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The Current State of Renewable Energies and Future Technologies

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **CHRISTOPHER JURANICH, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE CURRENT STATE OF RENEWABLE ENERGIES AND FUTURE TECHNOLOGIES", 62 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

The challenges in the context of climate change and the accompanying global warming are arguably the most complex challenge for today and future generations. To achieve a rapid, equal, and sustainable energy transition is in the interest of all involved, but technological, political and social challenges have to be overcome to achieve this. The fact that especially the social component has a leading role to play in the transition is often neglected.

Much hope is being placed on renewable energy, with wind and solar showing the most significant potential. The technologies are already mature and market-competitive. The recently released AR6 report of the IPCC provides an excellent basis for assessing the technological status quo and future needs. The advancement of these technologies is essential for a successful energy transition, but physical and economic factors determine the pace of progress. Rising temperatures reduce the efficiency of PV systems, and the constantly growing wind turbines are approaching their material limits.

Fusion energy is still in its infancy, but it could be the solution to a low-carbon, sustainable society. There have been significant breakthroughs in recent years, which significantly increase the likelihood of a transition to large-scale fusion power plants in the future. Given the current and future technologies, the international community will have to provide an improved framework and international cooperation to enhance the expansion of renewable energy sources to mitigate climate warming.

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List of Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
CAES	Compressed Air Energy Storage
CH_4	Methane
CO_2	Carbon Dioxide
EJ	Exajoules
FIA	Fusion Industry Association
GF	General Fusion
GHG	Greenhouse Gases
GMST	Global Mean Surface Temperature
Gt	Gigaton
H_2	Hydrogen (dihydrogen)
IEA	International Energy Agency
IPCC	International Panel for Climate Change
IRENA	International Renewable Energy Agency
ITER	International Thermonuclear Experimental Reactor
LAES	Liquid Air Energy Storage
LCOE	Levelized Cost of Electricity
LDV	Light-Duty Vehicles
LIB	Lithium-Ion Battery
LOHC	Liquid Organic Hydrogen Carriers
MW	Megawatt
NDC	Nationally Determined Contributions
NIF	National Ignition Facility
PA	Paris Agreement
ppb	Parts per Billion
ppm	Parts per Million
RHFC	Regenerative Hydrogen Fuel Cells
SAT	Surface Air Temperature
SCAP	Supercapacitors
SST	Surface Sea Temperature
TES	Thermal Energy Storage
VRE	Variable Renewable Energy

Acknowledgments

In these few lines, I am happy to express my gratitude and appreciation for all the people who have supported me in life and helped me get to where I am right now. A special thanks goes to my parents, Muniba and Franz, who have consistently and unconditionally stood by me, even when I was, as so often, quite a pain in the neck. It often takes patience with me and I am grateful to my family and friends who were able to bear it.

Further, I would like to thank my group of friends *Faith+1*, who were not only extremely talented in distracting me from this paper, but most importantly, gave me the emotional balance to finish this work sanely. My "reze" thereby also played an important role which I am thankful for.

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1. Introduction

The public debate about climate change has been significantly increasing since the beginning of this century (Boykoff & Roberts, 2008). This comes as no surprise since anthropogenic climate change affects not only a few countries but every nation and being on this planet. Carbon Dioxide (CO_2) and other greenhouse gases such as methane and nitrous oxide, which contribute to the warming of the atmosphere, are constantly present in the media. An expansion in renewable energy capacities and technologies such as direct air capture (DAC) is promoted as the solution to the climate crisis (IPCC, 2021).

Renewable energy capacities expanded sharply in the last decade, most significantly in the past ten years. Nevertheless, the total share of renewable energies, including hydropower, only amounted to 12,5% in 2020 (BP, 2021). Most energy is still supplied by fossil fuels such as oil, gas, and coal.

The debate about phasing out fossil fuels has already reached national and international policy maker (UNFCCC, 2015). Still, a discrepancy in the way this phase-out can be achieved exists not only among industrialized countries but, above all, the voices of the developing countries are becoming increasingly louder (Cust, et al., 2017). These countries see fossil fuels as an essential aspect of their future growth, just as the industrialized countries have relied on this energy source for their own development since the beginning of the 20th century (Smil, 2017).

Although renewable energy costs have been reduced considerably over the past decade due to better market competitiveness and supply, fossil-fueled power plants are still cost-competitive with ongoing demand and governmental subsidies (IPCC, 2021).

In this aspect, a key factor for a successful energy transition is the costs and the reliability of renewable energy sources. Variable renewable energy (VRE), as their names suggest, depends on factors that vary on a temporal resolution and show strong fluctuations in the various seasons (Shi, et al., 2020). A nuclear power plant or a coal-fired power plant, on the other hand, can guarantee a steady production of electricity throughout the year.

Another point that must be considered concerning a renewable energy transition is the capacities required to replace fossil and nuclear energy sources. Solar, wind, hydro, and other technologies are often bound to climatic circumstances hindering a viable expansion. The topic of land use and social acceptance also arises in this context. Considering that it would take almost 500 new wind turbines to replace one nuclear power plant, the question of where to safely install them rises, disregarding the number of resources needed to build all these turbines (ONE, 2021).

In the U.S., for example, only the Midwest (aside from offshore wind farms) would be suitable for installing large fields of wind turbines (Sayigh & Milborrow, 2020). In order to transport the energy to the energy-demanding regions on the country's coasts, the high-voltage grid would have to be renewed entirely with higher towers, more robust cables, and conductors. A billion dollars investment, which still does not solve the problem of reliability of supply by VRE. Much research and improvements have been made in scaling up cheap, energy-dense energy storage solutions, helping integrate VREs into the energy grid (IPCC, 2021).

The pace of the energy transition, with respect to the goal of keeping global warming below 1.5°, is a critical factor potentially thwarting a successful transition. Given that the digitalization end electrification of the world will continue, and we expect the world population to grow from 7.8 billion to almost 10 billion in 2050 (OurWorldInData, 2019), with most of this growth occurring in developing countries, the energy demand will also increase significantly (Roser, 2020). Policymakers are called upon lead a more rapid, sustainable, equal energy transition to address climate and social challenges.

This thesis intends to evaluate the status quo of VRE in global energy production and consumption and put them in relation to future tasks and challenges. Firstly, a description of why the energy transition is necessary is given before the CO_2 emissions and the global energy consumption is depicted.

In a further step, the status of the capacities and technological characteristics of the VRE technologies wind and solar are described, and a future outlook of the technologies is given. In addition to current statistics, the content of this work will refer to the future and present technological requirements and present and future challenges. A comprehensive account of socio-political challenges will complement the economic-technological aspects of this thesis and provide a starting point for future technologies.

The focus in this paper is on fusion energy since it is a known thermonuclear reaction we can induce, but we cannot yet control viably for energy generation. The status quo of this type of possible future energy source is described and discussed in the energy transition context to answer the question: "*Can the future world provide 100% of its energy from renewable sources, or is a technological revolution in energy generation necessary*?"

1.1. Methodology and Literature

A large body of literature from private individuals, academics, and international organizations discuss climate change and energy transitions. In order to get the essence of this broad literature, this paper uses, to the extent possible, the most recent statistics, especially for the years 2019 to 2022. Fortunately, with the beginning of this thesis, numerous highly respected international reports have been published, notably by the IPCC, IEA, BP, and IRENA. The original plan to conduct expert interviews was abandoned after the publication of these reports, as these thousands of pages of documents represent the latest state of the art.

To support future technologies and predictions for the energy transition with data, graphs, predictions, and statistics from OurWorldInData, Statista, BP, and the IPCC are included. Regarding the outlook of VRE technologies solar and wind, successful and failed projects are discussed to highlight these energy technologies' challenges and indicate development opportunities. Numerous books, journals, and websites were examined to achieve a comprehensible approach to the topic.

Predicting the future of energy transition is a challenging undertaking. This paper presents fusion energy, a promising future technology, and its status quo based on recent publications. In order to build future scenarios, this paper relies on the latest figures and findings of scientific institutions. However, socio-political challenges are the great unknowns that the author will reflect on based on personal experiences and impressions in his extensive travels.

