The Sustainable Energy Imperative:

A Future Generations Perspective on Technologies Leading the Clean Energy Transition

A Global Youth Council on Science, Law & Sustainability Report

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Table of Contents

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Abstract

Given the terrible existential risks of climate change (IPCC 2023), greenhouse gas (GHG) emissions must be halved this decade to limit temperature rise to 1.5°C, as per the objectives of the Paris Agreement under the UN Framework Convention on Climate Change (UNFCCC 2015). While the rate of GHG emissions increases may be finally slowing, global emissions are still rising overall, due especially to the rising demand for energy worldwide and the burning of fossil fuels to supply this demand (IEA 2023), as well as gaps in carbon removal technologies at scale (Counteract 2023).

Therefore, this GYC-SLS report focuses on scoping technologies that can optimize the clean energy transition, scaling up sustainable energy generation faster, more reliably and at lower cost. The study reviews, summarises and models, mathematically, sustainable energy technologies in the transition to net zero global emissions (and beyond), tracking rising levels of finance and investment in these technologies. In particular, research focuses on incentivizing clean and renewable energy capacity expansion in the next five years. Over 2022-2027, the GYC-SLS notes, renewables are projected to increase by almost 2 400 GW according to forecasts, an 85% acceleration from the previous five years, and almost 30% higher than initially estimated (IEA 2023. However, renewable electricity needs to expand faster to "reach the milestones in the Net Zero Emissions by 2050 Scenario, where the renewable share of generation increases from almost 29% in 2021 to more than 60% by 2030" (IEA, 2023). Recent international agencies also underline that annual generation must increase "at an average rate of over 12%… twice the average of 2019-2021" (IEA, 2023). To uncover and model progress, therefore, this GYC-SLS first surveys progress in clean energy science and technology, comparing and contrasting opportunities for sustainable energy generation across case studies of solar, wind, tidal, hydroelectric and geothermal technologies. Then, the research examines financing and adoption trends, modelling incentives for sustainable energy production and consumption across the same technologies. Finally, the project highlights emerging developments among technologies with significant potential to become 'game-changers', focusing on the potential breakthroughs for commercialisation of fusion power and carbon containment and removal, including in CO2 and atmospheric methane removal.

The study, which is only an initial survey, finds that all sectors of renewables have experienced excitingly high levels of growth in the last two decades and that both public and private investment, including under the Glasgow Financial Alliance for Net Zero, is still rising. Solar and wind especially have gone from futuristic ideas to becoming directly competitive (including on price) with fossil fuels. Oil price rises and the recent energy crisis may have influenced this trend, leading to a further 40% increase in investment in the last 2 years. The project also notes dramatic technological expansions through the rise of solar photovoltaics, especially due to increased investment in research and development of more affordable and efficient cells, which led to a 93% cost decrease in just a decade, with Southeast Asian markets accounting for much of recent progress.

The modelling demonstrates, based on IEA and IRENA sources, that in 2016 investment in renewables surpassed investment in oil and gas, and is now nearly twice as significant. However, a further three-fold increase, according to IPCC, UNFCCC and other data, is required to meet 2030 net zero global targets. The GYC-SLS also notes that further diversification and more consistent forms of clean, renewable energy are still needed and that renewables can be viewed as a solution, not an expense. Finally, the modelling shows that investment into game-changing clean energy technologies such as fusion power or potentially green hydrogen, as well as carbon containment and removal, is beginning to scale up significantly, and if current financing trajectories are maintained, these options may offer solutions to meet rising demand through longer-term, consistent clean energy. Overall, this GYC-SLS report calls for the urgent need for increased investment in these fields, particularly in key technologies which hold high potential, and offers certain early signs of hope.

The Sustainable Energy Imperative:

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1. Introduction: The Sustainable Energy Imperative

Our world is facing an extremely serious challenge. Rising greenhouse gas (GHG) emissions are causing rapid increases in average temperatures on Earth, and the impacts of this human-induced climate change which are already being felt worldwide are only becoming more dangerous over time. As the GHG emissions especially from global energy production and consumption patterns are a major contributor to climate change, humanity faces a sustainable energy imperative – there is an urgent need to identify, develop, adopt, and deploy the technologies for a clean energy transition worldwide.

This GYC-SLS report focuses on scoping technologies that can optimize the clean energy transition, scaling up sustainable energy generation faster, more reliably and at lower cost. The study reviews, summarises and models, mathematically, sustainable energy technologies in the transition to net zero global emissions (and beyond), tracking rising levels of finance and investment in these technologies. In particular, research focuses on incentivizing clean and renewable energy capacity expansion in the next five years.

1.1 Global Climate Change as the Challenge of our Century

According to the Intergovernmental Panel on Climate Change (IPCC) GHG emissions, which must be halved this decade in order to limit temperature rise to 1.5°C, are still instead increasing. (IPCC GST 2023) Annual emissions already exceed 40 Gigatonnes of carbon dioxide (CO2) per year, with a 66% chance of average increases in world temperatures reaching 2.8°C or higher by 2050.

As IPCC explains in its Sixth Assessment Report: "Globally, climate change is increasingly causing injuries, illness, malnutrition, threats to physical and mental health and well-being, and even deaths (and) climate change impacts are expected to intensify with additional warming… Where trends intersect they can reinforce each other, intensifying risks and impacts, which affect the poor and most vulnerable people the hardest." (IPCC VI 2021)

Youth are already among those suffering the most due to climate change, already, and we shall face increasingly severe impacts over time. As IPCC reports, "future generations are more likely to be exposed and vulnerable to climate change and related risks such as flooding, heat stress, water scarcity, poverty, and hunger" (IPCC VI 2022). One in five children are already living in extreme poverty, and between 68-132 million additional people will face poverty by 2030 due to climate change. According to the IPCC, children aged ten or younger in the year 2020 are projected to experience a nearly four-fold increase in extreme events under 1.5°C of global warming by 2100. Already, typhoons, hurricanes and extreme weather disasters caused $210 billion in damage in 2020, and the UN's Food and Agriculture Organisation (FAO) estimates that disaster-related losses exceeded US $280 billion in

2021 alone. Further, if warming exceeds 1.5 °C, Arctic sea ice will deplete 10 times faster and sea level rise could intensify, causing rapid erosion of coasts and drowning small island countries. As IPCC further explains, by 2050 “more than a billion people living in low-lying coastal cities and settlements globally are projected to be at risk from coastal-specific climate hazards...” (IPCC VI 2022) In a world beyond 2°C warming, the frequency of hurricanes and extreme events increases by 36%, with annual flood damage exceeding US$ 11.7 trillion. As IPCC projects under their high vulnerability-high warming scenario, up to 183 million additional people risk undernourishment in low-income countries due to climate change by 2050, with likely increases in poverty and inequality, as well as involuntary migration of people, due to climate-driven increases in the frequency and strength of regional wildfires, increased floods and droughts, and an increase in temperature-related incidences of vector-borne, water-borne and food-borne diseases such as dengue, malaria, cholera and Rift Valley Fever. (IPCC VI 2021)

Climate change will also affect water quality and availability for hygiene, food production and ecosystems due to droughts and desertification. As IPCC warns, globally “800 million to 3 billion people are projected to experience chronic water scarcity due to droughts at 2°C warming… Today’s young people and future generations will also witness stronger negative effects of climate change on food production and availability. The warmer it gets, the more difficult it will become to grow or produce, transport, distribute, buy, and store food… the number of people suffering from hunger in 2050 will range from 8 million to up to 80 million people.” (IPCC VI 2022)

Further, climate change threatens all species and ecosystems, not just people. According to IPCC, “increasing heat and extreme weather are driving plants and animals on land and in the ocean towards the poles, to higher altitudes, or to the deeper ocean waters. Many species are reaching limits in their ability to adapt to climate change, and those that cannot adjust or move fast enough are at risk of extinction.” (IPCC VI 2022) While 20% of terrestrial ecosystems worldwide are already degraded, deforestation and fires have destroyed over 420 million hectares of global total forest since 1990, a 9.7% decrease in global forests, also releasing an additional 105 Gigatonnes of additional C02 emissions.

As the UN Environment Programme (UNEP) has noted, without international science and technology cooperation, the transition to net zero global emissions could be delayed by decades, and these are decades that we simply cannot afford. (UNEP 2021) However, with immediate and major changes, drastic impacts including for future generations can still be prevented. As IPCC further explains: “Actions taken now to reduce emissions of heat-trapping greenhouse gases drastically and adapt to a changing climate will have a profound effect on… health, well-being, and security” (IPCC VI 2022).

1.2 Access to Affordable, Reliable, Sustainable and Modern Energy

Current climate change challenges present extremely serious threats, but also opportunities for a transition to a different kind of growth - towards cleaner, sustainable energy technologies which do not generate the same levels of climate-change-inducing GHG emissions. Indeed, one of the world’s highest priorities, adopted in 2015 as part of the UN General Assembly’s Agenda for 2030 and the global Sustainable Development Goals (SDG) is to "take urgent action to combat climate change and its impacts”, under which countries seek to strengthen resilience and adaptive capacity to climate-related disasters, to integrate climate change measures into policies and planning, and to build knowledge and capacity. (UN 2015) They also commit to implementing the UN Framework Convention on Climate Change (UNFCCC) and to raising capacity for planning and management. In reference to SDG 13, countries recognise the UNFCCC as the main intergovernmental forum for negotiating the global response to climate change, and under the UNFCCC 2015 Paris Agreement, nations collectively agreed to keep warming "well under 2 °C". However, even if all current pledges were met, we still risk surpassing a 2.7 °C temperature increase by the end of the century. As of 2020, many countries are also urgently adopting and implementing national climate change adaptation plans. SDG 13 is supported and complemented by SDG 7, under which countries agree to "ensure access to affordable, reliable, sustainable and modern energy for all." (UN 2015) Under SDG 7, countries agreed on several crucial targets, including ensuring universal access to modern energy; increasing the global percentage of renewable energy; and doubling the improvement in energy efficiency. They also prioritise the need to promote access to research, technology and investments in clean energy; and to expand and upgrade energy services for developing countries. These targets include access to affordable and reliable energy while increasing the share of renewable energy in the global energy mix, while also focusing on improving energy efficiency, international cooperation and investment in clean energy infrastructure. (UN 2015)

