WATER FOR CLIMATE MITIGATION: ESTIMATING THE GLOBAL FRESHWATER REQUIREMENTS OF CLIMATE MITIGATION MEASURES

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WATER FOR CLIMATE MITIGATION: ESTIMATING THE GLOBAL FRESHWATER REQUIREMENTS OF CLIMATE MITIGATION MEASURES

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AT A GLANCE

Climate mitigation measures for achieving net zero and implementing the Paris Agreement will consume substantial volumes of freshwater.

Estimates show that some measures provide a greater mitigation benefit for each unit of water consumed than others.

Clean energy measures subjected to this analysis are preliminarily estimated to require around 900 cubic kilometres of freshwater per annum, which equates to approximately a third of the water withdrawn by irrigation globally.

Significant amounts of water will also need to be retained and recharged in forests, peatlands and other natural ecosystems for these to perform their necessary carbon sequestration roles.

The broad estimates in this report rely on global and generic assumptions which may not apply in specific locations. Climate mitigation and water allocation decisions will need be based on data relevant to the location.

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This report has been produced as a result of generous in-kind contributions with all parties meeting their own costs and will be used to prepare a UN-Water Analytical Brief on this topic to be available in late 2024.

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SUMMARY

- Meeting climate targets is dependent on the sustainable management of water resources. Information presented in this study is intended to raise awareness of the critical links between the availability of water and implementing various Paris Agreement climate mitigation measures. At the national level, policymakers will need to assess the water requirements according to local conditions and regarding Nationally Determined Contributions.

- This study presents estimates for water requirements of clean energy and carbon sequestration measures expressed as tons of CO_2eq/ML values within a likely range of variability, which can range from a factor or 2 to over an order of magnitude.

- The figures presented should be considered preliminary, including the relative "ranking" of the measures based on their estimated water requirements and efficiency. On the one hand, the applicability of each measure is highly contextual and depends on the spatial and seasonal availability of water itself (which can be heavily regulated, in the case of rivers and lakes), on any specific requirements on water quality (costs associated to pre-treatment). On the other, the measures are not all directly interchangeable: while they are all climate mitigation measures, they respond to very different policy objectives (e.g. the decarbonization of the energy system, the transformation of agriculture, nature restoration, etc.) and are not all applicable in all countries. To allow the reader to appreciate how water requirements were estimated, all assumptions are explained in detail, for each measure.

- Notwithstanding this uncertainty on the estimated values, the report includes key global findings and points at clear trends related to the water intensity of key mitigation and adaptation options considered by the IPCC. Countries can consider such findings to reflect on the water implications of their climate policies.

- This study has shown the relative value of natural solutions, such as maintaining and restoring the water tables of peatlands and afforestation, however these climate action measures are location specific and are all attended by other ecological risks, specifically risks associated with the release of methane from peatlands and wetlands if systems are not managed well, and the potential for afforestation to change rainfall patterns and other land use measures.

- Optimising carbon sequestration of natural measures is reliant on the protection of their natural flow and flooding regimes.

- Natural solutions offer the best return on carbon sequestered per unit volume of water.

- Targets for coastal wetland protection and restoration identified in the IPCC AR6 report do not require additional freshwater resources due to the location of the wetlands in seawater and brackish water environments, however are at risk from decisions to divert freshwater flows from wetland areas. Estimates for the restoration of freshwater wetlands are difficult to undertake at the global scale.

- While direct air capture has reported high water efficiencies the technology has not been deployed at scale and is at early stages of development.

ABOUT THIS REPORT

This report, prepared at the request of the UN-Water Expert Group This report, prepared at the request of the UN-Water Expert Group on Water and Climate Change (UNEGWCC) following the Bonn 2023 technical workshop on water and climate mitigation interdependencies, offers preliminary global estimates of water requirements associated with the climate mitigation measures required to reduce greenhouse gas emissions and sequester carbon in the atmosphere. This is at a scale to achieve the Paris Agreement targets (measures necessary to limit global warming to 1.5 degrees celcius). The analysis covers water required for various clean energy measures assessed in the IPCC 6th cycle and discussed at the workshop, including the production of liquid biofuels, use of hydropower for dispatchable wind and solar, hydrogen, and natural systems that provide carbon sequestration services.

This study is a curation of peer reviewed data currently available in open access scientific literature that forms a preliminary accounting of the water requirements of a selection of the suite of mitigation measures required to achieve the Paris Agreement targets as assessed by the Intergovernmental Panel on Climate Change (IPCC). The objectives are:

- To improve understanding of the aggregate water requirements (in gigalitres per year) of each kind of climate mitigation measure that has been assessed by the IPCC, if implemented at the scale estimated by the IPCC required to achieve the Paris Agreement global warming targets.
- To improve understanding of the water efficiency of greenhouse gas reduction of each kind of climate mitigation measure that has been assessed by the IPCC, if implemented at the scale estimated by the IPCC required to achieve the Paris Agreement global warming targets.
- To assist national water managers to calculate estimated water requirements of each kind of climate mitigation measure at the national level.

STUDY INSIGHTS

The water required for various clean energy measures such as the production of liquid biofuels, use of hydropower for dispatchable wind and solar, hydrogen and natural systems that provide carbon sequestration services, all to keep global warming below 1.5 °C, has been estimated at the global level for the first time. The total volume of freshwater required for the assessed measures is not insignificant on a global scale. The inherent uncertainty in such global calculations need not detract from the broader findings of the study. Uncertainty cannot be the reason for inaction. The volume of water required by any measures in any location will depend on local conditions.

At the global scale, by 2030 just the clean energy measures considered are estimated to need around 900 cubic kilometres of water annually. New freshwater requirements for clean energy, sequestration and other Paris Agreement measures will be offset to some extent by less water being required from the 'old energy system' as the world transitions towards a clean energy future. They will also be offset to the extent that sea water and brackish water will become viable alternatives to freshwater.

This analysis also shows the relative 'water efficiency' of various mitigation measures. For example, green hydrogen production saves approximately 68 tonnes of carbon equivalent emissions for every million litres of water used, whereas in contrast the production of second-generation liquid biofuels could achieve 2 tonnes of emissions reduction for the same amount of water, while electrification of light duty vehicles could save 1.7 tonnes of carbon emissions for the same amount of water. By comparison, maintaining or restoring the water tables of peatlands could save 18.5 tonnes of emissions for the same amount of water. Poorly managed wastewater, and water in wetlands, and artificial reservoirs and irrigation systems are also a major source of direct emissions of greenhouse gases, especially methane and nitrous oxide. Improved management of these waters will also be make a significant contribution towards emission reduction targets globally.

Correction (1 July 2024): Study Insights (page 11), a typographical error by the publisher has been corrected. In an earlier version of this report, published on 3 June 2024, there was an inaccurate transposition of a figure from Table 2 on page 19. The following sentence: 'By comparison, maintaining or restoring the water tables of peatlands could save 3.08 tonnes of emissions for the same amount of water.' The number of tonnes of carbon removed per million litres for the maintenance of the hydrology of peatlands had been inaccurately transposed from 'Table 2: Water Dependencies of Sequestration Measures' (page 19) of the report as being 3.08 tCe/ML. The accurate figure is 18.5 tCe/ML. All published versions of this report have been corrected as of 1 July 2024.

STUDY CONTEXT

This study is a collaborative effort between the UN-Water Expert Group on Water and Climate Change and the International Universities Climate Alliance (IUCA). The Secretariat of the IUCA is currently hosted by the University of New South Wales (UNSW). The co-coordinators of the UN-Water Expert Group on Water and Climate Change, include the World Meteorological Organization (WMO), the United Nations Economic Commission for Europe (UNECE) and United Nations Educational, Scientific and Cultural Organization (UNESCO).

This study follows a Technical Workshop on Water and Climate Change Mitigation, held in Bonn on 13 June 2023, which set out to identify what is known and not known about the dependency of Paris Agreement targets (measures necessary to limit global warming to 1.5 °C under the United Nations Framework Convention on Climate Change) on the sustainable management of water resources.

This report will be used to prepare a UN-Water Analytical Brief on this topic to be available in late 2024.

About International Universities Climate Alliance

About International Universities Climate Alliance (IUCA)
The IUCA brings together leading universities from across 25 countries with critical capability in climate research. Universities are uniquely placed to share knowledge and expertise in climate science, climate change adaptation and mitigation. We believe it is through collaboration that we can create greater insight and action. Facilitating knowledge sharing and best practice approaches allows our members to establish a global perspective on localised challenges. Enabling informed policy-making and supporting global efforts to lower carbon emissions and increase the rate, scope and impact of climate action.

About UN-Water

UN-Water coordinates the United Nations' work on water and sanitation. There is no single United Nations Agency, Fund or Programme dedicated exclusively to water issues. In fact, over 30 United Nations organizations carry out water and sanitation programmes because these issues run through all of the United Nations' main focus areas. UN-Water is a 'coordination mechanism'. It is comprised of United Nations entities (Members) and international organizations (Partners) working on water and sanitation issues.

The UN-Water Expert Group on Water and Climate Change supports cooperation and coordination of UN-Water Members and Partners on water and climate change related issues. The overarching focus is to support UN Member States to sustainably manage water in the climate change context by informing policy processes and addressing emerging issues, supporting monitoring and reporting, as well as building knowledge and inspiring people to take action.

METHODOLOGY

A method was developed to quantify tons of carbon dioxide equivalent (tCO_2-eq) removed from the atmosphere per megalitre of water (ML) used for the purposes of comparing the effective efficiency (return on water consumed) for a suite of clean energy and carbon sequestration measures identified in the IPCC AR6.

Values for tCO_2-eq removed were based on the annual removal targets by 2030 to limit warming to 1.5 °C achievable at a price of USD $100 tCO_2-eq^{-1} (IPCC AR6). For the clean energy calculations, the International Energy Agency (IEA) estimates for the annual contribution of the global energy demand by 2030 were used to establish the Eta Joule (EJ) required for each action per year. Estimates for the water intensity of each measure were based on harmonised literature reports or in the case of batteries, life cycle assessment. While these results should be interpreted cautiously, they would enable ranking or comparison of the mitigation measures noting that the uncertainty associated with each estimate does not alter the ranking.

For the carbon sequestration calculations the actions were divided into two categories; natural solutions and engineered solutions. For the natural solutions, such as afforestation and peatland restoration, IPCC estimates for the annual removal targets (total) and where available carbon flux (tCO_2/unit area/year) were used to establish the annual tons removed.

Estimates for water demand were based on published literature values for the volume of water required per hectare to maintain ecosystem function. For the engineered solutions estimates for the water intensity of each measure were based on literature reports (e.g. Direct Air Capture or Carbon Capture and Storage from power plants).

Each calculation was based on assumptions for water efficiency or carbon sequestration efficiency published in the peer reviewed literature.

