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# Enhancing Renewable Energy Systems, Contributing to Sustainable Development Goals of United Nation and Building Resilience Against Climate Change Impacts

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**Climate change impacts due to unprecedented rising concentrations of greenhouse gas (GHG) are intensifying and widespread, making extreme climate events more widespread, frequent, and severe. To mitigate the worst consequences of climate warming, herein it is investigated how the global community can collectively achieve a large-scale, sustained reduction in GHG emissions, and how to effectively move away from a predominantly fossil fuel-based economy to one dominated by renewable energy? This transition is necessary to achieve the sustainable development goals (SDGs) of United Nations (UN) to ensure resilient and healthy environment for present and future generations, especially the SDG 7 of UN, "Affordable and Clean Energy", set up to achieve global development of modern renewable energy systems. Investment policies and patterns of developed and developing countries in transitioning to energy productions primarily from renewable sources and obstacles such as scale-up challenges, innovations in new energy systems, policies, financing mechanisms, and implementation strategies are examined. Furthermore, a comprehensive overview of the present global status of hydropower, wind, and solar, the three most significant renewable electricity technologies, as well as their basic operating principles, costs, and potential is conducted. Hydroelectric, wind, and solar power had grown from 3429, 346, and 34 TWh $yr^{-1}$ in 2010 to 4274, 1598, and 846 TWh $yr^{-1}$ in 2020, a growth of about 1.25, 4.60, and 24.9 times in a decade, respectively. Strategies to achieve energy systems that are of or near net zero GHG emissions by 2050s through the deployment of renewable energy systems are also investigated.**

## 1. Renewable Energy Systems and Global Climate Warming

In recent years, interest in renewable energy has grown in public and private sectors, with significant support from various government to construct large renewable energy systems (RES) such as hydropower, solar, and wind farms, and research in developing new technology in RES. We often refer to RES as green energy because green is a color of nature, is the dominant color of vegetation in a natural environment that is good and healthy, and supports human life. In another sense, green also implies not changing or harming the environment, as what many human activities are doing, such as deforestation, urbanization, and countless environmental pollutions that could ultimately destroy our environment and threaten our existence. In another sense, RES is referred to as green energy because it is "renewable" given no matter how much we use today. Hydropower, solar, wind, and wave energy are all renewable because the supply will be replenished and as much as it was when we first started using them. In contrast, carbon-based fossil fuels produced by

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Earth's natural processes over millions of years are not renewable. In view of the current climate crisis attributed to rising concentration of greenhouse gases (GHG), how could the global community radically address the global warming crisis by transitioning from a predominantly fossil fuel economy to one dominated by renewable energy.[1]

In recent years, climate change impacts due to unprecedented rising concentrations of atmospheric GHG such as carbon dioxide ($CO_2$) and methane attributed to anthropogenic emissions are intensifying, widespread, and have affected every region on earth in many ways, making extreme climate events such as heat waves, floods, and droughts more widespread, frequent, and severe, particularly in 2021 and 2022. Global climate warming is predominantly driven by continuous increase in atmospheric GHG concentrations that warm the Earth system, with natural climate variability playing a negligible role. The global surface temperature was 1.09 °C [0.95–1.20 °C] higher in 2011–2020 than in 1850–1900, with a stronger warming over land than over the ocean.[2] It is likely that GHG forcing contributed 1.0–2.0 °C of the global warming. Even though the increase in atmospheric GHG concentrations are the dominant drivers of the climate system, about a third of the warming is masked by the cooling effects of aerosols which also originate from human activities.

The International Panel on Climate Change (IPCC) has shown that concentrations of $CO_2$, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800 000 years.[2] Over 1850–2019, about 2390 $\pm$ 240 ($\pm$1 standard deviation) gigatonnes (Gt) of $CO_2$ had been emitted to the atmosphere (**Figure 1**), resulting in the concentrations of $CO_2$ rising to 410 parts per million (ppm) and methane to 1866 part per billion (ppb) by 2019 compared to preindustrial levels of 300 ppm and 720 ppb, respectively. Figure 1 shows the linear relationship between $CO_2$ emissions to the atmosphere and global warming for five Shared Social Pathway (SSP) scenarios projected to 2050. Meinhausen et al.[3] provided the standardized set of GHG concentration futures for $CO_2$, $CH_4$, $N_2O$, and other minor GHG. For the historical period, this GHG concentration data for the Coupled Model Intercomparison Project (CMIP6) are provided by Meinshausen et al.[4,5] The GHG concentration data are provided until 2100 based on the emission scenarios derived from socioeconomically explicit integrated assessment models (IAMs) under the SSP framework.[6] These concentrations datasets are part of the protocols for several CMIP6 experiments, most notably ScenarioMIP.[7]

Developed nations that play a major role in the emissions of GHG have remained the largest overall contributors, at ≈15 Gt of $CO_2$ equivalent per year ($GtCO_2eq\ yr^{-1}$) between 1990 and 2010 and were contributing around 40% of the global $CO_2$ emissions in 2010s, but Asian and Pacific countries have rapidly increased their contributions since 1990. GHG emissions have continued to rise, most rapidly from industry, energy supply, and transport sectors. Compared to 2000–2009, average annual GHG emissions for 2010–2018 grew by 36% in industry, 24% in energy supply, and 19% in transportation. In 2018, 34% (11.3 $GtCO_2$-eq) of global GHG emissions came from the energy sector, 23% (7.7 $GtCO_2$-eq) from industry, and others.

Recent extreme climatic events attributed to climatic change are such as the 2021 summer wildfire, and massive flooding and mud slides in British Columbia of Canada, Germany, flooding of South Africa in 2022, and many others. Such hazards are causing long-term impacts on terrestrial, freshwater, and marine ecosystems.[8] For example, heatwaves are driving large-scale loss of ecologically important habitats such as coral reefs and seagrass beds, while floods, drought, and wildfire result in the loss of biodiversity in various ecosystems. The amplified warming of the Arctic in recent years, known as Arctic amplification, with significant cryospheric changes–loss of permafrost, sea ice, and snowpacks–has resulted in cascading environmental impacts in the Arctic,[9] which include migration and redistribution of species, synchronous and widespread mortality in birds, whale, and fish.

Climate change is already increasing the frequency and intensity of extreme weather events leading to large human and socioeconomic costs and reversing development gains across various sectors. Economic development has been strongly correlated to increasing energy consumption and GHG emissions.[10] The Paris Agreement of 2015 adopted by 193 countries to the United Nations Framework Convention on Climate Change (UNFCCC) puts forth a goal to drastically reduce GHG emissions, to achieve net zero emissions (NZE) by 2050, and to reverse the deteriorating climate crisis. Investment in green technology that promotes economic and social sustainability, and environment protection, can contribute to sustainable developments.[11] In 2015, 23 years after the 1992 Rio Summit on a universal agreement in making sustainability as the future path of humanity, the global community has agreed in achieving the 17 comprehensive sustainable development goals (SDGs) of UN in 2030. The 2019 Global Climate and SDG Synergy Conference in Copenhagen Denmark on strengthening synergies between the Paris Agreement and the 17 SDGs of the 2030 Agenda of United Nation, are goals to build resilience against impacts of climate change and a pathway toward low GHG emissions, achieving the temperature goal of the Paris agreement, and building global resiliency against the adverse effects of climate change. However, for the last 7 years, there has been far too little progress in striving toward the SDGs of UN, even though there have been many sustainability activities among governments, societies, and businesses worldwide.[12] How could the global community effectively move away from the current predominantly fossil fuel-based economy to one dominated by RES such as hydropower, solar, and wind power? What is the status of these three key RES, and what strategies or pathways are necessary and what policies are essential for the global energy sector to achieve near net zero or net zero $CO_2$ emissions by 2050s, or earlier.

Section 2 provides a review of RES, Section 3 discusses SDGs of United Nations, Section 4 on solutions for sustainability, Section 5 on transition to renewable energy, Section 6 on hydropower, Section 7 on solar energy, Section 8 on wind energy,

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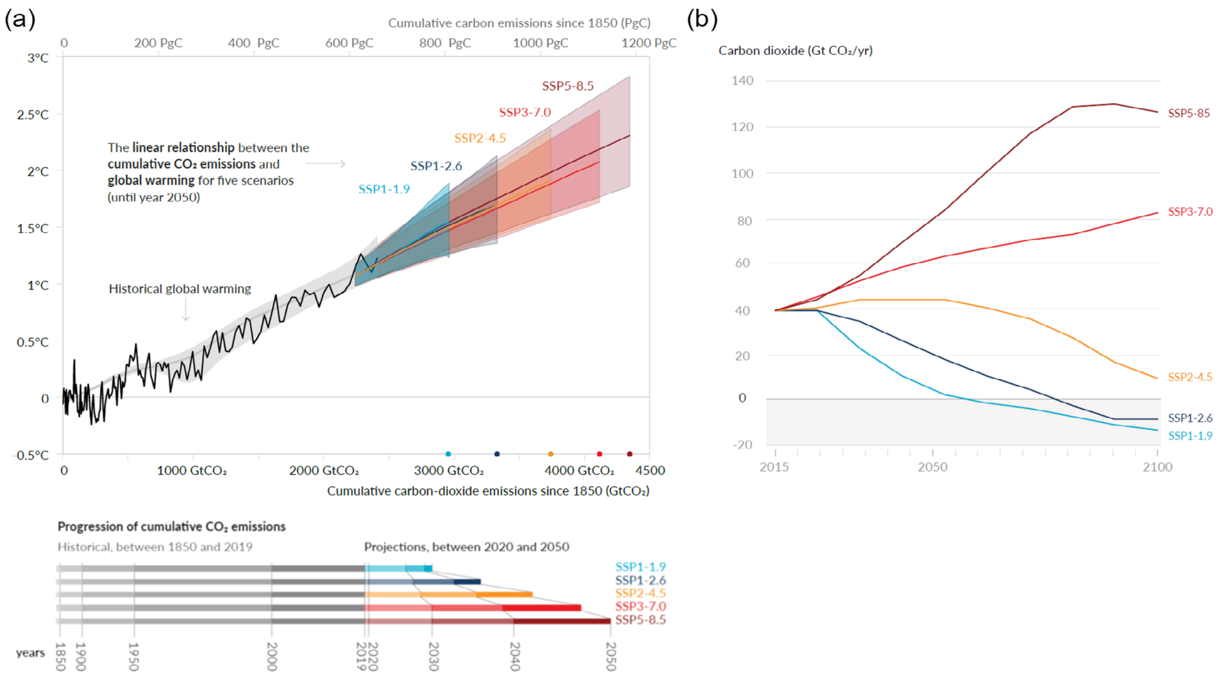


**Figure 1.** a) Global mean temperature increase since 1850–1900 in °C, showing the linear relationship between $CO_2$ emissions to the atmosphere and global warming for five SSP scenarios projected beyond the historical period of 1950 to 2019 to 2050, and b) projected future $CO_2$ emissions of the five SSP scenarios over the 21st century. Reproduced with permission.[2] Copyright 2021, IPCC.

Section 9 explains how renewable electricity supports deeper decarbonization, Section 10 on nonfossil as secondary energy supply, Section 11 on strategies to achieve net zero energy systems (NZES), and Section 12 on summary and conclusions.