To realise these opportunities, and keep with countries' commitments in the Paris Agreement under the UN Framework Convention on Climate Change (UNFCCC), the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), IPCC and many countries are calling for exponential increases in renewable energy capacity, including in the UNFCCC 28th Conference of the Parties in Dubai, United Arab Emirates in December 2023. (UNFCCC 2023) As IRENA explains, "global emissions, which must be halved this decade to limit temperature rise to 1.5°C, are still increasing. The energy crisis and threat of a global food crisis that the world now faces underline the equal urgency of increasing the affordability, accessibility, resilience, and security of the supply of humanity's most essential commodities and services. Transitions to sustainability can reduce the likelihood of such crises occurring in future. International collaboration will be critical to success, given the global scale and fast pace of change required. Action by governments and businesses individually is necessary, but not sufficient. Well-targeted international collaboration can make low carbon transitions faster, less difficult, and lower cost." (IRENA 2022)

Renewable energy is a crucial cornerstone of this collaboration. (IRENA 2022) Increasingly, countries, businesses and the entire research and development community worldwide, driven by many demands, are coming to recognise a global sustainable energy imperative. Improving access to sustainable, renewable energy sources is important worldwide, especially for youth. According to UN DESA in accordance with global Sustainable Development Goal 7, "sustainable energy is a critical enabler and dramatically improves the quality, accessibility and reliability of services," and youth rely on these services for survival, development and well-being. Further, as the UN explains, "Health centres and schools require energy for lighting, operating medical devices and life-saving procedures, cooking, heating, cooling and digital connectivity… Sustainable energy measures provide considerable benefits..." (UN DESA SDG 7 2023) Basically, as UN DESA underlines, while "access to electricity and clean cooking fuels has improved in many parts of the world… 675 million people are yet to be connected to the grids and 2.3 billion are still cooking with unsafe and polluting fuels." As they note, conflicts and economic instability in our world are causing "significant volatility in energy prices, leading some countries to raise investments in renewables and others to increase reliance on coal, putting the green transition at risk." If the current pace continues, the UN notes, about 660 million people will still lack access to electricity and close to 2 billion people will continue to rely on polluting fuels and technologies for cooking by 2030. "To ensure access to energy for all by 2030, we must accelerate electrification, increase investments in renewable energy sources and invest in improving electricity grids." (UN DESA SDG 7 2023).

Under the Paris Agreement, countries make net zero pledges in their Nationally Determined Contributions to the global response to climate change, and most countries have committed to achieving net zero emissions by around the middle century, as have many businesses, which hopefully leads us to a lower emissions trajectory now than they did before. As IRENA has proposed, “By aligning and coordinating actions internationally, countries and businesses can accelerate innovation, create stronger signals for investment and larger economies of scale, and establish level playing fields where needed to ensure that competition is a driver of the transition and not a brake. International assistance, finance, and the sharing of best practices can support the widespread adoption of effective policies and available technologies. International infrastructure can enable cross-border flows of clean energy. Without international collaboration, the transition to net zero global emissions could be delayed by decades.” However, “the world remains far off track to meet internationally-agreed climate change goals, despite action being taken in many areas.” (IRENA Net Zero by 2050 2022) A great deal more effort is needed, including through the development and financing of net zero energy sources, especially renewable energy technologies.

In this context, this GYC-SLS report begins by surveying progress in clean energy science and technology, comparing and contrasting opportunities for sustainable energy generation across case studies of solar, wind, tidal, hydroelectric and geothermal technologies. Then, the research examines financing and adoption trends, modelling incentives for sustainable energy production and consumption across the same technologies. Finally, the project highlights emerging developments among technologies with significant potential to become ‘game-changers’, focusing on the potential breakthroughs for commercialisation of fusion power and carbon containment and removal, including in CO2 and atmospheric methane removal. The study, which is only an initial survey, explores which sectors of renewables are experiencing excitingly high levels of growth in the last two decades and tracks trends in public and private investment. Through modelling, the study considers, based on IEA and IRENA sources, whether renewables are surpassing investment in oil and gas, and becoming significant. It also considers how further increases, according to IPCC, UNFCCC and other data, may be required to meet 2030 net zero global targets, exploring options for further diversification and more consistent forms of clean, renewable energy. It explores investment in game-changing clean energy technologies such as fusion power or potentially green hydrogen, as well as carbon containment and removal, and their potential as longer-term, consistent clean energy solutions to rising demand.

Overall, this report calls for the urgent need for increased investment in these fields, particularly in key technologies which hold high potential, and offers certain early signs of hope. With research and massive mobilisation on all levels, we may have a chance to respond globally to the sustainable energy imperative. Our future, and perhaps even all life on Earth, depends on it. As a contribution, this report especially focuses on which technologies that are leading the clean energy transition, and how to accelerate them.

2. Science and Technology Progress: Opportunities for Sustainable Energy Generation

In the bleak world of action on climate change, clean energy technology findings and conclusions reveal promising new trends and certain encouraging success stories. Efforts in the global transition to more sustainable energy are accelerating. Renewable energy capacity expansion in the coming five years is very likely to be much faster than was expected, even just a year ago.

According to the IPCC and other scientific authorities, there is a pressing need to transition away from greenhouse-gas-intensive fossil fuels (especially oil, gas and coal) as the main energy source for human endeavours. In this context, renewable and clean energy alternatives become highly significant. Renewable energy was already over 29% of energy production in 2021, according to IRENA, but our electricity obtained by renewable sources needs to expand even faster if we are to reach the milestones in IRENA's Net Zero Emissions by 2050 Scenario, where the renewable share of generation increases to more than 60% by 2030.

As IRENA explains, "annual generation has to increase at an average rate of over 12% during 2022-2030, which is twice the average of 2019-2021." (IRENA Net Zero by 2050 2022) Renewable capacity expansion in the next five years must be much faster than what was expected just a year ago, according to IRENA. As they report, over 2022-2027, renewables are seen growing by almost 2 400 GW in our main forecast, equal to the entire installed power capacity of China today. As IRENA notes, this is an 85% acceleration from the previous five years, and almost 30% higher than what was forecast in last year's report. It is the largest ever upward revision, a potentially inspiring trajectory.

In this section of this brief GYC-SLS report, several of these alternatives are discussed and compared.[1] The initial part section of the section addresses the science behind each of the technologies as well as their opportunities for use both economically and geographically. The section begins by briefly summarising the key renewable energy technologies considered: solar power, wind power, geothermal power, and biofuels.

Further, research through academic and other studies on the main advantages and disadvantages of these technologies relative to fossil fuels was undertaken, teasing out some of the main opportunities for further development of each different option. A table presents the findings of a brief comparison of the key renewable energy technologies that are considered in this study. This is followed by mathematical modelling of the changes in the costs of the technologies over time.

2.1 Solar Renewable Energy Technology Generation

How it Works, Trends in Adoption & Costs: Brief Summary of Solar Energy Technology for Renewable Energy Generation

Solar energy technologies are among the fastest-growing and most exciting options for renewable energy generation. Solar energy is premised on the understanding that can be harnessed directly from the sun, even in cloudy weather. It is used worldwide, and as IRENA notes, is increasingly popular for generating electricity, as well as for heating or desalinating water.

[1] Other options such as hydro-power and tidal power are also important, but are not considered in this brief report due to their particular characteristics and also space constraints.

There are two main solar power technologies shaping the markets today, according to IRENA, IEA and other international authorities.

First, we consider **solar photovoltaic (PV),** which uses electronic devices, also called solar cells, to convert sunlight directly into electricity. According to the world's renewable energy agency: "PV is one of the fastest-growing renewable energy technologies and is playing an increasingly important role in the global energy transformation. Solar PV is highly modular and ranges in size from small solar home kits and rooftop installations of 3-20 kW capacity, right up to systems with capacity in the hundreds of megawatts." (IRENA 2023, IEA 2024)

With regards to adoption, signs are encouraging. As IRENA notes, the total installed capacity of solar PV reached 710 GW globally at the end of 2020. About 125 GW of new solar PV capacity was added in 2020, the largest capacity addition of any renewable energy source. It has democratised electricity production. To calculate costs, a global weighted-average levelised cost of electricity is used by IRENA and other leading international authorities.[2] The cost of manufacturing solar panels has plummeted dramatically in the past decade, making them not only affordable but also often the cheapest form of electricity. Solar module prices fell by up to 93% between 2010 and 2020. During the same period, LCOE for utility-scale solar PV projects fell by 85%. (IRENA 2023) According to IEA, as well, solar PV is the fastest-growing energy technology, outstripping fossil fuels in many cases. (IEA 2024)

Second, it is important to also underline the growing interest in **concentrated solar power (CSP),** which uses mirrors to concentrate solar rays. These rays heat fluid, which creates steam to drive a turbine and generate electricity. CSP is used to generate electricity in large-scale power plants. As IRENA explains: "It is possible to classify CSP systems according to the mechanism by which the solar collectors concentrate solar irradiation: either "linear concentrating" or "point concentrating" varieties. Most existing systems use linear concentrating systems called parabolic trough collectors." They underline the need for solar towers, which are "the most widely deployed point concentrating CSP technology but represented only around a fifth of all systems deployed at the end of 2020." As IRENA explains: "one of the main advantages of a CSP power plant over a solar PV power plant is that it can be equipped with molten salts in which heat can be stored, allowing electricity to be generated after the sun has set." CSP with low-cost thermal energy storage has the ability to integrate higher shares of variable solar and wind power, meaning that while often underappreciated, CSP could play an increasingly important role in the future. (IRENA 2023)

With regards to adoption, there have been interesting recent developments. By the end of 2020, the global installed capacity of CSP was approaching 7 GW, a fivefold increase between 2010 and 2020. It is likely that some 150 MW was commissioned in 2020, although official statistics only captured 100 MW. According to IRENA, as the market has matured, the cost of thermal energy storage has declined, making a storage duration of 12 hours economic. This has resulted in an increase in the storage duration in CSP systems. (IRENA 2023)

[2] The formula used for calculating the LCOE of renewable energy technologies is provided in Annex 1, where the LCOE = the average lifetime levelised cost of electricity generation is derived from the relationships of l = investment expenditures in the year, Mt = operations and maintenance expenditures in the year, Ft = fuel expenditures in the year, Et = electricity generation in the year, r = discount rate, and n = life of the system. IRENA 2023

Solar energy technologies have many advantages, and only a few disadvantages (see Table 1), and the costs are trending lower every year in a highly encouraging direction (see Figure 1).

2.2 Wind Renewable Energy Technology Generation

How it Works, Trends in Adoption & Costs: Brief Summary of Wind Energy Technology for Renewable Energy Generation

Wind energy technologies are increasingly popular renewable energy alternatives. The wind is used to produce electricity by converting the kinetic energy of air in motion into electricity. As IRENA explains, in modern wind turbines, wind rotates the rotor blades, which convert kinetic energy into rotational energy, and this rotational energy is transferred by a shaft to the generator, thereby producing electrical energy.

