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# Climate Change Mitigation Technologies: Prospects and Challenges

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**Abstract**

One of the significant, perhaps momentous, developments in the effort to mitigate climate change has been the convergence around the target of Net Zero Emissions (NZE). The path to NZE envisions a massive increase in the installed capacity of renewable energies (REs)accompanied by a radical reduction in fossil energies. The paper outlines the main technologies required to make renewables a reliable alternative. Storage mechanisms such as batteries, hydrogen, and pumped storage are reviewed. Major impediments to the replacement of fossil fuels with renewable sources include technological, political, and social lock ins. Since NZE emissions are unlikely to be realized without installing negative emission devices, carbon dioxide removal methods and their concomitant challenges are discussed. Demand side mitigation in the transport, buildings, and industry sectors, relevant technological solutions, and adjustments to social preferences are briefly addressed.

In addition to analyzing the challenges to realize an NZE world, the paper cautions against a single metric focus while ignoring concerns over adaptation, rising inequalities, water and food availability, and biodiversity. The financial implications of the various mitigation technologies are highlighted along with the need to transfer technologies and funds to developing nations to avoid and/or reduce emissions.

**Keywords:** Net Zero Emissions, hydrogen, energy lock ins, carbon removal problems, emission metrics

## 1. Introduction

It is clear to leaders, policy makers, and citizens alike that climate change is an existential threat which has to be tackled through global collaboration. A significant development in this context has been the consensus on the need to reach net zero emission (NZE) world by mid-century. The transition to clean energy will depend substantially on renewable energies (REs) replacing fossil fuels. However, despite the meteoric growth in RE capacity, and even under the most optimistic scenarios, REs cannot electrify all energy needs (Section 3). The intermittency of REs makes energy storage, discussed in section 4, an essential component of any system in which REs comprise the bulk of the energy supplied. Fossil fuels are likely to remain significant sources of energy for decades to come, making carbon removal (section 6) central to an NZE world (IPCC, 2022a). The ambitious mitigation goal of reaching NZEs by 2050 by employing a suite of existing and emerging technologies might still falter if technological, social, and political lock ins are not addressed in tandem (section 5). The accuracy with which emissions are measured is a critical concern in tracking progress toward NZE, the pursuit of which may, on occasion, need to be balanced against desired economic outcomes and energy security (section 7). The concluding section briefly addresses some limitations of the study, some directions for future research, and the need to adapt to climate change while mitigating emissions.

## 2. Purpose

The path to a carbon-neutral world depends on a rapid expansion in renewable energies, but the simultaneous development of complementary capabilities (e.g. energy storage) is critical to sharply reducing dependence on fossil fuels. Since a complete decoupling of emissions and energy is unlikely, removal methods are indispensable to a net zero world. The challenges facing emissions reduction and removal technologies are developed in the paper. The political and social forces which need to be harnessed for a successful energy transition are explicated. The paper concludes that achieving a successful energy transition calls for addressing a variety of technological challenges, augmented by social, political, and behavioral expertise. Though the financial commitments needed for speedy mitigation are high, adaptation to climate change is likely to demand increasing effort and expenditure as well. A singular focus on decarbonization should not distract from other pressing climate-related concerns.

The paper delineates some of the prominent technologies which are viewed as critical to climate change mitigation. However, the paper's added value lies in its focus on technological, social, political, and demand lock ins which could seriously impede progress towards NZE. The paper cautions that carbon emission and removal technologies will prove inadequate in the ambitious quest for NZE unless the various lock ins are systematically addressed.

## 3. Mitigation Technologies

### *3.1 Renewable Energy*

Mitigation efforts are primarily focused on electrification using renewable energies, while removing a portion of existing and future GHGs emissions (Fawzy, Osman, and Rooney, 2020). Though solar and wind power generation capacity have grown at the remarkably high rate of nearly 15% per year over the period 2015-2020, they still constitute only about 10 % of total electrical capacity, with hydro adding another 15%. Nuclear contributes about 10%, with coal and natural gas making up the rest (Ritchie and Roser, 2021; IEA, 2020a). The rapid growth of solar and wind has been driven by falling costs, that of the former plummeting by over 80% since 2010, while wind power costs have halved in that period (Jaeger, 2021). Policies (incentives and subsidies, government support of R&D, feed-in tariffs, and competitive auctions) have spurred the exponential expansion. The availability of cheaper financing, the industry's growing political power, and a better appreciation of the risks of fossil energy have also contributed to a meteoric expansion in the installation of renewables.