## 2. Development of RES

Renewable energy is energy generated from renewable resources that are naturally replenished at a rate higher than they are consumed by humans. Sources of renewable energy include sunlight, wind, falling water, tidal waves, geothermal heat of the earth, and biomass of plants.[13] Most renewable energy sources are sustainable. RES produces power, mechanical energy, or heat by converting these energy resources mainly to electricity transported through electrical grids to consumers. These systems are commercially cost-effective for on-grid applications. In recent years, RES has generally shifted from small, private-owned systems designed to supplement utility power to large systems that produce significant amounts of power, megawatt (MW) to gigawatt (GW), owned by power companies. The cost of renewable electricity, particularly wind and solar, has declined rapidly in the last decade; so much so that the International Energy Agency (IEA) expects as much total renewable energy capacity to be installed in the next 5 years (2022–2027) as was installed in the previous 20.[14] Worldwide, large-scale solar farms are growing rapidly, and the IEA expects 2023 global solar investments to reach 382 billion USD, surpassing annual investments in oil for the first time.[15] This has been the result of a growing number of large-scale, multi-MW solar farms with solar energy systems that are concentrating, or that use tracking methods for panels and heliostats.

Wind energy also continues to improve as turbines are often taller and with larger rotors than the past,[16] with variable-speed generation and control systems to improve efficiency, increasing average installed capacities in the USA to 3.0 MW by 2021, an increase of 319% since 1999.[17] On the other hand, while hydroelectricity remains the largest renewable electricity source globally, its expansion is expected to slow in the coming decade. Large-scale hydropower projects involving water-impoundment dams and pumped storage systems are expected to make up the bulk of new installed capacity, with China's expected 93 GW of new capacity being overwhelmingly the largest market for new projects between 2021 and 2030, followed by India (27 GW) and Turkey (9 GW).[18,19] Hydro systems are not expected to see appreciable growth in North America in part due to political challenges due to potential adverse environmental impacts of these large-scale hydraulic structures, such as drowning large areas of land, siltation problems of dams, problems on salmon migration routes, etc. Many RES involve the development of photovoltaic (PV) or fuel cells to store power, battery chargers, charge controllers, and inverters.

## 3. SDGs of United Nations

The 17 SDGs of the UN are interconnected, with synergies between some SDGs that could produce an overall achievement greater than the sum of their separate achievements. On the other hand, to some degrees certain SDGs are also in competition or in contradiction with each other. Realistically, it will be a delicate balance between attaining environmental protection goals such as water and sanitation (SDG 6), sustainable cities (SDG 11), and climate action (SDG 13), economic development goals such as affordable and clean energy (SDG 7) and industry and innovation (SDG 9), and social inclusion goals such as reduced inequalities (SDG 10), and peace, justice, and strong institutions (SDG 16). The dynamic balance between environmental, economic, and social subsystems constitutes the crux of modern surface earth system science and is the scientific basis for coordinating necessary actions so that SDGs are achievable. Under ongoing global scale changes, making sustainable development a reality and building a global community with a shared future for human beings is the biggest challenging task of global governance, especially many developing countries are in fragile ecological environment and could face challenges achieving sustainable developments under multiple, concurrent environment changes.

### 3.1. SDG #7–Affordable and Clean Energy

The ecological environment carrying capacity and change thresholds of typical environment–economic–social systems are dependent on the sustainable usage of available water resources, soil resources, biological resources, and ecosystem services. This scientific SDG program of UN aims to provide scientific decision-making for the sustainable development of relevant countries and regions across the world. The SDG 7 of UN "Affordable and Clean Energy" has been set up to facilitate global challenges in the fast development of modern RES especially in the energy efficiency of transportation and heating sectors. The goal of SDG7 is twofold: to improve the human health and the standard of living of millions of people, and to address the potential catastrophic impact of climate warming such as hydrologic extremes, wildfire, and other natural hazards. In other words, SDG7 is to ensure that we will have access to affordable and reliable energy, while the future environment is also protected. Shobande[20] showed that energy predictors have a negative and significant impact on infant mortality rates among 23 African countries between 1999 and 2014, and having access to electricity reduces health risks associated with burning solid fuels in Africa.[21]

An integrated, systemic approach addressing various obstacles and involving active participants at all levels is essential to effectuate radical changes necessary to achieve SDGs of UN for 2030 designed to address the present environmental challenges: climate change, loss of biodiversity, and depletion of natural resources. We can only achieve SDGs of UN if we achieve deep technical, financial, and societal changes in transportation, energy, agri-food, and other systems, and if we together overcome critical factors to trigger a phase transition from our current predicament to the desired sustainable status. To be effective, SDGs policies must be measurable and monitored.

## 4. Solutions for Sustainability

Challenges to successfully transition toward sustainability are such as a lack of concrete policies, budget constraints, potential resistance among stakeholders, ignorance, a lack of public knowledge about sustainability, and a clear understanding of various social/economic barriers: global cooperation, path dependencies, rapid changes under tight time frame, cheap coal supply, and societal transformations. To develop principles for sustainability, governmental interventions are necessary so that sustainable development becomes the emergent trait of the human nature system, which requires all agents making up the system (e.g., consumers, citizens, professionals, politicians, and managers) taking correct actions and influences the development trajectory toward sustainability with their actions.

Adaptation solutions take many forms, scales, and approaches, depending on the unique context of a community, business, organization, country, or region. For example, Canada or the United States is not among countries with a National Action Plan, such as Brazil or Paraguay, or those that have initiated the process, such as Mexico (https://unfccc.int/topics/resilience/workstreams/nationaladaptation-plans/ldc-info). Least developed countries are eligible to submit NAPA (National Action Plan Action) to the UNFCCC secretariat to receive funding under the Least Developed Countries Fund (LDCF) (https://unfccc.int/process/bodies/constitutedbodies/least-developed-countries-expert-group-leg/ldc-portal/least-developed-countriesldc-fund) managed by the Global Environment Facility (GEF). Intense negotiations in the recent COP26 UNFCCC conference in Glasgow of Scotland in November of 2021 (https://unfccc.int/topics/un-climate-change-global-innovation-hub) have resulted in commitments by many countries to collectively achieve radical reductions in GHG emissions by 2030s and limit global warming to 1.5 °C by 2100.

Financial and technical supports are needed to build capacity such as the implementation of mitigation and adaptation measures, transition from fossil fuel to RES, and developing technical and institutional capacity gaps and needs. Concrete measures include GHG accounting, research and systematic observation, data collection, risk modeling, and vulnerability assessments, national communications, education, training, and public awareness, research and systematic observations, and technology transfer. Countries can build on existing processes, institutions, and endogenous capacities to implement effective, integrated programs to gain progress through an iterative, learn-by-doing process.

Given the negative impact of large-scale changes we currently experience is expected to increase with further warming, and the remaining carbon budget is about 500 $GtCO_2$ to limit global warming to around 1.5 °C above preindustrial, there is an urgent need for the global community to collectively achieve a large-scale, sustained reduction in GHG emissions.[2] Otherwise, limiting global warming to the 1.5 °C target relative to preindustrial levels will be beyond reach. Global energy system $CO_2$ emissions have closely tracked GDP per capita.[22] Together with economic growth, global fossil fuel $CO_2$ emissions have grown by 4.6% between 2015 and 2019 (1.1% $yr^{-1}$), reaching 33.4 Gt $CO_2$ $yr^{-1}$ in 2019 (https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020) and accounting for about 2/3 of the annual global anthropogenic GHG emissions. The development of new technologies and improvements in energy efficiency, e.g., a reduction of 2.2% $yr^{-1}$ in the use of energy per unit of gross domestic product (GDP) globally, has not overcome the increase of emissions from production and consumption. Instead, according to the IEA, the economic rebound from the

COVID pandemic is taking the global coal demand to over 8 Gt in 2022, the highest level so far.

Despite developing countries having lower per-capita emissions, they remain major accelerators of global $CO_2$ emissions growth since 2010, mostly driven by increased consumption and investment. How could countries across the world, which have adopted the Paris Agreement, implement effective domestic mitigation measures and adaptation strategies that provide a long-term horizon for climate action, leading to the NZE target by 2050? Many developed countries have begun reducing their reliance on fossil fuel, e.g., old coal fleets have been replaced approximately half by gas and half by renewables in the United States, mainly by renewables in the European Union, and by advanced coal plants and renewables in Asia.[23] On the other hand, growth in coal-fired electricity generation capacity in the Asia Pacific region has offset retirements in North America and Europe.[24]

The current war in Ukraine has resulted in Russia slashing deliveries of natural gas to Europe. Facing diminishing shipment of Russian natural gas, major European countries which have relied heavily on Russia for its gas supplies could face sky-rocketing energy costs, which could bankrupt energy companies across Europe, leading to energy rationing, industrial shutdown, job losses, massive protests, and potentially trigger another global financial crisis such as that of 2008. Countries such as Germany, France, Austria, and others could require major national bailout programs and emergency plans of rationing in late 2023. Given the impending energy crisis, it is time and prudent for Europe and other continents to invest more in RES.

To limit further, devastating temperature rises; the objectives of this study are to review the recent growth of global renewable energy resources from hydro, solar, and wind power, and the necessary scale and phases in transitioning from fossil fuel to RES to support the SDGs of UN, especially the SDG 7, to achieve net zero or near to net zero GHG emissions by 2050s (if we can achieve the most optimistic SSP1-1.9 scenario shown in Figure 1b). Transition to renewable energy, hydropower, solar energy, wind energy, renewable energy investments, nonfossil as secondary energy supply, strategies to achieve NZES, and summary and conclusions are discussed in Sections 4–11, respectively.

## 5. Transition to Renewable Energy

To mitigate the potential impact of global climate warming over the 21st century, renewables must work together to supercharge the clean energy transition. The economic and technical feasibility of solar and wind energy and electricity storage technologies have substantially improved in recent years and have become some of the lowest cost options regardless of their environmental benefits.[25] While hydropower supplies close to 15% of global electricity, wind and solar have also increased from less than 2% of total global electricity supply to about 10% by 2021.[26] For example, recently publicly announced wind and solar projects in Alberta, Canada have been contracted for 40 CAD/MWh and 60 CAD/MWh, respectively, compared to historic coal and gas dominated wholesale market prices of 60–80 CAD/MWh. Besides hydropower, solar, wind, other and forms of renewable energies of low GHG emissions are bioenergy, geothermal, marine, and waste-to-energy.

National policies in some countries notably Germany, Ireland, and Denmark in Europe and Uruguay, Honduras, and Chile in South America have been a major driver for transitioning electricity generation to more renewable sources. In other cases, subnational governments' policies are leading the growth of renewable energy, such as the United States, Australia, and Canada. Even though emissions from its electricity sector have grown as its demand continues to escalate, China remains by far the single largest renewable energy market, representing almost 70% of global wind energy growth in 2021.[27]

In addition to policy support, the improved technical performance and falling costs have driven the deployment rates of wind, solar, and batteries that far exceed earlier expectations.[28] However, even combined with other low-carbon technologies such as hydro and nuclear, collectively less than 40% of the global electricity is nonfossil fuel based, and the global reach of technological change is still insufficient to achieve the 17 SDGs of UN, although recent trends signal the potential to achieve the contributions required to limit warming to 1.5 or 2 °C.[10] About 10 800 GW of installed renewables capacity will be needed by 2030 to keep the 1.5 °C target within reach.

Global fossil fuel reserves are estimated to exceed 600 ZJ, of which coal represents the largest reserve (≈500 ZJ), compared to oil and gas which are about 15–30 ZJ each.[10] Close to 80% of our current energy needs are supplied from coal, oil, and natural gas. While these numbers are large compared to global annual primary demand of less than 0.6 ZJ, these fuels nonetheless have limited supplies on the Earth in addition to their resulting $CO_2$ emissions and air pollution pose significant near-term problems. Air pollution causes diseases like asthma, acid rain from sulfur dioxide and nitrogen oxides ($NO_x$) harms plants and fish, and $NO_x$ contributes to smog. In addition, oil price plays a major role in the global financial market, which tends to increase when demand exceeds oil supply or production, e.g., Urom et al.[29] found evidence of time variation in the comovement of interest rates and oil shocks; and when the oil price increases because of oil-specific demand (supply) shocks, the financial markets experience less (increased) stress.[30] Renewable sources on the other hand are continually renewed by natural sources, and typically have significantly lower lifecycle emissions compared to fossil fuel systems (https://www.nrel.gov/docs/fy21osti/80580.pdf), e.g., renewable energy sources typically emit about 18–80 g or less of $CO_2$ emissions per kWh over their life cycle, compared to about 1000 g $CO_2$/kWh for coal and 475 g $CO_2$/kWh for natural gas.

