Discussion paper

Political economy of carbon capture and utilization technologies

International policy designs in the context of climate change

GREEN TECHNOLOGY CENTER
녹색기술센터

| Author list |

- **Chaewoon Oh**, Senior researcher
- **Jongyeol Lee**, Researcher
- **Changsun Jang**, Researcher
- **Daye Eom**, Researcher
- **Inhye Bak**, Researcher
- **Wona Lee**, Researcher
- **Kyung Nam Shin**, Principal researcher

| Acknowledgments |

This discussion paper was prepared within the Green Technology Center's second-year (2018-2019) research project of "Study on the applicability of carbon mineralization technology through international mechanism" under the first-phase CCUS national strategic project. This research project was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1C1B6002093).

CONTENTS

GREEN TECHNOLOGY CENTER

SECTION

01

Introduction

01 SECTION

Introduction

As the new global regime on climate change, ushered by the adoption of the Paris Agreement in 2015, binds and simultaneously incentivizes the behavior of participating countries to respond to climate change, the importance of finding technological solutions was emphasized. In this regard, cooperative action on technology development and transfer came to the fore as participating countries' essential means of implementation to attain mitigation and adaptation obligations (PA 2015). Both existing climate technologies and emergent technologies must be explored and deployed to their full potential to contribute to the mitigation of and adaptation to climate change. Of the emergent technologies, this discussion paper focuses on carbon removal technologies that directly mitigate carbon emissions from point sources and have risen as a means of bridging between a fossil fuel-oriented economy and a renewable energy-oriented low-carbon economy in the near future (Bui et al. 2018).

One salient carbon removal technology is carbon capture and storage technology (CCS). CCS is a chain of technologies that separates CO_2 from emission sources, transports the captured CO_2, and stores it at a geological site. For its firmly recognized contribution to climate change mitigation, some CCS are branded as a crucial component of negative emission technologies (NETs) that remove carbon from the atmosphere. Two categories of NETs for the Intergovernmental Panel on Climate Change (IPCC) report include bioenergy production with CCS (BECCS) and the direct capture of CO_2 from ambient air with CCS (DACCS) (Rubin and De Coninck 2004)[1). Despite the position of CCS as a contributor to the mitigation of climate change, CCS projects have faced difficulties in their deployment

1) There are six types of NET. Four other categories are: i) afforestation and reforestation, ii) land management to increase and fix carbon in soils, iii) enhanced weathering, and iv) ocean fertilization to increase CO_2.

at both national and local levels due to technical and sociopolitical factors.[2)] For example, one is related to the geological storage of captured CO_2. Geological storage has a risk of CO_2 leakage, uncertainty regarding the varied estimation of CO_2 storage capacity at the national level, and the imbalanced distribution of storage availability across countries.[3)] Hence, policy instruments to overcome technical and sociopolitical factors and incentivize the deployment of CCS technologies have been explored (Honegger and Reiner 2018).

Meanwhile, other technologies focusing on the aspect of capturing carbon from point sources and "using/utilizing" carbon as a carbon resource have garnered attention. These are carbon capture and utilization technology (CCU) or carbon dioxide utilization technology (CDU). CCS and CCU have the commonality of capturing carbon from emission sources. However, they differ in their subsequent treatment of captured carbon. CCU captures CO_2 and converts it into carbon-based products through physical, chemical, or biological processes (Styring et al. 2011; Jones 2017). Therefore, while CCU is understood as an "alternative (of the CCS) for geological storage" by way of carbon mineralization (Smit et al. 2014, p. 3), CCU is highlighted in the name of "CO_2 recycling" by the conversion of CO2 to synthetic fuels and other chemicals (Bruhn et al. 2016, p. 38).

The development and deployment of CCU have been pursued by many developed countries in their efforts to achieve climate change mitigation targets and use energy efficiently. The US Department of Energy (DOE) has been conducting Carbon Storage Program. This program's core R&D component targets CCU and recycling technology. Cognizant that cost reduction is a critical factor in the deployment of CCU, the US DOE unfolded this program to achieve cost-effectiveness of less than $10 USD per ton of CO_2 by 2030 (DOE 2019). The European Union supports the demonstration of CCU, particularly that which processes the CO_2 emissions from steel, cement, and petrochemical industries, through the Horizon 2020 research funding program (Schlögl et al. 2018). In addition, developing countries see CCU as an important means of tackling climate change. China's 15-year science and technology

2) From previous studies, factors can be changed to "barriers" or "acceptance" (Buck 2016; Jones et al. 2017).

3) For example, the storage capacity estimates for the United States can vary from 5 to 20,000 Gt of CO_2, leading to uncertainty regarding the estimation of the potential lifetime of CCS technologies due to the different storage capacity estimations and classification systems (Szulczewski et al., 2012).

plan includes the development of "high efficient, clean and near-zero emission fossil energy utilization technologies", and China's Scientific & Technological Actions on Climate Change include CCUS as a technology to control and mitigate GHG emissions (Zhang et al. 2013, p. 537; China 2007).[4)]

CCU has been pursued as an instrument to attain national or global strategies in three aspects: i) climate change mitigation, ii) energy transformation from fossil resources, and iii) resource management and recycling. In particular, CCU's instrumental role in mitigating climate change has been quite strongly entrenched, so the CCU's standing has been germane to that of CCS. Along with CCS's contribution to mitigation, CCU has been understood in the context of CCS in three aspects: i) CCU is understood as a sub-category of CCS; ii) CCU has been combined with CCS to create a unified category of carbon capture, utilization and storage technologies (CCUS), which includes a stream of carbon capture from fuel combustion or industrial processes, the transport of carbon, and either the utilization of carbon as an industrial feedstock or the permanent storage of carbon in geological formations; or, iii) CCU is framed as an alternative to resolve public opposition to CCS for the environmental risks of storing captured technologies at geological sites (Metz et al., 2005; van der Zwaan and Gerlagh, 2009; IEA 2019). However, CCU has not been branded as negative emission technologies in the IPCC report. It has been pointed out that CCU's potential of mitigation by means of storing CO_2 in the carbon-incorporating products is negligible and that the mitigation discourse of CCU has been exaggerated (Mazzotti et al. 2005; Bruhn et al. 2016). Therefore, it was suggested that CCU should be framed in the context of energy transformation and resource security for its full potential to be realized rather than in the context of climate change mitigation (Bruhn et al. 2016, p.40).

Then, what should be the future of CCU in the context of climate change? Despite a limited contributory role in mitigating climate change than expected, CCU will without doubt work as "a component in a larger mitigation strategy" and at the national and

4) The 15-year plan is the National Medium-and-Long-Term Program for Scientific and Technological Development (2006-2020).

international level, as industrial CCU(S) is positioned as a 1.5°C-relevant mitigation option for transitioning industrial systems in the IPCC's 1.5°C report.[5)] Then, what kinds of national and international policy interventions are required for the further development and transfer of CCU? To answer this question, this discussion paper sees it as worthwhile to follow Honegger and Reiner (2018)'s scholarly approach to explore the technical (strictly speaking, economic) and sociopolitical barriers of the CCS and subsequent policy instruments, particularly international policy mechanisms under the UNFCCC to incentivize the uptake of CCS. This discussion paper will follow the previous work by exploring the economic and sociopolitical difficulties in the facilitation of technology development and the transfer of CCU and put forward design considerations for the proposed international policy instruments under the UNFCCC.

In this regard, Chapter 2 goes over previous studies of CCS in its economic and sociopolitical aspects and international policy approaches to CCS. Based on the analytical approach to barriers and policy instruments, Chapter 3 explicates the barriers of CCU in economic and sociopolitical aspects. Then, Chapter 4 explores international policy approaches to CCU, particularly how CCU can be incentivized under the UNFCCC, and deals with subsequent international policy instruments at the center of the UNFCCC. Chapter 5 concludes this discussion paper.

---

5) Elements enabling system change include energy system transitions, land & ecosystem transitions, urban & infrastructure system transitions, industrial system transitions, and CO_2 removal. Here, power sector CCS is the mitigation option for energy system change and BECCS and DACCS are options for carbon dioxide removal (de Coninck 2018; TEC 2019a, p.14).

GREEN TECHNOLOGY CENTER

SECTION

02

Previous studies on the political-economic barriers and policy instruments for CCS

02 SECTION

Previous studies on the political-economic barriers and policy instruments for CCS

Currently, 43 large-scale CCS facilities exist worldwide, capturing 800,000 tCO_2/ year from coal-based power plants and at least 400,000 tCO_2/ year from other emission-intensive industrial facilities (including natural gas-based power generation (Leeson et al. 2017; Global CCS Institute 2018). The question of why the large-scale uptake of CCS has not been facilitated has mainly been explored in economic and sociopolitical aspects. First, the decision to deploy CCS in a scaled-up manner is dependent on an economic factor, namely cost. The cost of CCS deployment is determined by the availability of CO_2 sources, the level of technological development, the maturity of CCS, geological circumstances, and selected technology characteristics. Though named in different factors, the cost is essentially technology-dependent.[1)] There are several cost-related challenges in CCS deployment. One major challenge is the high cost of CO_2 capture infrastructure and the power used to operate transport and storage equipment. Among the chain technologies for capture, separation, transport (compression), and storage, the first process of capturing CO_2 is known as the most cost-intensive part (Leung et al. 2014).[2)] In addition, the cost of transport varies by distance and geological terrain traversed to reach the storage site. Ultimately, the CO_2 is then stored in deep saline aquifers or carbonated minerals. The cost of CO_2 storage takes a relatively small part in the overall project costs. Another challenge is the variation of cost estimation

1) Both this technology-inducing economic factor and the geological factor influence the deployment of CCS technologies. The cost varies according to the adjacency of storage sites and the adequacy of seabed or geological conditions (including the ease of pipeline construction) (Leung et al. 2014).

2) The cost of capturing CO_2 differs depending on technology choice and design, the integration and flexibility of new technology, the type and quality of coal, and its effect on generation efficiency. Once CO_2 has been separated from flue gas, it is compressed and carried either in liquid or in supercritical conditions through diverse transportation means such as road tankers, pipelines, and ships, depending on the volumes carried and distance.

by the estimator, the type of CCS technology used, and the type of industry to which CCS is applied (POCA 1999; Irlam 2017; Leeson 2017). The other challenge is cost competition with other classical GHG mitigation options. Of course, several studies have shown that CCS deployment is cost-competitive. Figure 1 shows that from the perspective of the Levelized Cost of Electricity (LCOE), CCS is comparable to widely known renewable technologies such as offshore wind or biomass.[3)] As shown in Figure 2, CCS becomes more attractive than solar photovoltaic (PV), solar thermal, and wind offshore if the cost of avoided CO_2 is considered.[4)] However, there is an argument that neither LCOE nor the cost of avoided CO_2 can accurately reflect the cost competitiveness of CCS. LCOE is not appropriate when comparing non-intermittent technologies such as CCS and intermittent technologies such as renewable technologies. The cost of CO_2 avoidance can only work as a good metric if governments put a massive price on carbon in the form of a carbon tax. Without a carbon tax in place, project developers see no incentive to install CCS in their production processes. With a carbon tax in place, the additional investment cost for installing CCS can be offset by the reduced carbon tax that the project developer has to pay (Zapantis et al. 2019). Therefore, the cost of CO_2 avoidance can only give the right signal for a cost comparison with the consideration of national carbon pricing policies.

