

Article

CC(U)S Initiatives: Public Effects and “Combined Value” Performance

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Abstract: The changes in climate, which are associated with the emission of anthropogenic greenhouse gases, have been widely discussed by scientists and specialists during the last few decades. The promising way to reduce CO₂ emission is to implement CC(U)S technologies (carbon capture, (utilization) and storage). However, CC(U)S initiatives are challenging that prevent their widespread adoption. The main purpose of the research is to prove that CC(U)S should be considered broader than a way to reduce emission, and such initiatives could lead to various public effects and create long-term “combined value” for the industry and wider society; all of these should be considered when making decisions on CC(U)S implementation. The results of the research are presented by highlighting bi-directional interaction between CC(U)S and society, including public acceptance and public effects; identifying the possible positive and negative impact of CC(U)S initiatives on the public; developing a system of indicators for assessing the public effects of CC(U)S; proposing the framework for a value at stake analysis (VAS) of CC(U)S initiatives in order to reveal and assess their “combined value”. The methodology of this study includes desk studies, decomposition technique, environment (E), health (H) and safety (S) (EHS) approach, classification techniques, and VAS analysis.

Keywords: climate change; CO₂ emission; CC(U)S initiatives; project; public effects; society; system of indicators; assessment; value; combined value



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1. Introduction

The issue of climate change has been of concern to many scientists, ordinary people, and specialists for many years [1–7]. Rapid warming has been observed since pre-industrial times, and many of the negative changes that have occurred in the environment since the 50–60 s of the past century are unprecedented [8].

Many experts and scientists associate climate change and global warming with the emission of carbon dioxide (CO₂) [9–13], which amounted 33.9 billion tons in 2018, a maximum annual increase of 2.1% [14] during the last decade. In 2020, according to the International Energy Agency [15], global CO₂ emissions are likely to be reduced by 8%, a 10-year-old level. Nevertheless, it is predicted that lacking additional ways to cut carbon dioxide emissions the average temperature on the Earth is likely to increase by 1.65 °C over this century [16].

Many states, companies, society show great interest in the problems of carbon dioxide emissions, as well as in the development of technologies that reduce them [17–23]. Scholars believe that decarbonization strategy should include the following key low-carbon technologies directed at [24]: improving energy efficiency; using renewable energy sources and hydrogen instead of non-renewable ones; carbon capturing, (utilization) and storage.

Improving energy efficiency has the potential to avoid CO₂ emissions, but the global pace of progress has slowed down over the past five years [25] and this trend will not be reversed in the near future.

Currently, there is a diffusion of renewable energy technologies driven by environmental and political regimes [26–28]: in many countries the share of renewable resources in the fuel and energy balance is gradually increasing. Wind and solar energy as examples of variable renewable energy sources are considered the most promising for achieving cost effective reduction of carbon dioxide emissions [29]. However, these technologies face some challenges due to the volatility and unpredictability of solar and wind energy, high initial investment in generator construction, and possibilities of their nonlimited construction [30]. In the future, hydrogen may become an environmentally friendly fuel for cars, but now its widespread use is impossible due to many technical limitations [31,32]. Thus, fossil fuels will still form a crucial part in the fuel and energy balance of many countries which makes it important to use technologies that contribute to the decarbonization of the world economy.

The use and dissemination of CC(U)S—carbon capture, (utilization) and storage technologies—is a promising measure to control carbon dioxide emissions [20,33–35]. The typology of such technologies includes CCUS (carbon capture, utilization, and storage), CCS (carbon capture and storage) and CCU (carbon capture and utilization) technologies [36–38].

Many authors devoted their studies to various aspects of CC(U)S technologies. Some publications summarize the experience of CC(U)S initiatives [29,39–41], others focus on future opportunities [42], specific examples of successful CC(U)S development in various countries [43–46] and “lessons learned” on technical and non-technical aspects [47–51].

Many research papers consider the specifics of various technological stages of CC(U)S projects [52–54], government and private financing [51,55], technical and economic assessment of CC(U)S technologies [56–58], and examine the role of political support, regulatory framework, stakeholders, and public acceptance in the deployment of CC(U)S [59–64].

The authors highlight problems that may be directly or indirectly related to a failure in implementation and, consequently, a delay in the deployment of large and complex projects, such as CC(U)S [19,65–71]. In the publications mentioned above, the main challenges are immaturity of technologies used at various stages of CC(U)S chain; low commercial efficiency of CC(U)S technological schemes; lack of financial government and public incentives; high operating and capital costs; undeveloped and unpredictable regulatory framework; low public awareness and negative perception.

Internationally, issues related to public acceptance are recognized as one of the main problems in the adoption of complex low-carbon technologies such as CC(U)S [72–76]. Negative public opinion can sometimes lead to a project being canceled or postponed. The examples of such projects are Jamestown Oxycoal Project (USA), Barendrecht CCS Project (Germany), Wallula Project (USA), Greenville Project (USA), and the CCS Demonstration Project Jämschwalde (Germany) [60,77–79].

Thus, despite the fact that CC(U)S technologies are recognized to be significant for CO₂ emission reduction, the pace of successful CC(U)S implementation worldwide is very slow, and their impact as climate change mitigation measure is still insufficient. Scholars agreed that the global goal of reducing CO₂ emissions could not be achieved without CC(U)S [80], but they are considered to be expensive and technologically challenging methods, along with the existing uncertainty over business interests and public acceptance of CC(U)S.

In this article, we try to thoroughly analyze the interaction between CC(U)S and public, as well as possible business interest in CC(U)S. We believe that such an investigation could help us understand the situation around the possible increase in the value of CC(U)S.

A significant number of social and public studies conducted through interviews, questionnaires, and other similar surveys [80–86] provide insight into the public consciousness of CC(U)S and contribute to the study of how its acceptance is shaped today and in the future. Such studies can help advance CC(U)S initiatives, and develop plans in communication and public engagement towards increasing public support and enhancing the necessary public acceptance.

In addition, CC(U)S could bring significant environmental and various public benefits, protect human health and the environment in the long term [87]. In this case, the full life-cycle of CC(U)S should be considered in the context of the overall public effects it creates.

Considering the above, we highlight bi-directional interaction between CC(U)S projects and society, including public acceptance and related aspects, as well as public effects (Figure 1).