2. Why we should not exceed 1,5°

Our climate is in a constant flux. Changes in our global temperature, tectonic land distribution, the ratio between water and ice, and many other points of interest can be traced back to well before human existence (McNeill, 2000). Sediments from oceans and lakes, ice cores, stalactites, fossils, etc., are essential climate archives to understand past and predict future events. Modern humans have been confronted with climatic changes several times, such as during the Medieval Warm Period and the Little Ice Age in the second half of the last millennium. These changes have either been preserved by writings or can be determined by tree rings, corals, glass sponges, and cores from peatlands (McNeill, 2000).

The climate change we are confronted with today is particularly remarkable because of its pace of change, which is caused and accelerated by human activities. Human influence brought the predominantly stable Holocene period to an end. It ushered in the Anthropocene Era, in which humans have become one of, if not the most critical factor influencing biological, geological, and atmospheric processes on earth (Smil, 2017). The unabated and unmitigated emission of greenhouse gases, deforestation, albedo change, and our misanthropic consumption behavior is not only changing global temperatures but also endangering our biodiversity, food production, and the health of billions of people.

Today, more than 20-40% of the world's population has experienced temperatures above the 1.5°C average in one season in their region (IPCC, 2018). Considering global warming, one must keep in mind that the warming is not and will not be evenly distributed on the planet but shows significant spatial and seasonal differences. Thus, many land regions will experience a substantially higher warming and sea regions considerably lower warming than 1.5°C (IPCC, 2021). Weather extremes will substantially increase in their occurrence and consequently impact directly and indirectly life on earth. The immediate physical change of our environment and habitats in the form of melting glaciers, deforestation, and rising sea levels will create indirect feedback loops that we are still trying to understand and assess (Mysiak, et al., 2016).

Although humans can adapt to the consequences of increased heat waves and droughts, the consequences for our environment are far greater and still beyond our assessment capacities. Shifting rainfall patterns, loss of biodiversity, ocean acidification, insect outbreaks, change in plant productivity, coral bleaching, diseases, invasions of weed and salt, food and water insecurity are only an incomplete list of the likely to highly likely impacts (Allen, et al., 2018).

Already since the Copenhagen Accord in 2009, but at least since the Paris Agreement (PA) in 2015, there have been many agreements and disagreements about the goal of "*keeping global average temperatures below 1.5 degrees compared to pre-industrial times* (UNFCCC, 2015, 4)." Mitigating global warming has since become a common global target. The AR5 report by the International Panel for Climate Change (IPCC), defines "warming" as an overall increase in global mean surface temperature (GMST) over several decades relative to pre-industrial levels. The IPCC calculates the GMST as the average of near-surface air temperature (SAT) changes over land and changes in sea surface temperature (SST) over the oceans. Natural climate-changing events such as volcanic eruptions and increased solar activity change global temperatures but do not change "warming" as defined in the report (IPCC, 2018).

As highlighted in the AR5 report, since 1970, the global average temperature has increased at a rate of 1.7°C per century, with the contribution of human-induced warming accounting for 0.7°C over the period 1951-2020 (Marcott, et al., 2013). The human-induced warming is thereby proportional to cumulative carbon dioxide (CO_2) emissions (Allen, et al., 2018).

2.1. CO_2 Emissions and their role in Global Warming

Since the end of the 19th century, global CO_2 emissions per year have been increasing continuously, reaching an all-time high of 36,3 gigatons (Gt) in 2021. The nature and intensity of CO_2 emissions have changed fundamentally. While up to 1950, CO_2 emissions were mainly caused by biomass burning, deforestation/land change, and coal burning, since then, the primary sources of CO_2 emissions have been fossil fuels in the form of oil, gas, and coal (Friedlingstein, et al., 2021).

Significantly since the year 2000, the CO_2 concentration in the atmosphere has increased by 20 parts per million (ppm) per decade (Friedlingstein, et al., 2021), which is a ten times faster increase in CO_2 concentration compared to the past 800,00 years (IPCC, 2018).

The ongoing industrialization and globalization caused the CO_2 concentration in the atmosphere to increase from 284 ppm in 1850 (pre-industrial), to 294.22 ppm in 1900, 370.93 ppm in 2000, and peaked at 419 ppm in 2021. The increase in emissions thereby shows significant accelerations in the past four decades. The global average temperature also increased along with the steady increase in CO_2 concentration, as shown in Fig. 1.

There have only been a few years of crisis, such as at the time of the oil crisis in the 1980s, the global financial crisis in 2008, and the Covid pandemic, where emissions did not increase (IEA, 2022).

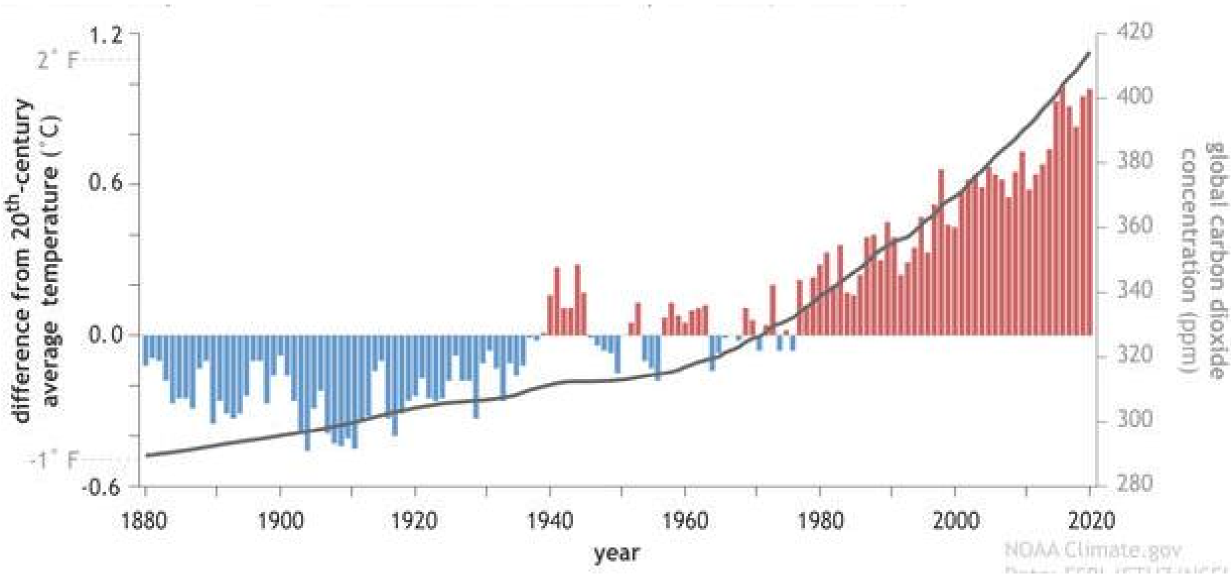

Figure 1: Global atmospheric carbon dioxide and surface temperature (1880-2020) [Source:(NOAA Climate,gov)].

Despite annual records, emissions have not yet peaked, and "*the world has not heeded the call for a sustainable recovery from the Covid-19 crisis*" (IEA, 2022, 4). The rebound in emissions in 2021 even exceeded those in 2019.

CO_2 emissions increased in almost all regions of the world after the first Covid year 2020, with significant differences in the annual increase in emissions. Brazil and India recorded an increase of 10%, the EU and USA 7%, China 5%, and Japan 1% (IEA, 2022). The most significant increase in emissions occurred in the transport and industry subsectors, where the corresponding emissions accounted for 15% and 24% of total CO2 emissions, respectively (IEA, 2022).

Increased CO_2 emissions from coal-burning, with 80% of added emissions concentrated in Asia, led to emissions hitting an all-time high. Contrary to the International Energy Agency's (IEA) forecast of coal emissions approaching the previous peak in 2014, they exceeded the previous record by 200 Mt and now stand at 15.3Gt (IEA, 2022).

One reason why considerable emissions from coal were emitted was that for most of 2021, including parts of Europe and North America, it was considerably cheaper to operate existing coal-fired power plants than gas-fired power plants (IEA, 2022).

With the ongoing war in Ukraine and the possible shortages in the natural gas market, this trend is likely to continue in 2022 and further hinder global climate mitigation efforts. Due to the Covid pandemic, global oil consumption, which plays a vital role in the transportation sector, plummeted by 10% in 2020. In 2021, due to the prevailing global lockdowns and other measures to contain Covid, this number recovered by 2% compared to 2020.