Second, the up-take of CCS is also influenced by sociopolitical attributes. On a positive note, CCS has been socially framed as contributing to the mitigation of climate change. In the broad sense, CCS is regarded as NETs that can contribute to mitigation in a short period, and BECCS and DACCS are NETs in the longer period (EASAC 2018, p. 10). In the IPCC Special Report that presents a modeled pathway to make global CO_2 emissions peak around 2020 and achieve net zero in global CO_2 emissions by 2055, CCS is set to play a critical role in the mitigation portfolio to bring deep emission cuts (IPCC 2018). However, on a negative note, CCS is cited as bringing negative environmental impacts such as the risk of groundwater acidification and the risk of leaks in CO_2 transport (Karayannis et al. 2014). Furthermore, environmental NGOs expressed worries that the introduction of CCS

3) The LCOE is the most common metric utilized for cost comparison; it calculates the present value of the total cost of building and operating a power plant over an assumed lifetime (US DOE 2016).

4) The cost of avoided CO_2 means the annualized total investment cost with CCS($) divided by the amount of annual CO_2 emissions avoided (tCO_2).

will defeat the adoption of more socially sound or preferable technologies and that energy transformation is deferred (L'Orange Seigo et al. 2014).

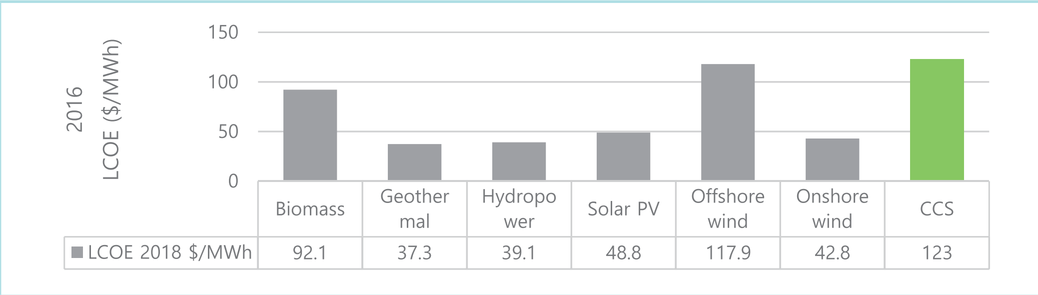

Figure 1 LCOE from utility-scale renewable power generation technologies (EIA 2019)

Source: Adapted from Table 1a on p. 7 of EIA (2019)

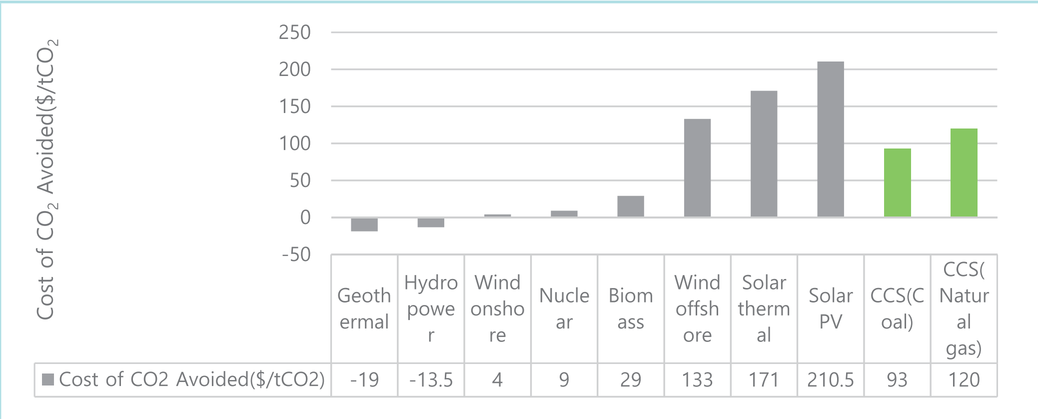

Figure 2 Cost of CO_2 avoided of other GHG mitigation technologies

Source: Adapted from Fig. 2 on p. 7 of Zapantis et al. (2019)

Therefore, the deployment of CCS requires the design of policy interventions and instruments in consideration of the aforementioned economic and sociopolitical challenges. However, the most important aspect of policy instrument design is that there should be political willingness for the deployment of NETs, including CCS, rather than other more competitive mitigation options (Honegger and Reiner 2018, p. 316). Most policy instruments focus on ways to financially incentivize the deployment of CCS technologies. At the domestic level, governments can provide financial incentives to the private sector in the form of carbon pricing such as carbon taxes and emission trading systems or as either subsidies or technology mandates (Irlam 2017). Both the installation of carbon pricing instruments and the political will to increase both carbon prices for mitigation and to increase subsidy levels even without demonstrated co-benefits are needed (Honegger & Reiner 2018). Meanwhile, for financial incentives at the international level, there can be three types of instrument: ⅰ) direct financial incentives, ⅱ) industrialized countries' leading role to provide financial stimulus and support to developing countries, and ⅲ) the utilization of international market mechanisms in pursuit of economic efficiency.

Of these instruments, the international market mechanism, particularly the Clean Development Mechanism (CDM), has been explored. CDM is a flexible mechanism for developed countries to meet their mitigation target in a cost-efficient manner under the Kyoto Protocol. Developed countries venture mitigation projects in developing countries by investing in offset technologies and financing and acquiring mitigation outcomes in return (Dixon et al. 2013). While the CDM has been a useful mechanism to obtain emission credits for host countries, no CCS projects have been accredited under the CDM thus far, since the decision was made in Durban, 2011 to adopt CCS projects. The major challenges remain in establishing a standard methodology. For instance, difficulties lie in the non-permanence of carbon storage, measurement, reporting, and verification (MRV), setting project boundaries and insurance and liability issues (Cook and Zakkour 2016). On the basis of this, the appropriate designs for the Sustainable Development Mechanism (SDM), which is assumed to replace the CDM, has been analyzed in order to make the SDM fit for CCS (Honegger & Reiner 2018). This section explored previous studies on economic and sociopolitical barriers in the deployment of CCS and related policy interventions; this provides a useful lens with which to explore the uptake of CCU. In this regard, the next section deals with the economic and sociopolitical attributes that hamper the uptake of CCU.

GREEN TECHNOLOGY CENTER

SECTION

03

Political economic barriers in the development and transfer of CCU

03 SECTION

Political economic barriers in the development and transfer of CCU

CCU utilizes captured CO_2 by chemical or biological processes rather than storing CO_2 in deep geological formations (e.g., cap rock and aquifer) and the ocean. The economic viability of technologies that capture and utilize CO_2 determines the applicability of CCU. However, "high technical cost, poor economic feasibility, and the absence of capital source" are all related factors that challenge the up-scaled application of CCU(S) (Li et al. 2016, p. 284). This section explores the political-economic barriers to CCU and possible solutions.

3.1 The economic aspect

There are three main categories in terms of CCU: Chemical conversion, carbon mineralization, and biological conversion (Table 1). In particular, chemical conversion is the most popular CCU technology. Carbon mineralization has taken recent attention because of its potential in long-term-CO_2 storage in mineral structure. Thus, this section takes chemical conversion technologies to explicate the economic barriers to the uptake of CCU.

Table 1 Major categories of CCU technologies

Category	Note
Carbon mineralization	Building materials (e.g., concrete and carbonate aggregates)
Chemical conversion	Chemical intermediates, fuels, and polymers
Biological conversion	Algae, biogases, and glasshouse gas

Source: modified from Matuszak (2017)

CCU has emerged in the middle of the merits and demerits of CCS. As mentioned in the previous section, CCS enjoys the environmental benefit of sequestering a substantial amount of CO_2 in the long-term but high costs in the uptake of CCS limits its application and demonstration. In contrast, CCU has comparatively more economic viability to generate revenues from manufactured marketable products (e.g., chemicals, fuels, and building materials). The global CCU roadmap provided the potentials of CO_2 utilization and market value by CCU at the global scale with five products: ⅰ) aggregates, ⅱ) fuels, ⅲ) concrete, ⅳ) methanol, and ⅴ) polymers (ICEF 2016). As shown in Figure 3, the production of aggregates and concrete is related to building materials and the other products are subjected to the chemical conversion of CO_2. The potential of CO_2 utilization is in the range 1,605-7,152 $MtCO_2yr^{-1}$, and the potential revenue coming from the CO_2 utilization is $1,780-8,370 billion USD yr^{-1}, depending on the implementation of strategic actions at the global scale. The production of aggregates and concrete accounts for approximately 66-70% of these potentials. The market for building materials (aggregates and concrete) seems the most economically viable among the five technologies (Figure 3). Furthermore, these technologies on building materials have favorable conditions in terms of technology maturity, large market size, fewer market competitors, and high potential for CO_2 utilization (Figure 4). Accordingly, a strategic investment on CCU is advantageous to establishing new climate industry and mitigating climate change.

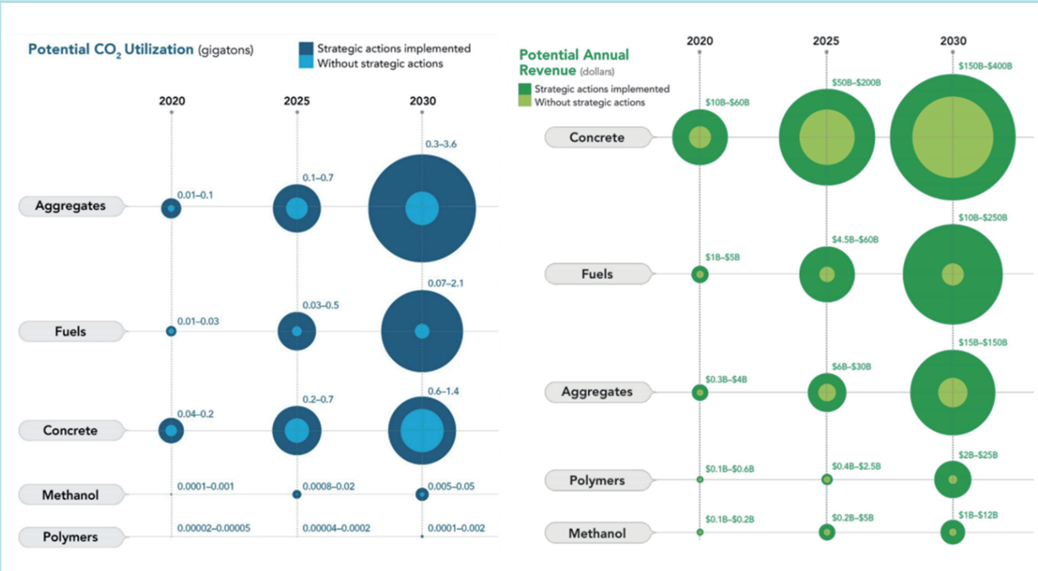

Figure 3 The potentials of CCU

Source: Fig. 0.1 and 0.2 in p.6-7 of ICEF (2016)