Wind turbine capacity has increased over time, after first emerging more than a century ago, according to IRENA. Following the invention of the electric generator in the 1830s, engineers started attempting to harness wind energy to produce electricity. UK and US began generating wind power generation in 1888, but modern wind power is often seen as having developed in Denmark after horizontal-axis wind turbines were piloted in 1891, with a 22.8-metre wind turbine beginning operations in 1897. As IRENA explains, the modern wind power sector mainly emerged in the 1980s and 1990s, however, as part of the push for renewable energy and directly due to improvements in the technology that have improved capacity. The amount of power that can be harvested from wind depends on the size of the turbine and the length of its blades. The output is proportional to the dimensions of the rotor and to the cube of the wind speed. In 1985, typical turbines had a rated capacity of 0.05 MW, with a rotor diameter of 15 metres. Today's new wind turbines have a capacity in the 3-4 MW range onshore and can reach up to 8-12 MW offshore. Theoretically, when wind speed doubles, the wind power potential increases by a factor of eight.

With regards to adoption, wind power has grown rapidly since 2000, driven by increasing levels of investment in research and development, supportive policies and falling costs. "Global installed wind generation capacity (onshore and offshore) has increased by a factor of 98 in the past two decades, jumping from 7.5 GW in 1997 to some 733 GW by 2018," according to IRENA data. Indeed, "onshore wind capacity grew from 178 GW in 2010 to 699 GW in 2020, while offshore wind has grown proportionately more, but from a lower base, from 3.1 GW in 2010 to 34.4 GW in 2020. Production of wind power increased by a factor of 5.2 between 2009 and 2019 to reach 1412 TWh." (IRENA 2023).

As the technology has improved and scaled up, IRENA notes, costs have fallen and capacity factors have risen. There have been very encouraging trends in terms of costs: between 2010 and 2020, the global weighted-average levelised cost of electricity (LCOE) of onshore wind fell by 56%, from USD 0.089/kWh to USD 0.039/kWh. Over the same period, the LCOE of newly commissioned offshore wind projects fell by around half (48%). (IRENA 2023)

Wind energy technologies also have many advantages and only a few disadvantages (see Table 1). Further, like solar, the costs continue to trend lower every year in a highly encouraging direction (see Figure 1), leading to greater adoption. Both onshore and offshore wind still have tremendous potential for greater deployment and improvement, globally.

2.3 Geothermal Renewable Energy Technology Generation

How it Works, Trends in Adoption & Costs: Brief Summary of Geothermal Energy Technology for Renewable Energy Generation

Geothermal renewable energy has garnered very high interest in some countries in recent years and is increasingly available as an important and stable renewable energy source.

Geothermal technology extracts the heat found within the subsurface of the earth, which can be used directly for heating and cooling, or converted into electricity, as IRENA describes. As they explain: “To generate electricity, medium or high-temperature resources are needed, and these are usually located close to tectonically active regions where hot water and/or steam is carried to the Earth’s surface or can be accessed at shallow depths. Many of the geothermal power plants in operation today are **dry steam plants or flash plants**, harnessing temperatures higher than 180°C.” Further, as IRENA explains, “medium-temperature fields are increasingly used for electricity generation or for combined heat and power thanks to the development of binary cycle technology, in which geothermal fluid is used via **heat exchangers** to heat a process fluid in a closed loop.”

There are different geothermal technologies with distinct levels of maturity, which makes tracking the development of the technology slightly more complicated. Technologies for **direct use** (district heating, geothermal heat pumps and heating greenhouses) are widely used and according to IRENA and others can be considered mature. The electricity generation technology from **hydrothermal** reservoirs with naturally high permeability is also mature and reliable, with commercial operations since 1913. Additionally, new technologies are being developed such as **enhanced geothermal systems**, which are at the demonstration stage. (IRENA 2023)

According to IRENA, one of the main advantages of geothermal energy is its low cost, which continues to decline. Already, the levelized cost of electricity (LCOE) from geothermal power projects averaged between USD 0.049 and USD 0.085 per kWh between 2010 and 2020, and costs are trending further downwards finally as pilots come online and the technologies are refined. (IRENA 2023). In addition, a further important advantage is that geothermal energy can operate year-round at high-capacity factors. This allows geothermal energy to provide firm, dispatchable electricity and, if incentivised, complementary power that contributes to the electricity system. As solar and wind power become more popular and widely developed, these aspects of geothermal energy become more valuable for adoption, and there have been even more encouraging signals from markets and consumers.

Understandably, with regards to adoption, in the countries where new developments are being implemented, geothermal has become a major renewable resource. Geothermal power, for instance, covers a significant share of electricity demand in countries such as Iceland, El Salvador, New Zealand, Kenya and the Philippines, offering a stable renewable energy source to offset or balance more variable wind, solar and other options. (IRENA 2023) As one example, geothermal power provides for more than 90% of heating and overall with other renewables over 99% of electricity demand in Iceland, which is one of the world’s leading renewable energy countries according to a recent IEA study summarised by Stanford University scholars in April 2024.

Geothermal energy technologies also have many advantages, and only a few disadvantages (see Table 1), and the costs are also starting to decrease considerably which is important (see Figure 1). Geothermal energy may have further potential for greater deployment and improvement, globally, especially in specific instances where it can complement solar, wind or other more variable renewables technologies.

2.4 Biofuel Renewable Energy Technology Generation

How it Works, Trends in Adoption & Costs: Brief Summary of Biofuel Energy Technologies for Renewable Energy Generation

Bioenergy has always been part of renewable energy generation systems, and if sustainably managed in a way that protects and restores soils, particularly through recycling of agricultural or other waste products, seems to offer great promise for some countries.

Bioenergy use falls into two main traditional and modern categories, according to IRENA: "Traditional biofuel use refers to the combustion of biomass in such forms as wood, animal waste and traditional charcoal, and has been subject to many concerns in terms of health impacts when burned." In contrast, IRENA explains: "Modern bioenergy technologies include liquid biofuels produced from bagasse and other plants; bio-refineries; biogas produced through anaerobic digestion of residues; wood pellet heating systems; and other technologies." This means that modern bioenergy can be directly burned for heating or power generation, or it can be converted into oil or gas substitutes, and further liquid biofuels which provide a convenient renewable substitute for petrol, are mainly relevant for the transport sector. (IRENA 2023) High-profile experimental flights and other uses of biofuels have attracted attention in the world media in recent years. It is difficult to reliably track the costs of traditional biofuels, and modern biofuel costs depend on many diverse factors. With regards to adoption, about three-quarters of the world's renewable energy use involves bioenergy, with more than half of that consisting of traditional biomass use. According to IRENA, modern bioenergy accounted for about 10% of total final energy consumption and 1.9% of global power generation in 2015. However, scientists especially consider that biomass has significant potential to boost energy supplies in populous nations with rising demand, such as Brazil, India and China. Brazil is the leader in liquid biofuels and has the largest fleet of flexible-fuel vehicles, which can run on bioethanol – an alcohol mostly made by the fermentation of carbohydrates in sugar or starch crops (for instance corn, sugarcane or sweet sorghum).

Bioenergy technologies have both advantages and disadvantages (see Table 1), with costs that appear to be decreasing as well (see Figure 1).

Table 1: Assessing Advantages/Disadvantages of Key Renewable Energy Technologies

Technology	*Advantages relative to fossil fuels*	*Disadvantages relative to fossil fuels*	*Opportunities for development*
Solar	• Low cost • Not natural resource-dependent • Easily scalable • Renewable • No GHG emissions in operation	• Requires strong and constant sunlight • Requires extensive land or space (with objections for competing uses) • Delivers irregular power	• Developing countries • Places where sunlight is intense and environmental requirements are met • Cities (rooftops, etc)

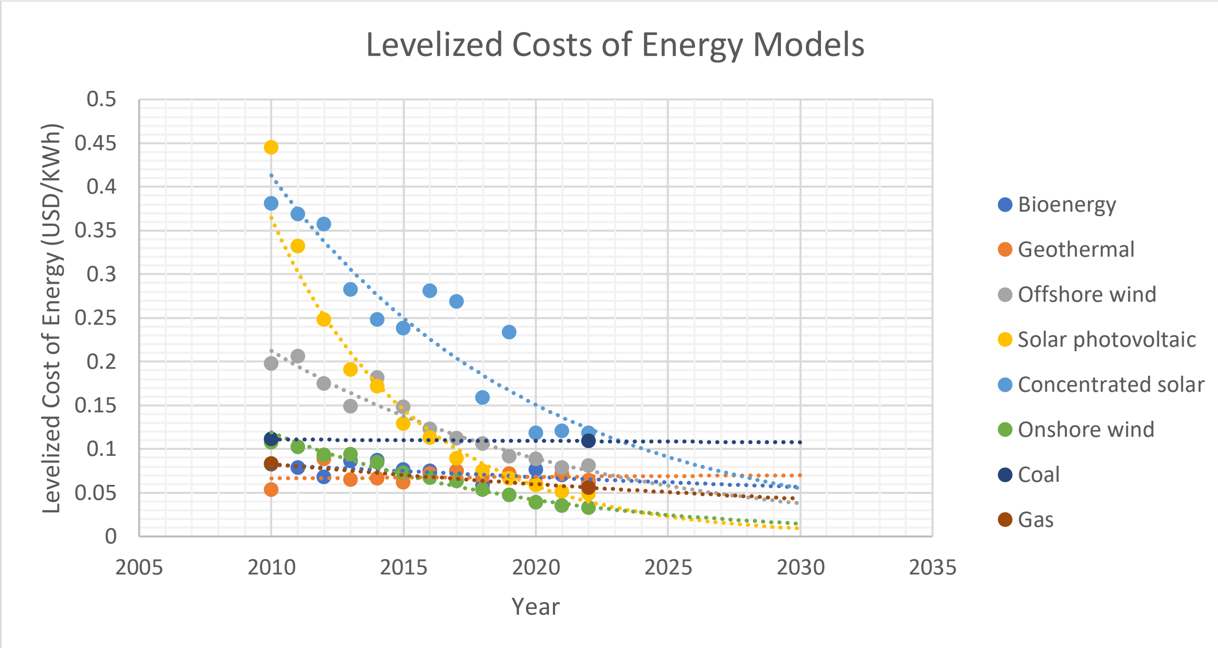
Wind	• Low cost • Can be used offshore • Not as scalable as solar, but still more so than fossil fuel power plants • Renewable • No GHG emissions in operation	• Requires certain climatic conditions, including strong winds • Requires extensive land or space (with objections for competing uses) • Delivers irregular power	• Lands where wind speed and other conditions are met • Open ocean areas • Island nations with long coastlines
Geothermal	• Long Lifetime • Uses heat as the power source, which can have other uses such as centralised heating systems on a smaller scale • Not dependent on natural resources for operation • Renewable • No GHG emissions in operation	• Location specific, unless large costs are involved	• Places that need a baseload power system, with the relevant natural resources • Relatively high-technology cities and communities
Biofuels	• Has wider applications than power generation • Renewable • Fewer GHG emissions	• Large land area required, and intensive use of that land, potentially damaging ecosystems	• Provides a baseload source • Fuel can be produced and then transported

Source: Compiled by author for GYC-SLS 2023

2.5 Mathematical Modelling of Decreasing Renewable Energy Technology Costs

For this GYC-SLS, mathematical modelling was a key aspect of the comparative research and analysis. In the case of renewable energy technologies, **modelling demonstrates that levelized costs of energy** are falling in many cases as renewable energy technologies are more developed and efficiency improves. In Figure 1, the exponential model of costs shows how by 2030, we can expect most renewable energy technologies to be considerably cheaper than coal, and wind and solar PV to be cheaper than gas as well, clearly showing the way forward.