The reduced air traffic resulted in emissions of only 60% of the pre-pandemic level, leading to CO_2 reductions of 250 Mt. If road and air traffic had recovered to pre-pandemic levels, we would have experienced the highest growth rate in total CO_2 emissions since the 1950s, at 7.8%. With the resurgence of the transportation sector, surpassing this record is very likely in the coming years (IEA, 2022).

Although sales of electric cars set a record in 2021, leading to a reduction in emissions mainly in developed countries, this reduction was reversed due to the parallel increase in SUV sales (IEA, 2022).

Our annual global carbon budget, the amount of CO_2 emissions which can still be emitted to meet our targets for limiting global warming to 1.5°C, 1.7°C, and 2°C, helps illustrate trends and setbacks in reaching our climate targets (MCC, 2022). With the current level of CO_2 emissions, we would exceed our goal of limiting GMST to 1.5°C as early as 2030-2035 since human-induced warming already accounted for 1°C above pre-industrial levels in 2017 (Hausfather, 2021). This event is likely to occur, where unforeseen feedback loops and climate tipping points are expect (IPCC, 2021).

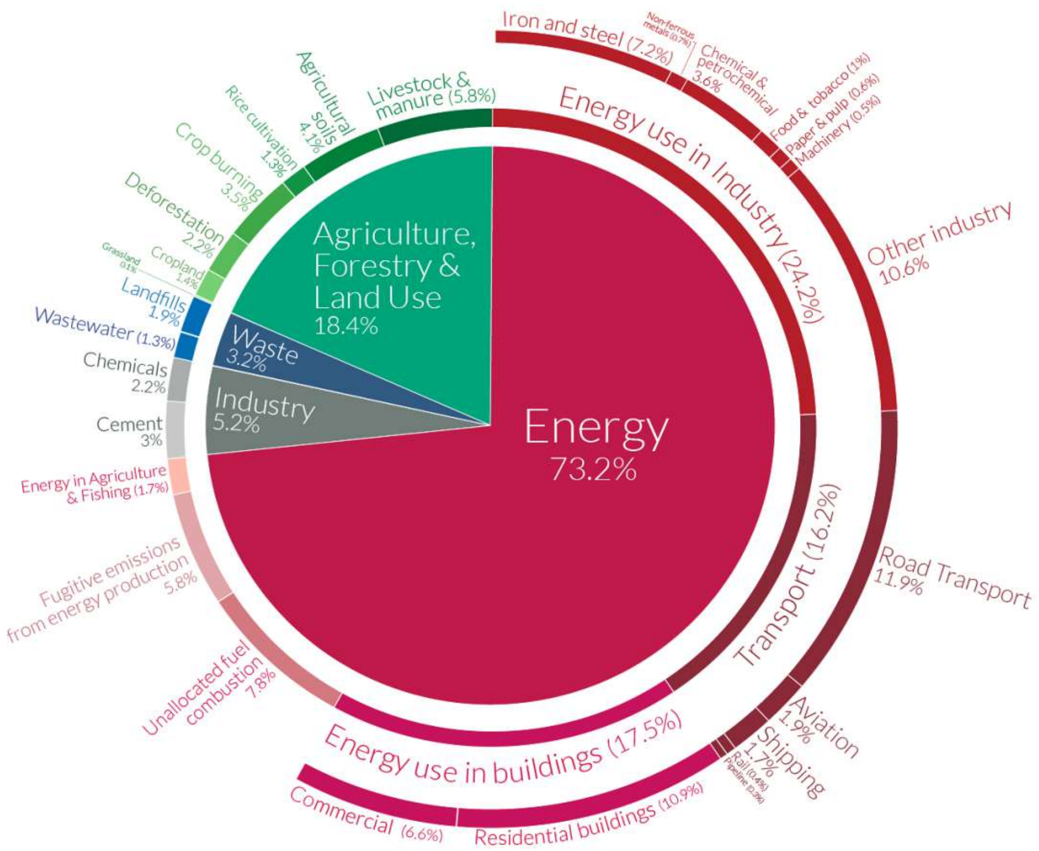

Figure 2: Global greenhouse gas emissions by sector 2016 [Source:(OurWorldInData 2020)].

Besides CO_2, other long-lived climate forcers, such as nitrous oxide (N_2O) and short-lived emissions such as methane (CH_4) and black carbon have an effect on increasing temperatures and their development remain hard to predict. These emissions experienced a peak in 2021, and their strong warming effect contributes significantly to the increase in global temperatures (Allen, et al., 2018).

The concentration of the potent GHG methane nearly tripled from 774 parts per billion (ppb) in 1850 to 1909.3 ppb in 2021. Similarly, N_20, a GHG 300 times more potent than CO_2, increased from 270.4 ppb in 1850 to a historic high of 334.8 ppb in 2021 (Ritchie, et al., 2022). Not only the reduction or elimination of CO_2 is of prime importance, but also that of other GHG, especially methane. For this gas with more potent warming effects, 1.5°C compliant pathways continue to assume substantial emissions by 2050, as the reduction potential is relatively low, especially in methane emitting agriculture, forestry, and other land use (AFOLU) sectors (Bauer, et al., 2020). The share of methane emissions from the AFOLU sector was nearing 50% in 2010. This percentage will likely increase to 55-70% by 2030 and 60-80% by 2050, assuming 1.5°C compliant pathways. However, no detailed assessment of measures to further reduce AFOLU CH_4 emissions has yet been carried out (Rogelj, et al., 2018).

2.2. Energy consumption

Global primary energy consumption in 2020 amounted to 557,10 exajoules (EJ), equivalent to 154,750 TWh. 39.9% of consumption occurred in OECD countries and 61.2% in non-OECD countries. 26.1% of global consumption occurred solely in China and 10% within the EU, and 15.7% in the US (BP, 2021).

The largest share of energy continues to come from fossil fuels, which covered 83.15% of worldwide demand, with oil accounting for 31.2%, coal 27.8%, and gas 24.7%. Regarding CO_2 low energy sources, renewable energy covers 12.54% of the world's demand and nuclear energy 4.31% (BP, 2021).

Energy demand increased by 1400 terawatt-hours in 2021, an increase of 5.9%, which coal-fired power plants mainly met. These power plants supply 36% of the electricity and heating sector with energy. However, this figure would have been significantly higher in 2021 if there had not been supplying constraints and high prices in China and India (IEA, 2022).

China, in particular, was the driving factor in the increase in energy demand. Their demand increased to an unprecedented 10%, to 700 TWh, which is comparable to the total energy demand of Africa. This increase in China's energy intensity is mainly due to the ongoing electrification of energy services, of which 56% was supplied by coal-fired energy (BP, 2021).

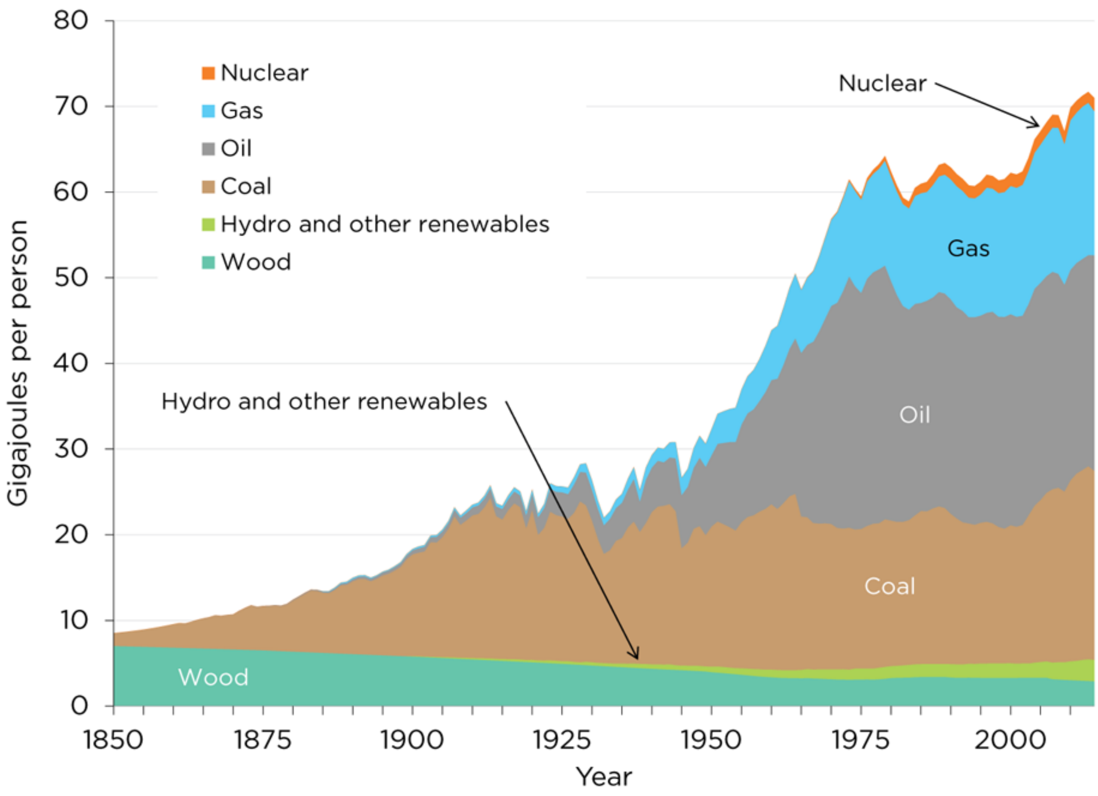

Figure 3: World per capita primary energy consumption per year by fuel type, 1850–2014. [Source:(Data compiled by J. David Hughes from Arnulf Grubler, "Technology and Global Change: Data Appendix," (1998), and BP, Statistical Review of World Energy)].

