

## Article

# Merging Climate Action with Energy Security through CCS—A Multi-Disciplinary Framework for Assessment

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**Abstract:** Combining biomass-fired power generation with CO<sub>2</sub> capture and storage leads to so-called negative CO<sub>2</sub> emissions. Negative CO<sub>2</sub> emissions can already be obtained when coal is co-fired with biomass in a power plant with CCS technology. The need for bioenergy with CO<sub>2</sub> capture and storage has been identified as one of the key technologies to keep global warming below 2 °C, as this is one of the large-scale technologies that can remove CO<sub>2</sub> from the atmosphere. According to the definition of bioenergy with CO<sub>2</sub> capture and storage, capturing and storing the CO<sub>2</sub> originating from biomass, along with the biomass binding with carbon from the atmosphere as it grows, will result in net removal of CO<sub>2</sub> from the atmosphere. Another technology option for CO<sub>2</sub> removal from the atmosphere is direct air capture. The idea of a net carbon balance for different systems (including bioenergy with CO<sub>2</sub> capture and storage, and direct air capture) has been presented in the literature. This paper gives a background on carbon dioxide removal solutions—with a focus on ecology, economy, and policy-relevant distinctions in technology. As presented in this paper, the bioenergy with CO<sub>2</sub> capture and storage is superior to direct air capture for countries like Poland in terms of ecological impact. This is mainly due to the electricity generation mix structure (highly dependent on fossil fuels), which shifts the CO<sub>2</sub> emissions to upstream processes, and relatively the low environmental burden for biomass acquisition. Nevertheless, the depletion of non-renewable natural resources for newly built bioenergy power plant with CO<sub>2</sub> capture and storage, and direct air capture with surplus wind energy, has a similar impact below 0.5 GJ<sub>3x</sub>/t of negative CO<sub>2</sub> emissions. When the economic factors are a concern, the use of bioenergy with CO<sub>2</sub> capture and storage provides an economic justification at current CO<sub>2</sub> emission allowance prices of around 90 EUR/t CO<sub>2</sub>. Conversely, for direct air capture to be viable, the cost would need to be from 3 to 4.5 times higher.



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**Keywords:** carbon dioxide removal; thermo-ecological cost; carbon dioxide capture and storage; direct air capture; bioenergy with carbon capture and storage; readiness index

## 1. Introduction

The increasingly visible effects of climate change and, simultaneously, the apparent slow pace of climate action, combined with shrinking carbon budgets, are forcing humanity to ask: what if cutting emissions solely is not enough? The 2 degrees (2DS) goal, set by the Intergovernmental Panel on Climate Change (IPCC), seems to be no longer achievable without carbon drawdown. The reduction in GHG emissions (mainly CO<sub>2</sub>) may not be enough to fully mitigate observed climate change. It is predicted that, in order to meet the target defined for climate change mitigation, the removal of 10 Gt of CO<sub>2</sub> per year should be met by 2050 and it should double by the end of century [1].

The technologies applied with this aim are known as carbon dioxide removal (CDR) or negative emission technologies (NETs) since they lead to a negative balance of carbon in

the atmosphere. Different approaches, ranging from the natural to the technological, are shown in Figure 1.

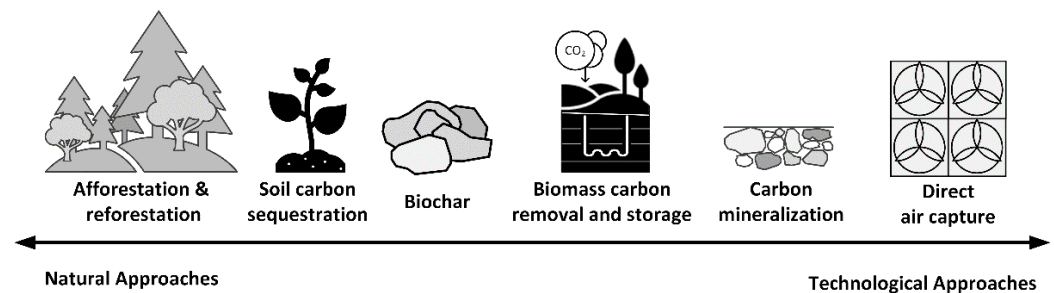


Figure 1. Carbon removal approaches in land (adapted from [2]).

Two main technological pathways are proposed, viz. bioenergy with carbon capture and storage (BECCS) or direct air capture (DAC). These technologies have been analyzed for a considerable time, but the latest research shows that their deployment, although much needed, remains uncertain [3].

Combining biomass-fired power (and/or heat) generation with CO<sub>2</sub> capture and storage (and/or utilization) leads to so-called negative CO<sub>2</sub> emissions [4]. The idea of a net carbon balance for a different energy system (including BECCS) has been presented in Figure 2.

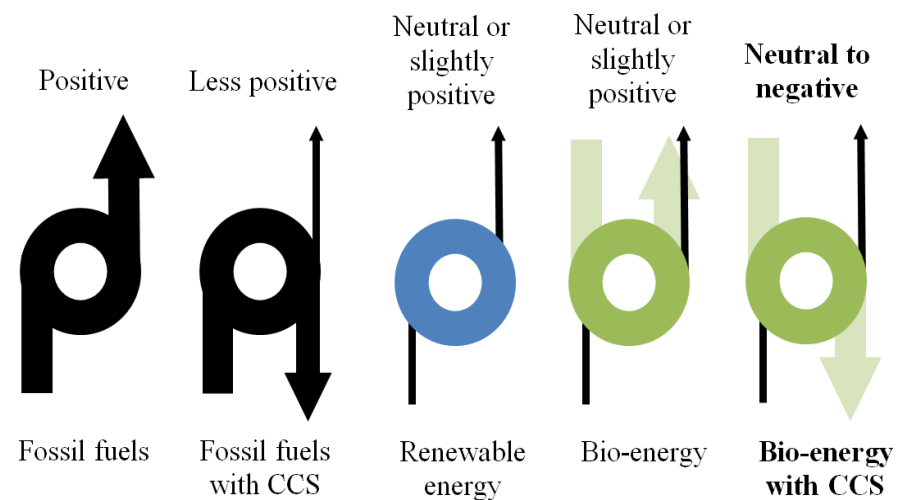


Figure 2. Carbon balance for different energy systems (adapted from [4]).

Negative CO<sub>2</sub> emissions can already be obtained by co-firing coal with biomass at shares of 85% to 15%, respectively [5]. Biomass combustion, combined with CO<sub>2</sub> capture and storage, is considered to be one of the crucial elements on the path to keeping global warming below 2 °C. Sustainable biomass itself, a clean energy source with net-zero CO<sub>2</sub> emissions, proceeds by binding carbon from the atmosphere through the photosynthesis process during its growth cycle. Thus, adding the CCS to a bioenergy power plant could result in a negative CO<sub>2</sub> balance in principle and contribute to emissions reduction [6]. Carbon dioxide direct air capture, besides BECCS, is the other option for removing CO<sub>2</sub> from the atmosphere, diluted gases and distributed sources of carbon via industrial processes [7].

The purpose of this paper was to evaluate the ecological performance of the CDR technologies using the theory of thermo-ecological cost (TEC). TEC was developed by Szargut [8,9] and is a tool employed to measure the efficiency of natural resource management. The method incorporates calculations of the cumulative exergy of non-renewable natural resources burdening a given product, along with the additional exergy consumption of non-renewable natural resources. The aim in doing so is to abate or compensate the

negative effects of harmful waste rejections (e.g., emissions) on the natural environment during the production process. The TEC analysis has been extended and developed in recent years by Stanek [10], Czarnowska [11] and other researchers who implemented the TEC evaluation in their analysis of miscellaneous energy systems with regard to the whole life cycle.

To form a better view of the CDR technologies, a framework for political assessment was determined. In 2021, the IEA argued that achieving a carbon-neutral society “will be virtually impossible without carbon capture utilization and storage (CCUS)” [12]. However, BECCS and DAC still lack global support, despite the notable exceptions of policies in favor of CDR [13]. The two central factors for the further development of DAC are support for R&D, as well as the high carbon price that would provide the necessary financial incentives [14]. This paper proposes a multidisciplinary framework to assess the state of technology-based solutions for the country case studies, including the review of a CCS readiness concept, an assessment of the shortcomings of the existing indices and an evaluation of the political viability of CCS projects. This work presents the core factors for policymakers and investors to consider before opting in favor of a specific CCS investment.

### 1.1. Literature Review

The following paragraphs give an overview of the existing literature on CDR technologies, CDR assessments from energetic, economic and environmental perspectives, as well as a review of CDR policies.

#### 1.1.1. CDR Technologies

One of the technological pathways used to reach negative emissions is BECCS. The conversion of biomass, with the aim of getting final energy products or chemicals connected with CCS, can be conducted in a couple of ways. These can be divided into:

- bio-chemical biofuels production;
- thermo-chemical production of biofuels and biochemicals;
- biomass combustion for electricity generation and/or heat production [6].

The application of BECCS technology is determined by the use of biomass for combustion or conversion. During the combustion process, biomass is utilized directly as a feedstock to produce heat for further power generation or other industrial purposes. The  $\text{CO}_2$  is then captured from the stream of flue gas. In the case of biomass conversion through digestion or fermentation,  $\text{CO}_2$  is one of the products, as are gaseous (biogas) or liquid (biofuel) fuels. The captured  $\text{CO}_2$  is subsequently transported and stored in deep geologic formations (Figure 3) [15].

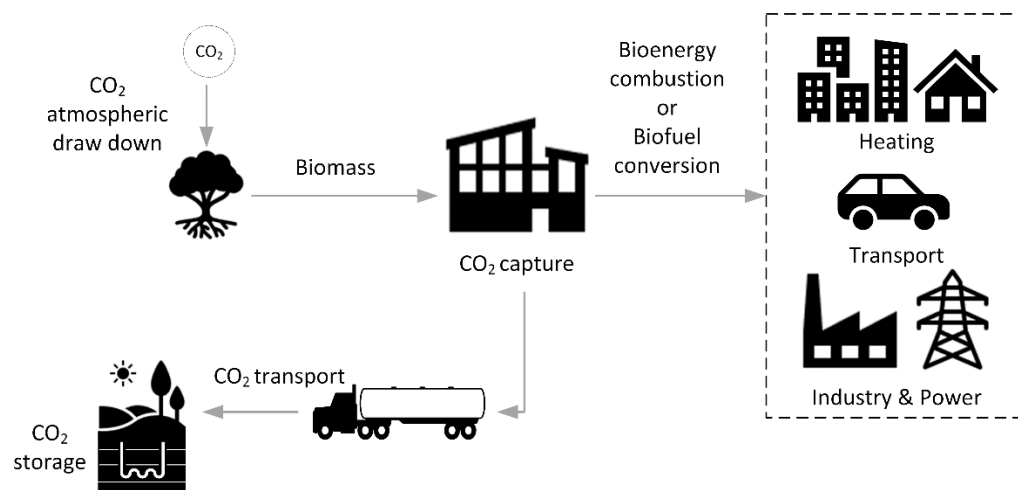


**Figure 3.** The concept of BECCS technology (adapted from [15]).

BECCS technology integrates a variety of possible biomass feedstocks, bioenergy technologies (e.g., combustion, gasification, fermentation) and CO<sub>2</sub> capture and storage systems. BECCS applications are classified into three CO<sub>2</sub> separation and capture methods:

- Pre-combustion—CO<sub>2</sub> separation from the H<sub>2</sub> with physical absorption methods. CO<sub>2</sub> and H<sub>2</sub> are main components of a shifted gas produced after gasification or steam methane reforming;
- Oxy-combustion—CO<sub>2</sub> separation via a condensation process from flue gas after burning fuel with oxygen and recycled CO<sub>2</sub>;
- Post-combustion—CO<sub>2</sub> separation from flue gas after fuel combustion, with chemical absorption processes applied [16].