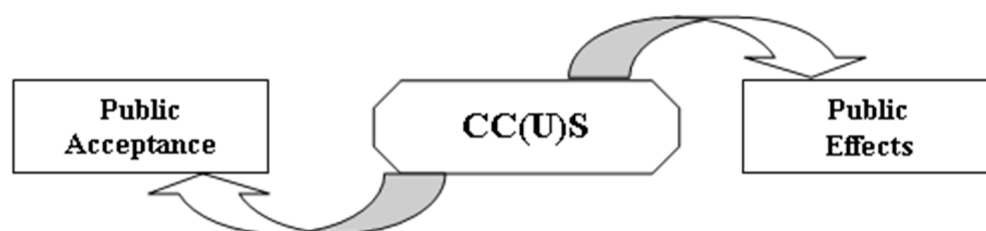


Figure 1. Bi-directional system of public and CC(U)S interaction. Source: created by the authors.

The public acceptance issues are widely discussed in the scientific literature. A lot of studies have been conducted to analyze the factors influencing acceptance and the model of public perception of CC(U)S [74–76,80,84–86,88–91], while others monitor and assess the level and perspective of awareness and acceptability of CC(U)S technology in different countries [61,72,74,82,83,92,93].

Different situations arise when studying public effects. The problem of their identification and definition is not covered in the scientific literature. Various search queries related to public effects did not lead to the expected results and brought us back to the problem of public acceptance, which was researched early, or just stated the need to take into account the socio-economic aspects of CC(U)S technologies [56].

The same problem arises when we look deeper to the interaction between business and CC(U)S initiatives. Many studies are devoted to the careful consideration of the problems of financing, high operating and capital costs. However, only a few of them present a systematization of the commercial effects that businesses can get from these technologies [94,95]; this case is also associated with broader public effects.

All these can be considered as a research gap and the reason and object of this work.

We assume that the assessment of public effects of CC(U)S initiatives is crucial for their deployment, since the cost of their implementation is high, and obtaining commercial effects is not always possible, or they are insignificant. Identifying and assessing the public effects will help re-evaluate such initiatives and add value. In the projects where commercial effects are possible the latter need to be clarified in the long term. This also explains the need to study the interaction of business and CC(U)S initiatives, which is also presented in this article.

A deeper analysis of the various types of CC(U)S initiatives allows us to take a broader look at the potential effects of CC(U)S and understand that all types of CC(U)S are sources of additional value for business and wider society. In this case, the main object of the article is to propose a framework for assessing, firstly, the public effects of CC(U)S, and secondly, the “combined value” that CC(U)S can create in areas such as society and industry.

A research hypothesis of the study suggests that the introduction of CC(U)S (like other low-carbon technologies) should be considered as initiatives with significant public and other long-term effects that increase their value. The assessment of such effects could contribute to the deployment of such technologies, improve their public acceptance and increase business interest in such initiatives. The possible outcomes for the public should be evaluated in different directions, with a set of indicators to be assessed; a “combined value” of CC(U)S should take into account the whole set of values of CC(U)S for society and industry.

The structure of the paper includes the following steps:

- identifying areas of positive and negative impacts of CC(U)S on public;
- creating a system of indicators and developing recommendations for the assessment of CC(U)S public effects;
- clarifying the differences in assessing public effects of different types of CC(U)S projects;
- proposing a framework for assessing potential value of CC(U)S for public and industry;
- providing the examples of application of the proposed system and framework.

We tried to confirm the applicability of the proposed system of indicators, as well as proposed framework for assessing “combined value” of CC(U)S using simple examples and open sources of information. We believe that having the necessary information in the hands of contractors and project participants will make it possible to apply the proposed approaches more widely.

2. Materials and Methods

Since the issues we address in this paper refer to theoretical and practical aspects of CC(U)S initiatives, we base our study on the open information sources on CC(U)S, as well as scholars’ research on the topic. Desk study served as the key research method.

We analyzed practical materials on CC(U)S in order to understand the situation around such initiatives [15,16,96–100]; academic literature presented above to identify the gaps in academic debates related to the public (social) aspects of CC(U)S. For academic literature analysis, the Scopus and ScienceDirect databases were used as the primary sources of information.

To identify the main areas of impact of CC(U)S on the public, thereby determining the main directions of public effects, we used the decomposition technique (Figure 2). We resorted to the environment (E), health (H) and safety (S) (EHS) approach that studies and implements practical aspects of environmental and health protection, as well as safety management [101]. We adopted this approach according to the specifics of CC(U)S.

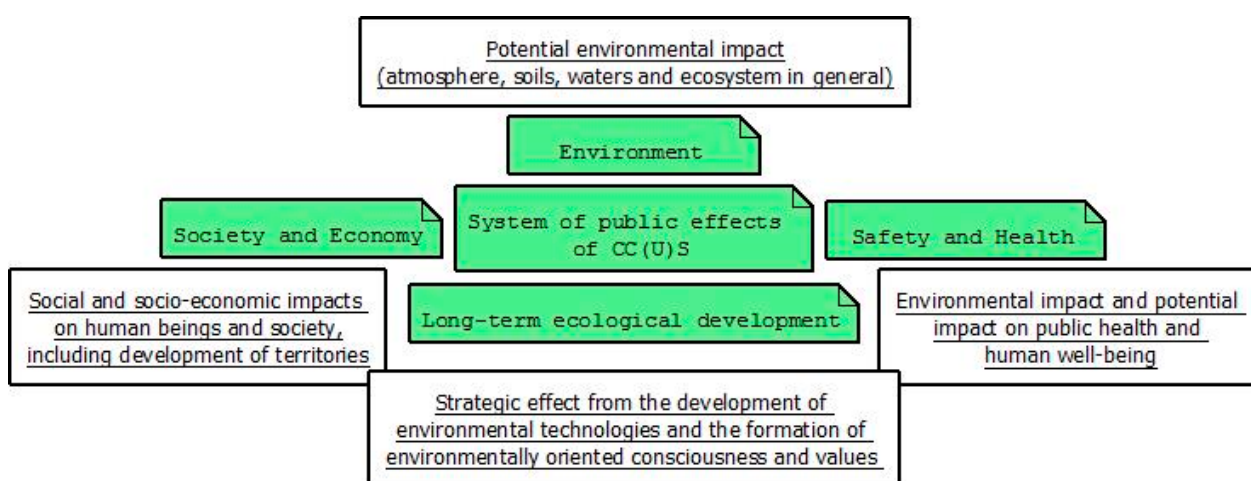


Figure 2. Directional influence of CC(U)S on public (EHS/SE and ED). Source: created by the authors.

