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Abbreviations

AU	adoption unit
CAPEX	capital expenditures
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
GHGs	greenhouse gases
Gt	gigaton

GWh	gigawatt-hour
GWP	global warming potential
GWP100	global warming potential, 100-year basis
GWP20	global warming potential, 20-year basis
ha	hectare
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
lbs	pounds
LCOE	levelized cost of electricity
Mha	megahectare
Mt	megaton
MW	megawatt
OPEX	operating expenses
R&D	research and development
t	metric ton
US	United States
U.S. EPA	U.S. Environmental Protection Agency
yr	year

Principles of the Drawdown Explorer project

The Drawdown Explorer builds on Project Drawdown's previous climate solutions library and the Drawdown Roadmap strategy for accelerating climate solutions to deliver information about climate solutions that is grounded in evidence and placed in its appropriate context. It goes beyond the previous work by incorporating these qualities:

- **Current:** We provide the latest information about what climate solutions are proven to reduce emissions or sequester carbon.
- **Transparent and Accessible:** We do this in a way that is transparent to the public and to other researchers by clarifying our assumptions and the limitations around our analytical work, as well as providing our calculations and sources.
- **Interactive:** We present this information with options for the user to select the regions, sectors, and technologies they are interested in, as well as opportunities to change the assumptions and view the effects on the key metrics.
- **Simple and Understandable:** We move away from using more complex modeling in our analysis to prioritizing simplicity in analytics, straightforwardness in our assumptions, and clear communication about what we know and don't know. We do this in a way that

makes sense to an intelligent, curious, high-school-educated audience without requiring specific background knowledge.
- **Explorable and Discoverable:** We design the structure of the website, links among solutions, and graphs to guide the user to discover connections and to find new solutions and new ideas for implementation as a result of browsing the content.
- **Geographic:** We highlight where solutions are most applicable, where they aren't applicable, and where solutions may have strong potential even if not being currently adopted.
- **Actionable:** We highlight *who* has influence over the solutions and *how* they can influence their adoption according to the role they're playing in society.
- **Holistic:** We recognize that benefits to new technologies and practices, as well as their limitations, extend beyond their impact on climate and highlight other benefits or risks to human well-being and broader planetary health.
- **Comprehensive:** We study proposed solutions that may not have all the characteristics of a Highly Recommended Project Drawdown climate solution with the same analytical attention to the evidence and we share information about their potential.

Solutions

A climate solution is a practice and/or a technology that can reduce the amount of warming agents in the atmosphere. A Highly Recommended solution is currently available, proven, low-risk, and has a meaningful impact given the scale of our current emissions. This typically means it has the potential to reduce or sequester at least 0.1 Gt CO_2-eq/yr.

The solutions are organized into groupings that indicate their means of impact as well as where it takes place.

Modes of Action

The mode of action for a given solution describes how it makes a material impact on the composition of the atmosphere. The options are:

- **Cut Emissions**
- **Remove Carbon**
- **Cut Emissions and Remove Carbon**
- **Other**

Cutting emissions means adding fewer warming agents to the atmosphere each year. Removing carbon includes sequestration in natural carbon sinks or engineered CO_2 removal. Some climate solutions achieve both emissions cuts and carbon removal. Solutions may be categorized as Other if they address climate warming through other means (e.g., Deploy Stratospheric Aerosol

Injection) or if they are societal improvements that can have climate effects (e.g., Support Family Planning & Education).

These modes of action correspond to the three areas in Project Drawdown's strategy for advancing climate solutions and transforming society, consistent with prior assessments (Wilkinson, 2020):

- reduce sources of emissions
- support sinks that take up carbon
- improve society so that transformation is safe and equitable.

Most societal improvements are not explicitly quantified as a separate climate solution in this assessment work; rather, the aspects of each climate solution relevant to human well-being, equity, and justice are addressed within each solution.

Sectors

The solutions are grouped into sectors based on where the material impact on the atmosphere takes place; that is, where the warming agents are being emitted or sequestered.

We group solutions for assessment into high-level sectors:

- **Buildings**
    - This sector includes solutions addressing emissions that occur at a building site due to construction, operation, and end of life. Any emissions removed from the atmosphere and sequestered by building materials at the building site also fall within this sector. Solutions addressing climate pollutants emitted during the manufacture and transport of building materials fall under the Industry, Materials, and Waste and Transportation sectors, respectively. Solutions addressing emissions from electricity used by buildings, including electricity generated at the building site, fall in the Electricity sector.
- **Electricity (see Sector-specific methodologies: Electricity sector assessments for details)**
    - This sector includes solutions that lower the emissions of GHGs and other climate pollutants from generating electricity. We also include solutions that may not mitigate emissions per unit of electricity generation, but instead reduce the amount of electricity we need to generate through efficient transmission and distribution of electricity or reductions in end-use demand for electricity.
- **Food, Agriculture, Land, and Ocean**
    - This sector includes solutions addressing emissions that occur on land, in oceans, and in parts of the food system. These include: curbing the growing demand for food and other land and ocean products; protecting and managing ecosystems;

and shifting agricultural practices. Some of these solutions also sequester carbon, and in that case they also fall into the Nature-Based Carbon Removal sector. Emissions resulting from transport of food, fiber, and other land and ocean products are addressed in the Transportation sector. Emissions resulting from industrial food processing are classified in the Industry, Materials, and Waste sector. Solutions addressing emissions from electricity used by the agricultural and food industries fall into the Electricity sector.

- **Geoengineering**
  - These are solutions that are designed to manipulate the environment to counteract the impact of climate pollutants in the atmosphere.
- **Health & Education**
  - This sector includes solutions that improve well-being for humans and the climate impacts of those changes.
- **Industrial Carbon Removal**
  - This sector includes solutions addressing emissions removed from the atmosphere by industrial processes and engineered devices. Solutions addressing emissions from electricity used by these devices fall into the Electricity sector.
- **Industry, Materials, and Waste**
  - This sector includes solutions addressing emissions that occur in manufacturing, waste management, and processing of materials. The transportation of materials to a manufacturing site or waste to a waste disposal site falls into the Transportation sector. Solutions addressing emissions from electricity used in industry and waste processing fall into the Electricity sector.
- **Nature-Based Carbon Removal**
  - This sector includes solutions removing carbon from the atmosphere by nature-based processes on land and in the oceans.
- **Other Energy (see Sector-specific methodologies: Methane abatement assessments for details)**
  - This sector includes solutions addressing emissions that occur in production, processing and refining, pipeline transmission, storage, and distribution of fossil fuels. Emissions resulting from transporting fossil fuels by ships, rail, or road fall into the Transportation sector. Emissions resulting from burning fossil fuels at the point of use fall into the Buildings; Electricity; or Industry, Materials, and Waste sectors, depending on where the fossil fuels are being consumed. Solutions addressing emissions from electricity used by the fossil fuel industry fall in the Electricity sector.
- **Transportation**
  - This sector includes solutions addressing emissions that occur in transporting people or goods via land, water, or air. Solutions addressing emissions from electricity generation used for transportation fall into the Electricity sector.

Some solutions have impacts in multiple sectors. Since we do not quantify the proportions of avoided emissions or carbon removed in each sector, we have cross-sector solutions that fall into the following combined sector categories:

- **Buildings & Electricity**
- **Electricity & Industry**
- **Food, Agriculture, Land, and Ocean & Nature-Based Carbon Removal**

If a technology or practice is physically located in one sector but the emissions reductions occur in another sector, the solution is classified in the sector where the emissions are reduced and not where the device is located. For example, emissions attributed to the Buildings sector only account for fuels burned on site (Wilkinson, 2020), but many technologies implemented in buildings can reduce emissions in the Electricity and Industry sectors.

Solution Categories

All Drawdown Explorer climate solutions are categorized as **Highly Recommended**, **Worthwhile**, **Keep Watching**, or **Not Recommended**. Solution categories are determined based on an assessment of the current state of the technology or practice, including current costs and potential impact on climate pollution or climate change using a specific set of evaluation criteria:

- **Plausibility:** Are the underlying physical, chemical, or biological processes understood to cut emissions or remove carbon from the atmosphere?
- **Readiness:** Does the solution exist in the real-world market beyond R&D or "pilot" scale and is it ready to deploy at scale?
- **Evidence:** Are there multiple, independent sources of credible (especially peer-reviewed) empirical evidence that allow us to quantitatively evaluate the effectiveness of the solution?
- **Effectiveness:** Does the solution reliably reduce emissions or remove carbon as intended?
- **Impact:** At a realistically achievable level of adoption, could the solution reduce emissions or remove carbon by ≥0.1 Gt CO_2-eq per year?
- **Risk:** At a realistically achievable level of adoption, are there potentially serious risks that are unlikely to be overcome? These include risk of harm to ecological or Earth systems, or risk of perpetuating fossil fuel production and use.
- **Cost:** Is the solution cost-effective (<~US$100–300/t CO_2-eq)? Is the solution more expensive than other functionally comparable solutions?

Possible answers for each of the evaluation criteria are: "Yes," "No," "Limited," or "?," which means the answer is unknown or uncertain. Answers for each solution category are provided in Table 1.

Table 1. Solution categories and evaluation criteria

Solution category	PLAUSIBLE Could it work?	READY Is it ready?	EVIDENCE Are there data to evaluate it?	EFFECTIVE Does it consistently work?	IMPACT Is it big enough to matter?	RISK Is it risky or harmful?	COST Is it cheap?
Highly Recommended	Yes	Yes	Yes	Yes	Yes	No	Yes/?/No
Worthwhile	Yes	Yes	Yes	Yes	No	No	Yes/?/No
Keep Watching	Yes	Yes/No	Yes/Limited/No	Yes/?/No	Yes/?/No	No	Yes/?/No
Not Recommended	Yes/No	Yes/No	Yes/Limited/No	Yes/?/No	Yes/?/No	Yes/?/No	Yes/?/No

A **Highly Recommended** solution needs to meet all these criteria except the cost criterion. However, the cost must not be exorbitant compared to another functionally equivalent solution.

