Environmental Policy

DOI: 10.1007/s10272-022-1060-7

Intereconomics, 2022, 57(4), 260-266

JEL: Q18, Q54, Q55

André Wolf

Sustainable Carbon Cycles: A Framework for the Ramp-up of Carbon Capture?

With its communication "Sustainable Carbon Cycles", the European Commission has opened a new chapter in European climate policy. For the first time, natural and artificial CO_2 capture and storage technologies are to be covered jointly in an overarching regulatory approach. This article reviews the techno-economic potentials of the application fields envisaged by the Commission's strategy, and defines central requirements for a future funding framework. The establishment of markets for carbon credits is identified as a basis for commercialising storage solutions. However, a prerequisite for efficient trading is to create transparency about the climate impact of the technology alternatives. Efforts to improve existing measurement concepts and test procedures as well as the development of certified standards are decisive steps on this path. The time horizon of carbon sequestration should be a crucial aspect in certification and monitoring. Double funding and unnecessary subsidisation of activities that are already profitable today need to be avoided.

With the communication "Sustainable Carbon Cycles" published in December 2021, the European Commission has opened a new chapter in EU climate policy (European Commission, 2021). For the first time, the promotion of both natural and artificial technologies for CO_2 storage is addressed in a comprehensive strategy and thus placed in the spotlight of the European climate debate. The Commission believes that Negative Emission Technologies (NETs) could play a key role in reaching the goal of climate neutrality by 2050. Since upscaling takes a long time, the necessary steps to build up capacities and subsequent value chains must be taken today. At the same time, given the wide range of available technologies, the individual potentials and risks must be assessed. This raises many questions: What potential do CO_2 storage technologies offer against the background of the EU climate targets? Which instruments are necessary to create sufficient economic incentives for their development? What are requirements for the support framework to be developed by the Commission? This article addresses these questions based on findings from the current literature. It analyses the characteristics and economic incentive problems of the various technologies and derives recommendations for a future funding framework.

Open Access funding provided by ZBW – Leibniz Information Centre for Economics.

André Wolf, Centre for European Policy, Berlin, Germany.

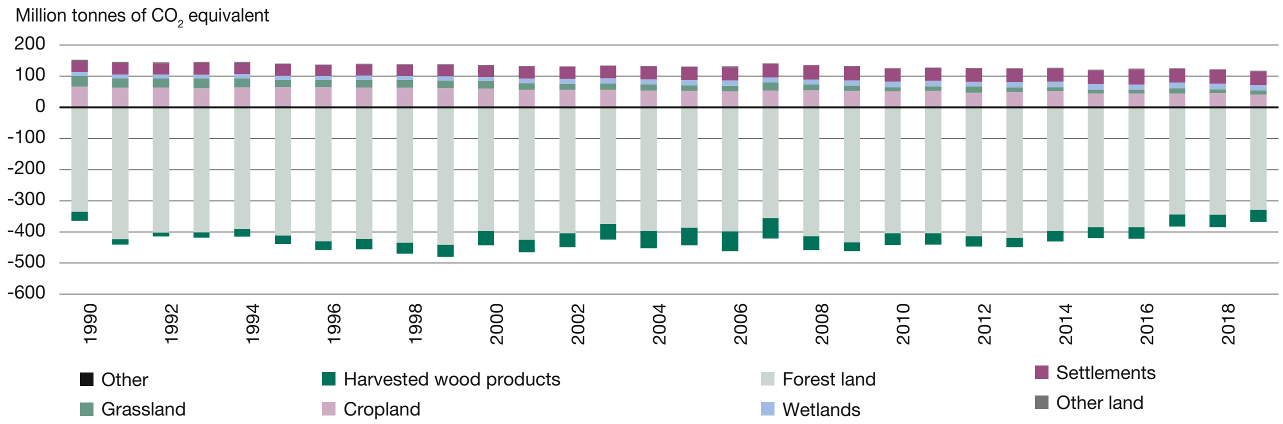
The role of CO_2 storage in climate mitigation policies