Direct air capture is another one of the NET technologies with a high development and improvement potential. Within this method, CO<sub>2</sub> is extracted directly from atmospheric air through an artificial contractor using chemical solvents that bind it or stick to it (Figure 4). Captured CO<sub>2</sub> can be then stored or used for other deployments [17].

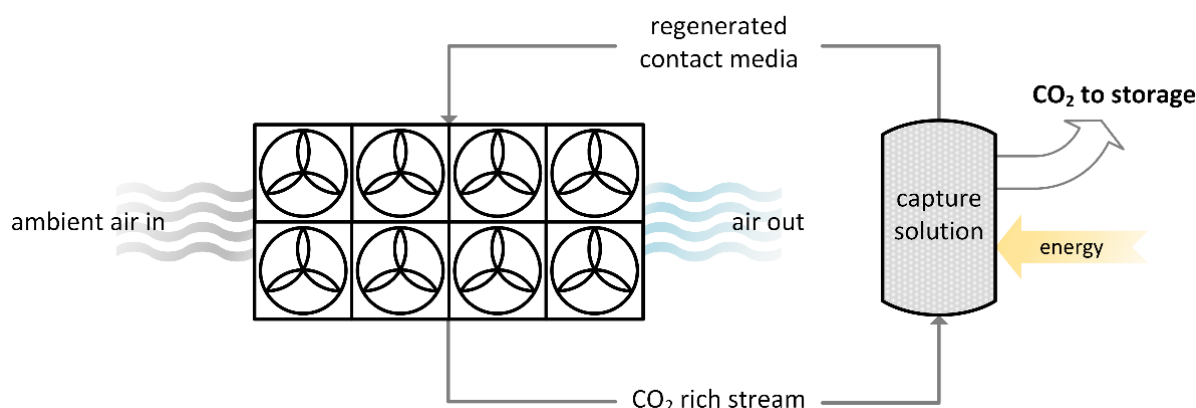


**Figure 4.** General principle of Direct Air Capture (adapted from [18]).

DAC is considered to be an energy-consuming method in view of the required air movement via an engineered system. The energy requirements for concentrating CO<sub>2</sub> from such low levels are considerably higher than those from more concentrated sources. Therefore, many separation processes with CO<sub>2</sub> capture from low concentrated streams are not viable due to economic reasons [1].

As opposed to BECCS, the DAC technologies demonstrate their benefits. These include flexible location, which may cause a reduction in transport costs due to an ability to situate these technologies nearby the storage location, a reduction in instrumentation cost for windy situations, or cooperation with local renewable energy resources [17].

#### 1.1.2. CDR Assessment (Energy, Economic and Environmental)

To perform an integrated assessment of CDR technologies, it is essential to present energy, economic and environmental characterizations of these systems.

The potential of DAC and BECCS technology for climate change mitigation is, respectively, up to 5 GtCO<sub>2</sub> per year and from 5 GtCO<sub>2</sub> per year [19] to 11 GtCO<sub>2</sub> per year [20]. According to [21], carbon removal remaining at the level of 7.9–10.6 GtCO<sub>2</sub> for BECCS, and 8–32 GtCO<sub>2</sub> for DAC, by 2100 would be essential to keep to a 1.5 °C global warming limit.

BECCS applications, such as the production of bioethanol or use in CCS, indicates its high deployment potential. This is indicated by the biomass supply, totaling about 52 GW for global power generation, with the production of around 68 Mtoe of biomass-derived biofuels [15]. Overall, the performance evaluation conducted by M. Bui et al. showed that the 500 MW BECCS system, which co-fires coal with biomass at a share of 50%, reached the power generation efficiency of 31% with a conventional monoethanolamine (MEA) solvent. The efficiency could be increased up to 34% with a high-performance solvent [22].

However, there are several BECCS challenges that influence system efficiency. In paper [23], authors mention an energy penalty on the technology, resulting from solvent regeneration in the post-combustion capture system, boiler efficiency losses or coal-fired unit conversion to biomass-dedicated boiler technology. Moreover, other ones are associated with fuel storage and size reduction due to the physical properties of biomass. In addition, the high moisture of biomass, combined with grindability lower than that of coal, result in increased energy and fuel processing costs. Nevertheless, studies conducted by Mac Dowell and Fajardy pointed out that less efficient BECCS facilities, which convert biomass to electricity, could remove more CO<sub>2</sub> at a lower cost than their more efficient equivalents [23]. This has an enormous impact on the CDR technologies. The cost of BECCS applications, specified by Fuss et al., depends on the sector and will vary enormously within the range of USD 15–400/tCO<sub>2</sub> avoided. The highest cost was estimated for combustion BECCS, and the value range was USD 88–288/tCO<sub>2</sub> [15].

As an instance of commercial application of DAC technologies, plants in Hellisheiði (Iceland) and Hinwil (Switzerland), operated by Climeworks, could be given. Their carbon capture efficiency reaches 93.1% and 85.4%, respectively [24]. DAC installations require a continuous energy supply for running fans and other equipment, as well as for heating to separate CO<sub>2</sub> from air in the scrubber [25]. Considering the relatively low concentration of CO<sub>2</sub> in the atmosphere (about 400 ppm), the minimum theoretical work for CO<sub>2</sub> separation hovers around 20 kJ/mol CO<sub>2</sub>, while the value for capturing from point sources is significantly lower (e.g., about 8.4 kJ/mol CO<sub>2</sub> for aqueous amine-based flue gas capture). Thus, the value of actual energy required will also be much higher for the direct separation from air, as well as the volume of considered gas stream [18]. These aspects influence the investment performance.

Cost estimates for DAC technology vary from USD 250/tCO<sub>2</sub> to USD 600/tCO<sub>2</sub> [17]. The values differ between technologies deployed or their scale, and result mainly from capital expenditures, energy costs of CO<sub>2</sub> capture, operational costs, sorbent loss regeneration and maintenance [19].

However, due to supportive policies for CDR technologies, a fall in cost is very likely in the future.

### 1.1.3. Carbon Dioxide Removal Policies Review

This paper aims to propose a comprehensive multidisciplinary framework for a single country's readiness to adopt and deploy CDR technologies, such as DAC and BECCS. As long as each country bears responsibility for their climate policies, there is a need for state-centered framework assessment.

The 1.5 °C Special Report specifies the following solutions for carbon removal: afforestation and reforestation, land restoration and soil carbon sequestration, and BECCS and DAC [26]. Earlier, BECCS appeared in the 2014 5th IPCC assessment [27]. Despite the overarching goal of carbon removal, something that allows us to group various solutions into one class, researchers have not yet decided to coin a unified umbrella term. For that reason, negative emissions techniques (NET), carbon dioxide removal (CDR), greenhouse gas removal (GGR) and geoengineering are used interchangeably [28]. The general definition may be that they represent "large-scale interventions into natural systems to counteract climate change" [28]. When seen from a geoengineering point of view, available solutions are divided into two broad groups of technologies—one that removes excessive carbon from the atmosphere, and the other aiming on lowering the level of radiation absorbed by the Earth. The former consists of land-based methods and ocean-based methods. It has been argued that the amount of land needed for land-based methods (including DACCS and BECCS) will cause them to be regulated by national laws [29]. A recent paper looked at policy development at the international level. It found that three narratives dominate CDR assessments that can be turned into specific policies: the first, arguing for investment and CDR upscaling; the second, arguing for mitigation, with a very limited and controlled role for CDR solutions; and the third, arguing for keeping all options open [28].

Both, direct air capture and bioenergy require CCS to result in negative emissions. To measure progress in CCS development, a “CCS Readiness Index” (CCS Index) has been created by The Global CCS Institute (Institute). It aims at measuring either major obstacles or accelerators of this technology with four sub-indicators: inherent interest, policy, legal and regulatory (legal), and storage [30]. The countries that achieved the highest positions in the index have introduced policy frameworks which decisively support CCS as an emissions reduction technology. Governments’ dedication, combined with specific policy means, yield legal and policy schemes. These countries also actively monitor their storage capabilities. These activities precede any actions in CCS project development, as a proper reservoir is a prerequisite, and may benefit from earlier experiences in oil and gas production. Furthermore, coincidence of high readiness and inherent interest in numerous countries suggest that significant production and consumption of fossil fuels may indicate interest and policy support [30]. These sub-indicators have been summarized as the following four pillars: “1. A predictable and enduring policy environment; 2. Effective and comprehensive CCS law and regulation; 3. Early storage site identification and site characterization; 4. Research and development into cost reduction in CCS technologies.” [30]. A paper, written for European Academies’ Science Advisory Council, stressed that CCS at the core of BECCS and DACCS is not readily available “off the shelf” and that economic incentives for its development still lacking in Europe. The paper also calls for support for CCS and DAC in order to reduce costs [18]. As early as in 2016 the UK’s Committee for Climate Change (CCC) called for global action, stating that “The aim of the Paris Agreement to balance sources and sinks of greenhouse gases implies the need for a globally coordinated strategy to develop and deploy greenhouse gas removal options” [31]. The following section presents four country-case studies to illustrate the level of commitment and political readiness and apply our framework. Despite recent advancements, several pilot plants built and assumed to be indispensable, there is still a lack of coherent policy frameworks for CDR/NETs.

### European Union

Member states of the European Union (EU) are among the most advanced in developing policy frameworks for CDR/NETs. One recent academic paper explicitly mentions BECCS and DACCS as the two most important technologies in terms of tCO<sub>2</sub> removed and proposes policy pathways [13]. Of the six EU states’ group [namely: Austria (2040), Germany (2050), France (2050), Finland (2035), Sweden (2045) and Portugal (2050)] that have already committed to a net zero target, Austria and Portugal and, to a lesser degree Germany, give priority to LULUCF (land use, land-use change, and forestry). The most advanced debate on CDR is in Sweden. There, a governmental report articulates the need for BECCS promotion. This can not only be used in energy and heat sectors, but also in the paper industry. France introduced CDR into the National Energy and Climate Plan (NECP), stating that BECCS will save 10 MtCO<sub>2</sub>, but did not specify how capacities and where storage spaces are to be built [32]. The European Commission (EC) explicitly mentions BECCS and DAC in its most recent climate strategy [33], but they have so far been absent in the European Green Deal (EGD) proposals. It is promising that both can be found in the draft of the European Climate Law [32]. According to one EU official, the EC is currently working on a certification system for carbon removals [34]. Research on DAC is currently funded through the Horizon 2020 research project STORE&GO [35].

### United Kingdom

The prime example and world leader in this area is the UK. This is due to a convergence of two key factors: the integration of scientific expertise into policy planning and a readiness to implement new technologies. The CCC, an independent advisory body instituted by the UK’s 2008 Climate Change Act, expressed the necessity for CDR deployment for the UK’s decarbonization effort as early as 2016 alongside BECCS, forestry and wood in construction [31]. One recent study [36] has also shown that financial support in the UK

should be shifted from intermittent RES to CDR, as the latter are indispensable for meeting the Paris targets effectively. Among the most significant barriers are the lack of effective financing mechanisms, as well as the lack of CO<sub>2</sub> transport and storage infrastructure and remuneration for CO<sub>2</sub> sequestration [36].

#### United States of America

Currently, two government-funded CDR supporting mechanisms are noteworthy: the 45Q tax credit and California's Low-Carbon Fuel Standard (LCFS). The former was created in 2008, while the latter came into force in 2006. Both were amended over the course of 2018–2019 and now include legal mechanisms supporting DAC development. Some researchers argue that these policies are most significant in terms of price incentive [37] and provide the largest overt support [38]. Despite the level of support that is provided by the California's LCFS, it may not be sufficient to enable DAC deployment [37].

Among the policies that could support DAC development are federal procurement (including military) of DAC-based fuels, the 45Q tax credit improvement and the introduction of a federal mandate for DAC-based fuels [39].

