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PHOTOVOLTAICS VERSUS NEGATIVE EMISSIONS TECHNOLOGIES

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ABSTRACT: Through the Paris Agreement, the world has acknowledged that climate change is a significant global concern for humankind. There is a need for overwhelming response to counter climate change. While nations have offered roadmaps for decarbonisation of their economies for the long term, significant short-term reductions in carbon emissions will be crucial. Several technical solutions exist in order to assist in this endeavour. With a huge portion of the population located in the equatorial regions, solar photovoltaics offer an appealing solution; however, it is imperative to note the inability of one technological solution to single-handedly meet global demands. This paper examines, *negative emissions technologies* (NETs) and balances their efficacy as tools working in tandem with solar *photovoltaics* (PV) for faster decarbonisation. Compared to certain NETs (up to US$ 600/t-CO2), PV (US$ 34/t-CO2) is found to be more economical. Energetic comparisons show similar results: PV requires only 53 kWh/t-CO2, less than an eight compared to certain NETs.
Keywords: Photovoltaics, Negative emissions technology, Carbon dioxide removal, Bioenergy with carbon capture and storage, Direct air capture.

1 INTRODUCTION

Climate change is a significant global concern. The world is at the precipice of irrevocable climate change if significant changes are not implemented across all sectors. The Paris Agreement, having recognised this matter of urgent concern, has set a target to limit the increase of global average temperature to well below 2°C above preindustrial levels, aiming toward a 1.5°C target [1]. This has brought renewed focus on *Renewable Energy Sources* (RES) as a particular effort to aid in the decarbonisation of the energy sector. *Negative emissions technologies* (NETs) have been recognised as another major aspect to counter the increase in global carbon emissions through the removal of atmospheric carbon, primarily in the form of *carbon dioxide* (CO_2), and achieving these targets [2–6].

Renewable energy is set to play a pivotal role in the future. Already, countries have increased the deployment of renewable sources in the energy sector, particularly wind and solar *photovoltaics* (PV). Whereas hydropower still accounts for majority of the renewable power generation, recent years have seen solar PV as the fastest growing technology (by capacity additions) [7]. For 2030, the *International Energy Agency* (IEA) projects the need for over 5 TW installed solar PV technology – amounting to over 7.4 PWh of energy generation – in order to meet their Net Zero Scenario [8].

Whereas RES work by replacing sources that are greater emitters, thereby avoiding emissions, NETs can be defined as those technologies that are employed to actively remove *greenhouse gas* (GHG) emissions from the environment [9]. Although there are several technologies/methods which can be included in NETs, "*almost all target CO_2*" [9, p. 489]. Subsequently, NETs in this report address, in principle, *carbon dioxide removal* (CDR) techniques. Thus, these refer specifically to "*intentional efforts to remove CO_2 emissions from the atmosphere*" [4, p. 3]. The *Intergovernmental Panel on Climate Change* (IPCC) suggest that 100-1000 Gt-CO_2 must be removed over the 21st century to limit global warming within 1.5°C [10]. Major techniques as identified include *afforestation and reforestation* (AR), *soil carbon sequestration* (SCS), *biochar* (BC), *bioenergy with carbon capture and storage* (BECCS), *direct air capture with carbon capture and storage* (DACCS), *enhanced weather* (EW), ocean alkalinisation and ocean fertilization [4]. Methods of carbon storage such as the use of magnesium cement, soil management, wetland restoration and the use of timber in construction are also considered as NETs [9].

Through this report, we have tried to identify the potential for PV in climate mitigation, study and offer a comparative analysis of various NETs. Finally, we quantitatively compare PV with some NETs based on emissions and costs associated with their deployment.

2 METHODOLOGY

The estimated scales of deployment for NETs and subsequently, the total quantity of removal of CO_2 from the atmosphere vary widely based on the parameters included in the scenario. The largest estimate is of 1200 Gt-CO_2 [9]. Data was collected via online searches, mainly through the '*Google Scholar*' search engine. Accessed data generally includes works addressing NETs, works addressing specific technologies and reports by international organisations on future scenarios vis-à-vis climate action and energy pathways. BECCS, DACCS and AR technologies were chosen for comparison with PV particularly due to the high contribution that is attributed to these technologies in various emissions pathways and reports. Figure 1 illustrates the approach taken in this report.