A major focus of the debate on CO_2 storage is on NETs, i.e. approaches that aim to remove greenhouse gases (GHG) from the atmosphere. This involves established techniques of sustainable land management as well as more recently explored technologies such as ocean fertilisation, biochar production, enhanced weathering or Direct Air Capture (Minx et al., 2018). This is to be distinguished from CO_2 storage processes that absorb emissions from the combustion of fossil or mineral resources. In the latter case, storage does not cause a reduction in the GHG content of the atmosphere.

CO_2 storage processes play an important role within climate projections, especially when considering the long term. Simulations by the UN Intergovernmental Panel on Climate Change (IPCC) identify comprehensive storage capacities after 2030 as a prerequisite for a realistic chance of achieving the 1.5 degree Celsius target (IPCC, 2018). The International Energy Agency (IEA) also identifies a critical role for storage technologies in its Sustainable Development Scenario, which envisages climate neutrality of industrialised countries by 2050 (IEA, 2021). At the same time, the IPCC warns against naïve confidence in these technologies. Knowledge about their long-term effectiveness and possible climatic and ecological side effects is still insufficient in many fields. In addition, processes for storing other important greenhouse gases besides CO_2 are currently still considered purely speculative (IPCC, 2018). Against this background, the EU Commission is focusing on two categories of measures: carbon farming and industrial carbon capture.

Figure 1

Land use, land-use change and forestry sector emissions and removals in the EU, by main land use category



Source: European Environmental Agency (2022).

Economics of carbon farming

Carbon farming can be broadly defined as all land management practices that aim to reduce GHG emissions and/or increase carbon storage in organic material. A study commissioned by the EU Parliament distinguishes between five areas of carbon farming measures: the management of peatlands, agroforestry measures, measures to increase carbon sequestration in soils, measures in the field of livestock farming, improved soil nutrient management (McDonald et al., 2021). This diversity of measures makes it difficult to compare their climate-related effectiveness. Significant differences can occur not only in the average duration of carbon storage achieved, but also in their vulnerability to external disturbances. In the case of carbon sequestration in soils, additional capacity limits must be considered. Moreover, maintaining the desired effect usually requires a long-term commitment (Thamo et al., 2016). This is an essential difference to climate protection measures in other sectors: A one-time avoidance of emissions in energy transformation or industrial production permanently improves the greenhouse gas balance.

In the EU, the land use, land-use change and forestry (LULUCF) sector is already a regular contributor to net CO_2 emission removals (-249 million tonnes of CO_2 equivalents in 2019), however, with a declining trend. The annual absorption of CO_2 by forests has decreased noticeably over the past decade, while gross emissions from land management have hardly decreased (see Figure 1).

Economically, carbon farming represents a form of service provided by agriculture and forestry to the climate system. Since the benefits of this service are not immediately visible, there are additional costs associated with verifying and reporting its results. On the revenue side, the problem arises that no immediate market for the provision of such a climate service exists. An alternative mechanism may be provided by supply chains. If consumers show a preference for food with a low carbon footprint, there is an incentive for companies in the food industry to reward their suppliers for climate-friendly agricultural practices in the form of higher purchase prices. Moreover, this mechanism can also work beyond the own supply chain if proof of the climate service is declared a tradable product. In this way, external companies get the opportunity to achieve compensation for their own emissions activities through the purchase of carbon credits.

A prerequisite is a high degree of credibility and transparency regarding the climate impact of the carbon farming activities. The resulting information costs should typically be higher for anonymous trading of carbon credits via markets than for supply chain-internal monitoring. However, a restriction to offsetting via the supply chains would miss efficiency potentials. The production techniques of different agricultural products are not equally suitable for the implementation of carbon farming activities; there are significant differences in the cost estimates per tonne of CO_2 stored. Tang et al. (2016) identify a range of \$5 to over \$100 cost per tonne of CO_2 in their literature review. Carbon credit trading could leverage these efficiency potentials by creating a steering effect towards the carbon farming methods with the lowest abatement costs.

