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CARBON DIOXIDE STORAGE AND UTILIZATION (CCS/CCU) OPTIONS IN HUNGARY

WHITE PAPER

EXTRACT

2023

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University of Szeged
E. Farkas-Csamangó • P. Gyenes • Cs. Janáky
K. Kádár • Zs. Kószó • M. Lukovics
O. J. Sziebig • M. Törőcsikné Görög

IFUA Horváth & Partners Ltd.
M. Czirók • K. Dobák • E. Gyurity
V. Parragh • S. Sorossy • A. Vass

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Written and edited by:

University of Szeged: Erika Farkas-Csamangó, Péter Gyenes, Csaba Janáky,
Krisztina Kádár, Zsófia Kószó,
Miklós Lukovics, Orsolya Johanna Sziebig, Márta Törőcsikné Görög

IFUA Horváth & Partners Ltd.: Márton Czirók, Katalin Dobák, Erik Gyurity,
Viktor Parragh , Sándor Sorossy, Antal Vass

Graphic design by:
Beáta Árokszállási

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Abbreviations

CAPEX	Capital Expenditure
CCE	Circular Carbon Economy
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCU/S	Carbon Capture, Utilization and Storage
CfD	Contract for Difference
DAC	Direct Air Capture
EKHE	Egységes Környezethasználati Engedély - Integrated Environmental Permit
EOR	Enhanced Oil Recovery
EU	European Union
EU ETS	Emissions Trading System
IPCEI	Important Projects of Common European Interest
OPEX	Operational Expenditures
ppm	Parts per million
R&D&I	Research&Development&Innovation
SMR	Steam Methane Reforming
TRL	Technology Readiness Level
WACC	Weighted Average Cost of Capital

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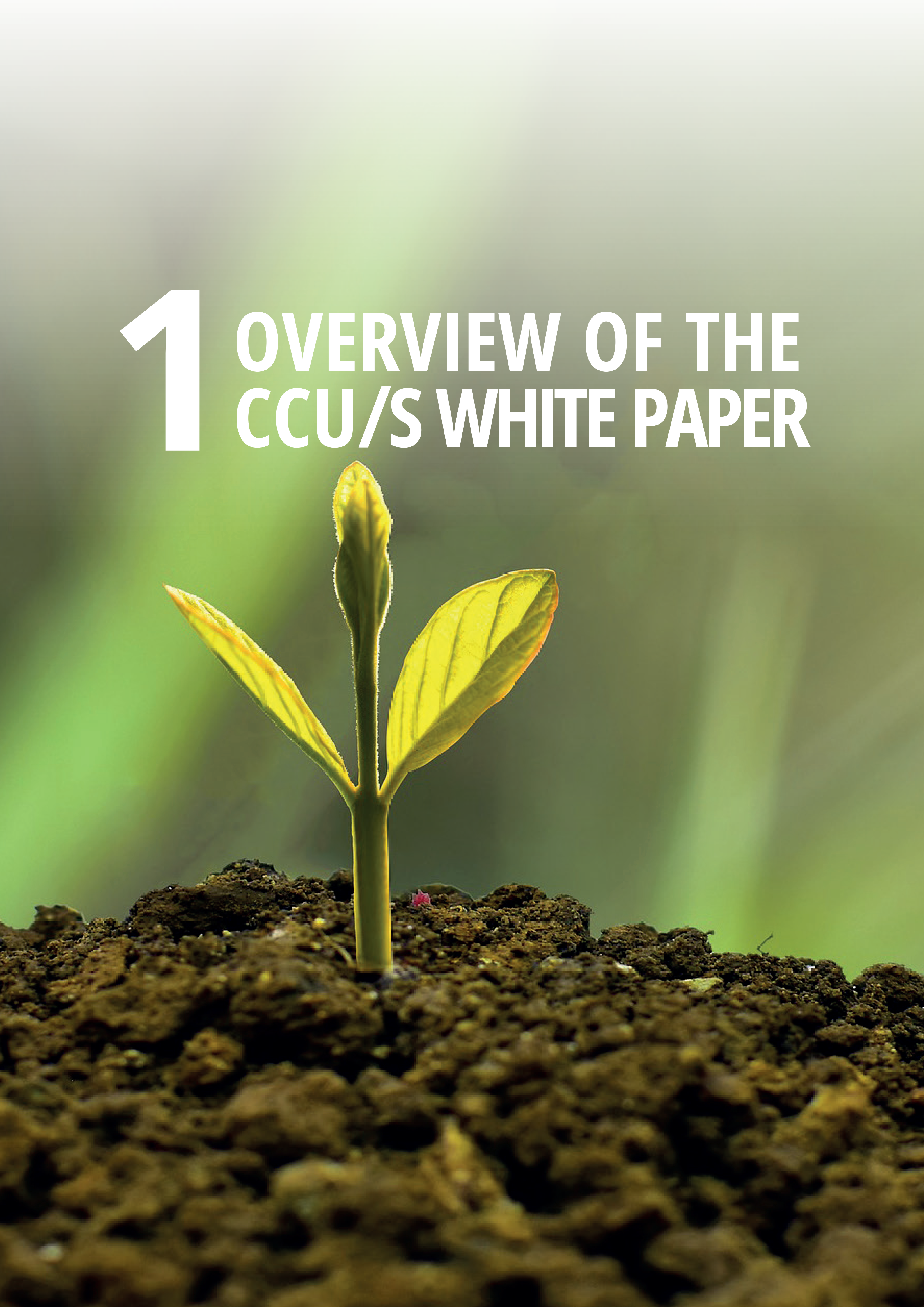

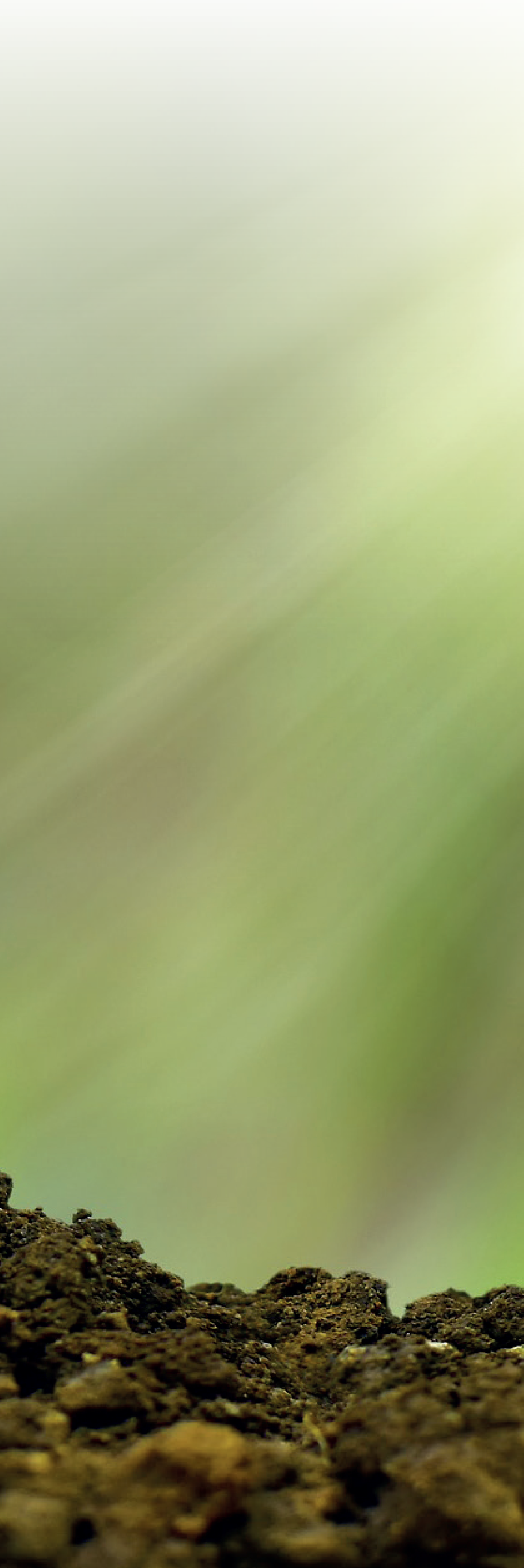

1. Overview of the CCU/S White Paper

The present document is the extract from the White Paper titled "Carbon Dioxide Storage and Utilization (CCU/S) Options in Hungary". The mentioned White Paper addresses the topic of carbon capture, utilization, and storage (CCU/S) technologies with the primary goal to provide a professional basis for the domestic CCU/S industry. This paper can serve as a starting point for the better integration of CCU/S technologies into domestic energy and climate strategies, as well as for helping economic operators to formulate the most suitable decarbonization strategy. To this end, there are comprehensive technological and economic analyses concerning CCU/S technologies and their applicability in Hungary. Alongside solutions of different types, development stages and prevalence, CCU/S technologies are also included in the decarbonization toolkit, and from a technological, economic or legal perspective, they are applied in a complex environment. The White Paper does not only draw on secondary sources, but has been prepared with the involvement of major CO_2 emitters, which allows us to better understand the characteristics of emissions and the emitters' attitude towards CCU/S technologies.

1.1. The role of CCU/S in achieving climate neutrality

There is no one-size-fits-all solution for the transition to a sustainable, climate-neutral economy, it can only be achieved through the application of a wide range of different technologies. In addition to efficiency gains, electrification, hydrogen and sustainable bioenergy, CCU/S plays an important role in decarbonization as well.

CCU/S serves a fundamental role in four areas: (i) tackling the emissions of existing power generation assets, (ii) providing a platform for low-carbon hydrogen production, (iii) solution for sectors that are difficult to decarbonize, (iv) removing CO_2 from the atmosphere to offset emissions that are unavoidable or cannot be directly reduced.[1,2]

CCU/S might be the only alternative to avoid the early retirement of existing power plants and industrial establishments due to otherwise unmanageable emissions, or to allow them to operate at a lower capacity utilization or with alternative fuels. In certain industries, achieving net zero emission is not possible without CCU/S, since efficiency gains, electrification or hydrogen offer only a partial solution. One example is cement production, as it involves significant process emissions not associated with fossil fuel use. We can also mention the iron and steel industry, in which CCU/S-based production is currently the most advanced and cheapest solution for low-carbon steel production. CCU technologies can also contribute to emission reduction by avoiding new emissions using captured CO_2, and, in some cases, by incorporating CO_2 into the final product for long-term storage.[3] In the perspective of circular carbon economy (CCE), CO_2 appears as a new type of resource, the utilization of which opens up previously unexploited opportunities for many industries in terms of reaching their climate strategy goals.[4]

1.2. Policy background

The policy and regulatory background of CCU/S applications is currently under development, however, certain regulatory proposals and programmes of the EU also contain provisions for such technologies. The question of CCU/S appears, for example, in the Renewable Energy Directive[5], the revision of the Emissions Trading System[6], and the REPowerEU plan[7]. Additionally, the Net-Zero Industry Act[8] of the EU set a target for 2030 to reach 50 Mt injection capacity annually in strategic carbon dioxide storage facilities within the EU. Reaching the goal of carbon neutrality set for 2050 encourages the spread of CCU/S technologies. The strategic vision for CCU/S drawn up by the European Commission will be the most significant CCU/S policy initiative of the EU.[9] Work began in 2022, and the official date of publication is expected in the fourth quarter of 2023. To support decarbonization, the EU offers a wide range of funding programmes ranging from research to commercial scale projects[10], among which the most significant financing instruments to support both CCS and CCU are the Innovation Fund[11] and Horizon Europe[12].