As an introduction, the case for PV technology and major NETs is briefly discussed. The potential for PV in climate mitigation is then addressed briefly. Results of the

Units
°C: degree Celsius
Gt-CO_2 pa: gigatonne of carbon dioxide per annum
PWh: petawatt-hour
t-CO2: tonne of carbon dioxide
TWH: terawatt-hour
W_p: watt peak
kWh: kilowatt-hour

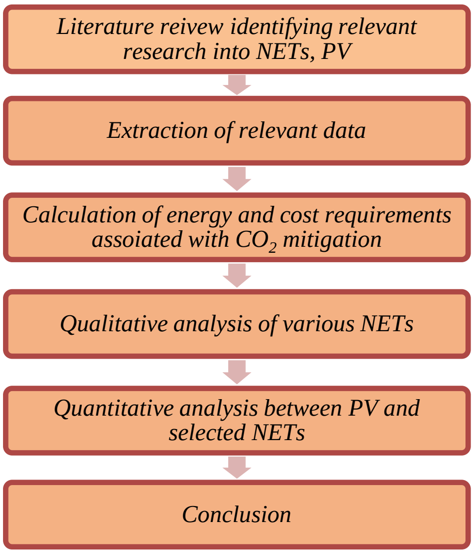

Figure 1: Flowchart depicting the methodology

literature review identify important NETs which have been tabulated in Table 2. Subsequent analysis focusses on selected NETs. A comparison between PV and select NETs is conducted by calculation of the costs and energy associated with the removal/mitigation of 1t-CO_2. Finally, some challenges to widespread implementation of NETs are summarised. The units used during the study have been defined in the box above.

3 RESULTS

3.1 Photovoltaics Technology

As reported by the IEA, PV-generation for the year 2021 exceeded 1000 TWh, owing to a record increase of 179 TWh compared to the previous year (22% growth) [8]. PV accounted for 3.6% of global electricity generation – the third largest source of renewable energy behind wind (over 1.87 PWh) [11] and hydropower (over 4.2 PWh) [12]. To achieve Paris climate goals, the *International Renewable Energy Agency* (IRENA) suggests that PV could account for a quarter of the global electricity, becoming the second-largest source of energy generation [13]. Furthermore, estimates suggest that PV will be the most installed technology (by power capacity), achieving a cumulative power capacity of over 2350 GW by the year 2027 [7], with total PV capacity projections at 8519 GW by 2050 [13].

PV technology is often an integral part of *Integrated Assessment Models* (IAMs) that forecast possible pathways for future energy scenarios. However, [14] have highlighted the underestimation of the contribution of PV technology, focusing on assumed costs during modelling PV technology. They note that reductions in *balance of system* (BoS) components and increase in reliability and lifetimes have led to the fall in the *Levelised Cost of Electricity* (LCOE) [14], while [15] have called the LCOE values for PV technology in the 5th Assessment Report by the IPCC "*outdated*". LCOE values as low as US$ 0.014-0.05/kWh by 2050, have been predicted [13].

Solar PV is a cheap and mature technological option, particularly since PV modules have "*maintained a learning rate of 23% since 1976*" [14, p. 1044] and "*learning rate estimated with data from 2007 is even higher at 40%*" [14, pp. 1044-1045]. The main contributor is high amount of research and development that has led to rapid technological advancement, increase in efficiency, reliability and reduced costs.

Crystalline polysilicon is the dominant technology in the market but since 2021, monocrystalline technology has seen growth and is expected to take over the crystalline polysilicon market [8]. Newer, more efficient technologies using *Tunnel Oxide Passivated Contact* (TOPCon) and heterojunction cell design have seen growth in recent years [8] and can be expected to grow more in future.

3.2 Negative Emissions Technology

Removal of carbon from the atmosphere is an important way to arrest the increasing rate of climate change. Political discussions as early as the 1990s have included carbon removal in the agenda of the *United Nations Framework Convention on Climate Change* (UNFCCC) [16]. Generally, NETs absorb carbon from the immediate environment around it and store it in sinks. These sinks may be local (AR, wetland restoration, soil mineralization and management) or in the form of geological formations (BECCS, DACCS), where the captured carbon may be stored [4, 9].

The inclusion of NETs into IAMs with an aim to achieve net-zero or global emissions targets is not a recent phenomenon. The strategy of removal of greenhouse gases was also recognised by the IPCC in their First Assessment Report [17]. All subsequent reports have recognised the need for the removal of carbon and the use of *carbon capture and storage* (CCS) technologies for the mitigation of climate change [18–21].

Table 1: Selective Negative Emissions Technologies

Technology	Description	TRL	Potential Capacity (Gt-CO_2 pa)	Estimated Costs (US$/t-$CO_2$)
Biochar	Preventing return of biotic carbon via decomposition by storage in soil as partially combusted matter	4-6	0.9-3.0[9] | 2.75-4.95[4]	8-300
DAC – Supported Amines	Pumped or circulated air through solid amines which capture CO_2 through adsorption	3-5	10[9] | 0.5-5[6] | 0-11.01[4]	40-300
DAC – Wet Calcination	Wet scrubbers using calcium/sodium cycling technology to capture atmospheric CO_2	4-6		165-600
BECCS (through combustion)	CO_2 captured from emission of bioenergy sources during combustion	4-6	0.5-5 [6] | 2.4-10[9]	70-250
BECCS (through ethanol/BLG)	CO_2 captured from emissions of bioenergy sources at earlier stages during formation of ethanol	5-6	0.048 (ethanol) | 0.25-0.375 (BLG)	<45
Forest Management	Increase in forest area through new forests and enhanced management to maximise carbon sink	6-7	1.5-3.0[9] | 0.5-75[6] | 0.73-5.5[4]	20-100

