Investing in a Carbon-Free Future:
Worldwide Opportunities in Carbon Dioxide Removal

Report prepared for Carbon Removal Solutions & Ventures by Hertzbreaker Consulting

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Executive Summary

Carbon dioxide removal (CDR) is likely to play an essential role as the world addresses the climate crisis, and Carbon Removal Solutions & Ventures (CRSV) can position themselves to drive innovation for the energy transition through investments in start-up companies and nascent technologies. To optimize their impact, however, CRSV must understand how and by whom CDR strategies are most likely to be deployed.

The literature suggests that several principles may dictate countries' contribution to the estimated 687 GtCO_2 of CDR necessary through 2100: *Responsibility* (historic CO_2), *Capability* (wealth), and *Equality* (population). Others should perhaps also be considered, including *Payback* (consumed CO_2), *Equity* (CO_2 per capita), *Practicality* (OECD status), and *Future* (projected CO_2). A multi-criteria decision-making analysis demonstrates that quotas differ across scenarios, characterizing potential stakeholder preferences for prioritizing principles. That said, under any allocation strategy, the U.S. (16-32%), the E.U. (14-23%), China (8-16%), and India (2-8%) will be responsible for more than 50% of CDR quotas. For several countries, however, what's fair and what's realistic are very different and developed; cooperative countries may have to contribute more to CDR than principles suggest.

While there are several prospective strategies for effective CDR, bioenergy with carbon capture and sequestration (BECCS), direct air capture with carbon sequestration (DACCS), and afforestation and reforestation (AR) have the largest potential for near-term commercialization and CO_2 removal. BECCS, with costs of \$15-400/tCO_2, combusts biomass for energy while directly capturing and storing associated emissions. DACCS, ranging from \$300-1,000/tCO_2, pulls ambient CO_2 from the atmosphere. AR, only \$1-100/tCO_2, simply adds plant biomass that naturally acts as a carbon sink. While global geologic formations provide storage an order of magnitude greater than needed sequestration, many countries' expected quotas exceed local capabilities. Furthermore, worldwide marginal agricultural land could capture 1.5-7.7 GtCO_2 per year, but many regions will be unable to meet their quota in a timely fashion. Technology transfer, by means of foreign direct investment or foreign portfolio investments, could allow physically constrained countries to meet their CDR targets and provide a path for a least-cost deployment strategy. Such a campaign for BECCS, DACCS, and AR is likely to cost from \$500 billion to \$1 trillion, from \$500 billion to \$1.5 trillion, and from \$18 billion to \$180 billion per year, respectively, to meet the full estimated quota of 687 GtCO_2.

We recommend that CRSV invest heavily in less costly AR projects in developing nations with marginal lands and BECCS in industrialized countries where biomass availability is high, feedstock prices are low, and electricity prices are high. DACCS remains the most expensive alternative, but our literature review suggests that all three CDR options will be necessary to meet climate goals. By investing in the nascent DACCS market early, CRSV has the opportunity to grow the market space, which may still evolve significantly over the next decade or so. By playing a part in further research and development, CRSV may see substantial benefits. Regardless, CRSV should stay on top of emerging and evolving regulatory landscapes to best leverage favorable policies and programs.

Introduction

Climate scientists agree that global greenhouse gas (GHG) emissions must reach net-zero by mid-century to mitigate the worst impacts of climate change (V. Masson-Delmotte et al. 2018). Achieving this goal will likely require carbon dioxide removal (CDR) technologies, as it may be technologically or economically prohibitive to completely decarbonize some industries such as heavy industry and long-haul freight. CDR technologies sequester carbon in plants, soil, and underground. Sequestering carbon can slow, and potentially reverse, the accumulation of carbon dioxide (CO_2) in the atmosphere, allowing hard to abate sectors to emit some GHG emissions while society pursues net decarbonization.

There remain open questions about how and by whom CDR strategies will be deployed. The impacts of climate change are incurred globally, with emissions from each country contributing to the problem. Therefore, it is necessary to set CDR quotas for different countries, identifying how much they should contribute to this global effort. However, there are several criteria to determine quotas (e.g., which countries have the highest historical emissions, which countries are most able to solve the problem). Additionally, multiple technology options exist to remove CO_2 from the atmosphere. CDR technologies include bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), afforestation and reforestation (AR), enhanced weathering, ocean fertilization, biochar, and soil carbon sequestration. Except for AR, CDR technologies and business frameworks remain in the nascent stage. Considerable technological development and research are required to develop a viable CDR industry. The development of a practical industry will depend heavily on supportive policy, as it is unlikely that the technologies will be financially viable without some recognition of their global social benefit.

Despite these challenges, CDR presents a tremendous market opportunity. To achieve the goal of limiting global warming to 1.5℃, models suggest that between 350 and 1,220 $GtCO_2$ must be captured globally before 2100 (Pozo et al. 2020). For context, 2019 global greenhouse gas emissions were 35.1 $GtCO_2$. The investment for the infrastructure required to capture 10 to 35 times current annual global CO_2 emissions represents a massive growth opportunity (Tiseo 2021).

Carbon Removal Solutions & Ventures (CRSV) is in a prime position to invest in start-up companies working to commercialize CDR technologies. With hundreds of $GtCO_2$ to capture globally, the market for CDR, as well as the research and development opportunities, is expansive. BECCS and DACCS are in the nascent stage of their development and need to be deployed worldwide. In this report, we outline CDR quotas by country under various allocation methodologies, the cost of the commercially viable CDR technologies, which countries may be the best targets for different technologies, and potential approaches to technology transfer of CDR. CRSV can use this report to better understand the state of CDR technologies, the scale of the total investment opportunities, and where CDR technologies may be deployed.

Country-Specific CDR Quotas

According to Our World in Data's (OWID) CO_2 and greenhouse gas emissions database, which provides various country-level emissions metrics, cumulative global historical emissions through 2019 are 1,610 $GtCO_2$ (Ritchie and Roser 2020). However, future CO_2 emissions must be considered as well. In the following assessments, we allocate a total global CDR quota of 687 $GtCO_2$ for carbon capture and storage (CCS) required through 2100 as defined by the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Global Warming of 1.5°C's 'middle-of-the-road' scenario (V. Masson-Delmotte et al. 2018). Under this scenario, technological development follows historical rates and emissions reductions are achieved chiefly by changes in energy production and economic product production.

CDR Allocation Strategies Review

There are several documented strategies for determining country specific CDR quotas. Pozo et al. 2020 formulated three effort-sharing approaches based on equity principles: *Responsibility, Capability*, and *Equality* (Pozo et al. 2020). In this section, we review each method and provide our estimates of country-level quotas associated.

- *Responsibility*: The obligation for CDR falls to those most responsible for emissions, meaning a country's quota is directly related to their historical CO_2 emissions. We extract cumulative emissions for each country from OWID (Ritchie and Roser 2020).
- *Capability*: Quotas are allocated based on the philosophy that a country's ability to pay should align with its contribution to the solution. We consider the current national gross domestic product (GDP) as the measure of countries' wealth. GDP data are from the World Population Review (WPR) (World Population Review 2021a). This method differs from that of Pozo et al. 2020, which uses GDP per capita. We assume that overall ability-to-pay for CDR exists at a country level rather than at an individual level.
- *Equality:* Equality is centered around the idea that everyone has the right to be protected from pollution, and every person is entitled to the same amount of reduction. Hence, CDR quotas are assigned per capita, independent of a country's historical emissions or economic ability.

Figure 1 shows our spatial assessment of country quotas using the different allocation strategies, which result in markedly different quotas for different nations. *Responsibility* quotas (Figure 1.A) are highest for the United States (U.S.) (25%), China (14%), Russia (7%), Germany (6%), the United Kingdom (U.K.) (5%), Japan (4%), India (3%), France (2%), and Canada (2%).

Responsibility quotas are strongly correlated with those determined via the *Capability* principle shown in Figure 1.B, which are greatest for the U.S. (24%), China (17%), Japan (6%), Germany (5%), India (4%), the U.K. (3%), France (3%), Italy (2%), and Brazil (2%). Results are similar because energy use contributes significantly to economic growth and development, and countries with high historical levels of CO_2 have reaped the economic benefits of burning fossil fuels. Finally, Figure 1.C shows quotas based on the *Equality* principle. The results differ from the other metrics because population is not necessarily tied to emissions or economic activity. Some of the top contributors stay the same, as China (18%), India (18%), and the U.S. (4%) have the highest quotas. That being said, there is a substantial increase in CDR attributed to India and, contrarily, a substantial decrease in CDR granted to the U.S. relative to the other principles. Other countries with high quotas are Indonesia (4%), Pakistan (3%), Brazil (3%), Nigeria (3%), and Bangladesh (2%), nearly all of which are new to the "greatest-quota list."