In Hungary, the majority of climate-related measures take the form of various strategies. Among the eight target areas of the National Clean Development Strategy adopted in 2021, we can find carbon capture, utilization and storage technologies.[13] The Strategy plans to promote and integrate these technologies into existing systems in the period after 2030, primarily in the energy production sector and industrial facilities with high emission levels. CCU/S technologies are also included in the National Energy and Climate Plan, which anticipates the emergence of power plants supplemented with carbon capture from the year of 2030[14], as well as in the National Hydrogen Strategy, in which the role of blue hydrogen produced by carbon capture will be decisive until 2050[15]. The National Energy Strategy does not deal with CCU/S technologies within the 2030 timeframe, on the other hand, it anticipates the survival of gas-fired power plants, and these plants can thus be potential CCU/S targets in the next 20-25 years.[16]

1.3. Overview of CCU/S technologies

Carbon capture

Carbon capture can be achieved from high-emission point sources as well as directly from the atmosphere (Figure 1). The higher the CO_2 concentration and pressure of the gas emitted, the simpler and cheaper the capture.[17] CO_2 that can be easily captured is typically

found in the chemical industry, natural gas treatment and fermentation (biorefinery) processes,

while in electricity production and the heavy industry, capture requires a more expensive and more complex solution.[18,19] The current atmospheric CO_2 concentration of 420 ppm is harmful for the environment due to the increasing greenhouse effect, but is technically too low for the effective application of capture technologies.

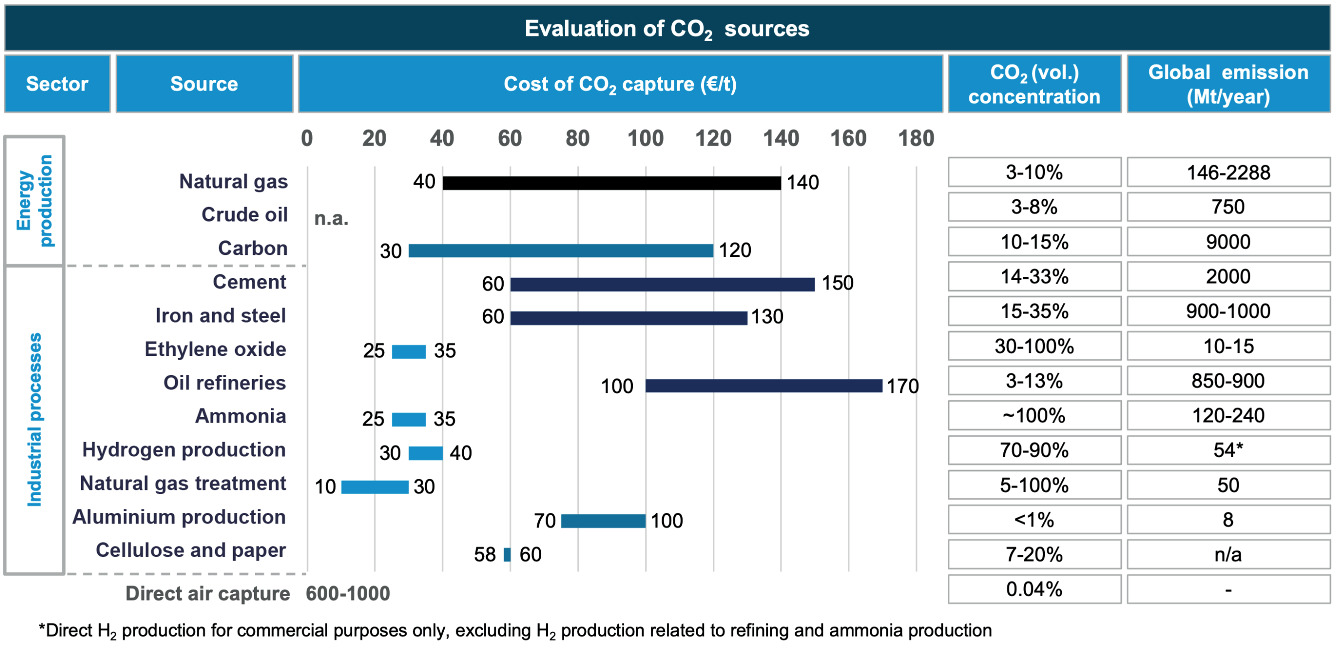

Figure 1 Evaluation of CO_2 sources, own edition based on [17,19].

Numerous technological methods are available for CO_2 capture, which allows for the given industrial process to select the solution most beneficial from a technical and economic point of view (Figure 2).[20] The three main method groups are pre-combustion/conversion capture, post-combustion/conversion capture, and capture after oxy-fuel combustion.[21] The fourth group could be the emerging technology of direct air capture (DAC).

In the case of the pre-conversion method, CO_2 is captured during steam methane reforming or coal gasification processes.[19,20,22] It is a typically complex solution with which CO_2 can be captured relatively easily but at high investment costs, however, it can only be applied in certain industrial technologies. It is primarily characteristic of industrial processes that produce synthesis gas from hydrocarbons (e.g. SMR-based hydrogen production).

	Post combustion			Pre combustion			Oxy-combustion
CO_2 Capture method	*CO_2 is captured from the flue gas produced during the combustion of fuels*			*Before burning fuels, CO_2 is separated, typically from synthesis gas*			*Clean flue gas by combustion with O_2*
strengths	Suitable for renovation of existing plants - preservation of existing infrastructure; well applicable to most existing coal-fired power plants Significant progress is still to be made in this field			High pressure and CO_2 concentration -> lower costs			Very high concentration of CO_2 in the flue gas
drawbacks	Low pressure and CO_2 concentration in the flue gas -> high power, energy demand and cost of CO_2 capture Output CO_2 at lower pressure - further compression required			Complex solution: it is not enough to capture the flue gas, a process is required where the fuel is pre-treated (e.g. SMR, gasification)			High O_2 and heat demand, which significantly increases energy demand and costs
CO_2 capture technology	**Absorption**	**Adsorption**	**Membrane sep.**	**Absorption**	**Adsorption**	**Membrane sep.**	**Air separation**
	CO_2 is passed through liquid phase	*CO_2 binds on a solid surface*	*CO_2 seperated by membrane*	*CO_2 is passed through liquid phase*	*CO_2 is bound to a solid surface*	*CO_2 seperated by membrane*	*Separation of oxygen from air*
strengths	Capable of trapping low concentration of CO_2	TSA, VSA technology can be used well, but only on a smaller scale	Scalable technology	Well known technology Low energy consumption	PSA: low energy demand due to high pressure Improved waste management	Well-known technology in natural gas management Efficient at high pressure and stable gas flow	Due to the combustion with O_2 instead of air, the difficult separation of N_2 and CO_2 is not required Output CO_2 is of high purity
drawbacks	Solution regeneration required Corrosion, degradation	TSA: not yet efficient on an industrial scale due to high heat demand	Very inefficient technology at low pressure	Solution regeneration required Corrosion and degradation	CO_2 can be separated from the solid adsorbent with low efficiency	Multi-step process by which CO_2 is separated, therefore more complex technology	A continuous high-volume oxygen supply is required, resulting in significant costs and energy Extremely high temperature required
Technology readiness	*Mature (TRL9)*	*Mature (TRL6)*	*Mature (TRL5)*	*Mature (TRL9)*	*Mature (TRL9)*	*Pilot (TRL7-8)*	*Mature (TRL5-6)*
Area of application	Ammonia, refining, chemical industry (SMR H_2) IGCC power plant	Ammonia, refining, chemical industry(SMR H_2) Power plant (coal, gas) Iron-steel, cement	Power plant (natural gas)	Ammonia, refining and chemical industry (SMR H_2) IGCC power plant	Ammonia, refining, chemical industry (SMR H_2) IGCC power plant	Natural gas treatment	Power plant (natural gas, coal), cement manufacturing, iron and steel

strengths · *drawbacks*

Figure 2 A summary evaluation of the most significant carbon capture technologies, own edition.

With the post-conversion method, CO_2 is captured from the flue gas after the burning of fuels.[19,20,22] This solution can be applied to almost all existing high-emission power plants and industrial facilities, but due to its significant energy demand, the cost of capture is high.

In the case of the oxy-fuel method, fuel is burned with oxygen instead of air, and the resulting clean CO_2 stream can thus be captured.[19,20] It is an energy-efficient solution that can only be used in certain processes with high investment costs. By utilizing the oxygen produced as a by-product during electrolysis-based hydrogen production, this method opens up opportunities for synergies and innovation.

Sequestration or separation processes are closely related to CO_2 capture methods used to purify CO_2. There are several sequestration technologies available, from which the appropriate solution can be selected based on the specific capture method, the given industrial process, and the characteristics of the CO_2 stream. The main capture processes are chemical and physical absorption, adsorption, membrane separation, the process based on change of state, and chemical looping. Several unique technical solutions are available within these categories. The most widespread and mature technology is chemical absorption, which can be used in the case of low CO_2 concentration and large volumes in both pre- and post-combustion methods.[20,23–25] Physical absorption is a mature technology applicable on an industrial scale and at high CO_2 concentrations.

Adsorption can also be used on a small scale and requires low energy.[20,23–25] Membrane separation is effective at high pressures and high CO_2 concentrations, and it is an otherwise mature technology in its demonstration phase to be applied in the chemical and heavy industry. The change of state based, liquid or supercritical technology is currently under development, is applicable to high CO_2 concentrations, and enables direct production and the high-pressure storage of liquid CO_2. Chemical looping is a promising yet low-maturity technology that can be used for oxy-fuel and pre-combustion solutions in power plants and during synthesis gas production.[26] The special case of this method is the more mature calcium looping technology.

Besides the ones listed above, many additional CO_2 capture technologies are available, or are in the research and development phase, all of which are remarkably diverse both in terms of the area of application and maturity level.[24,27–29]

Transportation and storage

The location of CO_2 capture does not necessarily coincide geographically with the location of storage and utilization, so transportation is required. Transport modes currently available on a commercial scale are pipeline, rail and road transportation, water transportation is available only in a demonstration phase. The main selection criteria for the appropriate solution are transport capacity, investment and operation costs, and distance.[24] Pipeline and water transportation are the most cost-effective solutions for transporting CO_2 over long distances and in large quantities.[30,31] The conversion of existing oil or gas pipelines may result in cost savings of up to 90-99% compared to the construction of new pipelines, however, the technical requirements for conversion are not always satisfied. The cost of rail and road transportation can be competitive only for smaller emission plants and over short distances. In addition to the above, working out complex transport solutions, such as transport centres and clusters based on the aggregation of demands, would also allow for cost reduction through the sharing of resources, the application of different transport solutions, and the centralization of handling and preparatory activities. Geographical proximity offers the opportunity for CO_2 emitters to co-create a CO_2 capture and/or storage cluster and, through an extensive infrastructure, to join a large-scale CO_2 storage facility.

The long-term storage of CO_2 is primarily possible in underground geological formations, with the depleted oil and natural gas fields and deep salt water formations (aquifers) being the major options.[24] Other possibilities include coal depots unsuitable for extraction, and basaltic/ultramafic rocks. Enhanced oil recovery (EOR) and coalbed methane production offer solutions for both utilization and long-term storage. The technology of CO_2 injection in depleted hydrocarbon fields is a decades-long mature technology. Storage is proven to be leak-proof and easy to monitor. For all these reasons, the above technologies are currently the preferred geological storage solutions. Less CO_2 injection experience is available in the case of saline aquifers. They are more expensive to construct, but can safely store large quantities. Several high-volume storage demonstration projects are currently being run.