Worthwhile solutions are plausible and effective based on existing evidence, but their projected global climate impact at a realistically achievable level of adoption is likely to be less than 0.1 Gt CO_2-eq per year. These solutions could still be appropriate to deploy, or more impactful in limited applications – for a particular region, company, or community.

Plausibility and risk are the key criteria used to distinguish between **Keep Watching** and **Not Recommended** solutions. Although all technologies pose risks, we specifically assess whether implementation of the solution would incur novel or unknown ecological and environmental risks (e.g., disrupt nutrient balance or food webs) or could drive future fossil fuel production or use.

Keep Watching solutions must be plausible, not incur serious risks, and not drive future fossil fuel production or use, but they could lack evidence, readiness, or effectiveness. Proposed solutions that have sufficient effectiveness and readiness are also categorized as **Keep Watching** if they are not cost-effective compared to a functionally equivalent alternative climate solution. These proposed solutions can be revisited and updated when they are further along.

Not Recommended solutions are either not plausible or too risky to implement at scale. Two broad categories of risk are considered when categorizing solutions: (1) risk to ecological processes or earth systems function; and (2) risk that implementation of the solution will drive future fossil fuel production and use. These proposed solutions are **Not Recommended** for implementation and are unlikely to be revisited unless risks are mitigated.

Methods for conducting solutions assessments

Solution assessment documentation and contributors

Each solution is assessed by a team of scientists and fellows. The lead research fellow is responsible for the literature review, primary data analysis, and narrative drafting and editing. The lead scientist guides the fellow and provides critical feedback on both the data and the narrative document, including determining the boundaries of the solution and verifying results.

For Highly Recommended solutions, data is captured in an assessment spreadsheet to estimate key quantities at a global level. A second scientist and fellow also provide a thorough internal review of the assessment spreadsheet and narrative for accuracy. After internal review by all scientists and fellows, Highly Recommended solutions are reviewed by external experts on the topic. The lead fellow uses the input of the reviewers to edit and improve the assessment with the help of the second fellow, and the scientists provide final approval for the solution assessment to be released to the public.

Studying and citing literature

We gather literature from peer-reviewed journals, governmental bodies, nonprofits, academic institutions, conferences, workshops, and industry information compiled for practitioners. While peer-reviewed literature in high-quality journals is preferable, the most practical and recent information may be located outside of the academic domain. Although we aim to be as comprehensive as possible when aggregating sources, we do not perform a formal statistical meta-analysis across all relevant single studies.

We typically survey literature from the past 10–20 years, and the results focus on the data relating to the solution's adoption in the past decade. For solutions that are changing rapidly, only data from a few recent years may be deemed relevant to estimating their adoption, effectiveness, or costs. Information from peer-reviewed literature is preferable as a general rule; however, peer-reviewed publications tend toward academic concerns while the more practical data we need for assessing a solution may be located elsewhere.

Selecting literature for global estimates

Each fellow has the responsibility to judge what literature is worth spending time studying, and what literature is relevant and trustworthy enough to be included in their assessment. Most solutions will not have comprehensive global coverage for all of the quantities we assess. When global data are available, we prioritize them and use regional and subregional data to add detail and substance to the Geographic Guidance section and to help put the global numbers in perspective. Where global data are not available, regional and sub-regional data may be used to estimate global quantities with the understanding that this imposes greater uncertainty on the global estimates.

Broadly, we give preference to:

- comprehensive and authoritative global data aggregated by a widely recognized source
- comprehensive regional data, typically covering a continent or a defined set of countries, that we record in its raw form and then aggregate into global data
- individual country data that we record in raw form and then aggregate into global data.

While it would be preferable to find data for each country and aggregate them, due to the time-consuming nature of the homogenization and aggregation effort, we select the most relevant countries for which data are available and base our estimate on those data. This means capturing the most populous countries, those with the greatest emissions relevant to that solution, and/or those to which the solution is most applicable.

Subnational data are of great interest to capture and use for geospatial analysis; however, we do not base global estimates for major assessment quantities on subnational data or single locations.

We avoid relying on a single study or a single source for data used to calculate the numbers presented in our assessment. When a thorough search reveals no alternative data sources, even regional or subregional, we attempt to find other data that can be used to verify the numbers from the single source and/or calculate our own high-level estimates.

Excluding literature from results

Occasionally we gather literature that is relevant to the topic, but decide that the data provided should not go into calculating the final results. Reasons include:

- The study is low quality.
- Its results do not directly answer the question we are investigating.
- Its methods are unclear or not well suited to the question we are investigating.
- It is specific to a particular city or region and cannot reasonably be weighted as part of the final global results.

Because the information may be useful to other researchers, we retain documentation of these sources, but exclude them from our quantitative assessment. In the assessment spreadsheet, this is indicated with a checkbox to “Exclude” which changes the formatting to visually and changes the results for median, mean, standard deviation, minimum, 25th percentile, 75th percentile, and maximum values so that the value for the excluded row is not taken into account. When only one paper remains in the calculated results, standard deviation will be undefined.

Capturing original data

Data taken from literature are entered in their original form with their original units. For consistency and comparison across solutions, these data are converted into a common implementation unit (Table 2).

If a source provides a conversion factor or information on how to obtain the conversion factor we need, we take the conversion factor directly from the source. Otherwise, we obtain or estimate the conversion factor and make sure we consistently use the same conversion factor anywhere the same conversion is needed.

We provide sources for every number unless we make an assumption ourselves, in which case we provide a justification for our reasoning.

Assessment key quantities

We calculate key quantities for each Highly Recommended solution, but specific units are necessary to ensure that climate impacts can be compared across solutions. Units may vary depending on whether adoption is based on cumulative implementation or on a rate of implementation. If adoption is based on cumulative implementation, we expect it to scale over time. If adoption is based on a rate of implementation, we do not expect it to scale over time. The assessment units used in each of these cases are summarized in Table 2.

Key quantities are calculated for each solution relative to a 2023 baseline. Where 2023 data are not available, the most recent available data are used. We calculate CO_2-eq values on both a 100-year basis and a 20-year basis for the reasons described in Global Warming Potential values below.

Table 2. Metrics used for solution assessment categories (AU = adoption unit)

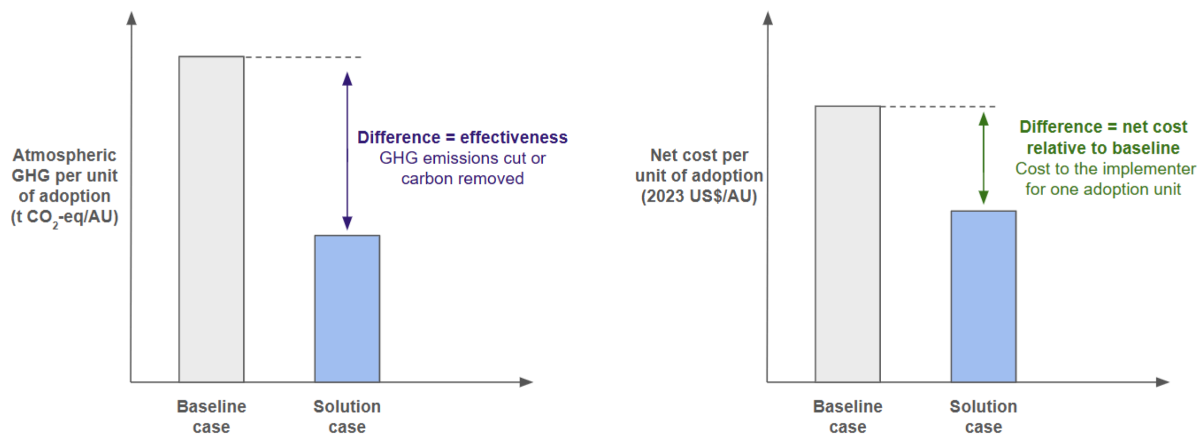
Key quantity	**Metrics for solutions where adoption is cumulative**	**Metrics for solutions where adoption is rate based**
Examples of solutions with this type of adoption	Use Heat Pumps, Protect Coastal Wetlands	Improve Cement Production, Mobilize Electric Cars
Effectiveness	t CO_2-eq/AU/yr (100- or 20-yr)	t CO_2-eq/AU (100- or 20-yr)
Adoption (Current, Ceiling, Low and High Achievable)	AU	AU/yr
Adoption Trend	AU/yr	AU/yr/yr
Cost	2023 US$/AU/yr	2023 US$/AU
Cost per Climate Impact (Cost / Effectiveness)	2023 US$/t CO_2-eq	2023 US$/t CO_2-eq
Climate Impact (Adoption x Effectiveness)	t CO_2-eq/yr (100- or 20-yr)	t CO_2-eq/yr (100- or 20-yr)

Units for Climate Impact and Cost per Climate Impact are consistent for all solutions regardless of whether adoption is based on cumulative implementation or on a rate of implementation (see Sector-specific methodologies: Capturing capacity and lifetime for rate-based adoption for details on Cost calculations).

Baseline cases

We define and quantify solutions in reference to a baseline, defined as the current activities or technologies the solution is replacing. The baseline represents the scenario if the solution is not adopted. Effectiveness and Cost are calculated as the difference between the baseline case and the solution case. We use 2023 or the most recent data available for baseline cost and emissions.

Figure 1. Example comparison of baseline and solution for Effectiveness (left) and Cost (right)



For all electricity generation solutions, we use a common baseline across technologies to allow for meaningful comparison. This baseline reflects the emissions intensity from electricity production worldwide as of 2023. See the Electricity sector assessments appendix for further details and implications of this methodology.

Capturing ranges, distributions, and uncertainty in data

Where the literature provides ranges and distributions of values, we capture this information to use for context for similar numbers found in other sources, and where possible, for providing graphs and charts that illustrate the possible ranges for that metric.

If a study reports a single value for the quantity of interest, we capture the data value of interest, the minimum value, if provided, and the maximum value, if provided.

If a study synthesizes multiple studies (including meta-analyses and reviews) or a database provides a distribution or collection of values, we capture the median, mean, minimum (0th percentile), 25th percentile, 75th percentile, and maximum (100th percentile) values.