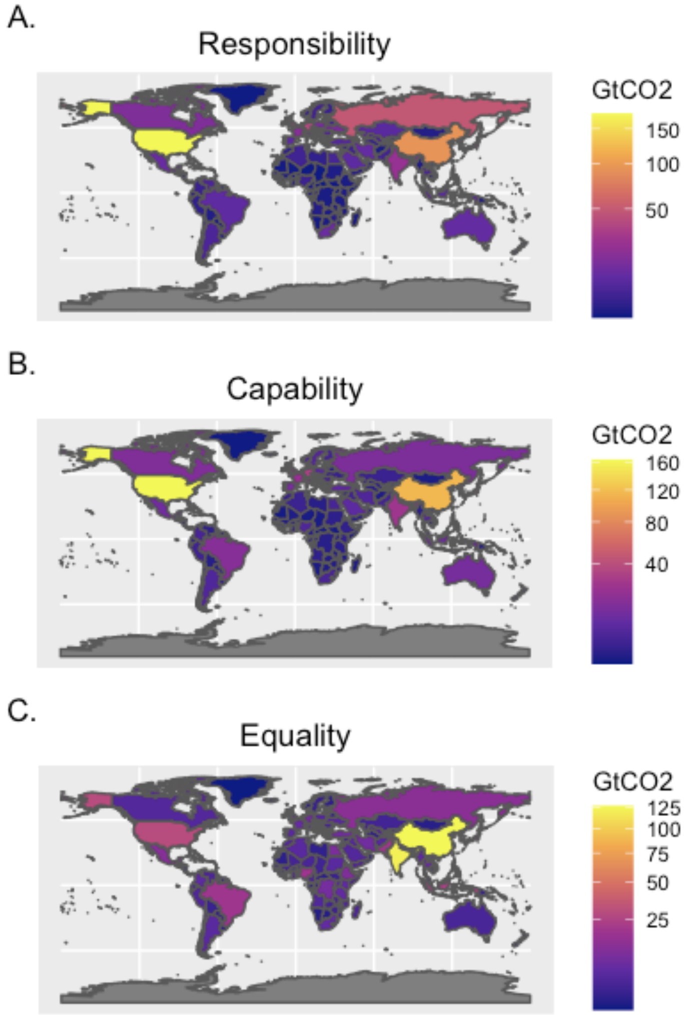

Figure 1: Cumulative CDR quotas by 2100 for specific countries according to the principles of Responsibility, Capability, and Equality.

The U.S., China, and India are responsible for at least 40% of CDR in each principle. A challenge arises given that China, India, and Russia, another consistently large-quota recipient, are not Organisation for Economic Co-operation and Development (OECD) members (World Population Review 2021b). OECD is an organization of countries collaborating to drive economic growth, adapt successful policies and practices, and solve shared international problems. The analysis herein assumes that all countries are willing to take on the climate crisis and deploy CDR technology cooperatively; however, that is a strong assumption, and quotas may need to adjust.

Alternative CDR Allocation Strategies

We design several alternate options to assess quotas in addition to those laid out by Pozo et al. 2020: *Payback*, *Equity*, *Practicality,* and *Future*. We draw all emissions data, including forecasts, from OWID (Ritchie and Roser 2020).

- *Payback*: The responsibility for CDR falls to those who have been the greatest consumers of emission-related goods and services. We examine each country's consumption-specific CO_2 emissions considering that lifecycle CO_2 emissions often trace back to international sources. Given data limitations, we extrapolate cumulative consumption-related CO_2 based on a produced-to-consumed ratio for each country determined via an average for all years with data. Where countries do not report consumption CO_2 data, we assume a 1:1 ratio.
- *Equity*: Our Equity principle assigns quotas based on historical CO_2 per person. This employs a different philosophy regarding equality, arguing that everyone has the right to benefit equally from emissions. However, this results in impractical quotas for small, affluent countries. We calculate CO_2 per capita for each country based on an average since 1970.
- *Practicality:* This principle takes a realistic look at CDR strategies, considering that relying on all countries to meet assigned quotas may be challenging. We assume that only OECD countries agree to a CDR quota and proportionally make up the difference based on *Capability* (World Population Review 2021b). See a list of OECD countries in Appendix A.
- *Future*: This allocation method assigns quotas based on historic plus expected future emissions through 2050. This principle accounts for the fact that many countries' CO_2 growth rate has been decreasing while others have seen large increases. We project emissions using annual rates of change since 2010.

Figure 2 shows quotas for *Payback*, *Equity*, and *Practicality*. *Payback* quotas (Figure 2.A) are highest for the U.S. (25%), China (16%), Russia (7%), Germany (5%), the U.K. (4%), Japan (3%), India (3%), Ukraine (2%), and Canada (2%). We find that CO_2 contributions from consumption are practically the same as those from production (Pearson's $r > 0.99$). While international trade does change allocations for some countries, responsibility generally remains the same.

Figure 2.B shows *Equity* principle results. We see vastly different quotas with this principle, the greatest being for Qatar (5%), Sint Maarten (5%), the United Arab Emirates (3%), Luxembourg (3%), Brunei (2%), Kuwait (2%), and Bahrain (2%). Sint Maarten, an island nation with < 50,000 people, contributing 5% to total global CDR efforts, demonstrates this principle's impracticality. The *Practicality* principle results in substantial quota increases for wealthy OECD members, as is shown in Figure 2.C. Given this scheme, the U.S.'s quota is 40% of the total. Japan (10%), Germany (7%), the U.K. (5%), France (5%), Italy (4%), Canada (3%), and South Korea (3%) all contribute much more to global efforts as well.

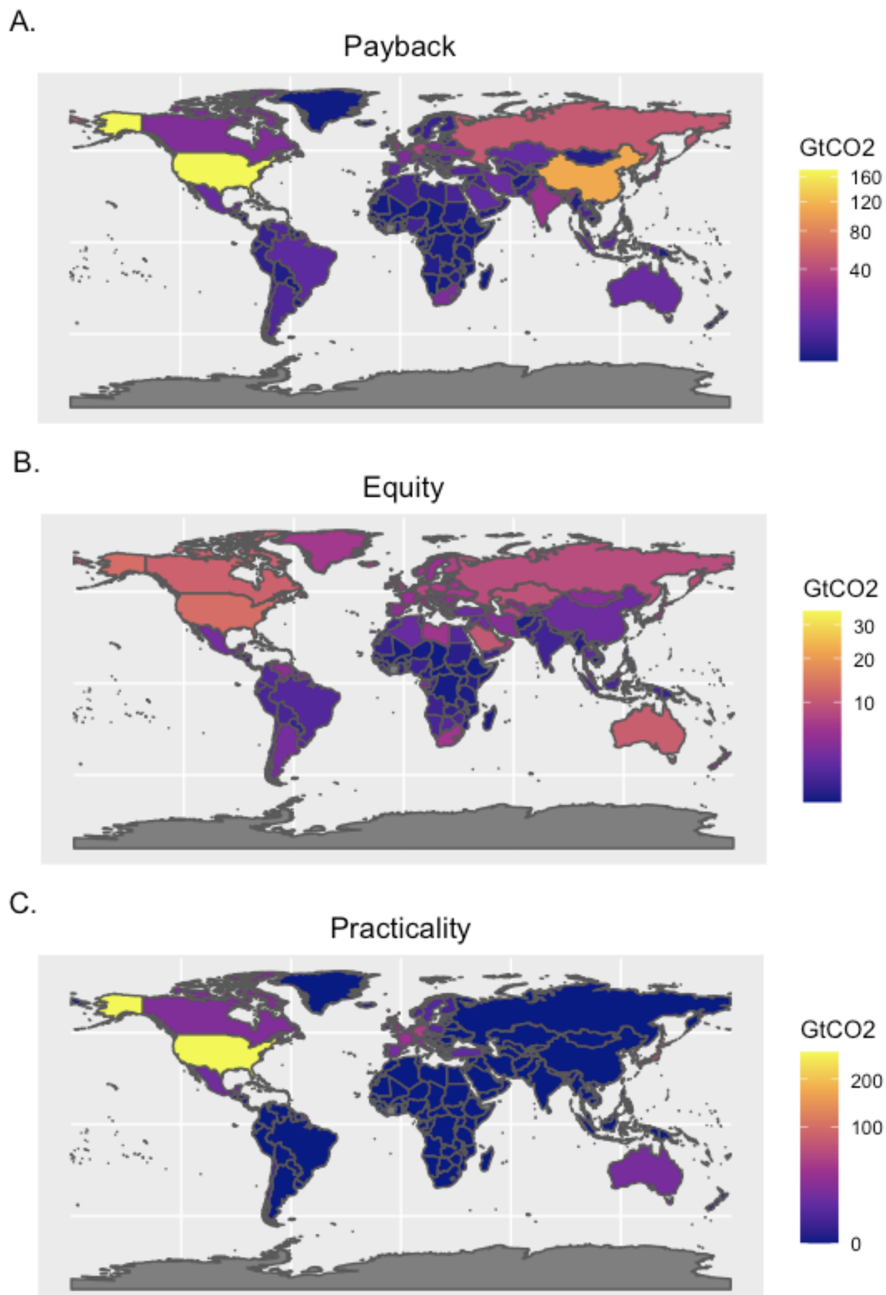

Figure 2: Cumulative CDR quotas by 2100 for specific countries according to Payback, Equity, and Practicality principles.