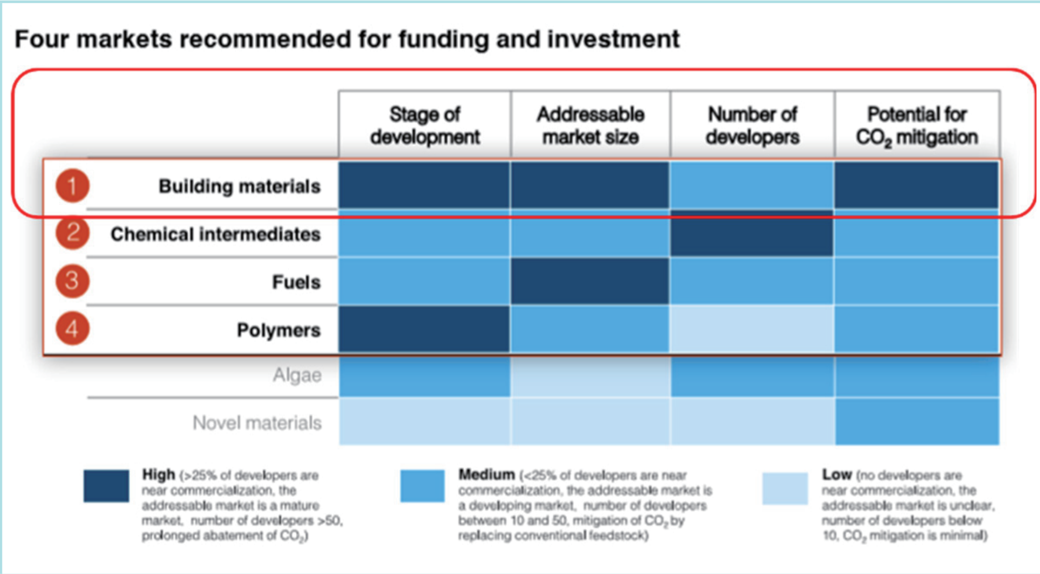

Figure 4 Examples of four prominent markets based on qualitative assessment

Source: Fig. 2.3 on p.14 of ICEF (2016)

Along this line, there is an exemplary case of strategic investment by the United States (US). The US analyzed the spatial CO_2 emission nationwide to identify a primary source for CCU. The electricity sector (e.g., thermal power plant), particularly from East regions of the US, emits the most abundant CO_2, and the chemical sector follows it. Then, the US determined five major CCU technologies of ⅰ) enhanced fuel recovery, ⅱ) plastics, ⅲ) biological conversion, ⅳ) mineralization, and ⅴ) chemical conversion (Figure 5)[1]. These technologies have been validated by lifecycle assessment (LCA), which can provide a quantitative basis for economic viability. Then, the national R&D budget for these prominent technologies will be invested intensively based on the LCA result.

1) These five technologies are similar to those identified in the global CCUS roadmap (ICEF 2016)

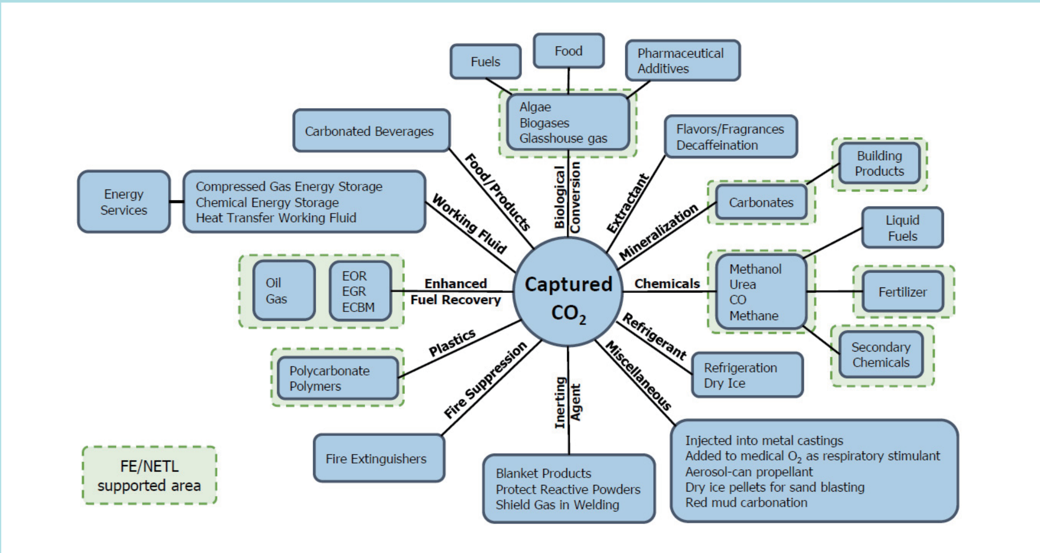

Figure 5 Marketable products and services derived from CO_2 utilization

Source: p.19 of Matuszak (2017)

An LCA has been recently conducted on CCU, particularly on the chemical conversion of CO_2, to investigate the economic viability of this technology at the project scale. However, these LCA studies reveal both the marketability and limitations of CCU in terms of the cost-benefit ratio. There are two issues regarding the cost: the cost of the CO_2 capture and conversion process. First, the benchmark cost of CO_2 capture in the capturing process depends on the purity of CO_2 emitted from plants and facilities (Figure 6). The benchmark cost, which represents the minimum cost of CO_2 capture by a best-practice process, is approximately \$40 USD per CO_2 ton based on the short-term demand for commodity CO_2 (Naims 2016). The demand for CO_2 comprises CO_2 emissions from fermentation, bioenergy, natural gas, and certain chemical production processes. However, CO_2 emissions from the other facilities (e.g. power plants and cement factories) seem unavailable because of the insufficient near-term demand for CO_2 utilization and the high cost of CO_2 capture. Technological improvement of CO_2 capture will be required to deploy CCU on a long-term basis. Second, the cost of electricity matters in the conversion process. Electricity is required for electrolysis to produce hydrogen, which is an important feedstock of chemical CCU technology (Chiuta et al. 2016; Hoppe et al. 2018). In particular, hydrogen reacts chemically with captured CO_2 to produce methane and methanol. Excluding the cost of CO_2 feedstock, electricity can account for 92% of variable operational costs in CCU (Szima and Cormos 2018). Meanwhile, in terms of the benefit, the revenue generation from CCU is determined by the price of the products and the carbon credit for CO_2 reduction. However, there are challenges. First, the prices of manufactured products and carbon credits are not yet sufficiently high to meet and surpass their cost-benefit breakeven point (Szima and Cormos 2018). Therefore, a certain form of financial support, such as a subsidy to stimulate investment in CCU in the manufacturing of eco-friendly products seems warranted. Furthermore, CO_2 credit is also a potential supplementary source of revenue, but there are technical and institutional challenges. Technically, there is a lack of LCA-based methodologies with which to estimate and calculate the reduction in CO_2 by the uptake of CCU. In addition, the uptake of CCU is not acknowledged as an eligible activity for the generation of carbon credits.

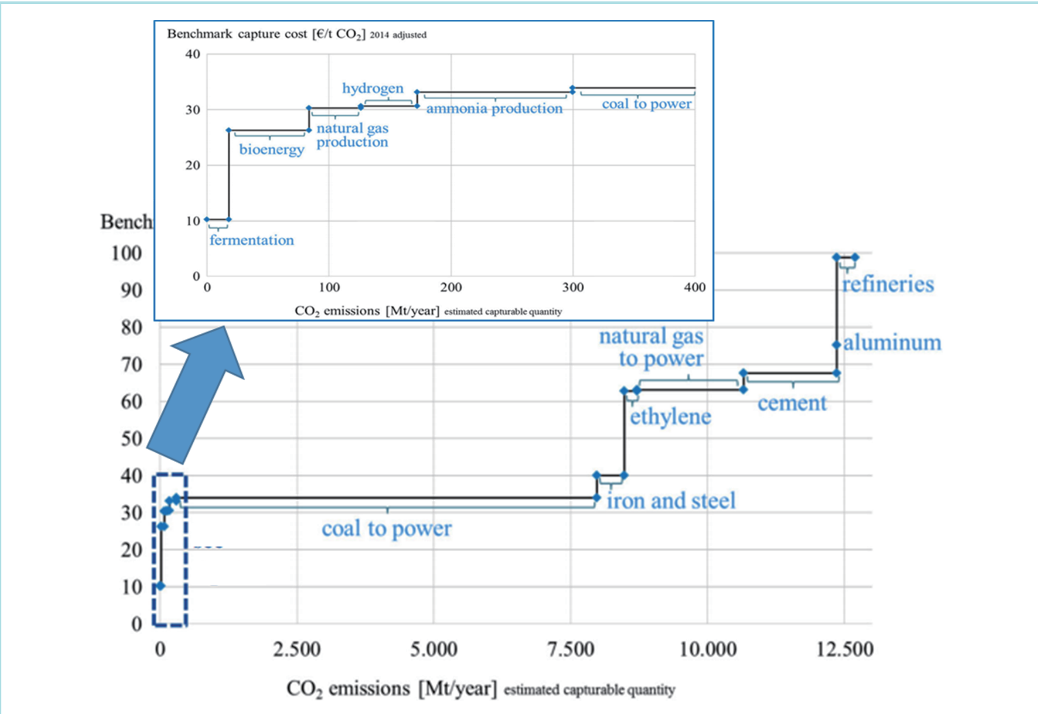

Figure 6 Benchmark cost of CO_2 capture

Source: Figs. 2 and 3 from p. 22234 of Naims (2016)

In explorations of the economic aspects to be considered in the uptake of CCU, two points must be considered. First, the quantitative approach can provide a scientific basis for economic incentives that stimulate investment in CCU; thus, LCA is essential to support the establishment of policy options for CCU. Sensitivity analysis on CCU's economic viability identifies breakeven points of input cost (e.g., electricity and feedstock) and output price (e.g., methanol and CO_2 mitigation credits) (Szima and Cormos, 2018). For example, methane can be a source of chemical conversion in the CCU process while it is more profitable to combust methane for energy production (Hoppe et al. 2018). Second, carbon mineralization technology needs more attention alongside conversion technologies because the potentials of CO_2 mitigation and market value by carbon mineralization are substantial (e.g. CCU in the production of aggregate and concrete). In addition, carbon mineralization requires relatively lower purity CO_2 from most power plants, implying its higher applicability in various facilities (Naims 2016; Lee et al. 2019).

3.2 The sociopolitical aspect

Unlike CCS, whose framing is mainly focused on their contribution to the mitigation of climate change, there are four dimensions in which CCU can be framed: i) climate change, ii) energy transformation, iii) resource security, and iv) a complement to CCS. First, CCU has been framed as contributing to the mitigation of climate change in the process of creating chemical products. The "captured CO_2" is stored in carbon-based products. Here, the amount of "captured and stored" CO_2 emissions can be regarded as reducing the amount of CO_2 emissions. However, this framing has received as dubious. In terms of the degree of mitigation, it is mentioned that there are two steps with which to be concerned when determining the exact amount of mitigation that occurred. In the first step, captured CO_2 is utilized in the process of capturing emitted CO_2 and converting captured CO_2 into chemicals or materials, so CO_2 emissions are controlled and reduced. However, this process requires energy[2)] and this energy consumption will result in CO_2 emissions. In the second step, carbon-based products made during the first step can store carbon. However, the period for which CO_2 can be stored in the form of carbon products varies by days, weeks (e.g. in liquid fuels), years (e.g. in polymers), and centuries (e.g. in cement). If we focus on the potential of long-term CO_2 storage in carbon-based products from CCU, CCU can become "direct climate change mitigation measure" like CCS (Bruhn et al. 2016, p.40). However, for these products to be acknowledged as carbon emission storages, this CO_2 storage in the form of products must be monitored and measured strictly and on a case-by-case basis (Ibid.). Furthermore, CO_2 conversions do not promise significant replacement of conventional products due to its small market size, which is determined by the amount of CO_2-based production, the amount of CO_2 sequestered, the growth rate of production, and the CO_2 utilization rate (MacDowell et al. 2017).

