_2 in plasma, biotech based methanation technologies, pathways for sustainable kerosene production, e.g. via methanol, ethylene, and e-crude, will be close to demonstration. By 2050 a whole range of solutions for PtX derived carbon-rich molecules will be available at distributed facilities at CO_2-sources based on bio-catalysis and green hydrogen.

Challenges: The development of utilization of CO_2 need focus on (1) processes with decreased energy losses and integration with renewable energy production; (2) the development of (bio)catalysts avoiding use of noble metals and working with electrical heating and (3) systems integration and assessment using system analysis (value chain) assessing and optimizing location, existing infrastructure, transportation, and usage of waste heat from other processes. Finally, (4) consumers (B2B and end-users) must adapt to PtX-based carbon molecules.

Business potential: Denmark has a significant potential as technology developer of the fuel technology chain from energy production to chemicals - selling specialized, high-end green products, solutions, and services.

4.1.10 Sector coupling

The successful implementation of CCUS involves coupling of a range of sectors across the many possible carbon value chains. Relevant sectors include:

- Carbon capture at CO_2 point sources: energy sector (district heating, electricity, biogas), industry sector, agriculture and forestry sectors
- Carbon storage: offshore sector, agriculture and forestry sectors
- Carbon utilization: energy sector (electricity as resource and heat as biproduct), transport sector, industry sector (materials).

Impact: Optimal sector coupling is a means for maximizing the benefits of CCUS and minimizing the costs. One example is the case of carbon capture and subsequent utilization for green fuels, where the energy losses through excess heat from the carbon capture and fuel synthesis processes can be utilized for district heating. By utilizing the excess heat as district heating, loss is turned into value, which can generate a benefit for the district heating company and the CCU value chain.

Readiness: In the energy sector, there are multiple Danish examples of sector coupling for example combined heat and power plants generating electricity and district heating, and biogas production where industrial and agricultural resources are turned into biogas. The readiness of a given sector coupling would depend on which sectors are coupled and therefore the TRL levels range from highest to lowest.

Challenges: Generally, the complexity of solutions increase when different value streams are combined and coordinated. Existing sector coupling experiences relate largely to the energy sector. In a fossil free future, the energy market as well as the drivers for carbon flow in society will look much different from today and involve new sectors. Consequently, there is a need to (1) identify new sector coupling demands and potentials, (2) establish regulatory means to facilitate responsibilities and incentives and (3) to agree on long term prices on the exchanged products/resources.

4.2 Prerequisites and cross-cutting challenges

The transformation of Danish carbon use, from largely fossil-based to CO_2-neutral green solutions, depends on research, development and innovation in aspects that transcend the technologies described above. These cross-cutting aspects have their own challenges and potentials as described below.

4.2.1 Renewable energy

Although Denmark has already transformed significant parts of its energy supply from fossil-based carbon sources to renewable wind and solar power, carbon-based resources in coals, natural gas and biomass are still heavily used for generating electricity and heating. It is a prerequisite for the green roadmap presented here that the energy sector continues to become progressively decarbonized, such that the Danish carbon budgets become small enough to be covered by predominantly green atmospheric sources. Carbon harvested in biomass or from the atmosphere must in the long-term future (2050) be reserved for chemicals, materials and special fuels, besides, of course, food produced by agriculture.

The energy sector and technology suppliers are preparing for meeting the rapidly changing demands. Relevant partnerships are being formed where industries, consulting companies and research institutes unite to shape the future projects and products. This includes the Copenhagen Carbon Capture Cluster, Energy Cluster Denmark, H2Res, Greenlab Skive etc. These partnerships have ambitions to build the future renewable plants and infrastructure in Denmark, but still there are many technological, regulatory and financial issues to be addressed as highlighted below.

4.2.2 Green hydrogen

The production of green hydrogen is a prerequisite for providing carbon-based renewable fuels through CCU, and thus a major global focus area. CO_2 provides the carbon source for renewable fuels, while the energy content comes from hydrogen. Denmark has strongholds in this area (ref. Hydrogen Denmark) and furthermore also has sufficient potential wind and solar energy to produce the hydrogen.

4.2.3 Digital technologies

Logistics, monitoring, and trust in the CCUS value chain can only be achieved with an efficient, transparent and safe digital infrastructure. Capture, storage, and use of CO_2 involves coordination of many processes with high complexity, critically relying on digital technology research and innovation in areas like:

- Real-time secure monitoring, forecasting, control of conversion and storage processes in highly fluctuating production and consumption scenarios. Research and innovation in IoT, cyber-security, digital twins and program verification is necessary.
- All units in the conversion process must be managed and coordinated in real time by means of models and algorithms providing reliable forecasts based on present data. Research and innovation in efficient distributed data management, computer vision and machine learning are necessary.
- The CCUS materials are intangible and hard to measure. New digital models, algorithms and interfaces need to be developed to create trust and deliver transparent and traceable measures of carbon that can be used as a basis for a dynamic price model for CO_2. Research and innovation in data modelling, info visualization, optimization, game theories and blockchains is necessary.
- Using CO_2 in the energy grid requires digital models that always keep the smart grid in balance within sub-second reaction time. This grid modelling and control become more advanced when more renewable components with different characteristics are added. Research and innovation in distributed systems and coordination without a center of complete knowledge is necessary.

The digital research and innovation will be integrated with chemical, physical and geological solutions. Moreover, a close coupling to the energy sector is facilitated. The research will produce both generic computer science results on methods, as well as interdisciplinary results with the other CCUS research disciplines.

Developing CCUS with novel digital solutions has great business potential both nationally and internationally. Solution providers, consultants, and energy supply companies all have significant business potential. Also, Denmark has unique strongholds within digital research where the IFD DIREC center, NNF Data Science Academy and the Pioneer center in AI (DNRF and more), can contribute with competences and results to be tailored to CCUS.