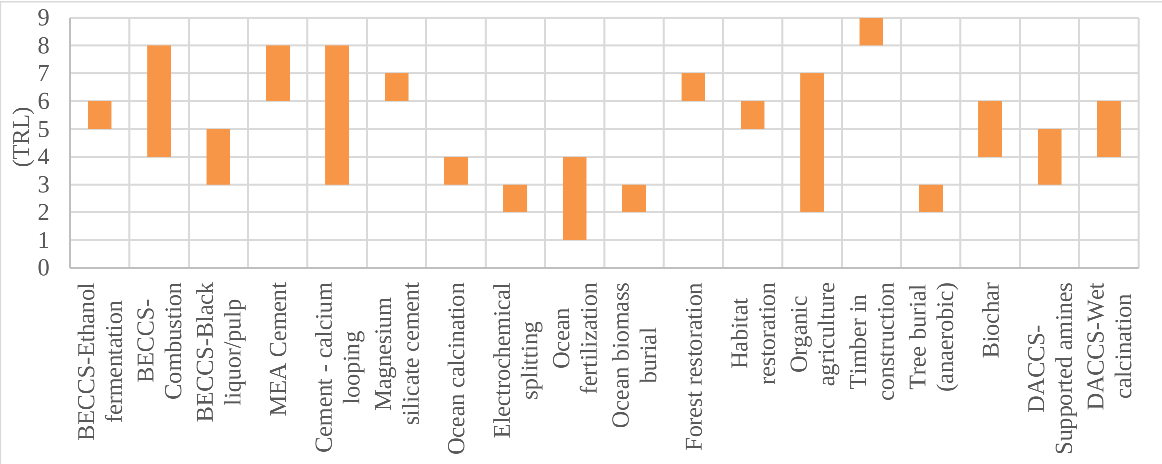

Figure 2: Technology Readiness Levels for various NETs [9, 25]

While some methods are already well-known (AR, SCS), recently other technologies (DACCS, BECCS) have also come under the scientific focus [4]. The research corpus is not evenly distributed amongst technologies. While there is a "*growing reliance on NETs in IAM projections*" [5, p. 2], the lack of available data and the need for further research, particularly as technological case studies and the uncertainty associated with the feasibility of deployment is also a concern [2, 5, 6].

Table 1 shows selected technologies and important parameters characterising them. The larger Table 2 from which Table 1 has been derived, has more NETs and can be found at the end of the report. Various important parameters including the *technology readiness level* (TRL), potential deployment capacity (in Gt-CO_2 pa) and the estimated specific costs (in US$) associated with the technology have been tabulated therein.

The TRL is a system of classification of the maturity of a particular technology as a method to classify technological feasibility [2]. TRL 1 is the lowest and TRL 9 is the highest level. Figure 2 shows TRLs for various NETs from [9, 22]. From Table 1 (*and Table 2*), it is evident that technologies with the greatest potentials (DACCS, BECCS) have low readiness levels (between TRL 3-6) and highest costs associated with CDR. Indeed, as observed by [23] in [2], most NETs have not advanced beyond the prototype/model demonstration phase (TRL 6). Furthermore, technologies which have relatively lower estimated costs (<US$50/t-$CO_2$), have either very low potential (BECCS through BLG, wetland restoration) or very low TRL (soil mineralisation, biomass burial).

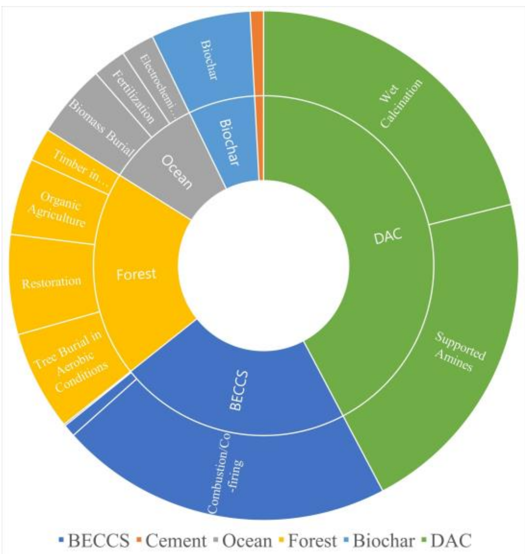

Figure 3: Global Potential Capacity (Higher Value) for NETs [9]

Based on selected data from Table 2, Figure 3 charts the global potential capacities for selected NETs, totalling 47.323 Gt-CO_2 pa. Though DACCS shows the highest global potential in Figure 3, it is important to note that nearly all the modelled NET capacity for various emissions pathways and scenarios comes from BECCS and AR [2, 24] and only some studies have included DACCS [5]. Combining information from Figure 2 and Figure 3 leads to the conclusion that the NETs which account for the greatest stated negative emission potentials (BECCS, DACCS) are not yet proven in deployment. Even in studies where BECCS is projected to contribute the greatest amount for carbon removal (5-20 Gt-CO_2 pa) by 2050, it is pointed out that there are currently no existent systems in deployment [5].