Basing on the “World Bank Group Environmental, Health, and Safety Guidelines” [102], we supplemented the above directions (EHS) with such aspects as society and economy, long-term ecological development, as the EHS addresses organizations’ environment and labor activities, while we study the overall impact of CC(U)S on public, including socio-economic (SE) effects and environmentally oriented development (ED). We called the system EHS/SE and ED (Figure 2).

Using general methods of scientific analysis, we identified the positive and negative impact of CC(U)S, and developed a set of indicators for assessing the public effects of CC(U)S targeting various project types within EHS/SE and ED system. The developed set of indicators includes common indicators characterizing public aspects, as well as specific

ones that relate only to CC(U)S and their impact on humans, environment, economy and safety as a whole.

To identify the main types of CC(U)S projects, we used classification techniques, where the CC(U)S technological chain was a base of the classification.

As we mentioned early, CC(U)S initiatives should be considered more broadly than a way to reduce carbon dioxide emissions with an assessment of all possible effects (including public ones) in the long term. For this reason, we also refer to value-at-stake (VAS) approach in the article.

VAS framework was presented within the World Economic Forum and designed to assess the impact of digital transformation of different industries on the society, customers, industries and the environment [103–105]. We have adapted this tool to assess the potential value that CC(U)S initiatives can provide to society and industry. This tool based on decomposition of the core values created by CC(U)S initiatives, helped us present all the potential “combined value” associated with their implementation.

3. Results

3.1. Positive and Negative Impact of CC(U)S on Public

The identified four directions of influence of CC(U)S on the public (EHS/SE and ED) (Figure 2) made it possible to determine the main areas of analysis, which we present in Table 1. We characterized these areas by identifying the possible positive and negative impact of CC(U)S initiatives on the public, since such initiatives and their perception, as discussed earlier, could be ambiguous.

Table 1. Possible positive and negative impact of CC(U)S on the public within EHS/SE and ED framework.

Direction	Positive Impact	Negative Impact (Perceived or Real)
Environment (E)	Emission reduction; contribution to mitigating the effects of global warming; following the principles of sustainable development; obtaining the status of a region with a safe environmental situation	Possible carbon dioxide leaks and air, soil, surface and groundwater pollution; biodiversity change; increased risk of seismic activity *
Safety and Health (SH)	Improving the environmental situation in the country/region/particular area; positive effects on human health	Adverse effects on human health in case of leaks and accidents; possible exposure to associated harmful gases (hydrogen sulfide); increased risk of seismic activity *
Society and Economy (SE)	Development of infrastructure, socio-economic development of territories; education at all stages (from childhood to adult); creation of new and maintenance of existing jobs; improving the efficiency of existing production facilities; influx of different groups of people to the site (research trips, business and educational tourism, etc.); development of scientific capacity	Negative impact on the economic activities of locals (farming, agriculture, fishery); land grabs; possible decline in land and real estate value on the territories near the CC(U)S site; use of taxpayer funds (through CC(U)S projects support)
Long-Term Ecological Development (ED)	Development and diffusion of eco-oriented CC(U)S technologies; creation of new business opportunities based on the sustainable development principles; popularization of environmental principles and formation of environmentally oriented consciousness and values (business, social and individual)	Reducing the pace of development of other environmentally oriented technologies aimed at CO ₂ emissions reduction; weakening incentives to reduce fossil fuel use

* Not proven. Source: created by the authors with the use of [38,56,87,101,106].

We based our analysis on the above bi-directional system of public and CC(U)S interaction (public acceptance and public effects) (Figure 1), assuming that the main positive aspects are related to the emergence of public outcomes, such as economic development of territories, creation of new and maintenance of existing jobs, improvement of environmental situation in the region, etc., while negative aspects are associated with land grab and, mostly, the safety of CC(U)S initiatives. The latter largely shapes the public perception and public acceptance of CC(U)S.

We used the results of this analysis to develop the system of indicators for the assessment of public effects of CC(U)S.

It is important to note, that «no CC(U)S» scenario could be discussed as well. We realize that measures discussed above aiming at improving energy efficiency of existing productions and household sectors, rapid development of renewables and hydrogen energy (and other options) could significantly decrease the level of CC(U)S deployment. However, we assume that «no CC(U)S» scenario is unlikely, since the fossil fuels will be used for a long time anyway. The share of their usage may decrease, but will not be zero for a long time, and CC(U)S could promote low carbon development, while their rapid growth could be forced by more promising options of CO₂ usages.

3.2. Overall Performance Assessment System of Public Effects of CC(U)S

A qualitative analysis of the impact of CC(U)S initiatives on the public, carried out within the EHS/SE and ED framework, helped us determine its types on all public aspects in areas; but it does not contain specific indicators. We assume that the identified impacts are the source of positive and negative public effects of CC(U)S. Therefore, the assessment of public effects of CC(U)S should be quantified as much as possible. A reliable presentation of both qualitative and quantitative estimates is required, in terms of EHS/SE and ED framework and the existing specifics of CC(U)S. It should be based on the above positive and negative impacts of CC(U)S on the public and consider the possibility of measuring them.

The system of indicators for assessing the public effects of CC(U)S is presented in Figure 3. It was developed based on a comprehensive literature review, analysis of the experience of various CC(U)S initiatives, as well as the approaches presented in the materials and methods section.