In order to reduce the monitoring effort, the instrument of certification is central. A certificate can be used to set clear requirements for the quality of carbon farming practices and the associated documentation obligations, compliance with which is checked by an independent certification body. The resulting certainty reduces costs on both sides of the market. Farmers can adapt to clear standards and draw on related experience, while buyers of carbon credits can better assess their quality and document it to the outside world.

However, the development of a suitable certification system in this case represents a particularly great challenge. It should consider both the diversity of carbon farming methods and the complexity of agricultural systems and related difficulties in measuring climate impacts. Potential impacts on non-climate related parameters such as soil quality should also be included in the formulation of standards.

Australia is a frontrunner in the establishment of carbon credit markets. As early as 2011, the country introduced a system of tradable carbon credits for the land use sector as part of a carbon farming initiative. The operators of carbon farming projects receive carbon credit units for the avoidance or storage of carbon emissions, depending on the number of metric tonnes of CO_2 that are avoided/stored. These can be sold either to a public regulatory body or to private players on the open market. The sale to the regulatory authority is organised via a reverse auctioning process. The projects place bids in the form of the amount of monetary compensation they expect to receive for storing one tonne of CO_2. The projects with the lowest bids are selected by the regulator (Clean Energy Regulator, 2022). In this way, the societal costs for achieving a given storage capacity are supposed to be minimised.

However, research on the Australian system casts doubt on the practical incentive effects of such a mechanism. For example, participation rates among farmers have remained relatively low (Kragt et al., 2017). Surveys identify regulatory and pricing uncertainty associated with participation as the primary barriers. On the other hand, the reasons for implementing carbon farming measures are not so much the prospect of carbon credits but more the individually achieved additional benefits, especially in the form of improved soil quality and yield (Dumbrell et al., 2016).

In general, the economic analysis of carbon credit markets must take into account the significant differences to the established system of emission allowance trading. Participation in the market is not mandatory but is based on a voluntary initiative. Moreover, there is no regulatory cap. Price expectations can also play a different role than in emissions trading. For example, the expectation of rising prices on carbon credit markets tends to have a counterproductive effect on the climate economy: Actors would have an incentive to delay the implementation of carbon farming measures. Also, unlike in emissions trading, the homogeneity of the traded good is not obvious: Carbon farming measures designed to store carbon may differ significantly in the expected storage period and nature of the associated risks. Such differentiation places high demands not only on the certification process, but also on the design of carbon credit markets.

Economics of industrial carbon capture

Industrial carbon capture can be defined as practices of CO_2 separation by means of engineering methods. On the one hand, these can be differentiated according to the origin of the captured CO_2. The CO_2 can be of fossil, mineral or biogenic origin, or taken directly from the atmosphere (direct air capture). A further distinction concerns the destination. The traditional option is to feed the captured CO_2 into air-sealed reservoirs for long-term storage (carbon capture and storage, CCS).

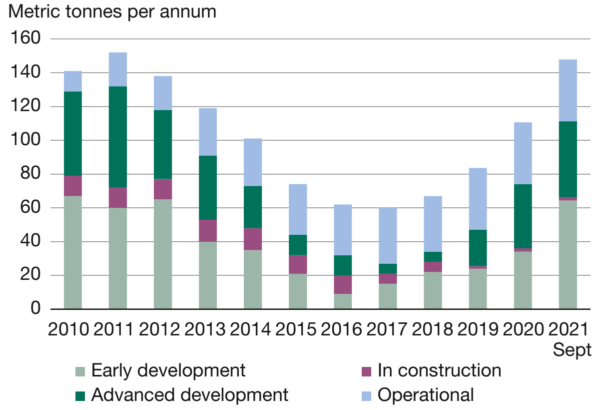
The suitability of CCS as an instrument of climate policy has been the subject of controversial debate for some time. Foremost, the risk of CO_2 leakage cannot be ruled out for the longer term, as studies of existing storage facilities have shown (Jones et al., 2015). Possible side effects of storage, such as acidification of groundwater resources or geological instability, must also be monitored, depending on the location (Gaurina-Međimurec and Mavar, 2019). Moreover, the net contribution of a CCS system to the greenhouse gas balance depends on the source of the carbon. While a combination of fossil fuels and CCS is almost climate neutral at best, a combination of biogenic energy sources and CCS has potential to effectively reduce greenhouse gas concentration in the atmosphere.