### 5.1. Transition to Renewable Energy in 2000–2020

**Figure 2** shows the transition of global primary energy in renewable sources over the last 20 years, 2000–2020 (**Table 1**). Primary renewable sources presented in Figure 2a include hydropower, solar, wind, geothermal, wave, tidal, and modern biofuels using data calculated by converting nonfossil fuel sources to the equivalent primary energy that would be required to produce the same amount of energy if it came from fossil fuels to account for the inefficiency of energy production from fossil fuels. Figure 2a

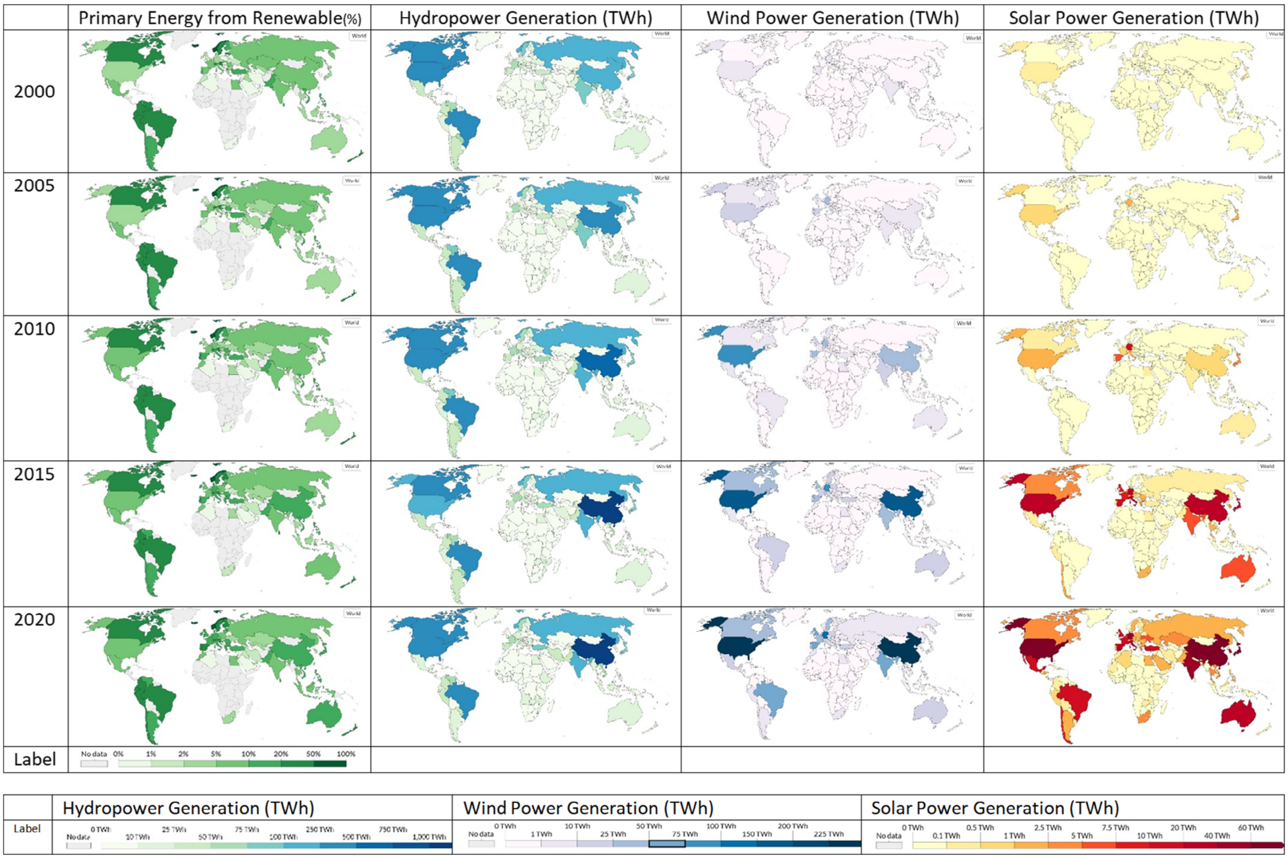


**Figure 2.** Changes of global share of renewable energy sources (hydropower, solar, wind, geothermal, bioenergy, wave, and tidal), annual hydropower generation, annual onshore and offshore wind power generation, and annual solar power generation in terawatt hours (TWh) over 2000–2020, based on BP Statistical Review of World Energy and Ember data.

**Table 1.** Global renewable energy generations by hydro, wind, and solar systems in the last 20 years based on BP Statistical Review of World Energy and Ember data.

| Renewable system | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| Hydropower [TWh yr$^{-1}$] | 2647 | 2911 | 3429 | 3878 | 4274 |
| Wind power [TWh yr$^{-1}$] | 31.4 | 105 | 346 | 831 | 1598 |
| Solar power [TWh yr$^{-1}$] | 1.1 | 4.2 | 33.4 | 255 | 846 |

shows that in the last 20 years, Canada, Brazil, Chile, Norway, and a few others have maintained over 20% of primary energy coming from renewable sources, which are also growing in countries such as China and Australia and parts of EU, but most African countries remain having less than 1% of renewable energy sources.

Hydroelectric power is the largest source of low-carbon, renewable energy, accounting for more than 60% of renewable generation, but the scale of hydroelectric power generation varies significantly across the world, with China as the largest hydroelectric power producer since 2010, where in the last decade it has grown to over 1000 TWh per annum, followed by Brazil, North America, India, and Russia (Figure 2b). Globally, next to hydropower, wind and solar power are both growing rapidly since the beginning of the 21st century, particularly in the United States and China, followed by India, Canada, Brazil, parts of EU, and Australia (Figure 2c,d). Major solar energy generation (over 60 TWh) comes from the United States, China, India, Australia, and some western EU countries. In contrast, majority of developing countries in Africa, parts of South America, SE Asia, such as Indonesia, and Middle East still trail behind in harnessing solar energy. Since 2010, wind energy is growing rapidly in the United States and China (>225 TWh), followed by India, Brazil, some western EU countries, and Canada while most other countries still produce less than 10 TWh of wind energy by 2020. There are still significant potentials for major wind and solar power developments across the world, particularly in developing countries.

Drivers to change to renewable energy include regulations, cost of renewable energy, and the recent natural hazards occurring worldwide that clearly demonstrate the urgency of radically addressing the global climate crisis. The cost of renewable energy per MWh especially solar PV has decreased significantly since early 2000s that it is now comparable to fossil fuel energy such as coal and gasoline (**Figure 3**). Despite their recent growth, and their importance in reducing emissions, renewable energy technologies are still largely considered "nonconventional" or "alternative". Sections 6–8 discuss the fundamentals of the three most significant renewable electricity technologies, hydro, wind, and solar, and their current status.

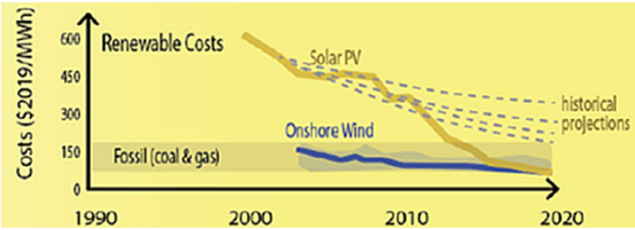


**Figure 3.** Costs of renewable energy from solar PV and onshore wind compared to fossil fuel energy. Reproduced with permission.[28] Copyright 2021, IPCC.

## 6. Hydropower

Hydropower generates about 15% of the world's electricity, and about 56% of the global renewable electricity.[26] With an installed hydropower capacity of 352 GW, China produces the most amount of hydropower, followed by Brazil, Canada, and the United States. Overall, Asia holds the largest hydropower potential (48%), followed by South America (19%).[31] The global hydropower potential is estimated to be approximately 15 000 TWh per year (**Figure** 4a). The estimated, theoretical global hydropower potential ranges between 31 and 128 PWh $yr^{-1}$ (112– 460 EJ $yr^{-1}$)[32,33,34] but is distributed over countless locations (Figure 4b). While many locations may have technical potential, development can be limited because of economic or political reasons.

Hydropower ($P$) turbines of efficiency $\eta$ convert the energy in water flowing at rate $Q$, density $\rho$, and hydraulic head $H$ into electricity ($P = \eta\rho QH$), either from water impounded behind a dam on a river, or a run-of-river system by diverting water from a river to a turbine. Hydropower is technically mature and a primary

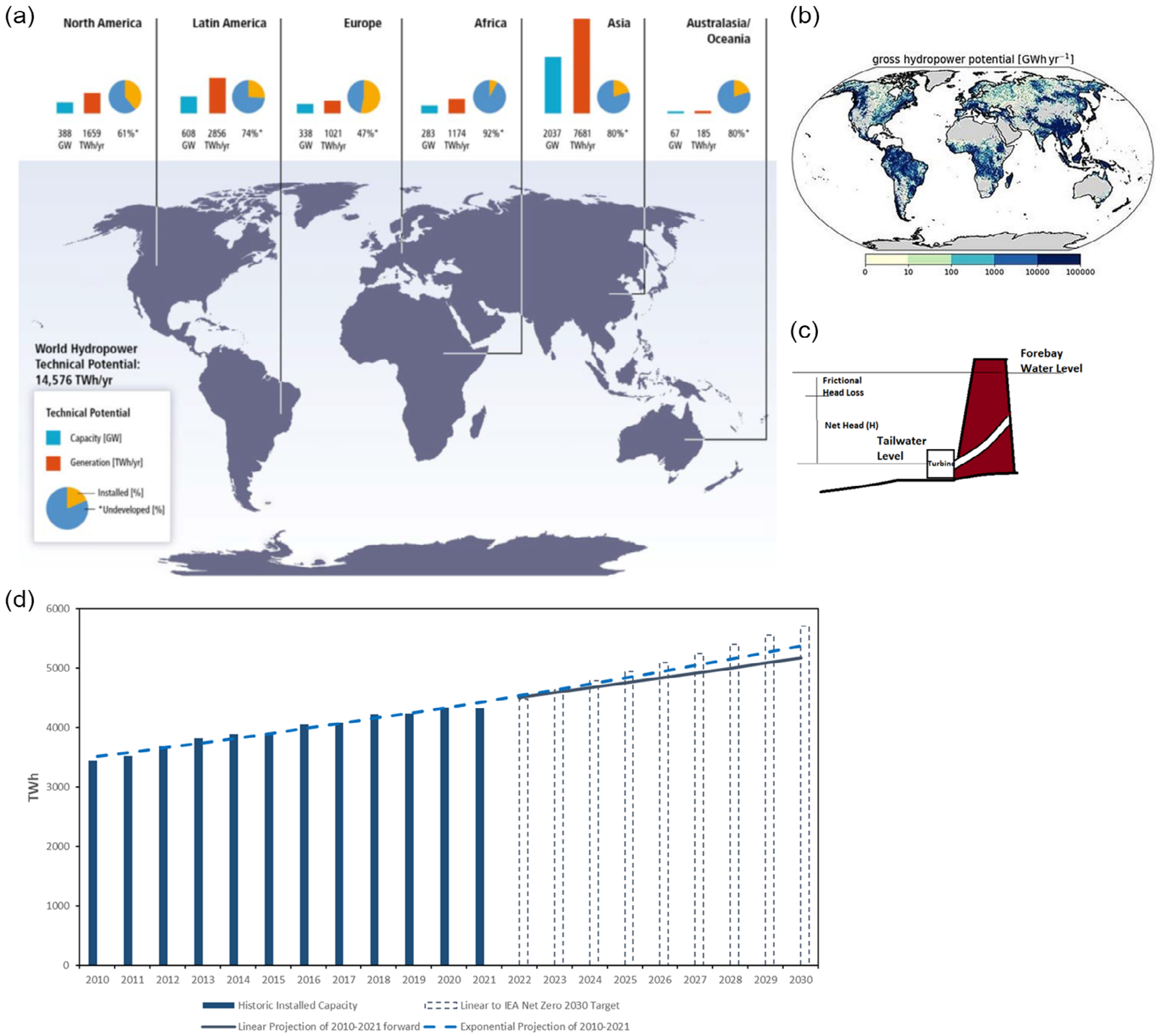


**Figure 4.** a) Regional hydropower technical potential in terms of annual generation and installed capacity, and percentage of undeveloped technical potential in 2009. Reproduced with permission.[80] Copyright 2010, Aqua Media International. b) Global hydropower potential in GWh $yr^{-1}$. Reproduced with permission.[10] Copyright 2022, IPCC. c) A hydropower system with a turbine driven by impounded water with a net hydraulic head $H$ = Forebay level – Tailwater level – Frictional head loss and d) global hydropower generation and forecast to 2030 to meet IEA net zero by the 2050 trajectory (data source: IEA).