The identification and construction of appropriate sites suitable for geological storage is expensive and can take a long period of time (up to 5-12 years).[32] The long-term and safe storage of CO_2 is confirmed by monitoring systems both during and after the injection period. The possibility of underground CO_2 leaks causes a safety concern for the population, which, in many instances, led to public resistance against CCS projects. However, based on several decades of experience with large-scale CO_2 storage, the risk of leakage into the atmosphere or the risk of groundwater pollution is low and can be managed effectively.

Utilization

Besides storage, the utilization of captured CO_2 is gaining more and more importance as it is used as raw material in many industries, and can play a role in the production of high value-added products (Figure 3). Today, around 230 million tons of carbon dioxide are used on an annual basis.[17] The direct utilization of CO_2 is primarily significant in the food industry, beverage production, pharmaceutical manufacturing, medical treatments, and the oil industry.[20] The methods as regards direct use are mature and commercially available technologies, and many promising new processes are being developed or introduced on a commercial scale (e.g. desalination, greenhouse yield enhancement). Through chemical or biological conversion, CO_2 can be principally used in the production of chemical products and plastic, synthetic energy carriers, construction materials, and biological products. The technology readiness of conversion-based utilization methods varies considerably, ranging from the commercial scale application to laboratory demonstrations. Thanks to the increased research and development activity and the growing number of pilot projects, the procedures are constantly developing and new, promising areas of application emerge.

Speaking of the various CCU solutions, the CO_2 utilized and so bound in the product is returned to the environment and to the carbon cycle at different time intervals, and can therefore also serve periodic storage functions.[18] Direct use and e-fuels have the shortest, shorter than 1-year CO_2 retention time. Chemical materials can bind the carbon dioxide used in their production for a few years, while polymers can bind CO_2 even for decades. The CO_2 retention time of construction materials is particularly long, and can serve storage functions for centuries.

The market potential of certain CCU products can be estimated based on their CO_2 binding capacity and current market size.[33] The chemical industry has great CCU potential, as it is able to utilize a large amount of CO_2 in the production of many products, the market of which is constantly expanding. In the case of energy carriers and fuels, a high CCU potential is expected to be achieved in submarkets (e.g. e-kerosene) thanks to the large number of different, competing green technologies available. The CCU potential of polymers is expected to increase, since their long retention time may attract industries seeking low-carbon plastics (e.g. car manufacturers). The CCU potential of construction materials is also high, as their market size is significant and there are few decarbonization alternatives available in the industry. As regards biological products, an increase in CCU potential is also expected due to their remarkable binding capacity, but their current market size is rather small.

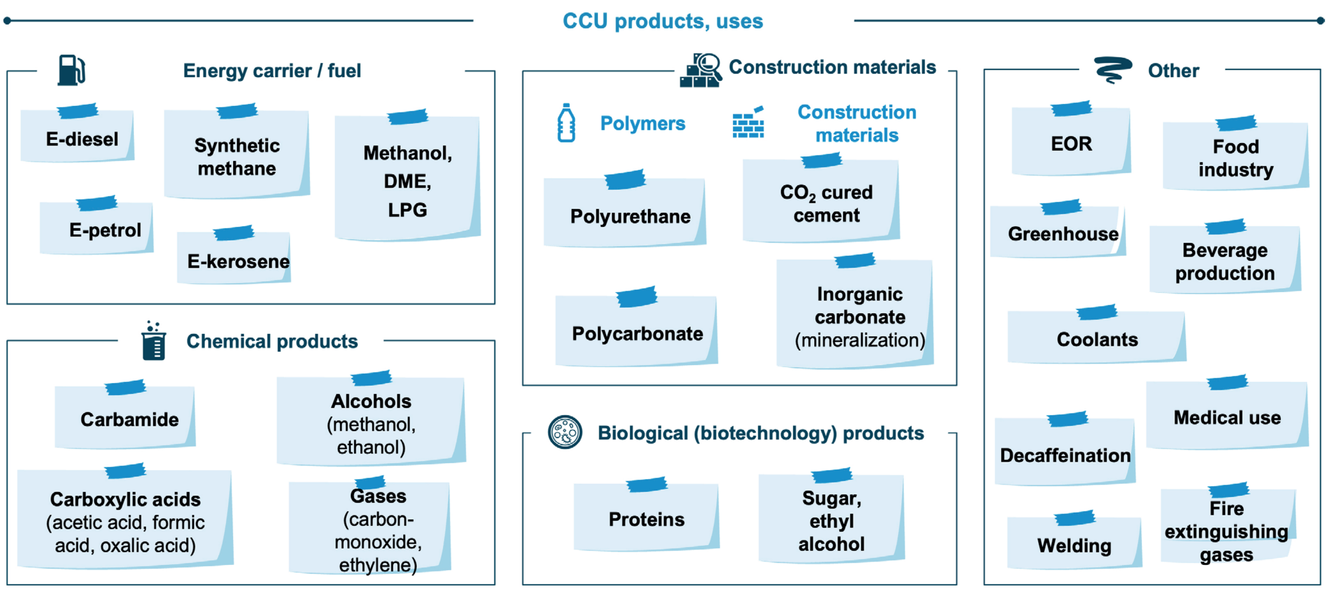

Figure 3 CCU products and their area of application, own edition.

Technology readiness along the value chain

There are mature technological solutions available for all elements of the CCU/S value chain, and new solutions have also emerged in many areas (Figure 4). Most of the technologies have already reached TRL 4 level, and by 2030 most of them may enter the TRL 7-9 phase or may reach commercial deployment. Despite high technology readiness and availability, a number of solutions have not yet become widespread as it would require additional support and incentive systems.

International use cases

There are many CCU/S applications in Europe and worldwide ranging in size and scope from laboratory development and demonstration projects to industrial-scale facilities and established clusters. Western and northern states are at the forefront of introducing CCU/S technologies in Europe. In this White Paper we have outlined international examples of CO_2 capture projects in the production of construction materials, the hydrogen production, the chemical industry and energy production, and have also described related CO_2 utilization applications.[54–60] Furthermore, we have presented two European CCU/S clusters currently under formation, in which, in addition to capture, storage also plays an important role.[61–63] The examples described cover only a small percentage of CCU/S projects in operation. The database of the professional organization named CO_2 Value Europe shows a total of 79 completed and 84 ongoing CCU/S projects in Europe.

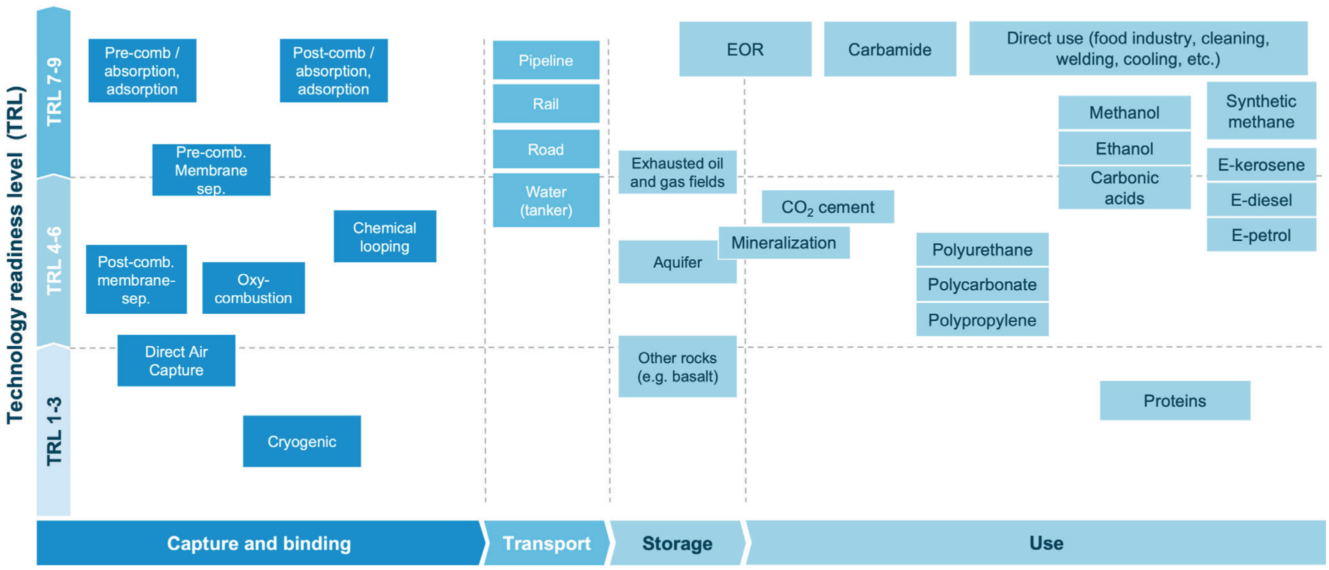

Figure 4 CCU/S value chain – technology readiness map (2023), own edition based on [23,34–53].

1.4. Domestic relevance

Hungary's annual CO_2 emission is estimated to equal 47 million tons, almost half of which, approximately 22 million tons per year, are relevant for capturing carbon dioxide.[32,64] Sectors with the highest emissions are the energy sector (public electricity and heat generation), the chemical industry (primarily ammonia and ethylene production), and petroleum refining, the mineral industry (mainly cement production), and the metal industry (iron and steel production). The spread of CCU/S in many industries can contribute to the increase of supply security by maintaining domestic production and reducing foreign exposure, the demand for imports. In electricity production it can also facilitate the maintenance of flexible gas-fired power plant capacities with low emission, which then helps the spread of planned weather-dependent renewable production.

In terms of the spread of CCU/S technologies in Hungary, domestic ammonia production and the chemical industry have the most favourable conditions. We can also expect to see its emergence in the domestic metal industry and cement production, since, despite their less favourable attributes, their emission is significant, and the number of alternative decarbonization solutions are limited. In the energy sector the preservation of existing infrastructure, the improvement of network flexibility, and the preservation of supply security are likely to lead to the spread of CO_2 capture. In Hungary, CO_2 capture solutions are already present in the chemical industry and petroleum refining, and the adaptation of international technologies to domestic conditions, the development of new, own technologies can also contribute to the spread of CO_2 capture technologies.

In Hungary, pipeline transportation will play a decisive role in the large-volume transmission of carbon dioxide. The method of pipeline transportation is initially expected in the case of large energy and industrial point sources, since the construction and operation of an own, independent infrastructure can offer an economically profitable solution. These lines can later serve as the backbone necessary for forming CO_2 transport clusters. Companies related to the oil and gas industry and to natural gas distribution have the competences required for the planning, construction and operation of the CO_2 pipeline infrastructure. By renovation and conversion, certain sections of the natural gas network covering the country can be made potentially suitable for the transport of CO_2, which can then result in significant cost savings. Rail and road transportation in Hungary are currently available solutions for the transport of carbon dioxide, but they will only play a limited role in the development of the CCU/S industry; their emergence is primarily expected in the case of lower quantities or quantities that vary over time.