One important constraint on the calculations was uncertainty on values for water abstraction and consumption in the process. It was generally assumed that water was consumed in the process unless explicitly stated. In some cases where it would be expected that the water consumed was less than the water abstracted (e.g. nuclear power plants) for the purpose of generating a global estimate it was assumed that 50% was returned to the environment.

For each calculation an assessment was made of the variability (or uncertainty) of the original estimate. Notes on uncertainty in the report indicate that while there will be variations of up to an order of magnitude in each measure the overall ranking of water efficiency (return on water used expressed as tCO_2-eq/ML) does not change.

HOW INFORMATION IS ORGANISED

The findings of this study, prepared by the IUCA, are presented in three parts, Part A. Water Requirements of Climate Mitigation Measures, Part B. Notes and Assumptions, and Part C. Considerations at a National Level. This structured framework is intended to capture the context, methodology, and guidance on the use of the estimates provided in this report at a national level.

Part A. Water requirements of climate mitigation measures

Part A of this report consists of clean energy, carbon sequestration measures (Tables 1 & 2) presenting information on the quantity of freshwater required to achieve each of the listed climate mitigation measures on a global scale. It also assesses the efficiency of water use concerning the amount of water needed for each unit of carbon mitigation.

Important notes on how these estimates should be interpreted are presented in Part B of this report.

Information presented in Part A Tables 1 & 2 is organised according to the following format.

- Column 1 = mitigation measure from IPCC AR6 Figure SPM.7 based on estimates at USD$100/ton Carbon Equivalents.
- Column 2 = water dependency: how water is needed to achieve the measure, as advised by Workshop.
- Column 3 = conversion factor:
    - Energy measures = clean energy produced each year by 2030 to limit warming to 1.5 °C (GJ/y).
    - Environment measures = square kilometres of sequestration sites
- Column 4 = climate benefit: emission reduction resulting from the measure in gigatonnes of CO_2 equivalent emissions abated per year (GtCe/y)
- Column 5 = water required: water used by the measure by 2030 in billions of litres per year (GL/y) as defined in the water characteristics section of each measure.
- Column 6 = water efficiency of the measure in terms of water required for each unit of climate benefit, in cubic metres per tonne of carbon equivalent emissions (m^3/t).
- Column 7 = water efficiency of the measure in terms of tonnes of carbon removed per million litres of water used (tCe/ML).

Part B. Notes and assumptions

Part B of this report includes notes surrounding all assumptions related to the estimates and provides references cited for each. This section offers a detailed context and basis for the water requirement estimates presented in Part A Tables 1 & 2.

In considering what is currently known and not known about the dependency of Paris Agreement targets (measures necessary to limit global warming to 1.5 °C under the UNFCCC) on the sustainable management of water resources, notes on uncertainty are to be considered non-exhaustive.

Unless otherwise stated the estimates do not take into consideration the effect of rising global temperatures on the water requirements of each adaptation or mitigation measure, including changing precipitation patterns, melting snow and glaciers, desertification and deforestation.

Information for each climate mitigation measure in Part B is organised under the following sub-headings:

1. Boundary Conditions: Describes which steps in each climate action were considered in the water dependency calculations.

2. Water Characteristics: Identifies the source of the water used in each measure (e.g. unless otherwise specified, freshwater), consequences for other water uses (e.g. consumptive vs non-consumptive use). This study assumes consumptive water use and where data is unclear or if it incorporates non-consumptive water use this will be noted. In the case of non-consumptive use if there is a change in the quality of the water.

3. Information Sources: Identifies the primary data source used to set targets for calculations.

4. Estimation Methods: Outlines the method used to calculate a single value associate with each adaptation and mitigation measure as reported in columns 5, 6 and 7.

5. Assumptions: Lists the key assumptions and metrics used in the single value calculations. Likely variations in these assumptions have been used to inform the precision (uncertainty) of the water dependency estimates.

6. Notes on Uncertainty: The precision (uncertainty) of each calculation was expressed as a likely range from minimum to maximum based on likely variation in each assumption.

7. References Cited: Peer reviewed references used in the calculations, in addition to those listed under information source (item) 3.

8. Appendix. Additional notes extracted from IPCC AR6, Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update. International Energy Agency (IEA) and references.

Part C. Considerations at a National Level

This section offers context on how the global estimates presented in this report should be interpreted at the national level or other 'sub-global' levels.

Definitions

'Boundary Conditions' means the functions or scope of the mitigation measure considered.

'Consumed' means the water is lost to other uses by being converted into other substances or being committed to an exclusive ongoing use or is lost in the short term by evaporation or transpiration.

'Dependency' means the measure cannot be implemented without the consumption or availability of freshwater.

'Freshwater' means any water that is not seawater or saline groundwater that has no other use without desalination.

PART

A

WATER DEPENDENCIES OF CLIMATE MITIGATION MEASURES

Tables 1 and 2 constitute the completed deliverable set out in the Terms of Reference (ToR) of this study, with the addition of Column 7, and additional clarifications around the measures under Column 1, as agreed upon with the UN-Water Expert Group on Water and Climate Change.

Table 1 summarises water dependencies of clean energy measures up to 2030, and Table 2 presents water dependencies of sequestration measures up to 2030. The numbers in the table give an order of magnitude of the water dependency of key mitigation measures in absolute terms. Any comparison should be done with caution because in some cases the measures considered can also deliver energy services other than provision of electrical power, for example heating via geothermal and mobility via batteries. Commentary on conventional hydropower is available in section 11.

The values presented were not rounded to the nearest integer, however the number of significant figures should not be interpreted as carrying any degree of precision.

TABLE 1: WATER DEPENDENCIES OF CLEAN ENERGY MEASURES TO 2030

1	2	3	4	5	6	7
Measure	**Water required for...**	**Clean energy produced** GJ/y **(a)**	**Climate benefit** GtCe/y **(b)**	**Water required** GL/y **(c)**	**Water efficiency of GHG reduction** m^3/tCe **(d) = (c)/(b)**	**Tonnes of carbon removed per million liters** tCe/ML
Use of geothermal energy to generate clean electricity	Water required per year for operation of geo-thermal plant	$1.1x10^{3}$	0.5	532	1.0	939.8
Use of solar and wind energy to generate clean electric power	Pumped hydro-power for dis-patchable energy supply	$6.08x10^{10}$	4.1	5,207	1.3	787.4
Hydrogen in de-carbonisation of industry via fuel switching	Electrolyser de-mand + cooling water demand	$1.8x10^{10}$	0.4	5850	14.6	68.4
Use of nuclear energy to generate clean thermo-electric power	Cooling systems oer year for oper-ation of nuclear plant	$1.42x10^{10}$	0.9	16,366	18.2	55
Use of bioenergy to produce liquid biofuel	Growrh of bio-mass, fermenta-tion, and refining	$1.1x10^{10}$	0.8	400,000	500	2.0
Use of batteries in electric light duty vehicles	Mining and pro-cessing lithium, copper, cobalt and rare earth elements	$1.05x10^{8}$	0.8	480,000	605	1.7

TABLE 2: WATER DEPENDENCIES OF SEQUESTRATION MEASURES

1	2	3	4	5	6	7
Measure	**Water required for...**	**Area** km^2 **(a)**	**Climate benefit** GtCe/y **(b)**	**Water required** GL/y **(c)**	**Water efficiency of GHG reduction** m^3/tCe **(d) = (c)/(b)**	**Tonnes of carbon removed per million liters** tCe/ML
Direct Air Carbon Capture and Storage	Solvent regeneration	NA	0.6	4,200	7	142.9
Maintenace of the hydrology of peatlands	Maintaining natural functions	4,733,645	0.88	47,623	3.08	18.5
Carbon seques-tration via carbon capture and storage (BECCS):	Maximising sequestration potential	NA	1.6	640,000	400	2.5
Tree planting (afforestation)	Maintaining natural functions	2,130,000	1.6	1,066,667	667	1.5

PART

B

NOTES AND ASSUMPTIONS

1. USE OF GEOTHERMAL ENERGY TO GENERATE CLEAN ELECTRICITY

1.1 Boundary Conditions

Boundary conditions for water dependencies of geothermal energy only considered use of external water (not geothermal water) in the operation of a hybrid cooled power (See appendix below). No allowances made of water use in construction of the plant or construction of the transmission/conveyance of electricity or heat.

1.2 Water characteristics

Calculation assumes use of locally available freshwater that is consumed in the process.

1.3 Information sources

IPCC Global energy use Scenario IMP-REN-2.0 projects an expansion of geothermal power to 10 EJ out of 554 EJ of global supply by 2060 (IPCC AR6 Figure TS.11)

The Net Zero Roadmap (IEA, 2023) estimates geothermal power will expand from 101 TWh (0.36 EJ) in 2022 to 306 TWh (1.10 EJ) by 2030 and 862 TWh (3.10 EJ) in 2050.

The Global Geothermal Alliance (GGA) projects a five-fold growth in the installed capacity for geothermal power generation and approximately two-fold growth in geothermal heating by 2030.

The associated 2030 emissions reduction potential of this expansion, compared to no policy, current policies or NDC baseline, is equivalent to a minimum of 0.2 and a maximum of 0.5 $GtCO_2$-eq yr^{-1}.

1.4. Estimation methods

The clean energy production target for 2030 and 2050 (Column 3) was taken from "Table A.3 World Electricity Sector" of the Net Zero Roadmap (IEA, 2023). Data was converted from TWh to GJ and compared with estimates from IPCC AR6 Report expressed in EJ (See Note 2 below).

The climate benefit by 2030 and 2035 (Column 4) for electricity generation only was based on the maximum GHG emission by 2030 of 0.5 GtCO2 eq/year estimated by Global Geothermal Alliance (GGA) as cited in IPCC AR6.

Water required per annum (Column 5) was calculated based on work of Meldrum et al (2013) which screened and harmonised literature and industry data on water consumption across the life cycle of different electricity generation methods. The authors note that water footprint of geothermal plants can vary by more than an order of magnitude based on technology and location (see Table 10 in notes below).

The climate benefit by 2030 and 2035 (Column 4) for electricity generation only was based on the maximum GHG emission by 2030 of 0.5 $GtCO_2$ eq/year estimated by Global Geothermal Alliance (GGA) as cited in IPCC AR6. Water required per annum (Column 5) was calculated based on work of Meldrum et al (2013) which screened and harmonised literature and industry data on water consumption across the life cycle of different electricity generation methods. The authors note that water footprint of geothermal plants can vary by more than an order of magnitude based on technology and location (see Table 10 in notes below).

1.5 Assumptions

Initial calculation was based on an operational water consumption of 460 gal/MWh corresponding to the median value of a hybrid cooled plant (Meldrum et al., 2013).

Gallons (US) converted to m^3 (x0.00378) and consumption per GWh obtained by multiplying by 1000 and GWh converted to GJ by multiplying by 360.

Uncertainty was demonstrated by using minimum and maximum values for mature technology.

Compared to other clean energy solutions, geothermal energy is much more limited in terms of where it can be developed.