Another important aspect associated with carbon storage is the duration for which the carbon can be stored and the reliability of the sink. High permanency and long-term storage is an important parameter that is seen in technologies like BECCS and DACCS, where the captured carbon is stored in geological sinks which can store carbon for centuries [4, 6, 9, 24]. Biochar, when used as soil amendment, can also act as long-term storage [25]. In contrast, AR, where captured carbon is stored as biomass, is considered a short-term storage option which is additionally susceptible to natural and human disturbances including fires and deforestation [25].

Scenarios studying global emissions until the end of the century estimate total negative emissions in the magnitude of 100-1180 GtCO_2 [4, 10] to 1200 Gt-CO_2 [9] are needed. Figure 2 [9, 22] maps technologies and their readiness levels. It can be seen that forest and habitat restoration, though subject to uncertain achievable rates of negative emissions, are among the readiest techniques [9]. Further, "*[L]arge-scale afforestation and reforestation can make an important contribution to the overall CDR effort*" [26, p. 327]. Timber in construction and cement-based NETs are also at, or close to, practical deployment stages [9].

Whereas Table 2 offers a more comprehensive view, it can be seen from Table 1 that there are steep costs associated with removal of carbon from the environment. Technologies which have become the focus of mitigation solutions in many scenarios (BECCS, DACCS) have enormous costs associated with their implementation. CDR via DACCS is limited to system demonstrations in relevant environments (TRL 6) and already cost estimates have touched US\$ 600/t-CO_2 removed. Worryingly, [9] points out that even these estimates might be "*highly optimistic*" [9, p. 495] and cost estimates for DAC could be as high as US\$ 800/t-CO_2. Similarly, in the case of BECCS via combustion, which has the highest potential of all BECCS technologies, cost estimates are as high as US\$ 250/t-CO_2 removed. Furthermore, as observed by [27], at present, BECCS and DACCS are operating only at a pilot-project stage and large-scale development in terms of scaling up and cost reduction is crucially needed over the next decade or two.

So far, we have identified important NETs and established the state of their art and noted the potentials for removal of atmospheric CO_2 and the costs associated with it. It is now evident how NETs can contribute toward a net-zero goal.

3.3 Comparison

A part of the analysis conducted included a comparison between PV and selected NETs. The aim was to measure the relative costs and energy consumptions associated with mitigation of 1t-CO_2.

Both PV and NETs offer solutions to reduce global carbon emissions; (I) PV via mitigation through replacement of more polluting sources and (II) NETs via removal of atmospheric carbon through capture and storage. This reduction can be considered indirect in the case of PV and direct in the case of NETs.

To quantitatively study (I), an analysis was conducted to study differences in the emission levels associated with various energy production technologies (Figure 4). The potentials and costs of individual NETs address (II). These have been discussed in the report. Finally, a comparison was also carried between PV and NETs. This comparison was carried out on the basis of costs associated with mitigation/removal of 1t-CO_2 from the atmosphere and the energy required to achieve this.

A brief assessment for different energy sources including Coal, Natural Gas, Petroleum, Nuclear and PV, technologies was conducted. These technologies were compared with PV since the fossil fuels are among the largest contributors to the energy mix, while nuclear is considered a low-carbon source [28]. The GHG emissions associated with generation of electricity were calculated and have been presented in Figure 4 [29]. The difference between emissions associated with fossil sources and nuclear and PV are quite significant. Coal is by far the most polluting of the technologies compared, followed by petroleum and natural gas. It is important to note that, while nuclear energy is a relatively 'clean', low-carbon source of energy, there are major security concerns associated with its use, the discussion of which is beyond the scope of this report.

To address (II), the following approach was applied. With the assumption that the PV technology, when applied, will replace coal, we see that coal produces roughly 1.1 kg-CO_2 more than PV for every unit electricity generated – thus, the generation of 847 kWh energy using coal produces 1t-CO_2. To achieve carbon mitigation, we consider that this energy will be generated using PV technology. Considering generation costs of around US\$ 0.04/kWh [30], generation of 847 kWh energy via PV will cost US\$ 34. This value has been used in Figure 5, where PV is compared with NETs. Costs for NETs were taken from Table 1. Graphical representation clearly demonstrates the disparity between the costs associated for mitigation using PV and mitigation using specifically designed negative emissions technologies, particularly DACCS. BECCS – ethanol fermentation is the only technology with costs similar to PV; however, it has limited deployment potential (<0.048 Gt-CO_2 pa).