Despite extensive support measures, the global capacity development of CCS has fallen short of expectations in recent years. The Global CCS Institute reports a total capacity of about 36.6 million metric tonnes of CO_2 per annum for plants in operation (September 2021). Although the number of planned projects has increased significantly again recently, the expected total capacity of all active and planned plants is also only 149.3 million metric tonnes of CO_2 per annum (see Figure 2). To achieve the climate neutrality targeted in the IEA's Sustainable Development Scenario, storage capacity would have to increase to 7.6 billion tonnes of CO_2 per annum by 2050 (Martin-Roberts et al., 2021). Among the currently operating CCS plants, there are only two significant commercial facilities on European soil, both of which are outside the EU (Norway).

The central economic challenge is the long-term nature of the investment in such a CCS plant. Not only is there a high initial outlay for building the necessary infrastructure, but there are also persistently high operating costs associated with maintenance and energy consumption

Figure 2

Global capacities of carbon capture and storage facilities



Source: Global CCS Institute (2022).

(Boot-Handford et al., 2014). This results in a long payback period. Against this background, regulatory uncertainty represents a major obstacle. Strategic changes in climate policy threaten to produce lock-in effects. In addition, there is uncertainty about the long-term reliability of storage and the resulting cost risks. On the revenue side, there is also uncertainty about the long-term development of the CO_2 price.

At the same time, studies point to significant cost differences between CCS deployment in different industrial processes. Production processes in which the capture of concentrated CO_2 streams is integrated from the outset exhibit a cost advantage. This applies, for example, to natural gas processing, ammonia production and bioethanol production. Other emission-intensive industries, such as cement and steel production face significantly higher conversion costs (Irlam, 2017). The Global CCS Institute's most recent estimates of capture costs range from about $10 per tonne of CO_2 for natural gas processing, fertiliser and bio-ethanol production to over $100 for iron and steel and aluminium production (Global CCS Institute, 2021).

For an economic assessment of CCS, such estimates must be weighed against the abatement costs of technological alternatives with comparable climate impact. Decarbonisation, i.e. switching to carbon-free energy sources and raw materials, is superior to investing in CSS technologies in some fields, not only in terms of independence from fossil sources, but also from an efficiency perspective (Sgouridis et al., 2019). However, not all sectors of the economy with high CO_2 emissions can be decarbonised in a timely manner at a reasonable cost.

Against this background, the use of biogenic carbon and subsequent CO_2 storage (BECCS) appears to be a promising variant. Since such a system implies a net withdrawal of CO_2 from the atmosphere, operators of BECCS projects could expect higher remuneration in a funding system based on climate impact. Since the bioenergy sector itself does not participate in the EU Emissions Trading Scheme (EU-ETS), such a remuneration system has yet to be developed. However, there are caveats against the origin of the required biomass. First, this concerns the capacity of suitable land area. Second, when bioenergy is produced from food and feed crops, there is competition for land with the food sector. Currently, about 20% of bioenergy in Europe (in energy units) is produced from agricultural sources. In the future, the industry association expects this share to increase significantly (Bioenergy Europe, 2021). This may result in new economic dependencies. Simulations show that a significant build-up of BECSS capacity can induce strong price correlations between carbon and agricultural markets. Thus, a long-term increase in CO_2 prices may also be reflected in rising food prices (Muratori et al., 2016).

