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Human Rights and Large-Scale Carbon Dioxide Removal: Potential Limits to BECCS and DACCS Deployment

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Abstract: Negative emissions technologies (NETs) approaches are an essential part of virtually any scenario in which global warming is limited to 1.5 °C in accordance with the Paris Agreement. Discussions often focus on two technologies due to their substantial carbon dioxide (CO_2) sequestration potential: bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). However, the large-scale deployment of both technologies—especially BECCS—may lead to significant human rights infringements. This paper aims to analyze the impact of both technologies on human rights from the methodological perspective of a legal interpretation of international law. It shows that a large-scale BECCS strategy, which inevitably requires enormous land-use changes, will most likely infringe upon the right to food, the right to water, and the right to a healthy environment. In contrast, large-scale DACCS approaches will likely have a smaller human rights impact, but the energy-intensive process could also infringe upon the right to energy. Balancing these human rights with other freedom rights, e.g., of consumers and enterprises, the paper will further demonstrate that from the perspective of human rights, rapid emission reductions and the minimization of livestock farming—and also less risky nature-based options such as peatland and forest management—should prevail before any large-scale industrial NET strategies.

Keywords: BECCS; DACCS; human rights; international law; Paris Agreement; NETs; CDR; climate governance; climate mitigation

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1. Introduction

In 2015, the Paris Agreement (PA) was adopted by the parties to the United Nations Framework Convention on Climate Change (UNFCCC). It was generally viewed as a milestone since it marked the first time the parties could agree on a quantifiable and legally binding climate objective—a result that most experts had not expected [1]. According to Article 2 para. 1 PA, states must limit global warming "well below 2 °C above pre-industrial levels" and further pursue "efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". However, seven years after the states agreed on a common objective in Paris, little has happened regarding the effective reduction of greenhouse gas (GHG) emissions [2–4]. While each newly published IPCC report makes more and more urgent appeals to national and international decision-makers, the necessary mitigation goals have not yet been achieved [5–7]. The IPCC's Working Group III report from March 2022 (AR6) stated that the "[a]verage annual GHG emissions during 2010–2019 were higher than in any previous decade." [7] (p. 4). Even worse, the actual carbon budget left to keep global warming below 1.5 °C is in all likelihood smaller than the IPCC assumes due to legal arguments regarding Article 2 para. 1 of the Paris Agreement [8].

Since there has been little observable progress concerning drastic emission reductions across sectors—which are necessary to keep global warming below the legally binding 1.5 °C limit (as we have demonstrated in earlier research in accordance with court rulings [8–10])—researchers and policymakers are increasingly embracing the idea of deploying large-scale negative emissions technologies (NETs). NETs—also known as carbon dioxide removal approaches (CDR)—have risen in prominence during the past decade because they are capable of removing GHGs from the atmosphere, thereby contributing to the PA's overarching objective. The idea of capturing GHGs and durably storing them in reservoirs is not novel—the idea of using "sinks" to bind atmospheric carbon dioxide (CO_2) was already included in Article 4 para. 1 lit. d UNFCCC—although the drafters likely assumed that this would be achieved via purely nature-based approaches [11]. Almost three decades later, researchers have proposed technology-based approaches that seem enticing—such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). These are sometimes portrayed as "silver bullets" in mitigation terms [12]. Article 4 para. 1 PA likewise presumes that at least some kind of NETs will be deployed "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". The IPCC, in its AR6 III report, similarly remarks that limiting global warming to 1.5 degrees will involve NETs to some extent [7]. Although the use of these approaches will be unavoidable, it is unclear whether NET policies will focus on less-controversial approaches such as peatland and forest management [13,14] instead of large-scale industrial CDR deployment, which may conflict with international law. Building on an earlier contribution that critically dealt with geoengineering in general without analyzing BECCS and DACCS [7], this article focuses on possible human rights infringements due to large-scale BECCS and DACCS scenarios.

BECCS and DACCS are two technologies that are increasingly being included in mainstream mitigation scenarios [15]. Although both technologies are expected to significantly contribute to reaching net-zero targets within the next few decades, they are far from being deployed on a large scale [16–19]. Besides the technological and financial hurdles still to be overcome [20], large-scale industrial BECCS and DACCS deployment would also entail significant human rights risks. While the literature has discussed this issue concerning BECCS to some extent [21], the scholarship still lacks a comprehensive human rights analysis. Furthermore, DACCS has often been left out of the discussion, even though its excessive energy demand is also a potential human rights issue. This paper aims to close both gaps. First, we will facilitate a comprehensive human rights analysis involving BECCS and demonstrate how large-scale deployment would likely affect the right to food, the right to water, and the right to a healthy environment due to the externalities associated with the required land-use changes. Second, we will compare these results to the human rights implications caused by large-scale DACCS deployment, a technology that is less problematic from a human rights perspective but still poses some problems.

Our thesis is that while large-scale BECCS deployment (as foreseen by most integrated assessment model (IAM) scenarios) is likely incompatible with human rights, DACCS is less likely so—but human rights may be an important limit to its usage. Having shown in an earlier contribution that emission reductions via phasing out fossil fuels and minimizing livestock farming as well as compensations via peatland and forest management should prevail before large-scale options such as solar radiation management, we will demonstrate that these options should be prioritized before BECCS and DACCS in light of human rights, too.

2. Materials and Methods

2.1. Legal Interpretation as Methodology

Concerning our methodology, we will proceed in two steps: First, we will critically examine the literature on BECCS and DACCS and the use of NETs in general. To that end, we will outline the approaches' technological and natural scientific underpinnings and the contentious debate concerning their socio-economic impacts. Next, we will investigate the different claims made in the literature concerning the negative emissions potential of BECCS and DACCS. In that context, we will question the role that IAMs have played in the recent surge of NETs [10,22–24]. Given the centrality of IAMs for climate policy, we will scrutinize the overly optimistic scenarios regarding BECCS and DACCS. As the topic of NETs and IAMs is quite contentious among scholars and decision-makers, this section will serve as a factual backdrop for the subsequent legal analysis. We assembled the relevant literature in this section by relying on a semi-systematic literature review.

Second, we will assess potential human rights infringements resulting from large-scale BECCS and DACCS deployment. For this purpose, we start by examining the legal status of the human rights concerned before determining their protective scope. We will only review the pertinent human rights for BECCS and DACCS, respectively. The same human rights guarantees are not relevant for both BECCS and DACCS, as the deployment of each technology entails specific consequences, which are only covered by the protective scope of certain human rights. In the following step, we will demonstrate how large-scale deployment of the respective technologies may lead to infringements in the future. Since a potential infringement does not automatically lead to a violation of a given human right, we will then examine potential justifications for the infringements. We will do so by analyzing the limits that public institutions have to observe while balancing conflicting rights. The process of balancing these limits is often called the proportionality test in the legal literature, which is commonly used in some form by several international, EU and national courts [25–27]. This will involve interpreting the pertinent legal norms, most notably of various international human rights that are codified in international conventions (e.g., the International Covenant on Economic, Social and Cultural Rights, ICESCR). Other norms of international climate change law—such as the PA and the UNFCCC—are also covered in the analysis. The relevant legal norms are interpreted according to the rules specified by Article 31 of the Vienna Convention on the Law of Treaties. This means that they are interpreted according to their grammatical meaning, systematic relation to other norms, historical genesis, or object and purpose. We will primarily focus on the first two interpretative approaches (grammatical and systematic) since the other two means of interpretation are prone to several issues [27]. For instance, there is limited access to the historical material relevant for sound interpretative assumptions and there is no consistent methodology to determine the "objective" of a given norm. A legal analysis typically includes discussing relevant case-law (at least in the Anglo-Saxon legal tradition). However, there are no cases that deal with either BECCS or DACCS; hence we do not review case-law in this article.

We close the article by reflecting on the role that BECCS and DACCS might be given in a portfolio of climate mitigation measures, and how the potential risks to human rights may pose a barrier to future deployment. All findings are based on extensive research in the area of climate change and human rights in general, which has been discussed in detail elsewhere [8–10,27].