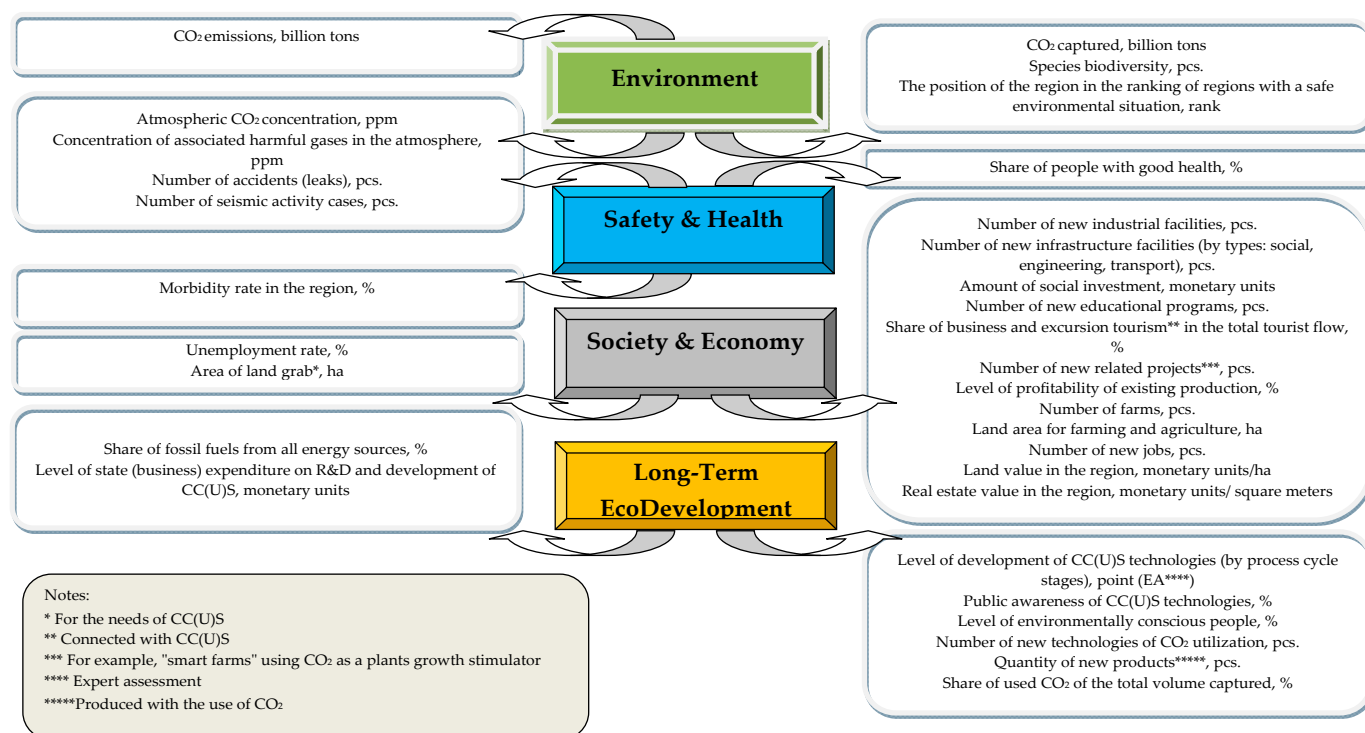


Figure 3. System of Indicators for Assessment of Public Effects of CC(U)S within EHS/SE and ED Framework. Source: created by the authors.

The presented system demonstrates a set of indicators that can be used to assess the positive and negative impacts of CC(U)S initiatives on the public, including both short-term

and long-term (strategic) impacts, which, in turn, determine the emergence of positive and negative public effects.

The proposed indicators are divided into groups of maximization (right side of the figure) and minimization (left side of the figure) indicators. A higher value of indicators of the first group and a lower value of the second one indicate a cumulative increase in public effects.

We have critically analyzed the proposed system of indicators and concluded that the assessment procedure has peculiarities. For example, it is necessary to separate public effects that are related directly to CC(U)S, and assess them in dynamics. We analyzed the possibility of the assessments of public effects of CC(U)S achieved with the use of all presented indicators, and developed the following general guidelines:

1. Indicators should be measured in direct relation to CC(U)S initiatives (as far as possible). For instance, the amount of social investment implies only those money that is invested in CC(U)S at any stage.
2. Almost all indicators (for example, CO₂ emissions, CO₂ captured, public awareness of CC(U)S technologies, and many others) can only be informative when studied in dynamics. The exception is those indicators that characterize the emergence of some phenomenon (for example, the number of new educational programs, the number of new related projects, etc.). However, in dynamics, such indicators show a cumulative effect.
3. Indicators such as the number of accidents (leaks), the number of seismic activity cases should strive to zero.
4. The level of state (business) expenditure on R&D and development of CC(U)S should strive to a minimum, since we recognize these expenses as taxpayer funds.
5. The values of indicators such as the number of farms, the land area for farming and agriculture can remain at an initial level (above all, not decrease), which is a positive fact, since the CC(U)S initiatives does not harm such activities. The same is true for such indicators as the land value in the region and the real estate value in the region.
6. The share of fossil fuels in all energy sources should strive to a minimum, as we assume that combined scenario is needed—CC(U)S options and the use of non-fossil fuels. All this could contribute to the low carbon future and long-term eco-development.

However, we recognize that the presented system of indicators is debatable. This is due to the different nature and units of the latter, lack of necessary quantitative data, etc. Moreover, the change in a number of indicators may also be unrelated to CC(U)S initiatives and could be influenced by other factors (for example, such an indicator as the unemployment rate in the region). Some indicators, in principle, are debatable regarding their direct relation to CC(U)S initiatives (for instance, share of people with good health, morbidity rate in the region, etc.). A number of indicators are directly or indirectly related to CC(U)S initiatives.

We assume that a separate scientific task is to refine the assessment system for various types of CC(U)S projects, as well as to assess not only public effects of CC(U)S, but the “combined value” that they could create for both society and business, as CCUS and CCU could set up a wide range of business opportunities. This led to the following studies aimed at examining the possible variability of the assessment depending on the type of CC(U)S project, as well as the analysis of value at stake of CC(U)S initiatives.

3.3. Different Types of CC(U)S Projects and Possible Variability in Assessing Public Effects

Different types of CC(U)S projects pushed us to analyze the peculiarities of their technological chains, since the public effects can vary depending on the type of the project, so the assessment procedures may differ.

Table 2 presents three main types of CC(U)S projects, their goals, as well as key economic, technological, and social aspects.

Table 2. Types of CC(U)S projects, its key characteristics and creating public effects.

