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Techno-Economic and Partial Environmental Analysis of Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCU/S): Case Study from Proposed Waste-Fed District-Heating Incinerator in Sweden

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Abstract: Sweden aspires to become totally carbon dioxide-neutral by 2045. Indisputably, what is needed is not just a reduction in the emissions of CO_2 (greenhouse gases in general) from the technosphere, but also a manipulated diversion of CO_2 from the atmosphere to 'traps' in the lithosphere, technosphere, hydrosphere, and biosphere. The case study in this paper focused on Stockholm Exergi's proposed waste-to-energy incineration plant in Lövsta, which is keen on incorporating carbon capture and storage (CCS), but is also interested in understanding the potential of carbon capture, utilization, and storage (CCU/S) in helping it to achieve 'carbon-dioxide-negativity'. Waste-to-energy incineration plants (in cases where the petro-plastics in the waste mix can be substantially reduced) are a key component of a circular bio-economy, though the circularity here pertains to recovering energy from materials which may or may not be recyclable. CCS (storage in the North Sea) was compared with CCU/S (CO_2 sintered into high-quality building blocks made of recycled slag from the steel sector) from techno-economic and environmental perspectives. The comparative analysis shows, inter alia, that a hybridized approach—a combination of CCS and CCU/S—is worth investing in. CCU/S, at the time of writing, is simply a pilot project in Belgium, a possible creatively-destructive technology which may or may not usurp prominence from CCS. The authors believe that political will and support with incentives, subsidies, and tax rebates are indispensable to motivate investments in such ground-breaking technologies and moving away from the easier route of paying carbon taxes or purchasing emission rights.

Keywords: carbon capture and storage (CCS); carbon capture; utilization and storage (CCU/S); carbon sinks; carbonation; building blocks

1. Introduction, Background Literature, and Motivation

In Paris in 2015 at the UN Climate Conference, an accord was struck whereby member states pledged to work toward the common goal of limiting the global temperature rise relative to pre-industrial times to less than 2 °C (and in the most optimistic case, 1.5 °C) [1,2]. Industrialization and urbanization have resulted in the increasing consumption of fossil fuels for energy generation, and land-use changes can be blamed for the rise in CO_2 levels in the atmosphere by 40% [3,4], with the concentration of CO_2 in 2017 being 405.5 ppm. While attaining the climate goals that countries have set for themselves will entail the reduction of greenhouse gases (GHGs) from the technosphere [5], it is necessary but not sufficient. Capturing and sequestering CO_2—the predominant GHG—from the atmosphere into the technosphere/biosphere/lithosphere will become indispensable. Industrialized countries will have to reduce their GHG emissions by 85–95% by 2050, relative to 1990 levels [6]. Nyström (2016) [7] observed that the concept of negative emissions (carbon-negativity in other words) is something that one must focus on in the future. Theoretically, this would imply that the emissions are less than zero, implying that if this succeeds on a large scale globally, the CO_2 concentration curve will stop sloping upward. The Swedish Parliament has set an ambitious but realizable goal for the country, of attaining a state of net-negative GHG emissions by the year 2045, for which the aforesaid research emphasized by Nyström (2016) [7] will become mandatory [8].

Incineration plants—with or without energy recovery—are major point sources of CO_2 emissions. While CO_2 is indeed recirculated back to the Earth (to the biosphere and the hydrosphere) when the rate of release is much greater than the rate of absorption, the concentration in the atmosphere tends to rise, as it has, over the years. This then leads to a global temperature rise. The CO_2 emissions from the stack are proportional both to the energy produced in the plant, and also to the emission intensity of the fuel mix used [3,9]. It is thereby imperative to invest in the capture and storage of CO_2 whereby this GHG can be permanently sequestered in geological sinks beneath the ground [10,11], which is an effective method that can be adopted by industries and thermal power plants to counter the current climate change challenge [12–14]. This approach, according to Viebahn et al. [15], can curtail GHG emissions by 50–85% by 2050. While CCS implies just 'pushing the CO_2 under the carpet' in other words, not to be seen again above the surface, lateral thinking has given birth to a new technique that goes by the name carbon capture utilization and storage (CCU/S), which retains the gas above the ground and uses it to confer desirable properties to products of commercial value [16] like building blocks produced by introducing CO_2 into slag from steel mills [17].

The Nordic Competence Center for CCS (NORDICCS) has mapped potential sites for carbon storage in the Nordic region, based on geological characteristics sub-terra, availability, and the associated risks that need to be minimized [18], and there exists ample space beneath the ground for CCS in this part of the world, to sequester 86 Gt of CO_2, which is equivalent to emissions over a period of 554 years in the Nordic region [19]. Sweden, unlike neighboring Norway, is not endowed with oil and gas fields, which can be utilized as traps for CO_2 after being harnessed completely. Furthermore, the bedrock in Sweden both onshore and offshore is largely composed of crystalline rocks like granite, which due to the lower porosity are not amenable for CO_2 storage. Sedimentary rocks like limestone and sandstone serve the purpose better. The authors of Mortensen et al. [20] have noted that the most favorable locations for CCS in Sweden are found in the southern reaches of the Baltic Sea and in the southwest of the Skåne region, while Mortensen [19] recommends deep saline aquifers in southern Sweden as potential sites with a capacity to store 1.6 billion tons of CO_2 [21]. The Norwegian continental shelf, meanwhile, can take in a total of 29 billion tons of CO_2 over a long period of time. In Norway, it all began with Sleipner in 1996, an oil-and-gas field offshore in the North Sea. As noted in Bellona and Ringrose [22,23], at the end of 2017, there were two CCS projects that had together captured and stored 22 Mt of CO_2 in saline aquifers. The Johansen formation in the North Sea reportedly has a potential of diverting 4 Mt CO_2 annually, into it [24,25]. Against this backdrop of the availability of sequestration space in Norway and the absence of sites in Sweden, transporting the captured CO_2 from Sweden to Norwegian sites is a process that cannot be overlooked [26]. As most of the CCS sites in Norway are to be found in the North Sea, the focus here is on sea travel, as observed by Chang et al. [27]. Most of the studies to date have focused on the capture and storage stages, as these were deemed to be technically more challenging than the intermediate transport stage. However, it must not be forgotten that CO_2 needs to be compressed and converted to a supercritical state before it can be transported to the storage site, and this entails energy use and costs [11,28].