2) For example, hydrogen-based CCU requires a large amount of energy in the co-reaction between captured CO_2 and hydrogen for chemical production. The per kilowatt hour of electricity used for hydrogen-based CCU is expected to be 18.1 - 32 petawatthour (PWh) at the global scale in 2030 (Kätelhön et al. 2019).

Second, CCU can be framed as a contributor to the transformation of energy structure (Bruhn et al. 2016). CCUs provide a way of "substituting carbon-rich energy with carbon-poor energy sources" (Markewitz 2012, p. 7295). In the pro-business focus, the CCU can be regarded as "bridging technologies" in response to climate change (Jones et al. 2017, p. 5). Of course, this framing has also faced a counter-framing that CCU rather defers the transformation of energy structure. CCU, like CCS, can detract from investment in more socially sound and preferable low-carbon technologies (Ibid.). Thus, CCU can come into conflict with broader sustainable development goals on the continued use of fossil fuels.

Third, resource security is another dimension where CCUs are harbored. CCU using captured CO_2 as non-fossil carbon feedstock can block the depletion of resources for fuels and production elements that have traditionally relied on petrochemical feedstocks (Schlögl et al. 2018). For example, using CO_2 as a feedstock to produce polyols for polyurethane can reduce the use of fossil resources by 13-16% (von der Assen and Bardow 2014). In the chemical utilization of CO_2, there can be unlimited availability of CO_2 from chemical industries that produce CO_2 during processes such as the synthesis of ammonia and the production of ethylene oxide. In addition, many different applications of captured CO_2 are possible such as in the production of urea, methanol, cyclic carbonates, and salicylic acid (Markewitz et al., 2012).

Fourth, CCU is framed as a complement to the limitations of CCS in terms of environmental risks; CCU is regarded as having relatively low risk. In terms of the risk of CO_2 leakage, there is opposition to CCS at the local level because of the transportation and storage of CO_2, not because of capture and/or conversion processes (Jones et al. 2017). Furthermore, in terms of the risk of environmental degradation, residents are concerned with environmental degradation in the course of storage. Meanwhile, CCU is applied to existing industrial operations with which residents are already familiar and on which their living relies in the form of employment (Ibid.).

Going over the current framings, how is CCU understood under the UNFCCC? The Technology Executive Committee, which is the policy arm of the Technology Mechanism, analyses climate technology and forms policy recommendations that ultimately support countries in their efforts to enhance climate technology development and transfer (TEC 2019b). The TEC started dealing with the subject matter of innovation in emerging climate technologies, including zero-emission technologies (ZETs) and negative emission technologies (NETs) in 2018. Currently, the TEC's work remains in a definitional stage on "emerging climate technologies." Emerging climate technology is defined as "any climate technology that can be described by one (or both) of the definitions" of such emerging technologies as ⅰ) technologies that arise from new knowledge or the innovative application of existing knowledge, ⅱ) technologies that lead to the rapid development of new capabilities, ⅲ) technologies that are projected to have significant systemic and long-term economic, social, and political impacts, ⅳ) technologies that create new opportunities for and challenges to addressing global issues, and e) technologies that have the potential to disrupt or create entire industries (TEC 2018, p.2). Regarding ZETs and NETs, the TEC takes the general definition of ZETs as "technologies that emit zero (or negligible) emissions when in operation." Instead of enumerating specific technologies, the TEC noted that most renewable energy technologies can be included. NETs are defined as "technologies that remove greenhouse gas emissions from the atmosphere" (Ibid.). However, the TEC has not yet categorized which specific technologies can be considered NETs.

Based on the aforementioned framing approaches and this TEC's definitional position, it seems difficult to brand CCU as NETs. This is because the degree of mitigation by CCU is determined on a case-by-case basis. However, CO_2 emissions are undoubtedly controlled somehow. That is, even though CCU is not at the point of being called entirely NETs, it has the potential to contribute to the mitigation of climate change in the production processes of chemicals and materials. CCU is regarded by China as "near-zero-emission fossil energy utilization technologies" that can control carbon emissions and decelerate climate change (Zhang et al. 2013, p.537). Furthermore, in the IPCC special report on global warming of 1.5°C, industrial CCUS is included as a relevant mitigation option with high confidence (TEC 2019, p.14). Therefore, it is possible that CCU can be framed as a potential NET. Of course, the TEC has not specified climate technologies under NETs and ZETs or considered cooperative work with the IPCC. How CCU is framed and categorized in the future under the TEC will influence the future global deployment of CCU.

SECTION

04

International policy instruments under the UNFCCC

04 SECTION

International policy instruments under the UNFCCC

In the furtherance of CCU in terms of RD&D and transfer, it is important to have various international cooperation mechanisms such that developed countries can provide relevant technical and financial support to developing countries (Zhang et al. 2013). These mechanisms can be diverse in format. If the CCU is in the R&D phase, a separate International Energy Agency (IEA) Implementing Agreement, which solely targets CCU, can be formed for knowledge exchange. A global initiative to create a global technology roadmap on CCU in terms of regulation, policy, and public perception can be taken. In addition, financial support for R&D can be considered and indirect support through incentive mechanisms such as the UNFCCC's Clean Development Mechanism (CDM) or the EU emissions trading scheme can be considered.[1)] Lastly, an international approach for structural economic or regulatory incentives in the form of sound accounting of GHG emission reductions on the uptake of CCU can be considered (String et al. 2011). Honegger and Reiner (2018) explored sustainable development mechanisms, which is a successor to CDM, as a possible approach to mobilize negative emission technologies under the UNFCCC.

Of these possible mechanisms and possible services to be provided, this paper focuses on the mechanisms of the UNFCCC, which has been a source of overcoming technical and financial barriers in the uptake of climate technologies with several mechanisms such as the Market Mechanism, the Financial Mechanism, and the Technology Mechanism (Zakkour et al. 2014). Thus, this section explores three major mechanisms of the UNFCCC to see whether and how they support the development and transfer of CCU; they are: ⅰ) Climate

1) Under the EU ETS, only emission reductions through CCS, not CCU, are accounted. The transfer of CO_2 to an industry that utilizes it as feedstock in the production process is not allowed to be termed "emission reduction" or "emission avoidance"

Technology Centre and Network (CTCN) of the Technology Mechanism, ⅱ) Green Climate Fund (GCF) of the Financial Mechanism, and ⅲ) Sustainable Development Mechanism (SDM) and Cooperative Approaches (CA) on the grounds of Article 6 of the Paris Agreement.[2)]

4.1 Climate Technology Centre and Network of the Technology Mechanism

The CTCN is an implementation arm of the Technology Mechanism that was established in 2010 under the UNFCCC by the decision of the sixteenth meeting of the Conference of the Parties of the UNFCCC (COP16). It began its operation in 2014 with its mission to "stimulate technology cooperation and enhance the development and transfer of technologies to developing country parties at their request" (CTCN 2019a). Under this mission, the CTCN provides three core services: i) technical assistance (TA), ii) information and knowledge, and iii) network and collaboration & capacity building. These services aim to promote the accelerated, diversified, and scaled-up transfer of environmentally sound technologies for climate change mitigation and adaptation in developing countries, in line with their sustainable development priorities (CTCN 2019a). Here, TA is provided in the form of ⅰ) technical assessments,[3)] ⅱ) technical support for policy and planning documents,[4)] ⅲ) training, ⅳ) tools and methodologies, and ⅴ) implementation plans (CTCN 2019b).

The CTCN has a particular governance structure when implementing its work. The CTCN is hosted by the United Nations Environment Program (UNEP) with the United Nations Industrial Development Organization (UNIDO) and 12 consortium partners who have expertise in international technology cooperation. The CTCN is governed by the CTCN

2) The Technology Mechanism and the GCF of the Financial Mechanism are under the UNFCCC but they also serve the implementation of the Paris Agreement.

3) Technical assessments are targeted for technical expertise and recommendations related to specific technology needs, technology identification, technology barriers, technology efficiency, and technology piloting and deployment.

4) This includes strategies and policies, roadmaps and action plans, and regulations and legal measures.

advisory board and consists of i) the Climate Technology Centre as a secretariat based in Copenhagen and ii) Climate Technology Network as a network of experts and organizations who deliver CTCN services worldwide (CTCN 2019c). Any organizations with climate technology expertise can apply for this network membership. In this governance structure, the National Designated Entity (NDE), which is a national focal point for technology development and transfer under the UNFCCC, cannot be excluded. The NDE is responsible for facilitating and engaging national stakeholders in activities and services on technology development and transfer under the UNFCCC (CTCN 2019d). In particular, one of the main roles of NDEs in developing country parties to the UNFCCC is to coordinate and manage the preparation and submission of TA proposals and involvement in TA implementation. Therefore, the CTCN does not directly provide expertise to developing countries but plays a coordinating role by finding and soliciting technology needs from the NDEs of developing countries and mobilizing policy and technical expertise of CTCN network members to deliver technology solutions, build capacity, and implement advice in developing countries (CTCN 2019e).

Climate technologies covered by the CTCN include any piece of equipment, technique, practical knowledge, or skills for performing activities that can be used to address climate change as defined by the IPCC (CTCN 2019b). In detail, the CTCN categorizes climate technologies by sector and theme. Sector is divided into the sub-categories of adaptation and mitigation, and theme is sub-categorized into cross-sectoral enabler and cross-cutting approaches, as arranged in Table 2 below (CTCN 2019f). In the mitigation sector, there is a technology type carbon fixation and abatement. Under this technology categorization, CCS is positioned as one potential fossil-fuel-based carbon abatement technology. In addition, “more efficient conversion processes, fuel switching and other established and innovative technologies” that implicate the type of CCU are targeted for support under the CTCN (CTCN 2019g).

Table 2 Sector and theme of the climate technologies that are eligible for support by the CTCN

Category	Sub-category	Technology
Sector	Adaptation	Agriculture and forestry; Coastal zones; Early warning and Environmental assessment; Human health; Infrastructure and Urban planning; Marine and Fisheries; Water
	Mitigation	Agriculture; Carbon fixation and abatement; Energy efficiency; Forestry; Industry; Renewable energy; Transport; Waste management
Theme	Cross-sectoral enablers	Capacity building and training; Communication and awareness; Economics and financial decision-making; Governance and planning
	Cross-cutting approaches	Community-based; Disaster risk reduction; Ecosystems and biodiversity; Endogenous technologies; Gender

Source: The author made this table with contents of CTCN (2019f).