1.6 Notes on uncertainty

Water efficiency of GHG reduction can range from 0.01 m^3/tCO_2eq for the minimum operational water use (5 gal/MWh) in a flash geothermal plant to 1.62 m^3/tCO_2eq for the maximum operational water use (700 gal/MWh) in a hybrid plant (refer to Meldrum et al. (2013), Table 10).

Compared to other clean energy solutions, geothermal energy is much more limited in terms of where it can be developed.

1.7 References cited

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1.8. Appendix

Appendix 1 - Supporting notes extracted from IPCC AR6 & IEA Net Zero Roadmap Update 2023

1) Geothermal Energy: Definition, Forms and Applications

Geothermal energy is heat stored in the Earth's subsurface and is a renewable resource that can be sustainably exploited. The feasibility of mitigation options varies according to context and time. The potential of geothermal is site specific (IPCC AR6 E.1.2).

There are two main types of geothermal resources: convective hydrothermal resources, in which the Earth's heat is carried by natural hot water or steam to the surface; and hot, dry rock resources, in which heat cannot be extracted using water or steam and require use of other fluids to transport thermal energy.

Geothermal energy can be used directly for various thermal applications, including space heating and industrial heat input, or converted to electricity depending on the source temperature (Limberger et al. 2018; Moya et al. 2018; REN21 2019).

Suitable aquifers for geothermal energy are located beneath 16% of the earth's surface. These locations store an estimated 110,000–1,400,000 PWh (400,000–1,450,000 EJ) that could theoretically be used for direct heat applications.

For electricity generation, the technical potential of geothermal energy is estimated to be between 30 PWh yr^{-1} (108 EJ yr^{-1}) (to 3 km depth) and 300 PWh yr^{-1} (1080 EJ yr^{-1}) (to 10 km depth). For direct thermal uses, the technical potential is estimated to range from 2.7–86 PWh yr^{-1} (9.7–310 EJ yr^{-1}) (IPCC 2011).

2) Current clean energy production

Geothermal energy sources produced 92 TWh yr^{-1} (0.33 EJ yr^{-1}) of electricity in 2019, up from 80 TWh yr^{-1} (0.28 EJ yr^{-1}) in 2015 (IEA 2017, 2021a). In 2019 Geothermal energy accounted for 1 EJ of 585 EJ of global supply (AR6 Figure TS.11). Based on analysis of IEA and IPCC reports, it was assumed that approximately 33% of geothermal energy was used in electricity generation for industry and 66% was used directly for heating in residential and commercial buildings.

3) Barriers to development of geothermal energy

The mismatch between potential and developed geothermal resources is caused by high upfront costs, decentralised geothermal heat production, lack of uniformity among geothermal projects, geological uncertainties, and geotechnical risks (IRENA 2017a; Limberger et al. 2018).

The main concerns about geothermal energy, particularly for large-scale, high-temperature geothermal power generation plants, involve water usage, water scarcity, and seismic risks of drilling (Dowd et al. 2011, Soltani et al. 2021).

4) Water footprint geothermal energy for electricity generation

The volume of water used in the operating of geothermal systems depends on the features of the geothermal source and configuration of the power plant (Meldrum et al, 2013). There are three basic types of geothermal power plants: (i) dry steam plants use steam directly from a geothermal reservoir to turn generator turbines; (ii) flash steam plants take high-pressure hot water from deep inside the Earth and convert it to steam to drive generator turbines; and (iii) binary cycle power plants transfer the heat from geothermal hot water to another liquid. Many of the power plants in operation today are dry steam plants or flash plants (single, double and triple) harnessing temperatures of more than 180°C.

Operational water use varies by more than an order of magnitude corresponding both to technology configurations (e.g., dry steam, binary, and flash) and to local contexts (Meldrum et al., 2013).

Table 10 from Meldrum et al (2013) provides a summary of statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for geothermal power-generated electricity..

2. USE OF SOLAR AND WIND ENERGY TO GENERATE CLEAN ELECTRIC POWER

2.1 Boundary Conditions

Water dependency of solar and wind energy is defined as the water demand of installed pumped hydro systems (L/MW) (reference 3).

2.2 Water characteristics

Calculation assumes the transfer and impoundment of freshwater resources from local catchments. Additional water losses, such as increased evaporation, associated with establishing new pumped hydro plants are not considered. We assume that the volume of water needed for the operation of these plants is considered equivalent to the capacity of their associated reservoirs.

2.3 Information sources

Estimates for clean energy produced (column 3) and climate benefit (column 4) from solar and wind are based on the IEA Net Zero Roadmap study (references 1 and 2).

2.4. Estimation methods

Data for the China Southern Power Grid was used to calculate the Ratio of Total capacity of solar and wind (GW) to total pumped hydro capacity (GW) (Tot Solar + Wind/Tot Pumped Hydro) for three hydrological conditions Median (normal inflow), Min (wet, +40%), Max (dry, -40%) (reference 2). The ratio ranges from a maximum of 0.65 (wet) to 0.56 (dry) with a median value of 0.64.

The estimates for the global annual capacity of additional pumped hydro for clean energy production (GW) were calculated by multiplying the IEA Net Zero Roadmap estimates for additional wind and solar energy (GW) by 2030 and 2050 by the ratio (Tot Solar + Wind/Tot Pumped Hydro) for the Southern China grid.

The estimates for the water required for the additional pumped hydro were calculated using estimates for the cubic meters required per megawatt of installed pumped hydro capacity (reference 4 & 5).

Which assumes 2.935 m^3 is required for storage per MW of installed pumped hydro capacity. This is derived by applying the ratio of total reservoir capacity to installed capacity for pumped hydro as outlined in the dataset from reference 5.

2.5. Assumptions

It is assumed that the ratio of installed capacity for solar and wind energy, in conjunction with pumped hydro, maintains a consistent proportionality both in the context of the China Southern Power Grid net-zero pathway and the global standard. This assumption is based on the understanding that the energy mix required to achieve net-zero emissions typically follows similar patterns in terms of renewable energy integration, irrespective of the regional or global scale.

2.6. Notes on uncertainty

Values presented in Table 1 are derived under normal inflow conditions. Water demand for storage of pumped hydro varies substantially depending on hydrological conditions which were assumed to increase by 40% in a wet year and decrease by 40% in a drought (reference 2).

For 2030, water efficiency is estimated to be between 1.262 to 1.459 m^3/tCe.

For 2050, water efficiency is projected to fall within a range of 1.037 to 1.199 m^3/tCe.

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3. HYDROGEN IN DECARBONISATION OF INDUSTRY VIA FUEL SWITCHING

3.1 Boundary Conditions

The most cost-effective production method for green hydrogen is via electrolysis using existing electrolysers using renewable energy. Water demands for green H_2 at the gigawatt scale are associated with electrolyser feed and supply to evaporative cooling to dissipate waste heat and achieve an economically viable asset life of the electrolysers (> 5 y).

3.2 Water characteristics

Water quality required to maintain electrolyser asset life is equivalent to ASTM Type II water with a resistivity of >1 MΩ/cm, a conductivity of <1 µS/cm and <50 ppb of total organic carbon. Water for electrolysers and evaporative cooling will be sourced from desalinated seawater. All water (100%) used in electrolyser will be consumed in H_2 production while 30-50% of cooling tower blowdown will be returned to environment.

3.3 Information sources

International Energy Agency Net Zero Roadmap (reference 1) assumes green hydrogen production will account for 1.8x10^{10} GJ per annum of clean energy equivalent to 0.5% of cumulative emission reductions by 2030.

Estimates for climate benefit of green hydrogen were determined from both IEA Zero Roadmap (reference 1) and IPCC AR6 Figure SPM.7 (reference 2). A climate benefit of 0.4 Gt CO_2 equivalents per year represents approximately <0.5% of the mitigation measures in the Net Zero Emissions scenario by 2030 and 4% by 2050 (NZE page 101).

It is noted that The International Renewable Energy Agency (IRENA) completed a study in December 2023, Water for Hydrogen https://www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production and the World Energy Transitions Outlook 2023: 1.5 °C Pathway in June 2023 and https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023

3.4 Estimation methods

Total water dependency of green hydrogen = electrolyser demand + cooling water demand (L/kg H_2)

Green hydrogen via water electrolysis assumes 9L of de-ionised water per kgH_2 (reference 3) and excludes treatment losses that range from 10% for fresh water to 60% for seawater.

Cooling water requirements for electrolyser operation assuming evaporative cooling range from 20-40 L/kgH_2. Range is based on dissipation of 9.3-16.7 kWh/kgH_2 (reference 4) depending on electrolyser specifications for efficiency (70-80%, HHV), stack operating temperature (60-90 °C), relative humidity (0-100%) and ambient temperature (20-40 °C).

Clean energy produced (GJ/y) assumes low heat value for combustion in gaseous phase at 33.3 kWh/kgH_2 equivalent to 0.11988 GJ/kgH_2.

3.5. Assumptions

Green hydrogen from electrolysis of water using renewable electricity is the only form of hydrogen with zero Scope 1 emissions. Assumes water for green hydrogen supplied via seawater desalination.

Reference considers future low-carbon hydrogen demand necessary to not exceed 1.5 °C global warming. Refer to Figure 2.5 of the IEA Net Zero Roadmap for contribution of green hydrogen to overall mitigation measures (Appendix 1).

Even though the IEA (reference 1) estimate that 2.3% of total hydrogen produced in 2050 will not be low-carbon, estimates for water demand assume 100% of total 2050 hydrogen demand is derived from electrolysis.

Data presented is for a 2030 scenario with mean compound annual growth rate of 5.54% per annum between 2022 and 2030.

3.6 Notes on uncertainty

Water use efficiency (tCe/ML) is likely to improve as hydrogen is substituted as an energy carrier in other applications. The IEA projects that hydrogen will account for 5% of global energy consumption by 2050 (IEA, 2023, A-2).

Values presented in Table 1 are based on 50^{th} percentile. While the stoichiometric equivalent is constant the cooling water demands vary as a function of ambient air temperature and humidity, as well as the electrolyser efficiency and stack temperature.

2030 estimates for water efficiency range from minimum of 10875 at 20 °C, 0% RH and stack operating temperature of 60 °C to a maximum of 18375 L/tCe at 40 °C, 100% RH and stack operating temperature of 90°C.

Dry cooling is an option but it is land intensive and inefficient at a gigawatt scale resulting in higher costs making projects unviable (reference 5). Therefore, while dry cooling would have water requirements at the low end of the uncertainty scale it is unlikely to be used in future green energy portfolios.

3.7. References cited

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3.8 Appendix

Appendix 1. International Energy Agency (IEA) Net Zero Roadmap Figure 2.5 on page 67.

4. USE OF NUCLEAR ENERGY TO GENERATE CLEAN THERMO-ELECTRIC POWER

4.1 Boundary Conditions

Boundary conditions for water dependencies of nuclear energy for clean thermo-electric power only considered use of surface water in the operation of the plant (see appendix below). No allowances made of water use in processing of the nuclear fuel or construction of the plant because the water used in the fuel processing is small compared to plant operation and would not alter either the estimate or uncertainty.