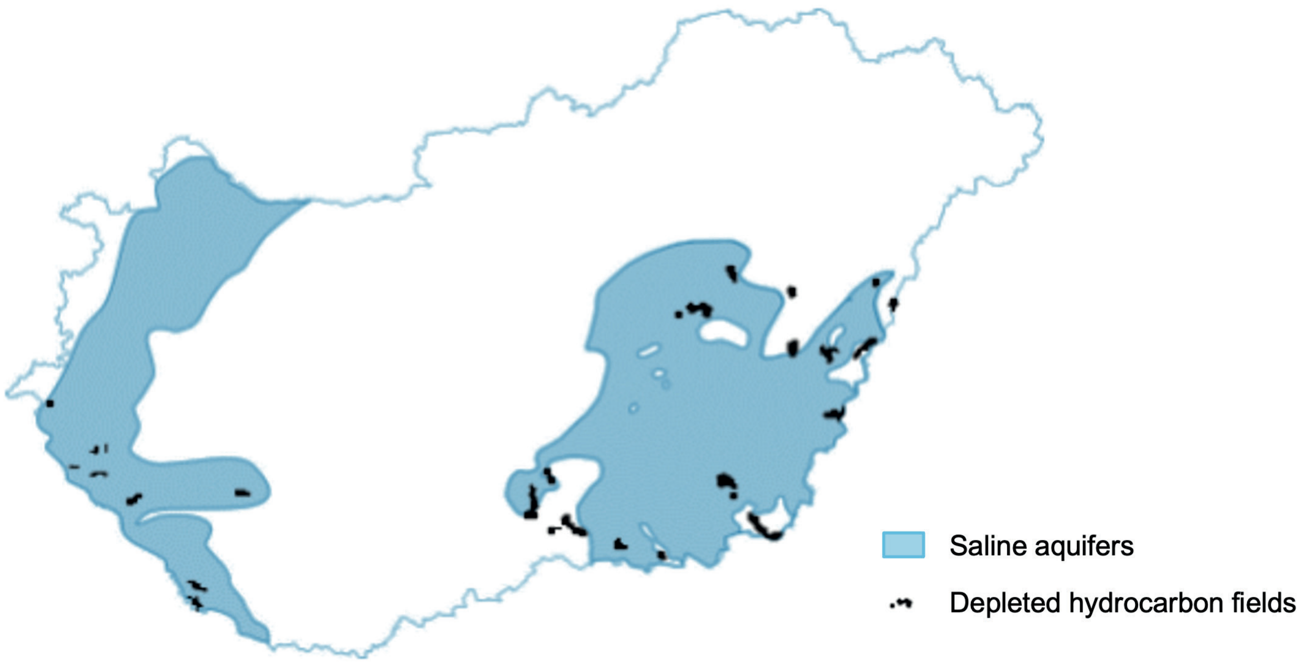

Figure 5 The geographical location of geological formations suitable for underground CO_2 storage in Hungary, own edition based on [65].

Depleted oil and natural gas fields, and saline aquifers are available within the territory of Hungary for the long-term and safe storage of large amounts of CO_2 (Figure 5).[65] Domestically captured CO_2 can initially be stored in depleted hydrocarbon fields, since these fields can be used cost-effectively and are already available in the short term. Thanks to decades-long experience in extracting from the country's oil and natural gas fields, there is a significant amount of knowledge and data at our disposal, and domestic stakeholders have the technology, the knowledge, and the skills necessary for compression and safe storage. In these formations, a total of approximately 25 million tons of CO_2 storage capacity can be set up economically, which number can be further increased with the help of incentives and state subsidies. In the later stages of the development of the CCU/S industry, domestic saline aquifers can play a decisive role with a *theoretical* capacity of 2,100-2,700 million tons that can account for up to 80% of the total storage volume in the country.[65,66] There is no domestic experience in compression and storage related to these formations, and in the course of researches carried out so far, aquifers have been surveyed only at a regional level. At the international level, however, demonstration projects on the exploitation of aquifers have already been launched. In Hungary, due to more competitive alternatives and the technological uncertainties these solutions create, the spread of geological storage possibilities other than those mentioned above is highly unlikely.[67]

In Hungary, captured carbon can be utilized in many sectors. In addition to the sectors that currently generate demand, new markets are expected to join in with the development of CCU/S technology (Figure 6). Currently, the food industry and the beverage industry are the most significant CO_2 receivers. The market for these sectors is small and there are few opportunities for growth. Market demand, however, is satisfied by the currently mined CO_2, the substitution of which has obvious environmental benefits. Another significant domestic user is fertilizer production. With the development of CCU/S industry and the maturation of relevant technologies and processes, domestic use of captured CO_2 is expected to be used in the chemical industry, construction material production, synthetic fuel production, polymer production, and, at a later stage, in agriculture as well. The domestic spread of CCU/S applications is generally limited by the fact that there are natural CO_2 reserves of considerable size and purity in the country. Extraction is relatively easy and cheap, so in the current regulatory environment they provide a more

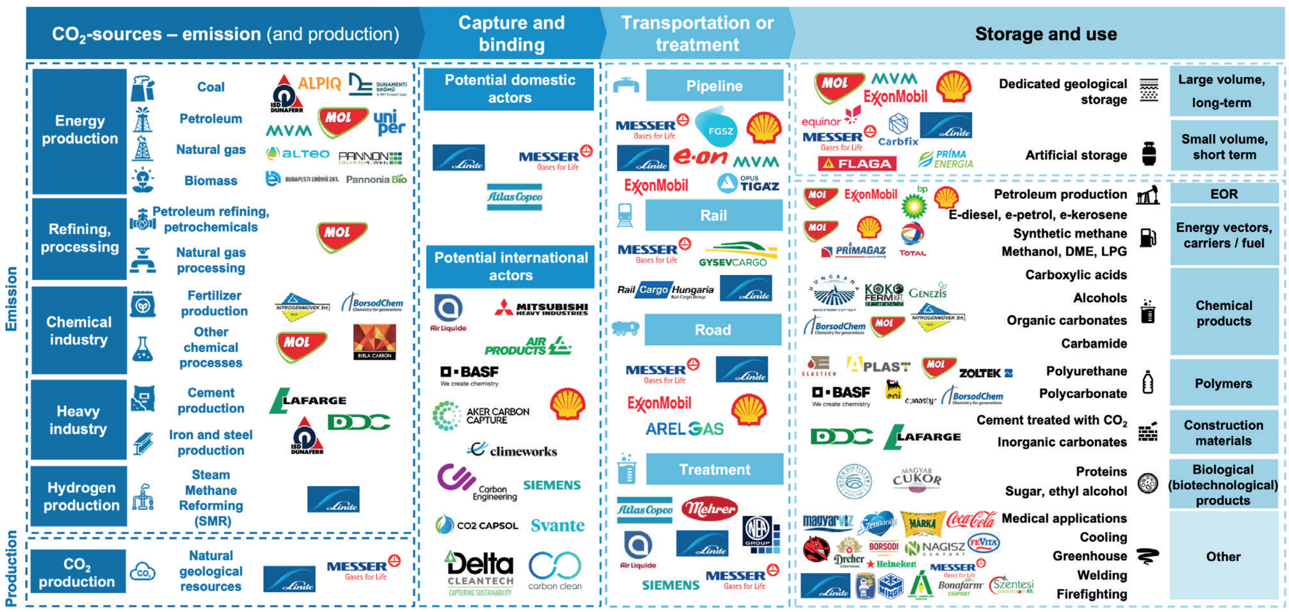

Figure 6 Summary diagram of the main actors of the domestic CCU/S value chain, own edition.

competitive solution for CO_2 users compared to CCU/S technology.

The key player in the domestic CCU/S industry might be MOL *(Hungarian Oil and Gas Public Limited Company)*, and other key players, based on their existing competencies, capitalization and involvement, are the large chemical, construction, metallurgical, energy and fermentation companies (Nitrogénművek, BorsodChem, Lafarge, DDC, ISD, MVM, Hungrana, Pannonia Bio), and technology service providers (Linde, Messer). Domestic companies are present along the entire CCU/S value chain covering all its elements. A significant means of broadening CCU/S expertise, technological know-how and the creation of related opportunities is the cooperation of domestic key players and participation in European-level collaborations and international projects.

1.5. Overview of domestic emitters

The majority of domestic CO_2 emission is generated during the burning of fossil fuels in power plants, and the top industrial emitters are metal production, the chemical industry and cement production. The energy sector and industry can be relevant as regards carbon capture, since their emission points release large volumes of emissions. There are three areas in the energy sector where emissions are released in large volumes, in a concentrated manner and at a small number of locations: public electricity and heat production, industrial energy production, and oil refineries. The annual CO_2 emissions of these areas combined is 17 million tons. Besides the energy sector (fuel combustion), emissions related to industrial processes and product use might be relevant in terms of carbon dioxide binding, as currently there is no other technological solution capable of significantly reducing emissions. This area includes emissions related to industrial production and generated by non-combustion processes. At this point, carbon dioxide is typically the by-product of chemical reactions during the manufacture of certain products. The most affected sectors are the chemical industry (mainly ammonia and ethylene production), the mineral industry (mainly cement production), and the metal industry (iron and steel production). The total annual CO_2 emissions related to all industrial processes and product use in Hungary equal 5.1 million tons. The annual CO_2 emissions of the energy sector (fuel combustion) (17 Mt) and industrial processes (5 Mt) are therefore approximately 22 million tons per year.[68] This quantity can be, broadly speaking, relevant for carbon capture. The two maps below show the largest industrial and power plant emitters (Figures 7 and 8):

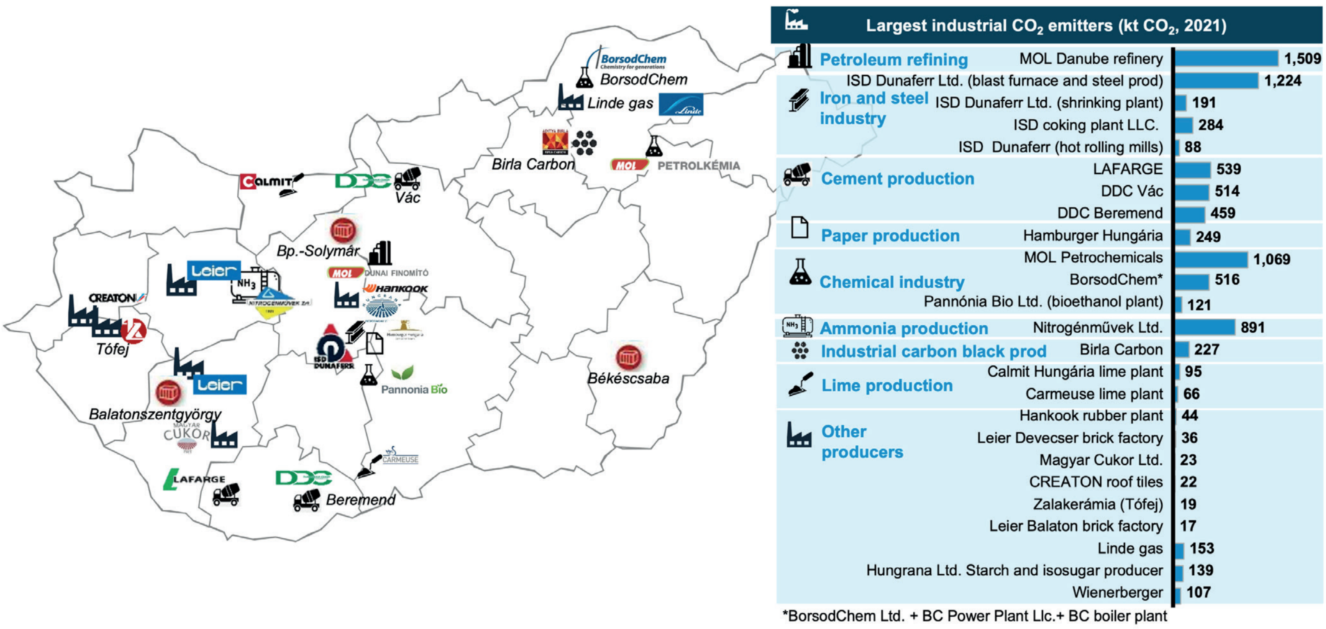

Figure 7 Hungary's largest industrial emitters, own edition based on [69,70].