4.2.4 Integration through modelling

It is critical for the implementation of the roadmap to develop multi-scale integrated modelling capacities for exposing efficient deployment pathways and predicting their effects on CCSU. These modelling capacities must be trans-technical and incorporate both CO_2 uptake and emission from capture, use and storage. Further, it must include economic modelling at both business and societal level, in order to integrate effects of regulation and market development, while identifying spill-over effects to other sectors

To assess the necessary effect on climate, modelling must address, and help us understand, the long-term stability of carbon storage in biomass, soils and materials and how natural processes in the atmosphere-biosphere-ocean system recycle CO_2 on human as well as geological time scales. Upscaled models must link to the global carbon cycle via Earth system and climate models as well as to global economic trade models. This will allow insights into the global effects of carbon capture, use and storage on future climate, and help guide the necessary balance between carbon storage and carbon use over time

The integrated modelling is advanced and will be developed at universities. However, more easily accessible digital tools must be developed already at an early stage of the envisioned partnership to allow stakeholders, as well as policy makers and the public, access to the knowledge that they generate, thereby allowing for insightful decision making and education.

4.2.5 Respecting environment and biodiversity

The roadmap critically depends on the availability of "green" carbon derived from biomass and DAC. Biomass in itself is unlikely to sufficiently deliver all the carbon needed for the roadmap, and therefore the demand for new biomass and thereby also land, which at the same time delivers food, nature and recreative means, will be a critical point. It is crucial that the supply of biomass for the roadmap will be sustainable and respects our responsibility to protect environmental conditions and biodiversity.

5 Implementation gap analysis

CCUS is still in its early phases, and also the societal readiness of implementation is in an early phase. Future implementation – apart from technology development – is to a large extent dependent on interplays between current and potential regulations (national, EU-level, and international), the development of cost of the technologies and costs of capital for CCUS investments, the price/value on carbon, market edge and consumer preferences as well as societal acceptance of the technologies and their impact. While all these areas have uncertainties, funding and development will require a level playing field, achieved by an international CO_2 tax, alternatively regulation on emissions. On that basis, cross cutting economic, legal, regulatory, behavioral, and sociological, and market research will be the basis for a successful implementation of CCUS in society (Fig. 2.2).

5.1 Law and policy

Achieving the overall 2030 and 2050 goals of the CCUS roadmap, as well as UNFCCC and EU climate goals, requires significant and widespread implementation of new CCS and CCU technologies, changed land use patterns and altered consumption patterns. This is critically dependent on clear and foreseeable legal and political conditions. Consequently, a policy and legal framework needs to be established/clarified on both International, EU and national level to create a clear operational space for the technologies. The CCUS framework must be multi-level, addressing both national policies and laws as well as being rooted in and dependent upon EU's policy and law in the area and ultimately international climate change policy and law. All levels of policymaking, law and regulation must be aligned, coordinated, and support each other.

5.2 Regulation – externalities and standards

Besides the need for a national and international legal framework, additional regulation is needed to forward and support an efficient transition and implementation. The specific regulatory needs must be investigated by research addressing relevant externalities arising from current and future CCUS strategies. For a green CCUS roadmap that relies on significant and optimal use of biomass, it is essential that the use and management of land and the biomass production is sustainable, and that biodiversity is not compromised. Therefore, policies and planning regarding resource allocation, biomass-production, nutrient management, and land use as well as environmental and biodiversity consequences and the link to possible alternative initiatives are regulatory critical areas, where research is needed, to identify trade-offs and provide insight into optimal regulatory mechanisms. This should be aligned with existing and coming environmental legislation and obligations that affect land

use and habitat management. Also, internationally agreed, and standardized methods for quantification of capture, storage and utilization of carbon as well as instruments and systems to verify, validate and control the carbon sinks at all scales are needed. Especially for biological sinks in forests, agriculture, and marine systems a credible, science based and applicable method and mechanisms for quantification and pricing of biogenic carbon sequestration must be developed. Furthermore, a green CCUS roadmap operating with multi-source carbon capture and multiple sequestration pathways is critically dependent on transparency in accounting, calling for research in this, for example how new technologies like blockchain can support accountability and hence value chain development. Finally, as the international climate agreements are continuously evolving, and not always in the same direction, we need to understand how national or regional regulation affects global emissions under different sets of international agreements.

5.3 Investments, CO_2-valuation and markets

The realization of the CCUS roadmap requires massive investments in research, development, implementation, and fundamental changes in consumption patterns. Current lack of investment attractiveness and the absence of (private-public) governance frameworks limit the development of economically viable business models for green or non-fossil CCUS. Non-fossil sources of CCUS are for many technologies still on low TRL levels, which adds to economic uncertainty. Therefore, the green CCUS is critically dependent on the establishment of a common and cross sectorial value/price and/or tax/credit of carbon, providing incentives for removing/replacing fossil CO_2, storing CO_2, and delivering green CO_2 for utilization. CO_2 taxes have been proposed as the most efficient and fair means of motivating for change but require strong measures to avoid leakage. CO_2 taxes motivate current actors to implement technologies and at the same time gives incentives to technology development. However, in some situations, it may not be sufficient, or transaction costs are high, and therefore, other types of regulation, and support mechanisms to a CO_2 tax should also be explored. Consequently, a research agenda is needed for modelling and testing scenarios of carbon value development and implications for CCUS attractiveness on both short and longer term (2030, 2050, 2100).

Technology complex	*Legal frame*	*Econ. incentive*	*Regulation*	*Societal acceptance*	*Market edge*	*Behavioral change*	*Other concerns*
CO_2 air capture	CO_2 market	C pricing	-	No	possible	No	Technological
CO_2 point source capture	CO_2 credit	C pricing	Can enhance	No	No	No	Sources depleting
Biomass photosynthesis	MRV needed Land planning	C pricing	Yes	Yes	No	Yes	Land scarcity Biodiversity
Biomass synthesis – algae/industrial	MRV needed		Yes	Possible if widespread	Yes	Possible	No
Biobased structures	CO_2 credit Law on Fossil C	Yes	Yes	Yes	Yes	Partly	-
CO_2 For PtX, chemicals and materials	CO_2 market	Yes	Yes	No	Yes	Unlikely	-
Biorefinery	CO_2 market	Yes	Yes	No	Yes	Possible	-
Storage in geology or minerals	CO_2 market Law	C pricing	International	No	No	No	-

Fig. 5.1: Key concerns and attention points of likely concern across the technology complexes

5.4 Societal acceptance and consumer behavior

Green CCUS is likely to generate controversy at several levels such as dispute over the desirability of technological solutions, fight for scarce economic resources among industrial actors, public dispute over land use decisions etc. (see Fig. 5.1). Therefore, a broad-based societal conversation is needed involving stakeholders at all levels of society, ensuring inclusion and equal representation across stakeholders in such policy dialogues. This calls for research on communication and media formats to enable participatory and deliberative processes at different societal levels addressing public engagement, public acceptance of decisions and implementation of CCUS

strategies, change and motivation in people's behavior and their adoption of new practices, consumption patterns and actions.