While CCS may be a tried–tested–trusted technology in Norway, technical hurdles and perceptions of the risks associated with the storage, absence of wholehearted social acceptance, and the need for a convincing and robust business model have hindered its entrenchment in other parts of the world [29,30]. Talking of CCU/S, which is a rung above CCS, thinking outside the box is of paramount importance here, for example, when metals, plastics, and paper can be recycled, why not look at ways and means of open-loop-recycling CO_2, and conferring added value to what would otherwise just be an obnoxious GHG, especially in countries and regions where storage is not a viable option [17,31]?

What has been presented heretofore, is a general and a region-specific background to the study the authors have carried out in this paper. This is followed by a more focused literature review, which in turn is followed by a succinct presentation of the aim and goals of this study. The methodology, results and discussion, and conclusions, recommendations, and limitations, are presented thereafter.

2. Focused Literature Review

In the literature review, both the background review in the preceding section and this one, which is more focused on CCS and CCU/S, there is a bifurcation of focus: published Swedish documents and articles on the one hand, and peer-reviewed international scientific journal publications on the other. These also include books (textbooks and otherwise) and so-called grey literature published by Swedish government agencies and international organizations (like the International Energy Agency for example). The underlying purpose of the review is to understand the state-of-the-art with regard to the capture, utilization, and storage of CO_2. As far as the scientific journal publications are concerned, the databases OneSearch and Scopus were used, and the keywords were combinations of 'CCS', 'CCUS', 'building blocks', 'carbonation', 'saline aquifers', 'CO_2 storage', 'transportation', and 'storage'. Focus was restricted to articles published during the last 10 years, and priority was accorded to case studies from Norway and Sweden.

As explained in [32], there are essentially three techniques for the isolation of CO_2 from the exhaust gases: pre-combustion, post-combustion, and oxyfuel combustion. The separation methods are illustrated in Figure 1 [11,12,32].

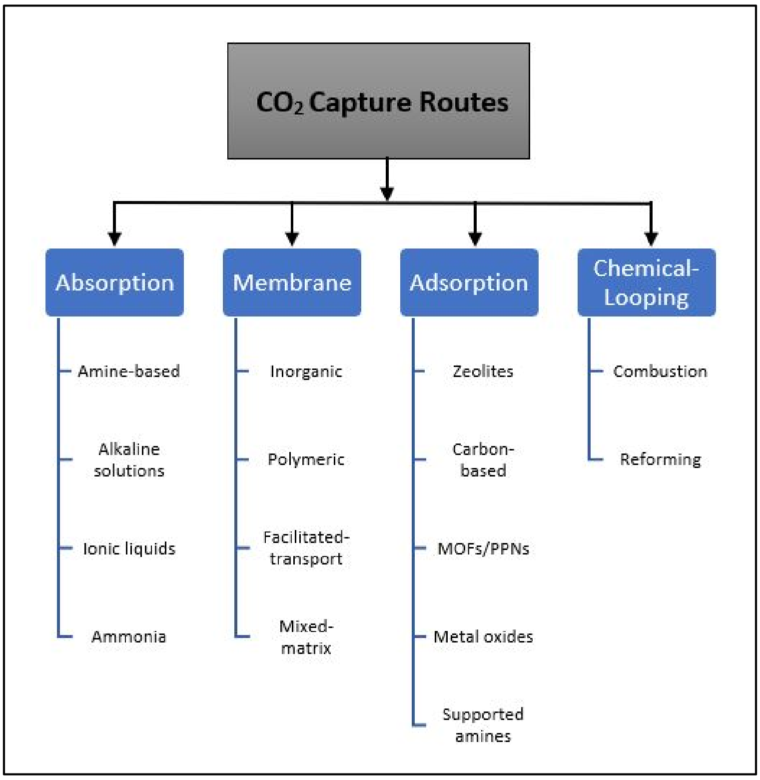

Figure 1. Techniques for the isolation of carbon dioxide from the exhaust gases.

The recommended separation techniques can trap about 85% to 95% of the CO_2 produced, resulting in a drop in CO_2 emitted per kWh electricity generated by 80–90% [12,33]. CCS enjoys, and will continue to enjoy, an important position in the EU's energy and climate politics, and will contribute significantly to limiting the global temperature rise below 2 °C and restrict the concentration of CO_2 in the atmosphere in 2100 to 450 ppm [12,34,35]. Rubin et al. [32] provided an approximate split of the additional energy requirement for the CCS processes: separation (60%), compression (30%), and pumping (10%). Bio-energy with CCS (BECCS or Bio-CSS) facilitates so-called negative emissions (carbon-negativity instead of carbon-neutrality), yielding a double climate-benefit [21,34], but it is still a nascent technology due to a range of obstacles that need to be overcome [5].

The compression process to a liquid or supercritical state in order to optimize the density (liquid CO_2 occupies one-fifth of the volume of the corresponding gas, as gathered from Chang et al.) [27], and economize transport [12,22,36] accounts for the highest share of the CCS process costs, according to Al-Mamoori et al. [11]. The liquid phase is often preferred to the supercritical state due to the relatively lower pressures that need to be handled [37]. As noted in Mortensen et al. [20], in the phase in which the compressed CO_2 gas is injected into saline aquifers, pressures higher than 74 bar have been recorded.

When a storage site is offshore, for instance, like in the North Sea (the largest available capacity in northwest Europe, according to Neele et al. [38]), the CO_2 needs to be liquefied and transported either in cargo ships or via subsea pipelines, quite similar to the transport of LNG [39,40]. The desired pressure and temperature at which CO_2 needs to be transported for CCS are 7–8 bar and −50 °C, respectively [41]. Transporting via cargo ships is more economical than via subsea pipelines [6], with the specific cost being around 13–33 Euro/ton of CO_2, for transport to, and storage in the North Sea reservoirs [39]. It is often just not a question of distance from source to storage-site, as evidenced by the poor injectability in the reservoirs in the Baltic Sea, which are closer to Sweden than the saline aquifers off the Norwegian coastline into which CO_2 can be more easily injected [42]. In Neele et al. (2017) [38], the authors remarked that injecting directly from the cargo ship is usually more expensive than doing so from a makeshift platform in the sea.