 

source of renewable energy worldwide since the early 20th Century. Run-of-river hydropower plants are generally small, tend to produce several to 10 MW of annual power, and are more susceptible to the impact of droughts, in contrast to plants with storage which may produce over 10 GW of annual power (0.36 EJ $yr^{-1}$). The peak efficiency of hydroelectric plants can exceed 85%. Typically, the operation and maintenance costs are 2–2.5% of the investment costs for a project life of say 50–100 years. The capital cost for large hydropower projects in the United States was about USD$3000 per kW (IEA, 2022). However, the levelized cost of electricity (LCOE) of hydropower is still mostly lower than new fossil fuel-fired power plants.[35]

A large fraction of the potential hydropower capacity has been developed in North America (NA) and Europe, but considerable potential hydropower capacity remains in Africa, Asia, and Latin America. The world generated 4300 terawatt hours (TWh) of hydropower in 2021, the highest ever contribution from a renewable energy source, as worldwide installed hydropower capacity consistently increased from about 150 GW in 1950s to just over 1300 GW in 2020. In 2018, about 720 TWh of hydropower was generated in NA. The amount of hydropower generation in 2019 was 4.2 PWh (15.3 EJ), equivalent to ≈16% of global electricity and 43% of global electricity from renewables.[34,36] Hydroelectric power grew from 3890 TWh $yr^{-1}$ (14.0 EJ $yr^{-1}$) in 2015 to 4290 TWh $yr^{-1}$ (15.5 EJ $yr^{-1}$) in 2019, or 10.3%; nuclear power grew from 2570 TWh $yr^{-1}$ (9.3 EJ $yr^{-1}$) to 2790 TWh $yr^{-1}$ (10.1 EJ $yr^{-1}$), or 8.6%. Hydroelectric and nuclear shares in global total electricity generation stay around 16% and 10%, respectively.[32]

In Canada, the hydropower capacity was about 81 GW in 2019, which accounts for about 60% of Canada's electricity generation. Quebec alone has 61 hydropower plants, which together have about 34.5 GW of total installed capacity,[9] generating about 94% of its electricity. Some northern cities rely almost entirely on hydropower, e.g., Yellowknife of Canada. Norway generates over 99% of its electricity from hydropower. However, only about 7% of the total energy production in the United States comes from hydropower, where the states of Washington, California, and New York are the most important producers. China, with over 390 GW of installed capacity, is the largest producer of hydroelectricity globally and is expected to account for 40% of new development between 2021 and 2030 despite its development slowing from 2010 to 2021 levels.[18] Outside of China, the subcontinent and Southeast Asian markets will lead capacity additions in the coming years with notable development expected in India, Pakistan, Indonesia, Laos, Nepal, and Vietnam.

### 6.1. Environmental Impact of Hydropower Plants

Due to the long lifespan, hydropower plants have the highest energy payback ratio of all energy technologies, the ratio of total energy produced during a system's normal lifespan to the energy required to build, maintain, and fuel that system, with values ranging from 170 to 267 for run-of-river, and from 205 to 280 for reservoirs.[37] Although hydropower plants produce no air pollution, they can affect water quality and wildlife habitats. The environmental impact of large reservoirs constructed for hydropower plants and the loss of land could be significant, and flooded land generate short-term GHGs, even though on a lifecycle basis, hydropower provides low-emission electricity. On the other hand, besides hydropower, reservoirs are multipurpose, such as for flood control, water supply, navigation, recreation, aesthetic values, irrigation, and others. Hydropower production could be adversely affected by aridity and hydrologic droughts. Hydropower plants should be designed and operated to minimize impacts on the river, such as diverting a portion of the flow around their dams to mimic the natural flow of the river, which improves the river habitat, but it reduces the power plant's output. In addition, fish ladders and improved turbines are used to assist fish with migration and lower the number of fish killed. The operation and management of complex hydropower systems that may consist of multiple reservoirs connected in series or in parallel, or both, can be optimized to maximize the system revenue and minimize generation costs by using system analysis techniques such as dynamic programming.[38]

In regions with existing hydropower plants, public support is generally high for small- and medium-scale new hydropower projects. There is high support for existing major hydropower projects in Switzerland, Canada, and Norway.[10] Public support could be low for some new hydropower projects[39] and could encounter strong resistance in some cases.[40] In some developed countries, partly because of social or environmental constraints, there may not be many sites where major hydropower projects can be developed.

Major technical advantages of hydropower are its ability to rapidly respond to variability in net demand, and particularly in the case of impoundment dams, its ability to store energy, thereby making it a natural partner to help integrate more variable renewable energy sources like wind and solar. These abilities have limitations though as witnessed in 2021 when droughts in many parts of the world caused a decreased in energy generation compared to 2020 despite increase in installed capacity. The IEA estimates that close to half of the economically viable hydropower globally has not yet been developed. To reach its 2030 scenario of 5700 TWh per year to be on the NZE by the 2050 trajectory, new generation would need to increase by 3% per year. This would require an increase in new generation beyond current trends illustrated in Figure 4d as current trends would fall about 10% (or 535 TWh) below.

## 7. Solar Energy

Solar energy is the driving force behind our hydrologic cycle and climate system. From an effective solar surface temperature ($T$) of 5800 K, an emissivity $\varepsilon \approx 0.98$, the solar radiant output $M$ estimated using the blackbody equation, $M = \varepsilon\sigma T^4 \approx 6.29 \times 10^7\ Wm^{-2}$, given the Stephen–Boltzmann constant $\sigma = 5.67 \times 10^8\ Wm^{-2o}K^{-4}$. Solar constant is the average solar energy reaching the top of atmosphere which is about 1350 W $m^{-2}$ or only about $2 \times 10^{-5}$ in fraction of the total solar output $M$ because the Earth is located about 150 million km away from the Sun. The global average solar radiation received is about ¼ of the solar constant (≈342 $Wm^{-2}$) because solar energy passing through a circle must spread over the earth which is a sphere of 4 times the area of a circle. The solar radiation received varies in terms of seasons, diurnal cycle, latitude, cloud cover effects, etc. The tropics receive more solar energy than the polar regions because solar radiation spreads over a larger surface area at the polar regions than at the tropics.

Examples of recent sustainable developments using solar energy are as follows: 1) From 359 Pakistani consumers using solar panels for households,[41] applied the structural equation modeling to examine the reasons, linkage, and attitude toward adopting renewable energy (RE). They found that value orientation, utilitarian benefit, collectivism, and RE attitudes significantly influence the reason for adopting RE and attitude toward RE. The literature on renewable practice has also enhanced scholars and professionals in adopting RE; 2) By driving the partial least square structural equation model (PLS-SEM) with a sample of 357 respondents,[42] demonstrated the benefit of adopting solar home system (SHS) in developing small-scale industry in Pakistan. They found that low-cost energy through SHS has a progressive and substantial linkage with small-scale industry and enhances the quality of energy supply in Pakistan. Awareness and understanding of SHS significantly moderate the relationships between enhanced energy supply through SHS, the quality of SHS, and the performance of small-scale industry; and 3) Based on the theory of planned behavior with respect to environmental knowledge and concern and benefits of solar energy to address climate change challenges to its sustainable development,[43] collected 847 respondents in the Hebei Province of China to study consumers' intention to adopt solar energy in the rural China for household purposes. They found that attitude, environmental knowledge, subjective norm, perceived behavioral control, and understanding about the benefits of solar energy positively influence buying intention of solar energy. Their study emphasizes the significance of changing societal norms, boosting consumer awareness, redesigning regulatory mechanisms, and stressing the benefits provided by solar power and environmental sustainability practices.

### 7.1. Solar PV Systems

As a major renewable energy source, solar energy can be converted to electricity directly from devices such as solar cells and collectors. The amount of energy produced depends largely on the incoming solar irradiance, the relative angle at which the sun hits the collectors, and the active area of the solar collectors. **Figure 5** shows that the long-term average solar irradiation in North America ranges from about 1000 to 3000 kWh $m^{-2}$. Solar energy is harnessed by solar PV systems which at small scales are typically placed on roof tops or parking areas, while large solar collectors for commercial purposes require many acres of land, e.g., at 200 $Wm^{-2}$; ideally 1 hectare ($10^4$ $m^2$) of land can generate up to 1.8 MW of power but because of the diurnal