Given the vast uncertainty surrounding future emissions, we consider several scenarios that are outlined in Table 1. Baseline emissions projections result in 2050 cumulative CO_2 nearly doubling over historical levels. A low emissions projection still results in a 50% increase in cumulative emissions, and a high emissions scenario results in cumulative emissions more than tripling. We also look at three other policy-relevant scenarios. The first assumes annual emissions freeze at their current levels. The second characterizes a global effort to meet net-zero emissions by 2050. The third describes a cooperative, aggressive effort among OECD countries to hit net zero emissions by 2035 while other countries continue along with the baseline projection.

Table 1: Future CO_2 emissions projections under various scenarios. Emissions are reported as just future projections (following +) as well as future projections added to historical levels (following =).

Scenario Name	**Scenario Description**	**Cumulative Historic + Projected CO_2 Emissions**	**Top Five Nations: Future**	**Top Five Nations: Historic + Future**
Baseline Emissions Projections	CO_2 emission changes for each country continue based on average of yearly growth rates since 2010 (Mean 2.1% & SD 3.4%)	+ 1,530 $GtCO_2$ = 3,140 $GtCO_2$	CHN (32%), IND (12%), USA (10%), RUS (4%), IRN (3%)	CHN (22%), USA (18%), IND (7%), RUS (6%), DEU (3%)
Low Emissions Projections	CO_2 changes for each country continue based on average of yearly growth rates since 2010 minus standard deviation (Mean -4.6% & SD 4.6%)	+ 810 $GtCO_2$ = 2,420 $GtCO_2$	CHN (31%), IND (14%), USA (12%), RUS (5%), IRN (3%)	USA (21%), CHN (20%), IND (7%), RUS (6%), DEU (4%)
High Emissions Projections	CO_2 changes for each country continue based on average of yearly growth rates since 2010 plus standard deviation (Mean 8.9% & SD 5.0%)	+ 3990 $GtCO_2$ = 5,600 $GtCO_2$	CHN (25%), IDN (11%), IND (7%), USA (6%), VNM (4%)	CHN (22%), USA (12%), IDN (8%), IND (6%), RUS (4%)
Constant Emissions Forward	CO_2 continues to be the same for each country based on 2019 amounts.	+ 1050 $GtCO_2$ = 2,660 $GtCO_2$	CHN (29%), USA (15%), IND (7%), RUS (5%), JPN (3%)	USA (21%), CHN (20%), RUS (6%), IND (5%), DEU (4%)
Net Zero by 2050	Each country decreases CO_2 emissions linearly to hit net zero by 2050.	+ 530 $GtCO_2$ = 2,140 $GtCO_2$	CHN (29%), USA (15%), IND (7%), RUS (5%), JPN (3%)	USA (23%), CHN (17%), RUS (7%), DEU (5%), IND (4%)
Net Zero by 2035 for OECD Nations	Each OECD country decreases CO_2 emissions linearly to hit net zero by 2035; others follow baseline projections	+ 1260 $GtCO_2$ = 2,870 $GtCO_2$	CHN (38%), IND (14%), RUS (5%), IRN (3%), USA (3%)	CHN (24%), USA (16%), IND (8%), RUS (6%), DEU (3%)

Table 1 includes future and cumulative emissions as well as the top five contributors to future and cumulative emissions for each scenario. While country-level absolute CO_2 contributions vary greatly across scenarios, relative responsibility remains more consistent. China, the U.S., and India remain in the top five under every scenario.

CDR Allocation Synchronization: Multi-Criteria Decision-Making

Given the multiple ways to allocate CDR quotas among countries, we conduct a multi-criteria decision-making (MCDM) analysis to assess how contributions may be allocated considering a combination of principles. In practice, we do this by assigning weights to different criteria depending on "what we most care about." In an ideal world, we would consult various global leaders to best understand stakeholder preferences. However, to evade this timely effort, we propose various preference scenarios that assign weights to each principle, a strategy used in previous MCDM studies (Klein and Whalley 2015).

Table 2 shows five preference scenarios and their respective weights. Our scenarios are *Traditional*, *Uniform*, *Accountable*, *Fair*, and *Realistic*. Traditional distributes evenly across the principles discussed in Pozo et al. 2020. *Uniform* distributes evenly across all principles (future only considered future emissions in the baseline scenario in this MCDM assessment, so as not to double count *Responsibility*). *Accountable* puts 50% of the quota on past production and consumption CO_2 and considers per capita CO_2 and expected future emissions. *Fair* puts a heavier weight on *Equity* and *Capability* while also considering historical emissions, *Equality* and *Future*. The *Realistic* scenario puts 50% of weighting on *Capability* (all countries) and 50% on *Practicality* (OECD countries), assuming that non-OECD countries will contribute less.

Table 2: Preference scenario weights for MCDM analysis. Weights add up to one for each scenario.

Scenario	Resp.	Capa.	Equa.	Payb.	Equi.	Prac.	Futu.
Traditional	0.333	0.333	0.333	-	-	-	-
Uniform	0.143	0.143	0.143	0.143	0.143	0.143	0.143
Accountable	0.250	-	-	0.250	0.250	-	0.250
Fair	0.200	0.300	0.100	0.200	0.300	-	0.100
Realistic	-	0.5	-	-	-	0.5	-

Figure 3 shows the results of our MCDM preference scenario analyses for the top 20 countries averaged across all preference scenarios. For this assessment, we group all 27 countries of the European Union (E.U.) as a single CDR deployer. The results demonstrate a few key takeaways:

1. Countries in Figure 3 (i.e., 46 when breaking down the E.U.) are allocated quotas covering at least 75% of global CDR in any preference scenario. The U.S., the E.U., China, and India cover more than 50% of global CDR quotas in any scenario.
2. The U.S. has the top quota across countries in every MCDM preference scenario, ranging from 16% to 32%. The E.U. (14% to 23%) and China (8% to 16%) are consistently second and third.
3. For most countries, what is *Accountable* or *Fair* and what is *Realistic* results in very different outcomes. China, India, and Russia, countries that have higher quotas by *Traditional* principles, see lower quotas under many of our preference scenarios. Consequently, the U.S., the E.U., Japan, the U.K., Canada, Korea, Australia, and Mexico are likely to have to cover a higher CDR quota than the literature suggests.

See Appendix A for an abbreviation-to-country crosswalk and a summary of the quotas under each principle, future projection, and preference scenario for the nations in Figure 3.

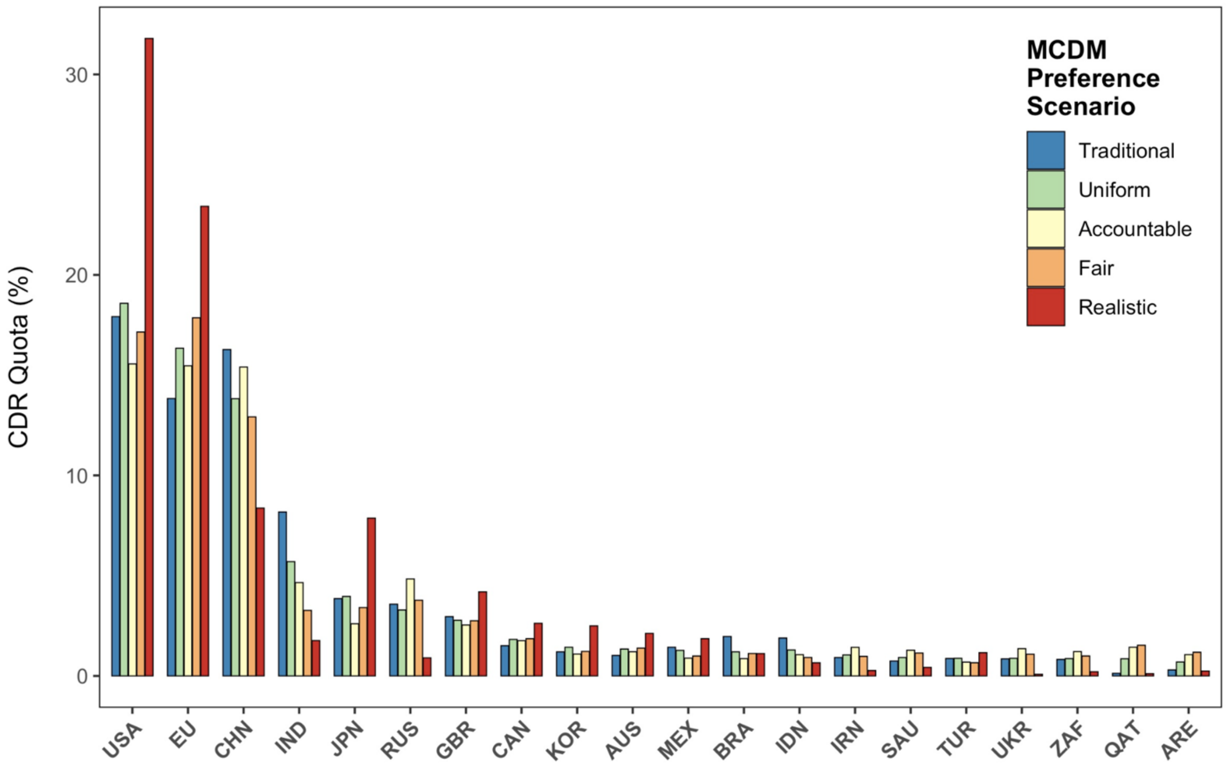

Figure 3: MCDM analysis results for preference scenarios defined in Table 2.