Figure 1: Comparing Costs of Key Renewable Energy Technologies through Mathematical Modelling



Source: Compiled by author for GYC-SLS 2024

If the modelling is accurate, current trends of decreasing costs in renewable energy technologies compare favourably to several major fossil fuel technologies. PV solar and concentrated solar start high, but decrease sharply. Offshore and onshore wind costs started medium and also decreased on a sharp downward curve. Bioenergy costs start medium and decrease steadily. Geothermal energy costs start reasonably steady and decrease only marginally. Indeed, due to the cost of fuel extraction and inherent limits on the efficiency of plants, among other factors, costs will not be able to be reduced much further and are expected if anything to increase long term particularly if subsidies are withdrawn and public pressure leads to divestment campaigns successfully persuading the best managers to back away. This allows renewable energy technology costs to become lower than many fossil fuel costs very shortly.

The costs of renewable energy generated, between solar power, wind power, geothermal energy and biofuels, have tracked steadily downwards since 2003, with greatest progress especially to be observed in solar and wind power, but further potential for increased savings, as can be observed in Figure 1, above and Table 2, below.

Table 2: Comparing Costs of Renewable Energy Technologies 2002-2022

Technology	*Cost in 2002 per KWh*	*Cost in 2012 per KWh*	*Cost in 2022 per kWh*	*Predicted Trends*
Solar	HIGH	FALLING	FALLING	FALLING
Wind	MEDIUM	FALLING	FALLING	FALLING
Geothermal	LOW	STEADY	STEADY	STEADY LOW
Biofuels	LOW	FALLING	MIXED	MIXED

Source: Compiled by author for GYC-SLS 2024

The period 2010 to 2021 has witnessed interesting improvements in the competitiveness of renewables. The global weighted average levelised cost of electricity (LCOE) of new onshore wind projects added in

2021 fell by 15%, year-on-year, to USD 0.033/kWh, while that of new utility-scale solar PV fell by 13% year-on-year to USD 0.048/kWh and that of offshore wind declined 13% to USD 0.075/kWh. (IRENA 2023) Encouragingly, the global weighted average cost of newly commissioned solar photovoltaic (PV), onshore and offshore wind power projects has fallen even further from 2021 to 2023. This happened despite rising costs in materials and equipment, perhaps in part because there is a significant lag in the impact on total installed costs. According to IRENA: "With only one concentrating solar power (CSP) plant commissioned in 2021, the LCOE rose 7% year-on-year to USD 0.114/kWh. The global weighted average LCOE of newly commissioned utility-scale solar PV projects declined by 88% between 2010 and 2021, whilst that of onshore wind fell by 68%, CSP by 68% and offshore wind by 60%." (IRENA 2023) While geothermal and biofuels costs have been low, and stayed low or mixed, the trend is still also fairly encouraging. In essence, if solar and wind trends continue, the benefits from renewables in 2024 offer signs of hope, given the fossil fuel price crisis.

While past performance is not the only indicator of potential future performance, most of the analysis reviewed for this GYC-SLS suggests that further cost decreases are still possible. Indeed, the lifetime cost per kWh of new solar and wind capacity added in Europe in 2021 - 2023 may average at least four to six times less than the marginal generating costs of fossil fuels, according to IRENA. (IRENA 2024) Globally, new renewable capacity added in 2021, 2022 and 2023 could reduce electricity generation costs by at least USD 55 billion. Between January and May 2022 in Europe, solar and wind generation, alone, avoided fossil fuel imports of at least USD 50 billion. Of course, it may be important for the current strong push of policymakers in the G20 decision-making circles, as well as by research, development and law-making communities in the Paris Agreement and other international legal negotiations to continue.

Table 3: Trends in Adoption of Key Renewable Energy Technologies 2002-2022

Technology	Adoption in 2003	Adoption in 2013	Adoption in 2023	Predicted Trends
Solar	STEADY	RISING	RISING	Upwards
Wind	STEADY	RISING	RISING	Upwards
Geothermal	NASCENT	STEADY	RISING	Upwards
Biofuels	DIFFERENTIATED	STEADY (modern)	RISING (modern)	Upwards

Source: Compiled by author for GYC-SLS 2024

As can be observed in Table 3 above as well, the adoption of renewable energy technologies, between solar power, wind power, geothermal energy and biofuels, has tracked steadily upwards since 2003, with greatest progress especially to be observed in solar and wind power, but also geothermal and modern biofuels. While past performance is not the only indicator of potential future performance, most of the analysis reviewed for this GYC-SLS suggests that further increases are still possible.

3. Financing and Scale-Up Trends: Incentives for Sustainable Energy Production and Consumption

Comparative costs of renewable energy technologies do not just drop magically, they are shaped by trends in investment and financing of the research, development and piloting of the technologies, particularly as subsidies for unsustainable energy generation are reduced or eliminated over time.

Therefore, an important element of understanding how technology development can lead the clean energy transition involves modelling of financing and investment trends.

3.1 Aligning Financing and Investment Policies with the Paris Agreement

Research for this GYC-SLS reveals encouraging trends and growing international collaboration, in an otherwise depressing global financial outlook, though a great deal more progress (and financial commitment) is required to ensure that investment levels can scale up to align with the objectives and obligations of the Paris Agreement under the UNFCCC, which at Article 2.1c commits countries to “make financial flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development’. (Paris Agreement 2015)

In the UNFCCC COP27 Sharm el-Sheikh Implementation Plan, no less than a “transformation of the financial system” is needed to mobilise the investments required for climate action, but regular assessments of climate finance flows show that we are not yet channelling capital to the right places. Despite reaching an all-time high of $850–940 billion per year, global climate finance flows represent only a small fraction of what is needed by 2030, estimated at $3.5 trillion in emerging markets and developing economies alone. (LSE 2023) Meanwhile, over $1 trillion in fossil fuel subsidies was still provided by governments last year. (LINGO 2024)

Basically, the financial targets of the Paris Agreement are very important for driving climate action. Scaling up finance and investment is crucial to reduce greenhouse gas emissions and increase resilience to climate change, allowing us to limit global temperature rise to 1.5°C above pre-industrial levels, without finance. As LSE and other studies suggest, “by adopting Article 2.1(c), 196 countries around the world effectively agreed to completely overhaul their financial systems to support net zero and resilience… (and) ‘making finance flows consistent’ with low emissions and resilience requires more than incremental changes to ‘scale up’ green finance flows or ‘scale down’ brown ones.” (Robins and Feyertag 2023) Leading academics are now arguing that the size of capital reallocation that is needed means that the rules and processes that underpin everyday decisions, across the nearly $500 trillion worth of assets of the global financial system, will need to be realigned with the Paris Agreement and the imperative of scaling up investment in renewable and clean energy transition.

Governors of such rules, holders of nearly US$ 44.1 trillion of those assets, have formed a Network of Central Banks and Supervisors for Greening the Financial System (NGFS) with 127 members and partners from different countries to ensure climate-consistency of private as well as public financial flows. They commit to help realign all aspects and types of investments and financing activities, including public or private, stocks or flows, domestic or international, and close to every economic actor. As NGFS’s submission to the UNFCCC explains, aligning Article 2.1(c) is about “starting from public climate and development finance and the private resources it mobilises to public finance in general and, eventually, to the financial system and all the financial flows it supports.” (NGFS 2023) According to LSE, “by supervising systemically important banks and other finance actors such as insurance groups, central bank policy and actions play a large part in channelling finance flows towards climate objectives.” (Robins and Feyertag 2023)

At COP27 in Glasgow in 2021, many investors committed to capital reallocation for transitions towards net zero and climate-resilient economies. (UNFCCC COP27 2021) The Glasgow Financial Alliance for

Net Zero (G-FANZ), which controls over US$ 132 trillion and was launched during COP27, has been very active in channelling investment towards renewable energy and net zero clean energy transition technologies. (G-FANZ 2024)

According to IRENA, global investment in energy transition technologies, including energy efficiency, reached a record high of USD 1.3 trillion in 2022. However, annual investments need to at least quadruple to remain on track to achieve the 1.5°C Scenario in IRENA's World Energy Transitions Outlook 2023. As IRENA argues: "Investment in renewable energy was also unprecedented – at USD 0.5 trillion." Still, these encouraging trends represent less than one-third of the average investment needed each year, as IRENA explains. They note: "Investments are also not flowing at the pace or scale needed to accelerate progress towards universal energy access; investments in off-grid renewable energy solutions in 2021 – at USD 0.5 billion – fell far short of the USD 2.3 billion needed annually in off-grid solar products alone not including mini-grids." (IRENA 2022)

As highlighted by the G20 Sustainable Finance Working Group and by the OECD, there are growing concerns over the actual progress on implementing billions of dollars worth of net zero financial commitments, including those made by public and especially private financial institutions. (G20 2023, OECD 2023)

To address this, according to British experts, ideas include: "ensuring financial institutions design and deliver credible net-zero transition plans, including publishing detailed, multi-year accounts of targets and actions that set out how each investor's business model and strategy are compatible with the objectives of the Paris Agreement; adjusting investment policy frameworks to support Paris-aligned finance flows more broadly, such as by introducing green differentiated capital requirements that favour Paris-aligned lending practices and penalise misaligned ones; and focusing on capital mobilisation." Further, ideas like scaling up blended finance, for example by building an attractive investment environment by harmonising regulatory approaches, are already being discussed, and the UK's submission on 2.1(c) calls for aligning central banks, investments and company disclosures with Paris temperature and adaptation goals. (UK 2023)