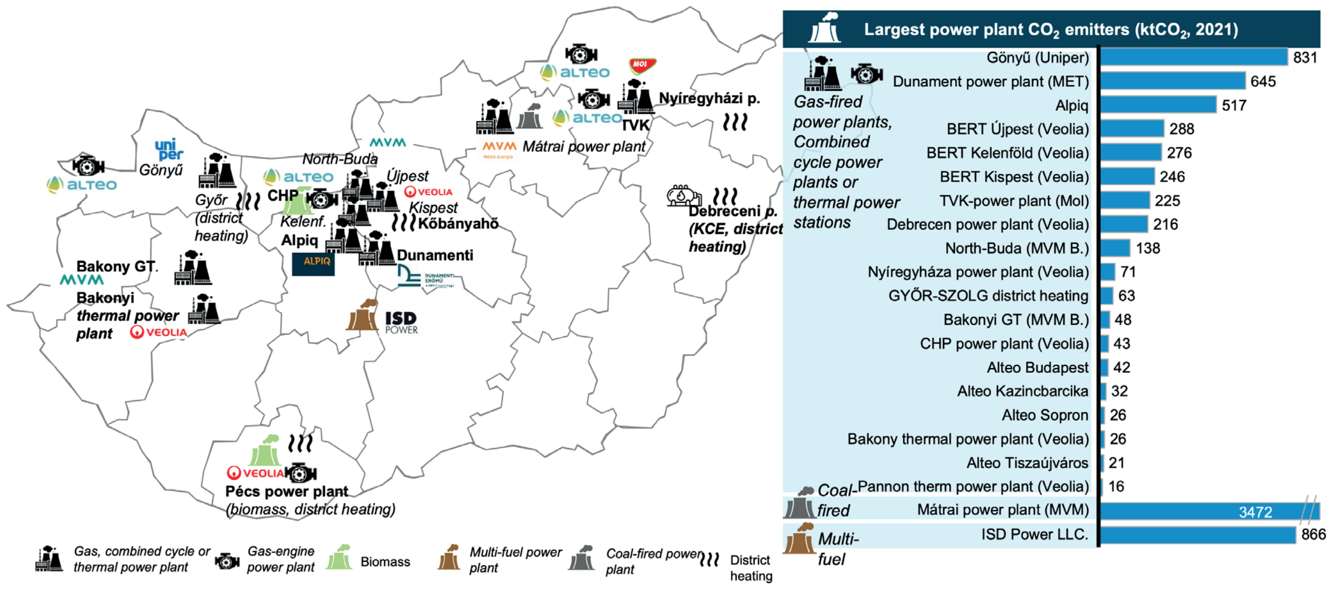

Figure 8 Hungary's largest power plant emitters, own edition based on [69,70].

An important change is expected in terms of emissions in the energy industry: the Mátra lignite-fired power plant is to be shut down in the second half of the decade and the domestic gas-fired power plant fleet will be significantly expanded: 2 CCGT power plants with a capacity of 500 MW and one of 650 MW are to be built in the area of the Mátra power plant and Tiszaújváros. This will eliminate the largest emitting unit, and gas-fired power plants will be the most important players in the domestic fossil energy industry.

1.6. Analysis of domestic TOP emitters

The most significant players in the CCU/S industry will be high-emission companies, and consequently, we have included these key domestic players in the White Paper through a questionnaire survey and conducted in-depth interviews with 16 of the TOP20 emitters (the ones who proved to be open to our inquiry). During the survey we collected data on emitter units, and these data help us

evaluate the CCU/S potential of the given emitters in accordance with the following criteria: the volume of annual emissions, seasonality/fluctuation of emission volumes, CO_2 concentration of emission, theoretical cost level of capture, and the possibility for on-site utilization.

In terms of CCU/S potentials, chemical companies appeared to be the most promising of all. The ammonia production plant of Nitrogénművek has the best facilities. It generates high-purity, high-volume continuous emission, and can even (partially) utilize captured CO_2 on site. Another promising area is the hydrogen production plants of MOL and Linde (and BorsodChem), as their emissions contain high concentrations of CO_2. Cement production is an additional important area, where CO_2 concentration is lower than that of chemical plants, but there is no other known alternative to reduce emissions significantly, and this way it can be an important player in this industry. The evaluation of gas-fired power plant emissions showed that although these plants emit large volumes of CO_2, the CO_2 concentration of the emissions is small, and they are expected to operate at a lower utilization rate in the future.

In addition to analysing emissions, the largest domestic CO_2 emitters were also asked about their attitude towards CCU/S technology and about their plans for emission reduction. Half of the TOP20 emitters have specific plans for the reduction of CO_2 emission. The goals as regards emission reduction will be achieved primarily through the use of renewable energies, increased efficiency, and the introduction of new production technologies. CCU/S technology was named by 7 actors.

More than half of the respondents (61%) do not currently have a running CCU/S project, nor do they plan to have one in the near future. These companies, almost without exception, justified their responses with the poor economic indicators of CCU/S technology (negative return, high investment requirements) and the lack of knowledge concerning the practical applicability of the technology. Actual carbon dioxide utilization exists in the case of one company, where part of the captured carbon is used to produce urea. However, five companies have CCU/S technology projects under way or in the preparation phase, and two other companies do not currently have any projects, but are planning to do so in the near future. These companies operate in the chemical and mineral industry, and the projects at present are typically at the level of preparatory studies, plans, and payback calculations. Most companies are seeking partners in carbon capture and carbon dioxide transport and storage. Carbon dioxide utilization partners were mentioned in only two cases, mainly in terms of utilization in the chemical industry (methanol production) and the construction industry.

The major hindering factors as regards CCU/S projects are mainly economic in nature. High investment requirements, high operating costs, and, as a result, low return regarding the technologies are the main economic obstacles to the realization of projects. Emitters also identified the lack of CO_2 infrastructure as a major problem. As long as there is no regionally organized CO_2 infrastructure (or any willing actor), emitters will not be able to engage in capture, and CCU/S will remain an option only in theory.

Other main hindering factors are policy uncertainty and the lack of regulatory incentives. There are specific legislative barriers, and due to the lack of commitment to CCU/S projects in domestic industrial and energy policies, emitters are not willing to opt for such investments.

1.7. Potential domestic CCU/S use cases

The White Paper provides numerous examples of the potential domestic uses of CCU/S technologies along the value chain. It describes 7 cases focusing on the capture and utilization of CO_2, 1 case for storage, and it also outlines 2 possible CCU/S clusters. Each case was described from the perspective of value chains, so the entire CO_2 life cycle is mapped, from its generation to its use and storage.
Application possibilities focusing on CO_2 capture include CCGT-based electricity generation at Mátra Energia, cement clinker production at Lafarge's factory in Királyegyháza, the blast furnace operating at ISD Dunaferr's ironworks in Dunaújváros, hydrogen production for petroleum refining at MOL Dunai Finomító, and petrochemical processes in MOL Petrolkémia's plant in Tiszaújváros. Application opportunities focusing on CO_2 utilization include the on-site utilization of emissions from fertilizer production and their sale to partners at Nitrogénművek, and the on-site utilization of CO_2 produced at BorsodChem hydrogen production plant for the manufacture of various chemical products. CO_2 storage opportunities include the utilization of the depleted hydrocarbon field in the Tázlár area. To present the potential domestic CCU/S clusters, we have outlined the CCU/S clusters in Northern Hungary and the Danube Region based on their geographical location, identified the key players, CO_2 emitters and users potentially involved in the cooperation, regions suitable for storage, and possible transport routes and networks.

Potential CCU/S business models

A successful CCU/S project launch and implementation requires business models that provide a funding source and a predictable revenue stream, ensure that risks are allocated between the actors and are kept at an acceptable level with full social acceptance, and also consider the position in the CO_2 value chain and the partnerships necessary for business activity.[71–73] To effectively develop their CCU/S business models, market organizations require, across the entire sector, a comprehensive support

framework and an economic-political environment formed by the regulator at the national (or even international) level. Frameworks that effectively support the development of the CCU/S industry ensure returns, clarify and allocate the risks through the specification of ownership rights and obligations, and, at the same time, protect the actors from the effects of the risks the value chain entails. Furthermore, the framework can attract market financing to the segment, and can contribute to the launch of first-generation and more mature projects as well. Also, the framework must ensure coherence with other sectoral and decarbonization policies, and cannot encourage the transfer of activities to locations outside the border.

The effectiveness of CCU/S projects depends primarily on whether there is a long-term and stable source of income ensuring return on investment.[74] There are also a number of subsidy-based and market-based monetization opportunities available for CCU/S applications, which are already well-known and play a significant role in the spread of decarbonization and other new technologies. One of the most common subsidy models is the contract for difference (CfD), where the regulator compensates the emitter for the difference between the market price of captured CO_2 and the specified target price providing the investor with a predictable source of revenue.[24,32,72,74] In addition, the state might also support the spread of CCU/S through the tax system by introducing tax incentives[24,32,74,75] or imposing carbon tax.[32,74]

The EU Emissions Trading System could be an effective incentive for the spread of CCU/S technologies, but the ETS does not yet include solutions for CO_2 utilization.[74,75] Revenue models can also be designed on a recognized cost basis through tariff regulation or direct state support ("cost-plus" mechanism).[24,32,72,74] For the time being, market-based revenue streams for CCU/S are limited by high technology costs and comparatively low CO_2 prices. The state, by regulations and incentives, can contribute to the increase in demand for CO_2 and the expansion of the end market. Such means can include prioritizing and differentiating products with low carbon intensity, mandating their use in a specified proportion, and increasing the competitiveness of captured CO_2 as opposed to mining.[32,74,75] The benefit of market-based revenue models is that, in the longer term, they can ensure the return on investment of projects in the advanced stage of the CCU/S industry even without state subsidies.

Numerous projects and business models can be defined along the CCU/S value chain. Initiatives can focus on a single element of the value chain, or they can set up integrated projects by the combination of several elements. The following aspects must be considered during the development of a business model: the position of the activity in the value chain, the allocation of liabilities and risks among stakeholders, potential revenue streams, and the main elements of cost. Based on international examples, the following potential models were identified: vertical integration, joint ventures, CCU/S operator model, cluster approach.[24,74,75]

1.8. Business case calculation of CCU/S solutions

The economic aspect and profitability of CCU/S solutions are also examined in the White Paper. Along the elements of the CCU/S value chain we have presented business cases found in international literature. As regards the business cases, it is important to note that individual CCU/S projects can vary significantly in terms of technical and economic results. The reason for the uncertainty is the uniqueness of each emission and capture technology, the different premises used, and the scarcity of the empirical data and studies available (due to the small number of ongoing projects). For this reason, the study does not provide general economic and return-on-investment data, but instead presents several individual cases for illustration and future orientation.