In mid-2020, Democratic Party members of the House Select Committee on the Climate Crisis proposed the creation of a comprehensive set of institutions and financial incentives for CDR development [40].

However, cumulative government spending in the US on DAC has been at the level of \$11 m, while the 10-year average federal funding on fossil fuels and renewable energy is \$998 m and \$937 m, respectively [39]. CDR deployment relies not only on technological progress but also on efficient and effective societal cooperation in other areas such as lawmaking, public acceptance, regulatory enforcement, and financing [38]. Importantly, a recent study found a significant mismatch between which CDR technologies are supported by the public and what the scientific community finds prudent and viable. For example, while afforestation received the highest level of support, negative perceptions of DACCS/BECCS may impede their deployment [41].

#### Australia

Current policies in Australia—the Emission Reduction Fund (ERF) and the Renewable Energy Target (RET)—do not explicitly support thermochemical CDR technologies, but projects classified as CDR would be awarded credits under the ERF [37]. A recent study [42] has argued that BECCS is yet to be recognized as a clean energy system in Australia. It was also suggested that there is potential in extending existing policies (i.e., RET amendment), introducing a carbon pricing scheme or establishing new measures, such as a negative emission refunding system.

#### Poland

Surprisingly, since climate change has entered the public debate in the 21st century, for a long time there has been only one energy-related strategic document officially adopted in Poland, as political divisions did not allow for updates for years. The “Polish Energy Policy until 2030” was adopted 10 November 2009. The document relates to CCS in the context of oil and gas and argues for intensification of R&D in this field to enable application of CO<sub>2</sub> in other industries. It also suggests that at least two demonstration CCS plants are to be built in Poland [43]. The assessment of the 2030 policy clearly stated that CCS-related activities were not fulfilled, but similar setbacks can be observed in other EU countries [44]. In the project itself, CCS was barely mentioned [45], while conclusions from forecasts included some role for CCS without any specific directions for development [46]. The project was abandoned in 2015 when the ruling party in Poland changed. In December 2019, Poland submitted its Intended Nationally Determined Contribution (INDC) according to the Paris Climate Agreement, called “National Energy and Climate Plan 2021–2030”. In terms of carbon removal, the plan focuses on exploiting LULUCF opportunities, while thermochemical methods are not mentioned. Moreover, CCS is considered in the context

of R&D (not projected for immediate deployment) and to be, in overwhelming majority, was financed from European funds [47]. The most recent document presented is “the Polish Energy Policy until 2040”. As its name indicates, the text remains tightly limited in time—emissions targets are established only for 2030. Even more importantly, CCS is only mentioned in the context of clean coal technologies, as the document does not mention any CDR technologies [48]. This oversight makes achieving a decarbonization of the coal-based energy system significantly harder and raises questions about the overall seriousness of the Polish government’s climate ambitions.

Non-governmental organizations, think tanks and consulting companies also attempt to create models of how Poland can reach a net-zero economy. A recent paper from WISE Europa—a think tank—puts a strong emphasis on CCS, though only in the conventional power generation context [49]. McKinsey—a consulting firm—published a roadmap for a carbon neutral Poland. It features CDR technologies, specifically LULUCF and CCUS, and mentions the emergence of carbon dioxide removal markets. CCUS is seen as one of key decarbonization levers, and therefore BECCUS is included in the presented scenarios. BECCUS is also seen as an economic growth accelerator, constituting a major factor in reducing industry emissions and supporting technology in agriculture. The report notices the power intensive-character of both technologies, BECCUS and DAC, and the resulting need for deployment of low-carbon power generation. However, one does not find BECCUS in Poland’s potential energy mix [50].

It can only be assumed that biomass use as a fuel will be combined with carbon dioxide capture.

Poland is characterized as a country that has favorable geological conditions: “the proximity of industrial sites and locations favorable for carbon storage—and sizeable natural storage”. Poland’s mesozoic rock formations have a total storage capacity of 22,342 Mt CO<sub>2</sub> for the next few hundred years [51]. The consulting firm McKinsey argues in favor of preparing to scale CCUS up through R&D support, deploying and facilitating CCUS pilots [50]. Poland receives special attention in this paper as it is the core case that is laid out in the political readiness index (see Table A1 in Appendix A).

## 2. Materials and Methods

Within this paper, the idea of thermo-ecological cost has been proposed to evaluate the ecological performance of the CDR technologies. Different case studies have been selected, including new and retrofit power plants used for the co-combustion of coal with biomass or a dedicated biomass-fired boiler, as well as three different configurations of DAC units.

### 2.1. Case Studies Selection

#### 2.1.1. Power Plants in Poland

Within the study, different retrofit options are investigated for both existing coal-fired units with bioenergy CCS installations and biomass-fired plants with CCS. The following coal- and biomass-fired units were proposed as reference (REF) ones:

- Hard coal power plant—based on Łagisza 460 MW unit (HC\_REF),
- Lignite power plant—based on Bełchatów 380 MW unit (L\_REF),
- Biomass power plant—based on Połaniec 225 MW unit (BE\_REF)

The reference parameters of the investigated power plants have been summarized in Table 1 [20,21]: ‘el’ refers to electric energy and ‘ch’ refers to chemical energy.

The assessment also covers the newly built bioenergy power plant. This is based on the Połaniec unit. The analysis will allow us to compare the energy penalty when CO<sub>2</sub> capture installation is completed at new power plant and existing power plants. For all the analyzed power plant cases, the 80% capacity factor has been assumed.

**Table 1.** Technical summary of analyzed Polish power plants.

| Parameter                         | Łagisza Power Plant           | Bełchatów Power Plant          | Połaniec Power Plant         |
|-----------------------------------|-------------------------------|--------------------------------|------------------------------|
| Gross electrical power            | 459.80 MW <sub>el</sub>       | 380.01 MW <sub>el</sub>        | 225 MW <sub>el</sub>         |
| Net electrical power              | 444.50 MW <sub>el</sub>       | 355.58 MW <sub>el</sub>        | 208 MW <sub>el</sub>         |
| Gross energy efficiency           | 45.16% <sub>LHV</sub>         | 38.78% <sub>LHV</sub>          | 40.61% <sub>LHV</sub>        |
| Net energy efficiency             | 43.66% <sub>LHV</sub>         | 36.28% <sub>LHV</sub>          | 37.50% <sub>LHV</sub>        |
| Chemical energy of fuel           | 1018.2 MW <sub>ch</sub>       | 980.0 MW <sub>ch</sub>         | 554.05 MW <sub>ch</sub>      |
| Specific CO <sub>2</sub> emission | 770.7 kg CO <sub>2</sub> /MWh | 1062.9 kg CO <sub>2</sub> /MWh | 1075.20 CO <sub>2</sub> /MWh |

### 2.1.2. Direct Air Capture Installations

In the case of DAC installation, two different technologies were considered [7]:

- High-temperature aqueous (DAC<sub>HT</sub>),
- Low-temperature solid sorbent, with two options for heat supply:
  - waste heat from industrial processes (DAC<sub>LTWH</sub>),
  - heat pump (DAC<sub>LTHP</sub>).

The data regarding the electricity and heat demand were taken over from [7] and summarized in Table 2.

**Table 2.** Technical summary of analyzed direct air capture installations.

| Parameter                       | High-Temperature Aqueous                  | Low-Temperature Solid Sorbent             |                                            |
|---------------------------------|-------------------------------------------|-------------------------------------------|--------------------------------------------|
|                                 |                                           | Waste Heat                                | Heat Pump                                  |
| Capacity                        | 1,000,000 tpa                             | 360,000 tpa                               |                                            |
| Direct electricity demand       | 1535 kWh <sub>el</sub> /t CO <sub>2</sub> | 250 kWh <sub>el</sub> /t CO <sub>2</sub>  |                                            |
| Heat demand                     | 0 kWh <sub>th</sub> /t CO <sub>2</sub>    | 1750 kWh <sub>th</sub> /t CO <sub>2</sub> |                                            |
| COP of heat pump                | -                                         | 36.28% <sub>LHV</sub>                     | 3.0                                        |
| Indirect electricity demand     | -                                         | 980.0 MW <sub>ch</sub>                    | 583.3 kWh <sub>el</sub> /t CO <sub>2</sub> |
| CO <sub>2</sub> outlet pressure | 1 bar                                     | 1 bar                                     |                                            |

As presented in Table 2, the CO<sub>2</sub> outlet pressure is 1 bar, which means that additional electricity consumption is required to compress the CO<sub>2</sub> before transportation to the storage site.

### 2.2. Process Synthesis and Design

Within the power plant analysis, the reference models were adopted to reflect the decrease in energy performance due to the CO<sub>2</sub> capture and compression installations. The approach presented in [52] was adopted, and the main assumptions were as follows:

- MEA post-combustion CO<sub>2</sub> capture technology,
- CO<sub>2</sub> capture efficiency of 90%,
- reboiler heat duty equal to 3 MJ/kg, with reboiler temperature of 130 °C,
- steam for reboiler is extracted on the crossover pipe and its pressure is adapted to fit with capture unit requirements by means of valve (retrofit cases) or dedicated turbine (new build),
- steam de-superheating options considered are associated with mixing with a fraction of the condensate (retrofit cases) or introduction of an additional heat exchanger (new build),

- in new-build cases, the heat integration is acknowledged by means of partial replacement of condensate and boiler feedwater preheaters,
- CO<sub>2</sub> pressure for transport equal to 130 bar.

In addition, different shares of biomass were analyzed. These ranged from co-combustion with coal up to 30%<sub>LHV</sub> in an existing boiler (options for the Łagisza power plant), through to material up to 40%<sub>LHV</sub> of total thermal input in the power plant's dedicated biomass boiler (option for the Bełchatów power plant, so called duo-unit). This ended with analysis of 100%<sub>LHV</sub> material in biomass boilers in the Połaniec power plant and a new power plant (based on the Połaniec power plant design).

For the DAC installation, the same CO<sub>2</sub> compression train is applied as in the case of the CCS power plants. In the analyzed scenarios, the electricity can come from the national energy system (NES) or dedicated wind turbines (WT).

### 2.3. Assessment Methods

Within this paper, the general assessment methods of the CCS technologies have been presented. These which allow us to determine the net energy efficiency decrease, as well as specific energy consumption per CO<sub>2</sub> avoided. In addition, two different methods of the negative emissions assessment have been presented, followed by the method for the thermo-ecological cost assessment of the carbon dioxide removal technologies.

#### 2.3.1. Performance Indexes

The overall performance of the analyzed power plants can be calculated with the following equations:

- net electrical efficiency ( $\eta_{net}$ , %<sub>LHV</sub>):

$$\eta_{net} = \frac{E_{el,net}}{\sum_n^i E_{ch,i}} \quad (1)$$

- loss of net electrical efficiency ( $\Delta\eta_{net}$ , % pts.):

$$\Delta\eta_{net} = \eta_{net,REF} - \eta_{net,CCS} \quad (2)$$

- specific primary energy consumption for CO<sub>2</sub> avoided (SPECCA, MJ<sub>LHV</sub>/kg CO<sub>2</sub>):

$$SPECCA = \frac{q_{net,CCS} - q_{net,REF}}{e_{CO_2,REF}^{dir} - e_{CO_2,CCS}^{dir}} = \frac{3600 \times \left( \frac{1}{\eta_{net,CCS}} - \frac{1}{\eta_{net,REF}} \right)}{e_{CO_2,REF}^{dir} - e_{CO_2,CCS}^{dir}} \quad (3)$$

where  $E_{el,net}$  is annual net electricity production, MWh<sub>el</sub>,  $E_{ch,i}$  is annual consumption of  $i$ -th fuel, MWh<sub>LHV</sub>,  $q_{net}$  is unit fuel consumption per net electricity production, MJ<sub>LHV</sub>/MWh<sub>el</sub> and  $e_{CO_2}^{dir}$  is specific direct CO<sub>2</sub> emission, kg CO<sub>2</sub>/MWh<sub>el</sub>.