Making conversions and assumptions

We record the original data coming from a source for transparency and completeness, but we also use a common adoption unit for comparing different numbers within the same assessment, and we calculate the same quantities in the same units (e.g., t CO_2-eq emissions reduced) across different solutions for comparison purposes.

We thoroughly document the transformation from the original data to the common unit. Each conversion factor (except standard unit conversions) is documented, and consistently applied across the solution (e.g., the same assumption of average heat pump capacity is used for all quantities for heat pumps where an average capacity is needed to calculate something).

If we need to make assumptions to reach our desired quantities, we:

- minimize the uncertainty associated with assumptions.
- minimize the number of assumptions we need to make.
- prioritize assumptions from authoritative sources on the topic.
- prioritize simplicity and explainability in assumptions.

For transparency, we record the conversion factors we use and assumptions we make.

Reporting quantities

Results of quantitative analysis

Reported values for quantitative sections of the assessment (Effectiveness, Cost, Learning Curve, Adoption, Climate Impact) are by default the median values of the sources used in each section. In cases when a different calculation such as a mean or weighted average would be more appropriate for a particular data set and calculation, the science team can approve this in place of a median. The type of calculated value should be clearly communicated in the spreadsheet and narrative. Excluded studies are not included when calculating the average or median values.

Some solutions require additional calculations to get an average global value. If calculated estimates are determined to be more appropriate than median or average values, we describe the methods and reasoning for using the calculated value.

Significant figures

To avoid losing information and minimize rounding error, we do not truncate values stored in the spreadsheet. We track the significant figures for all input data, and assessment results only include the appropriate number of significant figures according to Stewart (n.d.), up to a maximum of 4 significant figures.

Carbon, CO_2, and other GHGs

A metric ton (t) is 1,000 kg, or about 2,205 lbs, and is the standard reporting unit for quantities of GHG

Quantities measured in terms of elemental carbon are converted into units of atmospheric CO_2.

Global warming potential

Global warming potential (GWP) values indicate how much warming will result from 1 ton of an emitted gas compared with the warming resulting from 1 ton of emitted CO_2. CO_2 always has a GWP of 1 because it is the standard against which other gases are normalized. Because the warming associated with any given gas will change over time according to its ability to absorb energy and its lifetime in the atmosphere, a fully specified GWP value must indicate the time frame over which warming is considered. Multiplying an amount of a given GHG (in tons) by its GWP value will yield the CO_2-eq, which is the number of tons of CO_2 that would have the same warming effect as the specified tons of the specified gas within the specified time frame.

The most commonly used time frame for reporting GWP values is 100 years. Because this is the most commonly specified type of GWP value in the literature, including major climate data sources like the Intergovernmental Panel on Climate Change (IPCC), we show the CO_2-eq quantities based on 100-year GWP values by default.

However, a common alternative to the 100-year GWP value that is increasingly of interest to climate researchers is the 20-year GWP value. Gases that have a shorter lifetime than CO_2, such as methane (CH_4), will have a higher GWP within a 20-year time frame because they absorb energy very quickly after being emitted. Their 100-year GWP value will be lower because they do not persist in the atmosphere throughout 100 years, while CO_2 continues to absorb energy and contribute to warming after CH_4 is no longer in the atmosphere.

Because the 20-year GWP value prioritizes gases with shorter lifetimes (U.S. EPA, n.d.), it more heavily weights gases which, if their emissions were reduced, could have a quick impact on reducing climate change. Project Drawdown stresses the importance of quick, steep cuts in emissions to mitigate climate change immediately. Therefore, we show the CO_2-eq quantities based on 20-year GWP values *in addition to* the CO_2-eq quantities based on 100-year GWP values.

We always calculate CO_2-eq values on both a 100-year basis and a 20-year basis, for the reasons described above, and to enable comparison with other research which uses the more common 100-year time frame. If CO_2 emissions are the only type of emissions quantified in a solution assessment, both 20-year and 100-year values are equivalent; however, we present the 20-year values as well.

If we cannot derive the 20-year GWP value for a GHG or a group of GHGs associated with data used to assess a solution, we perform calculations based on a 100 year time frame only. We report CO_2-eq values specifying the 100-year time frame as usual with a brief note that 20-year values were not available.

Any CO_2-eq quantity in the solution narrative, spreadsheet, or any other materials associated with the solution assessment, must have a time frame specified.

GWP values in both 20-year and 100-year time frames are based on the most recent assessment published by the IPCC, currently AR6. If the IPCC does not publish a GWP value for a warming agent relevant to our solutions, we obtain the GWP value from a reputable source, such as the U.S. Environmental Protection Agency.

Money

Costs are reported in 2023 United States Dollars (US$).

For papers that contain US$, but were published in a prior year, we:

- Establish the base year for monetary conversions by:
    - Using the same base year, if explicitly stated.
    - Locating the data set if possible, and using the published date associated with the data.
    - Using the submission date for the manuscript, if available.
    - Using the publication date for the manuscript, if no options above are applicable.
- Convert the data in US$ (non-2023) to 2023 US$ using the conversions in the assessment spreadsheet. Those conversions were sourced from the Federal Reserve Bank of Minneapolis.

For papers that contain monetary quantities in other currencies, we:

- Establish the base year for monetary conversions as above.
- Locate the relevant currency and the base year in the World Currency Converter.
- Convert to US$ in the base year using the World Currency Converter.
- Adjust for inflation between the base year US$ and the standard of 2023 US$.

Guidance for preparing the assessment document

Unit of adoption

The adoption unit is how we quantify the implementation of the solution.

Key considerations for choosing the adoption unit:

- We keep the adoption unit as close as possible to the data in the literature. We minimize assumptions and conversions.
- We choose an adoption unit that is logically suited to estimating the key quantities we are assessing across all solutions.
- Where possible we use a unit consistent with prior Project Drawdown publications, unless it clearly violates the guidelines above.

We prefer a clearly defined physical unit. Ideally, the source data will require very few or no conversions or assumptions in order to estimate the key quantities in the solution assessment.

The adoption unit should be used for all adoption-related quantities, without requiring any additional assumptions. The primary scientist can grant an exception in unusual cases.

Effectiveness

Note that use of the term "effectiveness" in the Solution Assessments does not encompass all meanings of the colloquial term. In our assessment, we define Effectiveness as the ability of a solution to reduce emissions or remove carbon, expressed in t CO_2-eq per installed adoption unit.

Primary GHGs are identified on a solution-by-solution basis. For solutions that primarily mitigate CO_2 emissions, non-CO_2 emissions (including methane, nitrous oxide, and black carbon) may be neglected from calculations when they are small (e.g., less than 5% of total emissions). If data is available, climate pollutants in small quantities may be included at the discretion of the scientists and fellows evaluating that solution. When solutions mitigate emissions of multiple GHGs, all relevant gases are included in calculating Effectiveness.

We do not quantify all life cycle emissions for each solution. For more discussion of this, see Assessment Boundaries in the Limitations section.

Carbon sequestration is the removal and long-term storage of carbon in soils, sediment, biomass, oceans, and geologic formations through natural carbon sinks or industrial and power generation processes. Solutions in the Food, Agriculture, Land, and Ocean; Nature-Based Carbon Removal; and Industrial Carbon Removal sectors may use both "remove" and "sequester" when discussing processes that remove carbon from the atmosphere for long-term storage, whether biological or mechanical. Where applicable, carbon sequestration is included in calculating Effectiveness and accounted for as carbon removed from the atmosphere and stored, regardless of what system is involved, e.g., biomass, oceans, industrial processes, etc.

The Effectiveness of a particular solution is analyzed in isolation: we don't consider changes to the baseline picture of emissions or activities based on the implementation of other solutions, although they will certainly have an effect.

Units for Effectiveness: t CO_2-eq/AU/yr (100- or 20-yr) (cumulative adoption) or **t CO_2-eq/AU (100- or 20-yr)** (rate-based adoption) (see Table 2)

Cost

Cost provides an estimate of the cost to implement the solution, compared with a likely baseline alternative scenario if the solution is not adopted. When we include the initial cost in the Net Cost, we amortize it without discounting over 30 years. If 30 years is not an appropriate time period for implementing the solution, we may choose a different period and state it in the narrative.

We do not include discounted costs in our analysis to avoid making assumptions about future increases in price or inflation. For sources that do provide the discount rate and service lifetime, we recalculate undiscounted costs. We exclude data from sources that do not provide enough information to recalculate undiscounted costs.

$$Cost\ per\ Unit\ Solution\ or\ Baseline\ = \frac{Initial\ cost}{Lifetime\ (default\ 30\ years)} + \frac{Operating\ cost}{year} - \frac{Revenue}{year}$$

When amortizing costs for solutions that deal with material flows or production, we are careful not to combine facility lifetimes with annual capacities. See the Capturing capacity and lifetime for rate-based adoption appendix for more details.

We consider costs for a solution from the perspective of the implementer – those who would deploy that solution. Implementers are determined on a solution-by-solution basis. Depending on the solution, costs can be paid by producers, consumers or both. Initial costs include all up-front costs to deploy the solution. Operating costs include all costs associated with the solution while it is deployed. Reduced operating costs or cost savings that accrue to the implementer are simply negative operating costs. Revenues include money that the implementer makes as a result of deploying the solution.

We do not include end-of-life costs in Net Cost estimates for the solution or the baseline alternative. However, if end-of-life cost data are available, we mention them in the assessment.

For solutions that generate revenue from carbon credit systems (financial systems made to create an economic incentive to reduce GHG emissions), carbon credit revenue data are excluded from the analysis. Examples of solutions that rely on carbon credit systems to offset the cost of the solution are carbon capture solutions, biocovers for landfill management, and many nature-based solutions. We may discuss carbon credits qualitatively or, if data are available, specify the range of revenue that could occur.

We calculate the Cost per unit Climate Impact by dividing Net Cost by Effectiveness. This cancels out adoption units, allowing us to compare cost estimates across solutions that have different adoption units. We analyze the Cost per unit Climate Impact of a particular solution in isolation; we don't consider changes to the baseline picture of emissions or activities based on the implementation of other solutions, although they will certainly have an effect.