### *3.2 Hurdles to Electrification of All Energy*

The world's total production of electrical energy amounted to around 25,000 terawatt hours (TWh) in 2020 (Enerdata, 2021) while the quantity of energy consumed for all applications (which includes transportation, cement and steel production, plastics manufacture, etc.) was about 160,000 TWh (Ritchie and Roser, 2020). Even substantial reductions of around 40% in energy intensity will not enable the world to use electricity to fulfil all its energy needs, though a technological breakthrough in cement and steel production (replacing coal with hydrogen, say) could mitigate the emission of CO2 considerably.

A major impediment to the direct substitution of fossil energies by renewables is the intermittency of the latter. In the absence of grid-level storage capabilities, only about 15-30% of electricity (depending on the location) from renewable sources can be utilized. At this level of unpredictability, the retention of base load power, from hydro, nuclear, gas, or coal, becomes imperative and inevitable, though even base load power has its own uncertainties such as the dependability of electric grids stretched to their limits (Blunt, 2022).

## 4. Technologies to Complement Renewables

### *4.1 Batteries*

One of the prime requirements to be able to utilize variable energy sources such as solar and wind is energy storage (Hicks, 2020). The use of batteries for storage at grid levels is inching up, and may stabilize electricity supply, from solar in particular. In 2022-'23, solar capacity in the US is expected to grow by over 50 % and battery storage capacity by over 10GW, 60% of which will be coupled to utility-scale solar (EIA, 2022). The near 80% decline in the price of lithium ion batteries over the past five years makes this storage method increasingly viable (Chandler, 2021). Among the hurdles to be overcome are the development of battery systems which can store electricity at the scale of a few gigawatts (at present, the capacity is limited to about 10MW), for at least four hours (Blunt, 2022). Though lithium ion cells have dominated the market so far and hold a distinct price advantage, newer types are being investigated, including solid state batteries (Gitlin, 2022).

### *4.2 Hydrogen*

Another way to "buffer" fluctuating solar and wind outputs is by storing hydrogen for use in turbines in lieu of, or by mixing with, natural gas. Hydrogen can also be used in fuel cells, say, for long-haul trucks, and as a substitute for coal/coke in cement and steel production. Some countries, such as Germany, South Korea, and Japan, and the U.K. have big plans to produce and utilize hydrogen (Brooks, 2022). China and India are investing billions of dollars to create a "hydrogen economy". China's hydrogen plans might seem rather modest at 100,000-200,000 tons a year, though green hydrogen is expected to supply up to 20% of the country's energy by 2050 (Varadhan, 2022; Nakano, 2021). India's Hydrogen Mission targets production of 5 million tons by 2030, about one-third of it for export (Varadhan, 2022). Hydrogen is seen by some as potentially ushering in an era of carbon-free energy generation and storage, in turn enabling renewables to achieve electrification of a wider range of energy needs (Handa, 2020).

However, problems are associated with almost every step of the hydrogen value chain (Eljack and Kazi, 2021). Hydrogen is mainly produced at present through the electrolysis of water, the energy for which could be supplied by electricity from coal-fired, natural gas, or renewable energy sources, resulting in black, grey, or green hydrogen as per the EU's taxonomy (Brooks, 2021). Countries in the EU are planning to expand their use of wind power in slack demand periods to produce hydrogen. The US, China, India, and Qatar have unveiled ambitious plans to forge ahead in the anticipated 'hydrogen economy.' The U.S. 'hydrogen shot' (Energy.gov, 2022) aims to lower the price of green hydrogen to $1/kg by 2030, an 80% reduction from the current price, while plans are underway to establish massive storage in Texas (Blain, 2022). India's Hydrogen Mission is based on converting solar energy into hydrogen, while Qatar is planning on using natural gas with carbon capture to produce green hydrogen for export. Storage of hydrogen adds to the cost as does its transport. Ways of overcoming the numerous hurdles to commercializing hydrogen production, storage, transport, and usage are being researched, but it could take up to a decade to be market ready (Chugh and Talbi, 2021). Trade in hydrogen is expected to balloon to constitute a major part of international energy transfers by 2040. Long haul trucking, shipping, and aircraft appear to be the most promising initial applications due to the gas's high energy density (Edson, 2021). One of the challenges is increasing supply while generating demand at the same time (IEA, 2019). The IEA (2019) expects that nearly 15% of the world's energy will be derived from hydrogen in 2050.