To support global economic growth and enable billions of people to make the transition from low to middle income, more energy will be needed. Since human progress and energy consumption are closely related, an increase in energy consumption of about 100 gigajoules (GJ) per capita is associated with a significant increase in personal development and well-being (IEA, 2022) (IRENA, 2022).

Although energy demand in OECD countries has stabilized and renewable energy sources are on the rise, demand in non-OECD countries will increase manifold. Today around 80% of the world's population still lives with an average energy consumption of fewer than 100 GJ per capita. To significantly improve this situation, it would be desirable, in line with SDG 7, to reduce this figure to one-third of the world's population by 2040. This would require around 65% more energy worldwide than today (IPCC, 2021). The increase in energy demand is roughly equivalent to China's total energy consumption in 2017. For CO_2 emissions, this would mean an increase of almost 40% by 2040 (BP, 2021).

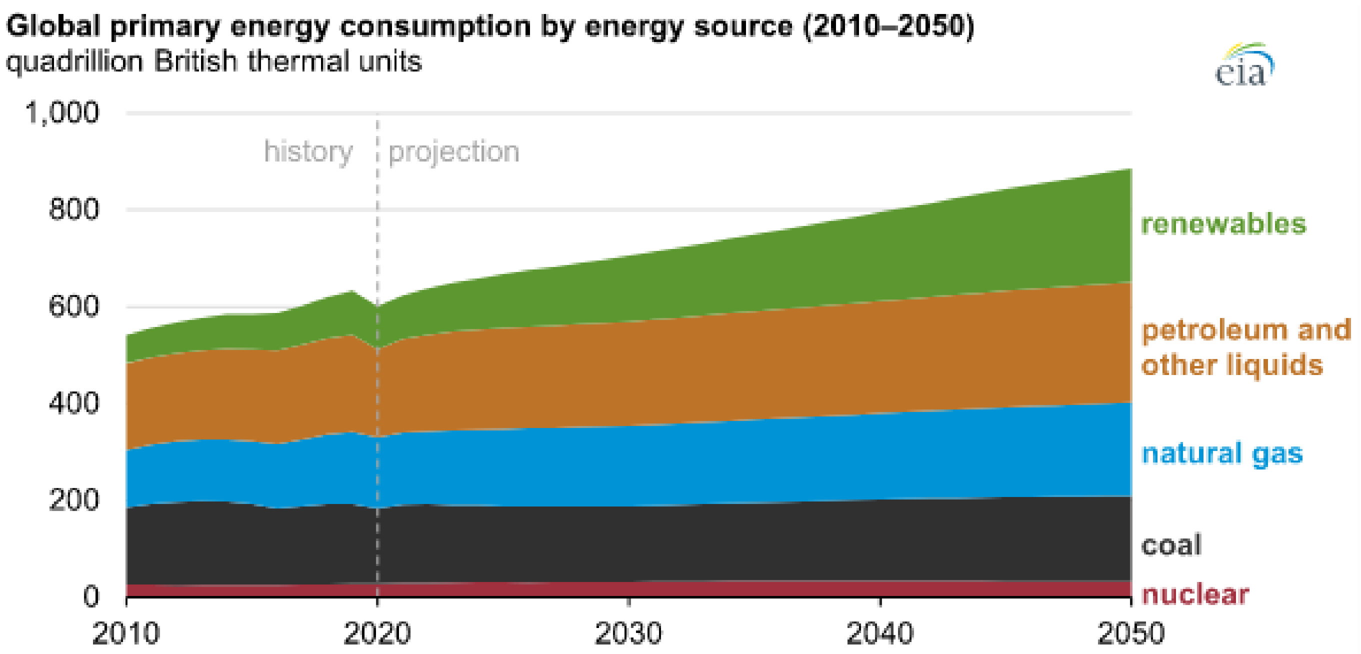

Figure 4: Global primary consumption by energy source (2010-2050) [Source:(EIA, 2021)]

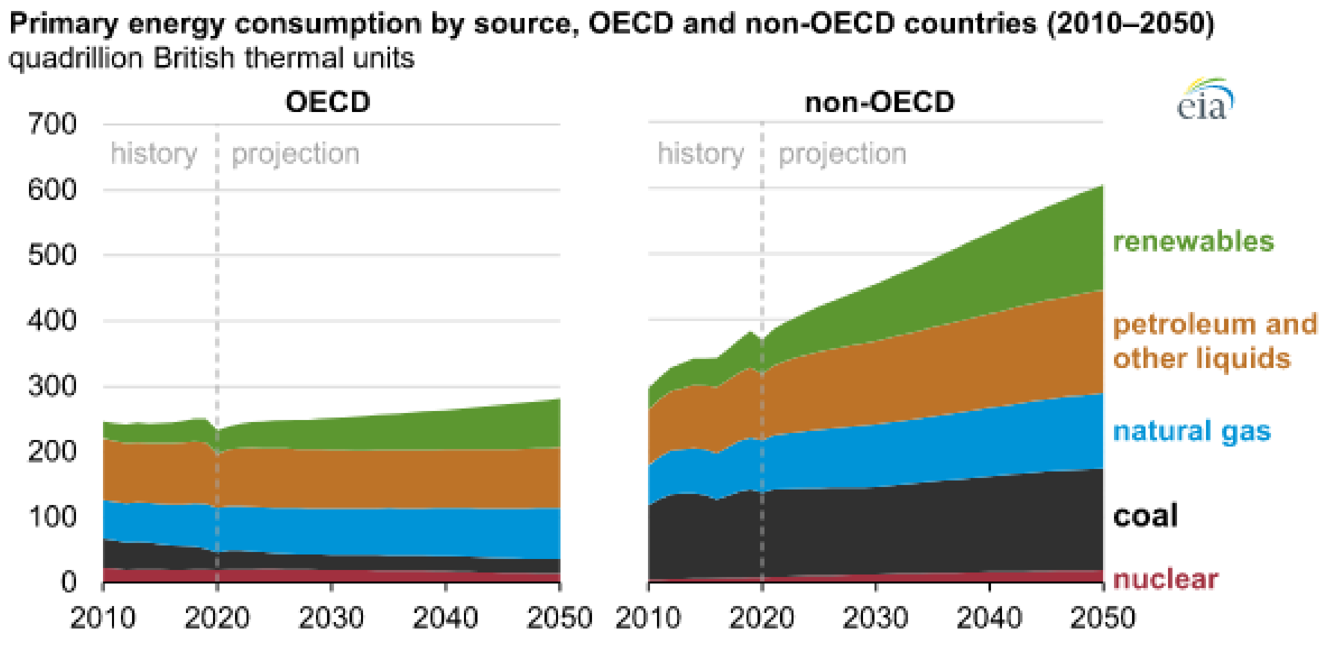

Figure 5: Global energy consumption by source, OECD and non-OECD countries (2010-2050) [Source:(EIA, 2021)]

3. Renewable energy

As our global system continues to electrify and the cost-performance factor of renewable energy continues to improve, increased attention has been placed on the possibility of supplying almost all energy services with renewables. Renewable energy includes biomass (wood, wood waste, municipal solid waste, biogas), hydropower, wind power, solar power, geothermal power, and tidal power. In the remainder of this paper, we will not discuss hydropower in further depth, as its ecological footprint on flora, fauna, and biodiversity and the often-associated displacement of people are considered by some legislators to be non-renewable or unsustainable (Botelhoa, et al., 2017) (Frey & Linke, 2002) (Williams, 2020). The focus will be on wind and solar.