4.2 Water characteristics

It was assumed that water used in the cooling process was withdrawn from fresh water sources. Calculations were based on the water withdrawals which were assumed to be 40% higher than the water consumed in the process with the difference available for return to the environment.

4.3 Information sources

Data from Meldrum et al. (2013) for operational water use (gal/MWh) were used.

4.4 Estimation methods

The clean energy production target for 2030 and 2050 (Column 3) was based on clean energy for electricity generation from Table A.3 World Electricity Sector (IEA, 2023). Data was converted from TWh to GJ and compared with estimates from IPCC AR6 expressed in EJ (see note 2 below). Differences between IEA and IPCC are associated with the use of the clean energy for thermal power in applications other than electricity generation.

The climate benefit by 2030 (Column 4) for electricity generation was based on the median GHG emission reduction of 0.9 $GtCO_2$-eq yr^{-1} by 2030 listed in IPCC AR6.

Water required per annum (Column 5) was calculated using gal/MWh reported by Meldrum et al. (2013) which screened and harmonised literature and industry data on water consumption across the life cycle of different electricity generation methods. The authors note that water footprint of nuclear power plants can vary by more than an order of magnitude based on cooling system design and location (see Table 7 in notes below).

4.5. Assumptions

Initial calculation was based on an operational water withdrawal of 1100 gal/MWh corresponding to the median value nuclear plant cooling tower (Meldrum et al., 2013).

Gallons (US) was converted to m^3 (x0.00378) and consumption per GWh obtained by multiplying by 1000 and GWh converted to GJ by multiplying by 3600.

Uncertainty was demonstrated by using minimum and maximum values for cooling systems noted in Table 7 in Appendix 1.

4.6 Notes on uncertainty

Water efficiency of GHG reduction can range from 8.3 m^3/tCO_2eq for the minimum operational water use (500 gal/MWh) for a plant using pond cooling to 992 m^3/tCO_2eq for the maximum operational water withdrawal (60000 gal/MWh) in plant employing open loop cooling.

In addition, the location of the facility in coastal or inland areas will influence the water consumption. In coastal locations some facilities utilise seawater which will result in water consumption at the low end of the cooling range.

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4.8 Appendix

Appendix 1 – Supporting notes from IPCC AR6 & IEA Net Zero Roadmap 2023 Update

1) Nuclear Energy: Definition, Forms and Applications

Nuclear power can deliver low-carbon energy at scale (high confidence). Nuclear generation grew 9% between 2015 and 2019 and accounted for 10% of total generation in 2019 (2790 TWh); (IPCC AR6 TS.5.1).

Nuclear contributions may be enhanced by new generations of reactors (e.g., Generation III) and small modular reactors (Knapp and Pevec 2018) (IPCC AR6 TS.5.1), the adoption of nuclear energy and carbon capture and storage (CCS) in the electricity sector has been slower than the growth rates anticipated in stabilisation scenarios. Nuclear power Is considered strategic for some countries, while others plan to reach their Mitigation targets without additional nuclear power (IPCC AR6 4.2.5.5).

Nuclear power generation is developed in many countries, though larger-scale national nuclear generation does not tend to associate with significantly lower carbon emissions (Sovacool et al. 2020). Unlike other energy sources such as wind and PV solar, levelized costs of nuclear power has been rising in the last decades (Grubler 2010; Gilbert et al. 2017; Portugal-Pereira et al. 2018).

Accelerated mitigation scenarios offer contrasting views on the share of nuclear in power generation. Many large-scale supply-side climate mitigation options, such as CCS or nuclear power, involve high technological risks, critically depend on a stable carbon price, and are controversial in terms of social and environmental impacts (Sovacool et al. 2014; Smith et al. 2016; Wilson et al. 2020a) (high evidence, medium agreement).

2) Current and projected clean energy production

Nuclear power is projected to expand with almost 15% more capacity in 2050 in the updated NZE Scenario than in the 2021 version, reflecting strengthened policy support in leading markets and brighter prospects for small modular reactors. All regions increasingly draw on advanced nuclear technologies, including new large reactor designs (generation III+ and IV) and small modular reactors. While the biggest opportunity for nuclear power is in the electricity sector, new nuclear power in this scenario helps to decarbonise heat and to supply low-emissions hydrogen.

Estimates for the current base and future growth of nuclear energy by IEA and IPCC are similar.

IEA Net Zero Roadmap 2023 estimates nuclear power will expand from 2682 TWh (9.7 EJ) in 2022 to 3936 TWh (14.2) in 2030 and 6015 TWh (21.7 EJ) in 2050 (IEA 2023, Appendix A3). The 2019 IPCC estimate for contribution of nuclear energy to global energy supply was 10 EJ out of a total 585 EJ and will expand by 2070, under Global energy use Scenario IMP-NEG-2.0 nuclear power will expand to 28 EJ out of 705 EJ of global supply (IPCC AR6 Figure TS.11)

3) IPCC AR6 Notes on expansion of nuclear energy

The fourth key milestone for the electricity sector is for nuclear power to more than double from 417 GW in 2022 to 916 GW in 2050. Despite this growth, the share of nuclear power in generation declines slightly in the NZE Scenario from 9% in 2022 to 8% in 2050. After three decades of modest growth, a changing policy landscape is opening opportunities for a nuclear comeback. As a means of pursuing emissions reductions targets and addressing energy security concerns, several countries have announced strategies that include a significant role for nuclear power, including Canada, China, France, India, Japan, Korea, Poland, United Kingdom and United States. At the start of 2023, nuclear reactors totalling 64 GW were under construction in 18 countries around the world. In the longer term, more than 30 countries which accept nuclear power today increase their use of nuclear power in the NZE Scenario.

To achieve the overall doubling of nuclear capacity by 2050, an average of 26 GW of new capacity comes online every year from 2023 to 2050 in the Net Zero Scenario, some of which is needed to offset retirements (Figure 2.16). This calls for average annual investment of over USD 100 billion, which is triple the level in recent years. Following the completion of projects already underway, the peak of expansion comes in the 2030s, when an annual average of 33 GW of new nuclear capacity comes online, marking a new high for the nuclear industry.

4) Barriers to development of nuclear energy

Nuclear power continues to be affected by cost overruns, high upfront investment needs, challenges with final disposal of radioactive waste, and varying public acceptance and political support levels (high confidence) (IPCC AR6 6.4.2.4).

Because of the sheer scale of the investment required (individual projects can exceed USD10 billion in value), nearly 90% of nuclear power plants under construction are run by state-owned or controlled companies, with governments assuming significant part of the risks and costs (IPCC AR6 6.4.2.4).

5) Water footprint of nuclear energy for electricity generation

Operational water use varies by more than an order of magnitude corresponding both to cooling system configurations and to local contexts.

Water-intensive inland nuclear power plants may contribute to localised water stress and competition for water uses. The choice of cooling systems (closed-loop instead of once through) can significantly moderate withdrawal rates of freshwater (Meldrum et al. 2013; Fricko et al. 2016; Mouratiadou et al. 2016; Jin et al. 2019). Reactors situated on the seashore are not affected by water scarcity issues (Abousahl et al. 2021).

Table 7 from Meldrum et al (2013) presents summary statistics of selected, harmonized estimates of water consumption and withdrawal for major life cycle stages and production pathways for nuclear power-generated electricity.

5. USE OF BIOENERGY TO PRODUCE LIQUID BIOFUEL

5.1 Boundary Conditions

Boundary conditions for water dependencies to produce liquid biofuels include three stages of the fuel cycle covering; 1) cultivation of second-generation feed stock; 2) secondary ethanol fermentation, biodiesel refining and separation; and 3) biofuel transportation.

5.2 Water characteristics

Sources used in estimates of the biofuel water footprint ($m^3 H_2O$/L biofuel) include direct rainfall (green water) supplemented by freshwater transfers (blue water) for growth of feedstock and blue water for biofuel production and transport. Residual water of a lower quality (grey water) is returned to the environment from irrigation and biofuel production.

Global water estimates for total water withdrawals expressed as m^3/L (green + blue) were expressed as average values for bioethanol and biodiesel from countries India, Indonesia, China, Taiwan, Thailand, Nicaragua, Brazil and Guatemala (Xie et al., 2017). Bioethanol estimates range from 2.96 m^3/L (0.4 + 2.56) for cassava feedstock to 9.81 m^3/L (4.25 + 5.56) for sorghum feedstock and 19.92 m^3/L (11.64 + 8.28) for Jatropha curcas biodiesel. Residual water returned to the environment (grey) range from 80 to 90% in China to approximately 3% in Thailand.

Additional estimates for global water withdrawals based on sum of green plus blue water inputs were sourced from Gerbens-Leenes et al. (2009).

5.3 Information sources

International Energy Agency (IEA) Net Zero Roadmap (reference 1) assumes liquid biofuels will account for 1.1×10^{10} GJ per annum of clean energy by 2030.

Estimate for climate benefit of liquid biofuels based on IEA Net Zero Roadmap (reference 1) and IPCC AR6 Figure SPM.7 (reference 2) was 0.8 $GtCO_2$ equivalent per year.

5.4 Estimation methods

The annual water demand, expressed in gigalitres/year (GLA) for the global production of biofuel with an energy equivalent of 1.1×10^{10} GJ was based on a net lifecycle water footprint of 36 litres of water per megajoule (L/MJ). This assumed the total demand (green plus blue) was 72 L/MJ and 50% of water was returned to environment via grey water.

5.5 Notes on uncertainty

The water footprint of biofuels is highly variable. Estimates for L/MJ depend on a range of factors including; the country of production and the average annual rainfall (green water); the location farms including irrigated versus non-irrigated broad acre cropping; the saccharide (C5 and C6 sugar) content of the feedstock crop; and, level of refinement to either an alcohol or diesel based fuel.

In this report, emphasis was placed on feedstocks that could be grown at scale with minimal competition with human food crops (i.e. minimal substitution of human food crops (e.g. maize, cane sugar, cereals) for biofuel production.

Xie et al. (2017) estimated life-cycle water footprint for bioethanol production via cassava to range from 73.9 to 222 L/MJ and from 115.9 to 210.4 L/MJ for bioethanol via sweet sorghum ethanol. Similarly, the water footprint of biodiesel production via Jatropha curcas seeds was estimated to range from 64.7–182.3 L of water per MJ of biofuel. Noting that this analysis considers both blue and green water makes allowances, particularly in China, for return flows to the environment via grey water. A value of 72 L/MJ was at the low end of the bioethanol and biodiesel estimates and 50% return was approximately the midpoint of grey water returns between Thailand and China.