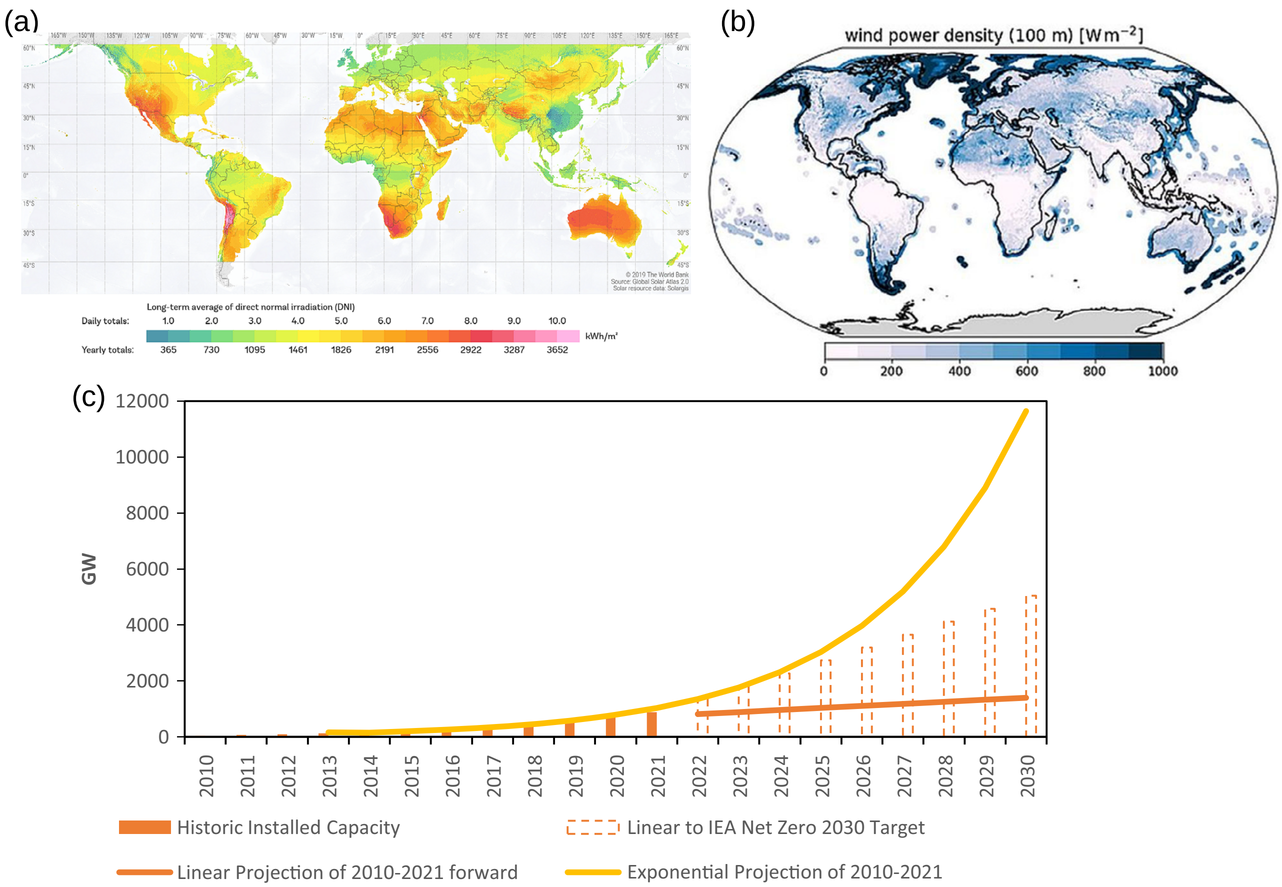


**Figure 5.** a) Average solar irradiation (KWh $m^{-2}$);[81] and b) wind power density ($Wm^{-2}$). Reproduced with permission.[10] Copyright 2022, IPCC. c) Global solar PV installed capacity and forecast to 2030 to meet IEA net zero by 2050 trajectory (graph plotted using historic data source: IEA).

cycle of solar radiation, and some land is required for accessibility, 1 hectare land can generate ≈0.5 MW of power from solar collectors.[13] For a large-scale system, solar energy is typically transformed into usable energy by, say, steam generators used in utility power generation where water is needed to drive the turbines and to clean solar panels. Solar irradiance data are available from the National Solar Radiation Database of the National Renewable Energy Laboratory, NREL (https://www.nrel.gov/gis/solar-resource-maps.html).[44]

Unlike hydropower which is generally available all the time except during severe droughts, solar energy is not available at nights, and therefore either backup power generation must be provided, or significant power storage capability must be installed to ensure a consistent supply of power to consumers. Further, commercial PV cells constructed from monocrystalline material to convert solar energy to electricity typically have efficiencies ranging from 14 to 18%, even though some manufacturers claim higher efficiencies.[45,46] Factors that affect the conversion efficiency of PV cells are the reflectance efficiency of the PV cell's surface, the thermodynamic efficiency cut-of-point, the quantum efficiency, the maximum power point, the internal resistances, and the temperature of the PV cells. Multiple PV cells, say 36–96, are connected in series to produce a specified power, voltage, and current output, with solar module mounted with a transparent material on the front and an insulation/waterproof material at the back. Multiple solar modules can be connected in parallel to increase the power output without changing the voltage, e.g., connecting three solar modules in parallel each producing 36 V and 10 A leads to a solar array of ($36 \times 10 \times 3$) 1080 W in maximum power output.

Total global solar capacity in 2021 was about 885 GW and the annual generation was 1003 TWh $yr^{-1}$. Solar electricity generation has been growing rapidly in recent years, providing close to 3.5% of global electricity supply in 2021, compared to almost none in 2010. PV's recent growth is expected to continue given its low cost and nearly limitless amounts of available land. Solar PV has a technical potential of about 300 PWh $yr^{-1}$ (1080 EJ $yr^{-1}$) for about 2 hectares of land are needed for 1 MW of solar electricity capacity.[10] Since 2015, the cost of solar PVs has declined by over 60%. The weighted average cost of PV was USD 68 per MWh. The cost of electricity from PV has been decreasing at ≈16% $yr^{-1}$. PV costs have fallen because of lower silicon costs, automation, lower margins, higher efficiency, and a variety of incremental improvements.[47] In Canada, majority of large PV solar farms built recently are located in Ontario, such as that at Sol-Luce Kingston and Sarnia of 100 (built in 2015) and 80 (2009) MW, respectively.[48] In southern Alberta, the Travers solar farm of 465 MW capacity was completed in 2022.[49,50]

In order to meet the IEA's net zero 2050 trajectory, solar will need to continue its rapid growth, increasing from global installed capacity of approximately 885 GW in 2021 to over 5000 GW by 2030–nearly a sixfold increase requiring an annual growth rate of nearly 25% (Figure 5c). Solar PV's recent cost declines and rapid adoption make its growth rates difficult to predict. If current trends were to be projected forward linearly, solar would not achieve this target, but if recent exponential growth rates were to continue it is possible solar PV could more than double the 2030 target as shown in Figure 5c. While solar PV systems will need to grow rapidly in the coming decades, it is inevitable it will play an increasingly large role in electricity systems worldwide.

### 7.2. Concentrating PV Systems

As large solar farms could occupy large land areas and semiconducting materials are costly, concentrating PV systems that use lens or mirrors oriented toward the sun to focus sunlight on PV cells of small areas have been developed. However, the mirrors or lenses of such systems will have to follow the sun's daily and seasonal movements using a single- or double-axis tracking methods, and for the mirrors or lenses to function properly, a clear instead of a cloudy sky condition is necessary for diffused light cannot be concentrated effectively. Even though well-designed concentrating PV system can produce many times the power of standard PV systems, by a solar concentration of up to several hundred suns,[13] mirrors are expensive compared to PV cells.

The technical potential for concentrating solar power (CSP) that uses reflective surfaces such as parabolic mirrors to focus solar sunlight on a receiver to heat a working fluid which is then transformed to electricity is estimated at 45–82 PWh $yr^{-1}$ (162–295 EJ $yr^{-1}$).[51] CSP system can deliver up to 200 MW of power per unit. Even though solar PVs with typical 30 year life cycle produce far less $CO_2$ per unit of electricity generated than that of fossil fuel, the recent estimated range varies widely, such as 80 $gCO_2$ $kWh^{-1}$,[52] 50 $gCO_2$ $kWh^{-1}$,[53] 18–60 $gCO_2$ $kWh^{-1}$,[45] and 20 $gCO_2$ $kWh^{-1}$.[54]

## 8. Wind Energy

Wind speed varies spatially and temporally (**Figure 6**), from day to day and season to season, and is dependent on weather conditions such as air temperature, sea surface temperature, atmospheric pressure, cloud conditions, and atmospheric circulations. The first known use of wind energy for mechanical devices was in Persia where it was used to grind grains. However, modern wind turbines that generate electricity have only been widespread in the last several decades (**Figure 7**a).

Ideally, we would like to place wind turbines in locations where wind is continuous and the strongest. As wind blows from high to low pressure area, wind velocity and direction will depend on the pressure difference between two or more locations. Annual wind speeds can vary widely depending on local surface roughness and topography, and are generally higher at higher elevations, or smooth surfaces such oceans (Figure 6a). In Northern Hemisphere, winds tend to blow in an anticlockwise direction in a low-pressure spot (Figure 6b). A wind turbine output rated using a power curve relating the output to wind speed is inevitably less than the kinetic energy of wind, with an efficiency typically ranging between 0.25 and 0.45, which is always less than the ideal efficiency of 0.593 known as the Betz Limit.

The theoretical wind power is $P_w = 1/2 C_t A \rho_a U^3$, where $C_t$ is the turbine efficiency at wind speed $U$, $A$ is the area swept by turbine based on the length of blade, and $\rho_a$ is the air density. Therefore, wind energy harnessed by a wind turbine depends primarily on the swept area ($A$) of the turbine and the cube of wind velocity. In developing a wind farm with a group of wind

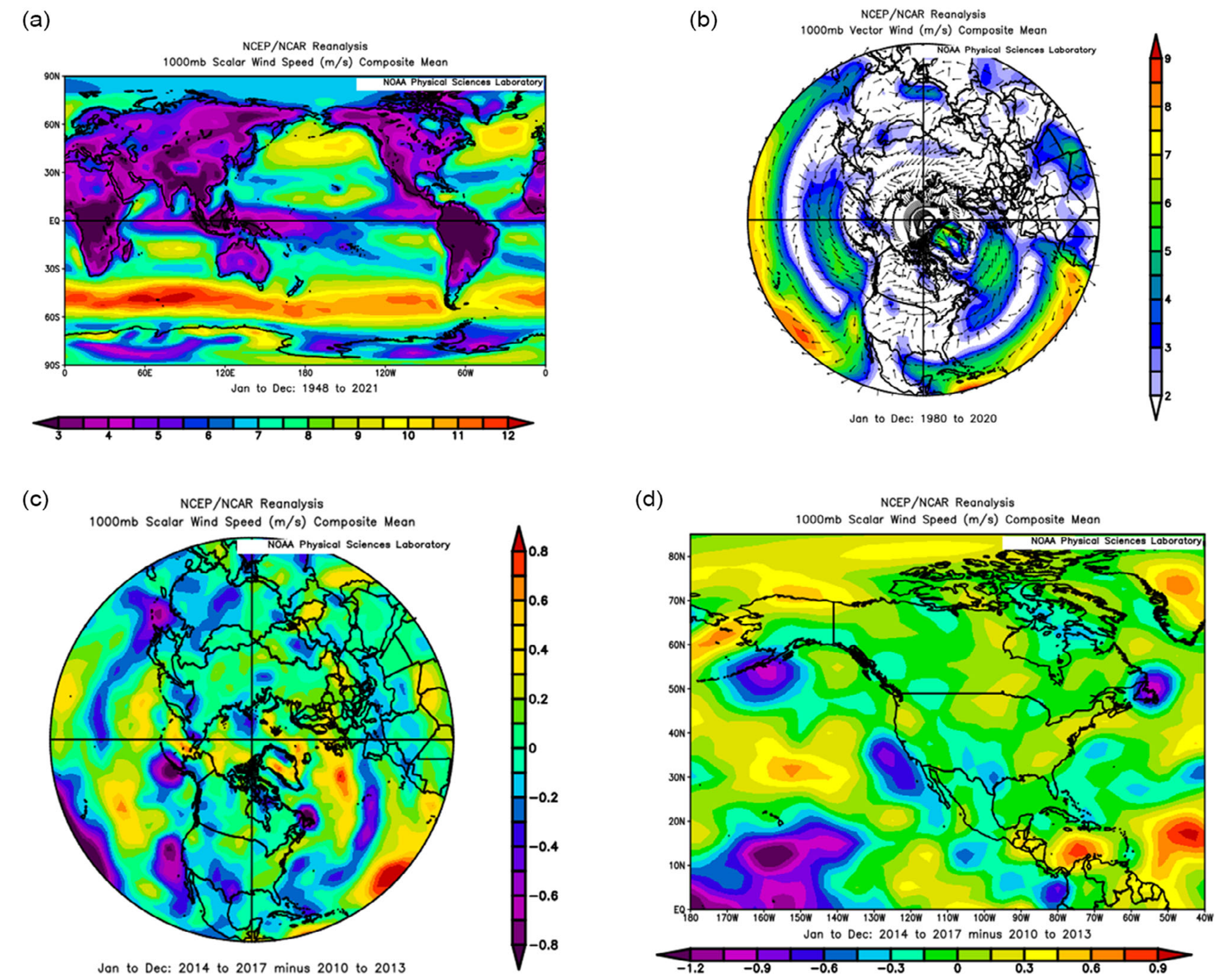


**Figure 6.** a) Global distribution of wind speed (m s$^{-1}$) at annual time scale over 1948–2021, b) global vector wind distribution over 1980–2020, c) changes of wind speed (m s$^{-1}$) between 2014–2017 and 2010–2013 over d) Northern Hemisphere and North America plotted using NCEP/NCAR reanalysis dataset, and the Analysis Tools of NOAA Physical Science Laboratory.

turbines, the distribution of wind speeds should be carefully evaluated. Given the sensitivity of wind energy to wind speeds, changing global weather patterns could impact projects over their 20–30 year lifespan. Since 1980s, there have been reductions in global average surface wind speed over land, a phenomenon known as global terrestrial stilling. However, Zeng et al.[55] showed that the decadal-scale variations of near-surface wind (e.g., stilling reversed since 2010) are probably determined by internal decadal ocean–atmosphere oscillations. The strengthening has increased potential wind energy by 17 ± 2% for 2010 to 2017 (Figure 6c,d).