In 2020 the global consumption of total energy in the form of electricity amounted to 17.3%, equivalent to 26,823 TWh (IEA, 2021). Of this percentage, 11.7% of the electricity was generated with renewable energy, and if hydroelectricity is included, this percentage amounts to 27.7%. Without considering hydropower, 5,6% of the total global energy demand was supplied by renewable energy sources (BP, 2021).

A closer look at the regional distribution of renewable energy consumption reveals a stark divide between the global west, China, and the rest of the world. Europe and North America accounted for 40.1% of global renewable energy consumption. This number is unchallenged by any other region in the world except China, which stands as the world's largest consumer of renewable energy at 27.95% (IEA, 2022).

In most of the oil-exporting countries of the Middle East and the CIS, and Africa, the share of renewable energy in the energy consumption mix is close to 0%.

In terms of renewable energy production, the pattern is similar to consumption. China is leading the production with 27.4%, followed by the US and the EU. China has invested heavily in wind and solar energy in 2019-2020, with the former growing at 14.8% and the latter at 16.2% (BP, 2021).

Although there was an increase in energy demand in almost all sectors after the 2020 pandemic year, the most significant increase, with 6,9%, occurred in the electricity and heat generation sector. At over 900 Mt CO_2, the increase in emissions accounted for 46% of new global emissions due to the increased electricity demand. There was a strong rebound in fossil fuels, especially coal, but renewable energy and nuclear sources contributed more to global electricity generation than coal (BP, 2021).

Herby, an all-time high of over 8000 TWh was reached, increasing 500 TWh compared to 2020. Wind energy increased its electricity generation by 270 TWh and solar PV by 170 TWh, respectively, with hydro recording a reduction in output of 15 TWh, due to droughts in the US and Brazil. Nuclear energy generated 100 TWh more electricity in 2021, which, together with the increase in renewables, led to a reduction in global CO_2 of 220Mt (IEA, 2022).

At the moment, many grids operate with sizeable renewable energy shares, and expectations are high for the critical role of renewable energy sources, especially wind and solar, in a future low-carbon electricity system. The trend toward renewable energies is ongoing, and a continued rapid increase in installations is projected (IEA, 2021). With the targeted decarbonization of the system and the political frictions and war, "*the economic outlook for renewable power is undeniably good* (IRENA, 2022, 17)."

With the increased demand and the increasing supply, market competitiveness, and energy demand, the cost of renewable energy installations has been expected to decrease further. As a result, between 2010 and 2020, the global weighted average cost of electricity for newly installed photovoltaic projects was reduced by 85%. Concerning wind energy, the corresponding costs fell by 56% for onshore and 48% for offshore projects.

In 2020, the trend of increasing reliance on photovoltaics continued. Since 2010, when the installed PV sources produced 40.1 GW of energy, this capacity had almost doubled already the following year (2011: 72GW), and since then has increased almost tenfold (2022: 767.7GW) (BP, 2021).

Wind power has also seen its capacity quadruple since 2010, reaching a cumulative capacity of 825 GW by 2021. The offshore wind market remains rich in potential, with 14 countries already installing offshore facilities and accounting for 56 GW of the total cumulative wind capacities (IEA, 2021) (IRENA, 2022). Today, with global installed capacities being comparable, the growth rate of PV capacities (21,5%) outperforms the growth rate of wind (17,5%).

The largest source of renewable energy in 2021 remains hydropower (excluding pumped hydro), with 40% of installed capacity reaching 1230 GW, with China alone accounting for 30% of this total (BP, 2021).

3.1. Wind Energy

In various reports and specialist groups, wind energy is regarded alongside solar PV as the critical driver in the energy transition. The electricity production from wind energy is more than twice as high as solar energy at the same installed capacities (IPCC, 2021). Wind capacities have grown by more than 70% since 2015, and further growth is expected (IPCC, 2021). Steadily increasing efficiency, low operating costs, abundant resources, and cost-competitive markets are some of the advantages attributed to wind energy. The International Renewable Energy Agency (IRENA) forecasts that wind will supply 24% of total electricity demand by 2030 (IRENA, 2022).

Wind energy is available in abundance, to the point where the estimated technical potential exceeds the total energy required to keep global warming below 2°C.

In its AR6 report in April 2022, the IPCC estimated the potentially generable energy from wind power at 557-717 Petawatt hours per year, which equals 20-25 times the energy demand from 2021 (IPCC, 2021). The potential for offshore wind turbines is considerably higher because they guarantee better energy production due to more stable and stronger winds. On the other hand, the costs for offshore plants are considerably higher, as installation, transportation logistics, maintenance, transmission, and grid expansion are more expensive (McKenna, et al., 2022) (Pryor, et al., 2020).

However, the most considerable decrease in costs in recent years happened in the offshore wind market. Until 2014, the cost of offshore wind increased, and since then, it has decreased by almost 50%. Today, offshore wind turbines' levelized cost of electricity (LCOE) is about 20% higher than that of onshore wind. None of the technologies show that they are approaching their limit of cost reduction (IPCC, 2021).

The reduction in the cost of wind energy has been achieved mainly through the construction of better turbines with higher capacities, larger towers, and rotor blades that can capture more energy through larger swept areas (IPCC, 2018). The fact that it is vital to increase the size of the rotors is primarily connected with the Betz limit, which describes the maximum efficiency of a wind turbine. According to the theory of Betz, a maximum of just under 60% of the energy contained in the wind can be harnessed. In the case of turbines currently on the market, the efficiency lies in the range of 40 to a maximum of 50% (Sayigh & Milborrow, 2020). The dimensions of the wind turbines will be discussed in detail in the next sub-chapter.

Considering the levelized cost of energy, the turbine accounts for the highest cost when installing wind energy technologies. However, with improved means of recycling and economies of scale, this and other cost components are predicted to decrease further. According to the information available on the website of the world's largest manufacturer of wind turbines, Vestas, the average recycling rate of onshore wind power installations is 86% for systems in the range of 4 megawatts (MW). The average return on energy breakeven is 6.6 months, and the lifetime return on energy is averagely calculated at 37 times (Vestas, 2022).

Reaching the 1.5°C target would require a quadrupling of onshore capacity and an elevenfold increase in offshore capacities by 2030. Until 2010, Europe was the world leader in wind power capacity, with a 50% share, until Asia surpassed it, with China leading the way. The most significant additional installations will occur in Asia in the future, and the difference in percentage growth of capacity between Europe and Asia is also predicted to increase (IPCC, 2021).

Many international organizations call for offshore capacity to be expanded in Asia, Europe, and North America, where the potential is high. In Asia, for example, only 2.5% of the possible potential has been exploited. It will be more challenging for countries in the Middle East and Africa to add new capacities, as the potential low is low, but a lack of infrastructure and funding also persists (IEA, 2021).