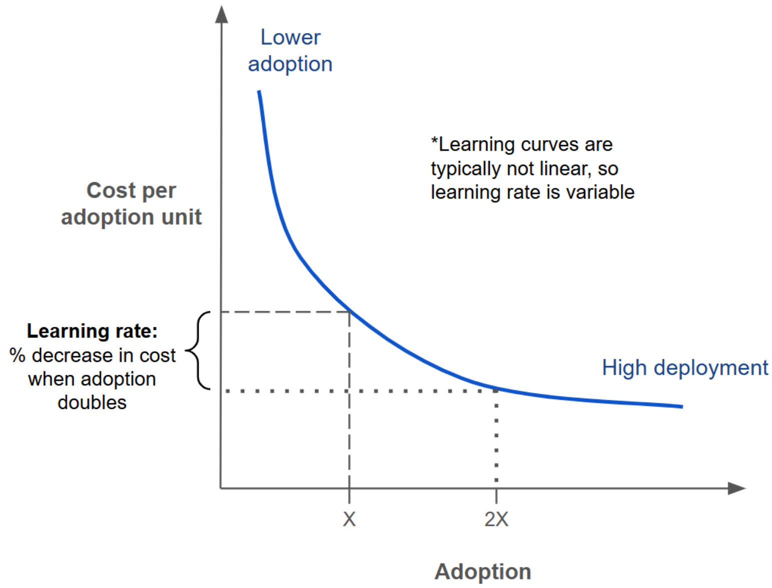
Units for Net Cost: 2023 US$/AU/yr (cumulative) or **2023 US$/AU** (rate-based) (see Table 2)

Units for Cost per Climate Impact: 2023 US$/t$CO_2$-eq (100- or 20-yr) (see Table 2)

Learning curve

The learning curve section captures the best evidence available about how costs change as more of the solution is adopted. When possible, we quantify the learning rate as the drop in cost of the solution (expressed as %) per doubling of adoption. For newer and less widely adopted solutions, the change in costs from the past 5-10 years is most relevant to understand how costs are currently changing with increasing adoption. For technologically mature solutions, considering a longer time period of cost trends may be more appropriate, or a learning rate may simply not be applicable. When it is not possible to estimate the learning rate, we describe the evidence relating increased deployment of the solution to its costs. This can include historical data relating to changes in adoption and changes in costs, while acknowledging factors that may cause our trajectory to diverge from historical trends.

Figure 2. Example of a nonlinear learning curve



Speed of Action

The term speed of action refers to how quickly a climate solution *physically affects* the atmosphere after it is deployed. This is separate from the *speed of deployment*, which is the pace at which solutions are adopted.

At Project Drawdown, we define the speed of action for each climate solution in terms of three categories: **emergency brake, gradual,** and **delayed**.

Gradual solutions have a steady, linear impact on the atmosphere. For example, if we replace a coal power plant with solar photovoltaic panels, the solar panels prevent the same amount of carbon dioxide from entering the atmosphere each year. The cumulative effect over time builds steadily over long time scales.

Emergency brake solutions work *faster* than gradual solutions. Some do so by mainly leveraging the physics of short-lived, extra-powerful climate pollutants, such as methane, fluorinated gases, black carbon, or contrails. Others, such as clearing a forest, do so by preventing a large, sudden "pulse" of carbon dioxide emissions, such as clearing a forest, the first year they are deployed.

Delayed solutions work *more slowly* than gradual solutions, mainly because they have a built-in delay to reach their full potential once deployed. Nature-based carbon removal schemes, for example, often experience some years of delay because trees and soils take time to ramp up their carbon accumulation potential. Solutions that affect long-term demographic and economic development trends in society also have built-in delays.

Most climate solutions fall into the “gradual” category. “Emergency brake” solutions deserve special attention because they can accelerate the impact of climate actions. “Delayed" solutions can be robust climate solutions, too, but due to their inherent time lags, it’s important not to expect them to reach their full potential for some time.

Current Adoption

Current Adoption captures the best data available about how many adoption units of the solution have already been adopted. Where recent data are not available, we may use data from the past 5 years to approximate the current adoption.

In non-wetland environments, soil carbon sequestration typically continues for 25–50 years (agricultural) and then asymptotically slows to close to zero as carbon accumulation comes into equilibrium with natural carbon release. We refer to this near-equilibrium state as “slowdown”. Much current adoption of biosequestration solutions has already reached slowdown and is sequestering little if any carbon. Note that this does not apply to coastal wetlands. For non-wetland solutions in the Food, Agriculture, Land, and Ocean sector, we use a conservative, simplifying adoption adjustment factor to account for soil carbon sequestration from current adoption based on land use history, time of adoption, and carbon dynamics. See Sector-specific methodologies: Adoption adjustment factor for current adoption for full details. We estimate additional sequestration potential for new adoption without an adjustment factor.

Units for Current Adoption: AU (cumulative adoption) or **AU/yr** (rate-based adoption) (see Table 2)

Adoption Trend

We capture the best data available about how much of the solution has been adopted year over year. Typically, the Adoption Trend from the past 5–10 years is relevant to understand how adoption is changing, why adoption is at its current level, and where adoption may be going based on the trend we are seeing now. For technologically mature solutions, we may consider a longer time period of Adoption Trends.

Units for Adoption Trend: AU/yr (cumulative) or (**AU/yr)/yr** (rate-based) (see Table 2)

In the text, annual trends for rate-based solutions can be described as the “annual change in adoption per year” to avoid “per year per year.”

Adoption Ceiling

Adoption Ceiling is a high practical upper limit. When applicable, this will be a physical limit based on the materials needed for the solution or on the amount of land area where the solution is applicable. To avoid overestimating carbon sequestration from land-based solutions, we only allow one solution on each unit of land (see Sector-specific methodologies: Land allocation for details). We take geophysical and ecological feasibility into account when determining adoption ceiling, but not types of feasibility addressing technological development, economic, social, and policy barriers. Adoption Ceiling is a generous upper limit of solution adoption – a number that probably can't be reached in the coming decades and will not be exceeded. When no clear limit exists, we may use a generous adoption projection for the year 2050 by a reputable source as an adoption ceiling estimate.

Units for Adoption Ceiling: AU (cumulative) or **AU/yr** (rate-based) (see Table 2)

Adoption Achievable Range

The Achievable Adoption Range is the most likely range for actual adoption within the next five to 25 years, not to extend beyond 2060.

Achievable Range estimates are consistent with Jewell and Cherp's (2023) definition of feasibility as being "do-able under realistic assumptions." We take all types of feasibility described by Steg et al. (2022, Table 1) into account when determining adoption achievable range. For technological solutions, the target characteristics described by Roberts and Nemet (2022, Section 3.2.1) are useful for selecting the characteristics of the technology that are most relevant to assessing its future adoption.

In identifying an Achievable Adoption Range, we are not predicting or forecasting what adoption will be in the future. While choosing this range requires subjective judgment, supporting data may often be found as part of the literature survey (e.g., 2050 Net Zero studies). When a reputable source provides projections between the present day and 2060, these adoption levels may be cited as guideposts for the Achievable Range.

Units for Adoption Achievable Range: AU (cumulative) or **AU/yr** (rate-based) (see Table 2)

Geographic guidance

To help users maximize the impact of their climate actions, we provide detailed maps highlighting where in the world solutions are most applicable, where they aren't applicable, and where solutions may have strong future potential. For instance, Improve Nonmotorized Transportation has greater potential for mitigating GHG emissions in urban areas than in rural ones, and Protect

Forests will be most impactful where intact ecosystems store millennia's worth of carbon in undisturbed soils.

Questions asked and answered include:

- *In what regions of the world is this solution most effective at mitigating climate change?*
- *Where is the solution adopted now? Where could it be best adopted in the future?*
- *What are the best geographic targets for scaling this solution, with maximum effectiveness and the highest potential for adoption?*

Depending on the solution, we provide a written summary of the solution's effectiveness around the world or in the regions in which it is applicable. Based on the geospatial analysis, we pinpoint hotspots for focusing future action with this solution.

The maps we include with each solution tell a place-based story that includes (as data are available):

- current status of the problem the solution is addressing
- potential effectiveness
- current levels of adoption
- corresponding impact on GHG mitigation
- potential for future adoption and GHG mitigation
- additional benefits the solution offers.

Depending on the data available, maps may present information at the level of an entire country, a smaller jurisdiction, or individual facilities. We use both raster (grids of cells like pixels) and vector (lines, points, polygons) geospatial data formats.

Raster

Figure 3. Example raster map of emissions reduction from the Protect Forests solution

Single Map | Compare Maps

Download

Select data layer: Effectiveness

t CO_2-eq/ha/yr

Effectiveness of emissions reduction from additional land protection

Legal protection of forestland is associated with decreased emissions. This map takes into account country-specific rates of successful forest protection as well as the carbon content in biomass and soils. We exclude protection of peatlands and mangroves because these lands are addressed in other solutions.

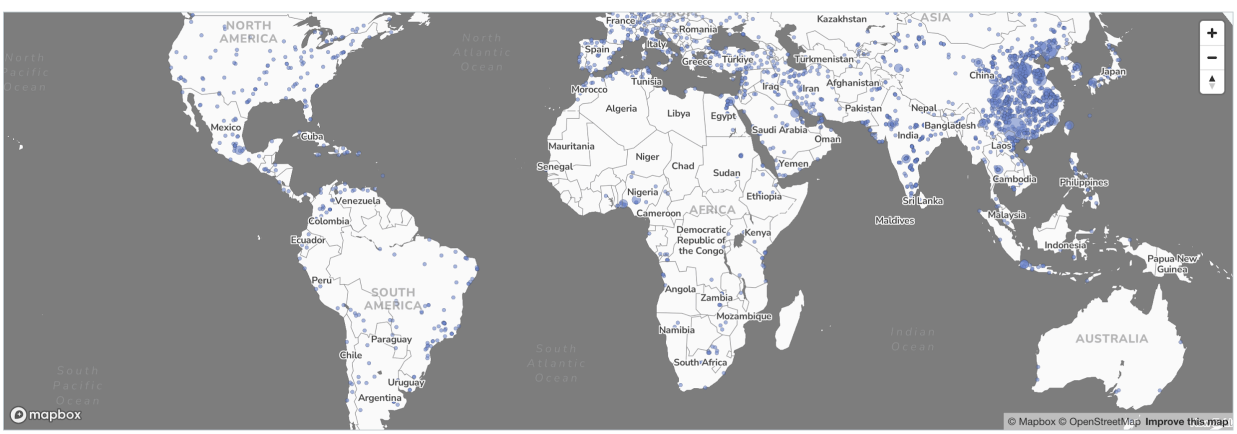
Vector

Figure 4. Example raster map of annual cement production from the Improve Cement Production solution

Single Map | Compare Maps

Download

Select data layer: Production



Mt cement/yr

< 5 | 5 - 10 | 10 - 15 | 15 - 20 | > 20

Annual cement production, 2024

Production data representing > 2.7 Gt of cement manufacturing in 2024.