#### 2.3.2. Negative Emissions Calculation Methods

In [53], the method for the assessment of negative emission was proposed. In this, the negative emissions are achieved when anthropogenic (or non-biogenic) carbon dioxide emissions for the combustion processes are less than the biogenic CO<sub>2</sub> that is permanently stored in geological reservoirs. In the discussed study [53], as well as in the presented paper, the biogenic CO<sub>2</sub> emissions ( $e_{CO_2}^{bio}$ , tpa) are considered to be carbon neutral. Thus, actual CO<sub>2</sub> emissions ( $e_{CO_2}^{act}$ , tpa) must discount biogenic emissions from the total amount of CO<sub>2</sub> released ( $e_{CO_2}^{tot}$ , tpa), which should account for the CO<sub>2</sub> from direct fuel combustions, as well as supply chains (upstream processes) and CO<sub>2</sub> transport and storage (downstream processes). The amount of biogenic CO<sub>2</sub> captured ( $c_{CO_2}^{bio}$ , tpa) is the total CO<sub>2</sub> captured

( $c_{CO_2}^{tot}$ , tpa) minus the CO<sub>2</sub> from fossil fuels combustion ( $c_{CO_2}^{fos}$ , tpa). Thus, the negative emissions ( $e_{CO_2}^{neg}$ , tpa) can be calculated as follows:

$$e_{CO_2}^{neg} = e_{CO_2}^{act} - c_{CO_2}^{bio} = (e_{CO_2}^{tot} - e_{CO_2}^{bio}) - (c_{CO_2}^{tot} - c_{CO_2}^{fos}) \quad (4)$$

For the BECCS power plants, the carbon intensity ( $CI$ , kg CO<sub>2</sub>/MWh<sub>el</sub>) can be calculated [53], which relates to the amount of negative CO<sub>2</sub> emissions per MWh of electricity generated:

$$CI = \frac{e_{CO_2}^{act} - c_{CO_2}^{bio}}{E_{el,net}} \quad (5)$$

For the DAC, a similar coefficient can be proposed. The carbon removal intensity ( $CRI$ , kg CO<sub>2</sub>/MWh<sub>el</sub>) relates to the amount of negative CO<sub>2</sub> emissions per MWh of electricity consumed ( $E_{el,con}$ ):

$$CRI = \frac{e_{CO_2}^{act} - c_{CO_2}^{atm}}{E_{el,con}} \quad (6)$$

where the  $e_{CO_2}^{act}$  is equal to  $e_{CO_2}^{tot}$  and refers to the associated CO<sub>2</sub> emissions in the supply chain (e.g., CO<sub>2</sub> emissions from the electricity in the energy system) and CO<sub>2</sub> transport and storage (e.g., CO<sub>2</sub> leakage), and  $c_{CO_2}^{atm}$  refers to the amount of CO<sub>2</sub> removed from the atmosphere.

In [54], a method of calculations of the positive effects of CCS and CCU on climate change was proposed based on three key performance indicators. One of the indicators refers to the mitigation of CO<sub>2</sub> emissions, expressed as the carbon to atmosphere factor (C2A), which “is intended to support decision makers and project developers to quickly and uniformly derive the emissions abatement potential of CO<sub>2</sub> capture projects in a directly comparable manner” [54]. As stressed by the authors, the C2A methodology may be applied to any kind of CCUS project, including direct air capture technologies.

The following equation is proposed:

$$C2A = f_{CO_2 \text{ source}} - (1 - f_{emitted}) - \left( \frac{f_{emitted} \times f_{CO_2 \text{ source}} \times f_{re-emitted}}{2} \right) \quad (7)$$

where  $f$  represents the following fractions:

- $f_{CO_2 \text{ source}}$  indicates the type of CO<sub>2</sub> we intended to be capture (e.g., =1 if CO<sub>2</sub> comes from geological sources or =0 if whole intended CO<sub>2</sub> comes from atmosphere),
- $f_{re-emitted}$  indicates the amount of CO<sub>2</sub> captured and which we intended to be re-emitted to atmosphere (e.g., =0 when whole CO<sub>2</sub> is being permanently stored or =1 when CO<sub>2</sub> will be re-emitted thru utilization process through means of synthetic fuels or other products),
- $f_{emitted}$  indicates the additional CO<sub>2</sub> emissions in the CCUS technological chain that must be accounted for. Thus, it can be calculated as a sum of CO<sub>2</sub> resulting from capture, conversion, use or storage, plus the re-emitted amount added.

Depending on the applied indicator ( $CI$ ,  $CRI$ ,  $e_{CO_2}^{neg}$  or  $C2A$ ) their final values can inform us about the effects of CCUS technologies on climate change. The summary of the indicators interpretations has been presented in Table 3.

It is important, especially in the case of first group of outcomes (presented in Table 3), to compare the obtained results with the reference plants or processes for the analyzed CCUS implementation.

**Table 3.** Indicators interpretation summary.

| C2A Indicator     | CI, CRI, $e_{CO_2}^{neg}$ Indicators | Outcome                                                                                                                                           |
|-------------------|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| $C2A \geq 1$      | $CI, CRI, e_{CO_2}^{neg} > 0$        | No mitigation or even increase in emission (when compared with reference plants).                                                                 |
| $0 < C2A < 1$     |                                      | Potential for emissions reduction (when compared with reference plants).                                                                          |
| $C2A = 0$         | $CI, CRI, e_{CO_2}^{neg} = 0$        | Potential to be carbon neutral.                                                                                                                   |
| $-1 \leq C2A < 0$ | $CI, CRI, e_{CO_2}^{neg} < 0$        | Potential for carbon dioxide removal. Processes with positive climate mitigation effects, also referred as carbon negative emission technologies. |

### 2.3.3. Thermo-Ecological Cost Assessment

In general, the specific thermo-ecological cost ( $\rho_j$ ) for a given system boundary can be calculated from the thermo-ecological balance equations:

$$\rho_j = \sum_s b_{sj} + \sum_k p_{kj} \zeta_k - \sum_i (f_{ij} - a_{ij}) \rho_i \quad (8)$$

where  $a_{ij}$ ,  $f_{ij}$  are coefficients of consumption of  $i$ -th material and by-production of  $i$ -th product per unit of  $j$ -th main product.  $b_{sj}$  is exergy of  $s$ -th non-renewable natural resource immediately consumed in the process under consideration per unit of  $j$ -th product;  $\rho_i$  is specific thermo-ecological cost of  $i$ -th product;  $p_{kj}$  is amount of  $k$ -th harmful substance for  $j$ -th process; and  $\zeta_k$  is thermo-ecological cost of  $k$ -th harmful substance.

The total thermo-ecological cost ( $TEC^{tot}$ ) for any energy process or installation can be obtained from the following equation:

$$TEC^{tot} = \sum_i E_i \rho_i + \sum_j G_j \rho_j + \sum_k P_k \zeta_k = \frac{\rho}{S} \quad (9)$$

where  $E_i$  is annual chemical energy consumption of  $i$ -th fuel;  $G_j$  is annual consumption of  $j$ -th feed (including electricity from the grid);  $\rho_i$ ,  $\rho_j$  is specific thermo-ecological cost of  $i$ -th fuel or  $j$ -th feed;  $P_k$  is annual direct emission of  $k$ -th harmful substance or waste in the analyzed system;  $\zeta_k$  is thermo-ecological cost of  $k$ -th harmful substance or waste; and  $S$  is the sum of the annual production of energy carriers in the analyzed system.

In cogeneration or polygeneration energy systems, the thermo-ecological cost can be allocated by means of the exergy allocation method [55]. In the case of BECCS power (or combined heat and power) plants, the same approach might give misleading results. Thus, within this paper, the thermo-ecological cost allocation for the negative CO<sub>2</sub> emissions for BECCS and DAC plants is proposed. In the case of DAC installation, Equation (9) can be used directly, as there is only one final product (captured and compressed CO<sub>2</sub>). However, for the BECCS power plant, the following formula for the calculation of the specific thermo-ecological cost of negative CO<sub>2</sub> emissions ( $\rho_{CO_2}^{neg}$ , GJ<sub>ex</sub>/t CO<sub>2</sub>) has been proposed:

$$\rho_{CO_2}^{neg} = \frac{(\rho_{el}^{CCS} - \rho_{el}^{REF}) \times E_{el}^{CCS}}{e_{CO_2}^{neg}} \quad (10)$$

where  $\rho_{el}^{CCS}$  is specific thermo-ecological cost of net electricity production in power plant with CCS, GJ<sub>ex</sub>/MWh<sub>el</sub>;  $\rho_{el}^{REF}$  specific thermo-ecological cost of net electricity production in reference power plant without CCS, GJ<sub>ex</sub>/MWh<sub>el</sub>;  $E_{el}^{CCS}$  is annual net electricity production in power plant with CCS; and MWh<sub>el</sub>/a  $e_{CO_2}^{neg}$  is annual negative CO<sub>2</sub> emission for the BECCS plant, tpa.

The presented formula allows us to include the additional cumulative depletion of non-renewable natural resources, caused by the CO<sub>2</sub> capture, transport and storage ( $\rho_{el}^{CCS} - \rho_{el}^{REF}$ ), for the amount of electricity introduced into the system by the power plant ( $E_{el}^{CCS}$ ) and the amount of obtained negative CO<sub>2</sub> emission ( $e_{CO_2}^{neg}$ ). For the cogeneration and polygeneration plants with BECCS, the other energy carriers produced should also be included.  $\sum_i (\rho_i^{CCS} - \rho_i^{REF}) \times E_i^{CCS}$ , where all *i*-th energy carriers produced should be included.

TEC of fossil fuels and biomass for the analyzed power plants has been evaluated on the basis of the thermo-ecological cost balance formulas, as well as the data concerning biomass acquisition in the literature [56,57] and LCA databases from SimaPro software [58]. Additionally, TEC of electricity from both national energy system and wind turbines was built on available LCA data and the statistics from the official Polish energy mix. Furthermore, TEC of harmful emissions has been extracted from [11]. The same approach was applied regarding the cumulative CO<sub>2</sub> emissions for all relevant inputs. In addition, the data regarding the TEC and cumulative CO<sub>2</sub> emissions of materials and other products (included in the life cycle assessment) have been taken from [59]. The most relevant data are summarized in Table 4. All parameters relate to Polish conditions, and ‘ex’ refers to exergy.

**Table 4.** Main input data for the analysis of Polish cases [60].

| Energy Carrier                     | Specific Thermo-Ecological Cost          | Specific Cumulative CO <sub>2</sub> Emission |
|------------------------------------|------------------------------------------|----------------------------------------------|
| Electricity—national energy system | 3.9 MJ <sub>ex</sub> /MJ <sub>el</sub>   | 931.2 kg CO <sub>2</sub> /MWh <sub>el</sub>  |
| Electricity—wind turbines          | 0.081 MJ <sub>ex</sub> /MJ <sub>el</sub> | 10 kg CO <sub>2</sub> /MWh <sub>el</sub>     |
| Biomass                            | 0.1 MJ <sub>ex</sub> /MJ <sub>ch</sub>   | 12.24 kg CO <sub>2</sub> /MWh <sub>ch</sub>  |
| Hard coal                          | 1.202 MJ <sub>ex</sub> /MJ <sub>ch</sub> | 15.12 kg CO <sub>2</sub> /MWh <sub>ch</sub>  |
| Lignite                            | 1.364 MJ <sub>ex</sub> /MJ <sub>ch</sub> | 8.82 kg CO <sub>2</sub> /MWh <sub>ch</sub>   |
| Harmful emissions:                 |                                          |                                              |
| - SO <sub>2</sub>                  | 136.24 MJ <sub>ex</sub> /kg              |                                              |
| - NO <sub>x</sub>                  | 112.97 MJ <sub>ex</sub> /kg              | -                                            |
| - PM                               | 72.89 MJ <sub>ex</sub> /kg               |                                              |

As presented in Table 4, the CO<sub>2</sub> was not considered as harmful emission due to the lack of reliable data in all instances considered in TEC impacts, as in the cases of SO<sub>2</sub>, NO<sub>x</sub> and particulate matter.