Currently, with regard to carbon fixation and abatement technologies, two TAs have been submitted to the CTCN: One is "Carbon capture and storage potential in Nigeria," which was requested by the Nigerian Maritime Administration and Safety Agency in 2016. The main activities of the TA include ⅰ) assessing CCS potential, ⅱ) strengthening the regulatory framework, and ⅲ) enhancing the institutional capacity for implementation (CTCN 2017). The other TA is "Substantial GHG emissions reduction in the cement industry by using waste heat recovery combined with mineral carbon capture and utilization" as requested by the Association of Cementitious Material Producers and the NDE of the Republic of South Africa in 2015 (CTCN 2016). The technical support was first centered on ⅰ) the assessment of technical feasibility, GHG reduction potential, and cost efficiency at selected plants and ⅱ) the study on linkages with and potential applications of CCU technology into other industrial sectors (CTCN 2016).

The CTCN services for network, capacity building, and information sharing also include contents and activities related to CCS (and/or CCU). CTCN has 41 members that mark themselves as CCS-related organizations in direct or indirect ways out of a network of 489 expert organizations as the CTCN network members as of July 2019. Among them, the CTCN Network members comparatively more related to CCS include the Korea Institute of Geoscience and Mineral Resources, the Vietnam Institute of Geosciences and Mineral Resources, the International CCS Knowledge Centre, the Korea Carbon Capture &

Sequestration R&D Center, and others (CTCN 2019h). In addition, for knowledge sharing and capacity building, the CTCN supports network members to organize webinars (web-seminar) to promote their technological expertise and experience. Four webinars were requested by CTCN network members and organized by the CTCN, inviting many participants worldwide. The topics and titles of the webinar on CCS were "The Shand CCS Feasibility Study - Second Generation CCS for the Globe and Multi-Sectors," "Biomass with carbon capture and storage - A review at the systems level," "BD3 CCS Integrated Facility - Technical Capabilities," and "CCS Takes the Biggest Bite Out of CO_2 - Small scale is not enough."

Currently, CTCN has provided a platform for facilitating the development and transfer of CCS and CCU technologies to developing countries through TAs, capacity-building, and information sharing. Then, what does the future hold for CCU in CTCN activities? TA services on CCU were already provided by the CTCN and these TAs can be scaled up or replicated in other regions or countries. However, two points need to be considered further. First, the CTCN started an impact analysis on TAs on the grounds of their monitoring and evaluation (M&E) mandates, and GHG reduction potential is included as a core indicator (CTCN 2019i). Internationally acknowledged methodologies to quantify emission reductions from CCU have not been formulated. Second, considering the limited amount of funding (up to $250,000 USD per TA) for CTCN TA and service areas of the CTCN, the CTCN TA for CCU can be a funding track for institutional setting, the assessment of technical feasibility, the estimation of GHG reduction potentials, capacity-building, and others. For R&D, pilot projects and facility installation of CCU with either linkage to or an exploration of additional financing channel seems necessary. The possible financing tracks for technology support include the Financial Mechanisms (GCF and GEF) under UNFCCC and other bilateral and multilateral funds for climate change (e.g. MDBs and bilateral ODA).

4.2 Green Climate Fund of the Financial Mechanism

The GCF, established in 2010 at COP16, is an operating entity of the Financial Mechanism. The GCF is designed "to support projects, programs, policies and other activities in developing country parties using thematic funding windows" (UNFCCC 2010a, para 102). The GCF is a unique global platform that promotes a paradigm shift toward low-emission and climate-resilient development pathways and provides financial resources in the form of grants and concessional lending to all developing country parties to the UNFCCC. The GCF tries to deliver a 50:50 balance between adaptation and mitigation allocations in its financial portfolio for appropriate allocation of resources for other activities, so the GCF operates two thematic funding windows for adaptation and mitigation. All developing countries are eligible to request the GCF project-based and programmatic support that incurs incremental costs for activities on adaptation, mitigation, technology development and transfer, capacity-building, and the preparation of national reports. Note that technology development and transfer fall within the eligibility criteria and that CCS is specifically indicated to be included as activities on technology development and transfer (GCF 2011, para 35). Inclusion of CCS does not mean that CCU is excluded.

The GCF has its financial resource access modalities. Two entities are important here: implementing entities and national designated entities (NDAs). Implementing entities accredited by the GCF governing body can access the GCF's resources in collaboration with recipient countries' NDAs. Considering their national climate strategies and plans, recipient countries will decide the mode of access with accredited entities and recommend funding proposals to the board through NDAs. In this regard, NDAs are the core in the interface between a country and the GCF, identifying their strategic priorities for engagement with the GCF (GCF 2015, p18). The GCF channels its resources to projects and programs through national, regional, and international accredited entities that can be public, private, or non-governmental institutions as long as they meet the GCF's standards. The main activities of such entities may be developing and submitting funding proposals, overseeing the management and implementation of projects and programs, deploying financial instruments, and mobilizing other resources (GCF 2015, p18). To encourage recipient countries to nominate competent national implementing entities for accreditation and thus directly utilize funding, the GCF considers additional modalities that further enhance direct access, including through funding entities with a view to enhancing country ownership of projects and programs.

To enable countries to directly access the GCF, it provides resources in several funding tracks of readiness and preparatory support programs (in short, readiness programs), project preparatory facilities (PPF), private sector facilities, and general funding proposals (FP) (Figure 7). The readiness program aims to empower developing countries to make use of climate finance by providing support on activities such as strengthening NDAs and focal points, developing country strategic programs and strategic investment priorities, accrediting implementing entities, pipeline development of projects/programs, and sharing information & experience (GCF 2019). The PPF was designed to support project and program preparation requests from all accredited entities as additional windows. The facility supports activities to enable accredited entities, particularly direct access entities, to prepare project funding proposals such as feasibility studies, environment, social, and gender studies, risk assessments, and other project preparation activities (GCF 2016a). To promote the participation of private sector actors in its activities at the national and international levels, the GCF introduced a private sector facility. Consistent with a country-driven approach, the facility can finance private sector mitigation and adaptation activities in developing countries both directly and indirectly.

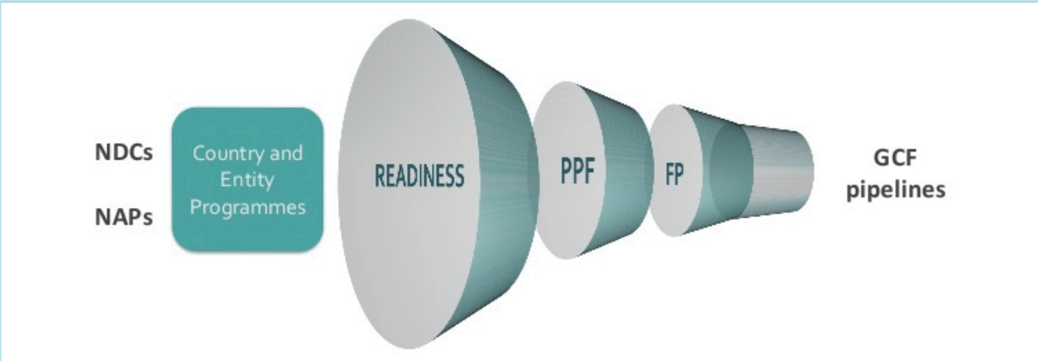

Figure 7 GCF funding window

Source: p. 4 of GCF (2017)

To maximize the results of mobilizing GCF resources for CCU projects and programs, it is essential to utilize GCF funding windows with appropriate access modalities. Recipient country NDAs or focal points are eligible to develop the concept of the CCU-based project/program through the readiness and preparatory support program allocating 50% of its support to particularly vulnerable developing countries. Based on the result of the readiness support, access to the PPF resources to prepare project funding proposals is possible for accredited entities that can submit funding proposals to the GCF. Considering the GCF's investment framework, accredited entities can prepare funding proposals for CCU projects or programs through PPF activities. The private sector has the fundamentally largest ability to mobilize funds at scale to distribute CCU technologies. Therefore, private finance should be considered the vehicle that crowds in third-party funds for CCU projects in collaboration with the GCF's private sector facility. The recent trend of project/program approval shows that approved project/programs do not design only one specific technology or target but instead a combination of technologies and targets. In addition, the GCF has more of an orchestrating role of financing other financiers to instigate climate-related projects and programs. Therefore, if CCU-related projects/programs are to be financed from the GCF, the readiness program or PPF can be utilized for project-level financing. If a large-scale project proposal is intended for the CCU with GCF financing, then the CCU should be a part of industrial transformative plan or national climate and energy policy program. Another noteworthy point is that the GCF sets its own mitigation and adaptation performance measurement framework with indicators that correspond to objective, impact, and outcome. The tons of CO_2 equivalent reduced or avoided as a result of projects or programs is included as an impact-level indicator (GCF 2016b). Therefore, under the GCF, the uptake of CCU requires the quantification of the mitigation impact.

4.3 Sustainable Development Mechanism and Cooperative Approaches of Article 6 of the Paris Agreement

Then, what is a market mechanism? It is a system to formulate a market in which tradable GHG emission permits are generated and traded. The first experimental global-scale carbon market was formed under the Kyoto Protocol, which is an international environmental agreement that sets and imposes legally binding emission reduction targets onto participating developed country parties in the first commitment period of 2008-2012. However, obligated developed countries can utilize a flexibility mechanism to achieve their national targets in a cost-efficient manner. The flexibility mechanism comprises ⅰ) international emissions trading, ⅱ) joint implementation, and ⅲ) clean development mechanism (CDM). Here, CDM is a project-based offset mechanism in which developed countries can carry out GHG emission reduction projects in developing countries with their financial resources and mitigation technologies, produce mitigation outcomes, and then earn "certified emission reduction (CER) credits". These CERs are used to help developed countries meet their mitigation targets. Besides offering flexible ways for developed countries to meet their targets, the CDM can contribute to technology transfer in developing countries as a co-benefit in the direct process of generating and trading carbon credits (UNFCCC 2010b).[5)]

The CDM is an attractive system through which carbon capture technology can be utilized in credit acquisition.[6)] However, negative emission technologies (NETs), particularly the CCS, have a hard time being accepted as eligible technology for the CDM. Above all, it was difficult to decide where to classify the CCS project between two mitigation types of CDM projects: emission reduction projects and emission removal (or carbon sequestration) project. CCS projects have characteristics from both types. CCS can be seen as an emission reduction technology because carbon does not enter the atmosphere, but CCS also has

5) In the 2007 and 2008 studies, technology transfer was found to occur in 39% and 36% of projects, respectively, which account for 64% and 59% of emission reductions from CDM projects, respectively (UNFCCC 2010b, p.10).

6) CO_2 capture is an acknowledged project type under the CDM

a removal component because already emitted carbon is sequestered (Supersberger et al. 2006). Furthermore, there were contentious discussions on technical issues related to environmental safety such as “criteria for selection of storage sites, monitoring plans, suitability of modeling, risk assessment, project boundaries, liability, and provision for damages” (Dixon et al., 2013, p.7598). Afterward, the modalities and procedures for CCS were adopted as the CDM’s “emission reduction” project activities in 2011. The adopted provisions for CCS include requirements that go beyond the requirements of general CDM project activities. Those requirements are “enhanced participation requirements for host countries (including the requirement to have national laws covering geological storage), the reserve account for the net reversal of storage, risk and safety assessment, and requirements for financial provision” (Ibid.). Even though the CCS-deploying project activities with modalities and procedures are acknowledged under the CDM, there are no approved baseline and monitoring methodologies for CCS projects as of November 2018 (UNFCCC 2018). For CCU, even project activities go unacknowledged under the CDM.