We obtain geospatial data from multiple sources, including peer-reviewed journals, credible international organizations, and national governments. We process the data using Matlab or Python and map the effectiveness of this solution across the world using meta-analysis, georeferenced data points, geospatial proxy data sets, and AI "data fusion" techniques that we have developed. In most cases, the Drawdown Explorer lets users zoom in on specific locations at a resolution that enables them to see large rivers, small countries, and subnational areas within large countries. Users can also compare two maps side by side within a solution and save specific map views for further analysis or sharing with others.

Climate Impact

We typically calculate Climate Impact as [Effectiveness x Adoption]. In cases where other calculations are used (such as when an adoption adjustment factor is used), those calculations are clearly stated in the text and the impact calculator. For all climate impact calculations, adoption units cancel out, so we can compare Climate Impact estimates across solutions that have different adoption units.

The Climate Impact of Current Adoption shows the estimated climate benefit of the current level of adoption relative to the baseline alternative. The Climate Impact range between Achievable – Low and Achievable – High shows the potential climate benefit of adopting the solution within the specified Adoption Achievable Range if Effectiveness remains unchanged. The Climate Impact at the Adoption Ceiling shows the theoretical maximum climate benefit, if Effectiveness remains unchanged.

Units for Climate Impact: t CO_2-eq/yr (100- or 20-yr) (see Table 2)

Additional benefits

We provide brief descriptions of additional benefits from implementing solutions to highlight how positive impact goes beyond emissions reduction and helps improve ecosystems and human health.

Additional benefit categories are:

Climate adaptation

- Heat stress: Adverse effects of extreme temperatures on humans, wildlife, ecosystems, and infrastructure
- Wildfires: Unplanned and uncontrolled fires that ignite and consume vegetation and structures in areas such as forests, grasslands, or prairies
- Sea-level rise: Increasing ocean levels that threaten coastal communities, livelihoods, ecosystems, and infrastructure

- Extreme weather events: Severe wind, dust, or storms, including hurricanes and tornadoes, that impact communities, ecosystems, infrastructure, and social systems
- Floods: Excessive and destructive accumulation of water from abnormal, prolonged periods of above-average precipitation or from the rising of waterways that impact communities, livelihoods, ecosystems, and infrastructure
- Droughts: Abnormal, prolonged periods of below-average precipitation affecting water supply that impact communities, livelihoods, ecosystems, and infrastructure

Human well-being

- Income and work: Access to employment opportunities that support the economic status of households, communities, or governments
- Food security: Sufficient, nutritious, and safe nourishment that is physically and economically accessible at all times
- Water & sanitation: Clean water and effective sanitation, such as waste management, promote hygiene and reduce the risk of illness
- Energy availability: Access to electricity and clean cooking fuels
- Health: Physical and mental wellness, including prevention of illness, injury, and premature mortality
- Equality: Equal rights, opportunities, and treatment of all populations regardless of social, economic, cultural, and gender identities

Environment

- Nature protection: Protections that safeguard the amount, health, and diversity of species and ecosystems
- Animal well-being: Treatment of animals so as to reduce physical and psychological harm
- Land resources: The amount and health of land, including soil quality, for ecological and human use
- Water resources: Surface, ground, and rainwater used for ecological and human use
- Water quality: The amount of pollutants, sediments, and microorganisms in fresh and marine water systems that affects the health of humans, wildlife, and ecosystems
- Air quality: The amount of pollution in the atmosphere that affects the health of humans, wildlife, and ecosystems

Caveats

Additionality

Additionality describes whether emissions reductions or carbon sequestration would have occurred in the absence of a payment, policy intervention, or other activity (adapted from IPCC

[2023b]). To be testable and quantifiable, additionality must include specific eligibility criteria (Streck, 2010), and the technology or intervention must be clearly defined, with specific boundaries in time and space.

We do not recommend one path to implementing a solution. We consider any adoption of that solution to be part of that solution's Effectiveness, regardless of whether the adoption was driven by policy, private financial decisions, other causes, or unknown causes. When a solution adoption is regulated by policy (e.g., refrigerant transitions regulated by the Kigali Amendment), we acknowledge that this is the driver but consider all GHG mitigation over baseline levels for that solution to be additional. This differs from what some GHG accounting or crediting organizations would consider additional due to regulatory additionality concerns.

We qualitatively describe additionality concerns where the literature provides well-specified and quantified relevant information. Because we do not have the resources to perform our own studies determining additionality for each solution, and because establishing additionality is inherently political (Streck, 2010), we do not quantify additionality for each solution.

Financial additionality: If the financing directed toward the solution, including any component of the cost to implement revenue gained per unit of adoption, is not certain to contribute toward additional adoption compared with the baseline case, the solution may have financial additionality concerns. Because we cannot reasonably study the potential consequences of any payment or other financial activity related to each solution, we do not quantify financial additionality. However, we do acknowledge concerns as appropriate.

Mitigation (cutting emissions) additionality: If the emissions reduced or the carbon sequestered by implementing the solution are included in the baseline case or might reasonably be understood to be part of the baseline case, we acknowledge that a solution may have mitigation additionality concerns.

We do attribute future adoption that is expected to happen based on Current Adoption, Adoption Trend, or specific policies to the implementation of the solution.

Permanence

Permanence refers to whether GHGs under consideration can be permanently isolated from the atmosphere (adapted from IPCC, 2023a).

If the emissions reduced or the carbon sequestered by implementing the solution could be reversed within the next 20 years or within the next 100 years, the solution may have permanence concerns. If other time horizons are reported in the literature, we identify the appropriate time horizon when describing that research in the solution narrative. We do not capture permanence concerns that occur more than 100 years in the future.

Permanence concerns we describe include:

- the potential mechanism for reversal
- the relevant time frame within which reversal is possible (up to 100 years in the future) indicating whether the potential reversal is likely *within 20 years*, *within 100 years*, or both.
- the risk of reversal
  - We describe the qualitative risk, using these terms where evidence will support them:
    - *High risk*: Reversal is the most likely outcome according to experts or high-quality research related to the solution or sector.
    - *Medium risk*: Reversal is a significant concern in plausible future scenarios, but we cannot reasonably predict what is most likely.
    - *Low risk*: Reversal is an unlikely outcome, but is possible according to experts or high-quality research related to that solution or sector.
  - We describe the quantitative risk of reversal (up to 100 years in the future) when we can find evidence from expert statements or high-quality research to support it.

Evaluating the risk of reversal of a climate solution is a judgment call.

We discuss other critical caveats to implementing the solution outside of additionality and permanence as appropriate.

Risks

We consider how implementing the solution could harm people and the environment, or what factors could impede the solution from reaching its impact potential. Examples include low resource availability, poor technological performance, necessary cultural or behavioral shifts, increased inequity, rebound effects, land use change, and increased waste.

We also consider risks related to incorrect assumptions. The Enhance Public Transit solution, for example, assumes that public transit rides replace individual car rides. If public transit replaces bicycling or walking instead, the climate impact will be far different. Similarly, a solution that depends on behavior change could be limited by a lack of willingness to change.

Trade-Offs

We look at how implementing a solution might have adverse effects elsewhere, such as increasing emissions in other sectors or increasing embodied emissions. For example, adoption of the Deploy Offshore Wind Turbines solution could incur GHG emissions related to the production and transportation of materials, installation of facilities and cabling, and so on. When possible, we describe the magnitude of these emissions relative to the emissions savings.

Interactions with Other Solutions

“Reinforcing” means a solution would potentially increase the beneficial impact of another solution from the Drawdown Explorer that is either Highly Recommended, Worthwhile, or Keep Watching. “Competing” means a solution would potentially lower the beneficial impact of another solution.

Beneficial impacts include increasing Effectiveness, lowering Cost per unit Climate Impact, improving ability for adoption to scale quickly and cheaply, enhancing global Climate Impact, and other benefits to people and nature. Competing interactions indicate that one solution can reduce the beneficial impacts of another solution.

Solution interactions are listed in order of importance. This is a judgment call, but generally the interactions that are strongest or most impactful to global climate are at the top of the list for both reinforcing and competing interactions.

Evidence base

Evidence base refers primarily to the scientific consensus regarding the solution’s effectiveness at cutting emissions or sequestering carbon from the atmosphere. Other important aspects of the solution that have higher or lower scientific consensus may be mentioned in this section.

Take action

We provide brief descriptions of how key actors could contribute to the beneficial impacts of the solution. We also provide links to external resources as a service to those who want to do more. We cannot guarantee that external material is appropriate or accurate, but at the time of writing, each resource is reviewed for technical concerns by the lead fellow conducting the assessment.