Three cases were examined in relation to carbon capture: CO_2 capture during hydrogen production (from an SMR unit)[76], cement production[77,78], and gas-fired power generation[79,80]. The cost of capture is mainly determined by the investment and operational requirements of the carbon capture equipment. In all three cases, the high energy demand of the carbon dioxide capture unit was the largest determinant of the cost of capture. Out of the three cases examined, hydrogen production has the most favourable capture costs. In the case of cement production and gas-fired power generation, capture is a significantly more energy and cost intensive solution. With hydrogen production, the final product's price has increased to a lesser extent, while cement production has seen a significant increase in the price of the final product.

Given the domestic CCU/S conditions, CO_2 can be transported relatively cheaply by pipelines, rail or road. In all of these three cases distance and the quantity transported are the determining factors in terms of transport costs. Seeing that pipeline transport in Hungary might be the dominant method of transporting large volumes of carbon dioxide, we have presented this subject in detail. The study analysing transport costs, often cited in international literature, shows that, among all the scenarios examined, overland pipeline transportation with a capacity of 2.5 million tons per year and a distance of 180 km is the best approximation to the domestic conditions.[81] In this case, the unit cost of transportation is estimated to be 5.4 euros/ton. Due to the expected lower transport volumes in Hungary (under 2 million tons per year on high-traffic routes), pipeline CO_2 transport can be realized at a higher unit cost. The conditions for cheaper CO_2 transport in Hungary include the establishment of CCU/S clusters and a common transport infrastructure, and the construction of saline aquifer storage facilities, ideally near the storage facilities constructed on depleted hydrocarbon fields. As for the geological potential of the country, domestic CO_2 can be initially stored on depleted oil and natural gas fields, and later in saline aquifers. Storage costs depend primarily on the characteristics of the given storage formation (size, geological properties). The study analysing storage costs, often cited in international literature, shows that, among all the scenarios examined, overland storage on depleted hydrocarbon fields without exploitable abandoned wells, and saline aquifer storage are the best approximation to the domestic conditions.[82] In the case of the former storage option, the unit cost of storage is between 1-10 euros/ton, while in the latter case it is between 2-12 euros/ton. In Hungary, due to the smaller capacity of certain depleted oil and natural gas formations, storage is expected to be feasible at a higher unit cost, while with saline aquifers the above-mentioned price range could be reached only if the geological conditions are favourable.

Carbon dioxide utilization business cases are important as they shed a new light on CO_2 emissions by showing that CO_2 should be seen as a resource, as a value that can be used to manufacture marketable products. Two specific cases were examined: synthetic kerosene production and CO_2-based polyol production. Synthetic kerosene production can use large volumes of carbon dioxide, but also has a significant demand for green hydrogen.[83,84] This requires large amounts of renewable electricity. Meeting this requirement needs significant investment in addition to carbon capture and fuel production: large capacities of renewable energy producers and electrolysers are required. This could make synthetic kerosene up to three times more expensive than conventional fossil-based kerosene.[85] This area, though, is of considerable interest due to expected regulations.

As far as polyol production is concerned, CO_2-based production can replace 20% of the fossil raw material demand, making the products cheaper than those of fossil-based production. In the cases shown, large volumes of carbon dioxide are captured from hydrogen production plants, 10% of which can be used in polyol production, and the majority is stored.[86] The CCU business cases highlight the value of looking at carbon dioxide as a potential resource, and also the importance of exploiting the potentials for utilization and other process synergies in addition to storage. The general conclusion based on the review of the business models is that a complex approach is needed, since CCU/S value chains are also complex and require careful coordination. It is necessary to build on the existing infrastructure and exploit as many synergies as possible to achieve the economic and technological optimization of the entire CCU/S value chain.

2 PROPOSALS

2. Proposals

2.1. Policy and regulatory proposals

Hungary has declared its support for the EU's target to reduce greenhouse gas emissions of the economy to net zero by 2050. The current regulatory environment covers the EU ETS, energy efficiency measures and support for renewable energy. While renewable energy sources and the improvement of energy efficiency form the basis of our decarbonization options accounting for around 80% of the expected emission reduction, there are activities where decarbonization proves to be difficult, such as in the case of cement production, the steel industry, chemical industry or waste processing, where the method of emission-free operation is currently unknown or would be a rather costly alternative.

The most noteworthy message of the feedbacks and questionnaires is that, while many requirements are already included in the existing legal or regulatory systems, requirements for transparency, the division of responsibilities, predictability, and traceability are not part of the current legislation in many economic sectors. There is a need to develop industry-specific recommendations and technical standards, safety requirements, and uniform guidelines. These standards can also promote a wider spread of technologies. The application of many non-EU technologies in Europe requires compliance studies and licenses, but this calls for flexible standards and faster bureaucracy. Due to the uncertainties in terms of measurement and control, a clear regulatory framework would boost the businesses' confidence and thereby accelerate the spread of technologies. This regulatory framework should be consistent with other measures taken in this area in relation with the promotion of European innovation capacity and competitiveness. It must also produce optimal results from a social, environmental and economic point of view, and ensure compliance with EU laws, principles and values.

The implementation and enforcement of regulations can be obstructed by the fact that some of the legislation supporting decarbonization is complex, constantly changing and often encourages costly technologies that are not yet widespread. To improve the legal framework, it is worth examining whether the current legislation is able to handle further developments and it can be effectively enforced, or whether it needs to be rectified, or a new regulation needs to be introduced. In order to ensure effective implementation and enforcement, it may be necessary to rectify or clarify the existing regulation in certain areas, such as carbon dioxide storage, as explained in detail in the previous section.

Given the rapid development of technology, the regulatory framework must leave room for further improvements. Any changes should be limited to clearly identified problems for which feasible solutions exist. A reliable and solid European regulatory framework and predictable long-term development strategies can provide protection for all companies in the Member States, and by providing a stable, predictable regulatory environment, they can contribute to strengthening Europe's industrial base, exploiting decarbonization potentials and reducing emissions.

Current legislation does not address in detail the standardization and definition of carbon dioxide emissions, negative emissions and their calculation methodology. This shortcoming calls for the clarification of the regulation. Definitions in all new legal instruments must be flexible enough to adapt to technical progress, and precise enough to ensure the necessary legal certainty. It can be deducted from the questionnaires that, for example, there is no foreseeable legal background for biomass sustainability requirements. The rules for CO_2-CCU/S from biomass are thus uncertain, and the accountability of these negative emissions in the ETS is not given.

Areas utilizing carbon dioxide include, for instance, the beverage or the food industry. The growth in demand for carbon dioxide in Hungary is primarily driven by the food and beverage industries, but its industrial use is also significant. Perhaps the most important factor for the users of the food industry, beer and soft drink manufacturers is that it does not contain harmful chemical impurities, and high gas purity strictly required with respect to the food industry is thus guaranteed, moreover, its extraction is not dependent on the production rate of a chemical plant, it can be flexibly adjusted to meet higher CO_2 demands as well. The questionnaires emphasize that, currently, regulations do not recognize the use of CO_2 in the food industry as emission reduction. The proposals call for the revision of such regulations as the near future of the carbon dioxide industry will be determined by the development of new application technologies that utilize CO_2, including, in particular, environmentally friendly "green" technologies aimed at reducing the environmental impact of various industrial processes. The emergence of large-scale CO_2 emitters in Hungary (e.g. bioethanol production or fermentation plants) could mean a new direction, where CO_2 recycling could become economically viable and can contribute to the reduction of industrial CO_2 emissions.

The conclusion drawn from the questionnaires is that, after mapping the potentials inherent in CCU/S technologies, related regulations for the planning, design, and implementation of projects must be improved. In particular, the process and the detailed rules for licensing should be improved in such a way that licensing would be subject to a simple and transparent procedure within a reasonable timeframe (e.g. in the case of environmental permits, construction permits, technical safety permits). Where possible, technology-specific rules should be incorporated into the relevant legislation to facilitate enforcement, licensing and planning procedures. In the case of both the Egységes Környezethasználati Engedély (EKHE) (Integrated Environmental Permit) – Government Decree no. 314/2005. (XII. 25.) – and the construction permit – Government Decree no. 253/1997. (XII. 20.) –, it would be necessary to apply less stringent requirements for the licensing procedure. In some sectors, EKHE can be obtained no less than 10-14 months after the start of the project. Afterwards, the general contractor agreement can be concluded for 18 months, and following 30-36 months, depending on various factors, the activity can be commenced. Consideration should be given to the prioritization of climate protection projects with a shorter licensing procedure.

It is recommended to revise the domestic licensing procedure for geological storage in order to clarify how the different uses with conflicting purposes can be authorized. Such a post-review amendment could allow for the possibility of geological storage in parallel with mining activities. Under the current legislation, carbon dioxide storage in not considered to be a mining activity, so it cannot be carried out on mining sites. If a depleting natural gas field is to be used for geological storage, current regulations specify that mining activities in given areas must be stopped in advance, stating that it is inconvenient if the mining contractor wishes to carry out geological storage activities in parallel with the mining activity. In the questionnaire, several emitting companies also proposed the review of the EU's ETS system. First and foremost, abolishing the allocation of free quotas and increasing quota prices were mentioned as possible incentives to reduce emissions.

There is no strategy for the widespread implementation of CCU/S in Hungary, but there are related initiatives that build on CCU/S. An example is Hungary's National Hydrogen Strategy, which foresees the production of large quantities of low-carbon hydrogen after 2030. It would promote the spread of CCU/S solutions if legislation created a market for the low-carbon technology mentioned in the Hydrogen

Strategy, for example in the areas of transport and agriculture. When drafting the regulation, it is desirable to place the emphasis on technology-neutral interventions in a way that it does not favour one alternative over another. And preferably, it should be done in a way that it does not result in discouraging green hydrogen related efforts. In the near future, the focus will shift to supporting the development of technological solutions that can economically provide decentralized green hydrogen production, and also to supporting the development of various "negative emission" technological solutions. For the latter reason, it would be advisable to create a uniform, official naming system for the different production methods.

It is also necessary to be able to distinguish products manufactured with low-carbon technology (e.g. hydrogen, fertilizers) from those produced conventionally. This could be achieved by introducing certificates of origin, verifiable proofs of the source of products and the amount of carbon emissions associated with their production (guarantees of origin).

Despite the fact that the role of the European Union is decisive in terms of the formation and the contents of the CCU/S-related framework, it is worth bringing these issues in line with regulatory needs in the context of the proposals identified as points of intervention in the research, such as the creation of standards, the rethinking and re-regulation of licensing procedures. It can be concluded from the research that the players of the industry are open to professional communication, and the stakeholders support close cooperation. The establishment of a professional coordination-communication network in Hungary should also be considered, which would serve as a due platform to bring together the necessary regulatory, technological and market-related knowledge.

2.2. Proposals to support the spread of CCU/S in Hungary

CCU/S technologies broaden the range of emission reduction tools available to countries and businesses, and complement the more widespread green solutions already at hand. Their use should be encouraged through a complex approach to emission reduction. Achieving climate neutrality requires a technology-neutral approach, a coordinated management of the alternative green solutions available, and the utilization of the synergies between them.