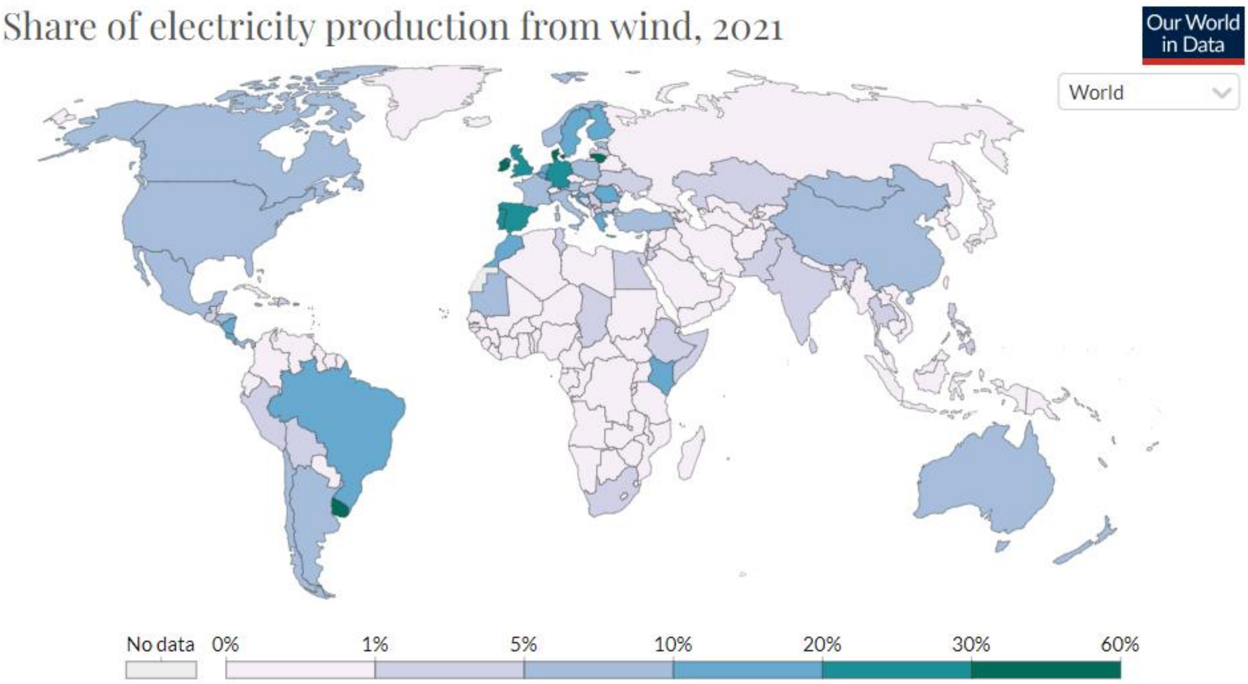

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Figure 6: Share of electricity production from wind, 2021 [Source:(OurWorldInData,2022)].

One of the “*numerous challenges that hamper growth and development”* (IRENA, 2022, 65) of wind power is to ensure a rapid expansion of capacities and an improvement of grid infrastructures whereby international cooperation will be needed in addition to national measures. The exchange of know-how and innovation cooperation has already led to an accelerated global spread of wind technologies. However, it needs to be intensified to reach current and future energy goals. As observed at the International Thermonuclear Experimental Reactor (ITER) project for fusion energy, international renewable energy cooperation should become an international effort and standard to ensure accelerated decarbonization (IPCC, 2021).

Along with international cooperation and social acceptance, which will be discussed in Chapter 5, ecological impacts from wind turbines have also become an increasing obstacle to expansion. While wind turbines are generally considered to have relatively low environmental impacts, they can sometimes have significant impacts at the local level. Not only bird species and bats are threatened, but overall biodiversity through land use and soil sealing and the overall carbon footprint concentrated in the manufacturing, transportation, construction, maintenance, and disposal of wind turbines (Liu & Barlow, 2017) (Mishnaevsky, 2021).

That weak correlations exist between wind farm noise and long-term human health was shown by Poulsen et at. 2018. This noise impact is increasingly significant as wind power installations are deployed, specifically in connection with increasing rotor dimensions. What other material, logistical, and physical obstacles wind energy faces will be further included and discussed in the following chapters.

3.1.1. The Future of Wind Turbines – Size and Limits

As mentioned earlier, there has been tremendous growth in wind energy over the last three decades. The concerns of the 1990s that wind energy could not be reliably integrated into the power grid vanished as operators learned how to adapt our grid to deal with the fluctuations of the wind. With the suitable climate, infrastructure, and policiy (Sayigh & Milborrow, 2020), wind energy can account for a significant share of a country's energy production. Denmark can be considered a very advanced example. In 2019, Denmark generated 47% of its energy generation with wind power, not just on one day but as an annual average. Denmark's wind installations could meet as much as 140% of its electricity needs with wind power on a particularly windy day (Gronholt-Pedersen, 2020). Denmark is benefiting greatly from robust interconnections with its neighboring countries and has been able to sell a large portion of the energy it produces to Norway, Germany, and Sweden.

Grid operators are learning how to reliably integrate wind energy into the energy market, where energy can be bought and sold like on the stock market. Countries like Denmark have adapted their grids well to the fluctuations of wind energy, and they are becoming faster and more responsive, using weather forecasts to schedule and release other energy sources as needed (Sayigh & Milborrow, 2020). Hereby, the importance of natural gas in this equation must be emphasized as a fast and responsive form of fossil fuel to deliver energy when winds die down. Natural gas is an unsung protagonist in the electricity system and will remain so until we develop a cheap and scalable energy storage solution. However, it is undeniable that inertia is with wind energy, and advances in offshore facilities will only amplify this trend. Last year alone, 58 billion dollars were invested in wind energy worldwide (Statista, 2022). One fascinating trend has been the steady increase in size of wind turbines over the past three decades.

When it comes to the future of wind power generation, we face limited possibilities apart from expanding capacities and enlarging rotor sizes. Low wind turbines could either become a mainstream player in the energy system, for example, or a completely new, more efficient, and cheaper design concept, such as vertical axis turbines, could become market viable (Brauner, 2016). Upscaling wind turbine installations and their size is the watchword to achieve higher outputs per installation. The average wind turbine height and diameter have grown steadily. The average wind turbine in the early 1990s was about 27 meters in diameter, with a capacity of 100 KW, and today standing at an average of 127 meters with an average capacity of nearly 3MW (IPCC, 2021).

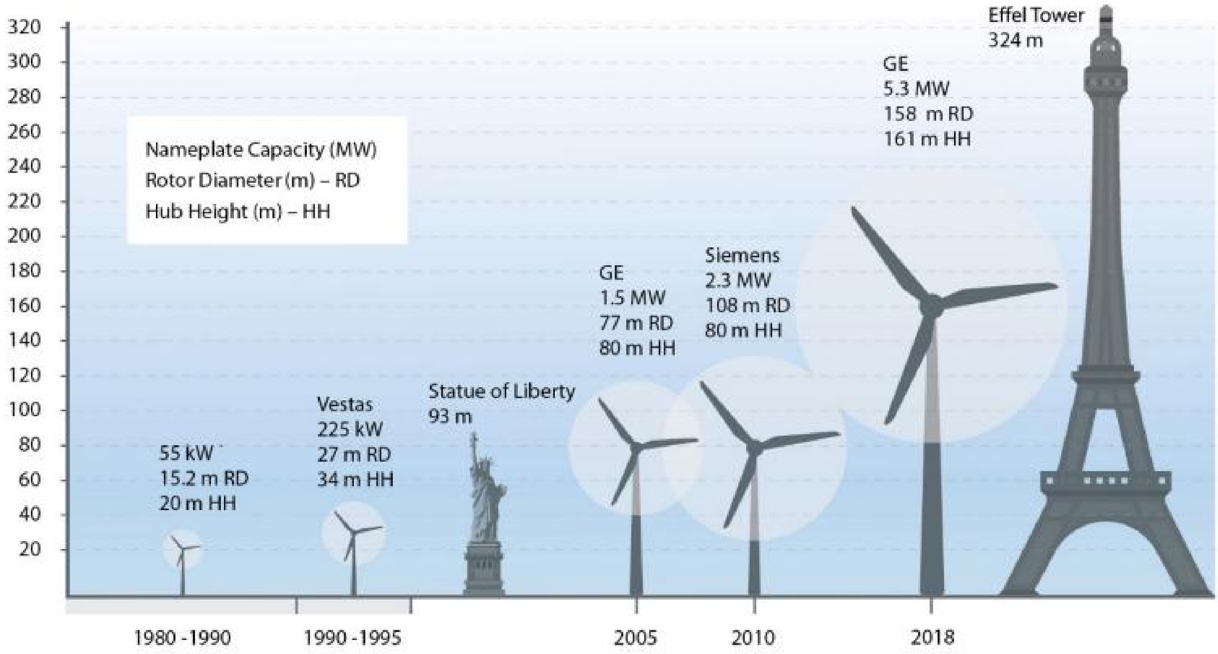

Figure 7: A small selection of turbines from a few global wind turbine manufacturers illustrate the growth in wind turbine sizes over time for land-based wind turbines in terms of hub height, rotor diameter, and power rating (in megawatts [MW] [Source: (National Renewable Energy Laboratory [NREL])]

The power a wind turbine can generate depends on its ability to convert wind's kinetic energy into electricity, so we can apply a straightforward formula to calculate how much power a wind turbine can generate if it is 100% efficient.

$$KE = \frac{1}{2} m v^2$$

$$mass(m) \longrightarrow mass\ flux\ (m = {}^{dm}/_{dt})$$

$$P = \frac{1}{2} m v^2$$

$$where,\ m = \rho A v$$

$$Power = \frac{1}{2} \rho A v^3$$

Equation 1: Fundamental Equation of Wind Power [Source:(Kalmikov, A., 2017)]

Since no energy but power is to be calculated, the equation for kinetic energy is taken ($KE = \frac{1}{2} mv^2$), and the mass variable is replaced by a variable that defines how much mass per time unit passes through the circular rotor surface of the wind turbine.
To calculate this, the surface of the rotating circle, the velocity of the air passing through this surface, and the density of the air are required. This equation defines how much power a 100% efficient wind turbine could extract from the wind (Manyonge, et al., 2012). With this formula, it is already apparent why wind turbines are getting steadily larger.