CDR Technologies Overview

A suite of solutions exists to remove carbon dioxide from the atmosphere. The best characterized CDR strategies include bioenergy with carbon capture and sequestration (BECCS), direct air capture with carbon sequestration (DACCS), afforestation and reforestation (AR), enhanced weathering, ocean fertilization, biochar, and soil carbon sequestration. Each of these technologies has the potential to contribute to climate change mitigation, but the extent to which each will do so remains uncertain, based both on technological and economic uncertainties.

AR is the most mature and straightforward CDR technology. AR refers to the practice of planting trees on land that has not been afforested within recent history, while reforestation signifies replanting trees on land that has recently been deforested (Fuss et al. 2018). When the trees are planted, new biomass growth sequesters atmospheric CO_2. While estimates of total AR sequestration potential vary, a recent analysis of CDR literature estimated that in 2050, annual potential likely ranges from 0.5 - 3.6 $GtCO_2$ per year, rising to 1 - 12 $GtCO_2$ per year in 2100 as more areas are forested (Fuss et al. 2018). Total capacity estimates vary based on land-use assumptions, with some studies assuming that only abandoned or low-productivity land is available (Fuss et al. 2018). According to the same study, there is widespread agreement in the literature that AR will cost no more than $100/ton CO_2 sequestered and could cost as low as

$1/ton CO_2 sequestered. AR may, however, have to compete with food production, as crop or grazing land could be converted for sequestration, potentially raising the price of food (Fuss et al. 2018). Additionally, it's efficacy is highly location-dependent; researchers agree that afforestation in far northern latitudes decreases surface albedo and has a counterproductive effect (Fuss et al. 2018). Further, carbon dioxide stored in trees is far less permanent than that stored in geologic formations, with a saturation time ranging from only decades to centuries (Fuss et al. 2018).

BECCS plants combust biomass in a power plant combined with carbon capture and sequestration (CCS). BECCS is dependent on bioenergy that can be provided by zero to low carbon emissions (Fuss et al. 2018). The limiting factors of BECCS are biomass and land availability (Fuss et al. 2018). Estimates for global bioenergy potential range from 60-1,548 EJ/year (Fuss et al. 2018). The large range results primarily from assumptions about global land availability to grow biomass feedstock. Costs range from $15-400/t$CO_2$ (Fuss et al. 2018). The large range in costs is related to access to abundant biomass and distances to storage sites. Additionally, costs can vary due to the specific source of CO_2 capture. BECCS can cause a variety of climate effects due to direct and indirect land use change and albedo effects. Emissions from land use changes are due to deforestation and using first-generation biofuels (corn ethanol). Emissions are lower when second-generation biofuels (woody sources, food waste, and forest residues) are used. Albedo effects from biomass depend on the geographical location. If biomass replaces areas with snow cover, that may lower the albedo effect and offset climate mitigation. Additionally, biomass requires fertilization, which leads to greenhouse gas emissions and water usage. Bioenergy will also compete with food for land, impacting food prices and security. Furthermore, BECCS may increase and diversify rural income, but also may expose small farmers to global market volatility. If the CO_2 is geologically stored, BECCS is an option that is less vulnerable to reversal (Fuss et al. 2018).

DACCS captures CO_2 from ambient air for geological storage. DACCS uses a sorbent to remove CO_2 from the atmosphere. The process requires large energy inputs to remove CO_2 from the sorbent, regenerate the sorbent, and pressurize CO_2 for transportation. CO_2 removal potential from DACCS has been assumed to be unlimited. However, some researchers maintain doubts about DACCS scalability. There are currently 15 small-scale plants operating, but large-scale scalability of the technology is unknown (Budinis 2020). Costs have been the primary discussion point about the viability and scalability of DACCS. Costs come from capital expenditures, energy, operating, and regeneration, and sorbent loss and maintenance. Transportation and grid costs may be less than other CCS technologies because they can be located close to storage facilities and can be co-located with renewable energy. However, there may be large labor and materials costs associated with DACCS, so having large capacities in a remote location may be challenging. An important consideration is that if DACCS is powered by coal, CO_2 emissions will be greater than CO_2 captured. If natural gas is used, not all potential CO_2 will be avoided. Costs of DACCS range from $30-1,000/t$CO_2$ (Fuss et al. 2018). However, the costs are not well defined because different studies capture different parts of the carbon removal process and make different assumptions on how much CO_2 can be captured per unit of energy used. Land use for DACCS is not much of a concern, but solid waste management may be an issue for the sorbent (Fuss et al. 2018).

The subsequent analysis focuses on the three technologies discussed above: BECCS, DACCS, and AR. Several other technologies exist, including biochar, soil carbon sequestration, enhanced weatherization, and ocean fertilization. We ignore biochar and soil sequestration technologies because of the possibility that their use may elevate other greenhouse gas emissions or release CO_2 back into the atmosphere if practices are not well maintained, reversing their effect. Enhanced weatherization analysis consists of only laboratory-scale studies and theoretical discussions and there remains a large amount of uncertainty in its potential to capture CO_2. In our assessment, ocean fertilization has too many potential negative externalities, ranging from altering local to regional food cycles, possible algal blooms, and increased N_2O and CH_4 emissions. After exploring the literature, we conclude that BECCS, DACCS, and AR have the largest potential for commercialization and carbon removal in the near-term.

We summarize estimated costs and capacities in Figure 4. Figure 4 further highlights why enhanced weathering and biochar are ignored. We draw all cost estimates in the figure from Fuss et al. 2018, which reviewed the CDR literature.

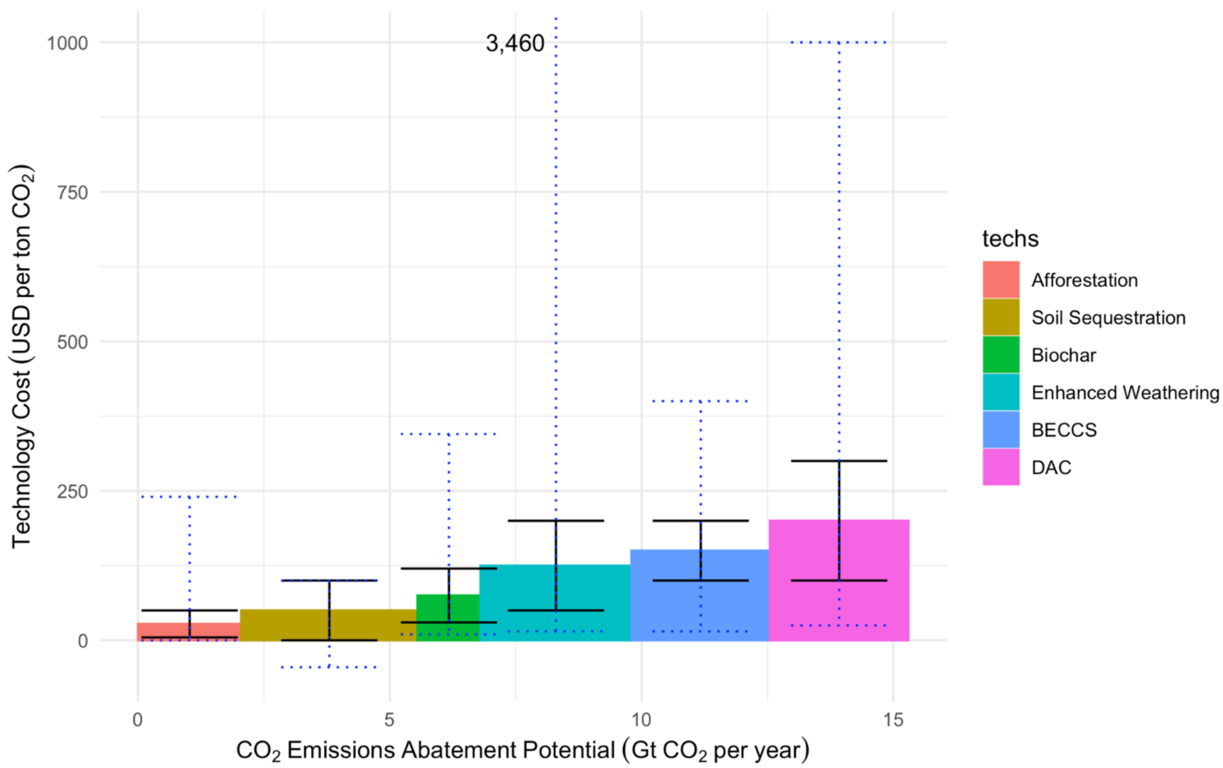

Figure 4: CO_2 emissions abatement potential and technology cost for five carbon dioxide removal technologies. Produced with data from Fuss et al. 2018.