For renewable energy and clean energy transitions in countries and regions that are not already wealthy, there is also a need to steer capital directly to climate-vulnerable segments of the economy in alignment with adaptation objectives, for instance with credit guarantee schemes for micro, small and medium-sized businesses. Progress on Article 2.1(c) was assessed as part of the first global stocktake (GST) at COP28 in Dubai, an audit of the world's collective progress against the goals of the Paris Agreement, and the resulting decision called for countries, investors and companies to further scale up finance. (UNFCCC COP28 GST 2023)

3.2 Mathematical Modelling of Increasing Renewable Energy Investment

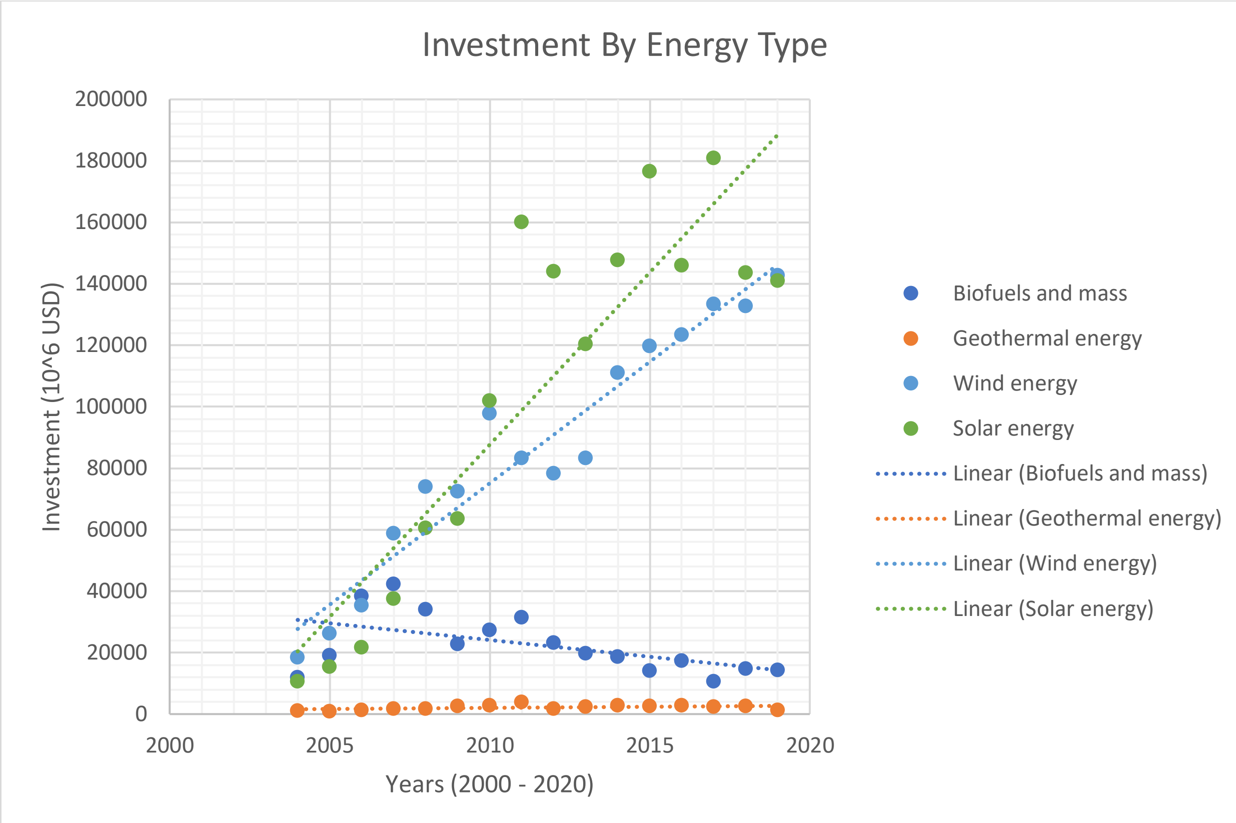
Fortunately, oil price hikes and understandable public reactions to the recent energy crisis are motivating further efforts, with a 40% increase in investment in the last two years (see Table 4, below). Indeed, solar power now occupies close to half of all energy investments globally, especially due to Asian government investments. Encouragingly, renewables overall are now 80% of energy grid investment worldwide, according to certain studies. (IEA 2024) Further, offshore wind is becoming a main new area of research and investment, while public and private interest in geothermal energy generation appears to be growing as well. (IRENA 2022)

Table 4: Trends in Investment in Key Renewable Energy Technologies 2002-2022

Technology	Investment in 2002	Investment in 2012	Investment in 2022	Predicted Trends
Solar	RISING	RISING	RISING	RISING
Wind	RISING	RISING	RISING	RISING
Geothermal	STEADY	STEADY	STEADY	STEADY
Biofuels	STEADY	MIXED	DECLINE	DECLINE

Source: Compiled by author for GYC-SLS 2024

Figure 2: Comparing Investments in Renewable Energy Technologies through Mathematical Modelling



Source: Compiled by author for GYC-SLS 2024

As the modelling in Figure 2 reveals, while solar energy investment continues to rise exponentially, wind energy investment is also rising steeply, while biofuels and biomass investment declines slightly. Geothermal investment levels, while not as high as others, continue steadily. While past performance is not the only indicator of potential future performance, most of the analysis reviewed for this GYC-SLS report suggests that further investment increases are still possible across the sectors examined, and it is to these trends that we turn.

3.3 Trends in Solar Energy Outputs and Scale-Up

According to IEA, solar PV generation increased by a record 179 TWh (up 22%) to exceed 1,000 TWh in 2021. The technology continues to be refined, with crystalline polysilicon remaining the dominant material for PV modules, with over 95% market share. However, the shift to more efficient monocrystalline wafers accelerated in 2021, with the technology capturing almost all crystalline PV production. In parallel, more efficient cell design (PERC) is also expanding its dominance with almost 75% market share. New, even higher-efficiency cell designs (using technologies such as TOPCon, heterojunction and back contact) saw expanded commercial production and captured about 20% of the market in 2021. (IEA 2022)

China was responsible for about 38% of solar PV generation growth in 2021, thanks to large capacity additions in 2020 and 2021. The second largest generation growth (17%) was recorded in the US, and the third largest in the European Union (10%). Solar PV proved to be resilient in the face of COVID-19 disruptions, supply chain bottlenecks and commodity price rises experienced in 2021 and achieved another record annual increase in capacity (almost 190 GW). This, in turn, should lead to further acceleration of electricity generation growth in 2022.

In essence, solar PV is becoming the lowest-cost option for new electricity generation in most of the world, which is expected to propel investment in the coming years. However, IEA argues, that reaching an annual solar PV generation level of approximately 7 400 TWh in 2030 from the current 1 000 TWh translates to annual average generation growth of about 25% during 2022-2030. According to IEA, for over threefold increase in annual capacity deployment until 2030, the world requires “much greater policy ambition and more effort from both public and private stakeholders, especially in the areas of grid integration and the mitigation of policy, regulation and financing challenges, which is very important for emerging and developing countries.” Although this rate is similar to the average annual expansion recorded in the past five years, IEA maintains it will require increased policy, technology, private sector and investment efforts on all fronts to maintain this momentum as the PV market grows.

Fortunately, there is further good news on adoption and development, as solar PV energy was the second-largest absolute generation growth of all renewable technologies in 2021, after wind.

3.4 Trends in Wind Energy Investment and Scale-up

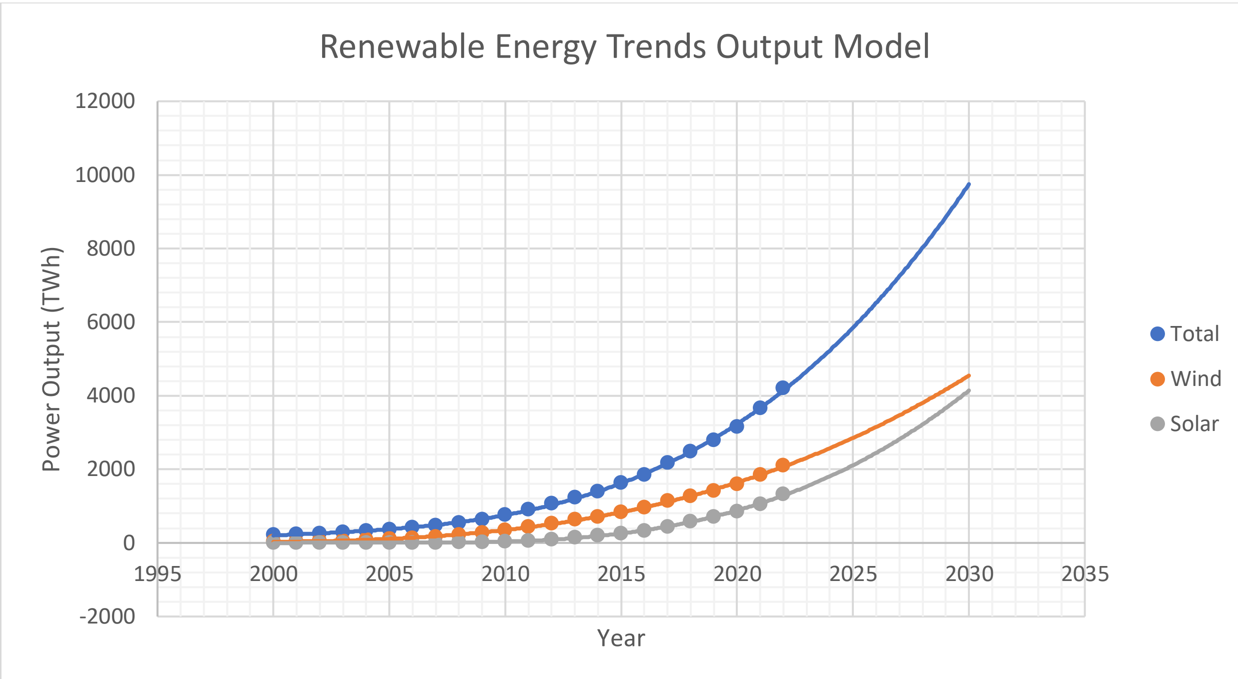
Trends in wind energy investment are encouraging, and indeed, as IEA notes, 2021 wind electricity generation increased by a record 273 TWh (up 17%). As IEA explains, this is significant, since this was 55% higher growth than in 2020, even highest among all renewable power technologies. According to IEA: “Such rapid development was possible thanks to an unprecedented increase in wind capacity additions, which reached 113 GW in 2020, compared with just 59 GW in 2019. China was responsible for almost 70% of wind generation growth in 2021, followed by the US at 14% and Brazil at 7%. The European Union, despite near-record capacity growth in 2020 and 2021, saw wind power generation fall by 3% in 2021 due to unusually long periods of low wind conditions.” Further, as IEA explains: “Globally, record generation growth was possible thanks to a 90% increase in capacity growth in 2020, which reached 113 GW, driven by policy deadlines in China and the US. In 2021 however, wind additions decreased by one-third in China and by a quarter in the US, partially offset by faster growth in other parts of the world, resulting in overall capacity growth reaching 94 GW.” (IEA 2023)

As IEA argues, however, “to get on track with the Net Zero Emissions by 2050 Scenario, which has approximately 7 900 TWh of wind electricity generation in 2030, it is necessary to raise average annual capacity additions to almost 250 GW, more than double 2020’s record growth. Much greater efforts are needed to achieve this level of sustained capacity growth, with the most important areas for improvement being facilitating permitting for onshore wind and cost reductions for offshore wind.”