2.2. BECCS

BECCS uses biomass as an energy source while capturing the CO_2 during the combustion or conversion phase and subsequently storing it underground (CCS) or utilizing it for other purposes (CCU). These processes involve a multitude of different technologies, which is why BECCS should not be understood as a single technology but rather as a cluster of natural processes and technologies [16,28]. BECCS plants rely on either primary or secondary biomass as sources of fuel [29,30]. Primary biomass includes all organically grown material, notably first-generation (e.g., maize, wheat, soy) and second-generation energy crops (e.g., switchgrass, willow) [31]. While first-generation crops are widely utilized as a source for biofuels in many countries, their use may negatively affect food supply [32–34]. In contrast, second-generation crops are considered non-food biomass but they have failed to establish themselves on the global bioenergy market, and it is unclear whether they will replace the dominant first-generation biofuel crops [30]. In contrast to primary biomass, secondary biomass is not grown; instead, it is generated through decomposition. Although there are some advantages to secondary biomass, it is rather unrealistic to assume that animal waste could be used to generate biofuels on a commercial scale since most animal and agricultural waste will be needed for sustainable fertilizer usage in the future [30].

Even though biomass is sometimes hailed as the renewable energy with the highest potential [35], its usage comes with many disadvantages [14,30,36]. Aside from the large land-use requirements, burning biomass is not particularly energy-efficient. Moreover, the production of biofuels results in significant GHG emissions [36]. For instance, cultivating biofuel crops, such as switchgrass, on land formerly used for corn—according to some studies—would result in an increase of GHG emissions by 50 percent in the next 30 years [37]. In this context, the IPCC states in one of its reports that "the combustion of biomass generates gross GHG emissions roughly equivalent to the combustion of fossil fuels." [38] (p. 877).

After the biofuel crops are harvested and transported to the BEECS facility, the biomass will go through the process of carbon capture. There are several types of CCS technologies that have been tested in the context of CCS operations, such as pre-combustion, post-combustion, oxy-fuel combustion, and chemical looping [39–41]. To date, post-combustion technologies are most mature for a large-scale deployment [42]. Post-combustion technologies capture the CO_2 after the combustion of syngas and before emissions are released into the environment [40]. In contrast to other CCS systems, the technology can be integrated into already existing power plants without significant interruptions of the main processes [43]. It also has a higher efficiency rate of capturing CO_2 than pre-combustion or oxy-fuel-based technologies [41].

Once the CO_2 has been captured in a BECCS facility, the carbon is liquified at high pressure to prepare it for long-term storage at a geological site. Several storage options for the captured CO_2 have been proposed, such as saline aquifers [44,45], depleted oil or gas reservoirs [46,47], unmineable coal beds [42,48,49], deep ocean storage [50–53], or in-situ mineral carbonation [54–56]. To date, storage in rock formations is considered to be the most viable option for large-scale and long-term CO_2 sequestration [48,57,58]. It is estimated that a typical storage site is able to hold tens of millions of tons of CO_2 [42]. This is achieved either via chemical or mechanical means [59]. However, one crucial aspect that needs to be addressed is the identification of suitable geological formations that are safe for long-term storage. Optimistic estimates indicate that geological storage spaces in the range between 8000–15,000 gigatons (Gt) of CO_2 are available [60]. However, this storage capacity is limited by a variety of physical, technical, regulatory, environmental, and financial factors. For the most part, the development of qualified storage areas has not materialized in the past decades because of, among other things, geographic accessibility and exploration costs. This factor is not mentioned by the IPCC since its models currently do not consider the development time of geological storage space as a limiting factor. The availability and accessibility of such space could thus be overvalued [60].

Capturing CO_2, transporting it via pipelines, and storing it for an unspecified amount of time poses a serious risk of physical leakage [61,62]. Besides the detrimental impact of CO_2 leakage on global warming, the resulting consequences for affected ecosystems would be severe. Leaked CO_2 in large quantities would not only lead to a drastic loss of biodiversity in the oceans but also on the earth's surface [63–65]. While the aforementioned methods of storing CO_2 are generally regarded as safe long-term options, a completely leak-proof system may not be achievable. Studies estimate the average leakage rate at between 0.1 and 0.0001 percent of the CO_2 stored within geological formations or otherwise [66]. This is problematic because a leakage rate above 0.1 percent annually may render the use of the entire CCS process irrelevant for the purposes of combatting the climate crisis [67].

In recent years, CCU technologies have also risen in prominence and have the potential to become a promising alternative to CCS [68–70]. As a result, several plants are now employing novel ways of recycling CO_2 [71]. There are, however, some significant drawbacks regarding the usage of CO_2 in those settings. For instance, the conversion process is quite energy-intensive [72]. Moreover, the transformation of CO_2 into fuels or chemicals only leads to the temporary storage of carbon dioxide [73].

2.3. DACCS

DACCS is a technology that pursues the idea of building artificial trees. Large turbines first suck CO_2 out of the ambient air via chemical agents [74,75]. These chemical agents are later stripped from the CO_2 by applying heat so that the CO_2 can be dehydrated and compressed for subsequent geological storage or used otherwise [76,77]. Compared to other CCS technologies, the most apparent disadvantage of DACCS is that the concentration of CO_2 in the atmosphere is extremely dilute [78]. Concentrated flue gas streams from the exhausts of coal-fired, natural gas-fired, or BECCS plants contain between 4 to 12 percent of CO_2, which facilitates the capturing process [79]. Ambient air, in contrast, only has a CO_2 concentration of 0.04 percent, meaning that the technological and economic hurdles for scaling-up DACCS are much more significant—mostly due to the high energy requirements [16,80,81].

While there are several different technical approaches to DACCS, all of them are comprised of two main processes that operate cyclically: capturing the CO_2 and separating it from the chemical agent. Large fans first drive air through the air contactor unit to capture CO_2 by binding it to a liquid or solid base. The chemical agent that has captured the carbon then needs to release the concentrated CO_2 so that the base can be reused again for the capturing process [77,82,83]. This separation process requires large amounts of thermal energy—depending on the respective DACCS approach [84,85]. The separated CO_2 is subsequently dehydrated and compressed for later storage or other industrial applications [77,86].

The two major DACCS systems in usage today—high and low-temperature DACCS—come with different advantages and drawbacks. High-temperature systems have already proven to be operable at small commercial scale and rely on mature methods and inexpensive components [75,87]. However, the regeneration process of high-temperature systems is highly energy-intensive and costly [16,79]. Moreover, designs for the energy-intensive regeneration process currently utilize natural gas as a fuel to heat the kiln—effectively emitting 0.5 ton of CO_2 per ton of atmospheric CO_2 captured [81]. Since these emissions can only be partially recaptured by an additional post-combustion system, they significantly increase the price of net-captured CO_2 [77]. Hence, this approach to DACCS is likely only sustainable if it relies on renewable energy sources.

In contrast, the major advantage of low-temperature DACCS systems are their low thermal energy requirements [88]. As such, the temperature is approximately nine times lower compared to high-temperature systems and therefore allows the integration of waste heat from industrial plants [89]. Additionally, the CO_2 capture rate of solid sorbent systems is much more efficient (90 percent) than that of high-temperature plants (42 percent) [90]. However, while low-temperature systems can, in theory, be scaled-up, there are several engineering issues concerning the piping and valve design that need to be resolved [87]. Furthermore, since the underlying adsorption mechanisms are not yet fully understood, a sorbent material that could guarantee yearly capture rates at Gt scale is not yet available [87].

One salient advantage of DACCS is that—in theory—it can be utilized in a decentralized manner since it is not dependent on point source capture, as are conventional CCS plants. The potential to use DACCS in a decentralized way opens a wide range of different applications. Compared to other NET options, DACCS could, for instance, be distributed evenly among most of the globe's regions [91]. Furthermore, DACCS could also be used in remote areas where the construction of BECCS plants is not possible. Some researchers have envisioned that the technology could be utilized in urban areas by retrofitting existing air conditioning units in larger office buildings [92]. In that regard, the only limiting spatial factor relevant to DACCS is the continuous supply of renewable energy [93].