Many actors in the value chain will have to transform their way of doing business considerably. Identifying levers in the form of "transitioning capabilities" among various actors', including the demand side, can help understand change capacity and accelerate change. Research into how actors can manage much longer time perspectives than currently is also important as a green CCUS scenario is long range. Both investment and business decisions need new perspectives. The preferences of the public can be both options and barriers for successful implementation. An understanding of what drives these preferences is needed to, in time, address them.

6 Roadmap

The vision is to achieve a fundamental change in the way we view, value, and use carbon resources. To lead the way to this goal a roadmap showing technological development needs, implementation requirements and a supporting finance landscape is needed (overview of elements is shown in Fig. 6.1). The roadmap is built upon the gap analysis (section 4 and 5) describing concrete technical and implementation challenges and solutions, prerequisites and cross-technological challenges (section 4.2), Danish strongholds (section 3.4), and shows the way for the green transition of the future carbon streams. The roadmap will serve as the backbone of the research, innovation and demonstration partnership, which will accelerate the development of the CCUS solutions on a short-, mid- and long-term. Further, elements for kick-starting the partnership are also a part of the roadmap (section 6.1).

Fig. 6.1: Elements that the roadmap is built upon

6.1 The CCUS partnership

6.1.1 Governance

The envisioned Danish partnership will be based on the joint expertise of research at Danish universities, RTOs, clusters and leading industrial partners, determined to kick-start a research, innovation and demonstration platform, that can contribute to achieving the Danish climate goals in 2030 and 2050, while at the same time increasing the competitiveness of Danish business and industry within CCUS.

The role of the partnership is to lead the way towards the goals of the roadmap, while at the same time creating commitment across the entire value chain and engaging with all relevant stakeholders around the partnership - such as investors, NGOs, legislators and authorities. The key success criteria for the platform are to (1) build a Danish knowledge and demonstration hub for development of new solutions and businesses around CCUS, and (2) fostering technical and societal competences, talents and start-ups.

The tentative governance of the partnership (see Fig. 6.2) entails a Board of Directors, a steering committee and a management group. The Board of Directors is the supreme authority of the partnership. It consists of executive leaders representing the three groups of partners (companies, RTOs, and universities), responsible for the vision, financing and external collaboration. The steering committee is the operation authority, with a secretary and an

advisory board to support them. In the steering committee all partners are represented by the head of department-level, sharing responsibility for progress, budget, internal collaboration and communication. The management group consists of work stream leaders responsible for the daily progress, impact assessment, coordination between work streams, sector integration and network activities. The operational part of the governance will be adjusted as the partnership's activities increase.

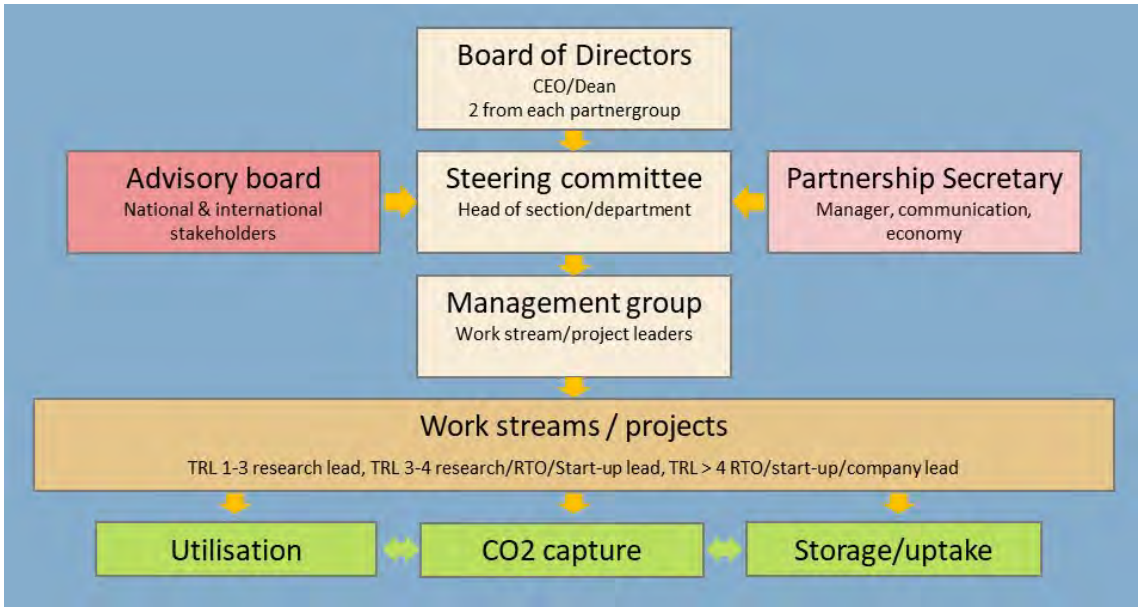

Fig. 6.2: Governance of the envisioned partnership

6.1.2 First year plan

An ambitious partnership that embraces the whole value chain must build on trust and transparency, and members of the board of directors and steering committee will have to allocate time for this. A first-year tasks is to create an overview of ongoing and possible future grants from public and private funds related to CCUS, to ensure good coordination across the partnership. In addition, it is important that partners already in the first year enrol in concrete activities, e.g. in terms of kick-starting research and innovation projects, developing joint EU-applications to expand the international network, and in communication and dissemination efforts to engage with all relevant stakeholders. A tentative timeline for the first-year activities is shown in Fig. 6.3