To date, geological storage in empty oil-and-gas fields (so-called enhanced oil recovery, EOR, and enhanced gas recovery, EGR, respectively), saline aquifers at a depth of 800 meters or more, high-porosity sedimentary bedrocks, and deep coal beds (enhanced coalbed methane recovery or ECBM), is the most preferred CCS technique [20,43–45]. Of these, EOR and EGR are the most common, according to the Global CCS Institute (2018b) [44], though the authors of IPCC (Intergovernmental Panel on Climate Change) (2005) [12] are of the view that saline aquifers would become the storage sites of choice in the future, provided incentives like tax rebates and subsidies are extended to those who opt for this alternative. However, a risk that cannot be overlooked is the leakage of CO_2 during transport, injection [46], and also after storage in these geological storage sites [12,43], though state-of-the-art monitoring has enabled the reduction of leakage risks to an extremely low level [47–50]. The reasons for leakage from the reservoirs can be microfractures, improperly-sealed boreholes, high gas pressure, and low permeability of the top rock-face.

As gathered from the Global CCS Institute [51], 43 large-scale CCS projects were in different stages of their life-cycles around the world in 2018: 18 in operation, five under construction (accounting for a total capacity of 40 Mt CO_2 per year), and 20 in the planning and development phase. By 2050, over 3000 CCS projects need to be in place, in order to ensure that the climate goals are reached and sustained over time [52]. Government incentives will play a key role in ensuring that this recommended rise in number of projects is achieved. In 2018, the USA set in place a linear increase in the tax rebates for CO_2 captured in oil fields for EOR, or captured and bound in saleable products, from 12.83 USD/ton of CO_2 in 2017 to 35 USD/ton of CO_2 in 2026; the corresponding increase for CO_2 sequestered in saline aquifers would be from 22.66 USD/ton to 50 USD/ton [53].

In Figure 2, the degree of geological and economic uncertainty is associated with the utilization of the capacity being represented by its place in the pyramid [54,55]. Despite a seemingly-quick learning curve when it comes to setting CCS projects in motion, the techno-economic aspects often pose challenges such as high investment costs [22], increase in demand for electricity in the capture, transport and injection stages, and associated energy losses, which have made the authors of Tan et al. [16] justify delays and the 'putting-on-ice' of planned CCS projects, and advocate a government-supported, centrally-managed storage and shared transportation infrastructure that a whole range of point sources can avail of.

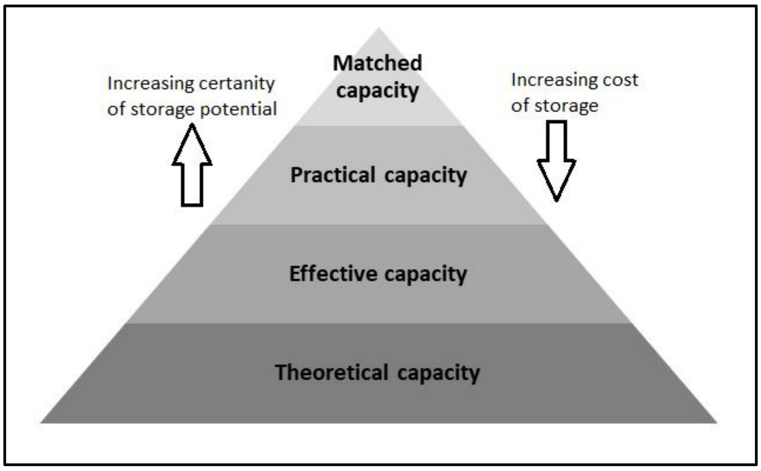

Figure 2. Techno-economic resource pyramid for CO_2 storage capacity.

CCU/S, as mentioned in the background literature review, is one-up on CCS, in that it looks at CO_2 as a reusable resource that can be (re)used to produce commercially-valuable goods [11,31,56] and also contribute to a drop in demand for fossil-based (carbonaceous) resources. The sequestration happens in products above the ground, and not sub-terra. CO_2 is not organic by itself, but forms the basic ingredient in the natural production of entities in the biosphere, which in turn are raw materials availed of in a bio-economy. To date, CO_2 has found use in applications in the chemical, petroleum, energy, food, pharmaceutical, paper and pulp, and steel sectors of economies around the world. It can either be converted into some other form (chemically, biologically, or by mineralization) thermochemically, electrochemically, or photocatalytically [57], or used directly in the applications in these industrial sectors. It is estimated that 10% of the CO_2 released from the technosphere can be (re)used in industrial applications, with the building/construction and chemical/petroleum sectors having a combined potential for reuse close to 600 Mt/year [56,57]. There can be an upscaling in the extent and scope of CCU/S in the years to come, if there is a willingness to take risks. Table 1 presents selected CCU/S processes, their technology-readiness-levels (TRLs), and conversion factors for Europe [58].

Table 1. Selected carbon capture and utilisation/storage (CCU/S) processes, their technology-readiness levels (TRLs), and conversion factors for Europe.