### *4.3 Gravity-Based*

Other storage methods are also attracting investment and innovative talent. When renewable energy is available but not needed, the electricity can be converted into potential energy to be released when clean energy is in short supply. The most widely used mechanical energy storage method is pumped storage. Water is pumped to an elevated location using electric power, which can be generated when needed by releasing the water through hydro turbines. About 95% of power storage capacity worldwide is of this type. Limitations include the need for large volumes of water, efficiencies of around 70%, and the lack of significant policy support (Hydropower, 2022). Variations of this technique are being tried out and have attracted significant investments. One approach involves pumping water underground, holding it under pressure, and releasing it through turbines when power is needed; another technique being tried out is to pump water under high pressure into large cisterns, storing the heat generated, and utilizing the pressurized water and heat to meet energy needs; based on a similar principle, trials are being run to use renewable energy to lift massive weights, which when lowered release usable energy. Most of such gravity-based methods are expected to prove increasingly useful for smoothing out localized energy supplies reliant on renewable sources (Holbrook, 2022). The combination of renewables, batteries, and hydrogen, along with pumped storage, and other gravity systems could ultimately hasten progress toward an NZE world. The storage capacity needed by 2050 would amount to 6TWh of energy at a cost of over $ 2 trillion (Weaver, 2022).

## 5. Energy Lock In

### *5.1 Technological Lock In*

For most countries, economic prosperity and energy security are imperative components of national wellbeing and security (Brookings, 2022; Yergin, 2020). Economic prosperity has become almost synonymous with GDP growth (Callen, 2020). As Hickel (2019) notes, even the Sustainable Development Goals assume that GDP growth will continue at a rate of about 3% in order to maintain adequate levels of employment and political stability.

Replacing imported fossil fuels with renewable energies sources domestically would greatly enhance energy security and offer the promise of economic wellbeing. One of the challenges to be overcome is the centralized nature of electricity generation, a model that has persisted for over a century (Agnew and Dargusch, 2015). Coal and nuclear power stations with outputs in hundreds of gigawatts seemed to be locked in, that is, they are difficult to replace in short order with wind and solar. Even if large chunks of REs are added, their variability imposes onerous pressures on the electric grid to switch between renewable sources, or from renewables to coal/nuclear and in the reverse direction. Expanding the grid to include more RE sources which have different peak generating times would ameliorate the problem but would strain the grid even further (The Economist, 2022). Artificial intelligence (AI) techniques have been developed to switch between renewables enabling power supplied exclusively from wind and solar energy. Though implementation has been on a limited spatial and temporal basis, AI-based grid management shows considerable promise in facilitating a renewables-only world (Murphy et al., 2020).

### *5.2 Socio-Political Lock In*

Energy lock in is exacerbated by the extent and intensity of commitment to fossil energies. Companies and nations which have invested heavily in coal-fired stations are reluctant to shut them down before their useful life of around thirty years has run its course. China and India both have thermal plants measured in hundreds of gigawatts not due to be shut down for decades (Arogyaswamy and Koziol, 2022). Coal-related employment runs to a few million in each country (Ibisworld, 2021; Mongabay, 2021), both of which are safeguarding their vital energy security concerns (Wu, 2018). In the United States, as coal ceded ground to natural gas (NG) as a power source, lock in of NG has become a reality to be dealt with. The EU had viewed NG as a transition fuel but, in the wake of the war in Ukraine, is finding that the extent of NG lock in that has occurred for industrial and residential use is extremely hard to loosen. Policies to substitute NG with liquefied NG are likely to result in locking in the latter to the delay and detriment of decarbonization (Popov, 2021).

### *5.3 Demand Lock In*

Transport, industry, and buildings are the three sectors which dominate the demand for energy (Creutzig et al., 2022). In regard to personal transport, petroleum lock in takes the form of affordability, parameters of comfort, fuel cost, ease of refueling, and so on. Auto firms are intensifying their efforts to introduce EVs to suit this wide range of needs, and the process could result in a third of all cars produced in 2035 being emission free. Plans to install sufficient charging stations to meet the burgeoning needs of the industry are under way as well. Changes in customs and lifestyle, which are notoriously difficult to initiate could help (IPCC, 2022b). For instance, if people could bicycle to work or take public transport, the use of cars might decline. If cities being built, many in LDCs, were designed to reduce distances traveled to work, school, stores, and so on, the need for mechanized transport could be whittled down (Seto et al., 2016).

Heating and cooling of residential buildings are responsible for about 30% of emissions and 20% of energy used, the difference being due to the use of electricity in many cases. A significant portion of the emissions occur during construction. Most new construction in the next few decades is scheduled to take place in developing countries. Just as transportation energy needs could be reduced by innovative urban design, modified building codes to minimize energy needed for heating and/or cooling could make a difference. Building-mounted solar panels, the use of improved insulation, better air circulation, and smart heating/cooling/lighting systems are among the possible innovations. In the case of both transportation and buildings, communication of the need for modified designs is essential to garner widespread social acceptance.