The black solid error bars represent the author's best judgment on the cost range, while the dotted blue error bars display the full range of cost estimates found in the literature. The figure does not display uncertainty in storage capacity, but we address this in the following section.

Global and Regional Limitations and Solutions

Geological Storage Potential

The use of BECCS and DACCS technology requires access to appropriate underground CO_2 storage sites, such as salt caverns, depleted oil and gas reservoirs, or possibly enhanced oil recovery (EOR) basins (Consoli 2016). While EOR decreases the CO_2 emissions reduction potential from CCS, it may aid in making the technology economically viable (Sun et al. 2018) The global geological storage capacity is uncertain, however many countries and regions have been assessed. While assessment methods and level of detail vary widely, the aggregate global storage capacity is estimated to be on the order of 7 to 27 $TtCO_2$ (Consoli 2016), at least an order of magnitude greater than what is needed to keep global temperatures below 1.5 ℃ (V. Masson-Delmotte et al. 2018). This range also covers historic cumulative CO_2 as well as our high emissions scenario projection (Ritchie and Roser 2020). Despite the uncertainty in generating that estimate, it is reasonable to expect that geological storage capacity exceeds future possible required injections for the next century.

Appropriate geology is not uniformly distributed, so regional storage constraints may exist. Figure 5 shows the cumulative storage quota as a fraction of geological storage potential for the 25 countries plus the E.U. represented in the Global CCS Institute's review of geological storage potential under three allocation scenarios (Consoli 2016). A country with 200% storage potential has the potential to store twice as much CO_2 as required by its CDR quota.

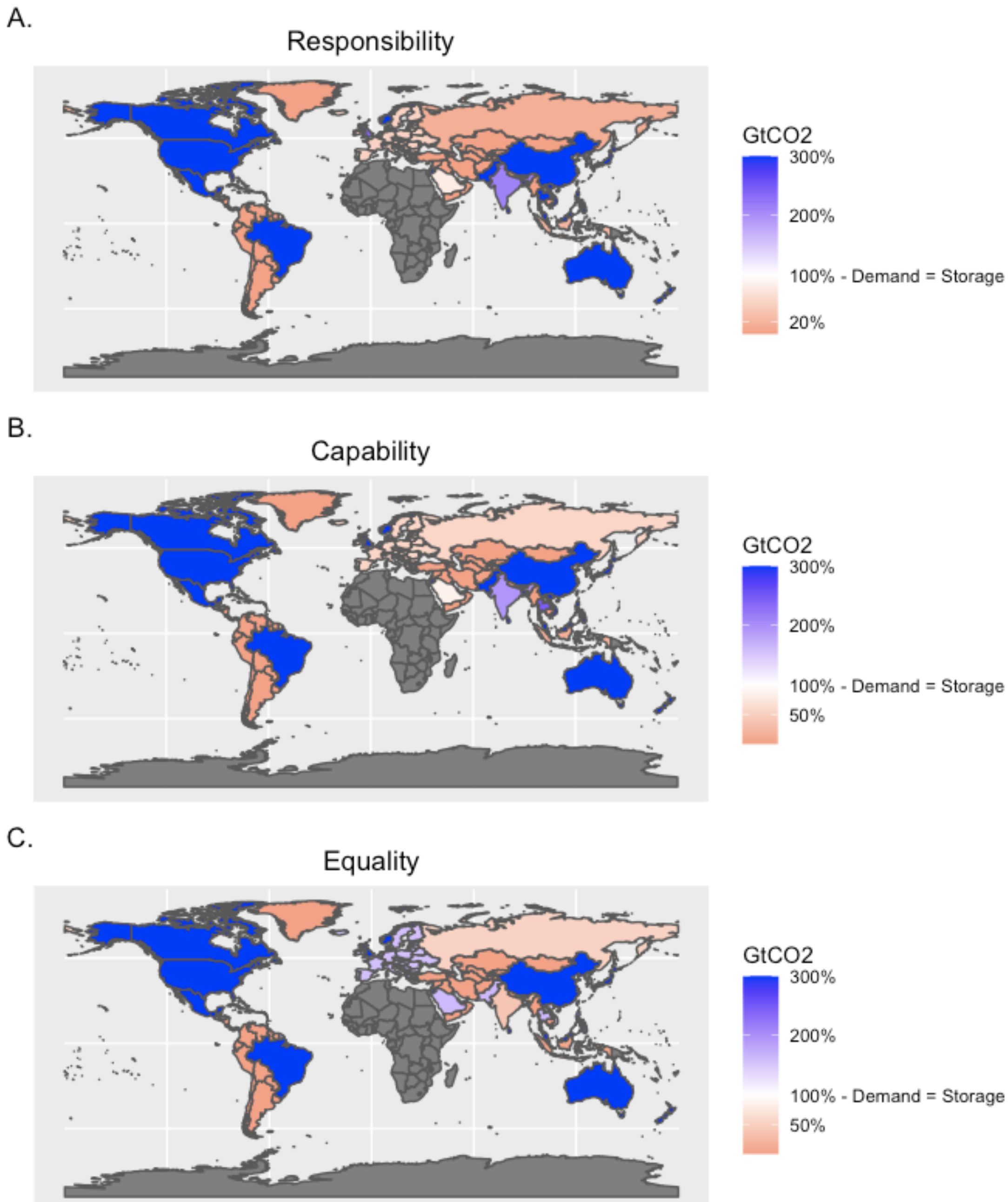

Figure 5: Country or region specific geological store potential shown as a percentage of that country's CDR quota based on the three metrics. The countries in blue have more potential than demand based on the quota, while the countries in red have more demand than storage potential.

Several of the countries in Figure 5 had storage potential larger than 300% of their CDR quota but are shown in this figure as having 300% for clarity. The complete list of countries and the ratio of their storage potential and CDR quotas can be found in Appendix B.

BECCS and AR Potential

A limitation on annual BECCS and AR potential is the amount of land that is available to grow the required biomass. Using prime agricultural land to grow biomass displaces food production and raises food prices, which could lead to particularly negative outcomes in developing countries. Afforesting lower carbon sequestration areas, like some grasslands, with higher storage vegetation, like some forests, will also have significant environmental effects by displacing the existing ecosystem. The worst of both outcomes can be avoided by using marginal agricultural lands for land-intensive CDR. Marginal agricultural land includes abandoned and degraded cropland and mixed crop and vegetation land that tends to be less productive (Cai, Zhang, and Wang 2011). These lands can be reforested or used to grow biofuels with significantly less food price effects than higher-quality land and minimal negative or even positive environmental effects.

Using estimates for marginal agricultural land in Africa, China, Europe, India, South America, and the U.S., we estimate that BECCS can capture 1.5 to 7.7 Gt CO_2 per year (Cai, Zhang, and Wang 2011). This range depends on a net energy gain range of 60 to 140 GJ/ha, representative of second-generation biofuel feedstocks like switchgrass and miscanthus, and the lowest and second lowest definitions of marginal agricultural land in Cai (Cai, Zhang, and Wang 2011). For details, refer to Appendix C. To contextualize these results, we used the BECCS capture rates from one scenario to show how many years it will take each region to reach their CDR quota's. It is important to note that the years required would go well past the 2100 goal for many regions.

Table 3: The estimated number of years each region will take to meet their CDR quotas based on the Responsibility, Capability, and Equality metrics

Years to Meet CDR Quota at S1 Max Rate			
Region	**Responsibility**	**Capability**	**Equality**
Africa	27	27	161
China	165	202	222
EU	392	366	128
India	111	121	610
South America	15	24	32
US	372	351	62

Technology Transfer

On a global scale, there is sufficient available marginal land and geological storage to meet the global quota of 687 $GtCO_2$, even under conservative assumptions. The majority of countries, with the exception of many in Europe, have enough storage capacity to meet their individual CDR quotas under every metric analyzed in this report. However, land availability and prices and energy prices vary between countries. We report land vs. electricity prices in Appendix D. To meet land requirements necessary for BECCS and AR, technology transfer should be used to achieve the least-cost deployment of CDR technologies. CRSV can consider several different types of technology transfer including foreign direct investments (FDI), foreign portfolio investments (FPI), training, research joint ventures, partnering with research universities in foreign countries, and contracted research and development. However, there are several factors to consider before investing in and partnering with companies and research institutions in foreign countries. Further, the cheapest deployment options and land availability for CDR will not align with the quotas discussed above. Therefore, the country that will pay for the technology will not necessarily be where it is implemented. While deployment of CDR technology in a developing country may bring economic benefits, rising food and energy prices, water stress, and biodiversity loss need to be considered.