Aligning with the Net Zero Scenario’s wind power generation level of about 7 900 TWh in 2030 calls for an average expansion of approximately 18% per year during 2022-2030. After the exceptionally high capacity additions of 2020-2023, the deployment is expected to stabilize in the coming years, highlighting the need for strong efforts to get on the Net Zero Scenario trajectory. (IEA 2022)

In Figure 3, below, this EPG deploys mathematical modelling to track the encouraging trajectories of growth in outputs from wind and solar renewable energy technologies, offering potential insights into future trajectories.

Figure 3: Tracking Wind and Solar Renewable Energy Technology Growth through Mathematical Modelling



Source: Compiled by author for GYC-SLS 2024

Wind and solar renewable energy outputs have been scaling quadratically for a long time now, with very high accuracy numbers for the trends for especially wind and solar. While past performance is not the only indicator of potential future performance, most of the analysis reviewed for this GYC-SLS REPORT suggests that they will continue to grow at an increasing rate, which is exciting for the prospects of future energy generation. Of note, if IEA and IRENA are correct in their analysis, significant investment and financing scale-up is still needed in order to increase the energy output in order to keep up with demand and climate commitments.

Similarly, geothermal energy resources could benefit from scaling up of investment, given the significant promise of the technology. This noted, geothermal energy could arguable be used even more effectively for heating, as will be explained in the next section.

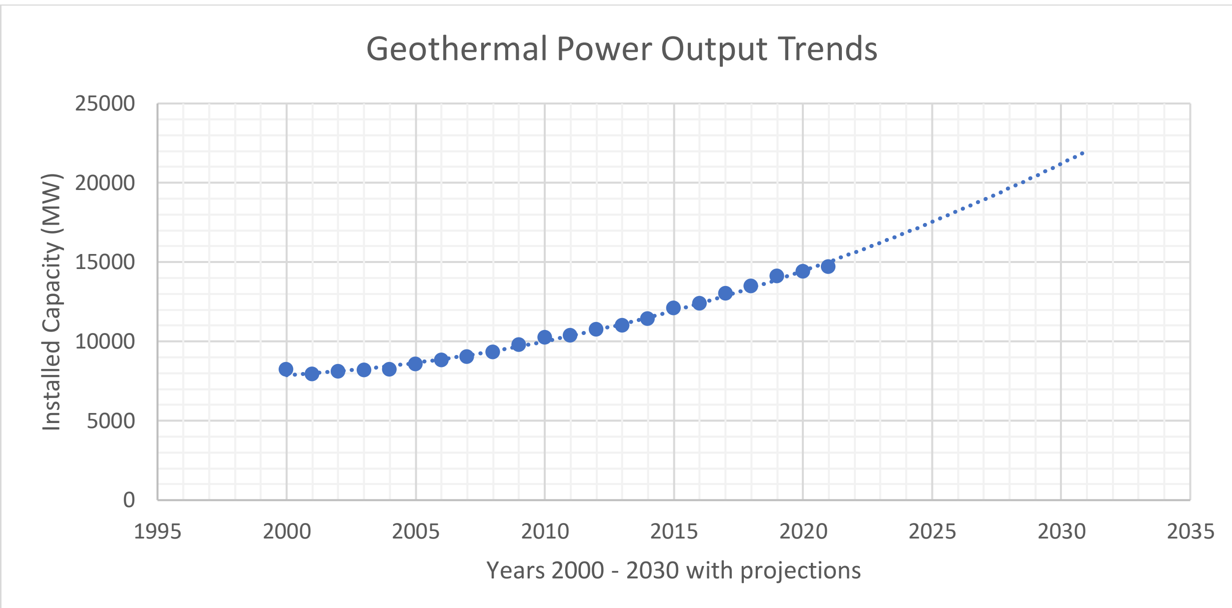
3.5 Trends in Geothermal Energy Investment and Scale-Up

Electricity generation from geothermal energy has grown at a modest rate of around 3.5% annually, reaching a total installed capacity of approximately 15.96 gigawatts electric (GWe) in 2021. As IRENA explains: "In the coming years, accelerated deployment of geothermal energy will be driven by advancements in geothermal technologies, cross-industry collaborations between geothermal and related sectors, as well as the rising deployment of geothermal for heating and cooling applications.

Geothermal still accounts for a mere 0.5% of renewables-based installed capacity for electricity generation, and heating and cooling, globally. On the other hand, geothermal deployment for heating and cooling grew at an average rate of around 9% annually between 2015 and 2020 to reach 107 gigawatts thermal (GWth) in 2020." IRENA and others are calling on policymakers, governments, potential investors, development partners and other stakeholders to redouble efforts to support the growth of the geothermal market, engage the full potential of geothermal energy and further expand its integration within global energy systems. (IRENA 2023)

However, as Figure 4 reveals, there is still potential to further develop and deploy geothermal renewable energy technologies more widely, and a positive trajectory can be glimpsed. While past performance is not necessarily an indicator of potential future performance, the analysis offers a hopeful note. Of note, if IEA and IRENA are correct in their analysis, significant investment and financing scale-up is still needed in order to increase the energy output in order to keep up with demand and climate commitments.

Figure 4: Tracking Renewable Energy Technology Growth through Mathematical Modelling



3.6 Trends in Bioenergy Investment and Scale-Up

Bioenergy is a source of energy deriving from the organic material that makes up plants, or biomass. As IEA explains: “Biomass contains carbon absorbed by plants through photosynthesis. When this biomass is used to produce energy, the carbon is released during combustion and simply returns to the atmosphere, making modern bioenergy a promising near zero-emission fuel.”

IEA argues that biofuels play a particularly important role in decarbonising transport by providing a low-carbon solution for existing technologies, first for light-duty vehicles, but also for heavy-duty trucks, ships and aircraft over the longer term. As IEA explains: “Biofuel demand in 2021 reached 4 EJ (159 200 million litres), returning to near 2019 levels after a decline due to the Covid-19 pandemic. However, a significant increase in biofuel production is needed to get on track with the Net Zero Emissions by 2050 Scenario and deliver the associated emission reductions. By 2030 under the Net Zero Scenario biofuel production reaches 15 EJ, requiring average growth of around 16% per year. Advanced feedstock usage must also expand: biofuels produced from waste and residue resources meet 45% of total biofuel demand by 2030, up from around an 8% share in 2021.” (IEA 2021)

Further, modern bioenergy is currently still one of the largest sources of renewable energy globally, accounting for 55% of renewable energy and over 6% of the global energy supply. According to the IEA and IRENA, the Net Zero Emissions by 2050 Scenario sees the need for "rapid increase in the use of bioenergy to displace fossil fuels by 2030." Since modern bioenergy has been growing by around 7% annually between 2010 and 2021, this seems possible. It is challenging, however, in part due to other sustainability concerns such as use of agro-chemicals or land degradation. As IEA explains: "More efforts are needed to accelerate modern bioenergy deployment to get on track with the Net Zero Scenario, which sees deployment increase by 10% per year between 2021 and 2030, while simultaneously ensuring that bioenergy production does not incur negative social and environmental consequences." (IEA 2023)

4. Emerging Developments: New Clean Energy Alternatives

Table 5: Emerging Developments in Renewable Energy Technologies

Technology	*New Developments*	*Advantages*	*Disadvantages*	*Assessment*
Solar	Perovskite (and tandem) solar cells	Vastly lower cost, higher efficiency solar cells, applicable to many more surfaces than traditional cells	Potentially cells could degrade faster, less durable, currently reliant on lead, still experimental	Very exciting area for new development, Perovskite will likely be market-viable as soon as durability is solved
Wind	Larger and vertical turbines Detailed aerodynamic modelling Offshore wind advances	More efficient, lower cost for the output power. Faster development and testing of new plants More reliable power supply offshore	Wake may reduce efficiency of larger windfarms Requires vast expanses of ocean or land for spacing	Already market viable and growing each year, may also allow for increased production from older wind farms, and add more viable locations
Geothermal	Laser drilling technology Enhanced Geothermal Systems which reduce reliance on location factors	Increases drilling rates in hardrock surfaces 10x Decreases costs Access to more locations	Costs remain comparatively high Locations with geothermal heat still not always available	Potential for further investment, adoption and scale-up, although impact may be limited by location dependence

Biofuels	Replacements for traditional fuels in otherwise hard-to-reach sectors, like shipping an aviation	Has the potential for very large reductions in total carbon emissions. Will allow many sectors to keep using old technology.	Large scale-up required for deployment, current progress far too little in a key technology, policy action needed	Large potential, but policy support and further investment required for potential to be realised

Source: Compiled by author for GYC-SLS REPORT 2024

As noted by IEA, IRENA and others in recent studies, achieving a low-carbon future will be challenging and will require a comprehensive portfolio of technologies and policy measures. However, there are encouraging signs, including across the spectrum of renewable energy technologies analysed in this report.