Direct air capture as a third capture technology can lead to real negative emissions just like BECCS, while avoiding the problems associated with biomass cultivation. However, the lower degree of maturity compared to the other technologies still stands in the way of a rapid roll-out. This applies first and foremost to high energy consumption. This not only affects the economic viability of the technology, but can also, depending on the electricity mix, have a massive impact on its climate footprint (Terlouw et al., 2021). At the same time, the comparatively early development stage offers the prospect of particularly significant learning effects in the future.

On the use side, carbon capture and utilisation (CCU) as an alternative to storing the captured CO_2 has gained relevance in the climate policy discussion. Using CO_2 as a raw material not only avoids the long-term risks associated with storage but can also save resources by replacing the use of fossil or mineral raw materials in production. However, the evaluation is highly process dependent. The IEA (2019) identifies four product categories with future potential: fuels, chemicals, construction materials and fertilisers. To produce CO_2-based fuels, the complementary use of hydrogen is usually necessary. At current process costs, this is the reason for the lack of price competitiveness compared to fossil alternatives in these fields. If the hydrogen is not produced via electrolysis using green electricity, the CO_2 balance of the CCU system is worsened. In the chemical industry, in addition to the established urea production, the use of CO_2 in plastics production is also an option (Muthuraj and Mekonnen, 2018). The use of CO_2 in the production of building materials is particularly attractive from a climate perspective in light of the long life cycle of the products. Technologies currently being researched for this purpose do not require the use of hydrogen as a cost driver. At the same time, they provide the sectors that are particularly difficult to decarbonise with an opportunity to recycle captured CO_2 using their own waste products. For instance, intensive research is being conducted into the mineralisation of CO_2 emissions in the steel industry using steel slag as a basis to produce construction materials. This technology is already considered marketable and climate-friendly (de Kleijne et al., 2022). In the cement and concrete industry, the use of CO_2 in the curing of concrete is being tested, offering the potential for particularly long-term storage (Liang et al., 2020).

The sustainable carbon cycles strategy

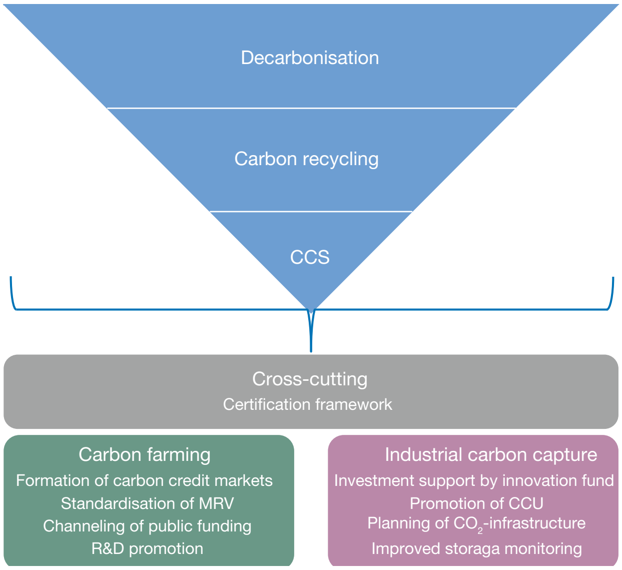
With its Communication "Sustainable Carbon Cycles" published in December 2021, the EU Commission has for the first time outlined an overarching plan for the development of a common regulatory framework for CO_2 capture (European Commission, 2021). The Commission divides its strategy into three fields of action that affect carbon cycles in different ways (see Figure 3).