Coupling DACCS with wind or solar power appears to be another promising development avenue [94,95]. A recent study has analyzed DACCS achieving net negative emissions while being supplied by an intermittent electricity system under diverse wind and solar resource conditions [96]. The analysis indicated that DACCS' potential to be coupled with renewables can reduce the overall cost of the system—possibly making it cost-competitive to BECCS [96]. Additionally, high, and low-temperature DACCS could both profit from either solar or wind power generation. Low-temperature DACCS would be more suitable for solar power systems [97] since the power output variations in this context are shorter and more regular. Conversely, high-temperature DACCS could benefit from wind power systems due to their lower total electricity costs [96], and the fact that DACCS could be switched on quickly as soon as there is excess energy provided by the wind turbines [98].

The prospect of powering DACCS plants with renewable energy sources could also enable the coupling with Power-to-X (PtX) systems [99], thereby establishing a closed carbon loop system that would continuously remove CO_2 from the air and produce carbon-free synthetic fuels [100]. However, such a system would likely require additional seasonal high-capacity storage units [101], which somewhat contradicts the decentralized DACCS approach and implicate a host of different environmental trade-offs [93]. The question of whether such coupled systems are indeed economically feasible and can be scaled up will most likely hinge on future trends of the electricity price [102]. The cost of capturing and storing CO_2, in contrast, will most likely play a minor role. It follows that such coupled facilities are therefore likely to emerge in regions particularly suited to renewable energy generation.

2.4. Carbon Removal Potential and IAMs

Both BECCS and DACCS are featured in virtually any mainstream climate mitigation strategy (that refuses to deal with non-technological options such as behavioral change and political constraints [27,103,104]) with varying projections concerning their CO_2 removal potential. For instance, the scenarios concerning BECCS' cumulative contribution to net negative emissions range between 0 and 1190 $GtCO_2$ [105]. In its 2022 Working Group III report, the IPCC estimated that BECCS is expected to sequester 0.5–11.3 $GtCO_2$ annually by 2050, and 334 $GtCO_2$ cumulatively by 2100 [7]. In contrast, DACCS is expected to sequester less CO_2 than BECCS. This is not too surprising because BECCS has the advantage that it does not require constant high energy inputs to capture CO_2 [43]. However, the IPCC, in the aforementioned report, has increased the role of DACCS in the overall NET portfolio [7]. Optimistic estimates have suggested that DACCS plants could sequester somewhere between 10–40 $GtCO_2$ per annum in 2100 [106]. More recent and comprehensive scholarship puts DACCS' sequestration potential between 0.5–5 $GtCO_2$ annually by 2050 [16].

The projections concerning the NET potential of the two technologies are based on the scenarios calculated by IAMs. IAMs are modelling systems that aim to represent human interactions with the earth's environment [107]. However, the term "integrated" obscures the fact that that they are often focused on cost-benefit analyses, which faces various severe objections [10,108]. IAMs are first and foremost an expression of mainstream economic theory, which assumes that systems need to achieve a market equilibrium [109]. The climate system, however, is never in equilibrium due to its complex interactions and sudden bifurcations [110]. As a result, IAMs fail to adequately express the complexity of dynamic system interactions [111–114]. Furthermore, IAMs have preferred NETs in general and BECCS specifically as mitigation measures over deep emission cuts due to two reasons: their ostensible economic advantage and the discount rates used in the current scenarios [115,116]. The argument goes that, since IAMs are based on a variety of economic assumptions, they are inherently cost-optimizing [23]. IAMs therefore prefer pathways that are less cost-intensive and reach the same level of net negative emissions compared to other decarbonization strategies [117]. IAMs specifically favor BECCS because it is the only NET that produces energy as well as sequestering CO_2. Certain IAMs even project that large-scale BECCS is cheaper than reducing residual emissions due to the relatively high discount rates applied to the technology [118]. This explains in part why BECCS remains the favored NET, with around 61 percent of the largest emitting countries committing themselves to employing BECCS in the near or long-term future [116]. However, discounting future costs and benefits faces strong legal and ethical objections [108].

Furthermore, the IAMs are based on a plethora of optimistic empirical assumptions that will likely not hold true, e.g., the possibility of infinite growth in a physically limited world [108,113,119,120]. The risk that a massive scale-up of NETs in the second half of the century might fail is not factored into the IAMs [121]. The possibility that large-scale NET deployment—specifically DACCS—could restrict the global energy supply is likewise omitted [115]. IAMs also do not price in inevitable temperature increases, which could make it more difficult to grow bioenergy crops [122]. In addition, some of the underlying assumptions on the costs of renewable energy sources—which have fallen during the last decade—have not been updated, which in turn skews the projected pathways [23]. BECCS and DACCS are thus likely to be much more costly and less effective than the IAMs currently project.

3. Results: Human Rights Analysis

To date, there are no specific international treaties or regimes that regulate the entire BECCS and DACCS life cycle. Instead, there are different international treaties governing some part of the technologies or their supply chains, each with their own different regulatory approaches and jurisdictions. For instance, the contracting parties to the London Convention and London Protocol (LC/LP) have tackled the issue of CO_2 underwater storage and its potential repercussions for the marine environment [123–125]. However, under Article 1 LP, the Protocol binds only its member states and only applies to offshore platforms, vessels, and aircraft. Hence, only a fairly small part of the BECCS and DACCS process would actually be regulated by the LC/LP. This regulatory approach exemplifies why the question of whether large-scale BECCS and DACCS employment is compatible with international law remains very challenging at the moment. There is only a patchwork of incomplete provisions, each of which has varying degrees of validity in different jurisdictions.

Therefore, the present contribution focuses on human rights which serve as framework for all legislation and legal practice on the constitutional level of a given jurisdiction. Given the international focus of this article, we do not analyze national and EU law, but human rights guarantees in international law. Before examining the specific human rights guarantees that will be affected by BECCS and DACCS, it will be necessary to explore the conceptual and dogmatic underpinnings of human and fundamental rights and how they relate to climate change, and mitigation measures.

The overall normative framework of climate change and climate protection is about balancing different spheres of freedom and the elementary preconditions of freedom—the core values of liberal-democratic constitutions represented in human rights [27]. This balancing situation is, on the one hand, about the freedom of consumers and enterprises on a global scale. On the other hand, it concerns the right to life, health, and subsistence as elementary preconditions of freedom [27], including the rights of future generations and people in other countries who did little to contribute to global warming but will suffer its worst consequences. This balancing situation gives substantial political leeway to democratic majorities. But where does this leeway end? Put differently: What exactly are the relevant encroachments of human rights and what are the balancing rules that mark the limits to this leeway? And what does the temperature objective in Article 2 para. 1 PA to keep global warming well below 2 degrees Celsius and to pursue efforts to stay below 1.5 degrees contribute to this debate? In earlier contributions—and by initiating on this basis the arguably most far-reaching ruling on climate change by a constitutional court worldwide, the verdict of the German Federal Constitutional Court in 2021 [8,27,126,127]—we have shown that human rights to freedom and the elementary preconditions of freedom also apply on an intertemporal and cross-border scale and contain a precautionary dimension. Having shown on this fundament in an earlier contribution that there is a human rights-based obligation to protect the climate and that emission reductions via phasing out fossil fuels and minimizing livestock farming, as well as compensations via peatland and forest management, prevail before large-scale options such as solar radiation management [8,10], we will discuss in the following sections whether these options should be prioritized before BECCS and DACCS in light of human rights and, also, Article 2 para. 1 PA.

3.1. BECCS and Human Rights

Scaling up BECCS to the extent projected by the models will inevitably cause environmental and social effects. Over the past two decades, we have seen the impact of increased bioenergy production on food security [30,128]. If BECCS is to have the most prominent position among the different NETs currently available, it will likely have a more significant impact on human rights than the initial scale-up of biofuel production. The following section will deal with the particular human rights affected by large-scale BECCS. Following the framework presented at the beginning of this section, each of these rights is essential for protecting elementary preconditions of freedom [27].