Key actor categories are:

- **Lawmakers and Policymakers**
    - Elected officials and their staff
    - Bureaucrats and civil servants
    - Regulators, Attorneys
- **Practitioners**
    - Those who most directly interface with the technology or solution and/or determine whether the technology or solution is used and/or available
- **Business leaders**

    - Businesses involved in the sale and/or distribution of related equipment and technology
    - Businesses that want to support adoption
- **Nonprofit leaders**
    - Social welfare organizations
    - Civic leagues
    - Social clubs
    - Labor organizations
    - Business leagues.
- **Investors**
    - Individuals or institutions willing to lend money in search of a return on their investment
- **Philanthropists and international aid agencies**
    - Private, national, or multilateral organizations that are dedicated to providing aid through in-kind or financial donations
- **Thought leaders**
    - Individuals with an established audience for their work, including current or former elected or government officials, authors, academics and researchers, experts, social commentators, entertainers, influencers, athletes, opinion makers, technical experts, pundits
    - Journalists
    - Educators
- **Technologists and researchers**
    - Technology developers, including founders, designers, inventors, R&D staff and creators seeking to overcome technical or practical challenges
- **Communities, households, and individuals**
    - Groups of people willing to act on the solution directly or indirectly, including neighbors, volunteer organizations, hobbyist and interest groups, online communities of early adopters
    - Households are a collection of individuals occupying a residence
    - Individuals are private citizens seeking to support the solution

Limitations

Changes in future demand

Our analyses are conducted relative to today's global activity levels and costs. Achievable adoption for many solutions assumes that the demand, consumption, or production of the solution stays constant from current levels. This is not likely to be the case, but predicting future demand also introduces assumptions and uncertainty, and we therefore do not include this as part of our assessment.

If demand for a technology or practice grows in the future, this could mean that overall GHG emissions increase despite increased adoption of the solution. For example:

- The Improve Cement Production solution involves lowering the GHGs emitted per metric ton of cement manufactured. If overall global cement production increases, the total emissions of cement manufacturing could increase even as adoption of low-emission cement practices grows.
- The Manage Oil and Gas Methane solution supports managing methane emissions from oil and gas supply chains. If adoption increases, this means more methane is abated. If oil and gas use is constant or decreasing, increased solution adoption results in overall GHG emissions reductions. However, if oil and gas production and use ramps up then overall methane release and other emissions from fossil fuel use could increase, even as the solution is adopted in higher quantities. This is an example of a solution where decreasing adoption could reflect a positive climate impact, if coupled with reduced oil and gas use.

While changes in demand impact the emissions baseline in cases like these, it does not mean that the solution is not important to adopt. Implementing Highly Recommended solutions lead to reduced climate impact relative to baseline activities. However, reducing consumption of high-emitting materials or activities is also important for reducing overall emissions. This is a complex issue, because indiscriminately reducing technologies and practices that produce GHGs can enhance inequities as the population and development levels grow.

When increased adoption may point to increased emissions

Solutions where increased adoption is, or is likely to be, tied to an increase in emissions-producing activities are a special case because reaching high levels of adoption of the solution may indicate a climate problem. For example, higher adoption of oil and gas methane solutions might suggest more use of oil and gas and associated fossil fuel emissions.
When possible, we use units or analyses that express the solution as a proportion (e.g., percent of oil & gas methane abated, instead of Mt methane abated). If we aren't able to analyze the solution in this manner, we note this fact and emphasize that our Adoption and Climate Impact estimates do not account for future changes in demand or supply.

Quantification of interactions between solutions

For the most part we don't quantify interactions among solutions that amplify or reduce impact. In reality, as solutions are adopted and the technology landscape changes, this will impact the Adoption, Effectiveness, and Cost of solutions that target the same emissions, compete for the same resources, or rely on the development of similar technologies.

Electricity sector baseline case (see Appendix: Electricity sector assessments)

Many technologies are used to generate electricity, such as coal, gas, hydropower, and many others. For Highly Recommended solutions that generate electricity, we use a common baseline mix of global electricity generation, based on an estimated generation capacity for each existing technology.

We assume that the MWh generated by each technology in the baseline mix is proportional to the emissions from that technology, which is not necessarily the case. We also lump classes of technologies together in the baseline (e.g., all types of wind energy generation), assuming a single emission factor across these broad equipment types.

Due to the challenges in estimating global baseline costs for electricity generation, we discuss but do not report electricity generation solution costs. Actual costs depend on the available infrastructure and possible revenues on a local level, and therefore we found that a single global value was not a representative or useful metric to report.

Assessment boundaries

Greenhouse gases may be emitted throughout the lifetime of a solution technology, from material extraction to end-of-life. These emissions are often released outside of the sector(s) where the solution is cutting emissions or storing carbon, such as industrial emissions associated with manufacturing. Although we cannot quantify emissions throughout the life cycle of every solution technology, we do qualitatively review studies that provide information about the emissions associated with the solution. We do not recommend solutions whose life cycle emissions are likely to be as large or larger than the emissions cuts or carbon storage the solution can provide in its sector of action. Solutions that target emissions from food and materials may quantify emissions from multiple supply chain stages. These solutions and their boundaries are in Table 3.

Table 3. Boundaries for solutions that include life cycle emissions

Solution	**Included supply chain stages**	**Excluded supply chain stages**
Reduce Food Loss and Waste	Food production and distribution	Waste management (disposal)
Improve Diets	Food production (including farm-level	Waste management (disposal)

	emissions and land use change for crops and pasture) and distribution	
Deploy Alternative Insulation Materials	Production, manufacturing, and installation of insulation materials	Waste management (disposal)
Increase Recycling	Production, manufacturing, and disposal of primary and secondary (recycled) materials, including paper, plastic, metal, and glass	Conversion to finished products (manufacturing) and distribution (transport)
Deploy Low-Emission Industrial Feedstocks	Production (including raw material extraction), manufacturing, and use of materials	Distribution (transport), use of green hydrogen for ammonia and methanol production, secondary manufacturing of bioplastics and other building materials
Use Corn-based Ethanol	Feedstock production (including on-farm emissions and land use change), fuel manufacturing, and fuel and feedstock transportation	Tailpipe emissions of corn-based ethanol

Data availability

Our assessment is limited by available global data around effectiveness, cost, and adoption of the solutions.

Geographic limitations

Our solutions assessments are global in scope, so results may not represent regional or local impacts or costs. In addition, many solutions do not have global data available, and assessments have to be completed using incomplete regional information. Assessments are often skewed toward countries and regions with greater data access and availability, and may not represent a true global picture.

"Maps" and "Geographic Guidance" sections capture some local and regional nuance for each solution.

Cost limitations

Global average costs are difficult to determine and not necessarily representative of real implementation. Most solutions have variable local costs depending on energy generation technologies, supply chains, local resources, land condition, and other factors. As a result, we don't rank solutions by Cost or Cost per Climate Impact, although we do provide these values in our assessment.

We don't quantify revenues that are due to carbon credit systems (systems that create economic incentive to reduce GHG emissions). Although many solutions have costs impacted by the carbon credit market, these markets tend to be volatile and are heavily influenced by policy. Carbon credits are levers that key actors in policy, investing, and business can push on to advance certain climate solutions, but are outside the scope of our assessment of climate solutions.

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Appendix: Sector-specific methodologies

Electricity sector assessments

This section summarizes the methodology used to estimate baseline global electricity generation mix (in GWh) and GHG emissions intensity (in g CO_2-eq/kWh) based on the global electricity generation mix in 2023. These estimates allow comparison among climate solutions that generate electricity. Here, *cost* refers to the generation cost for utility-scale power producers, described using reported levelized cost of electricity (LCOE) (see Levelized cost of electricity generation).

We use international energy agency reports to determine the global electricity baseline. Electrical energy production and emissions are aggregated by primary energy sources (solar, geothermal, bioenergy, hydropower, wind, natural gas, nuclear and coal).

This approach simplifies real-world energy market dynamics to highlight general global trends and relationships rather than decision-relevant criteria. These estimates are not appropriate for guiding investments or for policy making. Our goal in establishing the electricity sector baseline is to define a global, static reference point for electricity sector climate solutions. We do not intend for the global baseline to be prescriptive, and it cannot reflect regional differences in market characteristics or power system dynamics, which must be included for directing capital or policies.

Total electricity generated

We assess solutions with respect to a 2023 baseline or according to the most recent data available up to 2023. The most recent global electricity sector data available at the time of this analysis were for 2022. The 2024 edition of the International Energy Agency's (IEA) report on World Energy Balances only includes preliminary electricity production data for 2023, and estimates were set equal to 2022 values for many electricity sources (IEA, 2024a). More recent data will be included in updates to future solution assessments as available.

IEA's 2022 grid mix and electricity production worldwide are summarized in Table A1 (IEA, 2024a). For analytical simplicity, we have merged oil with gas and "Other" with coal in our global electricity grid assessment (Table A1).

Oil is not a significant source of utility-based electricity generation at the global level; it is primarily used for decentralized power production, such as backup generators and off-grid applications in developing countries like Nigeria. Oil-fired power plants are increasingly rare and are either being phased out or converted to gas. Moreover, there are limited data on utilities that rely on oil-based generators as their primary electricity generation source, making its inclusion as a separate category less meaningful in a study focused on utility-scale energy sources.

The "Other" category, which includes peat and other unconventional fossil fuel sources, accounts for just 0.16% of total electricity production. Because many of these sources are carbon-intensive and share combustion-based characteristics with coal, we have combined them with coal in the final grid mix for a more streamlined and practical classification.

Table A1. Total electricity production (in GWh) and percentages of the total grid mix for each energy source

Energy Source	Electricity Production (GWh)	Percent of Total Electricity Production (IEA, 2024a)	Percent of Total Electricity Production (This Report)
Coal	10440000	35.83	35.99
Gas	6522000	22.38	25.16
Hydro	4351000	14.93	14.93
Nuclear	2685000	9.22	9.22
Wind	2120000	7.27	7.27
Oil	805800	2.77	*Combined with Gas*
Bioenergy	760200	2.61	2.61
Solar	1308000	4.49	4.49
Geothermal	97360	0.33	0.33
Other	48010	0.16	*Combined with Coal*
Total	**29140000**	**100.00**	**100.00**

We acknowledge that the assumption of a single global electricity mix is a simplification. However, it allows us to compare the global impact of climate solutions worldwide in a standardized way that is analytically tractable. Our estimated percentages of the grid mix for the global electricity sector are also comparable to estimates from The 2024 Energy Institute Statistical Review of World Energy (Energy Institute, n.d.) and Ember's Global Electricity Review (Ember, 2024).