Industrial Process	Type of Use	TRL	Conversion Factor
Lignin production	CO_2 used in black liquor pH regulation	7–8	0.22 ton CO_2 per t of lignin produced
Methanol production	Electrochemical reduction of CO_2	7	1.7 t CO_2 per t of methanol produced
Polyurethane production	CO_2 used as raw material to produce plastics and fibers	7	0.1–0.3 t CO_2 per t of polyols
Polypropylene carbonate (PPC) production	CO_2 used as raw material to produce plastics and fibers	7	0.43 t CO_2 per t of PPC produced
Concrete curing (Concrete blocks)	CO_2 used for precast concrete curing	7–8	0.03 t CO_2 per t of block produced 0.12 t CO_2 per t of precast concrete
Mineral carbonation	CO_2 reacted with calcium or magnesium containing minerals	7–8	0.25 t CO_2 per t of steel slag
Bauxite residue carbonation	CO_2 is used to neutralize bauxite residues	9	0.053 t CO_2 per t of red mud
Horticulture production	CO_2 supplementation on plant growth	9	0.5–0.6 kg CO_2/h/100m^2 160 t CO_2 per ha (for tomatoes in Sweden)
Urea production	Urea production from ammonia and CO_2	9	0.74 t CO_2 per ton of urea

In the steel sector, the wastes are often reused in-plant, with landfilling being the last resort. In Sweden, relative to other countries in the world, more of the waste from the steel sector is landfilled. While steelworks in other countries usually have sintering facilities that enable in-house recycling, this is not the case in Sweden. Furthermore, Sweden, unlike many other countries in the world, is endowed with rich iron ore deposits, which takes away some of the appeal of recycling [59]. However, in the times that prevail, resource recovery through reuse/recycling is a sine qua non for sustainable development into the future in practically all the industrial sectors worldwide, if circular economies are to be realized. Slag from steel mills, for instance, is rich in magnesium and calcium silicates, and convertible to high-quality products [35,60] if reacted with captured CO_2 to convert the silicates to carbonates, in what is essentially an exothermic reaction [31]. This is a wonderfully symbiotic reuse of two different waste streams, converging to form a high-quality product. The process developed by the Carbstone Innovation Company accomplishes this without the need for any binding materials like cement [17]. The carbonation process (depicted in Figure 3) includes three steps: pre-handling of the slag; forming of the building block with a hydraulic press and subsequent compaction to achieve the desired porosity; and diffusion of CO_2 into the slag under high temperature and pressure in an autoclave [61]. The CO_2 reacts with the calcium silicate, forms calcium carbonate, which is a substitute for cement (binding material in the building block), and is thus sequestered for good within it [62]. This block has a negative carbon footprint (200 kg CO_2/kg less than the conventional concrete-making process), and has properties similar to the conventional alternatives they would replace [63].

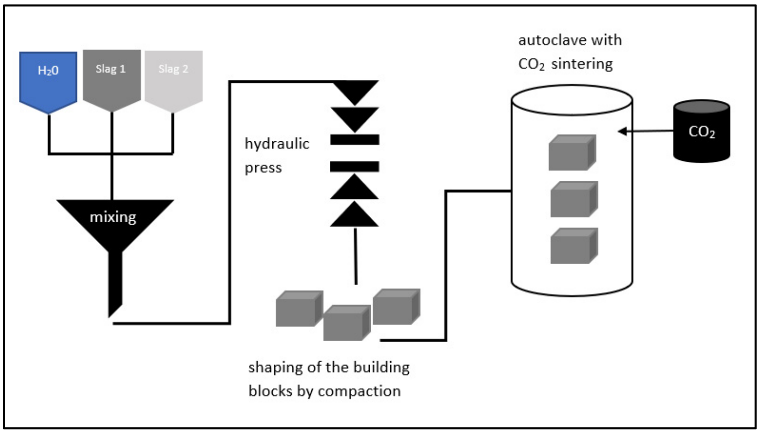

Figure 3. The 3-step carbonation process.

It can be implied that CCU/S to produce building blocks from steel mill slag, which could be termed as a disruptive innovation, has the potential in the future to compensate for the expenditure incurred on CCS. All that it needs is some initial economic incentive (sticks for emitters and carrots for technology-adopters [64]) to be kick-started and scaled up [16,65]. However, like with any decision that needs to be made from a sustainability perspective, the techno-economic, environmental, and politico-social aspects have to be factored in to understand the lay of the land, so to speak, and also the strengths that can be harnessed, weaknesses that need to be ironed out, opportunities that can be tapped into, and threats that need to be thwarted [57,66]. However, the good news is that interest in CCU/S is growing, as evidenced by Horizon 2020 [67], which supports high-end research in the utilization of captured CO_2 in sustainable industrial applications, which needless to say, is both sustainable and environmentally-friendly in more ways than one [30,68]. However, most of the CCU/S options are not really able to actually lock in the CO_2 permanently. At best, it is a delay-tactic, locking up the GHG a little longer before it may eventually be somehow released to the atmosphere.

Governance and legislation are of paramount importance to set disruptively innovative technologies in motion. The management and regulation of storage sites out in the international waters as well as reservoirs and aquifers that straddle national borders need international cooperation to be handled, managed, and harnessed well [64,69].

3. Aim and Goals of this Study

Stockholm Exergi plans to set up a new bio-and-waste-powered incineration plant in Lövsta, to the west of Stockholm, where there is space already allocated for CO_2-storage. The aim of this article is to investigate the possibility of attaining carbon-negativity in the production and distribution of district heating services.

The goal is to gain an understanding of the strengths, weaknesses, opportunities, and threats (SWOT analysis, in other words), of the two options available for diverting CO_2 from the chimneys back to the technosphere/biosphere/lithosphere—CCS and CCU/S—from environmental (climate change more specifically), economic, and technical perspectives. This study will aid Stockholm Exergi in its decision-making (the first author is an employee of said firm).

4. Methodology

Essentially, the methodology is comprised of the following four steps:

- Literature review (already presented in an earlier section);
- Data gathering for the case study;
- Techno-economic analysis (TEA); and
- Partial environmental life-cycle analysis (E-LCA) with a sensitivity analysis.

5. Data Gathering and Calculations

Stockholm Exergi wishes to estimate the CO_2 transport and storage costs for CCS, with the source being Lövsta and the destination as the Johansen formation in the North Sea just off the Norwegian coastline. The cost data and the related parameters (used for the calculations in the equations) are tabulated in Table 2 and were sourced from Stockholm Exergi.

Table 2. Cost data and related parameters for carbon capture and storage (CCS).