Steel and cement account for over 50% of the emissions by industry. Efforts are being intensified to find avenues ways to substitute for carbon used/generated in the production of both products (OECD, 2020). Even under an optimistic scenario, both industries have locked in emissions at least for the next ten years.

Assuming that the projected ambitious emission reductions are achieved overcoming the various lock ins, and demand side reductions also materialize, CO2 removals would still have to amount to 10 Gt per year to stay under a $2^0$C rise and 15 Gt/yr. for less than a $1.5^0$C rise, both in CO2 eq. (IPCC, 2022c).

## 6. Carbon Removal

The removal methods may be categorized as "nature-based" i.e. facilitating and complementing processes which already exist in nature to enable them to work more effectively, and "interventional" or employing machines to extract carbon from the atmosphere. Since the focus of the paper is on mitigation technologies, we restrict our attention to the interventional approaches.

### *6.1 Carbon Dioxide Removal*

Apart from the use of natural methods and offsets to remove carbon, Carbon Dioxide Removal (CDR) technologies are being hailed as an effective way to accelerate progress toward an NZE world (Chu, 2009; IEA, 2022). Carbon Capture and Storage (CCS) involves either removing CO2 at locations where fossil fuel combustion is occurring (e.g. power stations or cement plants) or Direct Air Capture (DAC), equipment for which may be installed anywhere (Wang, 2020). The process requires separation of the CO2 from other gases, compressing it, and storing it in underground caverns. It is less expensive if installed at the point of emission than when used for DAC, since CO2 concentrations in the atmosphere are extremely low. Even in the case of "tailpipe" removals, the technology is in its nascent stages and very expensive (Mehta, 2022; Hook, 2021). The extraction and storage could cost over $600 per ton, though that number could fall as new methods are developed (Mehta, 2022; Service, 2018). In the absence of high carbon prices and/or incentives for negative carbon, commercial scale CCSU and DAC are likely to take years, if not decades to realize with a capital investment ranging between $650 billion and $1.3 trillion (Oguntoye, 2021). The carbon captured could be used in making products such as building materials, though CCSU (the U being Usage) could require the expending of even more energy.

*6.2 Feasibility of CDR*

The expectation that CCS will significantly increase emission removal remains an idea whose practicality has yet to be established. The IEA (2022(a)) notes that CDR is not on track to achieve the 1.7 billion tons target by 2030. Some companies, particularly in the fossil energy sector, stake their claim to being climate-friendly on their investments in CCSU (Energyfactor, 2021; Temple, 2021). Given the track record of firms in the sector, one might be dubious both about the magnitude of investment made and the seriousness of intent. Two critical factors to consider with CCSU are its duration and the accuracy of measurement, both of which are works in progress (Plumer and Flavelle, 2021). Even if they succeed in expanding CCSU capacity to absorb, say, 2 GT of carbon annually at a cost of, say, $ 1 trillion, Jevon's paradox (Sorrell, 2009) suggests it is possible that this will only drive up demand for oil and gas. The outcome could well be an increase in fossil fuel use and profits for the firms in the industry. Issues such as the energy needed to operate CCSU on a massive scale and locations to store huge volumes of CO2 safely would also need to be addressed (IUPAC, 2022). Rather than rely on an unproven technology to get to NZE, raising carbon prices could facilitate rapid mitigation, with a lower need for, and perhaps at less expense than, CCSU (Straffer et al., 2021; Jaganathan, 2021).

*6.3 Geoengineering*

Geoengineering is another method which has been proposed as a way to reduce CO2 concentrations to accelerate emission absorption. Included under this umbrella are solar radiation management (SRM) through aerosol injection, the use of reflective mirrors, using sprayed sea water to reflect sunlight back, and so on. Research is proceeding on these and other approaches to SRM. While all scientific research in the service of reducing GHGs in the atmosphere is to be welcomed, the moral question of whether such techniques should be deployed at all needs to be addressed simultaneously (Wagner and Zizzamia, 2021; Shayegh, 2019).

## 7. Discussion

Emissions from uses of energy such as power generation and transport are based on estimates which may be inaccurate by as much as 10% or more (Pearce, 2018). Based on nationally reported data, CO2 concentrations should have risen by no more than 1.5-2% in the ten years ending 2019, but actually rose by 2.5%. Mooney et al. (2022) found that underreporting of emissions range between 8 and 12 Gt CO2 eq. annually, a counting error of 20-30%. The authors attribute the error to overestimation of the carbon absorbed, underreporting methane emissions, a lack of standards in measurement, and the desire to show progress in getting to NZE. As Muller (2018) and Stone (2020) note based on an extensive review of metrics in various fields, the motivation to reach the desired end may be so powerful that it induces participants to resort to a variety of methods to demonstrate that their actions resulted in the desired outcomes.