Type of the Project/Parameter	CCS	CCUS	CCU
Project Entity	Carbon capture and storage	Carbon capture, utilization and storage	Carbon capture and utilization
Project Goal	Environmental effect Improving the image of the country and participants Testing new technologies and getting new information Commercial effect (in some cases as an option to reduce the emission fee)	Commercial effect (if possible) Technological development (more related to the CO ₂ utilization) Environmental effect Responsible investing (business goal) Improving the image of the country and participants	
Economic aspects	Not commercial, high capital and operating costs, no income Exception: option to reduce the emission fee	Sources of new business opportunities; possible to obtain a commercial effect, however, the level of capital and operating costs at the current level of technology development is quite high and may not be comparable to revenues or cost savings	
Technological aspects	Technological cycle tested, special attention to storage disposal and monitoring	Technological cycle in testing and scaling phase, special attention to CO ₂ utilization, storage disposal and monitoring	Technological cycle in development, special attention to CO ₂ utilization
Social aspects	Environmental impact, socio-economic development of the region, creation of new jobs, etc.		
Suitable indicators for assessment of public effects	Number of accidents (leaks), pcs. Number of seismic activity cases, pcs. Area of land grab, ha Number of new educational programs, pcs. Number of farms, pcs. Land area for farming and agriculture, ha Public awareness of CC(U)S technologies, %		
	Number of new technologies of CO ₂ utilization, pcs. Quantity of new products produced from CO ₂ , pcs. Share of used CO ₂ of the total volume captured, %		

Source: created by the authors.

In general, CCS projects are not commercial, but they could serve as the option to reduce emission fee (for example, Sleipner and Snøhvit CCS projects in Norway). The main incentives for their deployment are the following: contribution to mitigating the effects of global warming, creation of a demonstration facility, improving the image of the state and participants, etc. Government has a key role, and society is an important stakeholder, as the safety of CO₂ storage in different regions provokes a controversial reaction [38,85].

CCUS and CCU projects implement CO₂ usage, while the former—CO₂ storage as well. This fact almost completely excludes the role of public in CCU projects in terms of its possible opposition to such initiatives.

As for the assessment of the public effects, there are the following differences (Table 2):

1. Indicators related to CO₂ storage are relevant for assessing the public effects of CCS and CCUS projects.
2. Indicators related to CO₂ usage are relevant for assessing the public effects of CCUS and CCU projects.
3. All other indicators of the system for assessment of the public effects of CC(U)S (Figure 3), that are not listed in Table 2, can be used for all types of CC(U)S projects, since they belong to the capture phase, which is common for all projects, or to the general implementation issues of such initiatives.

Considering the above, we draw the following main conclusions on giving a score for each indicator and conducting general assessment:

1. The number of indicators for the assessment could be different; an assessment system can be used in a full and shorten form depending on the stage of CC(U)S project, the availability of information, the assessment objectives, the specifics and type of the project, etc.

2. As for scoring, it should be done after the selection of indicators for each case. Preliminary information collection should be conducted in a certain form with the participation and involve of project initiators, contractors, experts, representatives of industry, scientific organizations, etc. The more information available, the more credible and useful the assessment will be.
3. We believe this system is suitable for assessing the public effects of existing CC(U)S projects that are under implementation, for monitoring and control purposes. This is due to the greater availability of information, the possibility to study it in dynamics, etc. At the initiation stage of CC(U)S project, such an assessment is difficult, since it requires estimates regarding the future and should be based on forecasts which, in our opinion, are uncertain.

All the above prove that integrating all indicators in order to show the value of public effects of CC(U)S may be difficult. For instance, one CC(U)S project can appeal up to 25 indicators, as the information is available and the assessment is possible, while another one—only 10–12 indicators. Different types of CC(U)S projects or projects of different scales can be assessed, so the selected indicators and their numbers may differ. Moreover, the significance of indicators for assessing the public effects of CC(U)S may vary. It does not seem reasonable to compare integrated assessments that involved different set of indicators or were calculated in different ways. However, we understand that presentation of such an assessment as a single result could be interesting, so we will try to demonstrate such a case in further research.

In the final part of the article we provide simple examples of the application of the proposed system of indicators.

Since all types of CC(U)S can create additional value for industry (in case of CCS—reduce emission fee, in case of CCUS and CCU—create new business opportunities), public effects can be broader than we discussed earlier. For instance, emergence of public effects through the new business operations. We suppose that it sounds reasonable to assess the “combined value” of such initiatives. We believe that such an assessment will provide a better understanding of CC(U)S potential value for society and industry, and will facilitate the deployment of CC(U)S initiatives.

3.4. “Combined Value” of CC(U)S Initiatives

In the context of the above, in this section we present a framework for the analysis of the potential value of CC(U)S initiatives based on VAS approach. This tool, as mentioned above, was designed as an analytical framework for assessing the potential value of digitalization for both industry and wider society [105]. The following key points allowed us to apply VAS analysis to assess the value that CC(U)S initiatives can create for both industry and society:

- CC(U)S initiatives are often not economically feasible, while a potential assessment of the commercial effects cannot be carried out directly in the early years of project development, since they take a long time to become commercial; in this situation, the assessment of the potential value of CC(U)S initiatives in the long term is reasonable;
- a large number of stakeholders take part in CC(U)S initiatives (government, contractor, business, society, environmental and public organizations, etc.) [62,74], therefore, all potential values for different stakeholders must be considered;
- CC(U)S initiatives have created multidirectional effects (reducing emissions, creating new business opportunities, socio-economic development of territories, creating new jobs, technological development, etc.), and such effects can be presented in the form of potential value in directions;
- quantifying a number of effects of CC(U)S initiatives can be difficult, while presenting potential value (which can be presented in non-quantitative form) can demonstrate the full range of effects.

In this regard, in the VAS framework, we presented an analysis of the “combined value” that CC(U)S initiatives can create in areas such as industry, highlighting value

migration and value addition, as well as society including customers, environment, public health and economic benefits to society (Figure 4).