The efficiency or a wind turbine will depend on the blade aerodynamics closely related to the design of a blade with a rounded front (leading edge) and a flat back (trailing edge) which rotates under a lift force created by pressure differences perpendicular to the apparent wind direction. The motion of the blade is opposed by the force required to spin the generator (which generates the electricity), the drag and frictional losses of the turbine. The rotational force depends on the angle at which the wind strikes the blade (angle of attack), the ratio of lift and drag forces (lift-to-drag ratio), blade tip speeds, twist, and the number of blades. The performance of wind turbine should be tested by testing laboratories such as the National Renewable Energy Laboratory (NREL) of the United States and manufacturers. The tower that carries a wind turbine may be over 100 m tall so that it is high enough to position the blade in the strongest wind flow, which tends to be well above the ground level. Horizontal-axis wind turbines in which the main rotor shaft is placed in the wind direction to extract wind power are overwhelmingly more popular than vertical-axis wind turbines such as the Darrieus wind turbine, Savonius wind turbine, and others.

### 8.1. Onshore and Offshore Wind Power

Wind energy is growing rapidly, at about 20–30% per year globally (Figure 7a). There are offshore installations of large turbines

 

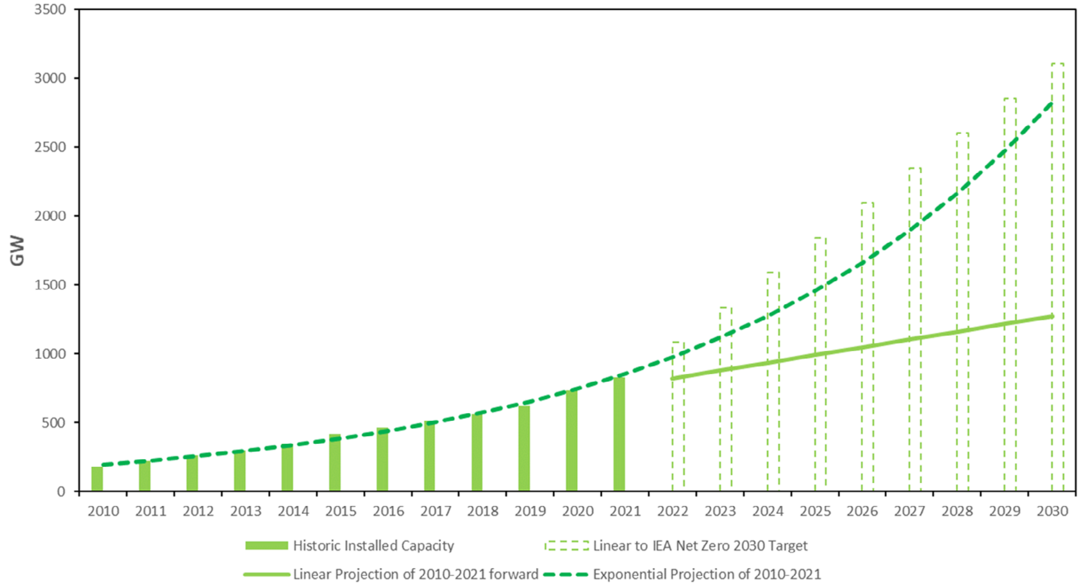


**Figure 7.** Global wind installed capacity and forecast to 2030 to meet IEA net zero by 2050 trajectory.[82]

because wind speeds tend to be higher and more continuous on oceans than on lands (Figure 6). Offshore windmill costs have fallen by 32%, and onshore windmill costs have fallen by 23%. Costs of wind power have declined, respectively, by 18% and 40% on land and offshore since 2015. Recent global estimates of potential wind energy resources are about 557–717 PWh $yr^{-1}$ (2005–2580 EJ $yr^{-1}$),[56–58]), or 20–30 times the 2017 global electricity demand. The potential for offshore wind power is larger than for onshore because offshore wind is stronger and less variable.[57] Major onshore wind turbines have grown in power ratings from 1.9 MW in 2010 to 3 MW in 2020, while offshore wind turbines grew from 1.6 MW in 2000 to 6 MW in 2020.[59]

A $1.5 billion wind farm of 385 MW capacity will be built in federal waters off Block Island of Rhode Island and Massachusetts, which means a capital cost of $3.90/Watt, which is considerably lower than a wind farm of 30 MW capacity (https://en.wikipedia.org/wiki/Wind_power_in_the_United_States) at the same area at $6.67/Watt. In northern Japan, the Akita Offshore Wind Corporation has almost completed two offshore wind farms, one at the Akita Port (13 × 4.2 MW wind turbine) and another at the Noshiro Port (20 × 4.2 MW wind turbine) with approximately 140 MW of total wind power (https://aow.co.jp/en/project/) and a capital cost of about US$5.37/Watt, which is in between the two wind farms of Block Island.

Total installed costs for onshore wind farms have decreased since 2015. In 2020, typical country-average total installed costs were about USD 1150 $kW^{-1}$ in China and India, and between USD 1403 and 2472 $kW^{-1}$ elsewhere.[35] The total installed costs of offshore wind farms rose, from an average of about USD 2500 $kW^{-1}$ in 2000 to about USD 3185 $kW^{-1}$ in 2020.[60] The global average LCOE from onshore wind has also declined to USD 0.039 $kWh^{-1}$ by 2020 but the cost varies widely from region to region.

Despite its low LCOE and GHG emissions, like all energy projects, wind farms can have adverse local environmental effects which need to be mitigated at the time of development or during operations. Bird and bat impacts can result in sensational headlines such as a company called ESI Energy which was recently fined millions of dollars in the United States due to bald and golden eagles' collisions. While domestic cats, windows, power lines, cars, and pesticides all have more significant negative impacts on avian populations, care needs to be taken when planning new projects. Other local concerns that may detract development include concerns over noise and visual aesthetic, high development costs, high initial cost of capital, and inadequate access to capital.

As of 2021, wind energy generated over 1870 TWh of electricity, making it the largest nonhydro renewable electricity source and providing close to 7% of the global electricity demand. To achieve the IEA's 2050 net zero scenarios, wind energy growth will need to accelerate from current rates by adding 250 GW of new capacity per year every year until 2030, more than double the most wind energy installed in a single year historically (113 GW in 2020) (Figure 7). However, if the exponential growth of wind energy over the last decade were projected forward, it would be within 10% of the IEA's scenario.

## 9. Renewable Electricity Supports Deeper Decarbonization

According to the IEA report of May 2022, annual renewable capacity additions broke a new record in 2021, have increased by 6% to almost 295 GW, and are expected to increase to over 8% in 2022, reaching almost 320 GW, as investment in renewable energy globally has been outpacing investments in fossil generated electricity capacity for close to a decade. According to the green energy report of UNEP and Bloomberg,[61] the 2016 annual global investment in new renewables capacity, at $266 billion, was more than double the estimated $130 billion invested in coal and gas power stations in 2015, adding 134 GW of renewable power worldwide, compared to 106 GW in 2014 and 87 GW in 2013. Due to falling generating costs per MWh especially solar PV, renewables excluding large hydro made up 54% of added power capacity of all technologies as far back as 2015. Since 2004, the world has invested \$2.3 trillion in renewable energy. Were it not for renewable energy excluding large hydro, annual global $CO_2$ emissions would have been about 1.5 Gt higher in 2015. Globally, investment in renewable energy has been growing consistently since 2000 (**Figure 8**a) while cost of electricity generated by offshore and onshore wind and solar (PV) have decreased by 46%, 44%, and 81% over 10 years, respectively (Figure 8b).

The decarbonization of the electricity system is important to enable GHG reductions in sectors such as transportation, where falling battery costs have given rise to electric vehicles (EVs) competing with internal combustion engines (ICEs). **Figure 9**a shows that the cost of energy storage from lithium-ion pack batteries has consistently decreased by about 20% per year annually since 2010. Globally, there were 10 million EVs in late 2020, after a decade of rapid growth. EV registrations increased by 41% in 2020 despite the pandemic-related worldwide downturn in car sales. About 3 million EVs were sold globally (a 4.6% sales share). Under the Stated Policies Scenario, the EV stock (except two/three-wheelers) would reach 145 million in 2030. Correspondingly, shares of global EV are projected to increase from 2015 to 2040 to about 60% in contrast to about 60% drop in ICE over the same period (Figure 9b).

## 10. Nonfossil as Secondary Energy Supply

**Figure 10**a is modified from Figure 4.2 of IPCC[62] showing the influence of energy demand on the projected deployment of energy supply technologies in 2050 for oil products and nonfossil systems (nuclear, biomass, solar, wind, hydro, and geothermal), so that mitigation climate scenarios could reach about 430–530 ppm $CO_2$-eq concentrations by 2100 under nonfossil energy supply. Blue bars for "low energy demand" show the range of deployment scenarios with limited growth in the final energy demand (EJ $yr^{-1}$) of $<$20% in 2050 compared to 2010. Red bars show the deployment range of technologies in a case of "high energy demand" ($>$20% growth in 2050 compared to

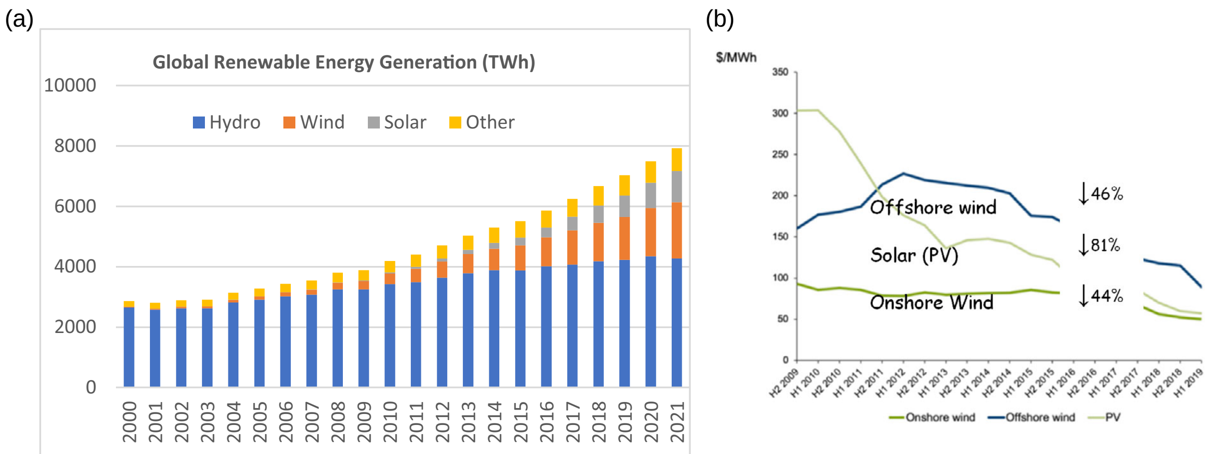


**Figure 8.** a) Global renewable energy generation from 2000 to 2021 (TWh) and b) levelized cost of electricity, \$/MWh by offshore and onshore wind and solar (PV) have decreased by 46%, 44%, and 81% over 10 years (2009–2019). Reproduced under the terms of the CC BY license.[61] Copyright 2016, The authors.