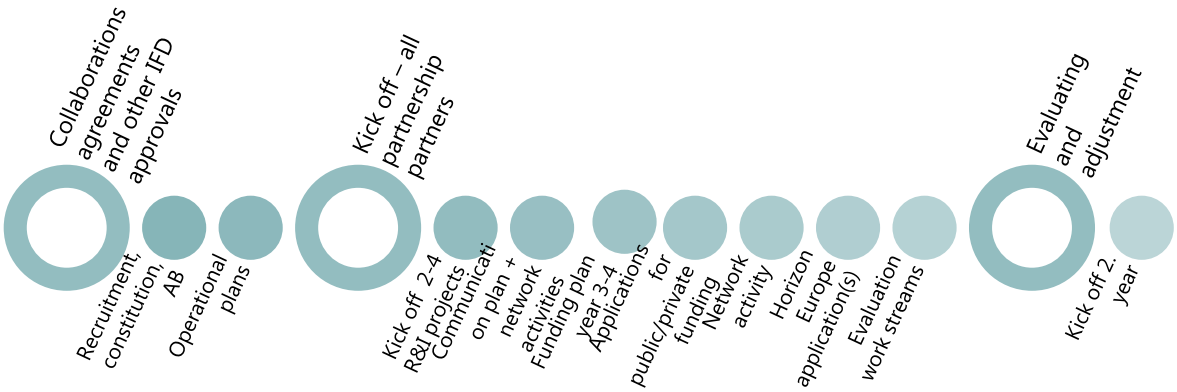

Fig. 6.3: Tentative timeline for the first year of partnership phase

6.1.3 Measurement of specific impact of work streams and projects

Quantifiable assessment of value creation based on accepted standard methods is important to document the progression towards the 2030 and 2050 goal. These standards assessment methods should be used consistent by all Danish partnerships striving to achieve the government's climate goals. In this way, activities can be benchmarked and provide valuable input e.g. for the Danish Council on Climate Change and their annual evaluations.

Until such national agreement on methods and standards has been reached, the assessment will be linked to a risk assessment related to development for the envisioned CCUS sector partnership (see section 6.2). The objectives will change depending on the TRL. Tentative qualitative objectives are listed in the Fig. 6.4.

Research projects (TRL 1-3)	Innovation (TRL 4-5)	Demonstration (TRL 6-8)
• Technology performance as CO_2 potential impact and other potential environmental impacts • Political elements as human resistance	• All of the technical and political elements in Fig. 6.2 can be relevant to address • Assessment of industry loss of competitiveness • Most of the cross-chain elements might be relevant to assess for innovation projects	• All of the risk factors listed in Fig. 6.2 might be relevant and also other more solution relevant elements

Fig. 6.4: Tentative qualitative assessment objectives

6.2 Risk management

The development of a new sector in an international competitive setting involves a broad number of risks. They range from technologies with low TRLs, low SRL-levels for storage, uncertainties related to investment-intensive complicated multi-actor value-chains, the absence of viable business models and uncertainties regarding political regulation (Fig. 6.5). Risk reduction activities should be planned, will vary and involve small scale experiments, large scale testing, continuous systems-analysis and modelling as well as stake-holder involvement. Risk management must be coordinated, and specific risk analysis results aligned with overall expectations for both mitigation and adjustment. Gradually relying more on green CCUS reduces risk in the sense that a multi-source, multi-technology, and multi-actor scenario allows for a diversified pipeline of innovation.

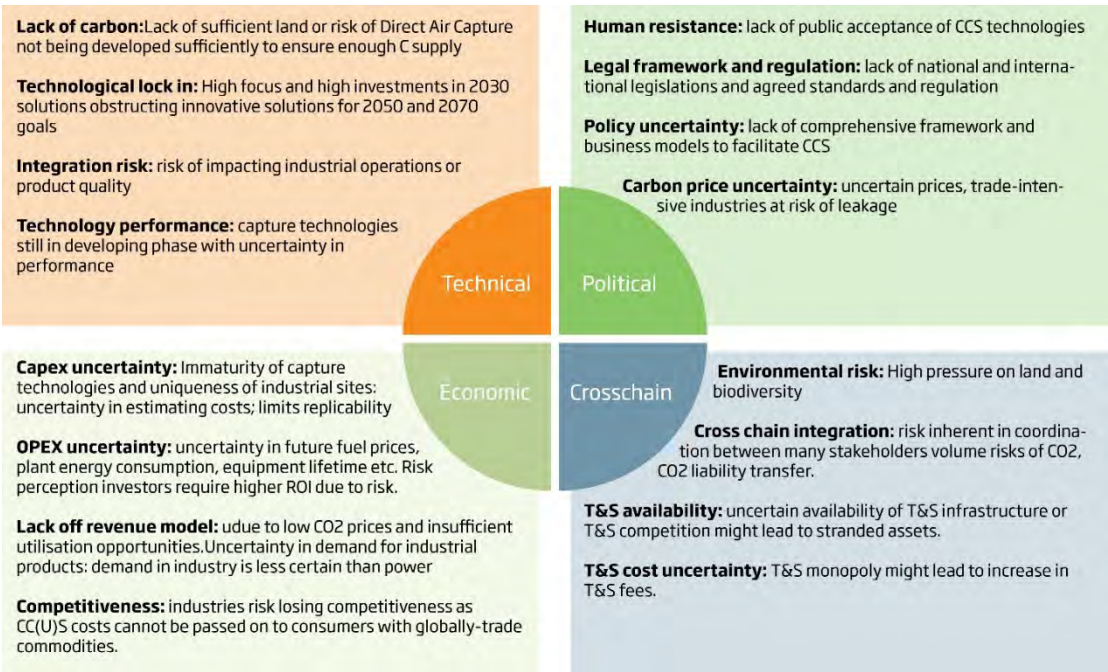

Fig. 6.5: Risk factors of CCUS implementation

There are four key inflection points for development of the CCUS sector (Fig. 6.5), and they will be of crucial importance for the development of the sector, and thus also for the roadmap. If the points are not solved, the roadmap has to be redefined. As a part of the risk assessment and management, these inflection points are in focus, but they cannot be solved by the partnership.

Regulation	Establishment of a common and cross-sectorial value/price and/or tax/credit of carbon, providing incentives for removing/replacing fossil CO_2, storing CO_2, and delivering green CO_2 for utilization is a fundamental requirement. Regulation must be international, and agreed at latest in 2025 for gradual implementation. This is a fundamental requirement for the realization of a fossil-free future.
Lack of biomass/land use	The demand for biomass is increasing globally, and the use of land for biomass production also needs to be considered in relation to food production, reforestation, biodiversity etc. The supply of carbon is a fundamental requirement.
Direct air capture (DAC)	DAC is a key to reaching the net-negative CO_2 emission goal, and as a carbon source in the non-fossil future. Development of the DAC technology is at a low TRL with critical challenges to be solved. If DAC fails to scale up, lack of carbon may become an obstacle to reaching the net-negative CO_2 emission goal
Green Hydrogen	Green hydrogen is a prerequisite for providing carbon-based renewable fuels through CCU. CO_2 provides the carbon source for renewable fuels, while the energy content comes from hydrogen.