The area figure is determined by the radius squared. By doubling the wind turbine radius, which has been happening approximately every ten years (EREE, 2021), we quadrupled the wind turbine's maximum generating power. Thereby, the cost of electricity for these turbines also decreases.

In 2021, the most powerful wind turbine, GE's Haliade-X, was commissioned in Rotterdam, with a diameter of 220 meters and a height of 260 meters. The Eiffel tower, a cityscape-defining landmark, would be only a few meters taller than the turbine, which, however, is not a static structure but a powerful dynamic machine. With its 14 MW capacity, the turbine could power an average British home for two days with a single rotation of its rotor (GE, 2022).

The manufacture of these massive rotor blades is not an easy task but a costly one. These are uniquely expensive components that drive up the capital cost of these installations. The costs of one of these large wind turbines, like the Haliade-X, currently stands at about 3 million euros (Ridden, 2021). However, not only is the costs, which can be reduced with improved manufacturing capabilities, but especially the size of the construction can be a limiting factor that could make the global distribution of the technology complex. Currently, no technology allows rotor blades to be divided into smaller modular sections and assembled on site. The rotor blades must be transported in one piece and lifted into place in special cranes (Sayigh & Milborrow, 2020). In the case of the Haliade-X, the 107-meter rotor blades had to be lifted 150 meters into the air using two gigantic cranes. Therefore, offshore wind parks have large wind turbines and capacity potential. Building a wind turbine factory right next to a port has the advantage that the blades can be loaded directly onto ships and transported directly to the wind farm site. Trying to transport rotor blades of this size on winding roads and rails full of obstacles will be incredibly challenging and expensive, not to say impossible.

Usually, the turbine and the tower make up the largest share of the cost of wind's LCOE (IPCC, 2021). However, with installations of this size, the transportation and installation costs take up almost two-thirds of the total cost, which further reduces the cost advantage of large turbines.

Another challenge with the increasing size of the installations is the structure's design (Saeed, et al., 2020). The longer the rotor blades become, the greater the forces acting on the structure. The longer the blades, the faster the blade's tip will travel. Being 0 at the rotational center and increasing with the distance from the center of rotation, longer blades will have higher tip velocities than shorter blades, even if they have the same rotational speed. This results in a further problem since the faster the tips rotate, the more noise is emitted (Manyonge, et al., 2012).

Therefore, large turbines are designed to rotate slower but with higher torque. This requires a larger and heavier drive shaft capable of transmitting the torque to an advanced gearbox capable of converting high-torque, low-speed rotation into the lower-torque higher-speed rotation required for the generator (Brauner, 2016). The increased complexity required to handle this higher torque results in heavier and more expensive drivetrains, which in turn reduces the cost advantage of higher power generation (Sayigh & Milborrow, 2020).

Another design challenge involves the lateral forces that the wind exerts on the turbine. The tower and foundation must be strong enough to withstand the forces of the wind, which constantly tries to topple the structure. This force increases with the increasing swept areas of the rotor blades, which at the same time must be stiff enough to withstand the bending forces (Manyonge, et al., 2012). The longer the blades are, the stiffer they must be to avoid possible bending and consequent collision with the tower. While there are design concepts for high winds or hurricanes where the rotors can be collapsed to evade the wind forces, this introduces more complexity to the system and potential points of failure (Chou, et al., 2019).

We may be approaching the limits of what we can achieve with fiberglass-reinforced plastics for blades like the Haliade-X. Heavier blades increase the centrifugal force that tries to break apart the entire structure. Slower rotational speeds help mitigate this, but it is still necessary to minimize the weight of the blades to reduce the force that tries to tear the panels off the hub. If wind turbine blades continue to grow, manufacturers may consider switching to carbon-fiber-reinforced plastics (McKenna, et al., 2016). This material is too expensive for the time being since our goal is, after all, to keep the costs of renewable electricity low.

In order to produce large turbines on a mass scale, the costs and weight of the rotors and drive trains must be lowered, the aerodynamics optimized to reduce noise, and solutions found to ensure more accessible transportation and installation.

One possibility to reduce the installation costs of offshore wind energy could be floating foundations. This could open the wind potential in deeper waters, solving economic and environmental problems. The environmental benefit comes from a reduced impact on the seabed, but the general environmental impacts are still unknown (IPCC, 2021) (IRENA, 2022).

However, due to the increased winds in deeper waters, the problem with the robustness and weight of the rotor blades remains and hinders growth.

Regarding the economic challenge to wind energy deployment, the "*high initial cost of capital, long payback periods, and inadequate access to capital*" (IPCC, 2021, 31) can be identified. To ensure optimal expansion of wind energy, policymakers should be required to provide higher levels of subsidies, encourage research and development to support and expand local supply chains, and maximize grid expansion (Diógenes, et al., 2020).

Other key factors for further advancement of wind energy include technological advances and economies of scale. Future global capacities, especially for large turbines, are restricted mainly "*by onshore land availability in wind power-rich areas, lack of supporting infrastructure, grid integration, and access to finance (especially in developing countries)* (IPCC, 2021, 28)."

3.2. Solar PV

Solar PV has taken on an indisputably important role in the energy transition in recent years. From 2010 to 2021, cumulative installed solar PV capacities worldwide increased nearly 20-fold (Statista, 2022) and stood as of 2021 at a total capacity of 707.5 GW (BP, 2021). In terms of total global electricity generation, 2.5% of electricity was generated by solar PV in 2021. Rapidly falling costs for the technology primarily drive the rapid spread of solar PV cells. The costs of solar energy fell by 85% from 2010-2020 (IPCC, 2021), and the latest World Energy Outlook refers to solar PV as "*the cheapest available source of new electricity generation* (IEA, 2021, 15)". Even though costs are projected to decrease further, the global installation of capacity shows striking disparities. The combined global PV share of Europe (24%), North America (12%), and China alone (36%) accounts for 72% of the world's capacities, with Africa, Latin America, and the Middle East jointly accounting for only 3%. This calls for more technological cooperation and funding for poorer countries on the one hand and shows the potential of energy production in many countries on the other (BP, 2021).