Emissions per unit of electricity generated

We used the IPCC Tier 1 emission factors to estimate the global electricity grid emission intensity (IPCC, 2006). Based on the same IEA dataset (IEA, 2024a), this grid mix results in the following emissions intensity (100-year):

Table A2. Total GHG emissions from baseline electricity production. Unit: g CO_2-eq/kWh (100-year basis)

CO_2 emission intensity	528.5

Methane emission intensity	2.04
Nitrous oxide emission intensity	3.41

This results in a total equivalent grid emissions intensity of 534 g CO_2-eq/kWh (100-year basis). On a 20-year basis, grid emissions intensity is slightly higher, but the difference is negligible (< 2%) since CO_2 makes up the majority of electricity sector emissions, with significantly smaller contributions from methane and nitrous oxide. This emissions intensity only applies to electricity generation at the site of power production and does not include upstream emissions from the oil and gas industry, manufacturing, transportation, or other life cycle emissions. Our estimate is within 10% of comparable global emissions intensity estimates from Ember (2024).

For all electricity sector solutions, we calculate Effectiveness based on the baseline global electricity grid emissions intensity assuming that each additional kWh generated or saved by a climate solution technology displaces an equivalent kWh of the global baseline electricity grid. We assume the reduction in emissions from increased adoption of the solution to be equal to emissions (per kWh) from the 2023 global electricity grid mix.

To calculate annual Effectiveness, we convert electricity generated in kWh to electric power output or capacity in kW by dividing total energy generated by the capacity factor for a specific solution and a specified time interval. The capacity factor captures the actual amount of electricity generated compared to maximum generation, if energy sources always operate at rated capacity. For annual generation, we multiply by one year.

*Capacity [kW] = Energy [kWh] / (capacity factor * 8760 [hours])*

Levelized cost of electricity generation

We reviewed the levelized cost of electricity (LCOE) from U.S. EIA (2024), IEA (2020), IRENA (2024), and IEA (2024b). These sources also provide assumptions on power generation facility lifetimes.

LCOE values represent the average cost of producing one megawatt-hour of electricity over the operational lifetime of a power plant. These values integrate capital and operational expenditures and are commonly used to provide a standardized basis for comparing power generation economics across energy sources.

While LCOE is often cited as a key metric in power generation economics, it has notable limitations. It does not capture the time-varying value of electricity or market dynamics such as fuel price volatility, interest rate fluctuations, and policy changes (Shah & Bazilian, 2020). Additionally, LCOE does not consider site-specific variation in costs and there can be significant variation in values depending on location (Malaguzzi Valeri, 2019). Despite these limitations, LCOE provides a useful summary measure of long-term generation cost and is included here to characterize the baseline cost structure of different technologies in the global electricity mix.

LCOE alone can be a misleading metric for comparing economic competitiveness across electricity generation technologies. Published LCOE values are purely cost-based and do not reflect the demand-based value of electricity generated or market-based factors like uncertainty in interest rates and fuel prices (Shah & Bazilian, 2020). However, LCOE provides a consistent method for estimating whether additions of energy sources have the potential to be economically viable compared to the existing level of deployment.

While there are more complex metrics, such as levelized avoided cost of electricity (LACE), that consider the value of electricity in addition to generation costs, calculating them requires analyzing hourly generation and consumption data from power generating plants (Timilsina, 2020; U.S. EIA, 2022), which is outside the scope of our baseline.

Assumptions

We assume that each kWh generated by a new climate solution will displace one kWh of the baseline 2023 grid mix established in this report (and its associated emissions). Because there is no worldwide grid, the actual displaced kWh will vary by location and time.

We do not distinguish between different technologies using the same primary energy source. For example, offshore and onshore wind are both in the Wind category.

Limitations

LCOE values simplify market dynamics and can underestimate the reality of financing renewable energy projects. In some emerging markets where initial costs are higher, high LCOE values for renewables could disincentivize funding for new projects. Additionally, in markets where renewables are subsidized through power purchase agreements and tax credits, auction prices for renewable energy can be much lower than published LCOE values (Shah & Bazilian, 2020; Timilsina, 2020). We recognize that as the proportion of renewables in the global grid increases, electricity generation costs will increasingly depend on fixed-price support mechanisms that guarantee generators payment per kWh produced, but these considerations are outside the scope of our baseline because we are not projecting future generation capacity or demand (Green & Léautier, 2015).

Electricity grid mixes vary regionally. Adding more renewables into regional grids supports systemic benefits, including improved energy security (IEA, 2025). At the same time, new adoption of renewables and increasing penetration of renewable energy in electricity markets may face barriers including, but not limited to, market failures and distortions, grid integration challenges, lack of access to financing and credit, poor transmission infrastructure, inconsistent policy support, lack of investor confidence, and social acceptance. These benefits and challenges are directly tied to market dynamics, energy demand, and policy decisions, so we discuss them qualitatively, where appropriate, but do not include these risks in quantification of Costs or Effectiveness.

This methodology summarizes publicly available data (generation, LCOE, etc) for the purpose of our assessment. We do not conduct additional simulations to inform our assessments.

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Methane abatement assessments

We frame many of the sections in the Explorer differently for solutions that directly reduce methane emissions:

- Manage Oil & Gas Methane
- Manage Coal Mine Methane
- Improve Landfill Management

The adoption unit of the solution is abating one Mt of methane.

Due to directly abating a GHG, we base the Effectiveness of the solution on the global warming potential (GWP) of methane because preventing the release of methane will directly reduce global temperature rise. Because methane's GWP on a 20-year basis is much greater than its GWP on a 100-year basis, the GHG emission savings achieved by abating a given amount of methane will vary greatly depending on the time period of interest. According to the IPCC (2023a), the GWP20 value for methane has a value of 81.2 while the GWP100 is 27.9.

We quantify adoption of methane abatement solutions according to tons of methane abated rather than units of technology installed as is the case for many other solutions. We quantify Current Adoption and Adoption Trend in terms of the total methane that has historically been abated per year. We estimate the Achievable Adoption Range and the Adoption Ceiling based on the amount of methane that could be abated using the solution based on historical trends, technology for abatement, and future projections and targets.

Adoption adjustment factor for Current Adoption

Terrestrial biosequestration

For biosequestration solutions that are adopted on terrestrial uplands (on land, and not wetlands), carbon sequestration typically continues for 25–50 years (agricultural) and then asymptotically slows down to close to zero as carbon accumulation comes into equilibrium with natural carbon release (Bukoski et al., 2022; Lal et al., 2018; Paustian, 2014). The IPCC guidelines suggest use of 20 years as the period of active soil carbon sequestration (Smith, 2016). We refer to this near-equilibrium state as "slowdown." Much Current Adoption of biosequestration solutions has already reached the slowdown period and is sequestering little if any carbon. Table A3 shows sample estimates of years to slowdown.

Table A3. Estimated years to equilibrium by solution

Solution	Years to Equilibrium (soil)	Years to Equilibrium (biomass)	Source
All solutions	20		Smith (2016)
Deploy Agroforestry (tree intercropping subsolution)	25–50	5–25	Lal et al. (2018)

Deploy Silvopasture	25–50	5–25	Lal et al. (2018)
Improve Annual Cropping	25–50	n/a	Lal et al. (2018)
Improve Livestock Grazing	30–50	30–50	Lal et al. (2018)
Restore Abandoned Farmland	50	50	Lal et al. (2018)
Restore Forests	25–50	50–80	Lal et al. (2018)
Restore Forests		50–100	Zhu et al. (2018)
Restore Coastal Wetlands	indefinite		UNEP (2022)
Restore Peatlands	100	50	Lal et al. (2018)
Restore Peatlands	indefinite		UNEP (2022)

To avoid overestimating carbon sequestration from land on which practices have already been adopted, we apply adoption adjustment factors to Current Adoption of most carbon sequestering solutions. These factors are very rough estimates but more accurate than either including sequestration from all Current Adoption (clearly overcounting sequestration impact) or excluding all sequestration from Current Adoption (clearly undercounting).

We lack precise estimates of Current Adoption, so, we assign adoption adjustment factors based on our best understanding of the percentage of area that adopted the practice within the past 20 years, how much of Current Adoption is old enough to have reached slowdown, and how much is young enough to still be sequestering net carbon. For example, we estimated Current Adoption of no-till / cover cropping to be 205 Mha in 2019. Adoption began in the 1970s, and reached 106 Mha in 2008 (Kassam et al., 2022). We estimated that roughly 50% of the adoption area began in the past 20 years and assigned an adoption adjustment factor of 0.5. Our estimates are conservative because more Current Adoption may still be in net sequestration than we account for (given the wide range of years provided by Lal et al., 2018), and recent adoption may be higher than our estimate.

We break solutions into categories based on land use, time of adoption, and carbon slowdown dynamics (Table A4). For each category we provide an adoption adjustment factor. The generic formula used to calculate climate impact is:

*Climate Impact = Effectiveness * Adoption Adjustment Factor * Current Adoption*

Adjustment Categories

Farming practices adopted since the 1970s. Some practices, such as the combination of cover crops with no-till, were developed and/or popularized in the 1970s (Toensmeier 2016). Adoption continues to grow annually with substantial adoption occurring in the past 20 years (Kassam 2022, Toensmeier 2016). Carbon sequestration slowdown in agricultural systems tends to occur after 20–50 years, so we assume that some of Current Adoption has already neared equilibrium. For these solutions, which include Improve Annual Cropping, Improve Livestock Grazing, and Restore Abandoned Farmland, the adoption adjustment factor is 0.5.

Traditional farming practices with centuries or millennia of adoption. Agroforestry practices including silvopasture have been practiced for millennia, and much of Current Adoption has been in place for many centuries. Equilibrium is nearly achieved in 20–50 years, so we assume that most of the land in these practices has done so long ago. However new adoption continues and is substantial in many cases. For these solutions the adoption adjustment factor is 0.25.

Upland ecosystem protection solutions. For these solutions we calculate carbon sequestration based on actual net primary productivity (NPP) of ecosystems based on satellite observation (forests) and a global dataset of site-level measurements (grasslands and savannas), so we assume that the sequestration rates are accurate. As a result the adoption adjustment factor is 1.0. Restored upland forests don't hit slowdown for 50–200 years (Zhu et al., 2018).