In succession of the Kyoto Protocol, the Paris Agreement includes Article 6, which is a ground rule for the formation of the international carbon market.[7)] There are three cooperation formats: ⅰ) cooperative approaches based on Article 6.2, ⅱ) sustainable development mechanisms (SDMs) based on Article 6.4,[8)] and ⅲ) non-market approaches based on Article 6.8. Parties can voluntarily utilize (participate in) these cooperation formats in the implementation of their nationally determined contributions (NDCs) to attain higher ambitions in their mitigation and adaptation actions (PA 2015, article 6.1).

Here, the basic concept of the SDM is quite similar to that of the CDM in several aspects: ⅰ) the CDM and the SDM are mitigation offset mechanisms; ⅱ) the SDM is under the supervision of a centralized authoritative body;[9)] ⅲ) participating parties jointly undertake

7) However, the term “market” does not appear in Article 6.

8) The SDM is not an official term to describe “a mechanism to contribute to the mitigation of greenhouse gas emissions and support sustainable development” (PA 2015, Article 6.4).

9) The SDM will operate under the authority and guidance of the Conference of the Parties serving as the meeting of the parties to the Paris Agreement (CMA), and the supervisory body supervises the mechanism

voluntary mitigation activities.[10] Of course, there are also differences. While the CDM is a mitigation offset mechanism that limits cooperative partners between developed countries (as project developers) and developing countries (as project host countries), the SDM does not divide between developed and developing countries in the development and hosting of projects. Currently, the rules, modalities, and procedures for SDM are negotiated. The rules/modalities/procedures for the SDM are explored from the perspective of mobilizing financing for CCU. There is a section that deals with the design requirements for the activity to be registered as the SDM activity. Currently, in terms of "the types of mitigation," it has not yet been decided whether only the activity that shall achieve "emission reductions" will be acknowledged as SDM activity. It is under discussion about the inclusion of activities that shall achieve "emission removals," "emission avoidance," or "emissions avoidance including mitigation co-benefits of adaptation actions and/or economic diversification plans" (UNFCCC 2018a, Annex para 31).[11]

Considering the CCU's mitigation contribution potentials in terms of permanent storage by mineralization, there is the possibility that CCU-based mitigation activities could be classified as achieving "emission reductions." Furthermore, CCU can utilize captured CO_2 in the production process instead of utilizing conventional fossil fuels, which leads to the avoidance of emissions. Therefore, to leave room for CCU-based mitigation activities to be acknowledged, both "emission reduction" and "emission avoidance" must be inserted. Of course, the general requirements of the SDM define that the activity shall "deliver real, measurable, and long-term benefits related to climate change in accordance with decision 1/CP.21, paragraph 37(b)" (Ibid.). Thus, although the type of mitigation that sets a broad boundary for the CCU-based activity is included, any activity to be recognized as leading to

under the authority and guidance of the CMA (PA 2015, Article 6.4; UNFCCC 2018a, p.42).

10) Mitigation activities under the SDM are broader than the project-based activities of the CDM. The activity type encompasses "a project, programme of activities, or other type approved by the Supervisory Body" (UNFCCC 2018a, Annex para 31(b))

11) Article 4.7 of the Paris Agreement stipulates that mitigation co-benefits that result from parties' adaptation actions and/or economic diversification plans can contribute to mitigation outcomes (PA 2015, Article 4.7).

emissions reduction or emissions avoidance must have a clear accounting methodology and monitoring system.[12)]

Meanwhile, under Article 6.2 of the Paris Agreement, a cooperative approach is an instrument with which parties can voluntarily engage in cooperation that involves the use of internationally transferred mitigation outcomes (ITMO) in the course of achieving their nationally determined contributions (NDCs) (PA 2015, article 6.2). ITMO refers to “tradable carbon credits” (Sharma 2016). Based on para 37 of the Paris Decision, guidance on cooperative approaches are under development by the SBSTA for adoption by the Conference of Parties to the Paris Agreement. This guidance is intended to ensure the avoidance of double counting based on a corresponding adjustment by parties “for both anthropogenic emissions by sources and removals by sinks” by parties’ NDCs under the Paris Agreement (UNFCCC 2015, para 37). Further specific guidance on cooperative approaches has also been under negotiation since 2016.

Unlike the SDM, cooperative approaches take a less centralized approach compared to the SDM in terms of governance. First, any cooperation form can be a cooperative approach as long as the parties recognize that cooperation is utilized in the implementation of NDCs. The form can be bilateral/multilateral/regional in terms of participation scope and can offset mechanism/emission trading system/whatever in terms of the mitigation approach. Second, there is no central body to supervise the operation of cooperative approaches. Technical expert review will be conducted with the information provided by participating parties and the UNFCCC secretariat will carry out a technical expert review (UNFCCC 2018b, paras. 4 and 5). Third, there seems to be no common accounting rules. Of course, participating parties in cooperative approaches also need to apply robust accounting like the SDM (PA 2015, article 6.2). However, at the current stage of negotiation on the guidance on cooperative approaches, common accounting rules will not be formulated. The establishment and operation of accounting rules are at the discretion of participating parties in cooperative

12) In the negotiation process at SBSTA50 held in June 2019, no clear meaning or definition of emission avoidance has yet been made. Therefore, negotiation participants feel doubtful about this term. It seems somewhat difficult to expect “emission avoidance” to be included as an eligible mitigation project.

approaches. From the perspective of mobilizing finance for CCU, participating parties can transfer ITMOs for “emission reductions and removals from sectors and greenhouse gases covered by the NDC” (UNFCCC 2018b, Annex, para 16). Thus, there is room for mitigation activity of CCU with CO_2 storage (mineralization technology) to be acknowledged as a cooperative approach. Although accounting rules can be discretionary, raising the credibility of generated and transferred ITMOs from relevant cooperative approaches seems to require that accounting rules applied in CCU-based mitigation activities are in line with those of the SDM.

Regardless of the cooperative format of SDM or cooperative approaches, there is commonly a challenge of accounting reduced (or avoided) emissions, so the development of methodologies for monitoring, reporting, and verifying mitigation outcomes from CCU is a prerequisite. In the development of methodologies, there are some points worth considering. First, in terms of the permanence-of-storage matter, not all CCU technologies allow for the long-term storage of CO_2. At this stage, if the mitigation activity of a CCU is hard to acknowledge, then only CO_2 mineralization technologies should be included in the CO_2 storage requirements of the CCS. Of course, in mitigation activities using CO_2 mineralization technologies, there can be physical leakage of CO_2 in the process of converting captured carbon into carbon-based products, so the amount of leakage must be monitored and accounted. In addition, the conversion process may require additional energy, which can lead to additional carbon emissions (GIR 2013; SCOT project). Furthermore, like CCS, for CCU to be deployed under cooperative approaches or SDM, the participation of host parties is required by the establishment and enforcement of domestic law and regulations. Second, it is quite difficult to acknowledge avoided emissions in individual industrial processes because the calculation of avoided emissions as an industrial average or in specific cases is “potentially arbitrary.” Therefore, preparing a standardized methodology and setting LCA boundary conditions for a transparent, robust, comparable, and fair LCA analysis in the case of the accreditation of avoided emissions are prerequisites (SCOT project 2019, p.5-6).

Korean national approach to the development of carbon mineralization technology

The Republic of Korea is devoted to R&D on CCUS technologies, which includes both CCS and CCU. For the R&D on CCU, Korea has focused on both chemical conversion and carbon mineralization. Recently, significant focus has been laid on carbon mineralization for its potential to mitigate climate change. The Korean government has unfolded policies and initiatives to lead the development and demonstration of carbon mineralization at both the ministerial (particularly at the MSIT) and presidential levels. Six major footsteps that have been taken are introduced as follows.

- **Master Plan on Climate Change Response** (Office for Government Policy Coordination, September 2008): determined CCUS as green technology of new growth engine (September 2008). This implied that CCUS can contribute to the mitigation of greenhouse gas and establishment of new industry for economic growth.
- **Mid-term National Goal of Greenhouse Gas Mitigation** (Inter-ministerial, September 2009): The application of CCUS for greenhouse gas mitigation was stipulated in the Mid-term National Goal of Greenhouse Gas Mitigation in the following year.
- **National Action Plan on CCS** (Inter-ministerial, July 2010) was announced by an inter-ministerial body steered by the Committee on Green Growth in July 2010. The main objectives of this Action Plan are demonstrating the pipeline of CCS, attaining CO_2 capture costs of $30 USD per CO_2 ton, stimulating commercialization, and establishing lifecycle environmental monitoring and commercialization.
- **The 3rd Master Plan on Science and Technology** (Presidential Advisory Council on Science and Technology, July 2013): in the context of interest in CCUS, the highest hierarchical plan in the science and technology sector, the 3rd Master Plan on Science and Technology appointed CCUS as a national strategic technology against climate change in July 2013.

- **Climate Technology Roadmap** (Inter-ministerial, August 2016): After the Paris Agreement in 2015, the Climate Technology Roadmap was developed by an inter-ministerial body that included the conversion of CO_2 and syngas and CO_2 mineralization in June 2016.
- **National Strategic Projects on Carbon Utilization** (Presidential Advisory Council on Science and Technology, August 2016): utilization (mineralization and chemical conversion) were developed in presidential meetings in August 2016. This implies that the importance of CCUS technologies was emphasized from environmental and economic perspectives.

Of the aforementioned national footsteps, the national strategic project on carbon mineralization aims to develop a packaged technology of carbon mineralization for abandoned mine reclamation accompanied by the standardization of products and environmental monitoring. This project consists of three major components: 1) the utilization of industrial residues and low-concentration CO_2 gas from factories and power plants, 2) the production of carbonate and eco-friendly cement for reclaiming abandoned mines, and 3) the development of methodology for CO_2 offset projects (Figure 8). In particular, demonstration was emphasized to attain the early commercialization of carbon mineralization technology. Three phases will be conducted, comprising demonstration of a mini-pilot to the operation of a demonstration plant.

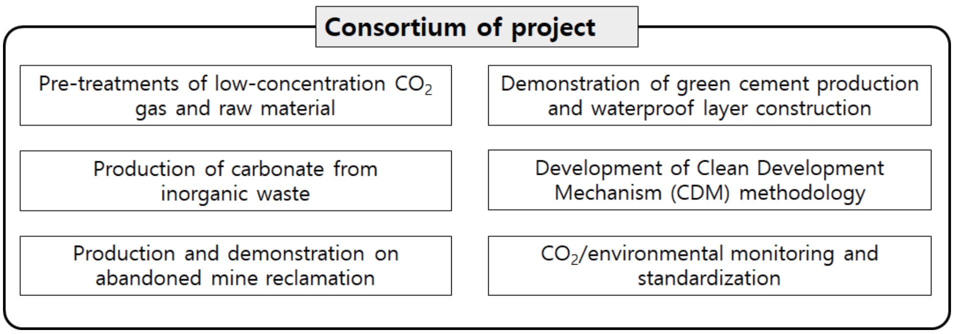

Figure 8 The consortium of the national strategic project on carbon mineralization in the Republic of Korea

Source: modified from Table 1 on p. 3 of Lee et al. (2019)

The national approach to developing carbon mineralization technologies suggests a national technology development model to obtain prominent CCUS technology (Figure 9). At the ministerial level, prominent technologies can be identified by MSIT, which organized official meetings to construct opinions and information on climate technologies from experts at research institutes and private companies. The Korea Institute of Geoscience and Mineral Resources is a leading research institute in Korea. Then, the inter-ministerial bodies, surely including the MSIT, were organized to establish an implementation system for developing and applying these technologies to national policies. Furthermore, scientific agendas on prominent technologies with the inclusion of CCUS technologies were addressed to presidential meetings, at which, the importance of technologies was prioritized. Then, intensive investment in prominent technologies was determined through national strategic projects and the impact of these technologies is expected to be amplified.