The following legal analysis will first examine the legal status of the human rights in question in the international law debate before determining the protective scope of the respective rights. In the next step, we will show how large-scale BECCS will likely infringe upon specific human rights. Finally, we will examine whether there are possible justifications for the infringements.

3.1.1. The Right to Food

The human right to food, at its core, encompasses the right to feed oneself as a vital basis of human autonomy and freedom [129,130]. As early as 1948, the right to food was included in Article 25 of the Universal Declaration of Human Rights (UDHR) as part of the right to an adequate standard of living. Although the UDHR itself is neither binding nor part of customary international law [131], it nonetheless has had a substantial influence on the establishment of successive human rights regimes [132]. Since then, several binding instruments of international law have recognized the right to food, most prominently the International Covenant on Economic, Social and Cultural Rights (ICESCR). Under Article 11 para. 1 ICESCR, contracting states recognize "the right of everyone to an adequate standard of living for himself and his family, including adequate food, clothing and housing, and to the continuous improvement of living conditions."

During recent decades, treaty bodies have increasingly given the right to food more substantive contours by issuing relevant reports and comments [133]. In 1999, the Committee on Economic, Social and Cultural Rights (CESCR)—the independent body that monitors the implementation of the ICESCR—issued its "General Comment No. 12 on the Right to Adequate Food" [134]. CESCR comments do not contain legally binding rules. They are nonetheless essential for interpretating the protective scope of the respective rights [135–137]. The General Comment clarifies that since the right to food is essential for human dignity (respectively, autonomy) and the fulfillment of all other human rights, the content of Article 11 para. 1 must be interpreted broadly [134].

Article 11 para. 2 ICESCR further establishes that states must actively ensure that "the fundamental right to freedom from hunger and malnutrition" is guaranteed by adopting effective measures. Consequently, the broad interpretation of Article 11 does not just mean that contracting states must provide a minimum number of calories or nutrients to each person to ensure survival [134]. The minimum subsistence level would admittedly be difficult to ascertain in each situation [129]. Rather, the substantive content of the right to food should be interpreted progressively, meaning that the right is realized when every individual has physical and economic access to adequate food or means for its procurement at all times [134]. Physical access is provided when adequate food is available for every person and every group. Economic access, in contrast, requires that the food prices are not prohibitively high so that the purchase of other essential items is prevented [134].

To assess the possible impact of BECCS on the human right to food, we first have to consider how much the technology would need to be scaled up to limit the rise of the global mean temperatures to 1.5 °C as prescribed by Article 2 para. 1 PA. According to model projections, to limit global warming to 1.5 °C, the conversion of roughly 380–700 million hectares of land area to biofuel crops could be required [105,106,138,139]. This would require the conversion of 7–25 percent of the world's agricultural land and 25–46 percent of arable and permanent cropland by 2100 [106,138]. The increasing demand for suitable agricultural land would in all likelihood pose a threat to food security in many regions [32]. For instance, food prices could rise by 110 percent by 2100 due land-use change for BECCS crops [140]. Even disregarding this argument, the claim that sufficient farmland would be available for large-scale BECCS deployment must be seriously doubted [141,142]. In this sense, the myth of "empty lands" appears to be still widespread among optimistic policymakers [141].

Considering the predictions just outlined, it is likely that a large-scale BECCS deployment would result in violations of the right to food [143]. The right to food encompasses three different state obligations—the obligation to respect, protect, and fulfil—which are an expression of the multipolarity of human rights (which means that public authorities have to respect human rights but also have to protect humans against their fellow citizens). A large-scale BECCS policy will not necessarily impact all three obligations. According to General Comment No. 12, a violation of Article 11 ICESCR would occur "when a State fails to ensure the satisfaction of, at the very least, the minimum essential level required to be free from hunger" [134] (p. 7). When considering BECCS and its potential impact on food security, the possible violation of the obligation to protect and fulfill the right to food become most apparent. The obligation to protect, for example, could be curtailed when a contracting state aggressively subsidizes the cultivation of biofuel crops as part of its nationally determined contribution (NDC). Farmers would then be incentivized to abandon cultivating food crops in favor of biofuel crops. As a result, the direct food supply could be endangered or food prices might rise significantly. If the state in question is then unwilling or unable to provide for its citizens, a violation of the obligation to protect pursuant to Article 11 ICESCR would arise. In sum, infringements of the obligations to protect and to fulfill under Article 11 ICESCR appear to be highly likely if BECCS deployment is pursued at the levels currently envisaged by the IPCC [144].

3.1.2. The Right to Water

Like the right to food, the right to water is one of the central preconditions for freedom that are currently being threatened by worsening climate change [27]. Implicit in the human right to water is the acknowledgment that the provision of safe drinking water is a prerequisite for every individual's life. From a legal standpoint, this right has been recognized, either directly or implicitly, in several human rights treaties, non-binding declarations, and domestic constitutions [145]. For instance, even though the ICESCR makes no express mention of a right to water, it nonetheless forms part of the overall right to an adequate standard of living. As such, it is inextricably related to the rights to health, housing, and food under Article 11 para. 1 and Article 12 para. 1 ICESCR [146]. Consequently, the CESCR clarified in its "General Comment No. 15 on the Right to Water" that the rights listed in Article 11 para. 1 ICESCR were not intended to be exhaustive [147]. Since water is essential for maintaining an adequate standard of living and is non-substitutable [148], the human right to water is thus said to be contained in Article 11 para. 1 ICESCR [145].

According to the 2002 CESCR General Comment, the right to water "entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses" [147] (p. 1). The preconditions for the fulfillment of the right to water consist of two core elements: safe drinking water and the access to it. The notion of safe drinking water relates to the quality that is required for personal or domestic use. This means the water that is provided needs to be free of chemical waste or harmful micro-organisms that could harm an individual's health [147]. Access to water concerns the availability of the resource. In this regard, the state has an obligation to provide water to all individuals in an equal and non-discriminatory way, irrespective of their physical, social, or economic circumstances [146].

A rapid scale-up of BECCS could infringe upon the right to water by rapidly increasing the demand for water in the agricultural sector, which would likely result in increased competition for freshwater supply [149]. At present, approximately 70 percent of total water consumption worldwide is used for cultivating farmland [150]. Since large-scale BECCS requires a substantial expansion of arable land, the aggregated water footprint of BECCS will be tremendous [151]. Stenzel and colleagues concluded, for example, that a stringent BECCS scenario would induce more competition for water than the total estimated impact of climate change [152]. Excluding any large-scale BECCS scenarios, the price of water is already expected to rise by around 20 to 30 percent by 2050 [153]. This increase in water prices is expected to disproportionately affect countries of the Global South, which are the most vulnerable to water scarcity [154]. Besides the adverse impact on water demand and prices, large-scale BECCS use also requires large amounts of fertilizers [155]. Extensively applying fertilizers to increase yields could likely impact the local freshwater quality [156].

If we consider the overall potential impact that BECSS could have on the quality and delivery of water, then a possible violation of the right to water is not an unlikely scenario. As in the case of the right to food, the right to water implies three different state obligations. A potential violation would be likely as regards the obligations to protect and fulfill the right to water. An infringement of the obligation to protect is possible because private actors around the world are increasingly supplying freshwater. Research has shown that pro-biofuel policies that were aimed at achieving a smaller carbon footprint have had a significant impact on the overall usage and quality of water since they incentivize private actors to grow biofuel crops [157]. For instance, consider the example of the United States' Renewable Fuel Standard, which led to an increase in biofuel demand in the U.S. market [158]. Since most of the biofuel supply comes from outside the U.S.—particularly Central and South America countries—the water footprint of such policies primarily affects those exporting countries [159]. After the Renewable Fuel Standard was introduced, land use in several of these countries shifted to sugarcane which had a detrimental impact on freshwater supply [159]. An infringement of the right to water by the U.S. on individuals living outside its jurisdictions is thus highly likely if similar policies were to be introduced to support large-scale BECCS.