Parameter	Value	Notation in Equations
Cargo ship capacity (t)	3500	S
Cost per trip (SEK/trip)	700	SEK/trip
Annually captured CO_2 (t/year)	650,000	M_{CO2}
Transport stretch (km)	1504	d_s
GHG emissions for the sea transport (kg CO_2-equivalents/tkm)	0.0267	$K_{tkm,s}$

Leakages occurring during the injection of the CO_2 and also from the storage site (over time) were neglected in this analysis. However, this distorts the reality. As the comparison here is between CCS and CCU/S, and the capture and compression are processes that are common to both these techniques, they were not considered in in this analysis. The incineration plant at Lövsta is located close to the port, and hence, the transport stretch from the plant to the port of the compressed CO_2 was neglected. The mode of transport is a small cargo ship (as gathered through personal correspondence with Erik Dahlen, Stockholm Exergi on 16 April 2019), and the distance was estimated by taking recourse to Google Maps.

Equations used for the techno-economic analysis and the climate change effects of the transportation stage in the process chain have been listed hereunder.

Total number of trips by sea, N_s =

$$M_{CO2}/S \tag{1}$$

$$\text{Cost per trip (SEK/trip)} = \text{Cost per ton of } CO_2\ (C_t) \times S \tag{2}$$

The total cost of transport thereby is simply the cost per trip from Equation (2) multiplied by the number of trips per year (N_s). In other words, this is simply the product of the quotient in Equation (1) and the product of Equation (2).

The cargo ship takes the CO_2 to an intermediate storage, where the gas is led through subsea pipelines to the storage site. This study factored in just the GHG emissions in kg CO_2-equivalents for the sea transport stretch (d_s) from Lövsta to the intermediate storage site ($GHG_{a,t,s}$), which is in close proximity to the Johansen formation, given by Equation (3).

$$GHG_{a,t,s} = d_s \times M_{CO2} \times K_{tkm,s} \tag{3}$$

As far as the CCU/S option goes, the CO_2 was assumed to be transported (as and when this would be entrenched into the system) via truck from the incineration plant at Lövsta to Avesta where the steel-mill slag is heaped. It was also assumed that this facility was solely for the purpose of injecting CO_2 into the slag to produce the building blocks. Table 3 shows the steel-mill slag production in Sweden for the year-2015.

Table 3. Slag production data for 2015 [59].

Slag	Quantity (tons)
Argon-Oxygen Decarburization	108,000
Linz Donawitz steel slag	18,000
Arc furnace slag (highly alloyed)	80,000
Arc furnace slag (low alloyed)	10,000
Ladle slag	51,000
Total	267,000

The reason why slag from electric arc furnaces and argon–oxygen decarburization alloy-steel plants are landfilled to a much greater extent than the others is primarily because the properties of such slags have not been studied in great detail. These two types were selected in this analysis as they do not have any competing applications at the time of writing, and also because they were the ones chosen in Quaghebeur et al. [61] and Snellings et al. [70] for the production of building blocks. According to Jernkontoret [59], the slags that are put to reuse are classified as inert and non-hazardous (they also are REACH-registered: Registration, Evaluation, Authorization, and Restriction of Chemicals). Table A1 in Appendix B tabulates the properties of the slag [70]. Table 4 lists all the data and parameters (used in the equations and also referred to in the flowing text) that are relevant for calculations related to CCU/S.

Table 4. Cost data and related parameters for CCU/S.

Parameter	Value	Notation in Equations
Truck capacity (t/truck)	40	T_{cap}
Cost per trip (SEK/trip)	9	SEK/trip
Transport stretch (km)	154	d_r
Slag available (Mt)	0.267	M_s
GHG emissions for the truck transport (kg CO_2-equivalents/tkm)	0.0584	$K_{tkm,r}$
Mass of building blocks		M_b

The annual emissions from the plant, as mentioned earlier, are 650 kilotons. However, the limiting factor for use of the CO_2 is the availability of slag of the right quality. The approximate ratio of CO_2 to slag is 3:7 (R), as gathered from Quaghebeur et al. [61]. Thus, multiplying the tons of slag (M_s) available by the ratio 3/7 yields the mass of CO_2 that can be sequestered in the building blocks. Equation (4) yields the mass of building blocks. What cannot be bound up in the slag would then have to be handled using the CCS technique.

$$\text{Mass of building blocks } (M_b) = \text{Mass of slag } (M_s) \times (1 + R) \quad (4)$$

The number of trips by road from Lövsta to Avesta (N_r) is determined by dividing the total mass of CO_2 that can be trapped in slag every year ($M_s \times 3/7$) by the capacity of the truck being used (say T_{cap}). The annual truck transport costs are then calculated by multiplying the specific cost per kilometer (C_{km}), the distance from source to destination (d_r), and the total number of trips made in a year (N_r). It must be pointed out here that only the one-way trip was accounted for here; and not the return trip in which the truck is empty. Equation (5) is used to calculate the GHG emissions in the truck transport stage.

$$GHG_{a,t,r} = d_r \times 3M_s/7 \times K_{tkm,r} \quad (5)$$

5.1. Techno-Economic Analysis

The economic feasibility, or more appropriately the techno-economic feasibility, of CCS and CCU/S needs to be assessed before deciding on one or the other, or a suitable combination of both of them. A highly-simplified techno-economic analysis was carried out in this paper by taking recourse to some of the equations listed and the data tabulated above.

5.2. Partial Environmental-Life Cycle Analysis

In Leung et al. [43], the authors emphasized that a (partial) environmental life-cycle analysis (E-LCA) is imperative if one needs to determine how effective (comparatively) CCS and CCU/S are in enabling the adopters to achieve a net reduction in GHG emissions. The results of the E-LCA, when properly communicated, serve as a decision-making tool for government officials who may make decisions regarding incentives such as tax rebates and subsidies, or for banks who may decide to offer loans on easier terms. E-LCA is a well-established method to systematically evaluate the potential environmental impacts associated with the life-cycles of products, processes, or services. 'Life-cycle' includes everything right from the raw material extraction upstream to production and manufacturing, to use, and to final disposal, reuse, recycling, composting, incineration for energy recovery or landfilling. All transport processes linking these stages are also included. The environmental impacts on air, water, land/soil, and the biosphere due to inflows from, and outflows to, the environmental media to/from the processes are calculated and categorized [3,71,72]. The E-LCA methodology is standardized by the ISO 14040 series of standards (International Organization for Standardization) and includes four steps: goal and scope definition, inventory analysis, environmental impact assessment, and interpretation [73].