The first field of action comprises all measures aimed at decarbonisation, i.e. reducing gross emissions by switching to carbon free products and energy sources. This field of action enjoys absolute priority: All potential for decarbonisation must first be exploited before measures to offset gross emissions come into play. The second field involves measures in the area of carbon recycling. The Commission understands these as activities aimed at replacing the use of carbon from fossil resources with alternative processes that remove carbon directly or indirectly from the atmosphere. The Commission emphasises that these activities must be limited to those economic sectors for which decarbonisation is not an option. The third field is the upscaling of solutions for the capture and permanent storage of CO_2 from the atmosphere. In this way, the remaining potential for reducing greenhouse gas concentrations after decarbonisation and carbon recycling is to be exploited.

Carbon capture is thus part of the second and third fields of action of the EU strategy. While the second field aims at the (re)utilisation of the captured carbon, the third field refers to a permanent storage and thus a permanent removal of carbon from its cycle. In both cases, the Commission distinguishes between two basic forms: carbon farming and industrial carbon capture technologies. The strategy paper proposes a variety of instruments for promoting these technologies.

Figure 3

Elements of the sustainable carbon cycles strategy



Source: Own representation.

Instruments for carbon farming

Promotion of tradable carbon credits in land use: The creation of markets for trading carbon credits is seen by the Commission as a way to ensure direct remuneration for activities to reduce net land-related emissions. At the same time, the market mechanism is expected to ensure that activities are focused on those areas of land use where they can be implemented at reasonable economic cost.

Standardisation of MRV procedures: The Commission will set up a group of experts to develop appropriate standards for monitoring, reporting and verification (MRV) of net emissions. In this way, it is also hoped to standardise the recording approaches that currently exist at the national level.

Channelling of support from public funds: Since the returns from carbon farming are delayed, the Commission sees a need for additional government support in the initial phase. The channels of support available to the sector are to be specifically adapted to this purpose. These include Common Agricultural Policy (CAP) funds, Cohesion Policy funds, support for pilot projects under the LIFE program, and additional aid at the member state level.

Support for research and development: In the new EU Horizon Europe framework research program, research into innovative approaches in the field of carbon farming occupies significant space. The Commission first plans to support the establishment of a demonstration network. Later, the use of digital technologies for emission control will be a focal point of research.

Instruments for industrial carbon capture

Expansion of investment support via the EU Innovation Fund: The EU Innovation Fund for commercial testing of emission-reducing technologies, with an expected total volume of around €25 billion for the period 2020-30, also serves to finance CCS projects. The focus here is on funding large-scale lighthouse projects.

Promotion of products: The production of industrial products and energy sources manufactured using captured carbon is to be promoted. This includes, for example, the promotion of synthetic fuels for maritime transport (Commission proposal for the EU Maritime Directive) and air transport (Commission proposal for the ReFuelEU Aviation Directive).

Planning of a cross-border CO_2 infrastructure: The necessary transport and storage infrastructure is to be planned on a cross-border basis in order to give countries the opportunity to participate, regardless of whether they have their own suitable storage sites. In the interest of competition between suppliers and CCS technologies, the open access principle should also prevail.

Improving the implementation of the monitoring system: The EU-wide implementation of the framework for monitoring and risk management of storage sites developed in the CCS Directive is to be improved. To this end, the guidelines for implementation are to be updated against the background of the new objectives.

Cross-cutting instruments

Regulatory framework for the certification of carbon removals: In the long term, NETs should be fully integrated into the existing framework of EU climate policy. As in other cases, the Commission would like to use the instrument of taxonomy and certification to ensure reliability and create trust. This is seen as a precondition for the availability of private funding and subsequent market penetration.

Requirements for a future support framework

From the economic analysis, concrete requirements for a future funding framework for CO_2 storage in the EU can be formulated. Foremost, against the background of existing measurement and monitoring uncertainties, the introduction of a public certification system represents an important step towards creating confidence in the climate effectiveness of CO_2 storage technologies and reducing related monitoring costs. In areas such as carbon farming and artificial storage from biogenic sources, certification will provide a boost to the development of carbon credit markets. Crucial to its impact is the definition of clear and reliable criteria for determining the carbon footprint of technologies and their practical measurement. On this basis, a segmentation of carbon credit markets could be introduced, depending on the respective scope of the climate service provided.