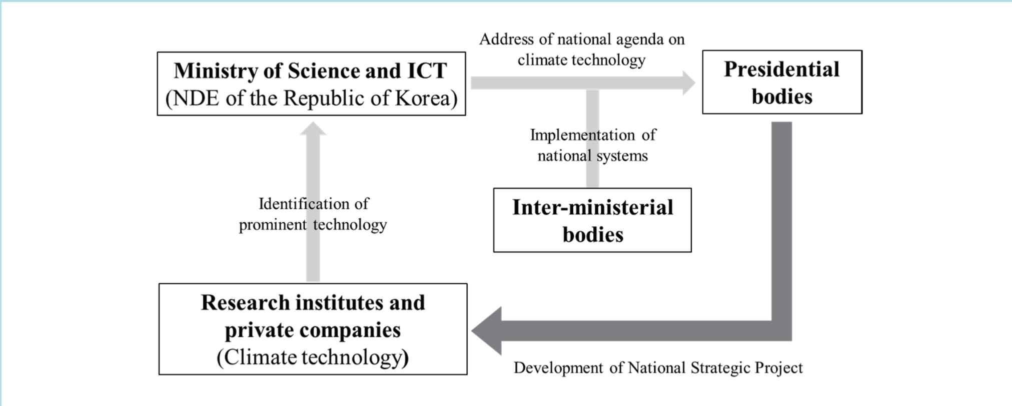

Figure 9 strategy of the technological development and international cooperation at the national hierarchy in the Republic of Korea

Source: modified from Fig. 7 on p. 9 of Lee et al. (2019)

GREEN TECHNOLOGY CENTER

SECTION

05

Conclusion: Steps forward

05 SECTION

Conclusion: Steps forward

This paper dealt with economic and sociopolitical barriers in the uptake of CCU and policy instruments to tackle these barriers. The technology-induced economic barriers of CCU are both the high cost taken in technology uptake and the exact estimation of cost and emission reduction amounts. Only exact estimation can help project developers' decisions regarding investment in the uptake of CCU, so more efforts that apply an LCA approach to existing CCU-based projects and programs are required. In particular, in the context of climate change, the quantification of exact emission reduction amounts becomes more important as mitigation activities are recorded, reported, and acknowledged as actions of migration. In this regard, out of numerous technology types of CCU, mineralization technologies are brought to the fore.

Meanwhile, from sociopolitical barriers, CCU has been framed in four types: ⅰ) contribution to mitigating climate change, ⅱ) energy transformation, ⅲ) resource security, and ⅳ) a complement to CCS. Although none of these has a salient framing position, there is no doubt that industrial CCU are a relevant mitigation option with high confidence in our efforts to meet the global temperature goal of 1.5°C. Currently, the TEC, which is a technology-policy organization of the UNFCCC, has been making efforts to define emerging climate technologies, including ZETs and NETs; its efforts remain at the definitional stage. Knowledge on the positive and negative impact of specific emerging climate technologies must be provided by the TEC. In particular, a "trusted source of information on the potential role of these technologies in supporting the global response to climate change and on policies that could support the innovation (and social consideration and acceptance) of such technologies" seems necessary (TEC 2018, p. 4). In this regard, CCU, which is currently an aspect of emerging climate technologies, has not been clearly framed by the TEC. Clear guidance by the TEC regarding the role of both CCU and CCS will greatly help countries design technology-based responses to climate change.

These economic and sociopolitical barriers are tightly related to technology financing, which requires certain cooperative mechanisms to provide technical and financial support to developing countries. Therefore, this paper explored the current international support instruments under the UNFCCC, which are the CTCN of the Technology Mechanism, the GCF of the Financial Mechanism, and the SDM and cooperative approaches on the grounds of Article 6 of the Paris Agreement. First, the CTCN forms grounds for support on CCU under the technology type "carbon fixation and abatement" and implements its actions of support on CCU together with CCS through technical assistance, knowledge-sharing, and network & capacity-building. However, the funding amount per technical assistance is up to $250,000 USD, so supportive activities are limited to institutional setting, assessment of technical feasibility, estimation of GHG reduction potentials, capacity-building, and others. In addition, as the CTCN is pressured to strengthen its transparency by reporting the impact of mitigation and adaptation, the estimated mitigation impact of CCU uptake becomes more important.

Second, the GCF can be a good candidate for scaling up CCU-related project funding after the CTCN's technical assistance. Although the eligibility criteria for the GCF financing specifically includes CCS, this does not mean that CCU is excluded. At the specific project level, the GCF's readiness program and the PPF will be useful funding tracks. However, for the preparation and approval of large-scale project-funding proposals, the CCU should be designed to be a part of the industrial transformative plan or national climate and energy policy program. In addition, due to the GCF's own mitigation and adaptation performance measurement framework, the uptake of CCU requires the quantification of mitigation impact.

Third, the SDM and cooperative approaches under the Paris Agreement will be important instruments with which the uptake of CCU can be further invigorated. However, this is only possible while mitigation activities utilizing CCU can be acknowledged as activities achieving "emissions reduction." As a part of specific implementation rules of the SDM and the cooperative approaches, whether only activities achieving "emission reduction" or other activities achieving "emission removals" or "emission avoidance" can be acknowledged remains under negotiation. Where can CCU be classified in the current framing of emission reductions, emission removal, or emission avoidance? Furthermore, regardless of framing, any CCU-based activity that can be recognized as leading to emissions reduction or emissions avoidance needs to have a clear accounting methodology and monitoring system.

05 SECTION Conclusion: Steps forward

In summary, there are four policy implications to ponder. First, as an emerging climate technology, CCU needs to be more clearly and specifically framed in a technological dimension. This framing is also related to the subsequent framing of whether CCU can be classified as eligible acknowledged activities that achieve emission reduction, emission removal, or emission avoidance; each of these terms also awaits further clarification. Second, the international policy instruments of the CTCN's technical assistance, the funding tracks of the GCF, and the SDM and cooperative approaches of Article 6 in the Paris Agreement all provide fertile grounds for the uptake of CCU. However, these grounds are rather fragmentary from the perspective of whether or how CCU can be acknowledged, further developed, and transferred. Since technological development and transfer, including CCU of course, is a cross-cutting issue, these policy instruments under the UNFCCC need clear common direction regarding which climate technologies can be acknowledged and encouraged for their development and transfer. This discussion paper sees that the guidance needs to come from the TEC of the Technology Mechanism under the UNFCCC (in collaboration with the IPCC). Third, the most important of these requirements for the facilitated uptake of CCUs is the clear estimation and quantification of GHG emission reductions from the CCU; this requires the scientific process of calculating reduced (or avoided) emissions. The development of methodologies to monitor, report, and verify mitigation outcomes from CCU is a prerequisite for the utilization of international policy instruments. Lastly, in this regard, out of the types of CCU, mineralization technology warrants further attention because it has the merit of comparatively clear mitigation impact for its long-term storage of captured CO_2.

References

von der Assen, N., & Bardow, A. (2014). Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study. *Green Chemistry*, 16(6), 3272-3280.

Bruhn, T., Naims, H., & Olfe-Kräutlein, B. (2016). Separating the debate on CO2 utilisation from carbon capture and storage. *Environmental Science & Policy*, 60(2016), 38-43.

Budinis, S., Krevor, S., MacDowell, N., Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews, 22*, 61-81.

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., ... & Hallett, J. P. (2018). Carbon capture and storage (CCS): The way forward. *Energy & Environmental Science, 11*(5), 1062-1176.

China. (2007). *China's scientific & technological actions on climate change*. http://www.most.gov.cn/eng/pressroom/200706/P020070716509738901418.pdf. Accessed on August 20, 2019.

Chiuta, S., Engelbrecht, N., Human, G., & Bessarabov, D. G. (2016). Techno-economic assessment of power-to-methane and power-to-syngas business models for sustainable carbon dioxide utilization in coal-to-liquid facilities. *Journal of CO_2 Utilization, 16*, 399-411.

CTCN. (2016). *Potential GHG emissions reduction in the cement industry by using waste heat recovery combined with mineral carbon capture and utilization*. https://www.ctc-n.org/technical-assistance/projects/substantial-ghg-emissions-reduction-cement-industry-using-waste-heat. Accessed on August 20, 2019.

CTCN. (2017). *Carbon capture and storage potential in Nigeria*. https://www.ctc-n.org/technical-assistance/projects/carbon-capture-and-storage-potential-nigeria. Accessed on August 20, 2019.

CTCN. (2019a). *What we do*. https://www.ctc-n.org/about-ctcn/what-we-do. Accessed on August 20, 2019.

CTCN. (2019b). *Technical Assistance*. https://www.ctc-n.org/technical-assistance. Accessed on August 20, 2019.

CTCN. (2019c). *About CTCN*. https://www.ctc-n.org/about-ctcn. Accessed on August 20, 2019.

CTCN. (2019d). *National Designate Entities*. https://www.ctc-n.org/about-ctcn/national-designated-entities#Roles and Responsibilities. Accessed on August 20, 2019.

CTCN. (2019e). *Network*. https://www.ctc-n.org/network. Accessed on August 20, 2019.

CTCN. (2019f). *Technology Sector*. https://www.ctc-n.org/technology-sectors. Accessed on August 20, 2019.

CTCN. (2019g). *Carbon Fixation and Abatement*. https://www.ctc-n.org/technology-sectors/carbon-fixation-and-abatement. Accessed on August 20, 2019.

CTCN. (2019h). *Carbon Fixation and Abatement* (filtered by contents type: organization). https://www.ctc-n.org/technology-sectors/carbon-fixation-and-abatement?f%5B0%5D=type%3Aorganisation. Accessed on August 20, 2019.

CTCN. (2019i). *Instructions to lead implementers for drafting the technical assistance closure and data collection report*. https://www.ctc-n.org/sites/www.ctc-n.org/files/ta_closure_report_template_fta_0.docx. Accessed on August 20, 2019.

de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, & T. Sugiyama. (2018). *Strengthening and Implementing the Global Response. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (eds.)]. In Press.

EIA. (2019). *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook* 2015. Independent Statistics & Analysis, (June), 1-12. http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf. Accessed on August 20, 2019.

EU. (2018). *Directives: Amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0410&from=EN. Accessed on August 20, 2019.

Dixon, T., Leamon, G., Zakkour, P., & Warren L., (2013). CCS projects as Kyoto Protocol CDM activities. *Energy Procedia, 37* (2013), 7596-7604.

EASAC (European Academies Science Advisory Council). (2018). *Negative emission technologies: What role in meeting Paris Agreement targets?* EASAC policy report 35, February 2018. https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf. Accessed on August 20, 2019.