4.1 Emerging Developments in Solar Energy Technologies

Perovskite solar cells are one of the most exciting technological advances today, according to MIT. They hold promise for creating solar panels that could be easily deposited onto most surfaces, including flexible and textured ones, and would also be lightweight, cheap to produce, and as efficient as today's leading PV materials, which are mainly silicon. Lead halide perovskites are particularly useful, and labs around the world are developing variations with the best performance in efficiency, cost, and durability, while also seeking to eliminate the use of lead, to avoid its environmental impact. Further, as MIT explains: "unlike silicon, which requires extremely high purity to function well in electronic devices, perovskites can function well even with numerous imperfections and impurities. However, while silicon solar panels retain up to 90% of their power output after 25 years, perovskites degrade much faster." MIT and others are optimistic, arguing: "Great progress has been made — initial samples lasted only a few hours, then weeks or months, but newer formulations have usable lifetimes of up to a few years, suitable for some applications where longevity is not essential. In terms of efficiency, progress on perovskites has been somewhere between 100 and 1,000 times faster than others, leading to great excitement among PV solar proponents and investors." Such developments are generating high excitement for the emerging technological advances. (MIT 2024)

4.2 Emerging Developments in Wind Energy Technologies

The size of wind turbines has continuously increased over several decades to boost power generation from this key renewable energy source. As recent technology briefs from IRENA and IEA note, large-scale wind farms and larger turbines drive the ongoing reduction of electricity costs. As IRENA argues: "Onshore wind power generation, with costs largely confined to turbines, installation and maintenance, has become highly cost-competitive against new-built conventional power plants. Offshore wind plants, while requiring greater investments in construction and grid connectivity, show long-term promise for high volumes of sustainable power generation." They note that there are important factors to consider such as weight reduction, aerodynamic efficiency, and material selection, all of which can reduce wind costs both onshore and offshore. As they note: "Detailed aerodynamic analysis of turbine blades and the development of lighter, stronger materials are essential to improve efficiency even more." (IRENA 2023)

Policymakers, meanwhile, can reduce regulatory risks by ensuring predictable time frames and putting appropriate frameworks in place for wind development. Wind developers can strengthen their investments by undertaking and following proper environmental impact assessments at the start of each project. (IRENA 2016)

4.3 Emerging Developments in Geothermal Energy Technologies

According to IEA, there is high potential for geothermal: "In the period to 2030, the rapid expansion of geothermal electricity and heat production will be dominated by accelerated deployment of conventional high-temperature hydrothermal resources, driven by relatively attractive economics but limited to areas where such resources are available. Deployment of low- and medium-temperature hydrothermal resources in deep aquifers will also grow quickly, reflecting wider availability and increasing interest in their use for both heat and power." Basically, as IEA argues, "by 2050, more than half of the projected increase may be generated by widely available hot rock resources, mainly via Enhanced Geothermal Systems (EGS)." They note that: "geothermal electricity generation could reach 1 400 TWh per year, i.e. around 3.5% of global electricity production, avoiding almost 800 megatonnes (Mt) of CO2 emissions per year. Geothermal heat could contribute 5.8 EJ (1 600 TWh thermal energy) annually by 2050, i.e. 3.9% of projected final energy for heat." (IEA 2021) Important further development priorities for geothermal energy consist of accelerating resource assessment, development of more competitive drilling technology and improving EGS technology as well as managing health, safety and environmental concerns. Advanced technologies for offshore, geo-pressured and super-critical (or even magma) resources could unlock a huge additional resource base. Where reasonable, co-produced hot water from oil and gas wells can be turned into an economic asset. (IEA 2011, IEA 2023)

However, as IEA notes, substantially higher research, development and demonstration resources are needed in the next decades to ensure EGS becomes commercially viable by 2030. IEA and others call for a "holistic policy framework… that addresses technical barriers relating to resource assessment, accessing and engineering the resource, geothermal heat use and advanced geothermal technologies." (IEA 2021) The key is to take down economic, regulations, market facilitation, and research and development support barriers.

4.4 Emerging Developments in BioEnergy Technologies

Modern bioenergy plays an essential role in the IEA 2°C Scenario (2DS),1 providing nearly 17% of final energy demand in 2060 compared to 4.5% in 2015. Bioenergy provides almost 20% of the cumulative carbon savings to 2060. To play this important role, IEA and others propose, that bioenergy must be produced and used sustainably – significantly reducing GHG emissions compared to fossil fuels and helping to achieve SDGs. Bioenergy is particularly important in sectors for which other decarbonisation options are not available. For example, in the transport sector, bioenergy complements improved efficiency and electrification and is particularly important in aviation and shipping. Its contribution to the sector grows tenfold between 2015 and 2060. The use of bioenergy is particularly important in scenarios aiming to go beyond the 2°C level, such as the more ambitious IEA Beyond 2DS (B2DS) low-carbon scenario.

However, according to IEA, current rates of bioenergy deployment in the transport, electricity and heat sectors are well below those needed to follow even just the 2DS trajectory. In addition, the current deployment is concentrated geographically. As IEA explains: “For example, 90% of transport biofuel use happens in Brazil, the European Union (EU), the People's Republic of China, and the United States (US). Achieving the levels associated with the 2DS will require bioenergy to be used much more widely. The growth of bioenergy will need to rely on a mix of technologies. Several mature technologies can be used to produce heat, electricity and transport fuels. These options can provide immediate benefits in the form of GHG emission savings, energy security and diversity, as well as complementary socio-economic benefits. Mature technologies include the production and use of biomethane from waste and residues, the production of heat for district heating networks, the efficient use of agricultural residues for electricity generation and a number of options for producing transport fuels.” Meeting the long-term potential of bioenergy may depend on novel technologies which are not yet fully mature and commercialised. One priority is the development and commercialisation of the range of technologies for transport fuels with significant GHG savings. As IEA argued in 2017: “progress has been promising in demonstrating the necessary technologies (such as biomass gasification, pyrolysis and the production of ethanol from cellulosic feedstocks), but much remains to be done. Policies to support the deployment of sustainable novel fuels, appropriate and dedicated financial mechanisms, and instruments to facilitate technological development and subsequent market deployment, such as loan guarantees, will be key. Enhanced support for research, development and demonstration aimed at expanding technology options and reducing costs will also be important.” (IEA 2017) To accelerate the uptake of these options, appropriate policies, market design and regulatory frameworks can help provide a low-risk investment climate, ensuring market access and predictable revenue streams that can facilitate lower-cost finance. Technical and institutional capacity-building support will also be essential in emerging and developing economies so that such enabling legislation and regulation can be put in place to stimulate the deployment of these solutions. (IEA 2017)

4.5 Further New Technology Developments in the Clean Energy Transition

Climate science shows that the world must nearly halve its greenhouse gas emissions this decade and reach zero net emissions by 2050 to keep global warming from spiralling to catastrophic levels, and as mentioned above this means making a rapid transition away from fossil fuels, like coal, oil and gas. (BBC 2024)

Though we need to act now, with what we have, there are also other very new trends and technologies with potential.[3] These include Carbon Capture and Storage (CCS) and carbon-negative technologies, such as the removal of atmospheric carbon and methane to turn back the clock. It also means the deployment of effective small-scale hydropower which does not depend on forced resettlement or ecological destruction. Green hydrogen, also, has been proposed as a fuel of the future. Fusion energy, the holy grail of the clean energy transition which involves harnessing the power of the sun and stars on Earth, has many inspiring new developments in just the last few years. In Table 6, certain selected emerging technology developments that can help with the clean energy transition are summarised and compared, with a focus on the most recent developments and their advantages, as their disadvantages are all similar – that being that they are currently high cost and are not able to be deployed at scale.

[3] Potentially, also the new generation of low-waste or fourth generation nuclear fission technologies might serve as a short-term fossil fuel replacement, but a discussion of these technologies is beyond the scope of this brief study.

Table 6: Emerging Technology Developments in the Clean Energy Transition		
Technology	*New Developments*	*Advantages*
CCS & GHG Removal	Direct air capture and carbon credits Removal of atmospheric carbon/methane	Allows for industries which do not have alternatives to contribute to net zero efforts Directly captures or removes GHGs from atmosphere, piloting and refining necessary reversal technologies
New Reservoir Hydropower	Utilization of new hydro capacity, especially in developing countries, supporting renewable grids	Offers a form of effective energy storage that can cover grid weaknesses from relying solely on renewables.
Green Hydrogen	Origin certificates with tailored legal landscape Green hydrogen facilities on hydropower plants	Makes hydropower more ecological, providing more options Drives development and refinement of hydrogen storage technology alternatives
Fusion Power	New electromagnets and superconductors removing cryogenic needs Financial success of commercial startups	Generates net energy gain with commercialization potential Offers potential fusion reactors significantly less difficult to build, and more likely to be mass-produced

Source: Compiled by author for GYC-SLS REPORT 2024

4.5.1 New Developments in Carbon Capture and Storage and GHG Emissions Removal

New developments in this area include direct air capture projects which expand the potential of carbon capture, utilization and storage (CCUS), and carbon credits which are driving investment in these technologies. CCUS is a critical component of most net zero plans, as it allows emission reductions even when producing carbon is not preventable and allows for additional offsets for industries looking to purchase them. Carbon credits have allowed incredible growth in this industry as a financing mechanism.

Around 40 commercial facilities are already in operation, working to apply CCUS to industrial processes, fuel transformation and power generation, partly thanks to the investment driven by carbon credits. As IEA explains: “CCUS deployment has trailed behind expectations in the past, but momentum has grown substantially in recent years, with over 500 projects in various stages of development across the CCUS value chain. Since January 2022, project developers have announced ambitions for around 50 new capture facilities to be operating by 2030, capturing around 125 Mt CO2 per year. Nevertheless, even at such a level, CCUS deployment would remain substantially below (around a third) the around 1.2 Gt CO2 per year that is required in the Net Zero Emissions by 2050 (NZE) Scenario.” (IEA 2023)

4.5.2 New Developments in Reservoir and Pumped Storage Hydropower

New hydropower plants can provide a critical source of cost-effective and flexible low-carbon electricity. Indeed, before the massive cost declines of solar PV and wind, hydropower was the most competitive renewable electricity source globally for decades. As IEA argues: “compared with other renewable options and fossil fuels, developing new large-scale hydropower plants remains attractive in many developing and emerging economies in Asia, Africa and Latin America where there is still significant untapped hydropower potential to supply flexible electricity and meet increasing demand.” IEA favours new pumped hydropower projects, which they suggest offer the lowest-cost electricity storage option. According to IEA: “Greater electricity storage is a key element for ensuring electricity security and a reliable and cost-effective integration of growing levels of solar PV and wind.” (IEA 2021)

However, as they also admit, there are key challenges for new hydropower projects. Such investments can face: “long lead times, lengthy permitting processes, high costs and risks from environmental assessments, and opposition from local communities.” The higher investment risks and financing costs can discourage investors, especially given the risks in emerging and developing economies where IEA underlines “the largest untapped potential for new hydropower lies.” In advanced economies, as they also note, there is a lack of incentives to modernise ageing fleets. (IEA 2021)

It remains a crucial option for new developments, as: “the flexibility and storage capabilities of reservoir plants and pumped storage hydropower facilities are unmatched by any other technology. Higher shares of variable renewables will transform electricity systems and raise flexibility needs. With low operational costs and large storage capacities, existing reservoir hydropower plants are the most affordable source of flexibility today.” IEA has begun estimating large energy value of water stored behind hydropower dams worldwide, noting that reservoirs of all existing conventional hydropower plants combined can store a total of 1 500 terawatt-hours (TWh) of electrical energy in one full cycle – the equivalent of almost half of the European Union’s current annual electricity demand. As they underline: “This is about 170 times more energy than the global fleet of pumped storage hydropower plants can hold today – and almost 2 200 times more than all battery capacity, including electric vehicles.” (IEA 2021)