The results of the analysis are sensitive to the assumptions made and the system boundaries chosen by the analyst, making E-LCA an extremely flexible tool that is powerful when used intelligently [74]. This necessitates a sensitivity analysis (discussed in the next sub-section). Last, but not the least, an external review of the LCA report cannot be overlooked [75]. In this analysis, the focus was restricted to climate change (or global warming potential IPCC GWP 100a, in other words, accessed through the software SimaPro). The functional unit chosen was 'per kiloton carbon dioxide handled (captured, stored, or bound)'. The system boundary was set around the transport stages only in this comparative E-LCA where some processes upstream are common to both alternatives. The impacts associated with the construction (happened earlier) and demolition (which will happen in the future) of existing infrastructure elements (the plants, vehicles, pipelines, etc.) were not considered on the grounds that these may amount to less than 0.3% of the total life-cycle impacts (International Energy Agency GHG R&D program) [76]. The contribution of the transport and storage stages is only about 2% of the life-cycle global warming potential [77]. For the cargo ship transport by sea (CCS), the dataset in the Ecoinvent database v3 in SimaPro was used where liquefied natural gas (LNG) as a fuel was chosen. For road transport by truck, the emission coefficient for Euro 5 vehicles were chosen [78]

5.3. Sensitivity Analysis

Due to the inevitability of the uncertainty surrounding the data obtained, the results cannot be taken at face value. Here is where a sensitivity analysis (testing the sensitivity of the final result/s to variations in the primary data elements such as proxies, assumptions, and data that may be outdated or pertaining to a different part of the world) is recommended [79,80].

The parameters that the authors tested in this analysis were the sea transport distance and the annual emissions of CO_2 for CCS. The transport distance was increased by 25, 50, and 100 km, and four possibilities were considered for the annual emissions including the baseline value: 550, 600, 650 and 700 kilotons. Two-parameter sensitivity analyses were performed for different combinations of the parameters in question: emissions from the stack and the transport distance in the case of sea transport (CCS). As far as CCU/S is concerned, the two parameters considered were the CO_2 emissions captured (550 kton, 650 kton, and 700 kton), and the mass of slag available for the sequestration (267 kton, 400 kton, and 500 kton), resulting in nine possible combinations. The sea transport distance in the case of the hybrid option—CCS + CCU/S—was maintained at 1504 km.

The increments of increase in the distances were chosen randomly (multiples of 25). These of course are hypothetical, but realistic. Readers wishing to test the effects of different levels can easily do so by taking recourse to the relevant equations. This is a project that is being conceived at the time of writing and there is a lot of uncertainty with regard to what the system would actually look like when it is operational with CCU/S. As far as the TEA is concerned, it is highly simplified. There are several variables that were not considered here, and therefore a sensitivity analysis would have been cumbersome. If this paper had a niche focus on the economic aspect alone, the authors would certainly have delved deeper. The sensitivity analysis attempted here is relatively superficial, although it provides the impetus and the foundation for more detailed investigations in the future.

6. Results and Discussion

Table 5 shows the results of the techno-economic analysis and the annual GHG emissions for cargo ship transport and storage of CO_2 for CCS for the baseline case of a 1504 kilometer transport distance and annual CO_2 emissions of 650 kilotons. The results of the sensitivity of the distance over which CO_2 is transported to the global warming impact, and that of the effect of changes in the CO_2 emitted and captured, are shown in Table 6.

Table 5. Techno-economic and environmental analysis for CCS.

Trips	Cost/Trip	Total Cost	GWP_{100}	CO_2-Sink
per year	mSEK	mSEK/year	kt CO_2-eq/year	kt-CO_2/year
186	2.45	455.7	26.1	623

The second column in the table shows the increase in the global warming potential over the baseline transport distance of 1504 kilometers for the four different CO_2 emissions considered in the sensitivity analysis. At one extreme, we had annual emissions of 550 kilotons and a transport distance of 1529 km, for which the increase was registered as 0.367 kt CO_2-eq/year (an increase of 1.7%). At the other extreme, we had annual emissions of 700 kilotons and a transport distance of 1604 km, for which the increase was 1.869 kt CO_2-eq/year (an increase of 6.7%). The parameter values considered were within reasonable limits and therefore one may, in all likelihood, find the actual increase to be somewhere in between these two extremes. The transport-related emissions for the baseline transport distance (1504 km), with respect to which the reported increases were calculated, were 22 kt (550 kt captured), 24 kt (600 kt), 26.1 kt (650 kt), and 28.1 (700 kt). The net amount of CO_2 sequestered varied between 526.4 kt (1604 km; 550 kt captured from stack) and 671.8 kt (1504 km; 700 kt captured from stack). As the captured CO_2 increased from 550 kt to 700 kt, the cost of transport rose from 385 mSEK to 490 mSEK.

Table 6. Sensitivity analysis for CCS.

Annual CO_2 emissions stand at 700 kilotons		
Increase in distance	**Increase in GWP_{100}**	**Percentage increase in GWP_{100}**
Kilometers	**kt CO_2-eq/year**	**%**
25	0.467	1.7
50	0.934	3.3
100	1.869	6.7
Annual CO_2 emissions stand at 650 kilotons		
Increase in distance	**Increase in GWP_{100}**	**Percentage increase in GWP_{100}**
Kilometers	**kt CO_2-eq/year**	**%**
25	0.433	1.7
50	0.867	3.3
100	1.735	6.7
Annual CO_2 emissions stand at 600 kilotons		
Increase in distance	**Increase in GWP_{100}**	**Percentage increase in GWP_{100}**
Kilometers	**kt CO_2-eq/year**	**%**
25	0.400	1.7
50	0.801	3.3
100	1.602	6.7
Annual CO_2 emissions stand at 550 kilotons		
Increase in distance	**Increase in GWP_{100}**	**Percentage increase in GWP_{100}**
Kilometers	**kt CO_2-eq/year**	**%**
25	0.367	1.7
50	0.734	3.3
100	1.461	6.7

Table 7 presents the cost and environmental data for the hybrid option of CCU/S + CCS. Table 8 shows the results of the sensitivity analysis for the same.