With regard to carbon farming, targeted funding requires that the climate balance of the many, very heterogeneous methods in the field can be reliably weighed against each other. Support for the development of improved measurement methods that sufficiently reflect the complexity of the interrelationships in ecosystems should therefore be given priority in the allocation of funding. An important criterion in the selection of projects to be funded should be, first and foremost, the expected permanence of carbon storage in biomass in the case of land-use storage projects. A further criterion is the additionality of the measures to be promoted, with a view to existing voluntary initiatives and the existing CAP subsidies. In the support mechanism, carbon farming practices should be clearly separated from industrial carbon capture technologies. While the latter in principle offer the prospect of a permanent removal of CO_2 from the carbon cycle, natural carbon sinks are always limited in time. For this reason, carbon credits from land use should not be applicable to offset industrial greenhouse gas emissions.

In industrial carbon capture, the combination of currently still high abatement costs and promising learning potentials justify the envisaged expansion of government support. To overcome CO_2 price uncertainty as an investment barrier, carbon contracts for difference should be introduced as a complementary instrument. When allocating subsidies, it is advisable to bundle them in a targeted manner in key sectors. Today's abatement costs should not be the sole yardstick for this. Instead, differences in expected future cost degression and alternative decarbonisation costs should also serve as criteria. In particular, the steel and cement industries should be classified as potential sectors in this regard. Regarding the use of captured CO_2, priority should be given to projects for productive use over underground storage. Uncertainty about the costs of long-term storage is thus avoided, and raw materials are saved in production. In this way, negative emissions are integrated into the overarching principle of a circular economy. Here, too, support should be targeted: The focus should be on products with a good climate balance from a life cycle perspective. In view of the long-term nature of carbon sequestration, the use of CO_2 in the production of durable goods is a particularly promising area of application.

Conclusion

With the "Sustainable Carbon Cycles" communication, the EU Commission has added a further field of application to its extensive range of climate policy instruments. Under the umbrella of a sustainable carbon cycle, different technologies of CO_2 capture and storage are united for the first time in a common regulatory approach.

Our analysis of the sustainable carbon cycles strategy shows the potential of these technologies, but also the economic obstacles that currently stand in the way of their widespread implementation. To realise their potential for climate protection, government support is currently still indispensable. However, this should not be limited to investment support, but should above all promote the development of new markets for carbon capture. Two factors are crucial for this: reliable monitoring of the climate balance of the technologies and their transparent verification via an EU-wide certification system. At the same time, the variety of technically feasible alternatives makes prioritisation indispensable. The promotion of carbon capture in the land-use sector should depend on the permanence of storage and possible ecological side effects of measures. Industrial carbon capture should focus on economic sectors in which the abatement costs of storage solutions are low compared to alternatives and which are as complementary as possible to the goals of decarbonisation and circular economy in the other sectors. This is an arguement for prioritising solutions of using CO_2 as a feedstock over long-term underground storage. In order to account for differences in the amount of climate service provided, the segmentation of future carbon credit markets is recommended.

References

Bioenergy Europe (2021), Bioenergy Europe Statistical Report 2021 Biomass Supply.

Boot-Handford, M. E., J. C. Abanades, E. J. Anthony, M. J. Blunt, S. Brandani, N. Mac Dowell and P. S. Fennell (2014), Carbon capture and storage update, *Energy and Environmental Science*, 7(1), 130-189.

Clean Energy Regulator (2022), Emissions Reduction Fund, Government of Australia.

de Kleijne, K., S. V. Hanssen, L. van Dinteren, M. A. Huijbregts, R. van Zelm and H. de Coninck (2022), Limits to Paris compatibility of CO_2 capture and utilization, *One Earth*, 5(2), 168-185.