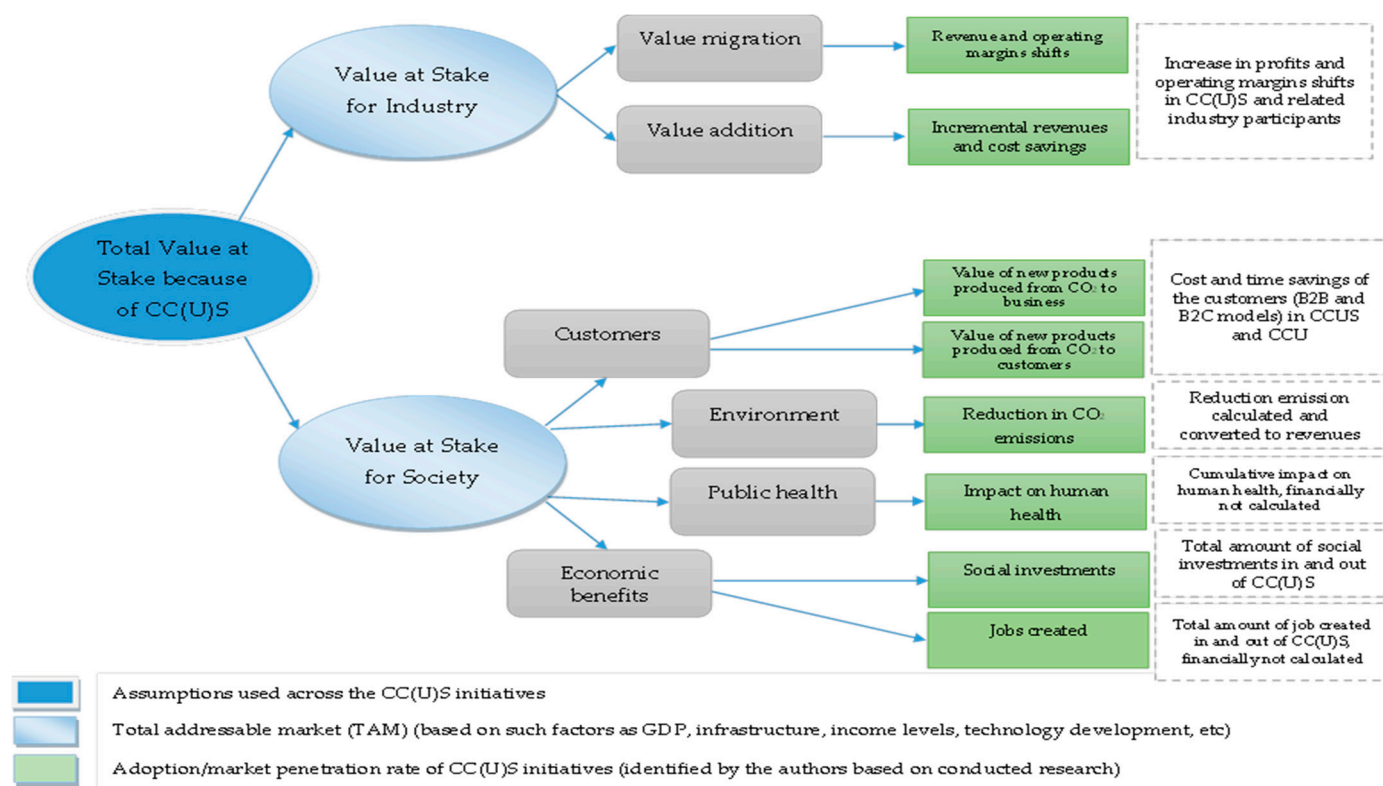


Figure 4. Value at stake analysis of CC(U)S initiatives. Source: created by the authors.

In each case, we have proposed projections of the emerging sources of value of CC(U)S initiatives to the industry itself and for wider society, measured (as in the case of digitalization) them using an intentionally narrow set of indicators [99,107]. Table 3 presents main parameters for assessing market penetration rate of CC(U)S initiatives with their interpretation and the proposed formulas for calculating them. We provide explanations and recommendations for the calculation of all parameters presented in Figure 4, excluding only the impact on human health and jobs created, since they are not monetary characteristics.

Table 3. Guidelines for assessing value-at-stake of CC(U)S initiatives.

Parameter	Interpretation	Financially Calculated	Formula (if Applicable), Monetary Units *
Revenue and operating margins shifts	Revenue and costs shifting due to transformation of value chains and conversion of CO ₂ from waste to valuable economic resource	Yes, but depends on created value chains	-
Incremental revenues and cost savings	Total increase in profits (based on increase in revenues and cost savings) for participants of CC(U)S initiatives (1) and related industries (2)	Yes	$P_{inc} = \sum_{t=1}^T (P_{inc1t} + P_{inc2t})$ <p> P_{inc}—total increase in profits P_{inc1t}—increase in profits of CC(U)S participants (1) P_{inc2t}—increase in profits of related industries' participants (2) </p>

Table 3. Cont.

Parameter	Interpretation	Financially Calculated	Formula (if Applicable), Monetary Units *
Value of new products produced from CO ₂ to business and customers	Total cost (and time, converted to money) savings of the end customers (B2B and B2C models) in CCUS and CCU initiatives	Yes	$C_{sav} = \sum_{t=1}^T (C_{savB2Bt} + C_{savB2Ct})$ C_{sav} —total cost savings $C_{savB2Bt}$ —cost savings of business $C_{savB2Ct}$ —cost savings of customers
Reduction in CO ₂ emissions	Total emission reduction calculated and converted to revenues (CO ₂ sale), profits (CO ₂ utilization) and cost savings (for instance, on payments and fines for CO ₂ emission)	Yes	$ER_{CO_2} = \sum_{t=1}^T (R_{salco2t} + P_{utco2t} + C_{savco2t})$ ER_{CO_2} —total reduction in CO ₂ emissions converted to money $R_{salco2t}$ —revenues from CO ₂ sale P_{utco2t} —profits from CO ₂ utilization $C_{savco2t}$ —cost savings related to CO ₂ emission (payments, fines, etc.)
Social investments	Total amount of social investments made directly in connection with CC(U)S initiatives	Yes	$SI_{CC(U)S} = \sum_{t=1}^T SI_t$ $SI_{CC(U)S}$ —total amount of social investments

* T—CC(U)S initiative implementation period. t—t-th index for the year of CC(U)S initiative implementation, $t \in \overline{1, T}$. Source: created by the authors.

This framework does not contradict the use of the system of indicators for assessing the public effects presented above (Figure 3). We assume this approach complements it, in part, it uses the same indicators and approaches presented in the system of indicators, but it is focused on revealing the long-term effects of these initiatives both for business with its commercial objectives and for society.

Regarding the application of this system, in addition to the recommendations and assumptions presented for the indicator system, the following conclusion can be made:

1. Collection of information on CC(U)S for the assessment of industry benefits and public effects should be done with the help of participants-project initiators, scientific organizations, industry, etc.; involvement of the widest possible range of stakeholders will make the analysis more reliable.
2. A set of indicators used should be individual for each particular case (similar to the system of indicators).
3. All assessed industry benefits and public effects should be popularized among society and business, as it will help improve the perception of CC(U)S initiatives, as well as increase business interest.