The final parameter that was used as a quantity for comparison between PV and aforementioned NETs was the energy associated with the removal (or mitigation) or 1t-CO_2. In order to do this, we calculate the total PV capacity required for the production of 847 kWh

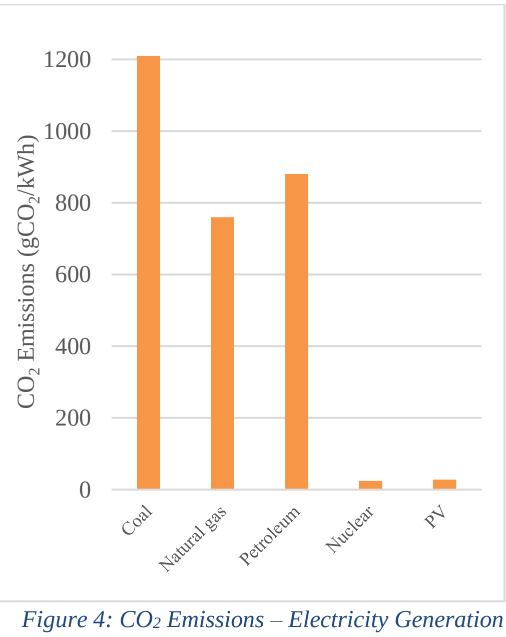

Figure 4: CO_2 Emissions – Electricity Generation (gCO_2/kWh) from [29]

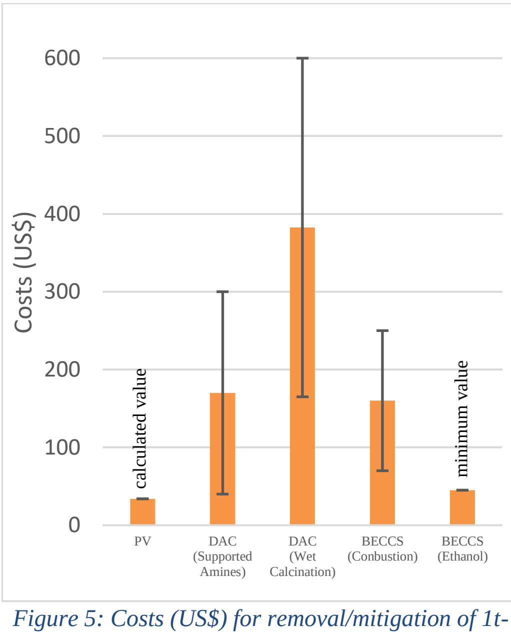

Figure 5: Costs (US\$) for removal/mitigation of 1t-CO_2 [9,30]

throughout its lifetime. For this calculation, power generation of 30 kWh/W_p was assumed throughout the lifetime of the module, considering 1600 hours of peak sunshine in a year, *performance ratio* (PR) of 75% and lifespan of 25 years [31]. Additionally, life cycle energy consumption (including module manufacturing, PV station operation, electricity transmission and other requirements) was assumed to be 1.9 kWh/W_p [31]. Using these values, we calculate a capacity of 28.23 W_p is required, which corresponds to approximately 53 kWh required. Similar data for the costs for NETs for DACCS could be found in [32]. Figure 6 graphically compares the energy associated with removal/mitigation of 1t-CO_2 from the atmosphere. It can be seen that energy requirements for DACCS-solid are more than four times PV while DACCS-liquid are more than eight times those of PV. Thus, we can conclude that PV is the more economical and energetically efficient than the studied NETs.

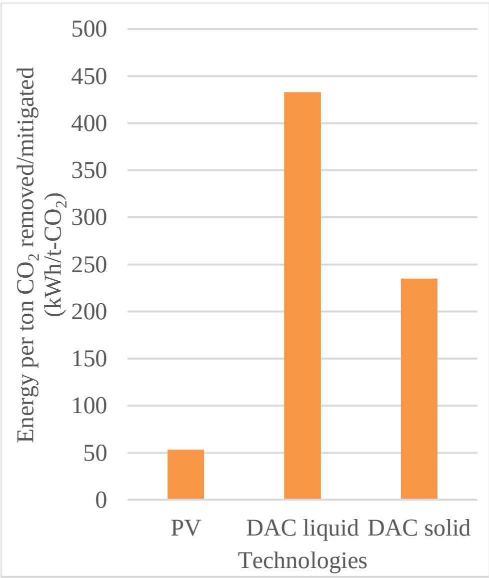

Figure 6: Energy required to remove/mitigate 1 t-CO2. PV requires less than a quarter of the energy required by DACCS [31,32]

3.4 On challenges for large-scale deployment of NETs

This section aims to offer a brief review of the challenges faced by certain negative emissions technologies which need to be addressed as a priority in order for these technologies to meet the levels of deployment suggested. This sense of urgency associated with implementation of NETs is missing in scientific literature, contemporary policy discussions and even policy itself [9].