Increasing the percentage of grey returns from 50% to 90% will increase the tons of CO_2 equivalents per mega litre by approximately a factor of 2 from 2 to 4 (tCe/ML). However, using the higher values of water footprint of 180 to 220 L/MJ at 50% grey water return will reduce the abatement potential by approximately a factor of 3 from 2 to 0.65 (tCe/ML). Moreover, the abatement potential would be a factor of 6 lower for bioethanol via sorghum and biodiesel via Jatropha curcas using water footprint data from Gerbens-Leenes et al. (2009) (Table 2 below) which has an estimate of 419 L/MJ for sorghum (compared to 210 L/MJ) and 574 L/MJ for Jatropha curcas (compared to 182 L/MJ).

Consequently, it is possible that the abatement potential of liquid biofuels based on the IEA production estimates for 2030 and the IPCC AR6 climate benefit could range from 0.4 to 4 tCe/ML.

5.6 References cited

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5.7 Appendix

Table 2 from The Water Footprint of Bioenergy (Gerbens-Leenes et al., 2009) presents the total weighted-global average WF for 10 crops providing ethanol and 3 crops providing biodiesel (m3/GJ), as well as their blue and green WF.

6. USE OF BATTERIES IN ELECTRIC LIGHT DUTY VEHICLES

6.1 Boundary Conditions

Boundary conditions for water dependencies of lithium-ion batteries for light duty vehicle were established at the global scale using the Regionally Weight Quantitative Water Scarcity Footprint method of Schomberg et al. (2021) which considers all the physical used water from mineral and metal ore mining, extraction and processing followed by the manufacture of the battery components, including transport. Used water accounts for 33,155 regionally weighted m^3 with highest contributions from Chilean lithium mining or 16,577 m^3/MWh.

6.2 Water characteristics

Water used across the material supply chain for light duty vehicle batteries covers all sources including untreated, mineral laden saline groundwaters, treated groundwater, freshwater and industrial recycled water. No assessment has been made of the quality, fate or possible beneficial reuse or return of these streams to the environment.

6.3 Information sources

Extended life cycle assessment reveals the spatially explicit water scarcity of lithium ion battery storage (Schomberg et al., 2021).

6.4 Estimation methods

The estimates from the Net Zero Roadmap (IEA, 2023) report for the growth in EV share of light duty market by 2030 and 2035 were correlated with the growth in Automotive LIB production (GWh/y) from IPCC AR6.

The market share of light duty electric vehicles (LDEV) was converted to a clean energy production target expressed as GJ/y (Column 3) based on the typical LDEV battery size expressed in kWh converted to GJ by multiplying by 3600.

The climate benefit by 2030 and 2035 (Column 4) was based on GHG emission reductions from conversion of Internal Combustion Engines (ICE) to electric vehicle engines (EVE) in light duty vehicles in advanced economies from the Net Zero Roadmap (IEA, 2023).

Water required per annum (Column 4) was calculated based on work of Schomberg et al (2021) which calculated a quantitative water scarcity footprint of 33,155 regionally weighted m^3 for 2MWh of battery storage.

6.5 Assumptions

Total size of LDV market in advanced economies (number of vehicles) is constant for the period 2022 to 2035.

Number of new LDEV per year increased as function of market share (%) with no allowances for replacement of existing EV's in the same period.

No additional allowances for old battery recycling.

See Appendix 1 for other supporting information.

6.6 Notes on uncertainty

Lithium extraction via brine evaporation is most water intensive. Moreover, the values used in the LCA method have standard deviations of more than 170%. Decreasing the water footprint to 10,000 m^3 for 2MWH would reduce the Water efficiency of GHG reduction from 604 to 182 m^3/tCe

Calculation was based on battery size of 67kWh which can range from 40kWh for smaller cars to 100kWh for larger SUV's. The GHG reduction efficiency is 361 m^3/tCe at a battery size of 40kWh and 906 m^3/tCe at 100KW (assuming water footprint of 33,155 m^3 per 2MWH).

6.7 References cited

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6.8 Appendix

Appendix 1 – Supporting notes extracted directly from IPCC AR6 & IEA Net Zero Roadmap 2023 Update

1) The Transformation in Energy Carriers: Electrification and Hydrogen (Box TS.9)

Batteries are currently a more attractive option than hydrogen and fuel cells for light-duty vehicles. Battery electric vehicles (BEVs) have lower lifecycle greenhouse gas (GHG) emissions than internal combustion engine vehicles (ICEVs) when BEVs are charged with low-carbon electricity (high confidence).

Battery electricity storage has emerged as important for supporting the flexibility of electricity systems as they accommodate rising shares of VRE. Although pumped-storage hydropower systems accounted for 160 GW, or over 90%, of total energy storage capacity in 2019 (IEA 2020c), battery energy storage systems, led by LIB technology, have accounted for over 90% of new capacity addition since 2015 (IRENA 2019a). In 2019, 10 GW of batteries were connected at the grid and consumer level, rising from 0.6 GW in 2015 (IEA WEO 2019; IEA 2020c).

2) Critical Strategic Minerals and a Low-carbon Energy System Transition (Box 6.4)

The secure supply of many metals and minerals (e.g., cobalt, copper, lithium, and rare earth elements (REEs)) is critical to supporting a low-emissions energy system transition (Sovacool et al. 2020). A low-carbon energy system transition will increase the demand for these minerals to be used in technologies like wind turbines, PV cells, and batteries (World Bank 2020). Concerns have also been raised about mining for these materials, which frequently results in severe environmental impacts (Sonter et al. 2020), and metal production itself is energy-intensive and difficult to decarbonise (Sovacool et al. 2020). However, excluding cobalt and lithium, no single country holds more than a third of the world reserves. The known supply of some strategic minerals is still close to 600 years at current levels of demand (BP 2020), but increased demand would cut more quickly into supplies.

3) Technical characteristics LIB state of the art (Table 6.6)

Maturity (High) Life span cycles (1000–6000) Energy density (200–680 Wh L^{-1}) Specific energy (110–250 Wh kg^{-1})

4) GHG emission reduction of EV's and current market share of EV's

The extent to which EV deployment can decrease emissions by replacing internal combustion engine (ICE) vehicles depends on the generation mix of the electric grid (Abdul-Manan 2015; Nichols et al. 2015; Canals Casals et al. 2016; Hofmann et al. 2016; Choi et al. 2018; Teixeira and Sodré 2018) although, even with current grids, EVs reduce emissions in almost all cases (Knobloch et al. 2020).

The median emissions intensity of a gasoline passenger vehicle is 222 gCO_2-eq vkm^{-1}, and 160 gCO_2-eq vkm^{-1} for a gasoline two wheeler (Cox and Mutel 2018). At a maximum occupancy factor of four and two passengers, respectively, the transport emissions intensity for these vehicles is 55 and 80 gCO_2-eq pkm^{-1}.

IPCC AR6 Figure TS.7 cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. Automotive LIB production rose from around 40 GWh in 2015 to 160 GWh in 2020 (32%). The stock of battery electric vehicles (BEVs) grew from around 0.7 million in 2015 to 4.8 million in 2019 (IEA 2020d). In 2020 EV's were 1% of the passenger vehicle fleet in 2020 (approximately $6.5x10^6$ vehicles). (Figure TS.7 also Figure 2.22).

The average battery size of BEVs reached 67 kWh in 2019 due to consumer preferences and government incentives for long range vehicles (Agency 2020; IEA 2021b).

5) Growth in LDEV's

IEA 2023 Net Zero Road Map makes following assumptions on Light-duty vehicles (LDEVs) which include passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes) in order to achieve 16% of cumulative GHG reductions through road transport from page 93 of the Net Zero Roadmap (IEA, 2023).

Market share increases to 13% in 2022, then 67% in 2030 and reaches 100% by 2035.

The corresponding reduction in GHG eq/y from cars and vans in advanced economies by 2030 was assumed to be 0.8 $GtCO_2$ by 2030. Graphs that show scaling investments in public chargers for cars, vans, trucks and buses, and declining road transport emmissions to 2050 are available on page 93 of the Net Zero Roadmap (IEA, 2023)

6) Water footprint of Li ion battery

For a 2 MWh Lithium-ion battery storage, the quantitative Water Scarcity Footprint, comprising physically used water, accounts for 33,155 regionally weighted m^3 with highest contributions from Chilean lithium mining or 16 577 m^3/MWh (Schomberg et al 2022).

7. MAINTENANCE OF THE HYDROLOGY OF PEATLANDS

7.1 Boundary Conditions

Boundary conditions for water dependencies of maintenance of peatlands considered both the transfer of freshwater to, and the prevention of drainage of water from, peatland areas across a range of climate zones.

7.2 Water characteristics

Conservation and restoration will require the maintenance of freshwater at critical water levels to maintain function of the peatland. Water inputs will be from precipitation. In each scenario (either maintenance or restoration) there is already existing water input (precipitation) into the system that maintains the peatland in its current state (either intact or degraded). We have assumed those inputs will continue, and included them in column (5a) in the table below.

7.3 Information sources

Targets for CO_2 equivalent sequestration through conservation and restoration of peatlands were derived from the IPCC AR6. In the section on peatland conservation, it was concluded that there is medium confidence that peatland conservation has a potential of 0.48 (0.2–0.68) $GtCO_2$-eq yr^{-1} is available at USD$100 tCO_2-eq^{-1} (Figure 7.11). In addition, there is medium confidence that peatland restoration has a potential 0.4 (0.2–0.6) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2-eq^{-1}.

7.4 Estimation methods

WATER DEPENDENCIES OF SEQUESTRATION MEASURES

-1	-2	-3	-4	-5a	-5b	-6
Measure	**Water required for...**	**Area**	**Climate benefit**	**Existing water required**	**New water required**	**Water efficiency of GHG reduction**
		km^2	GtCe/y	GL/yr	GL/y	m^3/tCe
		(a)	(b)		(c)	(d) = (c)/(b)
restoring boreal peatlands	restoration scenario 1	322,923	0.40	209,190	6,769	16.92
	restoration scenario 2			202,421	0	0.00
restoring temperate peatlands	restoration scenario 1	124,663	0.40	150,762	5,749	14.37
	restoration scenario 2			145,013	0	0.00
restoring tropical peatlands	restoration scenario 1	102,579	0.40	346,582	35,106	87.76
	restoration scenario 2			311,477	0	0.00
conserve boreal peatlands	maintaining existing water levels	2,479,094	0.48	1,553,994	0	0.00
conserve temperate peatlands		397,611	0.48	462,519	0	0.00
conserve tropical peatlands		1,306,775	0.48	3,967,956	0	0.00
all peatland	maintaining and restoring	4,733,645	0.88		47,623	3.08

Neighbouring undamaged ('intact') and damaged ('degraded') peatlands will receive the same amount of rainfall/precipitation as each other. We can also assume that they lose similar amounts of water via evaporation and transpiration (E_t). This assumption will only be approximately true because E_t is known to vary with plant type and water-table depth, both of which differ between intact and degraded peatlands. Nevertheless, if we accept the assumption, both degraded and intact peatlands will receive the same net rainfall as each other: $P - E_t$. P, E_t, and net rainfall have dimensions of a rate ($L\ T^{-1}$), with suggested units of $m\ yr^{-1}$. For these units, net rainfall is the amount of water added to a peatland in a year, per unit peatland area.