Currently, the introduction of CCU/S applications is considered a risky investment not easily profitable for market players. The main reasons are the high investment and operating costs, the low awareness and the limited spread of available technologies, the lack of CO_2 infrastructure, and the uncertain regulatory environment. For this reason, the spread of CCU/S solutions requires state intervention and support both in terms of CAPEX to stimulate investments, and of OPEX to ensure the continuity and safety of operations.

In Hungary, significant emission reductions could be achieved with the involvement and cooperation of a relatively small number of actors, given that only 20 major emitters account for approximately 70% of the relevant emissions of domestic CCU/S (c. 16 million tons per year). Furthermore, in terms of their capabilities and resources, these actors cover the entire CCU/S value chain, which includes dominant domestic companies operating in the field of CO_2 capture, transport, utilization and storage as well.

In the interviews and questionnaires, the relevant market players identified the factors that could support the spread of CCU/S solutions in Hungary. They emphasized the importance of state involvement and coordination, the introduction of economic incentives and subsidies, the promotion of CO_2 utilization, the development of a necessary infrastructure, a long-term, predictable regulatory environment, the implementation of pilot projects, and the need to consider the unique attributes and conditions of various sectors.

The following section will, based on the feedback received from domestic players, delineate the main areas that require intervention, and will outline the players' proposals to support the spread of CCU/S solutions, to exploit the economic-development, business, and emission reduction potentials inherent in these technologies. Some of the interventions need to be dealt with within domestic frameworks, while others require EU-level solutions, in which case it is essential that domestic interests are well understood and represented in the EU legislative process.

2.2.1. Steps to develop a domestic CCU/S strategy

- Carrying out a detailed assessment of the needs of CCU/S value chain actors (financing, regulatory environment, technological standards, infrastructure requirements, responsibilities)
- Providing business models to support the spread of CCU/S (revenue streams, economic incentives, definition of roles and responsibilities, risk allocation)
- Establishing domestic CCU/S strategic goals, implementation plans, schedules
- Identifying domestic CCU/S clusters, preparing and implementing programmes to support the formation and development of clusters
- Mapping of domestic CCU/S strategic goals into relevant sectoral strategies and policies, emission reduction and sustainability strategies
- Designating/establishing government agency(s) responsible for the CCU/S sector
- Creating technological neutrality in emission reduction strategies and support systems, allowing market players to choose the optimal green solution in the given context (e.g. switching to renewable energy, application of CCU/S, using different technologies)

2.2.2. CCU/S infrastructure development

- Creating an intercompany platform to coordinate the development of CO_2 transport and storage infrastructure (with the participation of emitters, technology providers, users, potential actors involved in transport and storage)
- Supporting market players in the coordination of CCU/S investment plans to exploit synergies and assist projects that show greater potentials
- Supporting the identification of potential storage sites (especially saline aquifers), and cooperating with market players in order to allocate the risks and share the costs
- Supporting the comprehensive exploration of specific storage sites
- Coordinating the creation of CO_2 transport infrastructure, including pipeline, rail and road transport
- Facilitating the laying of pipelines by simplifying the licensing process and limiting administrative obligations
- Removing regulatory barriers to the establishment of geological storage, reviewing mining regulations in order to support CO_2 storage

2.2.3. Economic incentives to CCU/S

- Creating economic incentives that are clear, transparent, predictable, reliable, and provide long-term support
- Establishing a support system for investment financing, which enables market players to implement projects with a long payback period
- Establishing a stable financial operating support system and fiscal frameworks to provide a predictable long-term revenue stream for those involved in implementing projects (e.g. government subsidies, CfD scheme, WACC premium)

2.2.4. Expanding the market for carbon dioxide users

- Creating and developing markets for low-carbon products (e.g. introducing quotas on the use of low carbon intensity construction materials and fuels, requiring the use of low-carbon hydrogen and fertilizers)
- Increasing the competitiveness of carbon capture based CO_2 and promoting its use as opposed to that of mined CO_2 (e.g. introducing mandatory usage quotas or tax reliefs for carbon capture based CO_2, and introducing carbon tax for mined CO_2)

- Introducing emission reduction (green) certificates and labels for products manufactured with CCU/S
- Advocating the revision of the EU ETS system so that the use of carbon capture based CO_2 be recognized

2.2.5. Broadening the sphere of CCU/S R&D&I activities, promoting national awareness and experience

- Establishing an R&D&I support framework that provides reliable and long-term support for research and development activities and projects as regards green transition
- Selecting and supporting CCU/S pilot projects in sectors deemed the most important for Hungary to gain experience for the implementation of more complex projects, and to set a useful example for market players

2.2.6. Guidelines, standards, regulations

- Establishing a reliable, solid European regulatory framework and predictable long-term development strategies that allow for planning long-term projects
- Setting clear emission reduction targets and supporting their achievement through action plans and financial support
- Examining the regulatory framework of countries pioneering in CCU/S (e.g. Norway) and exploring the possibilities for domestic adaptation
- Prioritizing climate protection projects and instituting shorter licensing procedures
- Standardizing and regulating the calculation methodology for avoided CO_2 emissions, preparing guidelines for stakeholders
- There is a need for the development of CCU/S technology recommendations and technical standards, safety requirements and uniform guidelines that can promote the wider spread of these technologies
- When drafting the regulation, it is desirable to place the emphasis on technology-neutral interventions in a way that it does not favour one alternative over another
- Amending and clarifying existing legislation on carbon dioxide storage

2.2.7. Stakeholder involvement, cooperation, and dissemination of know-how

- Facilitating cooperation between industries involved in the CCU/S value chain (emitters, users, infrastructure, technology), creating a platform for coordination
- Exploring CCU/S IPCEI project opportunities, supporting selected projects
- Encouraging and supporting long-term partnerships among the actors of the CCU/S value chain

2.2.8. Social aspects, supporting and shaping public opinion

- Promoting CCU/S and raising social awareness through information campaigns
- Providing additional, more extensive information in the regions of the clusters identified
- Open communication on CCU/S applications, in particular on storage risks and their management
- Cooperating with local authorities and communities in terms of CCU/S investments

References

1. International Energy Agency (IEA). *Energy Technology Perspectives 2020: Special Report on Carbon Capture Utilisation and Storage*. https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf (2020).
2. International Energy Agency (IEA). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. (2021).
3. *Summary Report on CCU/S Integration in Energy and Industrial Systems*. (2022).
4. Alsarhan, L. M., Alayyar, A. S., Alqahtani, N. B. & Khdary, N. H. Circular Carbon Economy (CCE): A Way to Invest CO2 and Protect the Environment, a Review. *Sustainability* 13, 11625 (2021).
5. Zygierewicz A & Sanz S. *Renewable Energy Directive:Revision of Directive (EU) 2018/2001*. https://euagenda.eu/upload/publications/eprs-bri2021662619-en.pdf (2021).
6. Liese, P. *Revision of the EU Emission Trading System (ETS)*. https://www.europarl.europa.eu/legislative-train/carriage/revision-of-the-eu-emission-trading-system-(ets)/report?sid=6001 (2022).
7. REPowerEU: Európa megfizethető, biztonságos és fenntartható energiaellátásáért. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_hu (2022).
8. European Commission. Net-Zero Industry Act: Making the EU the home of clean technologies manufacturing and green jobs. https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1665 (2023).
9. Biro H, Aragonés P M, Nagell S L & Wendolowski M. *Untapped potential: linking the CEE region to European CCS initiatives*. https://ccs4cee.eu/wp-content/uploads/2022/11/31-10-Bellona-Report-FINAL.pdf.
10. *The potential for CCS and CCU in Europe*. (2019).
11. European Commission. What is the Innovation Fund? https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/what-innovation-fund_en?fbclid=IwAR2ccVpj7d5AnHTVrk58tJzgNkfC2frxy8VxMQyyuMtVHm9DzurWpf2J2as.
12. Az EU Horizont Európa kutatási és innovációs keretprogramja. https://nkfih.gov.hu/hivatalrol/nemzetkozi-kapcsolatok/horizont-europa (2021).
13. Innovációs és Technológiai Minisztérium. *Nemzeti Tiszta Fejlődési Stratégia 2020-2050*. https://cdn.kormany.hu/uploads/document/5/54/54e/54e01bf45e08607b21906196f75d836de9d6cc47.pdf (2020).
14. Innovációs és Technológiai Minisztérium. *Magyarország Nemzeti Energia- és Klímaterve*. https://2015-2019.kormany.hu/download/b/40/c1000/Stratégiák_20200116.zip#!DocumentBrowse.
15. Innovációs és Technológiai Minisztérium. *Magyarország Nemzeti Hidrogénstratégiája*. https://cdn.kormany.hu/uploads/document/6/61/61a/61aa5f835ccf3e726fb5795f766f3768f7f829c1.pdf (2021).
16. Innovációs és Technológiai Minisztérium. *Nemzeti Energiastratégia 2030, kitekintéssel 2040-ig: tiszta, okos, megfizethető energia*. https://2015-2019.kormany.hu/download/b/40/c1000/Stratégiák_20200116.zip#!DocumentBrowse (2020).

17. *Putting CO2 to use: Creating value from emissions*. https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf (2019).

18. *Efficient MAN CCU/S*. https://www.man-es.com/campaigns/download-Q1-2023/Download/efficient-man-CCU/S/c76a4375-0ad3-4979-af06-4b9ed45956c4/Carbon-Capture-Utilization-Storage (2022).

19. Van Dael, M. *Market study report CCU*. https://vito.be/sites/vito.be/files/2019-sct-r-1876_-_enop_wp5-t5.2_market_report_public.pdf (2018).

20. Cuéllar-Franca, R. M. & Azapagic, A. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *J. CO2 Util.* 9, 82–102 (2015).

21. Deák, G. & Bartha, L. *A szén-dioxid befogás és tárolás*. (2009).

22. Khosroabadi, F., Aslani, A., Bekhrad, K. & Zolfaghari, Z. Analysis of Carbon Dioxide Capturing Technologies and their technology developments. *Clean. Eng. Technol.* 5, 100279 (2021).

23. Al-Mamoori, A., Krishnamurthy, A., Rownaghi, A. A. & Rezaei, F. Carbon Capture and Utilization Update. *Energy Technol.* 5, 834–849 (2017).

24. Debarre, R., Gahlot, P., Grillet, C. & Plaisant, M. *Carbon Capture Utilization and Storage*. https://www.kearney.com/documents/17779499/17781864/CCU/S-2021+FactBook.pdf (2021).

25. Global CSS Institute. *Technology Readiness and Costs of CO2*. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (2021).

26. Fan L S. *Chemical looping systems for fossil energy conversions*. (John wiley & sons, 2011).

27. Madejski, P., Chmiel, K., Subramanian, N. & Kuś, T. Methods and Techniques for CO2 Capture: Review of Potential Solutions and Applications in Modern Energy Technologies. *Energies* 15, 887 (2022).

28. Global CCS Institute. Technology Readiness and Costs of CO2 . at (2020).

29. Discepoli, G., Cinti, G., Desideri, U., Penchini, D. & Proietti, S. Carbon capture with molten carbonate fuel cells: Experimental tests and fuel cell performance assessment. *Int. J. Greenh. Gas Control* 9, 372–384 (2012).