GCF. (2011). *Governing instrument for the Green Climate Fund*. https://www.greenclimate.fund/documents/20182/56440/Governing_Instrument.pdf/caa6ce45-cd54-4ab0-9e37-fb637a9c6235. Accessed on August 20, 2019.

GCF. (2015). *Elements* 01. https://www.greenclimate.fund/publications/elements-01. Accessed on August 20, 2019.

GCF. (2016a). *Decisions of the Board-Thirteenth meeting of the Board, 28-30 June 2016*. https://www.greenclimate.fund/documents/20182/226888/GCF_B.13_32_Rev.01_-_Decisions_of_the_Board___thirteenth_meeting_of_the_Board__28-30_June_2016.pdf/c93a0291-28c1-4bfc-bc22-cf4c590c3c83. Accessed on August 20, 2019.

GCF. (2016b). *Further development of some indicators in the performance measurement frameworks*. https://www.greenclimate.fund/documents/20182/226888/GCF_B.13_26_-_Further_development_of_some_indicators_in_the_performance_measurement_frameworks.pdf/0ad22e10-703d-49ae-baad-eb87669d0223. Accessed on August 20, 2019.

GCF. (2017). *Update: GCF and support for facilitating access to environmentally sound technologies and for collaborative research and development*. https://www.ctc-n.org/sites/www.ctc-n.org/files/ab9_4d_gcf_2017_ctcn9.pdf. Accessed on August 20, 2019.

GCF. (2019). *Readiness support*. https://www.greenclimate.fund/gcf101/empowering-countries/readiness-support#faq-what-is-readiness-support. Accessed on August 20, 2019.

GIR (Greenhouse Gas Inventory and Research Center). (2013). *Basic research on the accounting for GHG emission from the uptake of CCU technologies*. Research report (in Korean).

Global CCS Institute. (2018). *Facilities Database*. https://co2re.co/FacilityData. Accessed on August 20, 2019.

Honegger, M. & Reiner, D. (2018). The political economy of negative emissions technologies: Consequences for international policy design, *Climate Policy, 18*(3), 306-321.

Howells, J. (2006). Intermediation and the role of intermediaries in innovation. *Research Policy, 35*(2006), 715-728.

IEA. (2019). *Carbon capture, utilization and storage*. https://www.iea.org/topics/carbon-capture-and-storage/. Accessed on August 20, 2019.

Cook, G. and Zakkour, P. (2016). *Review of accounting rules for CCS*. https://ieaghg.org/docs/General_Docs/Reports/2016-TR3.pdf. Accessed on August 20, 2019

Innovation for Cool Earth Forum (ICEF). (2016). Global roadmap for implementing CO_2 utilization. Accessed on August 20, 2019.

IPCC. (2014). Climate change 2014: Mitigation of climate change. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth., … J.C. Minx (Eds). *Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Irlam, L. (2017). *Global costs of carbon capture and storage-2017 Update*. https://www.scribd.com/document/374468832/global-ccs-cost-updatev4-pdf. Accessed on August 20, 2019.

Jones, C. R., Olfe-Kräutlein, B., Naims, H., & Armstrong, K. (2017). The social acceptance of carbon dioxide utilization: A review and research agenda. *Frontiers in Energy Research, 5*(11), 1-13.

Kätelhön, A., Meys, R., Deutz, S., Suh, S., & Bardow, A. (2019). Climate change mitigation potential of carbon capture and utilization in the chemical industry. *Proceedings of the National Academy of Sciences, 116*(23), 11187-11194.

Lee, J., Chang, C., Shin, K. N., Ahn, J. W. (2019). Strategy of developing innovative technology for sustainable cities: The case of the national strategic project on carbon mineralization in the Republic of Korea. *Sustainability*, 11, 3613; doi:10.3390/su11133613.

Leeson, D., MacDowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A techno-economic analysis and systematic review 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. *International Journal of Greenhouse Gas Control, 61*, 71-84.

Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews, 39*, 426-443.

Li, Q., Chen, Z.A., Zhang, J.-T., Liu, L.-C., Li, X.C., & Jia, L. (2016). Positioning and revision of CCUS technology development in China. *International Journal of Greenhouse Gas Control, 46*(2016), 282-293.

Liu, C. T., Hsieh, B. Z., Tseng, C. C., & Lin, Z. S. (2014). Modified classification system for estimating the CO_2 storage capacity of saline formations. *International Journal of Greenhouse Gas Control, 22*, 244-255.

MacDowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO2 capture and utilization in mitigating climate change. *Nature Climate Change, 7*(4), 243-249.

Markewitz, P., Kuckshinrichs, Wl, Leitner, W., Linssen, J., Zapp, P., Bongartz, R., Schreiber, A., & Muller, T.E. (2012). Worldwide innovations in the development of carbon capture technologies and the utilization of CO_2. *Energy & Environmental Science, 2012*(5), 7281-7305.

Matuszak, D. (2017). CO_2 utilization beyond EOR. US Department of Energy, presented on May 24, 2017.

Mazzotti, M., Abanades, J. C., Allam, Ro., Lackner, K.S., Meunier, F., Rubin, E., Sanchez, J.C., Yogo, K., & Zevenhoven, R. (2005). Mineral carbonation and industrial uses of carbon dioxide. In, Metz, B., Davidson, O., De Conninck, H., Loos, M., & Meyer, L. (2005), *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge University Press, New York.

Metz, B., Davidson, O., & De Coninck, H. (Eds.). (2005). *Carbon dioxide capture and storage: special report of the intergovernmental panel on climate change*. Cambridge University Press.

Naims, H. (2016). Economics of carbon dioxide capture and utilization-A supply and demand perspective. *Environmental Science and Pollution Research, 23*, 22225-22241.

PA (Paris Agreement). (2015). *Paris Agreement*. https://unfccc.int/sites/default/files/english_paris_agreement.pdf. Accessed on August 20, 2019.

Rubin, E., & De Coninck, H. (2005). IPCC special report on carbon dioxide capture and storage. *UK: Cambridge University Press. TNO (2004)*: Cost Curves for CO_2 Storage, Part, 2, 14.

Schneider, L. & La Hoz Theuer, S. (2019). Environmental integrity of international carbon market mechanisms under the Paris Agreement. *Climate Policy, 19*(3), 386-400.

Schlögl, R., Abanades, C., Aresta, M., Blekkan, E. A., Cantat, T., Centi, G., ... & Mikulcic, H. (2018). *Novel carbon capture and utilisation technologies*. European Commission.

SCOT project. (2019). *EU-ETS to incentivize CO_2 utilisation?* SCOT Project Briefing Paper. http://www.scotproject.org/images/Briefing%20paper%20EU%20ETS%20final.pdf. Accessed on August 20, 2019.

Sharma, A. (2016). *Carbon markets firmly back on the agenda*. http://sdg.iisd.org/commentary/guest-articles/carbon-markets-firmly-back-on-the-agenda/. Accessed on August 20, 2019.

Sizma, S., & Cormos, C.-C. (2018). Improving methanol synthesis from carbon-free H2 and captured CO_2: A techno-economic and environmental evaluation. *Journal of CO_2 Utilization, 24*, 555-563.

Smit, B., Park, A-H, A., & Gadikota, G. (2014). The grand challenges in carbon capture, utilization, and storage. *Frontiers in Energy Research, 2*(55), 1-3.

Styring, P., Jansen, D., de Coninck, H., Reith, H., & Armstrong, K. (2011). *Carbon Capture and Utilization in the Green Economy*. Centre for Low Carbon Futures, York.

Supersberger, N., Esken, A., Fischedick, M., & Schuwer, D. (2006). *Carbon capture and storage - Solution to climate change?* KyotoPlus-Papers. https://wupperinst.org/uploads/tx_wupperinst/CCS-KyotoPlus.pdf. Accessed on August 20, 2019.

TEC. (2018). *Background paper on possible work by the TEC on the innovation of emerging climate technologies, including zero-emission and negative emission technologies*. http://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/tn_meetings/13299e4f057e4b73a0398653c1dc17c6/0ee60aae9ad44fc6b4c91199468ca98b.pdf. Accessed on August 20, 2019.

TEC. (2019a). *IPCC special report on global warming of 1.5°C*. http://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/tn_meetings/6368935c5a214602b788244f3131f853/c2d4993488f4410abf322bb70d07086c.pdf. Accessed on August 20, 2019.

TEC. (2019b). *Overview*. http://unfccc.int/ttclear/tec. Accessed on August 20, 2019.

UNFCCC. (2010a). *Report of the conference of the parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010*. https://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf. Accessed on August 20, 2019.

UNFCCC. (2010b). *The contribution of the clean development mechanism under the Kyoto Protocol to technology transfer*. https://cdm.unfccc.int/Reference/Reports/TTreport/TT_2010.pdf. Accessed on August 20, 2019.

UNFCCC. (2015). *Adoption of the Paris Agreement*. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf. Accessed on August 20, 2019.

UNFCCC. (2018a). *Draft CMA decision containing the rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement* (in The Katowice Texts). https://unfccc.int/sites/default/files/resource/Katowice%20text%2C%2014%20Dec2018_1015AM.pdf. Accessed on August 20, 2019.

UNFCCC. (2018b). *Draft CMA decision on guidance on cooperative approaches referred to in Article 6, paragraph 2, of the Paris Agreement (in The Katowice Texts)*. https://unfccc.int/sites/default/files/resource/Katowice%20text%2C%2014%20Dec2018_1015AM.pdf. Accessed on August 20, 2019.

UNFCCC. (2018c). *CDM methodologies booklet*. https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf. Accessed on August 20, 2019.

US DOE (Department of Energy). (2016). *DOE Office of Indian Energy, Levelized Cost of Energy (LCOE)*. https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf. Accessed on August 20, 2019.

US DOE (Department of Energy). (2019). *Carbon Capture R&D*. https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd. Accessed on August 20, 2019.

Zakkour, P., Scowcroft, J., & Heidug, W. (2014). The role of UNFCCC mechanisms in demonstration and deployment of CCS technologies. *Energy Procedia*, 63 (2014), 6945-6958.

Zapantis, A., Townsed, A., & Rassool, D. (2019). *Policy Priorities To Incentivise Large Scale Deployment of Ccs. (April)*, 1-31. Retrieved from https://www.globalccsinstitute.com/wp-content/uploads/2019/04/TL-Report-Policy-prorities-to-incentivise-the-large-scale-deployment-of-CCS-digital-final-2019.pdf. Accessed on August 20, 2019.

Zhang, X., Fan, J-L, & Wei, Y-M. (2013). Technology roadmap study on carbon capture, utilization and storage in China. *Energy Policy*, 59(2013), 536-550.

van der Zwaan, B., & Gerlagh, R. (2009). Economics of geological CO_2 storage and leakage. *Climatic change, 93*(3-4), 285-309.

Political economy of carbon capture and utilization technologies

International policy designs in the context of climate change

Issuance | August 2019

Publisher | Green Technology Center
17th fl. Namsan Square Bldg., 173, Toegye-ro, Jung-gu, Seoul, 04554, Republic of Korea

Contact | Green Technology Center
☎ • 82-2-3393-3987

Design · printing | MisaWelfare
☎ • 82-2-6948-9650

Political economy of carbon capture and utilization technologies

International policy designs
in the context of climate change

GREEN TECHNOLOGY CENTER
녹색기술센터