We consider it as the first attempt to present “combined value” of CC(U)S. We expect that this approach may be expanded in the future.

3.5. Examples of Application of Proposed Approaches for Assessment of Public Effects and “Combined Value” of CC(U)S

3.5.1. Application of the System of Indicators for Assessment of Public Effects of CC(U)S

Putting the system of indicators for assessment of public effects of CC(U)S (Figure 3) into application, we briefly review the possibilities and give an example of its applying on Tomakomai CCS Demonstration Project in Japan [108–110] and the Sleipner CCS project in Norway [111–113].

Tomakomai CCS Demonstration Project was started in 2012 and the project was suspended in 2019, as the planned cumulative volume of CO₂ injection of 300,000 tons was reached [109]. The source of CO₂ emission was a hydrogen production unit (HPU) of an oil refinery, and CO₂ was being injected offshore [109]. It means that the area of land grab is

zero; we suppose that all other indicators related to land, farming and agriculture should be unchanged.

According to available data [108–110], such indicators as CO₂ emissions and CO₂ captured could be scored. The first one is equal to total CO₂ emissions on this area (from this HPU) without CCS minus CO₂ captured; the second one, due to our assumption, is equal to the volume of CO₂ injection—300,000 tons totally. In practice, it is better make this measurement by years in dynamics. The share of captured CO₂ in total Japanese emissions is negligible (300,000 tons of CO₂ during the all project lifecycle in comparison with annual emission in Japan around 1100–1200 million tons of CO₂ [14]), but we believe it is significant in any case.

As the project implied only CO₂ capturing and storage, the indicators on CO₂ usage are not applicable (Table 2).

According to the data of Japan CCS, the number of accidents (leaks) is zero, the same for the number of seismic activity cases caused by CCS [109].

Public outreach activities of Tomakomai Project in JFY2018 included 2276 site visitors, 22 mini seminars, six kids' lab classes and others [110]. All this created and showed public effects that could be assessed through such indicators as number of new educational programs, share of business and excursion tourism in the total tourism flow, public awareness of CCS technology, etc. We assume that during the project implementation and outreach activities the public awareness of CCS has increased significantly.

As the main goal of this project was to demonstrate the viability of a full CCS technological cycle, we suppose that the level of development of CCS technologies (from CO₂ capture to injection and storage) has increased significantly. The Ministry of Economy, Trade and Industry (METI) of Japan covered the operating expenses [108], but we do not know the volume of funds to measure the level of state expenditure on CCS.

The information of new jobs created is not available, however, we understand that the project provided supporting of existing jobs in Japan CCS, as well as created new jobs on the site, including extensive monitoring systems that are still in operating [108].

Another example is the Sleipner CCS project, that was launched in 1996 in the North Sea (Norway) and is still ongoing. The Sleipner project is the first commercially viable large-scale project in the world. The project was initiated with the aim of bringing the gas produced to commercial level and avoiding the payment of the CO₂ tax introduced in 1991 in Norway [111].

According to available data [111–113], we can determine the commercial effect, which is measured in annual carbon tax savings of about \$26.23 million and identify some indicators that creating public effects.

For example, CO₂ captured is more than 20 million tons since 1996, and equal to 0.9 million tons per year [111], which is about 2.5% of the annual total carbon dioxide emissions in Norway [14]; number of accidents (leaks) and seismic activity cases since 1996 till now—0 pcs.

Due to the lack of information, we cannot determine the number of new educational programs, the public awareness of CC(U)S technologies, share of business and excursion tourism in the total tourism flow, but according to [111–113] the information and experience of this project have been shared with numerous scientific and educational organizations and institutions, research networks globally, what creates huge value for public.

The level of development of captured, storage and monitor technologies is high because the Sleipner project received several technology awards and have been using as benchmark for many technologically similar projects [112].

Since the project is being implemented on the shelf, such indicators as area of land grab, number of farms, land area for farming and agriculture are not relevant for consideration. At this stage of the project, carbon dioxide extracted from gas is not utilized, but we believe that in the future appropriate technologies may be tested and then the indicators on CO₂ usage will be applicable.

3.5.2. Application of the VAS Framework for Assessment of “Combined Value” of CC(U)S

As it was mentioned above, proposed VAS framework could help to identify “combined value” of CC(U)S initiatives. Since it is assumed that this “combined value” appears mostly through business opportunities, this approach is more applicable to CCU and CCUS projects. In this context, the available CO₂ utilization technologies, their commercial potential and degree of deployment play a special role.

For several decades, carbon dioxide has been directly used to enhance oil and gas recovery (EOR and EGR), as well as to stimulate plant growth in greenhouses, beverage carbonization, produce fire extinguishers, or as a solvent. As a rule, the scale of these applications is small, the technologies are well developed and the chain of supply, production and sales is well-established [114].

Variety of CO₂ converting methods expands the options for its usage. CO₂-based products could be considering either as final products or intermediates. For example, it could be transformed into new organic compounds, as well as into chemical building blocks for the chemical industry or synthetic fuels for the transport sector. CO₂ can also be used for mineralization, e.g., for making building materials [115].

Overall, utilization technologies can be divided into seven general categories: construction materials, fuel, plastics, chemicals, industrial gas and fluids, agriculture and food, and new materials [116]. We believe that for most of these initiatives, the VAS approach is applicable because it provides a measure of the commercial value (such as revenue and operating margin shifts, incremental revenues and cost savings, value of new products produced from CO₂) in addition to environmental and public value (through such parameters as reduction in CO₂ emissions, impact on human health, social investments, job created).

Based on available data, we are trying to demonstrate the possibilities of VAS framework application on the example of George Olah Plant in Iceland (owned by Carbon Recycling International—CRI), which is producing a renewable methanol from CO₂ (captured from the Svartsengi geothermal power station) and hydrogen [117].

Regarding VAS for industry (Figure 4), we suppose that both the first parameter and the second can be used to determine the potential value of such initiative. Changes in profitability occur when the revenue appear in a new production (George Olah Plant) that uses CO₂ as a raw material for renewable methanol production instead of its existence as a waste (emission). A new value chain emerges [117].