Fig. 6.6: The CCUS inflection points

6.3 Technology and implementation roadmap

TRL and SRL are closely related and progression of the two readiness levels will go hand in hand, and will be the precondition for progress and maturation of the CCUS sector. Together with the Danish strongholds and the ability of the partnership, it will be the key elements for the success of this roadmap. Finally, education will become a significant issue and goal for the future. The CCUS development will drive new demands for competences at all levels in the value chain. This is an important priority and precondition for the roadmap. A relevant task for the coming partnership is therefore also a focus on education and entrepreneurship, as lack of competences will result in bottlenecks.

The implementation of the roadmap involves development of several necessary technologies and their integration/interaction supported and facilitated by fundamental and foreseeable societal tasks as economic, legal, and political instruments and in the end also the societal acceptance and consumer behaviour. The range of technologies have different potentials (volume, timeline, sources and scales) and are at different levels of readiness (Fig. 6.7). All technologies are necessary for securing the future fossil free society and involves a mix of decisions and activities from immediate implementation of technologies working at major point sources, the built environment and soils and ecosystems to initiating research and development on low TRL technologies to reach the necessary TRL-levels in time to replace current fossil technologies (Fig. 6.7). Consequently, the implementation involves a cascade of activities applied in close collaboration between all societal actors.

Fig. 6.7 represents the current TRLs for the Roadmap CCUS technologies and expected milestones for the implementation. Technology development and future goals for the roll-out of CCUS technologies will be supported by private and public funding programs dedicated to support the CCUS technology development by 2030 and 2050.

TRL 1 - 3	TRL 4 - 6	TRL 7 - 9	Rollout
Carbon capture at point sources			
Capture from large industry	2023 (7)	2030 (9)	
Capture from biogas plants	2023 (7)	2026 (9)	
Direct CO2 air capture			
Small-scale prototype 2025 (4)	Kiloton scale 2030 (7)	Megaton scale 2050 (9)	
CO2 for PtX, fuels, chemicals, carbon-rich materials			
Solutions for PtX derived carbon-rich molecules. All requires (bio) catalyst optimization, reaction condition exploration, and distributed facilities at CO2-sources	2030 (7)	2040 (9)	
Commercial solutions for PtX methanol derivaties e.g. DME. Ethylene, synthetic kerosene	2030 (7)	2035 (9)	
Plasma technology of processing of CO2	2025 (7)	2035 (9)	
PtX methanation and methanol production	2025 (8)	2030 (9)	
Storage in geological repositories, minerals, soil and sediments			
Subsurface	2025 (7)	2030 (9)	
Mineral & material 2025 (4)	2030 (7)	2035 (9)	
PyCCS 2025 (5)	2030 (7)	2035 (9)	
Blue carbon ecosystem restoration 2025 (5)		2035 (9)	
Biorefinery for chemicals and materials			
Microalgae	2025 (7)	2035 (9)	
Lignocellulosic biomass		2030 (9)	
Green biomasses (incl. grass)	2021 (6)	2035 (9)	
Green processes	2030 (7)	Aqueous catalytic 2050 (9)	
Carbon storage in the built environment			
Building with wood and concrete		2021 (8-9)	
• Biobased materials, agricultural waste products • Reuse of construction wood, modularity • Industrialization of the building industry • Large buildings	2021 (6)	2035 (9)	
Asphalt binders & new composites in the build environment, depending on application		2021 (9)	
Uptake and storage in biomass & ecosystems (incl. marine and biochar)			
• Identification of suitable restoration habitats maximizing C capture • Applying best practice restoration • Adoption of accounting and trade mechanisms that increase incentives for carbon storage in biomass and ecosystems • Novel afforestation practices to increase NPP and C storage		2030 (9)	

Fig. 6.7 - Technology Readiness Levels and milestones for implementation (TRL in parenthesis)

6.3.1 CCUS cost and investment perspectives

Costs and lack of transparent, commonly agreed and stable market/pricing conditions for CO2 are main barriers for the development and implementation of CCUS projects, and therefor also a main barrier for the needed R&D. The estimated cost of CCUS development for Europe could be up to 50 billion euros and the speed at which

CCUS costs can be reduced will be a driver for deployment of large-scale CCUS technologies. The CCUS roadmap relies on a combination of storage and utilization measures (section 4). A recent analysis shows that even if all current available technologies were put to action, c.25% of global GHG emissions would remain non-abatable under current technologies (primarily in seasonal heating, industrial processes, aviation transport and agriculture) (Goldman Sachs[1]) highlighting the importance of "storage" (removals), even in an intensive utilization future.

The CCUS technologies are at very different readiness and cost levels ranging from low cost natural sinks in forested land (<50 USD/tCO_2) to high cost technologies such as DACCS (<400 USD/tCO_2) and with significant uncertainty (Fig. 6.8 and 6.9). At the same time, they operate at different application scales and potentials meaning that DACCS is likely to become an inflection point for a long term solution and having a very high potential to capture CO_2 despite the currently higher costs.