3.1.3. The Right to a Healthy Environment

Explicitly linking human rights and the environment under the notion of a "right to a healthy environment" is a relatively new development [160], even though the interdependence between human wellbeing and ecosystems has been thoroughly studied [161]. Previously, states were reluctant to accept a novel right that protects against environmental harms [162] and instead assumed that the human right to health would be the principal legal boundary against the rapidly accelerating degradation of ecosystems [21]. However, more recent scholarship and resolutions by UN bodies such as the UN Environment Programme (UNEP) and the Office of the UN High Commissioner for Human Rights (OHCHR) posit that biodiversity is not only indirectly protected by the right to health but is also closely related to a number of additional human rights guarantees [163]. These include, among other things, the right to health, the right to food, the right to water, the rights of indigenous peoples and other natural-resource-dependent communities, the rights of women, and the rights of children [164,165]. As a result, the right to a healthy environment should be understood as an overarching human right that is derived from the specific human rights guarantees that have been established under international treaty or customary law [161]. An action or omission by a state that results in biodiversity and habitat loss and that at the same time infringes upon one of the aforementioned human rights guarantees of an individual may also be regarded as a violation of the right to a healthy environment. This line of reasoning—which involves coupling the right to a healthy environment with related rights—has been increasingly invoked in climate litigation cases and appears to have contributed to several successful judgments [166].

The overarching understanding of the right to a healthy environment was explicitly confirmed by the UNHRC in 2021 when it recognized "the right to a clean, healthy and sustainable environment as a human right that is important for the enjoyment of human rights" and "that the right to a clean, healthy and sustainable environment is related to other rights and existing international law" [167]. In July 2022, the UNGA likewise declared that the right to a clean, healthy and sustainable environment constitutes a human right [168]. While these resolutions are not legally binding, it is the first time that an international treaty body has officially acknowledged the human right to a healthy environment [160]. These resolutions could be a template for later binding treaties, they could be used as evidence for emerging customary norms, or they could be codified in domestic constitutions [164].

Before assessing whether a rapid expansion of BECCS may violate the right to a healthy environment, it is necessary to examine how the technology may affect natural living conditions such as biodiversity. BECCS' principal impact on biodiversity is due to terrestrial land-use change [14,30]. To date, agriculture-related activities are responsible for about 70 percent of global biodiversity loss, making agriculture by far the most significant contributor [169,170]. It is likely that a large portion of biofuel crops will be grown using monocultural methods, which would rapidly exacerbate biodiversity loss [171]. In addition, many biofuel crops grown in monocultures require extensive pesticide and herbicide application—a practice that results in soil degradation, pest vulnerability, and a decrease in genetic variety [172,173]. Accordingly, a recent study demonstrated that mitigation strategies focusing on BECCS deployment would likely be worse for biodiversity than a business-as-usual scenario, where GHG emissions would more or less remain at constant levels [174].

If we consider the possible infringements of the obligations to protect and fulfill in the case of the right to food and water as evaluated above, an infringement of the overarching right to a healthy environment seems highly likely if large-scale BECCS is pursued. A possible violation would become even more salient because large-scale BECCS may have a more negative impact on biodiversity than an unmitigated climate change strategy.

3.1.4. Justification and Balancing of Conflicting Human Rights

Pursuing large-scale BECCS at the scale envisioned by the IPCC scenarios will most likely result in infringements on the right to food, the right to water, and the right to a healthy environment. However, an infringement does not automatically result in a violation. Competing human rights may justify future infringements of BECCS on the four human rights presently discussed. In order to examine the leeway of international, EU, and national legislation, we will discuss the typical limits to legislatory balancing. They are very often bundled under the roof of a so-called proportionality test, for example, by the European Court of Justice (of the EU), the European Court of Human Rights, and various constitutional courts. First, we will identify a legitimate aim that justifies having a large-scale BECCS policy. Next, we will check whether the measure is adequate to achieve the desired goal; whether it is necessary to achieve the desired goal; and whether the measure imposes an excessive burden disproportionate in relation to the desired goal [26,27,175]. If any of these balancing limits is violated, the measure would ultimately be illegal. Thus, there would be no appropriate justification for the interference. Consequently, the interference would also constitute a violation of human rights.

The first element of the proportionality tests involves identifying the policy's legitimate aim [176]. In this context, we should ask "whether there are any interests that are candidates for justifying the interference in the sense that it is not entirely implausible that they will at least be rationally connected to the policy" [177] (p. 712). Concerning a large-scale BECCS policy, it is not implausible to assume that generating negative emissions to combat global warming may serve as a justification for infringements of the relevant human rights.

The policy in question must also—as the second step of the proportionality test—be adequate, i.e., there must be a rational connection between the infringement on the rights and the legitimate goal [175]. Establishing the "adequacy" of a policy enables us to examine whether the infringed upon rights and the legitimate aim actually clash [177]. If the policy is unable to achieve the legitimate aim, there is no need to balance conflicting rights—simply because there is no conflict.

Adequacy in technical terms means that the policy must help achieve the objective. In the present case, a large-scale BECCS policy would have to contribute to limiting global warming as prescribed by Article 2 para. 1 PA to some extent, however small. According to Article 4 para. 1 PA, to achieve the objective set out in Article 2 para. 1 PA, states must reduce their emissions and "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases". The Paris Agreement thus sees the possibility of using sinks—which also includes NETs—as instruments to combat climate change. A state-adopted policy of large-scale BECCS may then—in theory—contribute to the objective of Article 2 para. 1 PA and in turn ensure the continued existence of the elementary preconditions of freedom. At this point of the proportionality test, it is not yet necessary to provide full evidence that the policy pursued can indeed achieve the intended goal effectively. It will instead suffice to assume prima facie that BECCS can contribute to achieving the legitimate aim. In this sense, note that there is a broad scientific consensus that BECCS—in principle—can generate negative emissions under certain conditions [16,178]. Consequently, the policy may be considered adequate.

As a third step of the proportionality test, a policy of large-scale BECCS must be necessary with regard to the objective. In this sense, a policy is necessary if there are no other courses of action that are less intrusive on the rights in question and equally effective [179]. Thus, it is insufficient to consider the degree to which the policy in question may achieve the purported goal; we must also inquire into possible policy alternatives [180].

On current evidence, it is highly unlikely that BECCS will remove as much as carbon dioxide as predicted by the climate models [181–183]. There are several caveats and deficiencies related to the technology that remain unaddressed. First, it is uncertain whether there will be sufficient biomass or land area for feedstock growth for large-scale BECCS deployment. Recent estimates indicate that much less land would be available for BECCS than previously assumed [184]. The IEA has projected that 5 Gt of biomass could be used each year to produce approximately 100 EJ by 2050 [185]. If stringent sustainability criteria were applied, however, it is realistic to assume that this number will shrink to 40–60 EJ per year [186]. At the same time, the EU estimates that biomass demand in the power sector will double by 2050, which will exacerbate the growing gap between biomass supply and demand [187]. Competing utilization pathways for biomass, such as timber, pulp and paper, bioplastics, and biofuels for aviation alone will require 65 EJ each year, leaving little room for BECCS usage [186]. Additional biomass could only be cultivated through significant land-use changes—which would run counter to the objectives of Article 2 para. 1 PA and the Convention on Biological Diversity (CBD). Moreover, it is doubtful whether states would redesignate vast swaths of land to cultivate biofuel crops without endangering food security [141]. One must be also cognizant of the fact that the available arable land will likely sink in size due to the effects of global warming [188]. Arable land must be treated as a scarce resource and biofuel crops are a relatively inefficient use of land—they are 50 to 100 times less efficient than wind or solar [142], and 10 times less efficient than DACCS [186].