Technologies such as BECCS, which form a major portion of the CDR estimates, are complex in nature, which itself is a potential barrier [24]. An increase in BECCS and AR would negatively affect land-use, including for agriculture and food [33], while in the case of DACCS, which is an energy intensive method, providing energy using fossil fuels, would render it "*inviable*" [33, 34, p. 1815, 35].

4 CONCLUSION

Climate change is an issue which needs synergetic action across the globe to achieve swift but lasting changes to the atmosphere. Mitigation of future emissions and removal of existing carbon excesses from the atmosphere are important pathways to achieving this goal. RES are predicted to play an important role in reducing further emissions, while deployment of NETs will result in a net reduction of atmospheric carbon. Thus we have seen the need for carbon reduction and carbon removal.

Over the last few decades, PV technology has shown sustained growth and increase in its efficiency. PV remains a promising technology to achieve net-zero emissions targets. NETs have been increasingly crucial in the study of such future pathways.

Through this paper we have identified that there is still untapped potential for growth and proliferation of PV, particularly through the use of more efficient technology (e.g. TOPCon). Analysis shows that PV has very low GHG emissions associated with energy generation. Advancements in auxiliary fields such as battery storage will help in increasing deployment of PV.

From several NETs, BECCS, AR and DACCS have been recognised as the most promising alternatives. The first two account for maximum NET share in IAMs. DACCS, with sufficient research to lower costs and energy requirements is also promising alternative.

Finally, having reported on the state of PV and NETs, we conclude that with as low as US$ 34/t-CO_2 and energy requirements of 53 kWh/t-CO_2, PV has been found to be the better economic and energetic alternative. Ideally, both these technologies should work in synergy to achieve carbon reduction and negative emissions.

Table 2: Negative Emissions Technologies

Technology Category	Technique	Description	Sequestration Category	Technology Readiness Level	Potential Capacity (Gt-CO_2 pa)	Limiting Factors	Estimated Costs (US$/t-$CO_2$)	Comments	Reference
Mineral	Soil Mineralisation	Acceleration of natural process of carbonation with addition of silicate minerals to soils (or surface water)	*Possibly shorter-term (decades)*	TRL 1-5	1	Land availability	20-40	Requires a change in long-standing practices; full account of land-use change is difficult. Possible synergetic outcome including increase in productivity and yield in biomass	[9]
	Magnesium Cement	Carbon mineralisation during the formation of concrete through the use of magnesium oxides which combine with atmospheric CO_2 when setting	*Possibly shorter-term (decades)*	TRL 6-7	0.4	Demand for cement	'parity' with Portland Cement	Technology is at or close to practical deployment stage	[9]
	Biochar	Preventing return of biotic carbon via decomposition by storage in soil as partially combusted organic matter	Decades to centuries, dependent on soil type, management and environmental conditions	TEL 4-6	0.9-3.0[9] | 2.75-4.95[4]	Sustainable supply of biomass, suitable soil for storage	8-300	Zero water requirements, likely one of the only technologies without a water footprint; possible competition for biomass	[4, 9, 33, 36]
Pressurised	DAC – Supported Amines	Pumped or circulated air through solid amines which capture CO_2 through adsorption	High permanency	TRL 3-5	10[9] | 0.5-5[6] | 0-11.01[4]	Energy supply, storage capacity	40-300	Local dilution of CO_2 might increase difficulty of capture over time	[4, 6, 9, 32, 33]
	DAC – Wet Calcination	Wet scrubbers using calcium/sodium cycling technology to capture atmospheric CO_2		TRL 4-6			165-600		[4, 6, 9, 32, 33]
	BECCS (through combustion)	CO_2 captured from emissions of bioenergy sources during combustion	High permanency, long-term storage	TRL 4-6	0.5-5[6] | 2.4-10[9]	Storage, sustainable biomass supply, suitable facilities	70-250	Large amount of land and water required, would consume a major portion of the world's fertilizer supply; massive transformation of agricultural systems needed to achieve projected deployment levels; projected loss of biodiversity, food security concerns and access to water and energy	[4, 6, 9, 32, 33, 35]
	BECCS (through ethanol/BLG)	CO_2 captured from emissions of bioenergy sources at earlier stages during formation of ethanol		TRL 5-6	0.048 (ethanol); 0.25-0.375 (BLG) | 5.5-11[4]		As little as 45		[4, 6, 9, 32, 33, 35]
Oceanic	Ocean liming (calcination/ electrochemical)	Addition of calcium oxide/ hydroxide/ bicarbonate to surface waters to accelerate uptake of atmospheric CO_2	*Unclear/ unknown*	TRL 3-4	Multiple Gt-CO_2 (calcination); 1 (electro-chemical)	Energy for calcination, supply of $CaCO_3$, vessels/ port facilities	54-64 (calcination); 100-180 (electro chemical)	Promising technology though there is need for additional research and development	[9]