Net rainfall over a year will be roughly balanced by the losses of water from the peatland (over the same year). In many peatlands, subsurface seepage will be the main mechanism by which loss occurs. Therefore, we can write:

$$P - E_t = seepage \qquad (1)$$

From Darcy's Law [1,2], seepage (Q_s) from the peatland will depend on the product of:
(i) the hydraulic conductivity or permeability of the peat (K) at the margin;
(ii) the hydraulic gradient at the margin, which can be approximated by the water-table gradient, dh/dx, where x is distance, and h is the water table as defined below (under 'Assumptions / Peat depth');
(iii) the thickness of the flow at the margin (the depth of peat below the water table through which seepage occurs, or the height of the water table above the base of the peat (assumed horizontal), h); and
(iv) the length of the perimeter or margin of the peatland (W):

$$Q_S = K \frac{dh}{dx} hW \qquad (2)$$

The perimeter of an intact peatland is its literal edge or circumference. For a degraded peatland, its perimeter includes the same edge but additionally both sides of all of the ditches dug within the peatland because these also receive water discharging from the body of the peat. Therefore, a degraded peatland will have a much larger effective perimeter than an intact peatland.

K has dimensions of L T^{-1} (units of m yr^{-1}), h dimensions of L (m), x dimensions of L (m), and W dimensions of L (m), meaning that Q_s has dimensions of L^3 T^{-1} (m^3 yr^{-1}). Q_s is not, therefore, equivalent to $P - E_t$. which has dimensions of L T^{-1} (m yr^{-1}), as noted above. For that to be the case we have to normalise Q_s by area and this is best done by replacing W by W/A, where A is the total area of the peatland. We can call this normalised perimeter W_a and refer to it as perimeter per unit area. Combining equations (1) and (2), we can now write:

$$P - E_t = K \frac{dh}{dx} hW_a \qquad (3)$$

Each restoration and maintenance scenario has a value for seepage and E_t to maintain the existing peatland that will be met by existing precipitation inputs. However, as the climate changes, the water input from precipitation will also change.

7.5 Assumptions

Precipitation (P):

Values for precipitation were sourced from 20 papers and ranged from 467 mm yr^{-1} in boreal regions to 3600 mm yr^{-1} in tropical regions [3-22]. The mean value for each ecozone was used in the calculation. Precipitation is variable over time, and will be impacted by climate change; however, we have used a constant value for precipitation.

Evapotranspiration (E_t):

Values for evapotranspiration were sourced from 10 papers and ranged from 0.27 m yr^{-1} in boreal regions to 1.46 m yr^{-1} in tropical regions [3,5,18,23-29]. The mean value for each ecozone was used in the calculation.

Evapotranspiration rates will change due to changes in precipitation and air temperature, and so will be impacted by climate change.

Peatland area (*a*):

The recent Global Peatland Assessment showed there are 4,877,542 km^2 of peat, of which 11.7% is degraded and 88.3% intact [30]. The total peatland area, and proportion that is classed as degraded, in specific ecozones (boreal (and polar), temperate, and tropical (and subtropical)) peatlands across each continent was used for this assessment [30-32]. There were no data presented on the proportion of peatland degraded in each ecozone on every continent, so we had to rely on the assessment of the total proportion degraded per continent. These values were used to calculate a total area and proportion degraded for each ecozone in all continents, assuming the same proportion of degradation across each ecozone.

In the Global Peatland Assessment [30], there is a category of peat ("other"), of which there are 19,700 km^2 of degraded and 123,500 km^2 of intact areas. These peatlands represent 3.45% of all degraded peat, 2.87% of all intact peat, and 2.94% of total peat coverage, and include peatlands that do not fall into the main ecozone categories. These peatlands are not included in our assessment.

Hydraulic conductivity (*K*):

Hydraulic conductivity is difficult to directly measure in the field, and relatively few literature values are available (especially for tropical peatlands). We used literature values from four studies (these include studies which draw *K* data together from a range of sources) [28,33-35] as guides to estimate values for *K*, which we treated as a fitting parameter. This allowed us to take overland flow into account, in combination with seepage. Morris, et al. [33] included 'disturbance' as a factor but found no significant effect on permeability in temperate and boreal peatlands; however, as there were data available for degraded and intact peat, we have used depth-weighted mean values to guide the estimates used for degraded and intact, temperate and boreal peatlands. Baird, et al.[28] measured hydraulic conductivity in a tropical intact peat dome, and Kurnianto, et al. [34], Kunarso, et al. [35] measured and reviewed hydraulic conductivity in degraded tropical sites. We have used values from these studies to guide the values for intact and degraded tropical peatlands. This method resulted in values similar to those reported in literature and balanced equation (3).

As sites are restored and water tables move closer to the surface, the hydraulic conductivity of peat will change. However, we have used a constant hydraulic conductivity value for degraded sites to mimic a 'worse case scenario', which will result in maximum water requirements for peatland restoration.

Hydraulic gradient (*dh/dx*):

Values for hydraulic gradient were sourced from six papers and ranged from 0.0008 in temperate regions to 0.025 in boreal regions [5,36-40]. The mean value for each ecozone was used in the calculation. We assumed that *dh/dx* remains stable across the year or represents a time-averaged gradient.

In intact peatlands, the surface slope roughly equals the slope of the water table across the landscape. Hence the hydraulic gradient is assumed to equal surface slope. But for degraded peatlands, the hydraulic gradient is steeper than the surface slope due to the water-table drawdown pattern around ditches and drains. Once restored, then the water-table slope (~hydraulic gradient) in former degraded sites should be close to the surface slope again. So, given that we are assessing water to maintain the restored condition, rather than seepage out when it is unrestored, we have kept hydraulic gradient values the same for degraded and intact conditions as we are aiming to achieve the undrained state.

Peat depth (*h*):

Values for peat depth were sourced from the Global Peatland Assessment [30] and literature [3-5,13,14,16,19,20,41-43]. The mean value for each ecozone was used in the calculation for intact peatlands, as this represents the thickness of the flow (the depth of peat below the water table through which seepage occurs). For degraded sites, there is a proportion of the peat that is not experiencing 'active' flow, the drained top portion of peat. For these sites, the mean water-table depth (the depth from the peat surface that does not contribute to 'active' flow) was derived from Ma, et al. [44], in Figure S12, where the mean water-table depth (below peat surface) in drained peatlands is 44, 26 and 56 cm in boreal, temperate and tropical peatlands respectively. This assumption also means that h stays invariant across the year or represents a time-averaged water-table height.

Perimeter length (*W*):

From an area, it is possible to calculate a circumference, assuming the area is a circle. For example, for boreal peatlands, where the total intact area is 2,479,094 km^2; this results in a circumference of 5,582 km. However, all boreal peat is not contained within one circle. As we do not have data on the exact size, shape, or perimeter length of every peatland in the world, we have made certain assumptions about the area. If the peatland is distributed among *n* smaller, equally-sized circular peatlands, each with an area of *A/n* the circumference, and therefore perimeter (*W*) will be:

$$W = 2n\sqrt{\pi A / n} \qquad (4)$$

For example, if the boreal peatland (total intact area is 2,479,094 km^2) consisted of 1,000 smaller peatlands, each with an area of 2,479 km^2, the total perimeter length would be 176,503 km. For intact peatlands, we assumed that each ecozone peatland was comprised of 100,000 smaller peatlands with uniform area, where water drains from the edges of the peat (assuming there are no internal streams/rivers).

For degraded peatlands, perimeter length also includes the proportion of the peatland area that is covered in drains. 'FracDitch' was used to calculate the length of extra perimeter in degraded boreal, temperate and tropical peatlands [45]. The values were multiplied by two (as water will drain into a ditch from both sides).

Restoration Scenarios

Scenario 1: First, we can leave the drainage infrastructure in place (i.e., the ditches remain open) and consider how much *additional water* needs to be supplied to the degraded peatland to raise its water table to the level found in natural sites. To calculate this additional water, we first increase *h* on the right-hand side of equation (3) to the natural value. Doing so will increase the seepage loss. To balance that greater rate of loss we will need to increase the effective rainfall on the left-hand side. This increase in effective rainfall is the additional water needed. In effect, this means adding irrigation water to the peatland.

Scenario 2: Secondly, we can consider removing the drainage infrastructure. For example, by blocking ditches we will reduce the perimeter per unit area (W_a). As above, we use equation (3) for our calculations. If we halve 'FracDitch' in degraded peatlands, then the seepage will decrease. But the seepage must be in balance with $P\text{-}E_t$. We know that ditch blocking raises water tables, and we can assume that h will rise to balance the decrease in W_a. This approach does not require any additional water.

Maintaining Intact Peatlands

For natural sites, no additional water is required for their maintenance, provided the climate is not drying. They formed without artificial additions of water. If, however, the climate is drying, then their continued maintenance would require the addition of sufficient water to bring $P\text{-}E_t$ back to the value it was when they formed (other things being equal).

7.6 Notes on uncertainty

Range of values

All values used are means derived from literature and all have accompanying error values. Where literature has reported values from different peat depths, we have used either a depth-weighted mean of the whole profile or for the top 50 cm (as that is where the water-table depth change occurs) as appropriate.

To give a range to our 'new water required' estimates (column 5b), the water needed to restore water-table depths (as in scenario 1) were re-calculated, using the minimum and maximum values of peat depth in each ecozone, to give the minimum and maximum seepage values as a result of raising the water-table depth. For minimum peat depths, there is already enough water (from precipitation) to cover the smaller change in water-table depth and so there is no new water required. For maximum values, this assumes deep peat occurs across the entire ecozone (between 5.2 and 6 m deep; 1.5x the average values), and this increases the water demand significantly.

restoration scenario 1	New water required GL/yr	Minimum value GL/yr	Maximum value GL/yr
restoring boreal peatlands	6,769	0	33,882
restoring temperate peatlands	5,749	0	49,811
restoring tropical peatlands	35,106	0	143,997
All peatlands	47,623	0	227,691

Sensitivity analysis

As Darcy's Law (equation 3) is relatively simple multiplication of each parameter, a change of e.g. 10% in peat depth, perimeter length, hydraulic conductivity or hydraulic gradient results in a 10% change in the volume of water needed to balance equation (3). This makes the volume of water needed equally sensitive to each of those four parameters.

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8. DIRECT AIR CARBON CAPTURE AND STORAGE

8.1 Boundary Conditions

Water used in the operation of Direct Air Capture (DAC) only. Water used only for the preparation and regeneration of the solvents that absorb the CO_2.

8.2 Water characteristics

Fresh water consumed in the process assuming negligible returns to the environment.

8.3 Information sources

The IPCC AR6 medium confidence for carbon dioxide reduction at below USD$100 tCO_2^{-1} using DAC is 0.6 $GtCO_2\ yr^{-1}$.