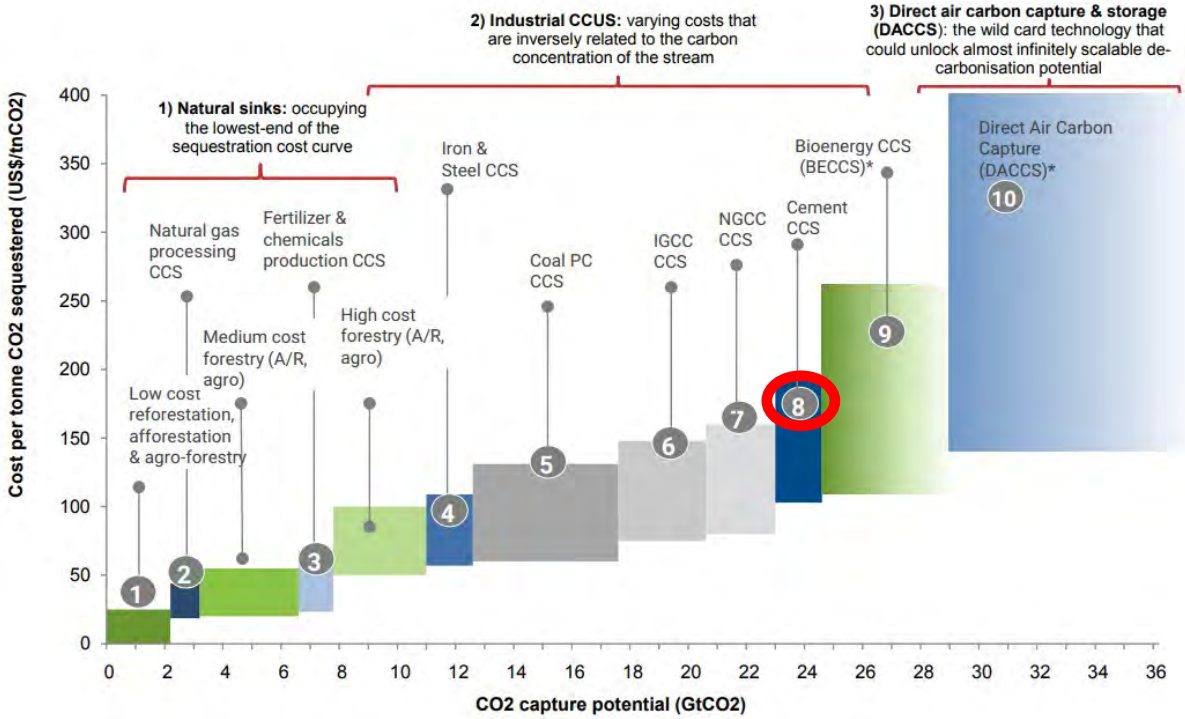

*Fig. 6.8: Carbon sequestration cost curve (US$/tn CO_2 eq) and the GHG emissions abatement potential (GtCO_2 eq). Source: IPCC, Global CCS Institute, Goldmann Sachs Global Investment Research. *DAC technologies still in early (pilot) stage. The read circle indicates that CO_2 capture in cement plants can be less expensive than capture from biomass or coal fired power stations, steel production, etc. See also Fig. 6.9 below.*

[1] https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-green-engine-of-economic-recovery-f/report.pdf

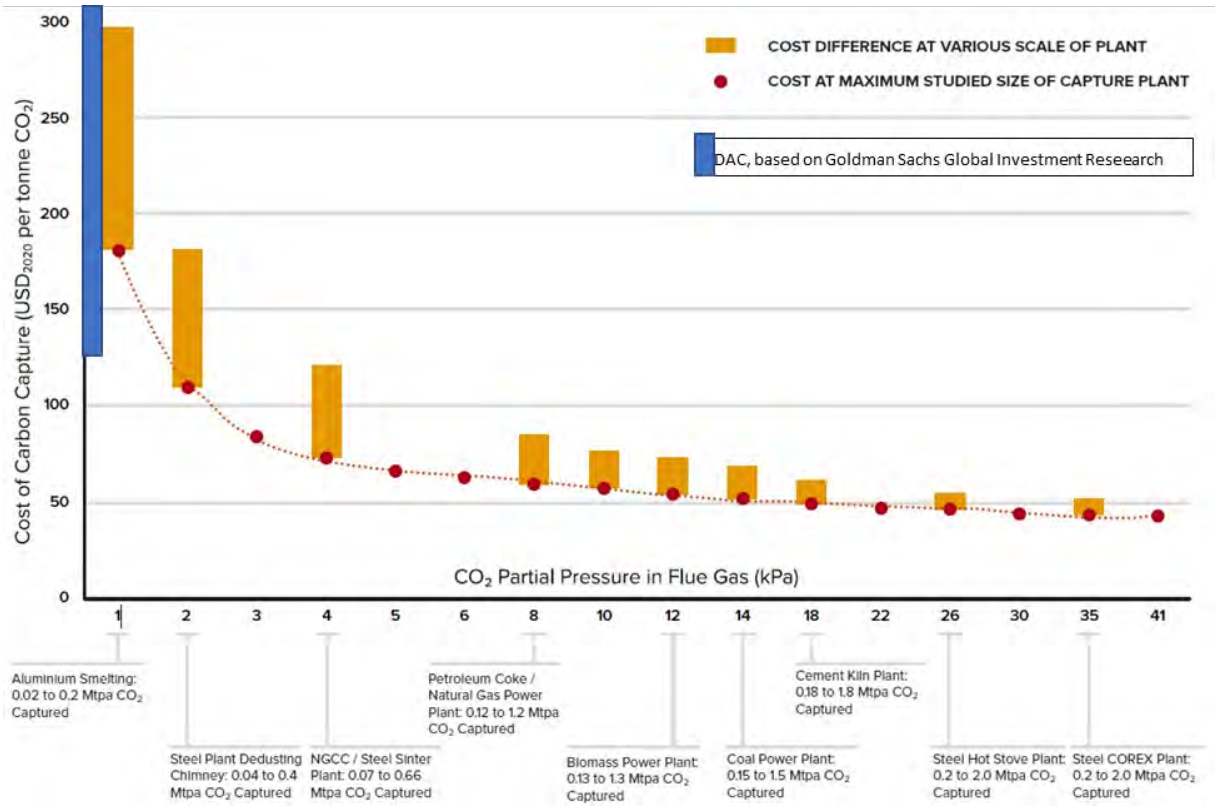

Fig. 6.9. Impact of CO2 partial pressure and scale on the cost of carbon capture. Studied flue gas streams are at atmospheric pressure. The circle marker indicates the cost at the maximum studied size of a single carbon capture plant. Each grey bar indicates the capture cost ranges from 10% to 100% of the scales shown in the callouts for that particular application.