Dumbrell, N. P., M. E. Kragt and F. L. Gibson (2016), What carbon farming activities are farmers likely to adopt? A best–worst scaling survey, *Land Use Policy*, 54, 29-37.

European Environmental Agency (2022), Greenhouse gas emissions from land use, land use change and forestry, European Environmental Agency.

European Commission (2021), Sustainable Carbon Cycles, Communication from the Commission to the European Parliament and the Council.

Gaurina-Međimurec, N. and K. N. Mavar (2019), Carbon capture and storage (CCS): geological sequestration of CO_2, CO_2 Sequestration, 1-21.

Global CCS Institute (2021), Technology readiness and costs of CCS, Global CCS Institute.

Global CCS Institute (2022), CO_2Re Database.

International Energy Agency (2019), Putting CO_2 to use – creating value from emissions, International Energy Agency.

International Energy Agency (2021), World Energy Outlook 2021.

Intergovernmental Panel on Climate Change (2018), Global warming of 1.5°C, An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways.

Irlam, L. (2017), Global costs of carbon capture and storage, Global CCS institute, 16.

Jones, D. G., S. E. Beaubien, J. C. Blackford, E. M. Foekema, J. Lions, C. De Vittor and A. M. Queirós (2015), Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage, *International Journal of Greenhouse Gas Control*, 40, 350-377.

Kragt, M. E., N. P. Dumbrell and L. Blackmore (2017), Motivations and barriers for Western Australian broad-acre farmers to adopt carbon farming, *Environmental Science and Policy*, 73, 115-123.

Leeson, D., N. Mac Dowell, N. Shah, C. Petit and P. S. Fennell (2017), A Techno-economic analysis and systematic re-view of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources, I*nternational Journal of Greenhouse Gas Control*, 61, 71-84.

Liang, C., B. Pan, Z. Ma, Z. He and Z. Duan (2020), Utilization of CO_2 curing to enhance the properties of recycled aggregate and prepared concrete: A review, *Cement and Concrete Composites*, 105, 103446.

Martin-Roberts, E., V. Scott, S. Flude, G. Johnson, R. S. Haszeldine and S. Gilfillan (2021), Carbon capture and storage at the end of a lost decade, *One Earth*, 4(11), 1569-1584.

McDonald, H. A. Frelih-Larsen, A. Lóránt, L. Duin, S. P. Andersen, G. Costa and H. Bradley (2021), Carbon farming – making agriculture fit for 2030, Study requested by the ENVI committee of the European Parliament.

Minx, J. C., W. F. Lamb, M. W. Callaghan, S. Fuss, J. Hilaire, F. Creutzig and M. Dominguez (2018), Negative emissions—Part 1: Research landscape and synthesis, *Environmental Research Letters*, 13(6), 063001.

Muratori, M., K. Calvin, M. Wise, P. Kyle and J. Edmonds (2016), Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS), *Environmental Research Letters*, 11(9), 095004.

Muthuraj, R. and T. Mekonnen (2018), Recent progress in carbon dioxide as feedstock for sustainable materials development: Co-polymers and polymer blends, *Polymer*, 145, 348-373.

Sgouridis, S., M. Carbajales-Dale, D. Csala, M. Chiesa and U. Bardi (2019), Comparative net energy analysis of renewable electricity and carbon capture and storage, *Nature Energy*, 4(6), 456-465.

Tang, K., M. E. Kragt, A. Hailu and C. Ma (2016), Carbon farming economics: what have we learned?, *Journal of environmental management*, 172, 49-57.

Terlouw, T., K. Treyer, C. Bauer and M. Mazzotti (2021), Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources, *Environmental Science and Technology*, 55(16), 11397-11411.

Thamo, T. and D. J. Pannell (2016), Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence, *Climate Policy*, 16(8), 973-992.