The fact that limiting emissions is tremendously complex involving much more than swapping one technology for another has been brought home by the war in Ukraine. The EU, which has been one of the leaders in pursuing a multifaceted mitigation agenda, has mooted the idea of expanding coal-based power, installing facilities for use of LNG, and so on. Short term reactions might lead to a lock-in of fossil energies and should be avoided. On the contrary, the push for renewables should accelerate in the interest of energy security (Lin, 2022), even if higher investments (and taxes), and changes in lifestyles are needed to facilitate the transition.

Achieving optimum levels of economic performance, energy security, and climate mitigation may be difficult to achieve. For instance, even in countries such as China and India where the levelized cost of electricity from solar power is lower than that from coal (See, 2022), capital is still needed to establish solar arrays. In addition, the number and types of jobs created in renewables are very different from those in coal mining and handling, possibly resulting in increased unemployment.

China and India are responsible for one-third of worldwide emissions, and their combined share could rise by 2040 to near 40% (EIA, 2018). Though both countries have rapidly ramped up their solar and wind installed capacities, the intermittency and lower reliability associated with these sources, has resulted in their being utilized only about 15-20% of the time. Coal still supplies a large proportion of their energy needs (around 50% for China and 70% in the case of India (IEA, 2020c). It is unrealistic to expect LDCs to make sacrifices in terms of economic advancement, which will affect populations which are among the world's poorest, while wealthy nations are still using substantial amounts of natural gas and coal for electricity to maintain or raise their standards of living (Tongla, 2021). China's and India's reluctance to curtail the use of coal for base load electricity supply is also, in part, based on energy security, China deriving about half its energy, and India nearly three quarters from coal. Rapid reductions in coal use could also jeopardize economic goals in both countries.

The transfer of funds from rich to less developed nations, committed to in the Paris Agreement has fallen short of the $100 billion promised annually (Shankleman, 2020). The present needs are estimated to be around $500 billion a year. In light of the unsettled nature of the global order, it remains unclear whether the financing and the political will to provide it are likely to materialize. In a deglobalizing world, sovereign nations are likely to act increasingly to serve their own interests even if it adversely affects mitigation and progress toward an NZE world.

## 8. Conclusion

The types of technologies needed for mitigation and the policies (subsidies, incentives) to facilitate their adoption are typically context specific. One of the limitations of this study is that these contextual conditions and the degree of government involvement in each have not been specified. The technological options are wide-ranging and need to be studied in detail to determine the most appropriate technologies along with the most optimal social, economic, and political policies. The paper has briefly noted these ideas but has not delved further into their implications. Potentially rich areas for inquiry include: (a) the rate of replacement of fossil fuels as the costs of REs decline employing moderating variables such as location, peak demand, etc., (b) the rate of rise in negative emissions compared to policy-driven emission reductions for the same cost.

The costs of decarbonization to get to an NZE world are daunting, amounting annually to around 3% of GDP till mid-century. However, pursuing a 'business as usual' approach could be far more costly in monetary terms. As the average global temperature rise approaches $1.2^{0}$ C over pre-industrial levels, the costs of adaptation are increasing faster than the rate of temperature increase. The worldwide costs of dealing with ongoing extreme weather events are estimated to be of the order of $600 billion. The harm caused by rising temperatures is incalculable in terms of human health, migrations, conflicts, impacts on agriculture and food outputs, loss in biodiversity, and much more. A cost-benefit analysis for mitigation carries little meaning since the intangible costs of inaction (or ineffective action) could become increasingly lethal to wide swathes of population around the world.

For a period of time, perhaps a few decades, investments in mitigation of around $5 trillion a year and adaptation funding of at least $600 billion a year are likely to be required (World Energy Investment, 2021). The potential for substantial private financing of mitigation exists, particularly if appropriate policy incentives and subsidies are instituted (UNFCCC, 2021). Adaptation expenditures, whether reactive or anticipatory, are less attractive to private investors since they do not generally offer lucrative returns. However, the need for resilience capacity-building should not be ignored or forgotten in the pursuit of an emission-free world. Concerns over sufficient food supplies, dwindling biodiversity, and the potential environmental damage and social harm caused by the mining and refining of cleantech materials also need to be part of any calculus to address climate change (Sovacool, 2021). That is, NZE should be viewed as a necessary but not sufficient criterion for climate change mitigation.

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