30. Zero Emissions Platform, Z. *IEA Greenhouse The Costs of CO2 Capture, Transport and Storage*. (2011).

31. Zero Emissions Platform (ZEP). *A Trans-European CO2 Transportation Infrastructure for CCU/S: Opportunities & Challenges*. https://zeroemissionsplatform.eu/wp-content/uploads/A-Trans-European-CO2-Transportation-Infrastructure-for-CCU/S-Opportunities-Challenges-1.pdf (2020).

32. International Energy Agency (IEA). *Special Report on Carbon Capture Utilisation and Storage: CCU/S in clean energy transitions*. (2020).

33. Turnau, S. *et al. Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects : final report*. (2019).

34. Baena-Moreno, F. M. *et al.* Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, Part A Recover. Util. Environ. Eff.* 41, 1403–1433 (2019).

35. Van Peteghem, L. *et al.* Towards new carbon–neutral food systems: Combining carbon capture and utilization with microbial protein production. *Bioresour. Technol.* 349, 126853 (2022).

36. Daneshvar, E., Wicker, R. J., Show, P.-L. & Bhatnagar, A. Biologically-mediated carbon capture and utilization by microalgae towards sustainable CO2 biofixation and biomass valorization – A review. *Chem. Eng. J.* 427, 130884 (2022).

37. Chauvy, R., Dubois, L., Lybaert, P., Thomas, D. & De Weireld, G. Production of synthetic natural gas from industrial carbon dioxide. *Appl. Energy* 260, 114249 (2020).

38. Huynh, H. L., Tucho, W. M., Yu, X. & Yu, Z. Synthetic natural gas production from CO2 and renewable H2: Towards large-scale production of Ni–Fe alloy catalysts for commercialization. *J. Clean. Prod.* 264, 121720 (2020).

39. Yang, N., Kang, F., Liu, Z., Ge, X. & Zhou, Y. An integrated CCU-plant scheme and assessment for conversion of captured CO2 into methanol. *Int. J. Low-Carbon Technol.* 17, 550–562 (2022).

40. Nyári, J., Magdeldin, M., Larmi, M., Järvinen, M. & Santasalo-Aarnio, A. Techno-economic barriers of an industrial-scale methanol CCU-plant. *J. CO2 Util.* 39, 101166 (2020).

41. Lee, U. *et al.* Using waste <scp> CO_2 </scp> from corn ethanol biorefineries for additional ethanol production: life cycle analysis. *Biofuels, Bioprod. Biorefining* 15, 468–480 (2021).

42. Liu, A.-H., Yu, B. & He, L.-N. Catalytic conversion of carbon dioxide to carboxylic acid derivatives. *Greenh. Gases Sci. Technol.* 5, 17–33 (2015).

43. Murcia Valderrama, M. A., van Putten, R.-J. & Gruter, G.-J. M. The potential of oxalic – and glycolic acid based polyesters (review). Towards CO2 as a feedstock (Carbon Capture and Utilization – CCU). *Eur. Polym. J.* 119, 445–468 (2019).

44. Iijima, T. & Yamaguchi, T. K2CO3-catalyzed direct synthesis of salicylic acid from phenol and supercritical CO2. *Appl. Catal. A Gen.* 345, 12–17 (2008).

45. LI, X., LI, Q., ZHAO, Y., KANG, M. & WANG, J. Utilization of carbon dioxide in polyurethane. *J. Fuel Chem. Technol.* 50, 195–209 (2022).

46. Wacht, A., Kaluza, S. & Fleiger, P. Carbon Capture and Utilization in Cement Industry—Aspects of the Production of E-Fuels by Upcycling Carbon Dioxide. in 603–612 (2023). doi:10.1007/978-3-031-15602-1_44.

47. Langanke, J. *et al.* Carbon dioxide (CO_2) as sustainable feedstock for polyurethane production. *Green Chem.* 16, 1865–1870 (2014).

48. Alagi, P. *et al.* Carbon Dioxide-Based Polyols as Sustainable Feedstock of Thermoplastic Polyurethane for Corrosion-Resistant Metal Coating. *ACS Sustain. Chem. Eng.* 5, 3871–3881 (2017).

49. Yi, N., Unruangsri, J., Shaw, J. & Williams, C. K. Carbon dioxide capture and utilization: using dinuclear catalysts to prepare polycarbonates. *Faraday Discuss.* 183, 67–82 (2015).

50. Romanov, V. *et al.* Mineralization of Carbon Dioxide: A Literature Review. *ChemBioEng Rev.* 2, 231–256 (2015).

51. Pan, S.-Y. *et al.* An Innovative Approach to Integrated Carbon Mineralization and Waste Utilization: A Review. *Aerosol Air Qual. Res.* 15, 1072–1091 (2015).

52. Hills, C. D., Tripathi, N. & Carey, P. J. Mineralization Technology for Carbon Capture, Utilization, and Storage. *Front. Energy Res.* 8, (2020).

53. Zajac, M., Skocek, J., Ben Haha, M. & Deja, J. CO2 Mineralization Methods in Cement and Concrete Industry. *Energies* 15, 3597 (2022).

54. CO2 Value Europe. AGGRECACO2. https://database.co2value.eu/projects/278.

55. Air Liquide. Air Liquide to build two new hydrogen production units with carbon capture technology in Shanghai Chemical Industry Park. https://www.airliquide.com/sites/airliquide.com/files/2022-10/air-liquide-build-two-new-hydrogen-production-units-carbon-capture-technology-shanghai-chemical_62d65264eede0.pdf (2022).

56. Patel, S. Carbon Capture Begins at India's Largest Coal Power Plant. https://www.powermag.com/carbon-capture-begins-at-indias-largest-coal-power-plant/ (2022).

57. Mitsubishi Heavy Industries. MHIENG's First Compact CO2 Capture System Goes into Commercial Operation at Biomass Power Plant in Hiroshima. https://www.mhi.com/news/22063001.html (2022).

58. NEFCO. Advancements in CCU/S offer new investment opportunities for impact investors – CRI commissions the world's first commercial CO2-to-methanol plant. https://www.nefco.int/news/CCU/S-offer-investment-opportunities-for-impact-investors/ (2022).

59. Carbon Recycling International. The Shunli CO2-to-methanol plant: commercial scale production in China. https://www.carbonrecycling.is/projects-shunli.

60. Carbon Recycling International. The Finnfjord E-methanol Project: Commercial Scale E-methanol Production in Norway. https://www.carbonrecycling.is/finnfjord-emethanol.

61. Porthos CO2 Transport & Storage. Project. https://www.porthosco2.nl/en/project/.

62. Trendafilova P. Porthos Plant Granted $2.4 Billion By The Dutch Government For Carbon Capture. (2021).

63. Biogradlija A. EPC awarded for world's first CCS at waste to energy plant in Norway CCU/S. (2022).

64. Országos Meteorologiai Szolgálat. Nemzeti Kibocsátási Leltár 1985-2020. at (2022).

65. Falusi, G., Szamosfalvi, Á., Vidó, M., Török, K. & Jencsel, H. A hazai földtani szerkezetek felmérése a szén-dioxid visszasajtolás szempontjából. *Magy. Tudomány* 450–458 (2011).

66. Kubus, P. *Szén-dioxid összegyűjtés és visszasajtolás realitása a hazai olajipar szempontjából*. (2010).

67. Szunyog I. A villamos erőműi szén-dioxid-kibocsátás föld alatti tárolásának lehetőségei Magyarországon. *Műszaki Földtudományi Közlemények* (2012).

68. United Nations Climate Change. *Hungary 2022 National Inventory Report (NIR)*. https://unfccc.int/documents/461959 (2022).

69. European Commission. EU ETS Database. https://climate.ec.europa.eu/index_hu (2021).

70. Nemzeti Klímavédelmi Hatóság. Klímagáz Adatbázis.

71. Goldthorpe, W. & Avignon, L. A Systems Approach to Business Models and Public-private Risk Sharing for Large Scale CCS Deployment. *SSRN Electron. J.* (2021) doi:10.2139/ssrn.3816435.

72. SPE London Net Zero. Business Models for Carbon Capture, Utilisation and Storage. (2022).

73. Honegger, M. Toward the effective and fair funding of CO2 removal technologies. *Nat. Commun.* 14, 534 (2023).

74. Muslemani, H., Liang, X., Kaesehage, K. & Wilson, J. Business Models for Carbon Capture, Utilization and Storage Technologies in the Steel Sector: A Qualitative Multi-Method Study. *Processes* 8, 576 (2020).

75. International Centre for Sustainable Carbon. CCU/S Business Models and Incentives. (2022).

76. Collodi, G., Azzaro, G., Ferrari, N. & Santos, S. Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as Feedstock and Fuel. *Energy Procedia* 114, 2690–2712 (2017).

77. Roussanaly, S. *et al.* Techno-economic Analysis of MEA CO2 Capture from a Cement Kiln – Impact of Steam Supply Scenario. *Energy Procedia* 114, 6229–6239 (2017).

78. Subraveti, S. G., Rodríguez Angel, E., Ramírez, A. & Roussanaly, S. Is Carbon Capture and Storage (CCS) Really So Expensive? An Analysis of Cascading Costs and CO 2 Emissions Reduction of Industrial CCS Implementation on the Construction of a Bridge. *Environ. Sci. Technol.* 57, 2595–2601 (2023).

79. Zero Emissions Platform (ZEP). *The Costs of CO2 Capture, Transport and Storage - Post-demonstration CCS in the EU*. https://zeroemissionsplatform.eu/wp-content/uploads/Overall-CO2-Costs-Report.pdf (2011).

80. Zero Emissions Platform (ZEP). *The Costs of CO2 Capture: Post-demonstration CCS in the EU*. http://www.graz-cycle.tugraz.at/pdfs/CO2-Capture-Report.pdf.

81. Zero Emissions Platform (ZEP). *The Costs of CO2 Transport: Post-Demonstration CCS in the EU*. https://www.globalccsinstitute.com/archive/hub/publications/119811/costs-co2-transport-post-demonstration-ccs-eu.pdf (2011).

82. Zero Emissions Platform (ZEP). *The Costs of CO2 Storage: Post-demonstration CCS in the EU*. https://www.globalccsinstitute.com/archive/hub/publications/119816/costs-co2-storage-post-demonstration-ccs-eu.pdf (2013).

83. Eberle, U. *Renewables in Transport 2050: Empowering a sustainable mobility future with zero emission fuels from renewable electricity*. (2016).

84. Adolf, J., Warnecke, W., Balzer, C. & Fu, X. *The Road to Sustainable Fuels for Zero-Emissions Mobility. Status of and Perspectives for Power-to-Liquids (PTL) Fuels*. https://www.researchgate.net/publication/350955491_The_Road_to_Sustainable_Fuels_for_Zero-Emissions_Mobility_Status_of_and_Perspectives_for_Power-to-Liquids_PTL_Fuels (2018).

85. IATA. Jet fuel price monitor. https://www.iata.org/en/publications/economics/fuel-monitor/ (2023).

86. Fernández-Dacosta, C. *et al.* Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO2 utilisation in polyol synthesis. *J. CO2 Util.* 21, 405–422 (2017).

87. Magyar Közlöny. A Nemzeti Tiszta Fejlődési Stratégia elfogadásáról. (2021).

88. Kengyel, Á. *Európai Uniós Politikák*. (Akadémiai Kiadó, 2020).

89. Európai Parlament. Energiapolitika: általános elvek. https://www.europarl.europa.eu/factsheets/hu/sheet/68/energiapolitika-altalanos-elvek.