Second, upscaling BECCS would lead to a sharp increase in supply chain emissions, stemming from land-use changes, growing, harvesting, and transporting biomass, energy conversion processes, constructing and operating the CCS infrastructure, and transporting and storing the captured CO_2 [183,189,190]. Each step of the BECCS process involves emitting significant quantities of GHGs, which are rarely factored into IAMs. According to the European Academies Science Advisory Council (EASAC), supply chain emissions due to cultivating, drying, and transporting the biomass coupled with the high energy demand of the CCS process and the incomplete CO_2 capture rate "substantially reduce the carbon efficiency of the whole system" [181] (p. 10). Even for dedicated biofuel crops with low carbon payback periods, supply chain emissions stemming from growing, processing, and transporting the biomass are greater than the CO_2 captured in a BECCS facility [191]. If we factor in other supply chains emissions currently not fully accounted for—e.g., foregone sequestration, infrastructure, CO_2 transport, and disposal—large-scale BECCS could result in generating positive emissions [190]. This could put the adequacy of the entire policy in question [192].

Third, using biomass as a fuel in the BECCS process results in significant carbon payback periods, i.e., the amount of time necessary until one BECCS life cycle becomes carbon neutral [116,181,193]. Compared to other renewables, such as solar or wind power, which have a carbon payback period ranging between months and years [194,195], BECCS only becomes carbon neutral after many decades or even centuries—depending on the type of biomass involved [193]. Reducing the accumulation of carbon debt and achieving shorter carbon payback periods by relying on short rotation coppice could, in theory, could be feasible [196]. However, these energy crops alone will not suffice to cover the estimated biomass demand that is necessary to sequester 5 $GtCO_2$ by 2050 [116]. Avoiding long carbon payback periods by solely employing short rotation coppice is only possible if existing croplands are significantly expanded, which is not viable without endangering food security and biodiversity.

Fourth, the parasitic energy load of CCS systems could undermine a sustainable BECCS strategy. Capturing, separating, and storing the CO_2 requires an extensive amount of energy—the so-called parasitic energy load [197]. BECCS is viewed as a silver bullet by policymakers because it is the only technology that can capture carbon while also producing energy [115]. However, recent evidence suggests that BECCS plants will likely generate relatively little net energy [198] and may even need additional power to capture carbon [199]. Future innovations may alleviate the parasitic load of the CCS systems. However, the BECCS process will always involve a trade-off between the carbon capture rate and the energy output [116]. If BECCS plants are expected to provide 14–20 percent of the global energy supply—as is suggested by some researchers—their ability to capture carbon will be significantly diminished [200].

Fifth, the technology is presently still far from being used on a large scale [201]. While some countries have committed themselves to using BECCS plants to achieve their nationally determined contributions under Article 4 PA, there is a significant implementation gap [202]. For BECCS plants to remove 2.5 $GtCO_2$ from the air in 2050, an adequate CCS infrastructure should already be in place or at least in the planning stage. Yet, there are only a small number of existing or planned BECCS facilities [203,204]. The development of all CCS projects has also been sluggish during the last decade, because some technological challenges—such as storage uncertainty, costs, and missing infrastructure—have remained unaddressed [19,205]. Governments and companies have been reluctant to make large investments in CCS to solve these challenges because of the enormous risks involved [206] and the availability of more effective alternatives such as solar or wind. Hence, every year that passes without BECCS being deployed in a significant way increases the expected cost of the technology while simultaneously decreasing the likelihood that the CO_2 removal targets can be met [207,208].

In sum, the effectiveness of BECCS in capturing CO_2 is highly uncertain. There is even a distinct possibility that net emissions would rise if BECCS were to be rapidly scaled up. Whether a BECCS measure is still necessary depends on what alternatives are available that are less harmful to human rights, and at the same time, effectively counteract climate change. In the following, we will compare two salient policy alternatives to large-scale BECCS deployment, namely fossil fuel reductions and animal husbandry minimization.

Although states have struggled to reduce GHG emissions, they are aware that phasing out fossil fuel and reducing livestock farming are the most effective climate policy options currently available [9,10,170]. Fossil-fuel-related emissions account for more than two-thirds of global GHG emissions [105]. Phasing out fossil fuels, however, will not be enough since the global food system accounts for approximately 30 percent of total GHG emissions [209]. Adjusting our dietary habits will also be necessary. Limiting global warming to

1.5 °C thus can only be achieved if states pursue both strategies in tandem [170,209]. For the purposes of the present proportionality test, both policies can nevertheless be classified as effective measures individually.

Despite the overwhelming evidence concerning the effectiveness of emission reductions, states and businesses are still pursuing large-scale fossil fuel projects [210]. The practice of livestock farming has likewise expanded during the past decade [7]. One could argue that these policy options are unrealistic because the implementation would be too onerous for most of the global population [211]. This argument, however, warrants closer attention since we must closely examine which rights would be infringed upon and to what extent. It is clear that the reduction of GHG emissions implies that states (and especially countries of the Global North) need to reduce current levels of production and consumption. This will inevitably lead to an infringement of some human rights. More profound changes to our current way of living (e.g., frugality) [27] will also be necessary, which is why policymakers view the phaseout of fossil fuel and livestock farming as particularly onerous on society at large [212]. However, it is less clear that these reductions would likewise impact the human rights that we have considered in the present analysis, and which are regarded as elementary preconditions for freedom. For example, minimizing livestock farming would mean that most people would need to switch to a more plant-based diet. Such a policy would not constitute an infringement because the right to food does not guarantee access to an animal-based diet. In fact, drastically reducing livestock farming and repurposing the land for food crop cultivation would improve food security in the long term since livestock farming uses nearly 83 percent of all agricultural land but produces only about 18 percent of total caloric output [213]. The two policies are therefore less intrusive on the relevant human rights. At least some courts and scholars even see a human rights-based obligation to protect the climate and to cut down fossil and livestock emissions, as mentioned earlier [8,27,126,127].

A strategy centering on reducing fossil fuel emissions would have another advantage over a strategy focused on large-scale BECCS, namely that would contribute to protecting public health. Bear in mind that states intend to use BECCS to achieve the goal of net-zero, i.e., that negative emissions will someday cancel out residual GHG emissions. The net-zero paradigm, however, overlooks the fact that continued fossil fuel emissions will have harmful effects on public health even if all emissions are compensated for by NETs [214]. According to a recent study by Vohra and colleagues, the burning of fossil fuels results in 10.2 million annual premature deaths [215]. Thus, air pollution due to fossil fuel combustion may be considered an infringement on the right to health, which is codified under Article 12 para 1 ICESCR [216]. General Comment 14 of the CESCR has further clarified that states party to the Convention have an obligation to adopt measures with a view to "reducing and eliminating pollution of air, water and soil, including pollution by heavy metals such as lead from gasoline" [217] (p. 13). The drawdown of fossil fuels would in turn support the fulfillment of this human right, which is an elementary precondition of freedom.

Some scholars have posited in a recent study that the large-scale deployment of NETs may also benefit public health in the long term [218]. They argue that "DACCS and BECCS could preserve a substantial number of years of healthy life, [. . .] with Africa and Asia benefiting the most from CDR because of the avoided risk of undernutrition and malaria." [218] (p. 2). Since BECCS and other NETs are theoretically capable of mitigating global warming, their large-scale use could help to protect soils from further deteriorating as a result of climate change. A large-scale BECCS policy—depending on the biomass source—ostensibly has several health co-benefits and may therefore also ensure the sustained existence of the elementary preconditions for freedom. However, this line of thought is based on the flawed premise that we must either pursue a strategy of large-scale NET deployment or follow the business-as-usual trajectory of unmitigated climate change. The authors of the aforementioned study do not consider an alternative climate policy involving emission reductions or nature-based solutions in their analysis, which would be both more effective on less onerous on human rights [9,13]. While it may be true that a large-scale BECCS strategy could alleviate some of the worst effects of climate change, which in in turn would benefit public health, the harmful implications of the measure undermine its suitability as a human rights-friendly policy altogether.