4.5.3 New Developments in Green Hydrogen Technology

For green or low-emission hydrogen, origin certificates with tailored legal landscape have boosted the industry’s chances to compete with cheaper fossil fuel-generated hydrogen. As IEA explained in 2023: “Green hydrogen facilities on hydropower plants using technology similar to that of carbon capture and storage have the potential to reduce the emissions and ecological damage of hydropower plants.” However, much of this is still in the early stages, with only a bit of progress in terms of adoption and uptake. The number of announced projects for low-emission hydrogen production is rapidly expanding. Annual production of low-emission hydrogen could reach 38 Mt in 2030 if all announced projects are realised, although 17 Mt come from projects at early stages of development. The potential production by 2030 from announced projects to date is 50% larger than it was at the time of the release of the IEA’s Global Hydrogen Review 2022. Only 4% of this potential production has at least taken a final investment decision (FID), a doubling since last year in absolute terms (reaching nearly 2 Mt). Of the total, 27 Mt are based on electrolysis and low-emission electricity and 10 Mt on fossil fuels with carbon capture, utilisation and storage. (IEA 2023)

4.5.4 New Developments in Fusion Power Technologies

Fusion, the process of combining light atoms to form heavier ones, is the same process that powers the sun and other stars and is widely seen as the holy grail of clean energy. The ground-breaking technology produces fusion power without the disadvantages of producing large amounts of radioactive nuclear waste as a by-product and can potentially generate far more energy than conventional fission reactions. Experts have worked for decades to master the highly complex process on Earth, and if they do, fusion could generate enormous amounts of energy with tiny inputs of fuel and emit zero planet-warming carbon in the process. The long-sought goal is to build a fusion power plant that produces more energy than it consumes. Such a power plant could produce electricity without emitting greenhouse gases during operation and generating very little radioactive waste. Fusion's fuel, a form of hydrogen that can be derived from seawater, is virtually limitless.

New developments in fusion have been promising, both advances in the technology and in attracting investment. In Oxford during its final runs after 40 years, the Joint European Torus (JET) tokamak set a nuclear fusion energy record, sustained a record 69 megajoules of fusion energy for five seconds, using just 0.2 milligrams of fuel, enough to power roughly 12,000 households for the same amount of time. At 150 million degrees Celsius (around 10 times hotter than the core of the sun), scientists forced deuterium and tritium (hydrogen variants) to fuse and form helium in a tokamak lined with strong magnets that hold the plasma, releasing enormous amounts of heat. The heat is then harnessed and used to produce electricity. ITER, the world's biggest tokamak being built in southern France, and DEMO, a machine planned to follow ITER to produce a higher amount of energy, like a fusion plant prototype, are already under construction to replace JET.

While fusion energy would be a game-changer for the climate crisis — which is caused primarily by humans burning fossil fuels — it may still need years to commercialise. Further, making it work requires compressing the fuel at extraordinarily high temperatures and pressures, and since no known material can withstand such temperatures, the fuel must be held in place by extremely powerful magnetic fields. Producing such strong fields requires superconducting magnets, but all previous fusion magnets have been made with a superconducting material that requires frigid temperatures of about 4 degrees above absolute zero (4 kelvins, or -270 degrees Celsius). In the last few years, a newer material nicknamed REBCO, for rare-earth barium copper oxide, has been added to fusion magnets at MIT and allows them to operate at 20 kelvins, a temperature that despite being only 16 kelvins warmer, brings significant advantages in terms of material properties and practical engineering. Taking advantage of this new higher-temperature superconducting material was not just a matter of substituting it in existing magnet designs. A further dramatic MIT innovation has been the elimination of insulation around the thin, flat ribbons of superconducting tape that formed the magnet. MIT has also built a 20,000-pound magnet that produced a steady, even magnetic field of just over 20 tesla — far beyond any such field ever produced at a large scale. Their magnet assembly will form the donut-shaped chamber of the new SPARC fusion device now being built by CFS in Devens, Massachusetts. (MIT 2024) As MIT explains: "The power sector's transition to lower carbon resources has spurred investment in fusion technologies, with the global demand for power expected to double by 2050. Fusion power plants, alongside hydrogen and energy storage, are envisioned as a crucial component for supporting intermittent renewables like wind and solar." Of particular excitement, "Commonwealth Fusion Systems, backed by nearly $2bn in private investment capital, aims to achieve commercially relevant net energy from fusion with its SPARC prototype reactor, being developed by MIT's Plasma Science and Fusion Centre, by 2025. Helion has already secured a power purchase agreement (PPA) with

Microsoft to supply baseload power to its campus and data centres from 2028 onwards. Other options are also pursuing similar low-cost fusion designs." (MIT 2024)

5. Conclusions: Findings and Future Directions

Out of the four technologies I presented, while it seems that solar and wind are leading the clean energy transition, in reality, all are necessary in different circumstances. Solar is extremely cost-efficient, however also requires the most land use, and still has intermittency issues, making it impossible to support a grid solely without heavy reliance on currently expensive battery power. Wind will run at all times of day, and can be built offshore, circumventing space requirements, but it also can vary wildly depending on windspeeds. To most effectively develop into the future, we must explore all the possible technologies and take advantage of all the available breakthroughs. As we have seen, we cannot afford the consequences of failing. Energy production, especially with many other sources of emissions electrifying, is a critical part of our strategy for mitigating climate change.

However, certain signs are encouraging, and the projections of what is needed and what is possible are proving interesting. The hope is that these technological developments might even reopen a pathway to keeping global temperature rise below 1.5 degrees, saving coastal cities and small island nations, and preventing many tipping points.

In 2024, IRENA and the IEA announced that seven countries now generate nearly all their electricity from renewable energy sources including geothermal, hydro, solar or wind power, such as Albania, Bhutan, Nepal, Paraguay, Iceland, Ethiopia and the Democratic Republic of Congo. Further, 47 more countries generate at least 50% of their electricity from renewables, including 11 European countries, with Scotland generating over 113% of their overall electricity, and the UK overall generating 41.5% from renewables in 2022, up 10.5% from 2021. (IEA 2024) These developments are backed by technological changes. Solar power has experienced 24% growth annually over the last decade, as costs have decreased exponentially. Wind power manufacturing is reducing costs by 56%. Geothermal power is already the source of many completely renewable countries like Iceland. Further, fourth-generation biomass fuels appear to be becoming cost-viable.

All sectors of renewables have experienced significant growth in the past decade, due to research and innovation across science, engineering and the private sectors, international legal advances like the Paris Agreement combined with supportive domestic policies and laws, great increases in available investment and finance, and other factors. Solar and wind especially have gone from niche futuristic ideas to being competitive with fossil fuels or even overtaking them. As a note of caution, the variable nature of the solar and wind resources still requires significant changes to the way the power system operates as the share of variable renewable energy (VRE) reaches high levels in different markets, to strengthen grid efficiency, stability and reliability. Changes will especially be needed to transmission systems efficiency, and the operation and management of the grid on a minute-by-minute basis, while also taking into consideration seasonal variations in solar and wind output. In an age of low-cost renewable power generation, the success of the energy transition will be underpinned by strategies to integrate high shares of VRE into power systems at the lowest possible cost. In Europe by 2017 the VRE share in Denmark reached 53%, in South Australia 48%, and in Lithuania, Ireland, Spain and Germany over 20%. (IPCC 2018) At present the share of VRE in the generation mix of the G20 countries is rising steadily. (IRENA, 2023)

However, as IEA and others argue, the most exciting technologies are solar photovoltaics which are developing more affordable and efficient cells that are leading to a 93% cost decrease in just a decade. (IEA 2024). Net zero emissions energy systems entail many other changes in our current economy and technology, however. These could include "a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels, and use of carbon capture and storage in the remaining fossil fuel systems; electricity systems that emit no net CO2; widespread electrification; alternative energy carriers in applications less amenable to electrification; energy conservation and efficiency; and greater integration across the energy system." Further, renewables are not the only necessary step. In 2023, IPCC projected the need for large contributions to emissions reductions with costs less than USD 20 tCO2-eq-1, which need to come from "solar and wind energy" but also "energy efficiency improvements, and methane emissions reductions (coal mining, oil and gas, waste)." (IPCC 2023) Still, as they also note, with very high confidence, there are "feasible adaptation options that support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (very high confidence)" and important "opportunities for energy generation diversification (e.g., via wind, solar, small scale hydropower) and demand-side management (e.g., storage and energy efficiency improvements)" which as they note, can increase energy reliability and reduce vulnerabilities to climate change. Such technologies, and the sustainable, clean energy policies that will support them, are only just starting to be adopted. As IPCC explains, these changes can be motivated by "climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits." (IPCC 2023)

In conclusion, while solar and wind deserve the most credit, all these technologies have future potential, and all of them require scale-up to help contribute to preventing climate change. Thankfully, we are making progress. In 2016, renewable investment in renewables surpassed oil and gas. Now, finance has increased two-fold, but we still need another three-fold rise before 2030 to meet targets. As IRENA explains, renewables are set to account for "over 90% of global electricity capacity expansion over the forecast period. The upward revision is mainly driven by China, the European Union, the United States and India, which are all implementing existing policies and regulatory and market reforms, while also introducing new ones more quickly than expected in reaction to the energy crisis." (IRENA Renewables 2022) Furthermore, much of the recent growth in renewables has been exponential, as shown by the models, especially thanks to developments in Southeast Asian markets. With further development and innovation, investment and finance, and global collaboration, these experiences are likely scalable. Diversification and consistent forms of energy, which are urgently necessary, are within reach through new technologies and scale-up in adoption.

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Annexe 1: IRENA Methods for Calculating Levelised Cost of Electricity Generation (LCOE)

To more accurately assess the competitiveness of renewable power, IRENA has created a database of fossil fuel price indices and of the capital costs, efficiency and O&M costs of fossil fuel power plants. The data collected by IRENA, as well as sources of that data, can be found in the online annex to this report.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. This has the advantage, however, of producing a transparent and easy-to-understand analysis. In addition, more detailed LCOE analyses result in a significantly higher overhead in terms of the granularity of assumptions required. This can give the impression of greater accuracy, but when the model cannot be robustly populated with assumptions, and if assumptions are not differentiated based on real-world data, then the accuracy of the approach can be misleading.

The formula used for calculating the LCOE of renewable energy technologies is:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:
LCOE = the average lifetime levelised cost of electricity generation
I_t = investment expenditures in the year t
M_t = operations and maintenance expenditures in the year t
F_t = fuel expenditures in the year t
E_t = electricity generation in the year t
r = discount rate
n = life of the system