There is a risk of a two-speed de-carbonization process emerging if financial stimulus accelerates the investment in clean tech already at scale (solar, wind, biofuels), while the development of carbon markets and nascent de-carbonization technologies (CCUS, clean hydrogen) may be slowed down or even pushed back (5). This may ultimately delay the technological breakthroughs. Further, massive investments in known technologies or technologies tailored to a short-term solution such as the 2030 goal may become obstacles to investments and development of long-term technologies and solutions. Therefore, de-carbonization may accelerate in the short term, but ultimately delay the long-term path towards net zero. Consequently, governmental legislations and the setting of long term and transparent market regulations such as CO_2 taxes and C/CO_2 valuation mechanisms are essential requirements to facilitate the green transition and development of the markets and long-term investments (Fig. 6.10).

Short-term (- 2025)	Mid to long-term (2025 -)
• Policies and appropriate regulatory framework to ensure transparent investment landscape and cover associated risks. • Mix of fiscal and financial public and private support and investments • Reduced capital cost by intensive R&D efforts in 2. generation CCUS technologies. • Cost reductions by research collaboration and national knowledge sharing. • CfD (Contract for Difference) on CO2 price relative to market CO2 price (e.g. EU ETS) to provide guarantee of revenue. • Market or public reimbursement of industrial CC operational costs • Close international collaboration on regulation and financial instruments.	• International agreed market conditions for CO2 (credits, tax, pricing) enabling investments and operations • Interactions between DK and e.g. the European Innovation Fund securing high up-front capital costs. • Loan guarantees and long-term funding to companies for high-risk projects (close European and Danish collaborative). • Fixed-price funding support providing revenue guaranties. • Public–private risk-sharing model

Fig. 6.10: Financial and regulatory measures for business model elements

6.4 Financial roadmap

The research and development called for by the present roadmap depend on large-scale funding from public and private foundations as well as industry. The source of funding depends on the TRL level, and for the technologies described here, we foresee an overall trend from public research funding to industry funding over time. In the short-term (before 2030) funding from Innovation Fund Denmark will be geared by other public funding (particularly from European sources) as well as private funding and industry.

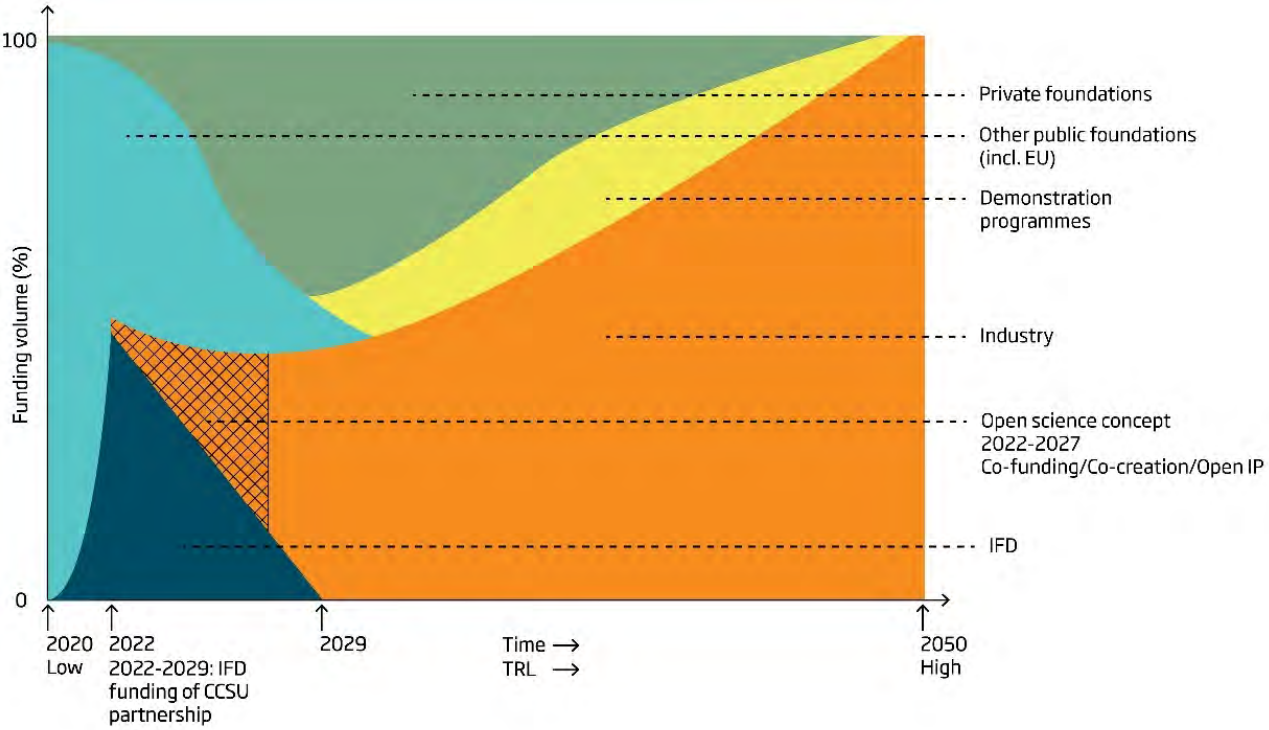

Fig. 6.11: The evolution of the funding landscape with time. The generic figure illustrates how distribution of public-, private-, and industry-funding evolves with time and TRL for technologies that initially start at relatively low TRL levels.

For low-TRL activities we propose to establish an open CCUS platform for research, innovation and development. This open-science platform allows partners from research institutions and industry to meet and collaborate preferably without or with shared IP at a pre-competition stage. The open-science platform is already productive for medicine development (AU's Odin project co-funded by the Novo Nordisk Foundation), and has proven to be an efficient measure for involving scientists from industry and academia in joint early-stage innovation and technology development. Similarly, private foundations have already expressed interest in providing significant funding for several of our roadmap's low-TLR research and development activities. The CCUS partnerships will coordinate closely with ongoing and new research centers that form on the initiative of universities and private foundations.

At intermediate TRL levels, funding from the will be an important stepping-stone to attract European funding and growing our network of international collaborations. Horizon Europe provides good opportunities, for a Danish partnership within its own areas of strength, to take lead on European projects, and thereby involve and build cooperation with relevant European partners. There are relevant calls in 2021, and more are expected within the timeframe of the work program. In addition, it will be relevant for a CCUS partnership to join CCUS-related European partnerships, such a European Partnership on Clean Hydrogen, People-centric sustainable built environment (Built4People), European Partnership for a Circular bio-based Europe, Processes4Planet – Transforming the European Process Industry for a sustainable society, and EIC Accelerator Challenge – Green Deal innovations for the Economic Recovery.