Reducing emissions by phasing out fossil fuels and minimizing livestock farming thus can be regarded as effective measures that are likewise less impactful on the relevant human rights. NETs will remain necessary if one assumes a very small remaining GHG budget. In this respect, however, forest and peatland management are available as more appropriate measures: unlike BECCS, they are not associated with an increase in the various ecological problems of agriculture and can protect biodiversity and the climate (provided that this does not entail monocultural afforestation) [13,14]. Other more suitable policies further include the renaturation of ecosystems, organic farming practices, frugality, and sustainable consumption and nutrition. It is, however, crucial to point out that the aforementioned fields of actions have mostly been neglected by IPCC scenarios, due to their focus on technological CDR and demand-side measures [8,10,127,182].

3.2. DACCS and Human Rights

As in the case of BECCS, there are no specific provisions of international law governing the entire process of large-scale DACCS deployment at the moment. International human rights guarantees are therefore an appropriate framework to examine whether there should be legal limits to future large-scale DACCS use.

3.2.1. The Right to Energy

Although even a cursory analysis of potential human rights interferences due to large-scale DACCS will likely find that the technology poses a low risk compared to BECCS, there are several pertinent questions that researchers have seldom addressed. First, the question of the incessant energy demand of DACCS plants raises the issue of whether there is a human right to energy—respectively, a right to a secure supply of energy—that likewise forms an elementary precondition of freedom. Second, if such a right exists today, we should pose the question of whether large-scale DACCS—as envisioned by the IPCC—is still compatible with the respective human rights guarantees or if states should instead pursue alternative mitigation options.

The excessive energy quantities required for DACCS not only hinder the dissemination of the technology but may also infringe on the emergent right to energy. Access to energy is crucial for meeting the basic needs of individuals around the world [219,220]. Without steady and reliable access to energy, it would be impossible to maintain agricultural activities, food preparation, and a modern health care system at current levels [185,220,221]. In addition, the access to energy is correlated with an increase in living standards [222–225], which in turn serves to fulfill a host of related human rights—specifically the rights codified in Articles 11 and 12 ICESCR [226,227]. Previous efforts to provide access to energy have been especially beneficial for the most vulnerable populations living below the poverty threshold [228]. For them, having access to modern energy services is one of the most effective and inexpensive means of overcoming extreme poverty [228].

Although all people's livelihoods depend on services that are powered by energy, scholars have been reluctant to recognize access to energy as a classical subsistence right that is comparable to access to food, unpolluted air and water, or an adequate shelter [27]. Access to energy or electricity is not enumerated in the pertinent human rights conventions as one of the rights that is essential for human well-being. This is correct in the sense that access to energy or electricity is not biologically necessary for survival. While electricity may be substituted in many cases, access to food or water is indispensable. However, the focus on biological needs in the discourse surrounding basic subsistence rights is too narrow—especially in the case of climate change [229]. Elementary preconditions for freedom do not only apply to life and health because freedom implies more than human survival [27]. Strictly linking freedom with basic subsistence rights undermines human autonomy, which is the central tenet of the liberal conception of freedom [27].

In the context of the climate crisis, it may also be argued that access to energy is, in many cases, essential for survival. First, current agricultural practices rely to a large extent on energy-driven equipment to produce sufficient yields [221,230]. Consequently, access to energy enables reliable access to food. Second, access to electricity may be necessary to withstand the extreme weather events and heat waves that are expected to occur regularly in the coming decades [231]. Heat waves increase the prevalence of cardiovascular and respiratory diseases and also the risk of death due to heat stress [232,233]. This is especially problematic because heat waves disproportionately affect poorer countries that emit a comparatively small amount of GHGs per capita. In such countries, the population usually lives in homes without air conditioning [234]. The 2022 heat wave in India and Pakistan, where temperatures above 45 °C occurred over a sustained period of time, may serve as an example. Experts have estimated that hundreds of people died as a direct result of the increased temperatures and lack of air conditioning [235]. Some commentators have started to advocate for a human right to air conditioning in the climate crisis [236,237]. These assertions underline the growing importance of access to energy and human well-being. We can therefore assume for the present analysis that access to energy may be considered an elementary precondition of freedom.

If we assume that a right to energy exists and is justiciable, we still need to address the question of what such a right should entail. Since energy usage is an elementary precondition of freedom, it follows that a right to energy should, in the first instance, entail access to energy in order to meet primary needs, such as cooking, refrigeration, and air conditioning. Energy must also be accessible in a way that is regular, safe, affordable, efficient, sufficient, and without discrimination [238]. The "adequate standard of living" under Article 11 para. 1 ICESCR—while ultimately a vague concept—may serve as a rough yardstick to ascertain what may be considered sufficient access to energy in a given situation. It follows that in order to guarantee an "adequate standard of living", the right to energy should primarily afford access to the 790 million persons currently living without electricity access [185]. The German Federal Constitutional Court has supported all this in 2021 in its landmark climate ruling by pointing out that freedom without energy is hardly possible [239].

A large-scale policy focused on DACCS could infringe on the right to energy in the future if the technology's excessive energy demand issue is not addressed. Optimistic scenarios project that DACCS may sequester 5–40 $GtCO_2$ per annum [240]. If we assume that DACCS will remove 30 $GtCO_2$—which would be in line with climate limits under Article 2 para. 1 PA—high-temperature DACCS systems would need 13.1 TW, which is more than half of the annual global energy supply [241]. Solely relying on low-temperature DACCS systems, which are more energy-efficient, would still consume about 20 percent of the annual global energy supply [242]. Hanna and colleagues likewise estimate that DACCS could require 14 percent of global electricity output and up to 83 of global gas usage [243]. If states embrace such a large-scale DACCS strategy, it would hence imply using roughly 10–50 percent of the global energy supply for carbon removal. Even if renewable energy sources continue to be scaled up at a rapid pace, an overambitious DACCS strategy would still pose a significant risk to energy security, since global energy demand is expected to increase by 50 percent before 2050 [244]. In this context, Fajardy and colleagues have investigated whether BECCS may be a future threat to energy security [199]. The authors concluded that a large-scale BECCS strategy "could represent a risk to both energy security and carbon dioxide removal" [199] (p. 1592). Large-scale DACCS could pose an even bigger threat to global energy security since it requires significantly more primary energy to sequester one ton of CO_2 [115,245,246]. Consequently, a large-scale DACCS policy may likely infringe on the emergent right to energy in the future.

3.2.2. Justification and Balancing of Conflicting Human Rights

The potential infringement on the right to energy could be justified. A given DACCS policy must be proportionate, namely that it must pursue a legitimate aim, it must at least be appropriate in helping to achieve the legitimate aim, it must be necessary in the sense that no alternative policy options that are equally effective and less onerous are disregarded, and it must be proportional in a narrow sense [247].

The policy in question must first pursue a legitimate aim. In a hypothetical scenario where a state implements a given large-scale DACCS policy, it is reasonable to assume that the state attempts to comply with Article 2 para. 1 and Article 4 para. 1 PA by limiting global warming. This would constitute a legitimate aim, all the more since climate protection as such is guaranteed by human rights.

A large-scale DACCS policy must also be adequate. This requirement entails that such a policy must at least aim to achieve the legitimate aim of limiting global warming. The purpose of DACCS is to generate negative emissions by capturing and storing CO_2 underground. It is therefore able, in theory, to limit global warming and remove historical GHG emissions. Since DACCS's potential to sequestrate CO_2 is largely uncontested—in contrast to large-scale BECCS—we can assume that a state-adopted large-scale DACCS policy may be adequate (in the sense of the proportionality principle) to achieve the goal of limiting climate change.

A large-scale DACCS policy must be necessary. Accordingly, such a policy is only proportional if there are no available alternative policy measures that would be equally effective in achieving the goal and less onerous on the affected rights. To that end, we will first examine the effectiveness of DACCS in sequestering CO_2 before comparing alternative courses of actions, namely GHG emission reductions and minimization of animal husbandry.