8.4 Estimation methods

Multiply the climate target in ton/y by the water footprint in m^3/ton from reference 1.

8.5 Assumptions

No assumptions on embodied water in materials or construction.

IPCC AR6 Assumptions

MERGE-ETL by 2100	38.3	GtCO2 y^{-1}
US RIO+PATHWAY	1.8	GtCO2 y^{-1}
World Energy Outlook by IEA by 2050	0.6	GtCO2 y^{-1}

Estimates of water footprint (Rosa et al. 2021)

25^{th} percentile	2	m^3/tCO_2
75^{th} percentile	7	m^3/tCO_2

8.6 Notes on uncertainty

DAC has not yet been demonstrated at a commercial scale. Based on available data the estimate would vary by a factor of 3.5 based on literature ranges. However, at full scale the water demands could be higher and there is no certainty that the cost assumption of $100USD per ton is valid.

While direct air capture has reported high water efficiencies the technology has not been deployed at scale and is at early stages of development.

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8.8 Appendix

1) Direct Air Capture

Direct Air Capture (DAC) is a chemical process to capture ambient CO_2 from the atmosphere. Captured CO_2 can be stored underground (direct air carbon capture and storage, DACCS) or utilised in products (direct air carbon capture and utilisation, DACCU).

Capturing the CO_2 involves three basic steps: (i) contacting the air, (ii) capturing on a liquid or solid sorbent or a liquid solvent, and (iii) regeneration of the solvent or the sorbent (with heat, moisture and/or pressure).

DAC options can be differentiated by the specific chemical processes used to capture ambient CO_2 from the air and recover it from the sorbent (Fasihi et al. 2019). The main categories are (i) liquid solvents with high-temperature regeneration, (ii) solid sorbents with low-temperature regeneration and (iii) regenerating by moisturising of solid sorbents.

2) Limitations and risks

CO_2 is present at 0.04% in the air. This is some 2–3 orders of magnitude lower in concentration than other commonly targeted sources for capturing CO_2, such as flue gases resulting from energy generation and industrial processes.

3) Amount of DAC

Marcucci et al. (2017) ran MERGE-ETL, an integrated model with endogenous learning, and showed that DACCS allows for a model solution for the 1.5 °C target, and that DACCS substitutes for BECCS under stringent targets. In their analysis, DACCS captures up to 38.3 $GtCO_2\ yr^{-1}$ in 2100**.**

At the national scale, Larsen et al. (2019) utilised the Regional Investment and Operations (RIO) Platform coupled with the Energy PATHWAYS model, and explicitly represented DAC in US energy systems scenarios. They found that in a scenario that reaches net zero emissions by 2045, about 0.6 $GtCO_2$ or 1.8 $GtCO_2$ of DACCS would be deployed, depending on the availability of biological carbon sinks and bioenergy.

The newest iteration of the World Energy Outlook by IEA deploys CDR on a limited scale, and DACCS removes 0.6 $GtCO_2$ in 2050 for its Net Zero CO_2 Emissions scenario.

Figure 2 from Rosa et al. (2021) presents the water footprint of carbon capture and storage technologies.

9. CARBON SEQUESTRATION VIA CARBON CAPTURE AND STORAGE

9.1 Boundary Conditions

Boundary conditions for water dependencies of bioenergy with carbon capture and storage (BECCS) include cultivation and post-harvest processing of the biofuel; 2) combustion, including operation of cooling towers and carbon capture process (pre or post combustion); and, 3) transport to reservoir for geological sequestration.

9.2 Water characteristics

BECCS was assumed to use freshwater for plantation management and biomass processing, freshwater without further processing in cooling process, treatment with demineralisation for high pressure boilers and turbines and preparation of solvents for carbon capture.

9.3 Information sources

The IPCC AR6 medium confidence for carbon dioxide reduction at below USD$100 tCO_2^{-1} using BECCS is 1.6 (0.5–3.5) $GtCO_2$ yr^{-1} Recent data from Rosa et al. (2021) estimates the median water demand for BECCS to range from 100 m^3/ton for high efficiency configurations to 700 m^3/ for low efficiency configurations.

9.4 Estimation methods

Annual global water demands were calculated by multiplying the IPCC CDR target by the BECCS water use efficiency per ton of carbon based on 400 m^3/ton.

9.5 Assumptions

A value of 400 m^3/ton of carbon was used as a mid-point for the low to high efficiency configurations for BECCS.

9.6 Notes on uncertainty

Column 7 (tCe/ML) values can be as much as a 400% higher using high efficiency configurations to 75% lower using low efficiency configurations.

9.7 References cited

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9.8 Appendix

Large-scale carbon dioxide reduction (CDR) to support Climate mitigation scenarios in the two recent special reports (SR1.5 and SRCCL) to limit warming to 2 °C involve significant land-use change to accommodate the deployment of biomass energy with carbon capture and storage (BECCS).

Bioenergy refers to energy products (solid, liquid and gaseous fuels, electricity, heat) derived from multiple biomass sources including organic waste, harvest residues and by-flows in the agriculture and forestry sectors, and biomass from tree plantations, agroforestry systems, lignocellulosic crops, and conventional food/feed crops.

Based on studies to date, the technical net CDR potential of BECCS (including LUC and other supply chain emissions, but excluding energy carrier substitution) by 2050 is 5.9 (0.5–11.3) $GtCO_2\ yr^{-1}$ globally, of which 1.6 (0.5–3.5) $GtCO_2\ yr^{-1}$ is available at below USD100 tCO_2^{-1}.

Figure 2 from Rosa et al. (2021) presents the water footprint of carbon capture and storage technologies and Figure 4 presents the water footprint of dedicated BECCS feedstock.

10. TREE PLANTING "AFFORESTATION"

10.1 Boundary Conditions

The total water footprint for afforestation consists of direct rainfall (green water) plus freshwater transfers for irrigated plantations (blue water) and less any recovered water (grey water) residual to the process.

10.2 Water characteristics

Water demands were assumed to be met via freshwater resources. Residual water from irrigation run off (grey water) and water losses from evapotranspiration both potentially have deleterious effects on ecosystem at the local scale and beneficial impacts on rainfall at the regional due to increased water levels in atmosphere (see appendix below).

10.3 Information sources

The economic mitigation potential of afforestation at (<USD100 tCO_2-eq^{-1}) is 1.6 (0.5–3.0) $GtCO_2$ yr^{-1} Carbon sequestration per hectare over 100 year sustained effect ranges from 5–10 t CO_2 ha^{-1} yr^{-1} (IPCC AR6 7.4.2.2) .

10.4 Estimation methods

Water demands were calculated via a three-step process.

Step 1 determined the afforestation area (mha) required to achieve the economic mitigation target of 1.6 $GtCO_2$-eq yr^{-1} based on the midpoint (7.5) of the IPCC AR6 range carbon sequestration per hectare per year tCO_2 ha^{-1} yr^{-1}.

Step 2 determined based on the literature a range for the Ecological Water Deficit (EWD) for different biomes (regions) calculated as the difference between green and blue water and precipitation ito assess the water utilization of afforestation.

Step 3 determined the tons of carbon per unit volume by dividing the annual economic mitigation target by the annual water demand (calculated) as the product of the EWD (step 2) and the afforestation area (step 1).

10.5 Assumptions

The ecological water deficit (mm) ranged from 5 mm (tropical) to 600 mm (arid). Calculation shown in Table 2 was based on an EWD of 100 mm.

A carbon sequestration per hectare per year of 7.5 tCO_2 ha^{-1} yr^{-1} was based on the midpoint (7.5) of the IPCC range of 5 to 10 tCO_2 ha^{-1} yr^{-1}.

Forest will return water through the transpiration and will create the local hydrological cycle. Often forest is able to develop horizontal atmospheric precipitation that increases the humidity and impact the recharge conditions.

Afforestation is location specific and attended by other ecological risks, such as the potential for afforestation to change rainfall patterns and other land use measures.

10.6 Notes on uncertainty

Water dependencies are the most variable of all the mitigation and adaptation measures assessed. The water utilisation estimate for 7.5 tCO_2 ha^{-1} yr^{-1} ranges from 13 m^3/tCO_2-eq at a EWD of 1 mm for a tropical region to 8000 m^3/tCO_2-eq at an EWD of 600 mm for an arid region.

10.7 References cited

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3) Ricciardi, L., D'Odorico, P., Galli, N., Chiarelli, D. D., & Rulli, M. C. (2022). Hydrological implications of large-scale afforestation in tropical biomes for climate change mitigation. Philosophical Transactions of the Royal Society of London. Series B. Biological Sciences, 377(1857). https://doi.org/10.1098/rstb.2021.0391

10.8 Appendix

Appendix 1 – Supporting notes from IPCC AR6

Afforestation is an activity that converts land to forest on land that historically has not been forested. Large-scale carbon dioxide reduction (CDR) to support Climate mitigation scenarios in the two recent special reports (SR1.5 and SRCCL) to limit warming to 2 °C involve significant land-use change to accommodate afforestation.

Afforestation is an established method for carbon dioxide reduction. Measures with greatest potential for CDR were afforestation/reforestation (0.5 to 10.1 $GtCO_2$-eq yr^{-1}) (IPCC AR6 7.4.1.3).

Risks of afforestation

However, afforestation, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous people (IPCC AR6, C.11.2) Afforestation can increase competition for scarce resources, including land, water and biomass, which can reduce adaptive capacity, especially if deployed at larger scale and with high expansion rates thus exacerbating existing risks, in particular where land and water resources are very limited (IPCC AR6, D.2.3).

Afforestation can have minor to severe consequences for surface water acidification, depending on site-specific factors and exposure to air pollution and sea-salts (Futter et al. 2019). The potential effects of coastal afforestation on sea-salt related acidification could lead to re-acidification and damage on aquatic biota. Planting trees in deforested areas (reforestation) or in other areas that could support forest vegetation (afforestation) is expected to lead to a reduction in water availability and access both locally and in downstream locations.

Benefits of afforestation

Afforestation/reforestation (Lejeune et al. 2018; Strandberg and Kjellström 2019), urbanisation (Li and Bou-Zeid 2013) and irrigation (Mueller et al. 2016 and Thiery et al. 2017) modulate the likelihood, intensity, and duration of many extreme events including heatwaves (high confidence) and heavy precipitation events (medium confidence) (Haberlie et al. 2015). There is high confidence and high agreement that afforestation in the tropics (Perugini et al. 2017), irrigation (Alter et al. 2015; Mueller et al. 2016) and urban greening result in local cooling, high agreement and medium confidence on the impact of tree growth form (deciduous vs evergreen) (Naudts et al. 2016; Luyssaert et al. 2018 and Schwaab et al. 2020), and low agreement on the impact of wood harvest, fertilisation, tillage, crop harvest, residue management, grazing, mowing, and fire management on the local climate.