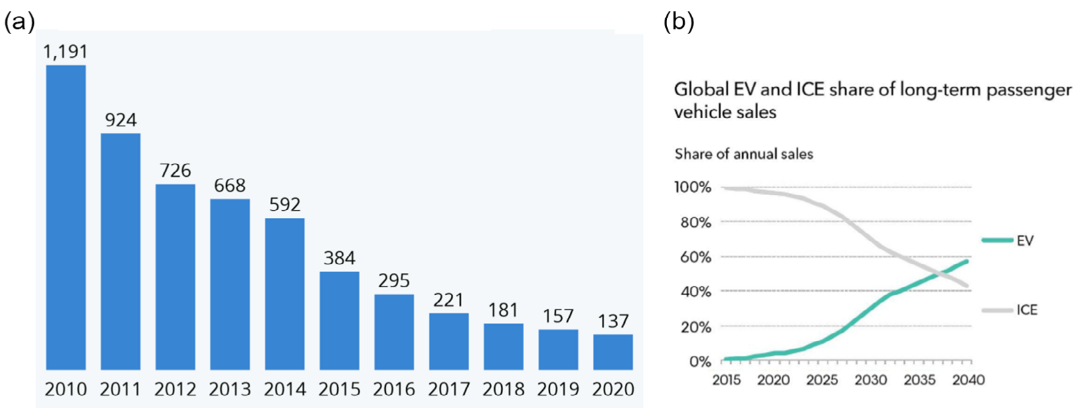


**Figure 9.** a) Volume weighted average lithium-ion pack price (US\$), and b) global EV and ICE share of long-term passenger vehicle sales. Reproduced under the terms of the CC BY license.[61] Copyright 2016, the authors.

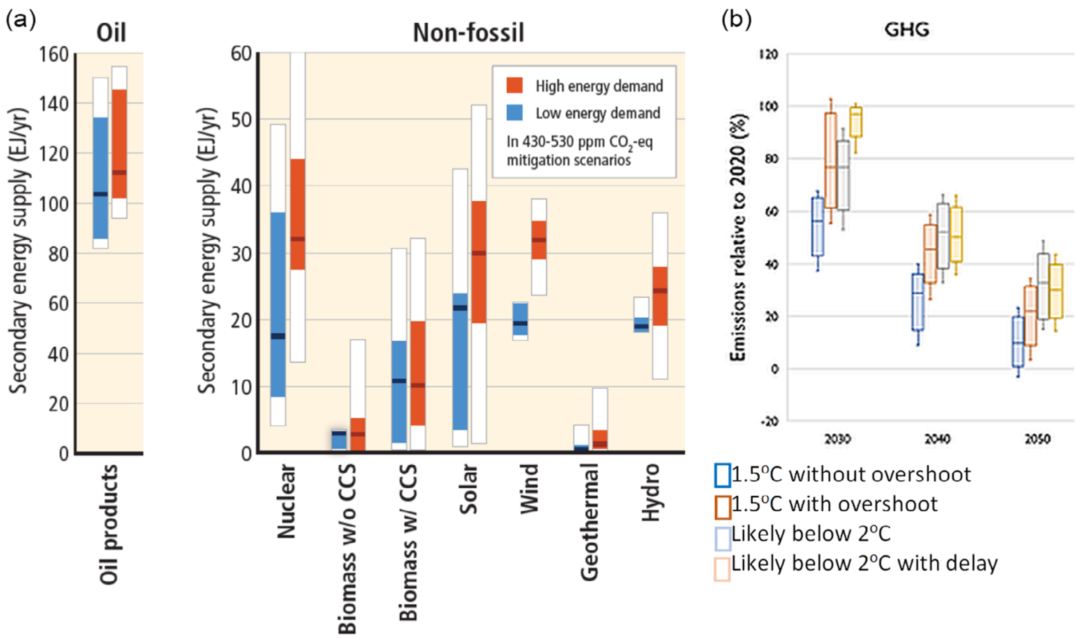


**Figure 10.** a) The influence of low (blue bars with limited growth in final energy demand EJ $yr^{-1}$ of $<$20%) versus high (red bars with $>$20% growth in 2050 compared to 2010) energy demands on the deployment of energy supply technologies in 2050, for mitigation climate scenarios reaching 430–530 ppm $CO_2$-eq concentrations by 2100. Reproduced with permission.[62] Copyright 2014, IPCC. b) Projected energy sector GHG emissions for the 1.5 °C scenarios (with and without overshoot), and likely below 2 °C (without and with delayed policy action). Reproduced with permission.[64] Copyright 2022, IPCC.

2010). Ranges include results from many different integrated models. High energy demand scenarios show higher levels of oil supply and nonfossil electricity generation technologies especially nuclear, solar, and wind are also scaled up more rapidly.

RES are essential in reducing and managing the risks of climate change. Substantial reduction of GHG emissions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, and contribute to climate-resilient pathways for sustainable development according to the 17 SDGs of UN. Figure 10b shows the projected levels of GHG emissions needed over 2030-2050 to achieve limiting climate warming to 1.5 °C or below 2 °C. There are multiple mitigation pathways in limiting climate warming to 1.5 °C relative to preindustrial levels, which would require substantial emissions reductions over the next few decades and near zero emissions of $CO_2$ and other long-lived GHG by the end of the century, which would require at least a sixfold scale-up of renewable energy deployments.[63] According to the recent AR6-WGIII report of IPCC,[64] the solar capacity will need to increase by a factor of 15 by 2050 compared to 2020, the wind capacity by a factor of 10, and phase-out of coal-fired power plants needed will be about 87%.

## 11. Strategies to Achieve NZES

Limiting warming to 1.5 °C by 2050 requires that $CO_2$ emissions from the energy sectors of many countries, especially China, the United States, India, and other major industrial countries, transition to near net zero, net zero, or even below NZES.[28] Net zero GHG goals require a global net negative $CO_2$ emissions to compensate for residual non-$CO_2$ emissions. However, there are many essential energy services that are difficult to provide without adding $CO_2$ to the atmosphere, such as long-distance transport, shipping, and aviation; manufacturing of carbon-intensive structural materials such as cement and steel; and supplying reliable electricity meeting varying daily and seasonal demands. In recent years, difficult-to-eliminate emissions listed above total over 25% of global $CO_2$ emissions from all fossil fuel and industrial sources (≈32–33 Gt $CO_2$ $yr^{-1}$). So long as carbon remains involved in these future services, NZE will also require active management of carbon and integrating currently discrete energy sectors and industrial processes which may require infrastructural and institutional transformations.

A precise description of a NZES is complicated by different scenarios of future GHG emissions to the energy systems, and by the dependence of energy system configurations on unknown future conditions such as future technology, economy, climate, population growth, and others. Net zero GHG energy systems also require concurrent efforts to reduce non-$CO_2$ emissions such as $CH_4$ and $N_2O$. Configurations of NZES will vary between countries, which are subjected to the influence of different socioeconomic, policy, and market uncertainties. In addition, different countries have different preferred system configurations, policy priorities, resources, industrial bases, climate, governance, and public acceptance.[65–68] However, despite regional differences, there are likely some common features between different NZES which can generally be developed by some of the following possible measures: 1) NZES will require using significantly less fossil than today, depending on the level of electrification, alternative nonfossil fuels, costs of fuel, carbon capture storage (CCS), and $CO_2$ removal (CDR). In addition, the residual demands for fuels will likely be dominated by oil and natural gas instead of coal and the overall quantity will depend on the feasibility of CDR and CCS technologies and carbon sequestration; 2) Reliance on decarbonized or net negative $CO_2$ emissions electricity systems could involve a mixture of renewables such as hydro, solar, and wind energy (Figure 9a), adjustable renewables, firm, dispatchable low-carbon generation using say nuclear, energy storage, transmission, carbon removal (e.g., bioenergy with carbon capture and storage [BECCS], direct air carbon capture storage [DACCS]), and demand management.[69,70] The proportion of mixture depend on relative costs, potential benefits of systems, local resources, regional integration, transmission and trade, existing infrastructure, public preferences, and regional policy priorities. However, compared to fossil fuel systems, energy systems dominated by renewables can face various regulatory, market, operational, and technological challenges; 3) $CO_2$ emissions from aviation, long-distance freight by ships, and process emissions from cement and steel production are very difficult to reduce and direct electrification of such heavy industrial sectors is also challenging. To decarbonize the transport sector, there should be a substantial shift of air and truck freight to rail and widespread use of electricity (electrification) in public transportation, e.g., light rail and light duty vehicles (LDV), as LDV can be electrified or can use hydrogen as fuel without drastic decline in performance except for range and/or refueling time. Road transportation efficiency can be improved by shifting from liquid fuels of ICE vehicles to electricity in electrical vehicles (EV), hydrogen, or synthetic fuels, vehicle automation, ride-hailing services, online shopping with door delivery services, lighter vehicles, more public transit than private vehicles, and incorporation of two- and three-wheelers; 4) Using improved construction materials, increase the number of multifamily dwellings, phasing out inefficient buildings, building smaller floor areas, and optimizing energy use in buildings, namely, heating, cooling, LED lighting, water heating, and electrification of most building services, etc. are practical measures to lower energy consumption and emissions of buildings; 5) Reliance on alternative fuels such as hydrogen or biofuels in sectors not amenable to electrification can be promising, but the low volumetric energy density of hydrogen favors transport and storage at low temperatures (–253 °C for liquid hydrogen) and/or high pressures (350–700 bar) require heavy and bulky storage containers. Carbon-based fuels (e.g., methanol), hydrogen, ammonia, or alcohols can be produced with NZES and without fossil fuel inputs, e.g., liquid hydrocarbons can be synthesized via hydrogenation of nonfossil carbon. If hydrogen can be produced affordably without emitting $CO_2$, its use in the transport sector could be boosted by the fuel's potential. Large-scale production of carbon-neutral and energy-dense liquid fuels such as liquid hydrogen may be critical to achieving NZES. However, costs to synthesize NZE fuels could be high, e.g., hydrogen obtained by electrolysis of water.

To achieve NZES or to minimize emissions of process-related $CO_2$, the carbon contained in hydrocarbons must be removed from the atmosphere through, say, direct air capture (DAC) (see **Figure 11**), or by photosynthesis for biofuels,[71] or by CCS technologies, or by using alternative materials that do not emit $CO_2$ during manufacture; 6) There must be more efficient and lower use of energy across all sectors than those of today with improved energy intensity, with a local final energy consumption considerably lower than the global final energy per capita of 55 GJ per capita in 2018. Technologies must be developed that allow electricity demand (load) to be shifted in time or controlled to better correlate with supply would improve the overall system reliability while reducing the need for underused, flexible back-up generators; 7) More integrated energy systems need to be developed by connecting operations and planning across energy carriers, which include higher electrification, fuels, and thermal resources to lower system costs, increase reliability, and minimize emissions. Carbon neutral systems require production, transport, storage, and consumption of different fuels to be well integrated (Figure 11). However, carbon neutral electricity sources, energy-storage facilities, and demand management that can accommodate large, multiday mismatches in electricity supply and demand could incur high capital costs compared with the current costs of some variable electricity sources or natural gas-fired generators. Achieving affordable and reliable NZES would be systems with substantially lower capital costs, systems using gas separation and compression to capture industrial $CO_2$, continued innovation and deployment, and systems that can be operated to provide multiple energy services.