Cost savings could be presented in reduced payments for CO₂ emission, as annual reduction in CO₂ emission is around 5400 tons [117,118]. According to available data, the carbon tax rate (per ton of CO₂) in Iceland is \$30.00 [119]. There is no data in open resources about current plant’s profit, but planned profit in 2024 is around 95 million euros [117,118]. Taken together, this could represent total increase in profits (Table 3). According to the proposal in Table 3, total emission reduction (5400 tons annually) could be calculated and converted to revenues (CO₂ sale from Svartsengi geothermal power station to George Olah Plant), profits (CO₂ utilization on George Olah Plant and renewable methanol sale) and cost savings (payments and fines for CO₂ emission on Svartsengi geothermal power station).

The annual production of renewable methanol produced from CO₂ is 4000 tons; the added value of renewable methanol is that it is a low-carbon product [117,118]. Currently markets are developing where consumers are willing to pay for low-carbon products, even if they are more expensive. It is a matter of image and supporting the status of environmentally responsible business.

Total investments in this project is around \$8 million, but we do not have data on the amount of social investments. A total of 25 jobs were created for this plant [117,118].

4. Discussion

World experience and the above analysis show that CC(U)S initiatives are one of the options that could help address global climate change and contribute to a carbon-free economy. Along with that, they are characterized by high capital and operating costs, low

commercial effectiveness and low deployment levels. Government and public support is crucial for such challenging initiatives.

In this regard, according to the research results we recommend the government and companies consider CC(U)S initiatives broadly when making decision on their implementation, mainly in terms of the public effects and the additional value for business and society that they can create. We reinforce this recommendation with the proposed system of indicators for assessment of public effects of CC(U)S, as well as with VAS approach for identifying the overall «combined value» of CC(U)S. The usage of proposed tools are aimed at considering such initiatives more broadly, not only as the option of CO₂ emission reduction. By focusing to how such initiatives could affect society and other industries, their value increases.

Regarding the impact of such projects on society, we should consider them as projects for job creation and territorial development together with their low carbon goals. Moreover, they could significantly contribute to shaping environmentally-friendly consciousness and values in society. An even broader view offers a VAS approach that identifies «combined value» of CC(U)S—not only for society, but also for business. This is reflected in the emergence of business opportunities through the use of carbon dioxide as a valuable raw material for the production of products.

Moreover, all of these should be properly communicated to the society, in order to increase the public perception and business interest in such projects. Not only the safety of CC(U)S, but also the potential public effects and other values of CC(U)S should be the focus of their popularization. It should be presented and popularized on project sites, web sites and in other ways (at conferences, during educational courses and seminars, etc.).

The analysis presented plays a crucial role in decision-making for CC(U)S initiatives. We believe that this analysis will allow policymakers and the business community to more fairly assess the investments made and planned in CC(U)S. This can help measure, create, optimize, and report on the impact of their investments [120]. Industrial pragmatism often does not correlate with environmental initiatives, since the latter are most often expensive rather than profitable. Nevertheless, the growing demands on environmental and social responsibility of business oblige to take into account such factors as the impact on the environment and human health.

The efficiency of investment is still the most important criterion for decision-making in business. However, when planning and implementation of CC(U)S initiatives it is necessary to assess not only the direct benefits of the invested money, but also other effects that may result from the additional value of using carbon dioxide as a raw material. The economic, environmental and social impacts are crucial, and the assessment of all these impacts should be popularized in society. In this case, society could have a deeper and stronger appreciation and perception of the value of such initiatives.

As for the putting proposed frameworks into application (cases presented in Section 3.5), we used only some indicators to show the applicability of proposed systems. The entire range of emerging public effects and «combined value» of CC(U)S can be assessed only if an effective system for collecting information about CC(U)S projects and initiatives is created before and at the time of their initiation.

It is important to note that the availability of information on CC(U)S is a key factor in determining the applicability of the proposed system and framework. Since we conduct our research based on open sources of information, we can only give some examples and directions for such an assessment based on available data.

5. Conclusions

Summarizing the conducted research, the following received results could be highlight:

- Identification of positive and negative (real and perceived) impact of CC(U)S on the public within EHS/SE&ED framework in the following areas: environment, safety and health, society and economy, long-term ecological development.

- Development of the system for assessing the public effects of CC(U)S with a set of indicators that can be used to assess the positive and negative impacts on the society.
- Verification of specifics of assessing the public effects of CC(U)S, and the analysis of the possible variability of the assessments depending on the type of the project (CCS, CCUS, CCU).
- Development of the framework for revealing and assessing the “combined value” of CC(U)S via VAS analysis.

Since the problem of identifying and evaluating the public effects of CC(U)S and its “combined value” is poorly covered in the scientific literature, we can conclude that the developed approach is new, presented for the first time. The research results are of a long-term nature and can be used by the government and companies when initiating, implementing, and monitoring CC(U)S initiatives, as well as in their popularization.

At the same time, the results of the paper can provoke discussion and contain the following limitations:

- The negative impact of CC(U)S on the public within one area (for example, the environment) may be the cause of the negative impact in the other area (for example, safety and health). The same situation may concern the positive impacts and indicators for their assessment; in this case the list of positive and negative impacts, as well as indicators, can be limited and adapted, where applicable.
- Allocating the possible positive and negative impact of CC(U)S initiatives on the public in one area is not always obvious and could be debatable. Consequently, the same is true for the indicators.
- In the proposed approach, several indicators for assessing the public effects of CC(U)S should strive to a minimum, while others—to a maximum, but in some cases this requirement cannot be met. For example, the area of land grabbing should strive to a minimum, but land acquisition is required for the implementation of CCS and CCUS initiatives. The same situation can arise with the other indicators.
- Some indicators in the proposed system of indicators, as well as in the VAS framework, should be measured in direct relation to CC(U)S initiatives, but in some situations, it is rather difficult to determine how many effects are caused exactly by the implementation of CC(U)S.
- Some indicators are quite difficult to determine; using the full system of indicators and VAS framework implies collecting much information, most of which is not in open access.
- Since this paper presents the “combined value” of CC(U)S for the first time, we believe that all the values presented are predictive in nature, and this system should be improved and refined as initiatives are rolled out.

Regarding issues mentioned above, the further research areas will be related to a more detailed practical application of the proposed approach on the example of a specific CC(U)S initiatives, as well as to a more detailed elaboration of the CC(U)S “combined value”.

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