#### 2.3.4. Negative Emissions Readiness Index

The term “readiness” is widely used, from education to military and technology. The term is as poorly defined as it is widely used. “The technology-readiness construct refers to people’s propensity to embrace and use new technologies for accomplishing goals in home life and at work. The construct can be viewed as an overall state of mind resulting from a gestalt of mental enablers and inhibitors that collectively determine a person’s predisposition to use new technologies” [61].

As such, it is worth asking how ready societies are to deploy carbon removal technologies? A recent paper [13] explicitly mentions BECCS and DACCS as the two most important technologies in terms of removing tCO<sub>2</sub> from the atmosphere, and suggests this policy pathway. At the national level, three kinds of policies can be implemented:

1. direct policies that provide either encouraging or punishing incentives for deploying CDR;
2. enabling policies, facilitating innovation and infrastructure;
3. integrating policies that build connections with other policies.

It furthermore suggests establishing a supporting scheme for CDR technologies, but leaves specific incentive systems and regulatory options up for debate [13].

The Socio-Political Negative Emissions Readiness Index is composed of two different and broad groups of indicators—geopolitical, which can be understood as international indicators, and domestic, which is comprised of indicators related to states’ internal features

and capabilities. The index is relational, which means that the majority of sub-indicators are made from measuring one value against another. As a result, they fall within a 0–1 scale. One sub-indicator is dichotomic. Each of them is given equal weight.

The first group of sub-indicators aims to measure various international dimensions of states' approaches to NET and is constructed of six indicators: Firstly, the existing infrastructure is assessed, both whether (1) CO<sub>2</sub> can potentially be transmitted abroad, and to what the level of (2) gas interconnectors is available. The following three indicators measure the country's diplomatic position in the context of climate change: (3) its lock-in into international treaties, (4) the level of ambition of its climate agreements (the most ambitious states serve as the reference point), and (5) the country's international posture regarding climate change (measured by its timeframe to achieve net-zero). The last of these measurements is represented by the (6) level of domestic availability of hydrocarbon resources, as higher dependence on foreign resources leads to more incentives for carbon removal.

The group that measures internal factors is made of 10 indicators. The first one is (1) RES potential. The higher it is, the less prone a state will be to introduce NETs, as further investments in RES will be more cost-efficient. The next one (2) measures predictable and enduring policy environment that is a *sine qua non* condition for NETs development, as they require long-term commitment on the government side. Subsequently, we developed four indicators related to CCS. The (3) scale of CCS legislation in force in a given state is quantified, and the (4) storage capacity is accounted for. Then, (5) spending on CCS is measured—against spending on climate change mitigation. Subsequently, we conducted an (6) estimation of the costs for a potential NET support scheme. Sixthly and seventhly, it is proposed that the influence of legacy networks—(6) electric grid and (7) gas pipelines be used, as they make impact on decision makers' willingness to support carbon removal. Another factor that has to be accounted for in this assessment is (8) dependency on industries which are difficult to decarbonize—the more important its role in a given state's economy, the higher the incentive to support NETs. (9) High dependency on the hydrocarbon industry may also incentivize activities aimed at keeping it alive as long as possible in the context of growing pressure to eliminate carbon-intensive industries. Finally, (10) the availability of biomass is assumed to be negatively correlated with the willingness of NETs introduction.

For a thorough assessment, local peculiarities of the respective political system need to be accounted for by three indicators. Firstly, the framework for local consultations (1) for infrastructure development plays a significant role in the viability of planned projects. The higher local participation, the more costly the deployment of large-scale technologies is. Secondly, the possibility of (2) potential financial involvement of local communities in carbon storage activities is important. Although such activities are currently predominantly state-directed or funded by the private sector, financial participation by local populations can serve as a strong incentive to deploy carbon storage infrastructure, benefitting both local populations and the central government. The higher levels acceptance for these new technologies that is prerequisite for financial investments would be a key benefit. The final indicator would gauge the (3) level of environmental awareness of local citizens and their potential opposition to both transportation and storage infrastructures (known as "not in my back yard" issue). One example of this is the protests that occurred against the CCS installation planned in the Bełchatów power plant. This is, however, more relevant for the assessment of regional readiness and is therefore not applied in this study.

### 2.3.5. Economic Assessment

The economic assessment includes Levelized Cost of Electricity (LCOE), Levelized Cost of CO<sub>2</sub> Avoided (LCAC), Levelized Cost of Negative CO<sub>2</sub> emissions (LCNC) calculation, as well as Levelized Cost of CO<sub>2</sub> DAC (LCOD). The net present value (NPV) for the analyzed systems was also evaluated.

The Levelized Cost of Electricity is an indicator usually used to compare the costs of electricity production in various technologies. LCOE represents the average electricity price that must be incurred for 1 kilowatt-hour energy generation over the project lifetime. It contains investment costs, operational costs, fuel costs and electricity production. LCOE is performed to evaluate system profitability. The remaining LCAC and LCNC refer to the CO<sub>2</sub> avoided and CO<sub>2</sub> negative emissions. They are defined as follows:

$$\text{LCOE} = \frac{\text{CAPEX} \cdot f_r + \sum_i \text{OPEX}_i}{E_{el}} \quad (11)$$

where CAPEX is total capital expenditure, OPEX refers to annual operational costs (both fixed and variable),  $E_{el}$  is electricity generation per annum and  $f_r$  discount factor:

$$f_r = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (12)$$

where  $r$  is discount rate and  $n$  is a number of years of project lifetime.

Levelized cost of CO<sub>2</sub> DAC calculation was based on Equation (11) using the capacity for CO<sub>2</sub> capture instead of annual power generation.

Levelized cost of CO<sub>2</sub> avoided as well as levelized cost of negative CO<sub>2</sub> emissions are evaluated using the net present value [62]. LCAC denotes the average cost of CO<sub>2</sub> emissions reduction by unit through adding CCS to biomass or coal power plant. This indicator is used to compare different CCS projects and to identify the most economically viable ones. LCAC is given by:

$$\text{LCAC} = \frac{\Delta \text{NPV}}{\sum_{\tau=0}^N \delta^\tau G_{ref} - \sum_{\tau=0}^N \delta^\tau G_{CC}} = \frac{\text{NPV}_{CCS} - \text{NPV}_{ref}}{\sum_{\tau=0}^N \delta^\tau G_{ref} - \sum_{\tau=0}^N \delta^\tau G_{CC}} \quad (13)$$

$$\delta = \frac{1}{(1+r)^\tau} \quad (14)$$

LCNC refers only to achieved negative CO<sub>2</sub> emissions and is calculated as follows:

$$\text{LCNC} = \frac{\Delta \text{NPV}}{\sum_{\tau=0}^N \delta^\tau G_{neg}} = \frac{\text{NPV}_{CCS} - \text{NPV}_{ref}}{\sum_{\tau=0}^N \delta^\tau G_{neg}} \quad (15)$$

where  $G$  is mass emission rate to the atmosphere in tonnes per MWh, “cc” and “ref” refer to plants with and without carbon capture installation and “neg” to obtained negative CO<sub>2</sub> emissions.

The net present value of project is defined as:

$$\text{NPV} = \sum_{\tau=0}^n \frac{CF_\tau}{(1+r)^\tau} - \text{CAPEX} \quad (16)$$

where  $CF_\tau$  is project's cash flow realized in period  $\tau$ .

In Table 5, a summary of economic assumptions is presented for all of the analyzed systems. The financial assessment was conducted on the basis of business as usual and relates to current Polish market.

All of the analyzed projects were assumed to be 100% equity financed. For CCS installation added to existing Łagisza, Bełchatów and Połaniec power plants, as well as for Direct Air Capture installation, one year of construction time is assumed. The four-year period required to build a new bioenergy power plant is taken into account.

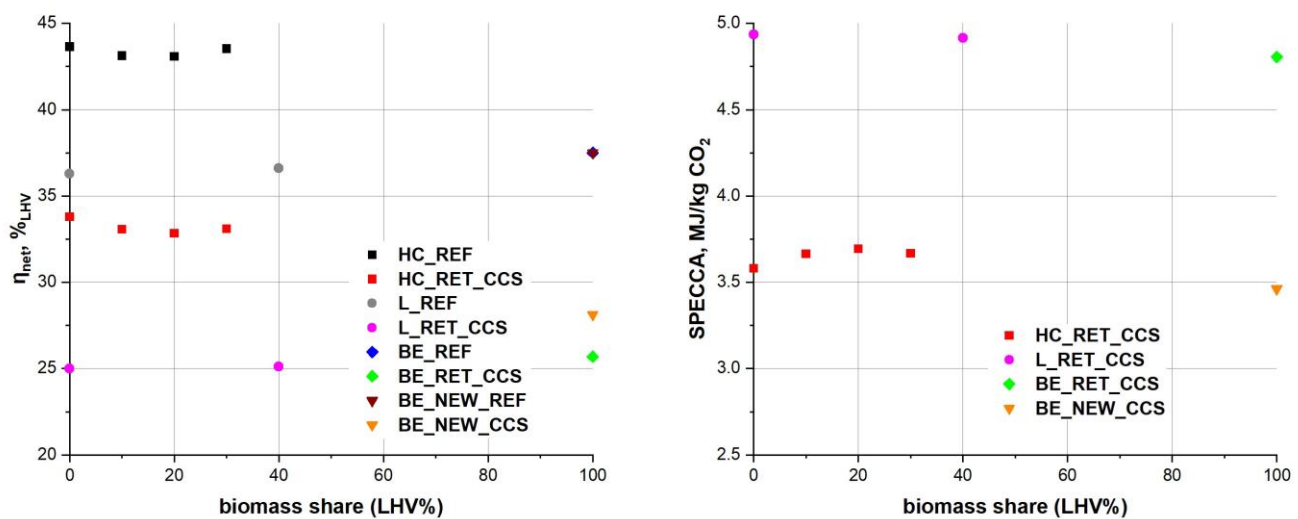
**Table 5.** Summary of financial assumptions.

| Parameter                                                                              | Value                   |
|----------------------------------------------------------------------------------------|-------------------------|
| Cost base year                                                                         | 2021                    |
| Base currency                                                                          | EUR                     |
| Project lifetime (power plant with CCS, DAC—HT aqueous solution, DAC—LT solid sorbent) | 30, 25, 20              |
| Capacity factor for power plants                                                       | 80% (7008 h)            |
| Full load hours per year for DAC                                                       | 8000                    |
| Discount rate                                                                          | 6%                      |
| Electricity price                                                                      | 110 EUR/MWh             |
| Biomass price                                                                          | 8 EUR/GJ                |
| Coal price                                                                             | 70 EUR/t (3.3 EUR/GJ)   |
| Lignite price                                                                          | 24 EUR/t (2.7 EUR/GJ)   |
| EU-ETS emission allowance price                                                        | 45 EUR/tCO <sub>2</sub> |

### 3. Results

#### 3.1. Energy Assessment

For the analyzed power plants, based on the performed calculations, the energy assessment results indicate a net electrical efficiency decrease of between 9.4 and 11.8 percentage points. The obtained values correspond with the ones in the literature. The summary of the energy assessment has been presented in Figure 5.

**Figure 5.** Energy assessment results.

The obtained values of SPECCA also correspond to the ones found in the literature. As expected, the SPECCA for the retrofit cases are higher than for the new builds—mainly due to available heat integration options and additional turbines being installed.