Besides physical energy systems, innovations, societal integration, and infrastructure transformation should also be part of the overall integration effort. Challenges include technological changes and costs, public acceptance, policy changes, interactions, and interdependence between different feasible paths. Countries with less developed energy systems should have more flexibility to create energy systems that best match their long-term goals, but there still will be challenges transitioning to highly integrated energy systems; 8) Recycling and removal of carbon from the atmosphere is likely to be an important activity of any NZES, such as CDR by some combination of BECCS and DACCS. Energy-sector CDR may potentially remove annually 5–12 $GtCO_2$ globally[72] as a complementary effort to emissions reduction, to offset residual emissions from sectors that are not decarbonized and from other low-carbon technologies such as fossil CCS.[73,74] The present global carbon capture is estimated at 45 million tonnes (Mt) per annum of $CO_2$, which is projected to increase by over 10 folds to more than 550 Mt of $CO_2$ per annum by 2030 as the drive to decarbonize accelerates, according to the Rystad Energy (https://www.rystadenergy.com/) (**Figure 12**). This means that by 2030, the total market value of the sector could reach $55 billion annually, but to meet the NZE by 2050, it is estimated that the annual global carbon capture needed will be about 8 Gt of $CO_2$ by 2050. Europe and North America are expected to dominate (>80%) the future carbon capture industry.

As global final energy demand could be more than doubles by 2100,[75] demand for the energy services and processes associated with difficult-to-eliminate emissions will also increase substantially in the future. It is essential to develop technologies and processes, and systems integration that can provide these difficult-to-decarbonize energy services in a reliable and cost-effective way. Further, many such challenges could be reduced by moderating demand, by major improvements in energy and materials efficiency. A successful transition to a future NZES is likely to depend on the availability of substantial amounts of inexpensive, emissions-free electricity; mechanisms to balance large and

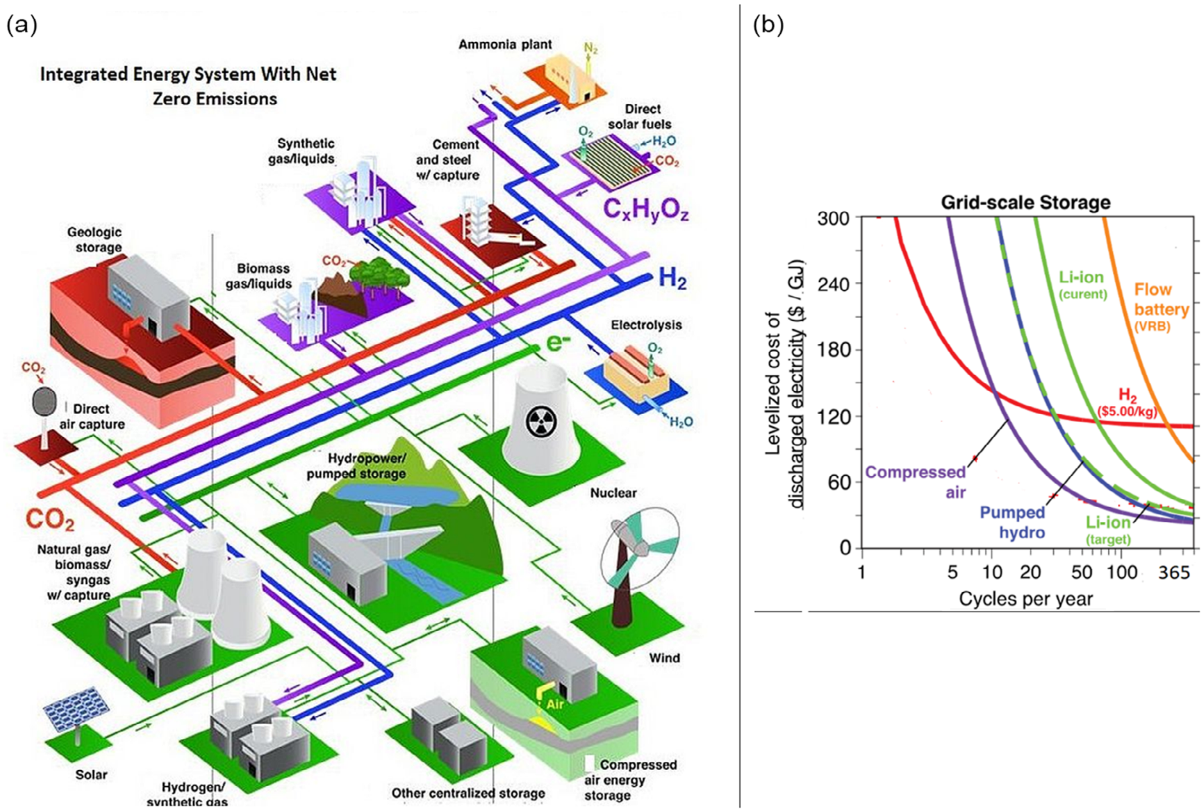


**Figure 11.** a) An energy system that attains NZE by integrating energy production, transport, storage, and consumption of different fuels, including difficult-to-electrify sectors. Colors indicate the dominant role of specific technologies and processes: green, electricity production and transmission; blue, hydrogen production and transport; purple, hydrocarbon production and transport; orange, ammonia production and transport; and red, carbon management, and b) comparison of the levelized costs of discharged electricity in terms of cycles per year, assuming constant power capacity, 20 year service life, and full discharge over 8 h for daily cycling or 121 d for yearly cycling. Dashed line for lithium ion reflects aspirational targets. Reproduced with permission.[75] Copyright 2018, American Association for the Advancement of Science.

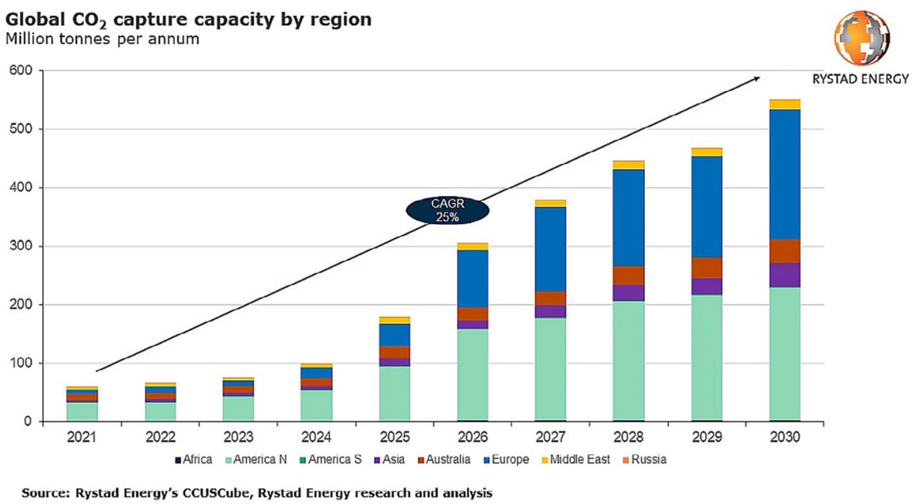


**Figure 12.** Global $CO_2$ capture capacity of 2021–2030 by regions (Mt $yr^{-1}$) projected by Rystad Energy. Reproduced with permission.[64] Copyright 2022, IPCC.

uncertain time-varying differences quickly and cheaply between demand and electricity generation; electrify most fuel-using devices; alternative materials and manufacturing processes including CCS for structural materials; and carbon-neutral fuels for the parts of the economy that are not easily electrified; 9) Shobande and Ogbeifun[76] identified the mechanisms by which information and communication technology (ICT) can combat climate change impact and promote environmental sustainability in 24 Organisation for Economic Cooperation and Development (OECD) countries over 1980–2019, which are education, transportation, foreign direct investment, regulatory quality, and institutional quality. Shobande and Asongu[77] showed the above mechanisms and clean technology investment can mitigate carbon emissions and promote sustainability in Eastern and Southern Africa; 10) Grass root public support and social acceptance are necessary to sustain a future NZES. To examine the social acceptance of renewable energy in Shandong province of China,[78] extended the theory of planned behavior by incorporating, risk perception, environmental concern, and belief about renewable energy costs. They emphasized the importance of enhancing public awareness and highlighting renewable energy benefits to win public acceptance. They found that an increase in individuals' education, personal income, awareness, and belief of renewable energy consumption cost positively affect their willingness to utilize renewable energy. Young people with higher education and income are willing to pay extra for green energy. To identify consumers' intentions to buy eco-friendly appliances for their households,[79] examined the linkage between environmental knowledge (EK), consumer attitude (CAT), green trust (GT), and purchase intention (PI) in an emerging economy's context based on a survey of 331 Pakistani consumers using energy-efficient household products. Their findings suggest that EK positively and significantly influences CAT and GT, which is significantly and positively related to PIs. Further, perceived consumer effectiveness and perceived behavioral control positively influence PI.

## 12. Summary and Conclusions

This article provides an overview of the current global climate crisis, potential, technology performance, deployments, costs, and the urgency in adopting renewable, low-emission modular technologies such as hydropower, solar, and wind energy systems to address this crisis. In Introduction, we have highlighted climate change impact due to unprecedented rising concentrations of atmospheric GHG attributed to anthropogenic emissions, which are intensifying, widespread, and have affected every region on earth in many ways, making extreme climate events such as heat waves, floods, droughts, and wildfire more widespread, more frequent, and severe, particularly in 2021/2022.

To mitigate the impact of climate warming, the global community must collectively achieve a large-scale, sustained reduction in GHG emissions by moving away from a predominantly fossil fuel economy to one dominated by renewable energy, to achieve the SDGs of UN that provide pathways for positive, systemic change to ensure resilient, productive, and healthy environment for present and future generations, as explained in Section 2. Subsequent sections include 3–solutions for sustainability, 4–transition to renewable energy, 5–hydropower, 6–solar power, 7–wind power, 8–renewable electricity supports deeper decarbonization, 9–nonfossil as secondary energy Supply, and comprehensive strategies to support the SDG7 of UN, "Affordable and Clean Energy," to achieve NZES by 2050 in Section 10. To achieve NZES, nine key strategies are presented, such as using significantly less fossil fuel than today, implementing CCS and CDR by some combinations of BECCS and DACCS, more integrated and carbon neutral energy systems, more efficient and lower use of energy, and social acceptance to sustain a future NZES, etc.

The three key RES, hydroelectric, wind, and solar power, have grown from 3429, 346, and 34 $\text{TWh yr}^{-1}$ in 2010 to 4274, 1598, and 846 $\text{TWh yr}^{-1}$ in 2020, respectively. Furthermore, recently the annual global investment in new renewable capacity has grossly exceeded investments in conventional, fossil fuel capacity, adding over 100 GW of renewable power worldwide. For the first time in 2015, developing world investments in renewables topped developed nations' investments. Since 2004, the world has invested $2.3 trillion in renewable energy.

In conclusion, investment policies and patterns of both developed and developing countries should transition to energy productions predominantly from renewable sources despite of various obstacles such as scale-up challenges, innovations in new energy systems, policies, financing mechanisms, and implementation strategies. This review article is limited in providing primarily a global overview of the transition to RES in recent years. Future research directions will focus on case studies and technologies to improve the efficiency of hydro, solar, and wind energy systems, the policy, and financial support to achieve large scale, and sustained growth in RES to achieve near net zero or net zero $CO_2$ emissions by 2050 or earlier.

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## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Keywords

fossil fuel economy, global warming, greenhouse gas emissions, hydropower, renewable energy economy, solar, wind technologies

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