FDIs and FPIs are similar in that they involve one company investing in an foreign company. However, FDIs will give the company much more control in foreign companies than an FPI. FDIs have a much higher level of political risk and may provide larger gains. Before issuing an FDI, investors must consider the environmental performance, economic and political factors, and natural conditions. Li, et al. 2019 have found that FDI is not a significant factor in determining the environmental performance of a foreign country, specifically in developing countries. Therefore, developing countries should have strict and distinct environmental standards before FDI is introduced (Li et al. 2019). As CDR is a technology designed to improve the environmental performance of a country, investors will need to consider if policies and standards in a country are favorable to CDR before investing. Further, government stability and accountability, ethnic tensions, and the quality of law enforcement and bureaucracy are strong determinants of FDI. Macroeconomic considerations are access to local finance, exchange rate stability, and labor cost. Land availability and natural resources (quality of land for AR and BECCS) are natural considerations for FDI (Keeley and Matsumoto 2018).

AR is well understood and does not require scaling of large infrastructure. Therefore, investments can go towards scaling and planting trees in different countries. However, there are no direct revenue streams from AR. Revenue will need to be obtained from either a carbon tax, land leasing, and/or providing training. Costs are primarily dependent on land and labor costs, and storage capacity is primarily dependent on land availability. Tropical regions are the best suited to AR and have costs in the range of \$5-50/tCO_2. Approximately 500 Mha of marginal land is available in the tropics (Fuss et al. 2018). Ignoring all other soft costs (legal fees, etc.), technology transfer investment could be between \$18 billion and \$180 billion per year, assuming a sequestration rate of 3.6 GtCO_2/year. A carbon tax above \$50/tCO_2 in the country invested in can make AR profitable.

The largest regional limitations of BECCS include availability of biomass and land (Fuss et al. 2018). Therefore, BECCS will likely be deployed in areas with high land availability and low land costs. South America (excluding Brazil), Africa, Russia, and countries in Eurasia (Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan) all have marginal land available for BECCS deployment (Fajardy et al. 2021). Ignoring all other soft costs, technology transfer investment could be between \$500 billion and \$1 trillion per year, assuming a sequestration rate of 5 GtCO_2/year. Favorable BECCS policies, electricity generation revenue, and enhanced oil recovery can make BECCS profitable.

DACCS does not have any physical deployment limitations, and its main constraints include electricity consumption and costs. Due to the high costs of DACCS, DACCS will likely be deployed in locations with low energy prices after lower cost options have been exhausted. Ignoring all other soft costs, technology transfer investment could be between $500 billion and $1.5 trillion per year, assuming a sequestration rate of 5 $GtCO_2$/year. Favorable DACCS policies and enhanced oil recovery can make DACCS profitable.

Recommendations and Conclusions

Least Cost Investment Portfolio

As discussed above, the least-cost portfolio of CDR technologies in each country will vary based on a variety of factors, leading to large uncertainties surrounding the ideal portfolio of country-level investment decisions. Rather than outlining an investment strategy for CRSV on a country-by-country basis, we instead make generalized recommendations based on geographic and economic factors. Subsequently, we identify a small group of countries as key target markets and outline CDR technologies that are most appropriate for these markets.

According to our study of the literature, AR costs substantially less in developing nations than industrialized ones (Richards and Stokes 2004). Further, AR is most feasible in marginal lands in the tropics (Fuss et al. 2018). Many developing nations exist in the global south and are therefore dually favorable for AR investments. BECCS is best suited for countries or regions where biomass availability is high and biomass feedstock prices are low. High electricity prices may also favor BECCS, as electricity is produced as a co-product from BECCS operation. BECCS facilities remain expensive, with abatement costs ranging from $100 - $200/$tCO_2$ (Fuss et al. 2018). According to the literature, DACCS remains the highest cost CDR technology ($100 - $300/$tCO_2$) (Fuss et al. 2018).

Our MCDM analysis suggests that while the magnitude of CDR responsibility for each country varies depending on decision criteria, several key countries hold a bulk of the burden under most scenarios. Using the MCDM, we identified the countries with the ten highest CDR quotas under each scenario (Traditional, Uniform, Accountable, Fair, Realistic.) We find that across all metrics, the ten highest CDR quotas are held by fifteen countries, indicating high levels of overlap across allocation metrics. The fifteen countries vary widely in development status, demographics, and political ideology, enabling a wide range of investment opportunities for CRSV.

AR may be limited by competition with agriculture and other land uses while BECCS and DAC may face scale-up challenges due to the required infrastructure for the facilities and for the CO_2 transport infrastructure, emphasizing the need for simultaneous deployment of all three options. As private companies and federal and state governments aim to decrease their carbon footprint, CRSV can position themselves with a portfolio of all three CDR options to maximize investment opportunities. For example, airlines operating in the U.S. and Canada could pay CRSV and its technical partners for each ton of CO_2 captured by BECCS and DACCS or for each tree planted. The state of California already allows polluters to purchase emissions offsets in the form of planting trees, and numerous corporations have net-zero emissions targets that will likely require a negative emissions source (Temple and Song 2020). European countries including Germany, France, and Italy have relatively high CDR quotas as well, ranging from 14 - 30 $GtCO_2$ depending on the country and the scenario. Investments in these countries may set CRSV up well for a possible amendment to the E.U. Emissions Trading Scheme (ETS).

While the ETS does not currently provide for negative emissions technologies, as the E.U. targets net-zero by 2050, CDR will almost certainly need to be adopted into the legislative platform (Rickels et al. 2021). Emitters could purchase carbon offsets from CRSV and its industrial or forestry partners to meet the increasingly strict ETS.

China and India offer unique investment opportunities. While both have low historical emissions, rapid growth and industrialization has resulted in high CDR quotas under most of the MCDM scenarios. Researchers forecast that both China and India will see electricity demand rise by a factor of at least two, depending on GDP, population growth, and electrification of end uses (Barbar et al. 2021; Wong 2020). Cai et al. 2011 estimate that India has 18 - 110 mha of available marginal land for biomass production while China has 52 - 134 mha, corresponding to 1.1 - 2.5 billion GJ and 3.1 - 7.3 billion G.J., respectively (Cai, Zhang, and Wang 2011). In these instances, CRSV can earn revenue both from captured CO_2 and from electricity produced as a co-product.

Recommendations

1. In developing and non-industrialized countries, we recommend that CRSV invest heavily in AR projects. Specifically, we recommend Brazil and Mexico, which have CDR quotas ranging from 11 - 18 $GtCO_2$. Both countries lie at least partially between the Tropic of Cancer and the Tropic of Capricorn, making them ideal for inexpensive and effective CDR via AR.
    a. We recommend partnering with local landowners and governments to explore AR options in these countries. Successes here could pave the way for CRSV to invest in smaller countries with similar climates to increase revenue and achieve decarbonization goals.
2. We recommend that in the U.S., the E.U., and Canada, CRSV invests in AR, BECCS, and DAC, as the political discourse has already moved towards implementing decarbonization strategies.
3. We recommend additional DACCS investments in regions where BECCS and AR are not suitable, or regions where the full suite of options will be necessary to meet decarbonization goals. Importantly, unlike BECCS, DACCS will be penalized for high energy prices, as DACCS facilities are energy intensive.
4. In China and India, initial investments should focus on BECCS, as low-carbon electric generation is critical to ensuring environmentally sustainable development and economic growth.

While we believe the above recommendations to be robust, a critical aspect of both BECCS and DACCS investment is that both technologies remain at the demonstration scale. As of 2019, only five BECCS facilities were in operation around the world, with a cumulative capacity of 1.5 million tonnes of CO_2 annually (Consoli 2019)**.** As of 2020, there were 15 operational DACCS globally, removing 9,000 tonnes of CO_2 each year. Technological advancements are key to both cost reduction and carbon removal potential. As a result, we recommend that in addition to investing in DACCS and BECCS pilot plants, that CRVS support research and development initiatives with private firms and universities to improve the cost effectiveness of these critical CDR technologies. For example, to reduce competition with food production, future large scale BECCS feedstock must be second generation biofuels, which remain at a nascent stage. Furthermore, there are a range of carbon capture and storage technologies that can be used to capture the CO_2 from biomass combustion, many of which have not been tested beyond the laboratory or pilot plant scale. CRSV could invest separately in efforts to develop viable second-generation biofuels and initiatives to improve upon carbon capture processes. Further, profitable investments into CDR technologies, especially investments in BECCS and DACCS, will rely on the regulatory environment. We suggest that CRSV prioritize investments in countries with climate policy that favor these technologies. Examples of such policies include, but are not limited to, legislatively binding commitments to net-zero emissions, an emissions trading scheme, certain carbon pricing regimes, or tax credits for zero-emissions technologies, such as the 45Q tax credit in the United States (Jones and Sherlock, 2021.). In our literature review, multiple sources highlighted that BECCS and DACCS will likely not be profitable barring a favorable regulatory environment (Fajardy et al. 2021; Realmonte et al. 2019).