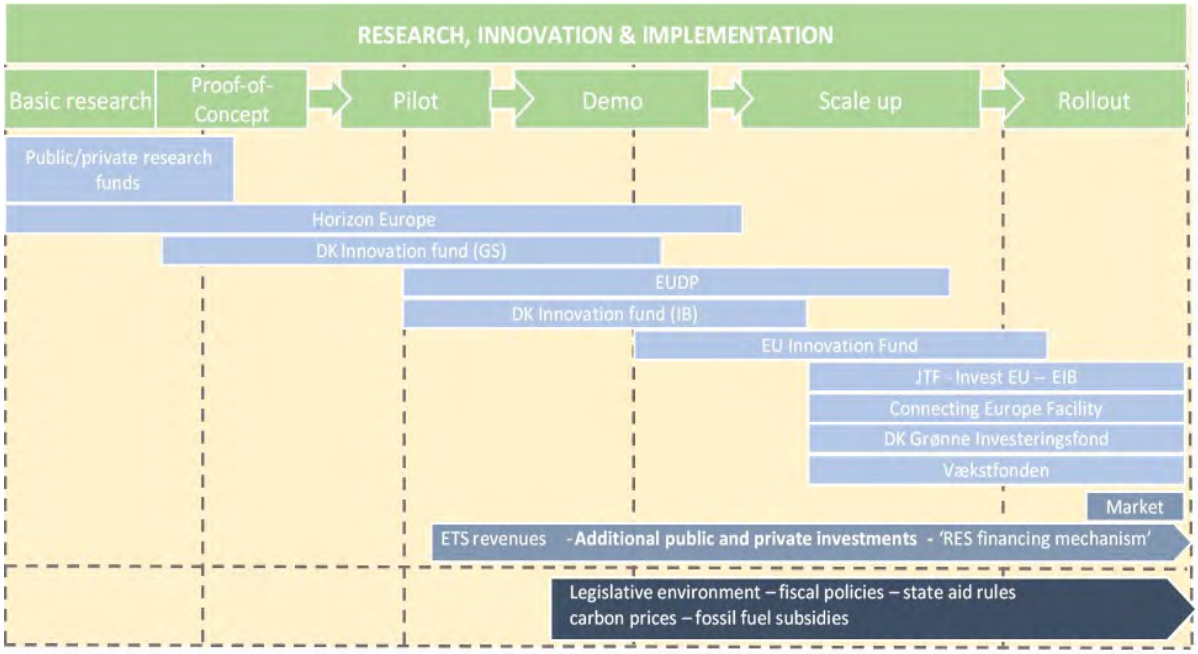

Fig. 6.12: Financial landscape and funding opportunities for Research and Innovation in CCUS

Market-driven industry funding at high TRL

As technology matures, market-driven industry funding becomes progressively more important, while most public and private research funding activities shift focus to support new emerging technologies. This CCUS Roadmap recommends close national co-operation on the repatriation of funding from European funding programs aimed at demonstrating and implementing large-scale CCUS infrastructure. These targeted European financial instruments can greatly minimize the investment risk for industry, and thus provide an incentive to implement new CCUS technologies in the context of research and development programs such as Horizon Europe.

The European Innovation Fund is supporting the demonstration of innovative low-carbon technologies and will provide around €10 billion of support from 2020 to 2030. The Connecting Europe Facility, a €30 billion fund for boosting energy, transport, and digital infrastructure, could be used to fund CO_2 transport. The Just Transition Mechanism that consists of three pillars is part of the Sustainable Europe Investment Plan, which is the finance component of the European Green Deal. Pillar I: The Just Transition Fund (JTF) with a budget of 17.5 billion euros will support the economic diversification and conversion of affected regions, including by investing in small- and medium-size enterprises (SMEs), the creation of new firms, research and innovation, environmental restoration, clean energy, reskilling of workers, job search assistance, and the transformation of carbon-intensive industries. The EU Commission has chosen North Jutland Region as the only possible Danish beneficiary due to the presence of Aalborg Portland. Pillar II: The InvestEU that provides another 1.8 billion euros for investments in a wider range of projects than the JTF, including investments in energy and transport infrastructure. Pillar III: The public sector loan facility that combines a 1.5 billion euro grant component from the EU budget and a loan component of up to 10 billion euros from the European Investment Bank.

In total there are good possibilities for co-funding and gearing of an Innovation Fund Denmark CCUS partnership grant within the first five years. As CCUS becomes more important in the years to come, also globally, the financing landscape is expected to follow this development. Therefore, good financing opportunities are also expected after the first five years of the partnership's lifetime.

7 Closing Remarks

This "Green CCUS roadmap" materialized over six weeks in spring 2021, in an intense and remarkable collaboration between 6 universities, 3 technological service institutes, industry cluster organizations, NGOs, regulation advisors and industries. The process has generated a strong and shared understanding of the utmost importance of the CCUS-agenda for our society and the importance of broad and collaborative engagement of all societal actors along the value chain in our quest to achieve the necessary goal of keeping global temperature rise below 1.5 °C, as defined as a goal by IPCC. It is an ambitious and complex journey, and our roadmap partnership has proven to be complementary, and much stronger than any of the individual contributing institutions.

The work on the ”Green CCUS roadmap” has also very clearly demonstrated how the challenge of developing CCUS to the necessary level of maturity and delivering the necessary contribution is strongly interwoven with the other major societal areas at stake in the current green transformation and in the governments four green missions.

Finally, the work on the “Green CCUS roadmap” has shown that the CCUS mission is not just a technological challenge. The CCUS development has significant implications for land use, environment, biodiversity and societal/human dimensions and it requires clear and strong regulatory and market related means. This highlights the need for clear political strategies and decisions to explore the full and complex potential of CCUS and to facilitate the necessary framework.

Our roadmap was formed in parallel with other roadmaps within the same and other missions, and while our roadmap outlines a coherent and clear path to a fossil-free carbon future, it is evident that strong links, overlaps and interactions exist with the other roadmaps. Consequently, the potential links and interactions must be explored in the further process and the four missions must be implemented in parallel with intentional overlap and coordination.

We look forward to the future work to implement the roadmap.

“Act now, CCUS unlocks full decarbonization of the energy sector” (UNECE)