	Ocean fertilisation	Increase in ocean productivity through addition of limiting nutrients like iron, phosphate or nitrogen	Unclear permanence, varying from days/months to millennia	TRL 1-4	0-1[9] | 2[4]	Impact on ocean biology, suitable locations, sustainable supply of nutrients	n/a	Unknown impacts on marine biology, great uncertainty over the effectiveness of these techniques	[4, 9, 33]
Biotic	Forest Management	Increase in forest area through new forests and enhanced management to maximise carbon sink	Saturation of forest lands, high vulnerability to disturbances	TRL 6-7	1.5-3.0[9] | 0.5-75[6] | 0.73-5.5[4]	Land availability	20-100	Potential employment opportunities, agricultural pressure including competition with food crops and changes to land use and farming, permanence of CO_2 at risk due to natural and accidental degradation of carbon stock	[4, 6, 9, 33]
	Wetland Restoration	Rewetting and restoration of peatlands, tidal salt marshes and mangrove swamps to enhance anaerobic storage of dead organic matter	Long-term storage	TRL 5-6	Several hundred Mt-CO_2 pa	Land availability	10-20	Can be combined with Biochar; large uncertainties associated with harmonisation of definition of wetlands (data varies from 2-8% pf global land surface)	[9, 37]
	Soil Management	Better agricultural practices to reduce loss of carbon through oxidation	*Possibly shorter-term (decades)*	TRL 2-7	2.3	Land availability	n/a	Fairly large uncertainties regarding actual achievable net negative emissions; changes to agricultural practices	[9]
	Timber in Construction	Increased use of harvested timber in long-life construction applications	*Possibly shorter-term (decades)*	TRL 8-9	0.5-1	Construction demand, sustainable supply of timber	Negligible in most applications	Ecological resourcing of timber on a large scale is a possible challenge in case of widespread implementation	[9]
	Biomass Burial	Burial of harvested biomass in anaerobic conditions on land or in the deep ocean	*Possibly shorter-term (decades)*	TRL 2-3	1-3.0	Sustainable supply, suitable sites, logistics	7-50	Possible conflict with biomass usage for BECCS technologies	[9]

Note: marked in italics are estimates by the authors.