Afforestation, when well planned, can help address land degradation and desertification by reducing runoff and erosion and lead to cloud formation however, when not well planned, there are localised trade-offs such as reduced water yield or biodiversity (Teuling et al. 2017; Ellison et al. 2017). The use of non-native species and monocultures may have adverse impacts on ecosystem structure and function, and water availability, particularly in dry regions (Ellison et al. 2017). A/R activities may change the surface albedo and evapotranspiration regimes, producing net cooling in the tropical and subtropical latitudes for local and global climate and net warming at high latitudes (Section 7.4.2). Very large-scale implementation of A/R may negatively affect food security since an increase in global forest area can increase food prices through land competition (Kreidenweis et al. 2016).

Estimates of sequestration potential of forestry mitigation options. The AR5 provided top-down estimates of costs and potentials for forestry mitigation options – including reduced deforestation, forest

Estimates of sequestration potential of forestry mitigation options.

The AR5 provided top-down estimates of costs and potentials for forestry mitigation options – including reduced deforestation, forest management, afforestation, and agroforestry, estimated to contribute between 1.27 and 4.23 $GtCO_2$ yr^{-1} of economically viable abatement in 2030 at carbon prices up to USD100 tCO_2-eq^{-1} (Smith et al. 2014).

The SRCCL remained with a reported wide range of mitigation potential for A/R of 0.5–10.1 $GtCO_2$ yr^{-1} by 2050 (medium confidence) (Kreidenweis et al. 2016; Griscom et al. 2017; Hawken 2017; Fuss et al. 2018; Roe et al. 2019) (SRCCL Chapters 2 and 6). The higher estimate represents a technical potential of reforesting all areas where forests are the native cover type (reforestation), constrained by food security and biodiversity considerations, considering above and below-ground carbon pools and implementation on a rather theoretical maximum of 678 Mha of land (Griscom et al. 2017; Roe et al. 2019). The lower estimates represent the minimum range from an Earth System Model and a sustainable global CDR potential (Fuss et al. 2018). Climate change will affect the mitigation potential of reforestation due to impacts in forest growth and composition, as well as changes in disturbances including fire. However, none of the mitigation estimates included in the SRCCL account for climate impacts.

Sectoral studies that are able to deal with local circumstances and limits estimate A/R potentials at 20 MtCO2 yr^{-1} in Russia (Eastern Europe and West-Central Asia) (Romanovskaya et al. 2020) and 64 MtCO2 yr^{-1} in Europe (Nabuurs et al. 2017). (Domke et al. 2020) estimated for the USA an additional 20% sequestration rate from tree planting to achieve full stocking capacity of all understocked productive forestland, in total reaching 187 $MtCO_2$ yr^{-1} sequestration.

Bioenergy production and afforestation take place largely in the (partly) tropical regions ASIA, LAM and AFRICA, but also in OECD90+EU. Land for dedicated second generation bioenergy crops and afforestation displace agricultural land for food production (cropland and pasture) and other natural land. For instance, in the <1.5 °C mitigation pathway in ASIA, bioenergy and forest area together increased by about 2.1 million km^2 between 2020 and 2100, mostly at the cost of cropland and pasture (median values). Such large-scale transformations of land use have repercussions on biogeochemical cycles (e.g., fertiliser and water) but also on the economy (e.g., food prices) and potential socio-political conditions.

11. WATER DEPENDENCIES OF OTHER MEASURES

11.1 Wastewater and irrigation

Poorly managed wastewater, artificial reservoirs and irrigation systems are also a major source of direct emissions of greenhouse gases, especially methane and nitrous oxide. Improved management of these waters will also be critical towards emission reduction targets globally.

Irrigation water management does not require additional water, however this measure provides a water saving capability if well managed.

Optimising wastewater management will not result in the diversion of freshwater as part of the strategy but will require improved operation of existing or new waste collection and treatment systems.

Calculations of carbon emission reduction, at a global scale for optimal wastewater and irrigation water management cannot be completed at this time within this study timeframe as information at a global scale has not been determined.

11.2 Wetlands

In contrast to estimates of the water required to achieve the climate benefit of peatlands, global estimates for the climate benefit of freshwater wetlands were not made because the IPCC AR6 report did not contain an estimate for the likely range of cost per ton of carbon removed for this AFOLU mitigation measure. However, it can be assumed, based on the morphology and carbon density of freshwater wetlands, that the water efficiency expressed in terms of tonnes of carbon removed per million litres of water used (tCe/ML) on a global scale would rank below Peatlands, which contain more carbon per unit, but above afforestation in tropical biomes. Moreover, to maintain optimal carbon sequestration of freshwater wetlands, these areas must have their natural flow and flooding regimes protected.

It is well known that wetlands biodiversity is affected by both drought and flooding, and that changes in the wetland ecosystem this will limit carbon sequestration potential and increase carbon and methane emissions from these areas (e.g. inundated vegetation through flooding or through the death of flood plain forests through drought). An assessment of how changes in flow plus other factors including biodiversity loss, pollution, fires and changing weather patterns will alter the reduce the carbon sequestration potential of wetlands needs to be assessed at local scales.

11.3 Hydropower

The IEA Net Zero Roadmap defines hydropower as the energy content of the electricity produced in hydropower plants assuming 100% efficiency. Hydropower is estimated to contribute 20EJ (3%) of the global energy supply, equivalent to 5507 TWh or 14% of total electricity generation by 2030 (IEA 2023 Table A.1).

Given the critical role hydropower will play in climate adaptation and mitigation measures. Hydropower is attended by a suite of benefits including low operation and maintenance costs, high availability and response and co-benefits for water supply and irrigated agriculture. Notwithstanding this, hydropower is vulnerable to climate change including increased evaporation from storage due to rising temperatures, reduced on-going carbon sequestration capacity and increased short term carbon emissions due to loss of vegetation decomposition of organic matter in the flooded area and changes in biodiversity due to impacts on fish migration and other fish dependent fauna.

IPCC AR6 estimates that the mitigation potential of hydropower by 2030 at levels below \$100USD/tCO_2-*eq* is 0.32 +/- 50% $GtCO_2$-eq per annum (IPCC AR6 Table 12.1). However, the mitigation costs have large variation and may be above this range due to the global uncertainty in location, vegetation, topology and geology. In addition, there is considerable variation in both the methods and estimates for water consumption per unit of hydropower. Bakken et al. (2013) attributed the wide range (0.011 m3/GJ to 58 m3/GJ) in the IPCC Special Report on Renewable Energy (2012) to limited data, while Scherer and Pfister (2016) based on the analysis of 1500 sites, estimated the median net global impact of water in reservoirs allocated to hydropower at 10.6 m3/GJ.

Based on the median estimate of 10.6 m3/GJ by Scherer and Pfister (2016), the global water demand of 20 EJ of hydropower required to remove 0.32 $GtCO_2$-eq is approximately 210,150 GL per annum at a water efficiency of 1.5 tCO_2-eq/ML, compared to a minimum of 0.27 tCO_2-eq/ML and a maximum of 1467 tCO_2-eq/ML when estimates from the IPCC Special Report on Renewable Energy (2012) are applied.

11.3.1 References cited

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PART

C

CONSIDERATIONS AT A NATIONAL LEVEL

This section provides considerations to support policy makers and national water managers in estimating water requirements of each kind of climate mitigation measure at the national level. The global estimates, while containing uncertainty, demonstrate clear trends in water intensity of the key mitigation and adaptation options that countries should consider.

Next steps

- Nations will need to ensure the availability of relevant data.
- Assumptions will need to be adapted in Part B of this report to national circumstances.
- Nations will need to calculate the estimated freshwater demand of each planned mitigation measure. Initial estimates can utilise the water intensity calculation methods used in this report. The 'water cost' and 'climate benefit' for each measure will need to be calculated.

Further research into the above at a national level will assist governments to identify the hydrological, financial and broader socio-economic and environmental consequences of meeting the water demand of planned measures, and ways of managing those consequences. There are important limitations and assumptions in this study. Overall. the study provides global estimates to encourage further investigation on the water footprint of climate mitigation at a national level.

Future analysis will need to consider the questions and assumptions raised in this study, water quality and the international (transboundary) nature of water resources in addition to consideration of local contexts.

This resource also aims to encourage governments and inter-government processes to further consider the importance of understanding the aggregate water requirements of each type of climate mitigation measure that has been assessed by the IPCC. This understanding is crucial if these measures are to be implemented on the scale estimated by the IPCC to achieve the global warming targets set by the Paris Agreement. Where the data allows, understanding is also needed of the regional and national requirements and the intra-annual variability of the water requirements. Governments also require technical guidance for calculating estimated water requirements of each kind of climate mitigation measure at the national level.

- This study has shown a clear trend favouring natural solutions, however these climate action measures are very location specific and are all attended by other ecological risks
- Optimising carbon sequestration of natural measures is reliant on the protection of their natural flow and flooding regimes and further work is required to assess the resilience of such measures within a local or regional context.

- There is a need to achieve better integration between water and climate policies and practice as called for in the Water and Climate Leaders' Call to Action on Water for Climate Solutions.

- Electrification remains important however the water required for clean energy measures at a Nationally Determined Contribution (NDC) level to meet Paris Agreement targets, may not be sourced from within that country. As such direct decisions regarding water allocations may not apply to all measures for all countries.

- Optimising water management practices creates an opportunity to reduce pressures on other important measures.

- The reduction in unabated thermal coal power will create opportunities for reallocation of freshwater resources for clean energy projects listed under Nationally Determined Contributions.

- The IEA Net Zero Roadmap 2023 assumes that the global power generation from unabated thermal coal will decline from 17636 TWh in 2022 to 11066 TWh by 2030. Over the same period it is estimated that power generation via thermal coal with carbon capture and storage will increase from 1 TWh to 156 TWh. Based on median values for water consumption per unit power generation (m3/GWh), the volume of water available following the reduction in power generation from unabated thermal coal at 2578 m3/GWh and increased power generation from clean coal at 4997 m3/GWh, is 16 158 GL/y (Meldrum et al 2013). This volume is equivalent to 72% of the water required for the projected increase in nuclear, geothermal and pumped hydro for dispatchable wind and solar power over the same period estimated at 22,400 GL/y (Part A, Table 1).

- Each measure should be considered at a national and regional level and consider the NDC commitments made. Climate mitigation measures should also consider local population growth, economic development, seasonality, climate scenarios, carbon levels and other geographical variability.

- Methodologies used to calculate the global estimates based on what is currently known can be applied to data that may or may not be currently known at a local level.

- Further work is required by nations to understand estimated water requirements for each mitigation measure committed to under the Paris Agreement targets (measures necessary to limit global warming to 1.5 °C under the UNFCCC) on the sustainable management of water resources.

- Countries need to consider water requirements relative to NDCs. National level assessments and both national and local level planning is required for the water dependencies of climate mitigation measures. With options for sustainable implementation addressed.

- Global organisations may be able to provide guidance and share best practice for specific measures.

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