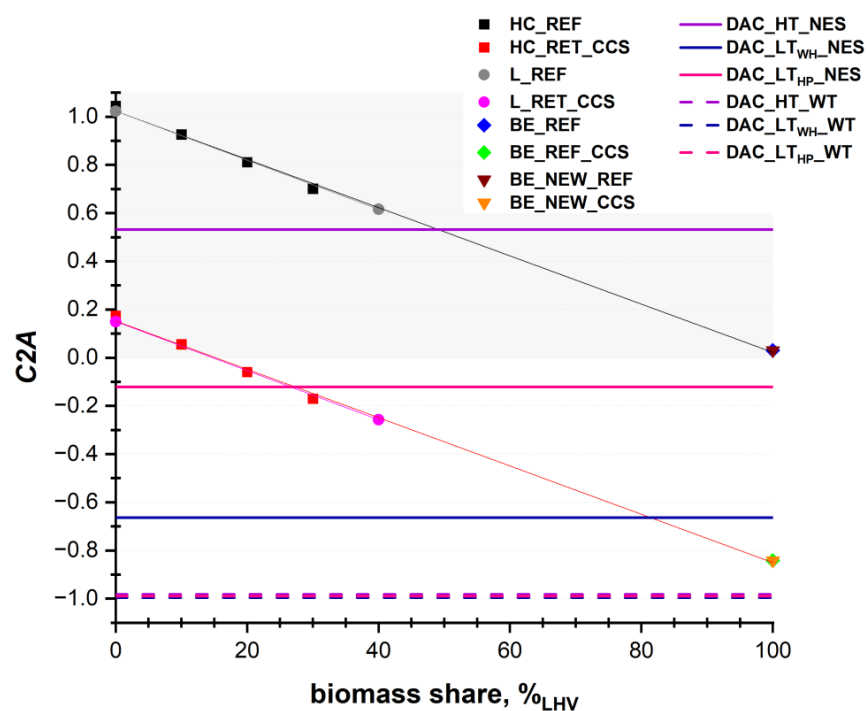
#### 3.2. Achieving Negative Emissions

For carbon intensity and carbon removal intensity, the results of the study are presented in Table 6. As already mentioned, for the power plant, the share of the biomass needs to be above 15%<sub>LHV</sub> for the plant, integrated with CCS installation, to obtain negative emission and be classified as carbon dioxide removal technology. In the case of the DAC installations, when high-temperature processes are realized to be taking the electricity from the current Polish national energy system, the positive values of the CRI are recorded. As stressed in Table 3, the technology cannot be considered as climate positive. Thus, it is crucial to decarbonize the energy system before introducing the DAC technologies for the CO<sub>2</sub> removal from the atmosphere.

**Table 6.** Carbon Intensity and Carbon Removal Intensity of analyzed power plants and DAC installations.

| Case                             | CI, kg CO <sub>2</sub> /MWh <sub>el</sub>  |       |                            |        |                         |         |
|----------------------------------|--------------------------------------------|-------|----------------------------|--------|-------------------------|---------|
|                                  | Biomass Share, % <sub>LHV</sub>            |       |                            |        |                         |         |
|                                  | 0                                          | 10    | 20                         | 30     | 40                      | 100     |
| Łagisza power plant:             |                                            |       |                            |        |                         |         |
| - without CCS (HC_REF)           | 805.3                                      | 736.5 | 658.4                      | 573.7  | -                       |         |
| - with CCS (HC_RET_CCS)          | 156.0                                      | 38.9  | −82.2                      | −202.0 | -                       |         |
| Bełchatów power plant            |                                            |       |                            |        |                         |         |
| - without CCS (L_REF)            | 1087.2                                     | -     | -                          | -      | 659.9                   | -       |
| - with CCS (L_RET_CCS)           | 207.8                                      | -     | -                          | -      | −427.5                  | -       |
| Połaniec power plant:            |                                            |       |                            |        |                         |         |
| - without CCS (BE_REF)           | -                                          | -     | -                          | -      | -                       | 32.6    |
| - with CCS (BE_RET_CCS)          | -                                          | -     | -                          | -      | -                       | −1346.3 |
| New build bioenergy power plant: |                                            |       |                            |        |                         |         |
| - without CCS (BE_NEW_REF))      | -                                          | -     | -                          | -      | -                       | 32.6    |
| - with CCS (BE_NEW_CCS)          | -                                          | -     | -                          | -      | -                       | −1229.9 |
| Case                             | CRI, kg CO <sub>2</sub> /MWh <sub>el</sub> |       |                            |        |                         |         |
|                                  | High-temperature aqueous                   |       | Low-temperature waste heat |        | Solid sorbent heat pump |         |
|                                  |                                            |       |                            |        |                         |         |
| Electricity sources:             |                                            |       |                            |        |                         |         |
| - PL national energy system      | 323.73                                     |       | −1846.94                   |        | −128.29                 |         |
| - wind farms                     | −597.44                                    |       | −2768.12                   |        | −1049.46                |         |

The second indicator—C2A—shows similar results to *CI* and *CRI* regarding the impact of the share of biomass and source of electricity for DAC installations. The results, presented in Figure 6, allow us to directly compare the effects of the proposed solutions to climate change.

**Figure 6.** Carbon to Atmosphere Factor for the analyzed cases and scenarios.

As marked in Figure 6, the processes in the grey area have a C2A of above 0, which means that they lead to no mitigation, or even to an increase in emissions, or have a potential for emissions reduction (when compared with reference plants). If the electricity for the DAC installations comes from wind turbines (WT), their potential can be fully utilized. However, when the electricity is supplied from a highly carbonized national energy system (like in the case of Poland), their effect is significantly reduced and in some cases can actually add additional emissions to the atmosphere.

### 3.3. Thermo-Ecological Cost of Negative Emissions

In Table 7, the specific thermo-ecological cost of net electricity production for the analyzed power plants is presented. As can be noticed, with the increase in the biomass in the fuel input, the TEC decreases. On the other hand, CCS installation adds around 30% to 50% in terms of the depletion of non-renewable natural resources per unit of net electricity production.

**Table 7.** Specific thermo-ecological cost of net electricity production for the analyzed power plants.

| Case                             | $\rho_{el}$ , MJ <sub>ex</sub> /MWh <sub>el</sub> |       |       |       |       |       |
|----------------------------------|---------------------------------------------------|-------|-------|-------|-------|-------|
|                                  | Biomass Share, %LHV                               |       |       |       |       |       |
|                                  | 0                                                 | 10    | 20    | 30    | 40    | 100   |
| Łągisza power plant:             |                                                   |       |       |       |       |       |
| - without CCS                    | 2.777                                             | 2.555 | 2.301 | 2.025 | -     |       |
| - <b>with CCS</b>                | 3.617                                             | 3.364 | 3.053 | 2.698 | -     |       |
| Bełchatów power plant            |                                                   |       |       |       |       |       |
| - without CCS                    | 3.346                                             | -     | -     | -     | 2.112 | -     |
| - <b>with CCS</b>                | 4.901                                             | -     | -     | -     | 3.123 | -     |
| Połaniec power plant:            |                                                   |       |       |       |       |       |
| - without CCS                    | -                                                 | -     | -     | -     | -     | 0.290 |
| - <b>with CCS</b>                | -                                                 | -     | -     | -     | -     | 0.477 |
| New build bioenergy power plant: |                                                   |       |       |       |       |       |
| - without CCS                    | -                                                 | -     | -     | -     | -     | 0.289 |
| - <b>with CCS</b>                | -                                                 | -     | -     | -     | -     | 0.437 |

One of the goals of this paper was to assess the TEC of negative CO<sub>2</sub> emissions for the analyzed units that can be recognised as CDR technologies. In Table 8, the results have been presented for both BECCS power plants and DAC units.

As presented in Table 8, the increase in the share of chemical energy of biomass in the analyzed co-firing power plants decrease the thermo-ecological cost of negative CO<sub>2</sub> emissions. When DAC units are considered, the obtained values can be even lower than for the dedicated BECCS power plants, but only if the electricity is provided from renewable energy sources (e.g., wind turbines as in this study).

When the values are compared with other studies referring to the abatement TEC of CO<sub>2</sub> removal [60], the presented values are between 3.2 GJ<sub>ex</sub>/t CO<sub>2</sub> (for the integrated blast furnace with CCS) to 3.6 GJ<sub>ex</sub>/t CO<sub>2</sub> (for the power plant with CCS), which means that in the analyzed cases of the DAC units power by renewable energy sources or dedicated BECCS power plants, the values are significantly lower for the removal than abatement of carbon dioxide.

**Table 8.** Specific thermo-ecological cost of negative CO<sub>2</sub> emissions for the analyzed CDR.

| Case                             | $\rho_{CO_2}^{neg}$ , GJ <sub>ex</sub> /t CO <sub>2</sub> |       |      |      |
|----------------------------------|-----------------------------------------------------------|-------|------|------|
|                                  | Biomass Share, % <sub>LHV</sub>                           |       |      |      |
|                                  | 20                                                        | 30    | 40   | 100  |
| Łagisza power plant:             | 32.92                                                     | 11.99 | n/a  |      |
| Bełchatów power plant            | n/a                                                       | n/a   | 8.52 | n/a  |
| Połaniec power plant:            | n/a                                                       | n/a   | n/a  | 0.50 |
| New build bioenergy power plant: | n/a                                                       | n/a   | n/a  | 0.43 |

| Case                        | $\rho_{CO_2}^{neg}$ , GJ <sub>ex</sub> /t CO <sub>2</sub> |                               |           |
|-----------------------------|-----------------------------------------------------------|-------------------------------|-----------|
|                             | High-temperature aqueous                                  | Low-temperature solid sorbent |           |
|                             |                                                           | waste heat                    | heat pump |
| Electricity sources:        |                                                           |                               |           |
| - PL national energy system | not CDR                                                   | 7.60                          | 109.46    |
| - wind farms                | 0.49                                                      | 0.11                          | 0.28      |

### 3.4. Economic Evaluation

Both capital costs (CAPEX) of carbon capture installation and operating expenses were based on [63] accordingly to a power plant type. The capital costs were derived from a cost difference between plant with and without CCS multiplied by factor 1.1. The calculation also includes the capital scalar for Europe in an amount of 1.42. The cost estimation for DAC was based on [7]. Costs were updated to EUR2020 from their origin years and currencies according to Chemical Engineering Cost Index in 2020 and the EUR/USD exchange rates. Financial parameters are presented in Table 9.

**Table 9.** Economic parameters of analyzed power plants (in 2020EUR).

| Case                             | Biomass Share | CAPEX, MEUR | Fixed O&M, MEUR/y | Variable O&M, MEUR/y | Fuel Cost MEUR/y |
|----------------------------------|---------------|-------------|-------------------|----------------------|------------------|
| Łagisza power plant:             | 0%            | 1260.1      | 20.6              | 13.3                 | 84.0             |
|                                  | 10%           | 1333.7      | 25.4              | 13.0                 | 96.1             |
|                                  | 20%           | 1324.2      | 25.2              | 12.9                 | 108.3            |
|                                  | 30%           | 1334.5      | 25.4              | 13.0                 | 120.4            |
| Bełchatów power plant:           | 0%            | 896.7       | 14.6              | 9.4                  | 66.0             |
|                                  | 40%           | 974.5       | 18.5              | 9.5                  | 118.7            |
| Połaniec power plant:            | 100%          | 1244.2      | 23.2              | 8.4                  | 112.0            |
| New build bioenergy power plant: | 100%          | 2275.1      | 25.4              | 9.2                  | 112.0            |

| Case                              |            | CAPEX, MEUR | OPEX, MEUR/y | Electricity cost, MEUR/y |
|-----------------------------------|------------|-------------|--------------|--------------------------|
| DAC High-temperature aqueous      |            | 815         | 30.2         | 164.5                    |
| DAC Low-temperature solid sorbent | Waste heat | 262.8       | 10.5         | 14.2                     |
|                                   | Heat pump  | 262.8       | 10.5         | 37.3                     |

Total capital requirement depends on the technology and size of the unit thus the lowest cost was obtained for coal power plant with CCS. Co-firing coal with biomass increases the capital investment from 1260.1MEUR to 1334.5MEUR for 30% biomass share in Łagisza power plant and from 896.7MEUR to 974.5MEUR for 40% biomass share in Bełchatów power plant. Fixed operating and maintenance costs and fuel costs also rise with increase in the biomass share. Variable O&M costs remain on similar level in each case. High

capital costs result mainly from capture unit (e.g., absorber, desorber, compression unit) but also necessary plant modifications, e.g., turbine adjusting, rebuilding. The additional solvent in capture system increases the O&M costs.