Table 7. Techno-economic and environmental analyses for the hybrid option of CCU/S + CCS.

CO_2 to building block production	tons per year	114,429
Number of truck trips	per year	2861
Building block production	tons	381,429
Total cost for the CCU/S part	mSEK/year	3.96
CO_2 which has to be handled by CCS	tons per year	535,571
Number of cargo ship trips	per year	153
Total cost for the CCS part	mSEK	374.85
GWP_{100} for the CCU/S part	kt CO_2-eq/y	1.03
GWP_{100} for the CCS part	kt CO_2-eq/y	21.5
Total GWP_{100}	kt CO_2-eq/y	22.53
CO_2-sink	kt CO_2-eq/y	627.4

The global warming potential ranged from 15.4 kt CO_2-eq per year for the hybrid option (550 kton CO_2 captured from the CHP stack; and 500 kton slag available for sequestering in the building blocks) to 24.5 kt CO_2-eq (700 kton and 267 kton slag available). The variable (operating) cost for the CCU/S is a very small fraction of the total cost for the hybrid option, indicating the potential for optimizing expenses by increasing the amount of CO_2that can be circulated back into the technosphere.

Access to other port facilities and ability to avail of larger cargo ships will doubtlessly optimize transport and bring down the costs. The results show that if the incineration plant emits 650,000 tons of CO_2 annually (baseline case), a trip would have to be made every other day (185 trips). This is more or less the case for the other three possibilities considered for annual emissions in the sensitivity analysis, with the number increasing from 157 (550 kt) to 200 (700 kt). However, in reality, there are drastic seasonal variations in the emissions (much greater in the winter months obviously), which need to be factored in. Transport and storage costs may also fluctuate during the year. Inflation and exchange rates are usually never constant. Leakage was neglected in the analysis. LNG (liquefied natural gas) was the fuel of choice for this analysis, and the impacts can be substantially decreased if an alternate fuel such as biofuel or biogas can be considered.

Table 8. Sensitivity analysis for the hybrid option (CCS + CCU/S).

CO_2 emissions captured from stack—650 kton						
Slag mass available (kton)	**CO_2 in concrete block (kton)**	**Mass of concrete blocks (kton)**	**Cost for the CCU/S (mSEK/year)**	**GWP_{100} (kt CO_2-eq) per year CCUS**	**GWP_{100} (kt CO_2-eq) per year CCUS+CCS**	**Total cost for CCU/S + CCS(mSEK/year)**
267	114.4	381.4	3.96	1.03	22.5	378.8
400	171.4	471.4	5.94	1.54	20.8	341.6
500	214.2	714.3	7.42	1.92	19.5	313.7
CO_2 emissions captured from stack—550 kton						
Slag mass available (kton)	**CO_2 in concrete block (kton)**	**Mass of concrete blocks (kton)**	**Cost for the CCU/S (mSEK/year)**	**GWP_{100} (kt CO_2-eq) per year CCUS**	**GWP_{100} (kt CO_2-eq) per year CCUS+CCS**	**Total cost for CCU/S + CCS(mSEK/year)**
267	114.4	381.4	3.96	1.03	18.5	307.8
400	171.4	471.4	5.94	1.54	16.7	270.5
500	214.2	714.3	7.42	1.92	15.4	242.6
CO_2 emissions captured from stack—700 kton						
Slag mass available (kton)	**CO_2 in concrete block (kton)**	**Mass of concrete blocks (kton)**	**Cost for the CCU/S (mSEK/year)**	**GWP_{100} (kt CO_2-eq) per year CCU/S**	**GWP_{100} (kt CO_2-eq) per year CCU/S+CCS**	**Total cost for CCU/S + CCS(mSEK/year)**
267	114.4	381.4	3.96	1.03	24.5	413.1
400	171.4	471.4	5.94	1.54	22.8	375.9
500	214.2	714.3	7.42	1.92	21.5	347.9

As far as the CCU/S alternative is considered, only 114.4 kilotons of CO_2 can be used with the slag to produce building blocks (Table 7). The availability of usable slag is the limiting factor here. The remaining CO_2 will have to be handled using CCS. When the available slag increases to 500,000 tons, the amount of CO_2 that can be bound in building blocks rises by 100 kilotons (Table 8). It can be concluded that the hybrid approach works out to be economical (378 mSEK), vis-a-vis a case in which all the emitted CO_2 is handled by CCS (455 mSEK), a savings of 77 mSEK per year.

7. Conclusions, Limitations, and Recommendations

In this case study of Stockholm Exergi's proposed bio-and waste-based incineration plant for district heating, a comparative analysis between CCS and CCU/S was done from technical, economic, and environmental perspectives. Stockholm Exergi is keen on attaining carbon negativity and hence, looks favourably at CCU/S as an option to be possibly availed of in the future. A bio-and-waste powered incineration plant is well and truly a component of a bio-economy, and capturing the CO_2, which is one of the vital 'raw material' inputs upstream of the life-cycles of the organic/biological substances/products, interrupts the linearity—which would imply a flow from the technosphere to the atmosphere—and circulates the CO_2 back to the lithosphere (CCS) or the technosphere (CCU/S). The latter could be looked upon as an open-loop recycling of CO_2–carbon, which was in the organics, being looped out to useful products like the one discussed in this article.

The partial E-LCA shows that despite the GHG emissions from the transportation phase (Sweden to Norway), CCS in saline aquifers will enable Stockholm Exergi to deliver carbon-negative district heating. This also applies to CCU/S as the process of binding CO_2 to steel-mill slag is exothermic, and therefore not demanding too many external energy inputs. From an economic point of view, combining CCS and CCU/S in suitable proportions would facilitate the sequestration of larger quantities of CO_2

more economically, compared to availing of only CCS for this purpose. As far as the technical aspect is concerned, CCS is well-entrenched, the risk of leakage is considered to be very low, and the monitoring systems in vogue are state-of-the-art. The authors would like to point out that economic incentives for CCS in saline aquifers have to be put in place in order to enable it to compete with enhanced oil recovery and enhanced gas recovery. As and when and if CCU/S catches up, subsidies and tax rebates must be introduced to help it to entrench itself as a complement to CCS. Furthermore, with CCU/S, an innovative product with a specific function, in this case, the construction sector, can be introduced into the marketplace (Read Appendix A for an interview with Nick Mayelle of Orbix, Belgium).