Upland ecosystem restoration and management. In these solutions, equilibrium is typically reached after 50–200 years or even longer (Zhu et al., 2018). Given that our Current Adoption estimate is based on satellite images, we can assume that Current Adoption has not yet achieved slowdown. Deliberate forest restoration is also in some ways a recent development in the past 50 years (Mansourian et al., 2021). As a result the adoption adjustment factor is 1.0.

Perennial food and biomass crops. Slowdown in agricultural systems typically occurs after 20–50 years, so we can assume that much of Current Adoption has already reached saturation. However, adoption of these solutions has continued to grow in recent decades. For these solutions the adoption adjustment factor is 0.5.

Wetland protection and restoration solutions. Unlike uplands, coastal wetlands and peatlands can continue to sequester carbon for millennia in their soils because the low-oxygen environment prevents decomposition and release of CO_2 (UNEP, 2022). This is not the case for biomass, and for this reason our solutions do not calculate biomass carbon sequestration. For wetland protection and restoration solutions the adoption adjustment factor is 1.0.

Ocean solutions. Ocean solutions will have different times to saturation and will be addressed as we complete those solution assessments.

For solutions that do not rely on biosequestration mechanisms for significant climate impact, no adoption adjustment is needed, therefore the adoption adjustment factor is 1.0.

Table A4. Adoption adjustment factor assumptions, by category

Adjustment Category	Solutions	Adoption Adjustment Factor	Rationale
Farming practices adopted since 1970s	Restore Abandoned Farmland Improve Livestock Grazing Improve Annual Cropping	0.5	Slowdown typically occurs after 20–50 years, so we can assume that some of current adoption has already nearly reached equilibrium.
Traditional farming practices with centuries or millennia of adoption	Deploy Silvopasture Deploy Agroforestry	0.25	Slowdown typically occurs after 20–50 years, so we can assume that most of current adoption has already nearly achieved equilibrium even if there is much recent adoption
Upland ecosystem protection	Protect Forests Protect Grasslands & Savannas	1.0	We calculate carbon sequestration based on actual net primary productivity of ecosystems based on satellite observation (forests) and a global dataset of site-level measurements (grasslands and savannas).
Upland ecosystem restoration & management	Restore Forests Restore Grasslands & Savannas Improve Forest Management	1.0	Slowdown typically occurs after 50–200 years. Given that our current adoption estimate is based on satellite images, we can assume that current adoption has not yet achieved equilibrium.
Perennial food and biomass crops	Deploy Perennial Crops Deploy Biomass Crops	0.5	Slowdown typically occurs after 20–50 years, so we can assume that most of current adoption has already achieved equilibrium even if there is much recent adoption.
Wetland protection and restoration	Protect Coastal Wetlands Protect Peatlands Restore Peatlands Restore Coastal Wetlands	1.0	Slowdown does not occur in these wetland systems – they continue to sequester carbon for many centuries, at least in soil (and our peatland and coastal wetlands solutions

			track only soil carbon, and exclude biomass carbon).

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Land allocation

Potential adoption of some land-based solutions is limited by land availability since land is a limited resource. Emissions reduction solutions can be used on the same unit of land without overestimating mitigation because they operate independently of each other. For example, on the same hectare of farmland, both irrigation efficiency and nutrient management can be practiced without interference. Nutrient management reduces nitrous oxide emissions from fertilizer and irrigation efficiency reduces carbon dioxide emissions from pumping water.

However, multiple carbon sequestration solutions cannot necessarily be used on the same unit of land. For example, forest restoration and improved annual cropping are not compatible uses of land. Even when two solutions can be practiced on the same land, the carbon impacts of combined practices are largely unknown. For example, “conservation agriculture with trees” combines the Improve Annual Cropping and Agroforestry solutions, but we do not yet know if the resulting carbon sequestration is less than, more than, or equal to the combined impact of each individual solution. In the absence of guidelines for calculating combined impacts, we allow no more than one carbon sequestration solution per unit of land.

We first assumed no reduction in crop production area and no expansion of grazing land. In allocating land to solutions, we determined how much land is available in key categories including forests and woodlands, peatlands, coastal wetlands, grasslands and savannas, and cropland. Then, we determined which land categories are suitable for our land-based solutions.

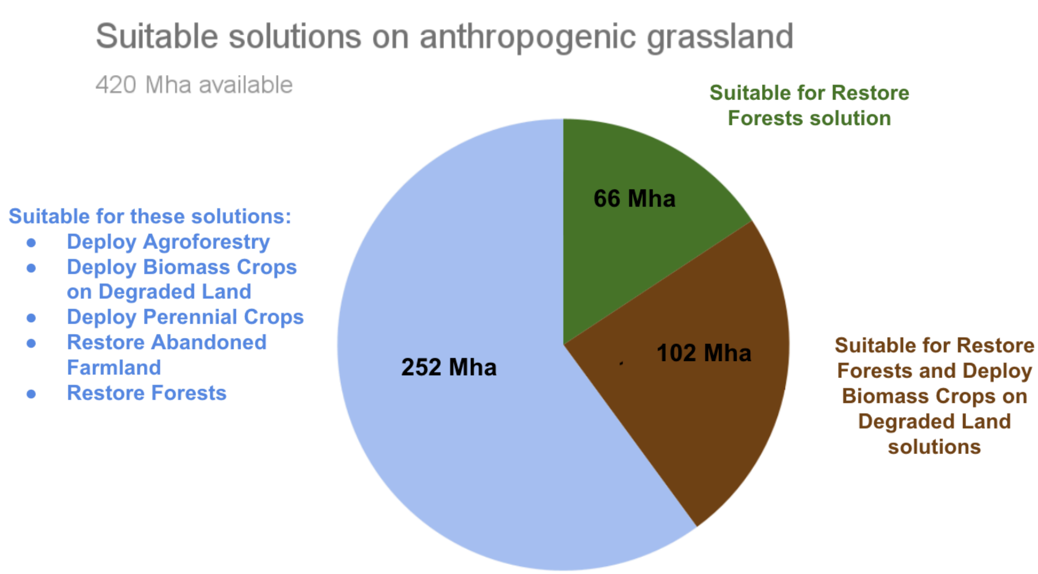
Peatlands, rice paddies, and coastal wetlands are only suitable for one solution, so there is no competition. Other land categories are suited to a limited number of solutions, like cropland, which is suited only for improved annual cropping, agroforestry, and perennial crops.

The land category suited for the most solutions is grassland. We determined that natural grassland, whether intact or degraded, would remain as grassland. However 420 million hectares of grassland are anthropogenic. These grasslands are in areas that were historically forest and receive enough rainfall to support the growth of trees. Anthropogenic grassland is suitable for five solutions: Deploy Biomass Crops, Deploy Perennial Crops, Restore Abandoned Farmland, Deploy Agroforestry, and Restore Forests.

Using remote sensing data (Amatulli et al., 2018a; Amatulli et al., 2018b; Weiss et al., 2018), we determined that 66 million hectares are too steep or remote to be economically viable for most solutions, and made this area available for forest restoration only. Another 101 million hectares were moderately steep and deemed only suitable for timber and biomass production. The remaining 252 million hectares were determined suitable for any of the five solutions.

These totals were used to set the adoption ceilings of the five relevant solutions and avoid overestimating carbon sequestration.

Figure A1. Breakdown of solution suitability for available anthropogenic grassland



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Capturing capacity and lifetime for rate-based adoption

For solutions dealing with material flows and production, data units from primary sources are often based on a rate of implementation (e.g., metric tons of waste processed annually). We use caution with any values obtained from reviewing literature for these solutions because key variables may be reported relative to the throughput of the facility (its annual capacity) or relative to the total capacity over the facility lifetime (lifetime capacity). It is important to understand how time factors into the original source data in order to correctly convert it into an adoption unit without a time component so we can quantify effectiveness and cost.

When compiling data for solutions with rate-based adoption, we carefully review the units in the original sources to determine whether they are based on lifetime capacity, annual capacity, or another metric. If reported, we document the facility lifetime, annual capacity, and other relevant details (e.g., capacity factors, if available).

If a source does not *explicitly* state that the units are lifetime capacity or capacity in terms of annual material flow through the facility, and we make an assumption about units, we thoroughly describe the assumption. If the assumption is based on backtracking to another source, we provide that citation. If units are ambiguous or an assumption would be risky, we may exclude the source.

Additionally, in the literature annual capacity can be reported based on the maximum capacity of the facility or actual yearly throughput of materials. If it's not clear whether the units are based on maximum capacity or actual throughput, we note this. When any error arising from this is likely to be in one direction (e.g., costs in real life will be higher if throughput is below maximum capacity), we note this in the narrative. If the source acknowledges that operational costs vary due to fluctuating facility operations, but the value they provide is representative, we include the data and note this as an assumption.

Example units for costs reported based on annual capacity are included in Table A5. To amortize costs in these units, we use the facility lifetime in the formula below and calculate the net cost in units of 2023 US$/AU.

$$Net\ Cost\ per\ Unit\ Solution\ or\ Baseline\ = \frac{Initial\ cost + (Operating\ cost * Lifetime) - (Revenue * Lifetime)}{Lifetime\ (default\ 30\ years)}$$

Initial costs may be reported in the literature as 2023US$/(AU/yr), where AU/yr is the annual capacity, so dividing by the facility lifetime annualizes upfront costs. If operating costs and revenues are reported as annual costs relative to annual capacity (2023 US$/AU = [2023 US$/annual capacity]/yr), then costs do not need to be annualized by the facility lifetime again when calculating net cost.

Table A5. Example cost units for rate-based adoption

Cost component	**Units**	**Equivalent units (in terms of capacity)**
Initial costs [Capital expenditure (CAPEX)]	2023 US$/(AU/yr)	2023 US$/annual capacity
Operating costs [Operating expenses (OPEX)]	2023 US$/AU	(2023 US$/annual capacity)/yr
Revenues	2023 US$/AU	(2023 US$/annual capacity)/yr