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Appendix A: CDR Quota Supporting Information

Table A1: 36 Countries in the Organisation for Economic Co-operation and Development

Abbreviation	Country
AUS	Australia
AUT	Austria
BEL	Belgium
CAN	Canada
CHE	Switzerland
CHL	Chile
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GBR	United Kingdom
GRC	Greece
HUN	Hungary
IRL	Ireland
ISL	Iceland
ISR	Israel
ITA	Italy
JPN	Japan
KOR	South Korea
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MEX	Mexico
NLD	Netherlands
NOR	Norway
NZL	New Zealand
POL	Poland
PRT	Portugal
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
TUR	Turkey
USA	United States

Table A2: 27 Countries in the European Union

Abbreviation	Country
AUT	Austria
BEL	Belgium
BGR	Bulgaria
CYP	Cyprus
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GRC	Greece
HRV	Croatia
HUN	Hungary
IRL	Ireland
ITA	Italy
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MLT	Malta
NLD	Netherlands
POL	Poland
PRT	Portugal
ROU	Romania
SVK	Slovakia
SVN	Slovenia
SWE	Sweden

Table A3: Abbreviation-to-country crosswalk for countries in Figure 3

Abbreviation	Country
USA	United States
E.U.	European Union
CHN	China
IND	India
JPN	Japan
RUS	Russia
GBR	United Kingdom
CAN	Canada
KOR	South Korea
AUS	Australia
MEX	Mexico
BRA	Brazil
IDN	Indonesia
IRN	Iran
SAU	Saudi Arabia
TUR	Turkey
UKR	Ukraine
ZAF	South Africa
QAT	Qatar
ARE	United Arab Emirates

Table A4: Quotas for top 20 countries under different principles

Country	Responsibility		Capability		Equality		Payback		Equity		Practicality	
	Percent	GtCO2	Percent	GtCO2	Percent	GtCO2	Percent	GtCO2	Percent	GtCO2	Percent	GtCO2
USA	25%	175	24%	165	4.2%	29	25%	172	1.9%	13.3	40%	272
EU	18%	122	18%	124	5.7%	39.0	16%	108	24%	162	29%	198
CHN	14%	93.9	17%	115	18%	127	16%	110	0.3%	2.21	0.0%	0
IND	3.2%	22.2	3.5%	24.2	18%	122	3.4%	23.2	0.1%	0.59	0.0%	0
JPN	4.0%	27.6	5.9%	40.9	1.6%	11.0	3.5%	23.9	0.9%	6.02	10%	67.3
RUS	7.1%	48.6	1.8%	12.4	1.9%	12.8	7.2%	49.4	1.2%	8.56	0.0%	0
GBR	4.8%	33.2	3.2%	21.8	0.9%	6.0	3.9%	26.9	0.9%	6.36	5.2%	35.8
CAN	2.1%	14.1	2.0%	13.6	0.5%	3.3	2.1%	14.1	1.7%	11.5	3.3%	22.4
KOR	1.1%	7.28	1.9%	13.0	0.7%	4.5	0.9%	6.52	0.7%	4.85	3.1%	21.4
AUS	1.1%	7.76	1.6%	11.0	0.3%	2.3	1.3%	8.73	1.6%	11.0	2.6%	18.1
MEX	1.2%	8.43	1.4%	9.65	1.7%	11	1.2%	8.13	0.4%	2.54	2.3%	15.9
BRA	0.9%	6.45	2.2%	15.3	2.7%	19	0.9%	6.19	0.2%	1.14	0.0%	0
IDN	0.8%	5.76	1.3%	8.99	3.5%	24	0.9%	6.24	0.1%	0.78	0.0%	0
IRN	1.1%	7.80	0.5%	3.69	1.1%	7.4	1.2%	8.51	0.5%	3.60	0.0%	0
SAU	0.9%	6.36	0.9%	5.88	0.5%	3.1	1.0%	6.94	1.5%	10.1	0.0%	0
TUR	0.6%	4.46	0.9%	6.02	1.1%	7.5	0.6%	3.97	0.3%	2.10	1.4%	9.9
UKR	1.8%	12.6	0.2%	1.09	0.6%	3.8	2.4%	16.3	0.9%	6.17	0.0%	0
ZAF	1.3%	8.84	0.4%	2.88	0.8%	5.3	1.8%	12.7	0.8%	5.77	0.0%	0
QAT	0.1%	0.87	0.2%	1.52	0.0%	0.3	0.2%	1.41	5.1%	34.8	0.0%	0
ARE	0.3%	1.99	0.5%	3.34	0.1%	0.9	0.3%	1.76	3.4%	23.1	0.0%	0

Table A5: *Responsibility* quotas (% of 687 $GtCO_2$) for top 20 countries under different emissions projection scenarios

Country	Project Emissions Only						Historic + Projected					
	Base	Low	High	Constant	All Net Zero (2050)	OECD Net Zero (2035)	Base	Low	High	Constant	All Net Zero (2050)	OECD Net Zero (2035)
USA	10%	12%	5.9%	15%	15%	3.1%	18%	21%	12%	21%	23%	16%
E.U.	5%	5%	3.6%	8.3%	8.3%	1.9%	11%	14%	7.7%	14%	15%	11%
CHN	32%	31%	25%	29%	29%	38%	22%	20%	22%	20%	17%	24%
IND	12%	14%	7.3%	7.4%	7.4%	14.4%	7.5%	7.0%	6.1%	4.9%	4.3%	8.1%
JPN	2%	2%	1.3%	3.1%	3.1%	0.7%	3.0%	3.5%	2.1%	3.7%	3.8%	2.5%
RUS	4%	5%	2.2%	4.8%	4.8%	4.6%	5.5%	6.4%	3.6%	6.2%	6.5%	6.0%
GBR	0%	1%	0.3%	1.1%	1.1%	0.2%	2.7%	3.4%	1.6%	3.3%	3.9%	2.8%
CAN	1%	2%	0.6%	1.6%	1.6%	0.3%	1.7%	2.0%	1.0%	1.9%	2.0%	1.3%
KOR	2%	2%	1.3%	1.7%	1.7%	0.4%	1.3%	1.3%	1.2%	1.3%	1.2%	0.8%
AUS	1%	1%	0.4%	1.2%	1.2%	0.2%	1.0%	1.2%	0.6%	1.1%	1.1%	0.7%
MEX	1%	1%	0.5%	1.2%	1.2%	0.3%	1.0%	1.1%	0.7%	1.2%	1.2%	0.8%
BRA	1%	1%	1.7%	1.3%	1.3%	1.7%	1.2%	1.0%	1.5%	1.1%	1.0%	1.3%
IDN	2.4%	0.7%	11.4%	1.8%	1.8%	2.9%	1.6%	0.8%	8.3%	1.2%	1.1%	1.7%
IRN	2.8%	3.1%	2.0%	2.2%	2.2%	3.4%	1.9%	1.8%	1.7%	1.6%	1.4%	2.1%
SAU	1.7%	1.0%	3.1%	1.7%	1.7%	2.1%	1.3%	0.9%	2.4%	1.2%	1.1%	1.4%
TUR	1.2%	1.2%	1.0%	1.2%	1.2%	0.2%	0.9%	0.8%	0.9%	0.8%	0.8%	0.5%
UKR	0.3%	0.3%	0.4%	0.6%	0.6%	0.4%	1.1%	1.3%	0.8%	1.4%	1.5%	1.2%
ZAF	0.9%	1.0%	0.6%	1.4%	1.4%	1.1%	1.1%	1.2%	0.8%	1.3%	1.3%	1.2%
QAT	0.3%	0.2%	0.5%	0.3%	0.3%	0.4%	0.2%	0.2%	0.4%	0.2%	0.2%	0.2%
ARE	0.3%	0.2%	0.6%	0.5%	0.5%	0.4%	0.3%	0.3%	0.5%	0.4%	0.4%	0.3%