References

[1] United Nations Framework Convention on Climate Change, *The Paris Agreement.* [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed: Jan. 18 2023).
[2] T. Thoni *et al.*, "Deployment of Negative Emissions Technologies at the National Level: A Need for Holistic Feasibility Assessments," *Front. Clim.*, vol. 2, 2020, doi: 10.3389/fclim.2020.590305.
[3] B. K. Sovacool, C. M. Baum, and S. Low, "Determining our climate policy future: expert opinions about negative emissions and solar radiation management pathways," *Mitigation and adaptation strategies for global change*, vol. 27, no. 8, p. 58, 2022, doi: 10.1007/s11027-022-10030-9.
[4] J. C. Minx *et al.*, "Negative emissions—Part 1: Research landscape and synthesis," *Environ. Res. Lett.*, vol. 13, no. 6, pp. 1–29, 2018, doi: 10.1088/1748-9326/aabf9b.
[5] J. Fuhrman, H. McJeon, S. C. Doney, W. Shobe, and A. F. Clarens, "From Zero to Hero?: Why Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better," *Front. Clim.*, vol. 1, 2019, doi: 10.3389/fclim.2019.00011.
[6] M. Fajardy, P. Patrizio, H. A. Daggash, and N. Mac Dowell, "Negative Emissions: Priorities for Research and Policy Design," *Front. Clim.*, vol. 1, pp. 1–7, 2019, doi: 10.3389/fclim.2019.00006.
[7] IEA, "Renewable Electricity," IEA, Paris, 2022. Accessed: 30 January, 2023. [Online]. Available: https://www.iea.org/reports/renewable-electricity
[8] IEA, "Solar PV," IEA, Paris, 2022. [Online]. Available: https://www.iea.org/reports/solar-pv
[9] D. McLaren, "A comparative global assessment of potential negative emissions technologies," *Process Safety and Environmental Protection*, vol. 90, no. 6, pp. 489–500, 2012, doi: 10.1016/j.psep.2012.10.005.
[10] IPCC, *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2018.
[11] IEA, "Wind," IEA, Paris, 2022. Accessed: Feb. 2 2023. [Online]. Available: https://www.iea.org/fuels-and-technologies/wind
[12] IEA, "Hydropower," IEA, Paris, 2022. Accessed: Feb. 2 2023. [Online]. Available: https://www.iea.org/fuels-and-technologies/hydropower
[13] IRENA, "Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects: (A Global Energy Transformation: paper)," International Renewable Energy Agency, Abu Dhabi, 2019.
[14] M. Victoria *et al.*, "Solar photovoltaics is ready to power a sustainable future," *Joule*, vol. 5, no. 5, pp. 1041–1056, 2021, doi: 10.1016/j.joule.2021.03.005.
[15] S. Philipps, C. Kost, and T. Schlegl, "Up-to-Date Levelised Cost of Electricity of Photovoltaics: Background from Fraunhofer ISE relating to IPCC WGIII 5th Assessment Report, Final Draft, September 2014," pp. 1–7, Oct. 2014.
[16] W. Carton, A. Asiyanbi, S. Beck, H. J. Buck, and J. F. Lund, "Negative emissions and the long history of carbon removal," *WIREs Clim Change*, vol. 11, no. 6, 2020, doi: 10.1002/wcc.671.
[17] IPCC, "Climate Change: The IPCC Response Strategies," 1990.
[18] IPCC, "Second Assessment Report: Climate Change 1995: Synthesis Report," 1995.
[19] IPCC, "Climate Change 2001: Synthesis Report," 2001.
[20] IPCC, "Climate Change 2007: Synthesis Report," 2007.
[21] IPCC, "Climate Change 2014: Synthesis Report," 2014.
[22] M. Lyons, P. Durrant, and K. K., *Reaching Zero with Renewables: Capturing Carbon*: International Renewable Energy Agency, Abu Dhabi, 2021.
[23] G. Lomax, T. M. Lenton, A. Adeosun, and M. Workman, "Investing in negative emissions," *Nature Clim Change*, vol. 5, no. 6, pp. 498–500, 2015, doi: 10.1038/nclimate2627.
[24] M. Fridahl and M. Lehtveer, "Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers," *Energy Research & Social Science*, vol. 42, pp. 155–165, 2018, doi: 10.1016/j.erss.2018.03.019.
[25] H. K. Jeswani, D. M. Saharudin, and A. Azapagic, "Environmental sustainability of negative emissions technologies: A review," *Sustainable Production and Consumption*, vol. 33, pp. 608–635, 2022, doi: 10.1016/j.spc.2022.06.028.
[26] J. Rogelj *et al.*, "Scenarios towards limiting global mean temperature increase below 1.5 °C," *Nature Clim Change*, vol. 8, no. 4, pp. 325–332, 2018, doi: 10.1038/s41558-018-0091-3.
[27] R. S. Haszeldine, S. Flude, G. Johnson, and V. Scott, "Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments," *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, vol. 376, no. 2119, 2018, doi: 10.1098/rsta.2016.0447.
[28] H. Ritchie, M. Roser, and P. Rosado, "Energy: Energy Mix," *Our World in Data*, 2022. [Online]. Available: https://ourworldindata.org/energy-mix
[29] V. Fthenakis and M. Raugei, "Environmental life-cycle assessment of photovoltaic systems," in *The Performance of Photovoltaic (PV) Systems*: Elsevier, 2017, pp. 209–232. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781782423362000070
[30] IRENA, "Renewable Power Generation Costs in 2021," International Renewable Energy Agency, Abu Dhabi, 2022.
[31] G. Hou *et al.*, "Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China," *Applied Energy*, vol. 164, pp. 882–890, 2016, doi: 10.1016/j.apenergy.2015.11.023.
[32] M. Ozkan, S. P. Nayak, A. D. Ruiz, and W. Jiang, "Current status and pillars of direct air capture technologies," *iScience*, vol. 25, no. 4, pp. 1–23, 2022, doi: 10.1016/j.isci.2022.103990.
[33] S. Fuss *et al.*, "Negative emissions—Part 2: Costs, potentials and side effects," *Environ. Res. Lett.*, vol. 13, no. 6, p.

63002, 2018, doi: 10.1088/1748-9326/aabf9f.

[34] F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G. P. Peters, and R. Socolow, "The mutual dependence of negative emission technologies and energy systems," *Energy Environ. Sci.*, vol. 12, no. 6, pp. 1805–1817, 2019, doi: 10.1039/C8EE03682A.

[35] H. J. Buck, "Rapid scale-up of negative emissions technologies: social barriers and social implications," *Climatic Change*, vol. 139, no. 2, pp. 155–167, 2016, doi: 10.1007/s10584-016-1770-6.

[36] P. Smith, "Soil carbon sequestration and biochar as negative emission technologies," *Global change biology*, vol. 22, no. 3, pp. 1315–1324, 2016, doi: 10.1111/gcb.13178.

[37] D. Were, F. Kansiime, T. Fetahi, A. Cooper, and C. Jjuuko, "Carbon Sequestration by Wetlands: A Critical Review of Enhancement Measures for Climate Change Mitigation," *Earth Syst Environ*, vol. 3, no. 2, pp. 327–340, 2019, doi: 10.1007/s41748-019-00094-0.