As expected, the new build bioenergy power plant has the highest capital expenditures totaling 2275.1MEUR which is almost twice as much as in retrofitted cases. High-temperature aqueous direct air capture installation's capital and operational costs are significantly higher than for low-temperature systems mainly due to bigger CO<sub>2</sub> capture capacity. The additional cost of heat was taken into account within DAC LT solid sorbent with waste heat calculation.

Evaluated results for NPV for analyzed units within their lifetime are presented in Figure 7. For coal-fired power plants with CCS the NPV is above 0. For remaining retrofitted cases in Łagisza power plant the value is close to 0 and it could be reached with the discount rate equaling 5.7%, 4.7% and 3.8% for the biomass share of 10%, 20% and 30%, respectively. The negative cash flow for both retrofitted and new bioenergy power plant as well as for DAC installations can be seen. This means that there is no economic justification for these units and the financial support system is needed.

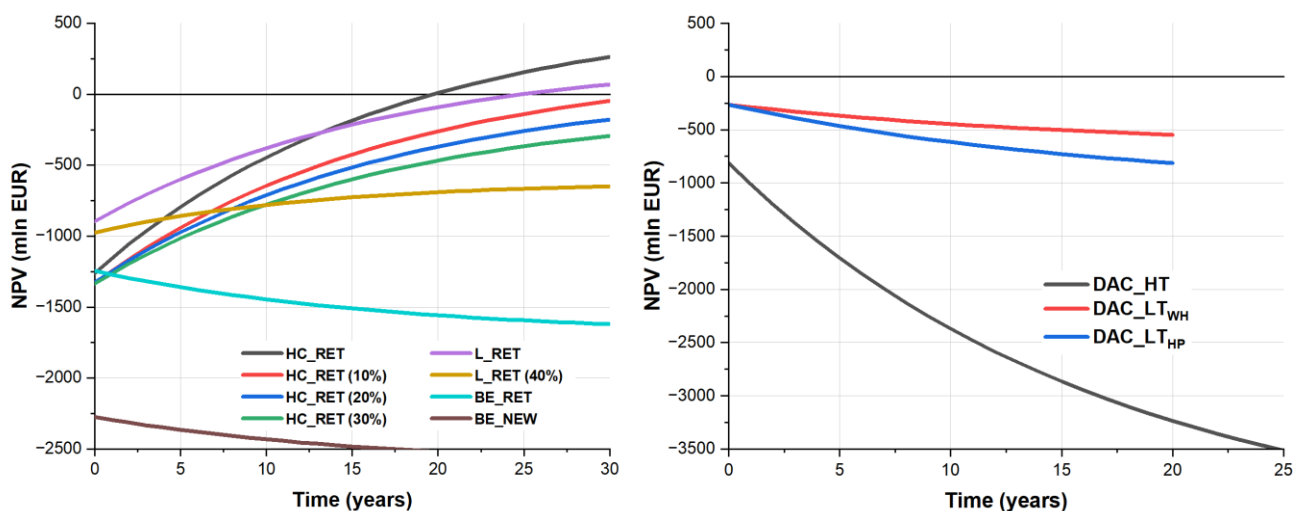


Figure 7. The Net Present Values (NPV) for analyzed units.

In Table 10 a summary of results regarding the levelized costs evaluation is presented. Obtained LCOE increases from 86.8 EUR /MWh to 108.3 EUR /MWh in Łagisza power plant and from 90.5 EUR /MWh to 126.1 EUR /MWh in Bełchatów power plant. Results in this paper are similar to those found in the literature [53,64,65]. The LCOE of bioenergy power plant is more than twice as high as LCOE of coal-fired power plants. In analyzed case, where the biomass cost was assumed as 8 EUR/GJ, the fuel cost appears to be the most significant. LCAC and LCNC are based on Equations (13) and (15). The negative values of LCAC and LCNC stem from negative difference between projects' NPV.

LCNC values are lower those of LCAC because LCNC refers only to the negative emissions which correspond to CO<sub>2</sub> emissions captured from biomass combustion or direct air capture. LCAC comprises the difference between plant emissions from the combustion of coal, both without and with CC.

The LCOD of the HC DAC is higher than LT DAC because of the high electricity cost. The LCOD for LT DAC systems differ because of an access to free waste heat.

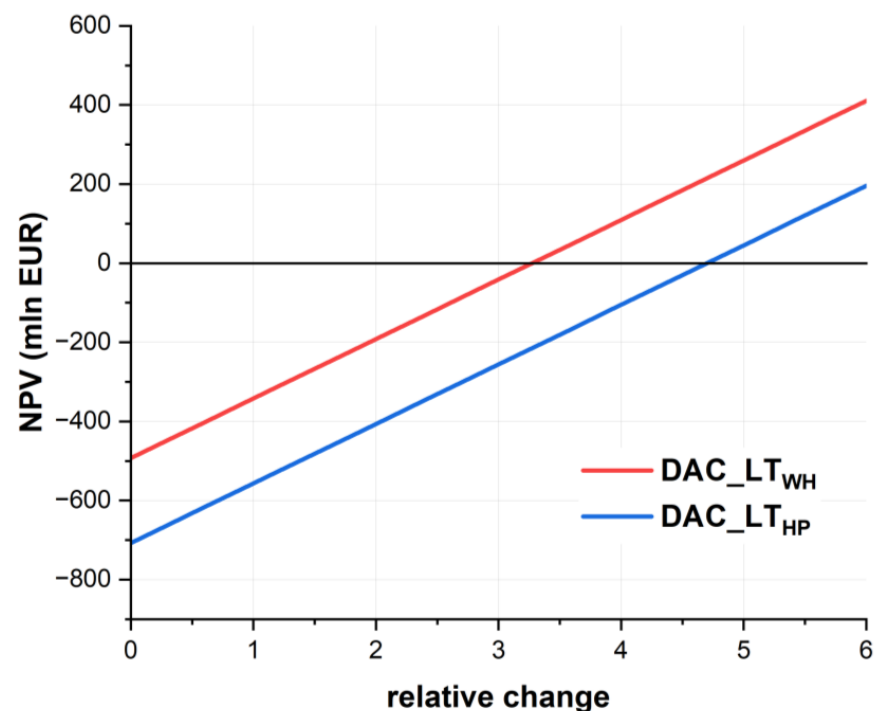
**Table 10.** Summary of economic evaluation.

| Case                             | BIOMASS SHARE | CO <sub>2</sub> Captured tpa | LCOE EUR /MWh | LCNC EUR /tCO <sub>2</sub> | LCAC EUR /tCO <sub>2</sub> |
|----------------------------------|---------------|------------------------------|---------------|----------------------------|----------------------------|
| Łagisza power plant:             | 0%            | 2,160,717                    | 86.8          | n/a                        | −51.1                      |
|                                  | 10%           | 2,203,580                    | 98.0          | n/a                        | −65.5                      |
|                                  | 20%           | 2,246,443                    | 103.5         | −261.3                     | −78.3                      |
|                                  | 30%           | 2,289,306                    | 108.3         | −187.8                     | −96.4                      |
| Bełchatów power plant:           | 0%            | 2,383,847                    | 90.5          | n/a                        | −28.8                      |
|                                  | 40%           | 2,427,193                    | 126.1         | −185.2                     | −139.9                     |
| Połaniec power plant:            | 100%          | 1,410,552                    | 234.3         | −103.4                     | n/a                        |
| New build bioenergy power plant: | 100%          | 1,410,552                    | 273.2         | −74.5                      | n/a                        |

| Case                              |            | CO <sub>2</sub> captured tpa | LCOD EUR /tCO <sub>2</sub> | LCNC EUR /tCO <sub>2</sub> |
|-----------------------------------|------------|------------------------------|----------------------------|----------------------------|
| DAC High-temperature aqueous      |            | 1,000,000                    | 274.8                      | −3513.1                    |
| DAC Low-temperature solid sorbent | Waste heat | 360,000                      | 132.4                      | −1518.6                    |
|                                   | Heat pump  | 360,000                      | 196.6                      | −2254.6                    |

For the financial assessment, the sensitivity analysis was performed for DAC units. In Figure 8, the impact is presented, including the income resulting from the negative CO<sub>2</sub> emission credits on the low-temperature DAC installations NPV. The NPV was calculated for the DAC project lifetime amounting to 20 years. The revenue from the negative CO<sub>2</sub> emission credits as the support scenario was evaluated as EU ETS price multiplied by the change factor in a range from 0 to 6. As can be seen DAC units become economically favorable options with the EU ETS price above 147.3 EUR/tCO<sub>2</sub> and 211.5 EUR/tCO<sub>2</sub> for DAC low-temperature solid sorbent installation with waste heat and heat pump, respectively.

**Figure 8.** Sensitivity analysis for DAC low-temperature solid sorbent installations.

#### 4. Conclusions

The goal of this paper is to provide a methodology for and to assess the carbon dioxide removal technologies, taking into account the depletion of non-renewable natural resources. Thus, for this purpose, the thermo-ecological cost analysis has been adopted and performed, including analysis of the BECCS power plants and DAC units. The main findings of the presented paper are as follows:

- Thermo-ecological cost can be a suitable tool for the assessment of the burdens associated with obtaining negative CO<sub>2</sub> emissions with different technologies and processes.
- For the DAC units powered by renewable energy sources or dedicated BECCS power plants, the values of the TEC of negative CO<sub>2</sub> emissions are significantly lower for the removal than the abatement of carbon dioxide.
- The sources of energy supply (biomass/coal and electricity) significantly impact the obtained results, and in less favorable cases the CDR technologies can actually add CO<sub>2</sub> emissions to the atmosphere instead of removing it.
- The costs of CO<sub>2</sub> capture varies due to capture technology, power system, plant design, fuel properties or economic factors.
- High capital expenditures for both retrofitted power plants and DAC installations indicate that there is a need to introduce a financial support system in Poland and economic incentives to make their use more economically feasible.

The summary of the obtained ecological, economic and energy assessment results is presented in Figure 9. Applying CCS to the existing coal-fired power plants yields higher carbon intensity, thermo-ecological cost and cumulative energy consumption (CEC) per unit of CO<sub>2</sub> avoided than in bioenergy plants. The same cumulative energy consumption parameter, calculated per unit of CO<sub>2</sub> captured in DAC installation, is significantly higher due to high primary energy demand for regeneration in these systems. For all analyzed cases obtained, NPV has a negative value because of the high cost of CO<sub>2</sub> capture installation cost. However, a decrease in the investment costs is expected in view of the development and maturity of the technology.