Some recommendations for Stockholm Exergi can be listed as follows:

- Stockholm Exergi must look into other possibilities for transport and storage to optimize the CCS process chain. For instance, if the favourable sites in southwestern Sweden can be harnessed, it would reduce the GHG emissions from the transport stage.
- If the firm acquires its own infrastructure such as pipelines and/or cargo ships and/or storage sites, the cost profile would be very different from the one in which it pays for the use of infrastructure it does not own.
- Optimization of the transport stage in the process chain is also likely to yield benefits, both environmental and economic. Due to the location of the incineration plant at Lövsta, there is a lock-in when it comes to the allowable sizes/volumes of the cargo ships that Stockholm Exergi can avail of. There may be other ports in the Stockholm region which may allow the use of larger ships, and greater flexibility in the choice of sea routes.
- In order to justify the employment of larger cargo ships, it may be a good idea to think in terms of creating a 'CO2-cluster' of all the incineration plants owned and operated by Stockholm Exergi, and if possible, other point sources that may be beyond the firm's remit. Alternately, a centralized hub can be created to which smaller carriers can ferry CO2 from different point sources in the area, and a larger cargo ship can thereafter travel from the hub to the storage site.
- CO2 is a raw material input in many processes in the industry both as gas and solid (dry ice). Stockholm Exergi can even consider finding markets for a part of the CO2 captured.
- CCU/S, as has been mentioned earlier, is a nascent technology. It is imperative to scout for potential buyers and investors in technologies like the one described in this article. Furthermore, studies to test different slag-types to identify the most suitable ones for the purpose of producing building blocks infused with CO2, are called for. The firm must also make sure that the slag-types they select are REACH–registered.
- There is no dataset in SimaPro for marine transport powered by biogas, which is what Stockholm Exergi wishes to incorporate in its operations. The dataset used in this analysis was one in which liquefied natural gas was used (this is a fossil fuel, while biogas is not). The exact route followed by the cargo ship needs to be known for a more precise estimation of GHG emissions during the transport stage. Once the location of the plant in which the building blocks would be produced has been determined, a new LCA can be carried out, knowing the distance travelled and considering an electric vehicle.

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Appendix A

Telephone interview with Nick Mayelle from Orbix, which is a Belgium firm that develops and sells sustainable materials and technologies in the construction and steel sector. Carbstone Innovation is a patented technology that produces high-quality materials and has a pilot plant for this purpose in Belgium. This technology was developed along with collaborators VITO and Walloon CTP. The interview took place on 24 May 2019. Excerpts hereunder:

- Q1. How much carbon dioxide is incorporated/used per block and how much slag do you need for this purpose?
- A1. It depends on the material we use, for most of them, the carbon dioxide would account for 30% of the total mass.
- Q2. How much energy does the process require?
- A2. It is an exothermic reaction and so there is a lot of 'free energy' available. One needs a little energy to introduce the gas at atmospheric pressure into the blocks.
- Q3. How much time does it take to create these blocks? Do you produce these blocks piecemeal—one at a time—in the autoclave, or can several blocks be produced simultaneously?
- A3. We have a pilot plant with big autoclaves, and we can put around 1–2 tons into it at one time, per batch, that is, and fill it with CO_2 thereafter. I am not very sure about the exact amount of CO_2.
- Q4. Can all slag from the stainless steel industry be used for this purpose or are certain types of slag better suited for this?
- A4. Yes, all types of slags may not be suitable for the purpose. It depends on the content of magnesium and calcium in the slag.
- Q5. Is there an existing market for such blocks in Belgium? Your comments on the future market?
- A5. At the time of answering, we are collaborating with a partner firm which is doing the necessary research. Time will tell us if there is a market for this technology.

Appendix B

Table A1. Summary of the process parameters, performance, and properties of the investigated slag-block [70].

Material Type	Steel Slag	Stainless Steel (SS) Slag	Steel Slag	SS Slag (EAF)	SS Slag (EAF)	SS Slag (AOD)
Comp. (wt.%)	CaO: 56.8% MgO: 3.7%		CaO: 41% MgO: 7.6%	CaO: 44% MgO: 6.8%	CaO: 45% MgO: 9.3%	CaO: 55% MgO: 8.0%
Precursor particle size [µm]	Median diameter 610	<125	5–24	<500	5–300 D50: ~100	10–200 D50: ~60
Compact size and compaction pressure	100 mm dia. × 200 mm height 25 × 25 × 25 cm 1 × 1 × 1 m bulk density: 2.30 g/cm^3		90 × 40 × 10 mm 7.75 MPa	61 × 61 × 40 mm 17.85 MPa	300 × 100 × 50 mm 29.42 MPa	40 × 40 × 40 mm Fresh bulk density: 2.25 g/cm^3
Pressure/CO_2 conc.	1.005 atm 1 L/min 1.030 atm	0.3 MPa 100% CO_2	0.536 MPa 100% CO_2	2.0 MPa 100% CO_2	2.0 MPa 100% CO_2	Atm. Pressure 5 vol.% CO_2 0.8 MPa 100% CO_2
Temp [°C]				140	140	22 80
Moisture content/ RH	L/S = 0.053-0.063	L/S = 0.125	L/S = 0.125 RH: 60–80%	L/S = 0.12	L/S = 0.10	L/S = 0.15 RH: 80% L/S = 0.15
Duration			120 min	16 h	16 h	3 weeks 15 h
CO_2-uptake	6 ± 1 weight %	18	108 g CO_2/kg slag	177–188 g CO_2/kg slag	150–200 g CO_2/kg slag	4.3 weight % 8.1 weight %
Compressive strength [MPa]	18.3 19	9	45	55 (tensile splitting strength: 2.7MPa)	134	43 60

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