In contrast to BECCS, DACCS can, according to scholars, provide negative emissions at scale—provided that the necessary infrastructure becomes available in the coming decades [32,240,248,249]. This is primarily due to the fact that—unlike in the case of BECCS—a large-scale DACCS policy will not automatically imply significant supply chain emissions. Supply chain emissions related to a future DACCS policy will be smaller since DACCS requires comparatively limited land-use changes [78]. Even coupling DACCS plants with renewable energy sources will require only a minute share of that needed by any large-scale BECCS approaches [102,241,250]. However, other supply chain emissions related to the buildup of the CCS infrastructure, CO_2 transport, and CO_2 storage should not be underestimated. For instance, the negative emissions potential of DACCS would be undermined if the captured CO_2 had to be transported via pipelines for hundreds of kilometers before being injected underground due to the lack of appropriate storage facilities in the proximity of the DACCS plant. Since there are few locations that could both support DACCS plants being reliably powered by renewable energy and feature suitable geological storage sites [251], there may be an upper limit to DACCS' potential to generate negative emissions. However, this hypothetical problem should not obscure the fact that DACCS has the potential to generate negative emissions in a relatively short time. Unlike BECCS, DACCS does not accumulate a significant carbon debt over its deployment that would prevent it from becoming a NET after decades or even centuries [252]. In that sense, a rapid scale-up of DACCS would not imply an almost insurmountable task of sequestering the immense of amounts of carbon debt accrued due to the harvesting of energy crops.

Nevertheless, substantial factors could still have implications for the effectiveness of DACCS as a NET in the future. First, as in the case of BECCS, the maturity or lack of scale-up of the CCS industry in general threatens the technology's development [19]. If the technology is unable to commercialize until the 2030s, it is unlikely that CO_2 removal targets for 2050 will be met [253]. Second, the high energy demand and related costs of the technology are critical limiting factors [254]. The high costs of maintaining a DACCS plant may limit the technology's effectiveness since there is no profitable business model as yet [251]. Financial support for a potential DACCS scale-up is lacking because operating a plant is not financially viable without integrating the technology into a carbon pricing scheme [255]. Consequently, McCormick has expressed the concern that DACCS will play only a limited role if no one is willing to finance it [256]. In addition, the social acceptance of the technology might be at risk if costs do not come down significantly [251]. Granted, there is a possibility that costs could decrease in the future [257]. It is, however, not clear whether these novel systems can be deployed at commercial scale during the next decade. To remove emissions at Gt scale would require establishing a DACCS industry as large as the current automotive sector [258]. The uncertainty about the scale-up is compounded by the fact that most companies active in the DACCS industry only release limited information concerning their technology [251]. It is not certain whether the DACCS plants will indeed be able to deliver the CO_2 removals that the companies promise since their technologies are protected by patents and are therefore not available for thorough scientific review [251]. In sum, large-scale DACCS will likely deliver some amount of negative emissions, but it is highly uncertain if the plants will remove as much CO_2 as foreseen by the IPCC.

Whether a policy of large-scale DACCS is necessary depends on the alternative policy options. As previously demonstrated, other policy options (such as phasing out fossil fuels and minimizing livestock farming as well as compensation measures regarding peatlands and forests) are more effective at limiting global warming to 1.5 °C under Article 2 para. 1 PA than CO_2 removal. This is even more true given that this norm demands "keeping the temperature well below" the respective limit, which means that no overshoot is accepted (as it is typically the case in many DACCS and BECCS scenarios) [8,10]. The same principle applies in the case of large-scale DACCS—especially because the technology accounts for a comparatively small share of the overall NET portfolio in the IPCC scenarios [7]. Possibly removing 5–30 $GtCO_2$ annually through DACCS by 2050 will not yield the same effect as drastically reducing the majority of current fossil fuel emissions [259].

Phasing out fossil fuels and decreasing animal husbandry are also less onerous on human rights than a large-scale DACCS policy that could threaten global energy security in the future. As mentioned earlier, drastically reducing GHG emissions will inevitably lead to human rights infringements, too [27]. For instance, the current modes of production and consumption will likely not be sustainable at present levels if states implement these stringent policies [27]. But first, economic freedom can be restricted in a proportionate way. Secondly, the threat of undermining freedom-related rights in the future argues precisely for reducing greenhouse gas emissions quickly (and thus in a way that citizens can plan for) now [127,239]. Consequently, the alternative policy options are less onerous on human rights than a potential large-scale DACCS policy.

4. Discussion and Conclusions

The analysis concerning BECCS has shown that, on current evidence, a policy of large-scale BECCS is not necessary because alternative policy measures are more effective and less restrictive on basic human rights. If states were to implement such a policy in the future, the infringement of the relevant human rights would therefore not be justified because the policy is ultimately disproportionate.

What kind of courses of action might policymakers derive from this assessment? First, states should abandon policies of large-scale BECCS because they run counter to several human rights guarantees. Second, researchers should further question the prominent position occupied by BECCS in IAMs and other climate scenarios since it there is a significant risk that BECCS may underperform or even generate positive emissions [181]. A strategy focused on NETs, such as BECCS, would then exacerbate the worst effects of global warming due to delayed emission reductions [118,260].

Small-scale BECCS may still have a role in a diversified climate policy portfolio if NET options such as peatland and forest management will not suffice [261]. However, this presupposes that "any BECCS projects should be of limited scale, all feedstocks provided locally with very low supply chain emissions, and feedstock payback times should be very short" [181] (p. 15). Waste-to-energy BECCS plants may be a promising option, but it is uncertain if the technology will soon reach maturity levels. With regard to other biomass sources, it will be sensible for all states to institute the "cascading principle", as already advocated by the European Commission in its "Fit for 55" package [262]. According to the principle, biomass should only be used for combustion if there are no higher-value usage, re-use and recycling options available and mainly in places where other energy sources that deliver substantive energy such as PtX and hydrogen do not offer better solutions [14,30,262].

Perhaps future BECCS projects should aim to be "biomass carbon removal and storage" (BiRCS), a term introduced by Sandalow and colleagues to differentiate between potentially harmful BECCS and BECCS that is compatible with the objectives of the UNFCCC and CBD [263]. According to this concept, BiCRS is defined as a process that "(a) uses biomass to remove CO_2 from the atmosphere, (b) stores that CO_2 underground or in long-lived products, and (c) does no damage to—and ideally promotes—food security, rural livelihoods, biodiversity conservation and other important values." [263] (p. 1). If these three conditions are fulfilled in a sustainable way, bioenergy may make a decisive contribution to climate mitigation.

As regards DACCS, a potential large-scale DACCS policy is not necessary and thus not proportionate, because it would interfere with the human right to energy in an unjustified manner. The human rights analysis shows that DACCS cannot be implemented at such a scale that it might endanger energy security which would jeopardize an elementary precondition of freedom. This, however, does not automatically imply that DACCS is incompatible with human rights guarantees per se. A proportionality analysis only indicates whether a particular policy violates certain human rights under specific circumstances. In the present case, the necessity test requires us to compare hypothetical measures with the aim of eliminating the policy that is more onerous on the relevant right while not having the same effectiveness. As a result, there is a clear priority of courses of action that states should take before pursuing large-scale DACCS (or BECCS): cutting down fossil fuels and livestock emissions as well as gaining negative emissions via well-approved approaches such as forest and peatland management.

Finally, if we apply the precautionary principle to the present cases, the same result emerges mutatis mutandis. The obligations arising from the precautionary principle are two-fold. First, in a situation of factual uncertainty concerning an emerging technology, states should regulate respective policies more restrictively in order to minimize risks [264]. Second, the lack of a scientific consensus does not imply that no actions should be taken when states are faced with irreversible harm [265]. In the context of global warming, states therefore have an obligation to adopt proactive measures to prevent the worst effects of climate change. However, since they may choose from a plethora of different mitigation measures, they should first implement those policies for which there is sufficient evidence to establish that they do not unduly affect human rights. Thus, emission reductions and nature-based solutions should be prioritized over large-scale BECCS and DACCS deployment since there is a broad consensus that such solutions would not pose a danger to the pertinent human rights.

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