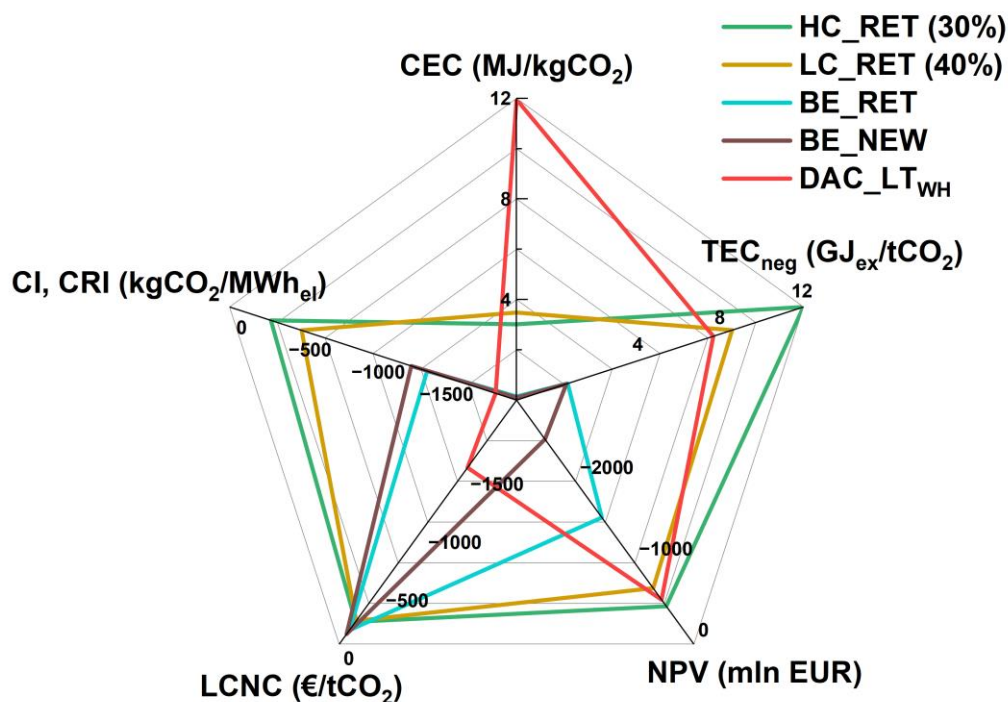


Figure 9. Summary of the analyzed cases.

**Author Contributions:** Conceptualization, P.G.; methodology, P.G., Ł.B. and M.H.; software, P.G. and M.S.; validation, P.G., Ł.B. and M.H.; formal analysis, M.H. and T.F.; investigation, P.G., M.S. and Ł.B.; resources, P.G., M.S., M.H. and T.F.; data curation, P.G., M.S. and Ł.B.; writing—original draft preparation, P.G., M.S., Ł.B., M.H. and T.F.; writing—review and editing, P.G., M.S. and T.F.; visualization, P.G. and M.S.; supervision, P.G.; project administration, P.G.; funding acquisition, P.G. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Political readiness level assessment for Poland.

| Level         | Indicator                                         | Measurement                                                                                        | Explanation/Comment                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Poland's Score |
|---------------|---------------------------------------------------|----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| Geo-political | 1. Gas connections                                | Gas interconnectors capacity/CO <sub>2</sub> emissions                                             | Higher connectivity leads to more incentives to cooperate on carbon removal. Poland emitted 227 bln cubic meters of CO <sub>2</sub> (source: Such, Piotr. “Sekwestracja CO <sub>2</sub> w Polsce nie ma sensu?!” Nafta-Gaz 76 (2020).) Gas interconnectors export capacity is 0.5 bln cubic meters in 2021 but is projected to reach 10.1 bln in early 2020s.                                                                                                                                                                                       | 0.002          |
|               | 2. Lock-in into climate policies                  | Number of climate policies implemented/number of climate treaties implemented by the top performer | Data acquired from the climate change mitigation policies and measures (PaM) database provided by the European Environment Agency. At the beginning of 2022, Poland has implemented 43 policies while leader—France—has affected 155.                                                                                                                                                                                                                                                                                                               | 0.27           |
|               | 3. Lock-in into international treaties            | Number of climate treaties ratified/number of climate treaties ratified by the top performer       | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | n.d.           |
|               | 4. Level of ambition of climate agreements        | Number of years to net zero/Number of years to net zero declared by the top performer              | The top performer here is defined as the developed country with the nearest date of achieving net zero pledged internally (in law) or internationally (submitted to international body)                                                                                                                                                                                                                                                                                                                                                             | 0              |
|               | 5. International posture regarding climate change | Net-zero year declared? y/n                                                                        | For net zero year declared country is given 1, with no such declaration being given 0.                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 0              |
|               | 6. Domestic availability of hydrocarbon resources | Hydrocarbons imports                                                                               | Higher dependency on imported hydrocarbons (oil & gas) leads to more incentives for carbon removal. Import dependency for crude oil it was 98.3%, and 77.6% for natural gas in 2018 (source: Energy statistics in 2018 and 2019 <a href="https://stat.gov.pl/files/gfx/portalinformacyjny/pl/defaultaktualnosci/5485/4/15/1/gospodarka_paliwowo-energetyczna_2018_i_2019.pdf">https://stat.gov.pl/files/gfx/portalinformacyjny/pl/defaultaktualnosci/5485/4/15/1/gospodarka_paliwowo-energetyczna_2018_i_2019.pdf</a> , accessed on 4 January 2022) | 0.88           |

Table A1. Cont.

| Level                 | Indicator                                                                                                     | Measurement                                                                          | Explanation/Comment                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Poland's Score |
|-----------------------|---------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| Domestic/<br>National | 7. Location of and access to renewable energy resources (on-/offshore wind, solar potential, hydro potential) | 1-RES potential of electricity generation                                            | Higher RES potential leads to less incentives for carbon removal. Data for Poland, 2050 from: Polish energy sector 2050   4 scenarios; <a href="https://forum-energii.eu/en/analizy/polska-energetyka-2050-4-scenariusze">https://forum-energii.eu/en/analizy/polska-energetyka-2050-4-scenariusze</a> ; renewable scenario (accessed on 4 January 2022)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 0.27           |
|                       | 8. A predictable and enduring policy environment                                                              | World Bank's GCI 4.0: Government ensuring policy stability indicator                 | World Bank's policy stability indicator is applied and scaled to fit 0–1 scale ((GCI/10) × 1.43). Data for Poland from 2019.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 0.42           |
|                       | 9. Effective and comprehensive CCS law and regulation                                                         | Number of CCS policies in force/Number of CCS policies in force of the top performer | These numbers are taken from the IEA policy database. The top performer at the end of 2021 is the UK with 19 policies in force.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 0              |
|                       | 10. Early storage site identification and site characterization                                               | CCS Storage indicator                                                                | CCS Storage indicator, divided by 10. Alternatively, the indicator might be expressed as “Identified storage capacity/CO <sub>2</sub> emissions”. However, it has been suggested that Poland's storage capacity is relatively low and could potentially cover only 3.5 year of Polish emissions (source: Such, Piotr. “Sekwestracja CO <sub>2</sub> w Polsce nie ma sensu?!” Nafta-Gaz 76 (2020).)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 0.63           |
|                       | 11. Research and development into cost reduction in CCS technologies                                          | Spending on CCS R&D projects in millions of euros/spending climate change mitigation | The cost of Poland's CCS program was assessed at the level of 624 million euro, without operating costs (from <a href="https://docplayer.pl/9230785-Budowa-instalacji-demonstracyjnej-ccs-zintegrowana-z-nowym-blokiem-858-mw-w-elektrowni-belchatow-warszawa-czerwiec-2011r.html">https://docplayer.pl/9230785-Budowa-instalacji-demonstracyjnej-ccs-zintegrowana-z-nowym-blokiem-858-mw-w-elektrowni-belchatow-warszawa-czerwiec-2011r.html</a> , accessed on 4 January 2022). 100 mln euro should be added to adjust this number to current conditions—but the project was not finally funded. Rough estimation of climate protection is made by combining pollution abatement and R&D on environmental protection for Poland in 2019 (source: <a href="https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Main_Page">https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Main_Page</a> , accessed on 4 January 2022) | 0              |

Table A1. Cont.

| Level         | Indicator                                             | Measurement                                                          | Explanation/Comment                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Poland's Score |
|---------------|-------------------------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| 12.           | Establishing a supporting scheme for CDR technologies | 1—(CCS costs/EU ETS allowance cost)                                  | CCS costs assessed for unfinished CCS Bełchatów installation from 2011 (65 euro/t from <a href="https://docplayer.pl/9230785-Budowa-instalacji-demonstracyjnej-ccs-zintegrowana-z-nowym-blokiem-858-mw-w-elektrowni-belchatow-warszawa-czerwiec-2011r.html">https://docplayer.pl/9230785-Budowa-instalacji-demonstracyjnej-ccs-zintegrowana-z-nowym-blokiem-858-mw-w-elektrowni-belchatow-warszawa-czerwiec-2011r.html</a> , accessed on 4 January 2022; would probably be lower today), EU ETS average median price in 2021 (ca. 52 eur/t) from <a href="https://afsgroup.nl/news/eu-ets-market-outlook-13-12-2021/">https://afsgroup.nl/news/eu-ets-market-outlook-13-12-2021/</a> , accessed on 4 January 2022 | −0.25          |
| 13.           | Legacy networks—electric grid                         | 1—Projected share of electricity in final energy consumption in 2050 | The legacy networks direct path dependencies. If a country is widely electrified (e.g., France), the switch to low levels of carbon is easier, hence less incentives for carbon removal. Lack of data.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                |
| 14.           | Legacy networks—gas pipelines                         | Projected share of gas in final energy consumption in 2050           | The legacy networks direct path dependencies. If there is a large domestic/consumer gas distribution network, decision makers will be hesitant to change, hence carbon removal more likely.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 0              |
| 15.           | Dependency on industries difficult to decarbonize     | Share of industry in a country's GDP                                 | dependency on industries that are difficult to decarbonize, e.g., aluminum, steelmaking, higher dependency on those leads to more incentives for carbon removal<br>source: <a href="https://databank.worldbank.org/views/reports/reportwidget.aspx?Report_Name=CountryProfile&amp;Id=b450fd57&amp;tbar=y&amp;dd=y&amp;inf=n&amp;zm=n&amp;country=POL">https://databank.worldbank.org/views/reports/reportwidget.aspx?Report_Name=CountryProfile&amp;Id=b450fd57&amp;tbar=y&amp;dd=y&amp;inf=n&amp;zm=n&amp;country=POL</a> , accessed on 22 December 2021                                                                                                                                                         | 0.28           |
| 16.           | Economic dependency on hydrocarbon industry           | Mining contribution/Country GDP                                      | Coal industry's contribution to real GDP growth in Poland in 2013. (source: Whither are you headed, Polish coal? Development prospects of the Polish hard coal mining sector <a href="https://wise-europa.eu/wp-content/uploads/2016/03/Whither-are-you-headed-Polish-coal.pdf">https://wise-europa.eu/wp-content/uploads/2016/03/Whither-are-you-headed-Polish-coal.pdf</a> , accessed on 4 January 2022                                                                                                                                                                                                                                                                                                         | −0.15          |
| 17.           | Availability of biomass                               | (PJ of biomass potentially produced/year)/(PJ tons of produced/year) | Data for biomass potentially produced (900 PJ) from Gładysz P.: Analiza techniczna możliwości redukcji emisji dwutlenku węgla z elektrowni Bełchatów. 2018, data for production of primary energy in 2019 (2528. PJ) from Energy statistics in 2018 and 2019 ( <a href="https://stat.gov.pl/download/gfx/portalinformacyjny/pl/defaultaktualnosci/5485/4/15/1/gospodarka_paliwowo-energetyczna_2018_i_2019.pdf">https://stat.gov.pl/download/gfx/portalinformacyjny/pl/defaultaktualnosci/5485/4/15/1/gospodarka_paliwowo-energetyczna_2018_i_2019.pdf</a> , accessed on 4 January 2022)                                                                                                                          | 0.35           |
| Average Score |                                                       |                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 0.159          |

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