Table A5: Quotas for top 20 countries under MCDM preference scenarios

Country	Traditional		Uniform		Accountable		Fair		Realistic	
	Percent	$GtCO_2$	Percent	$GtCO_2$	Percent	$GtCO_2$	Percent	$GtCO_2$	Percent	$GtCO_2$
USA	18%	123	19%	128	16%	107	17%	118	32%	218
EU	14%	95.1	16%	112	15%	106	18%	123	23%	161
CHN	16%	112	14%	95.0	15%	106	13%	88.8	8.4%	57.5
IND	8.2%	56.2	5.7%	39.2	4.7%	32.0	3.3%	22.5	1.8%	12.1
JPN	3.9%	26.5	4.0%	27.2	2.6%	17.9	3.4%	23.4	7.9%	54.1
RUS	3.6%	24.6	3.3%	22.6	4.8%	33.2	3.8%	25.9	0.9%	6.20
GBR	3.0%	20.3	2.8%	19.1	2.5%	17.5	2.8%	18.9	4.2%	28.8
CAN	1.5%	10.4	1.8%	12.5	1.8%	12.1	1.9%	12.8	2.6%	18.0
KOR	1.2%	8.25	1.4%	9.83	1.1%	7.49	1.2%	8.40	2.5%	17.2
AUS	1.0%	7.01	1.3%	9.22	1.2%	8.28	1.4%	9.51	2.1%	14.6
MEX	1.4%	9.8	1.3%	8.76	0.9%	6.09	1.0%	6.81	1.9%	12.8
BRA	2.0%	13.5	1.2%	8.25	0.9%	5.92	1.1%	7.69	1.1%	7.67
IDN	1.9%	13.0	1.3%	8.90	1.1%	7.27	0.9%	6.33	0.7%	4.50
IRN	0.9%	6.31	1.0%	7.19	1.4%	9.79	1.0%	6.70	0.3%	1.84
SAU	0.7%	5.11	0.9%	6.32	1.3%	8.82	1.1%	7.85	0.4%	2.94
TUR	0.9%	5.98	0.9%	6.04	0.7%	4.72	0.7%	4.51	1.2%	7.97
UKR	0.8%	5.84	0.9%	6.03	1.4%	9.33	1.1%	7.44	0.1%	0.547
ZAF	0.8%	5.66	0.9%	5.93	1.2%	8.34	1.0%	6.82	0.2%	1.44
QAT	0.1%	0.881	0.9%	5.87	1.4%	9.83	1.5%	10.5	0.1%	0.759
ARE	0.3%	2.07	0.7%	4.76	1.1%	7.28	1.2%	8.10	0.2%	1.67

Appendix B:

Table B1: Geological Storage as a Percent of CDR Quota

Country	Responsibility	Capability	Equality
Australia	2926.2%	2060.1%	10046.6%
Bangladesh	3169.9%	783.3%	137.3%
Brazil	31456.6%	13232.6%	10827.1%
Canada	1401.4%	1452.7%	5936.5%
China	1675.9%	1367.2%	1243.1%
EU	51.1%	54.6%	155.7%
India	212.1%	194.0%	38.5%
Indonesia	24.3%	15.6%	5.8%
Japan	529.8%	357.2%	1322.0%
Jordan	3124.4%	2605.0%	1000.3%
Malaysia	1144.3%	936.5%	975.0%
Mexico	1186.2%	1036.0%	876.2%
New Zealand	2028.0%	956.3%	3757.0%
Norway	7754.6%	2636.0%	17957.5%
Pakistan	1516.7%	1522.9%	162.2%
Philippines	1658.8%	794.8%	236.4%
Russia	14.0%	54.8%	53.2%
Saudi Arabia	78.6%	85.1%	161.5%
South Korea	1372.7%	770.7%	2224.6%
Sri Lanka	2911.2%	896.9%	318.6%
Thailand	327.7%	245.6%	163.2%
United Arab Emirates	251.0%	149.7%	571.2%
United Kingdom	234.9%	358.3%	1305.2%
United States	1352.3%	1433.6%	8114.9%
Vietnam	773.5%	571.3%	139.5%

Appendix C: BECCS capacity

Table C1: BECCS capacity using marginal agricultural land

Land by regions (mha)							
	Africa	**China**	**Europe**	**India**	**South America**	**U.S.**	**Total**
S1	66	52	33	18	108	43	320
S2	132	134	102	110	156	68	702
S3	481	213	109	138	343	127	1411
S4	314	152	111	151	256	123	1107
Net energy gain (GJ x 10^9)							
	Africa	**China**	**Europe**	**India**	**South America**	**U.S.**	**Total**
S1 Min	4.0	3.1	2.0	1.1	6.5	2.6	19
S1 Max	9.2	7.3	4.6	2.5	15.1	6.0	45
S2 Min	7.9	8.0	6.1	6.6	9.4	4.1	42
S2 Max	18.5	18.8	14.3	15.4	21.8	9.5	98
GHG Content (Gt CO_2)							
	Africa	**China**	**Europe**	**India**	**South America**	**U.S.**	**Total**
S1 Min	0.39	0.31	0.19	0.11	0.64	0.25	1.89
S1 Max	0.91	0.72	0.45	0.25	1.49	0.59	4.41
S2 Min	0.78	0.79	0.60	0.65	0.92	0.40	4.14
S2 Max	1.82	1.85	1.40	1.52	2.15	0.94	9.67
Net emissions, 90% CO_2 capture rate (Gt CO_2/year)							
	Africa	**China**	**Europe**	**India**	**South America**	**U.S.**	**Total**
S1 Min	0.31	0.25	0.16	0.09	0.51	0.20	1.51
S1 Max	0.73	0.57	0.36	0.20	1.19	0.47	3.53
S2 Min	0.62	0.63	0.48	0.52	0.74	0.32	3.32
S2 Max	1.45	1.48	1.12	1.21	1.72	0.75	7.74

Notes:

1. From (Cai, Zhang, and Wang 2011): "S1, marginal mixed crop and vegetation land (part of abandoned land); S2, S1 and marginal cropland (abandoned and degraded crop land); S3, S2 and marginal grassland, savanna, and shrubland (land with LIHD); S4, S3 discounted by the land possibly used for pasturing at present. The [net energy gain is] 60-140 GJ/ha for mixed second-generation biofuel feedstocks such as switchgrass and miscanthus, [...] planted on the marginal croplands."
2. Only S1 and S2 are used to calculate potential CO_2 capture capacity for BECCS, as the environmental impact of S3 and S4 would be considerably higher.
3. The Min and Max designations are related to low and high ranges for net energy gain (60-140 GJ/ha).
4. The emission factor for miscanthus of 98.4 kg CO_2 per G.J. is used, which is lower than the value for switchgrass of 104.5 kg CO_2 per G.J. This results in a lower, and therefore more conservative, carbon capture potential. Emission factors are derived from feedstock lower heating values and carbon contents.
5. Feedstock emission factors would more accurately be applied to gross feedstock energy capacity, which would increase net capture potential. However, the current method does not consider emissions from harvesting, transporting, and converting feedstocks into useful energy, which would decrease capture potential. The degree to which these considerations offset is not explicitly assessed.

Appendix D: Land Versus Electricity Prices in Select Countries

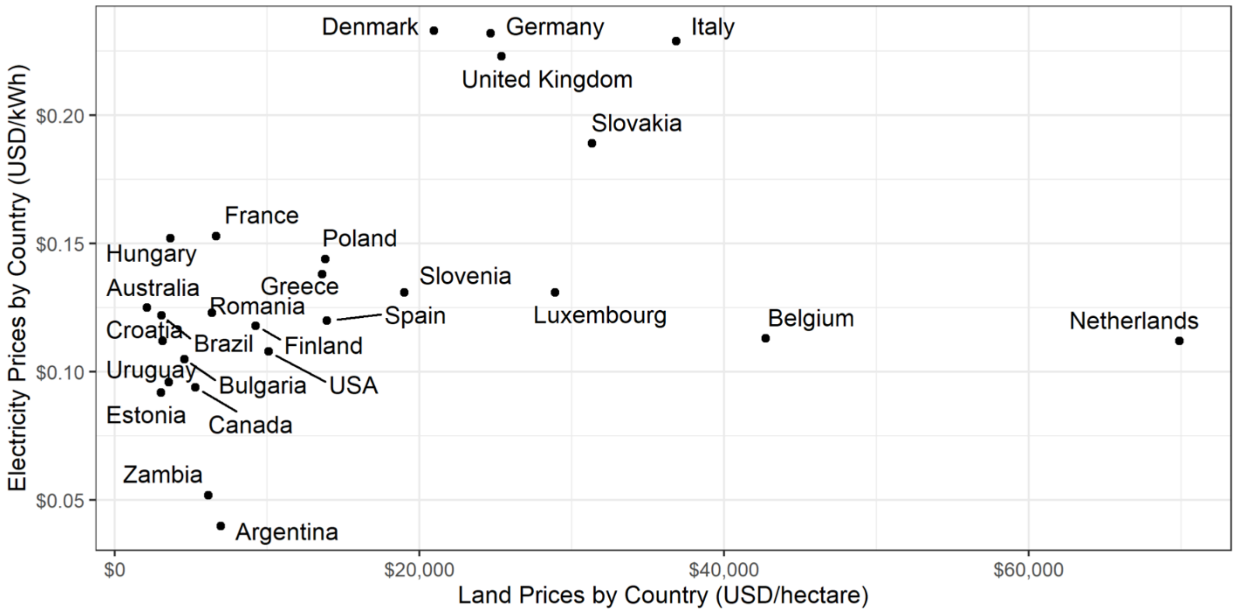

Figure D1: Land prices vs Electricity prices. With the exception of Belgium and the Netherlands, land and electricity prices are largely correlated. Areas with higher land prices also have higher electricity prices("Eurostat - Data Explorer" n.d.; Bailey, Buckingham, and Coghill 2018; "Electricity Prices around the World" n.d.).