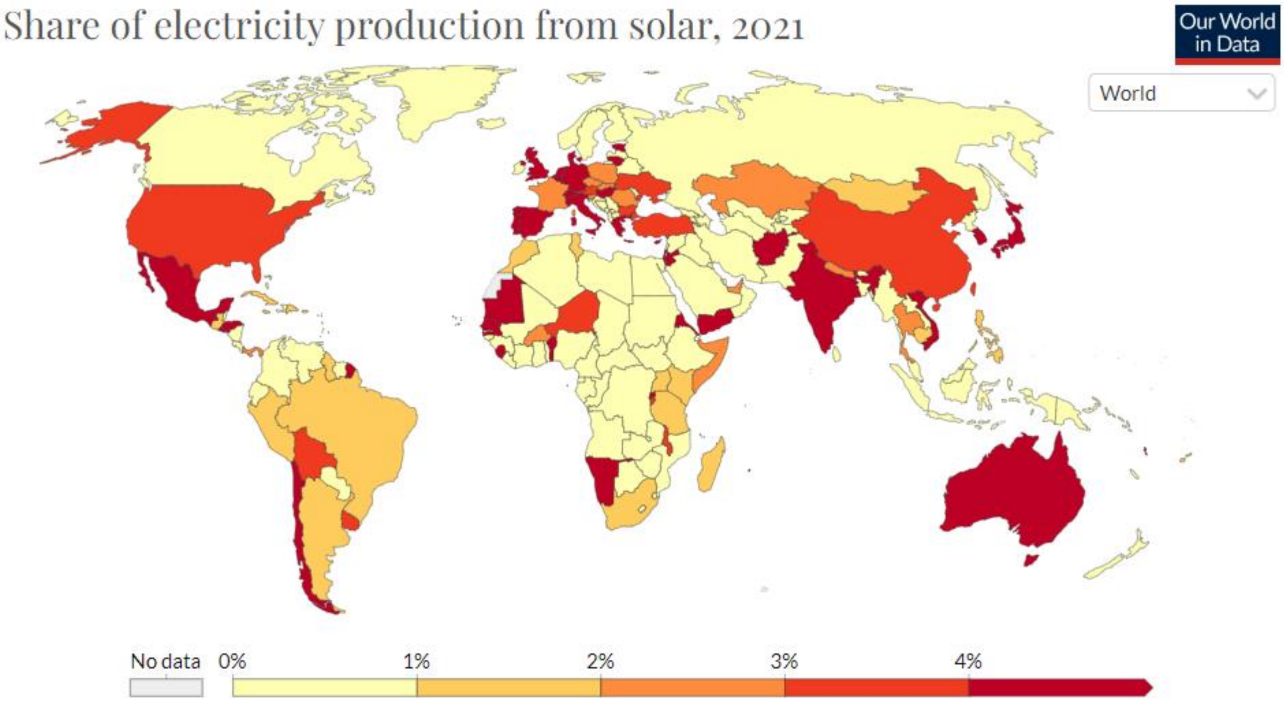

Figure 8: Share of electricity production from solar, 2021 [Source:(OurWorldInData,2022)]

Other reasons why in many parts of the world, the cost of electricity from PV is now cheaper than that of fossil fuels (IRENA, 2019b) are easier access to essential resources like silicon, automation, and, so far, steadily improving efficiency (IPCC, 2021). Solar panels on the market at present have efficiency ratings up to 25%, while most panels have an efficiency of 18-20% (Brauner, 2016).

In leading PV countries, costs are shifting more and more towards "soft costs," i.e., those costs that can be attributed to advertising, distribution, permits, etc., and not directly to the modules. Only 30% of rooftop solar costs in developed countries are directly related to the modules, with especially favorable prices in "PV-rich" countries like China, India, and Germany (IPCC, 2021). For developing countries, financing still poses a substantial barrier. Allowing access to low-cost financing would significantly impact the expansion of PV capacities and energy sustainability for developing countries (Ondraczek , et al., 2015) (Creutzig, et al., 2017). Access to financing and increased incentives will become an integral part of getting solar PV on the roofs of this world. Feed-in tariffs, tax credits, and other financial incentives have already led to more residential solar PV installed in many countries (Creutzig, et al., 2017). Such access to installation resources for the average citizen can create *peer pressure* among the population and contribute to faster expansion. One study showed that a rooftop solar system installed at the beginning of the adoption cycle, on average, leads to a copycat system in the same area within four months. Within two years of the initial installation, rooftop solar projects multiplied to 32 without facing environmental concerns as frequently associated with wind projects (IPCC, 2021). A sharp expansion of PV capacities is considered essential by the IEA to keep warming below 1.5°C, and the resources required to reach this goal are neither considered critical nor potentially scarce (IEA, 2021). 95% of PV production in 2020 was concentrated on silicon-wafer-based solar PV with an average output of 0.17 kWh to 0.35 kWh panel and an efficiency of around 20% (ISE, 2022).

This PV modules consist of 70% glass and almost 20% aluminum, readily recyclable. After an average service life of 30 years, almost 83% of the PV module can be recycled, with silver and silicon being the most valuable PV material components (Heath, et al., 2020). One scenario predicts that by 2050 as much as 10% of global electronic waste could come from discarded PV modules, but even today, the scale and percentage of recycling are still too low (IPCC, 2021).

Life cycle analysis (LCA) shows that CO_2 emissions per unit of electricity are lower for photovoltaic systems than for fossil fuels. However, environmental concerns lay mainly with large-scale projects (Mahmud, et al., 2018). While impacts such as the panels' effect on the planet's albedo are claimed to be trivial, local and regional effects on the climate can be more significant. Measurements from rural Arizona, USA, show that nighttime temperatures near PV facilities can be up to 4°C warmer than in natural surroundings. On the other hand, rooftop power generation facilities in urban areas have resulted in a cooling effect (IPCC, 2021).

Another critical issue with large-PV installations is the amount of open space needed compared to their electrical output. Adding 1 MW of capacity with 20% efficient PV modules, about 2 hectares of land are needed that could otherwise be used differently. This also impacts biodiversity as ground vegetation is cleared and soils are generally graded. The structures and any additional buildings also create barriers to the migration of various species and affect the local microclimate (Hernandez, et al., 2015).

Due to the land problem and rising surface temperatures, solar energy could be conceptualized as "agrivoltaics" (land use for agriculture and solar production). Using shade-tolerant crops and their radiative cooling effect could help to reduce drought stress and compensate for the temperature-related decline in PV efficiency (IPCC, 2021).

Other obstacles that reduce the electricity generation potential of PV systems include the elevated surface temperature, wildfires, sandstorms, and increased cloud formation due to evaporation (Bartok, et al., 2017).
Nevertheless, the efficiency and potential of the modules are expected to improve so that the critical challenges for global PV are not directly related to the modules but to grid integration, non-module costs, and energy storage possibilities.

3.2.1. Concentrated Solar Power, PV, and intercontinental grids

As a global problem, climate change affects every living being on earth. The political and economic initiatives to prevent further warming fall far short and will have to be improved or relaunched in the immediate future to achieve our set climate goals. Strong international cooperation will be crucial to provide a stable grid amid volatile energy sources to enable an energy transition with renewable energy. Intercontinental energy supply lines are also being considered or are in the process of implementation (IPCC, 2021).
Approximately 120,000 TW of sunlight, 10,000 times the world's energy consumption, continuously reaches the earth's surface. Northern Africa, the Middle East, and Australia are among the areas with the highest solar irradiance. The annual potential of solar PV cells is equivalent to about 300 PWh -yr-1, which is about twice the current consumption (Dupont, et al., 2020). The Sahara desert is thereby one of the most considerable unexploited energy resources in the world. The solar energy that hits the surface of this desert has the potential to supply the whole world with electricity, whereby a single solar panel in, e.g., Algeria can generate three times more electricity than the same panel in Germany (GSA, 2022). What was once a geographic disadvantage, namely the scorching sun in these desolate areas, could now mean an economic boost for these historically impoverished nations.
On average, a panel in a solar farm located in the Saharan desert, measuring one square meter, would generate five to seven kilowatt-hours of energy per day. If this figure was increased to one kilometer, five to seven-gigawatt hours of energy could be generated each day. If increased to thousand square kilometers, enough energy would be generated to supply nearly 100% of Europe's electricity demand (Dupont, et al., 2020) (eurostat, 2021). This impressive and frequently repeated statistic sketches a drastic new vision of a solar-powered utopian world. Plans have even been drawn to turn these simple mathematics into reality, but turning this dream into reality has so far failed.

Transporting electricity from these remote regions is the primary challenge. Currently, there are only two connections between North Africa and Europe, both located between Morocco and Spain. Two 700 MW links, one of which was completed in 1998 and the second in 2006, with a third link expected to be completed sometime before 2030, for a total of 21 megawatts (Escribano, 2019). To supply Europe with enough electricity from the desert, ignoring transport losses and storage problems, we need over 600 more of these 700 MW connections. These are not just simple cables laid between countries, but very sophisticated pieces of infrastructure, which correspondingly come at a price. The estimated cost of the latest cable between the two continents is 150 million dollars. Considering the 600 cables required, the cost amounts to a minimum of 9 billion dollars. It must be kept in mind that this reflects the costs for the shortest and thus cheapest connections. The costs to connect Tunisia and Algeria with Italy, Libya with Greece, and Turkey with the Middle East will be significantly higher (von Hirschhausen, et al., 2010). In addition, there is a need for internal interconnections to be built on the different continents to facilitate the transmission of solar power to the north while wind power is traded to the south.

Although this plan would require a vast amount of financial and natural resources, European politicians have already drawn up plans for connecting North Africa and the Middle East to Europe. They believe that the costs can be recovered in an intercontinental super grid. Desert Tech is, or instead was, a German-led initiative centered on a half-trillion-dollar investment fund that would invest in power generation and transmission

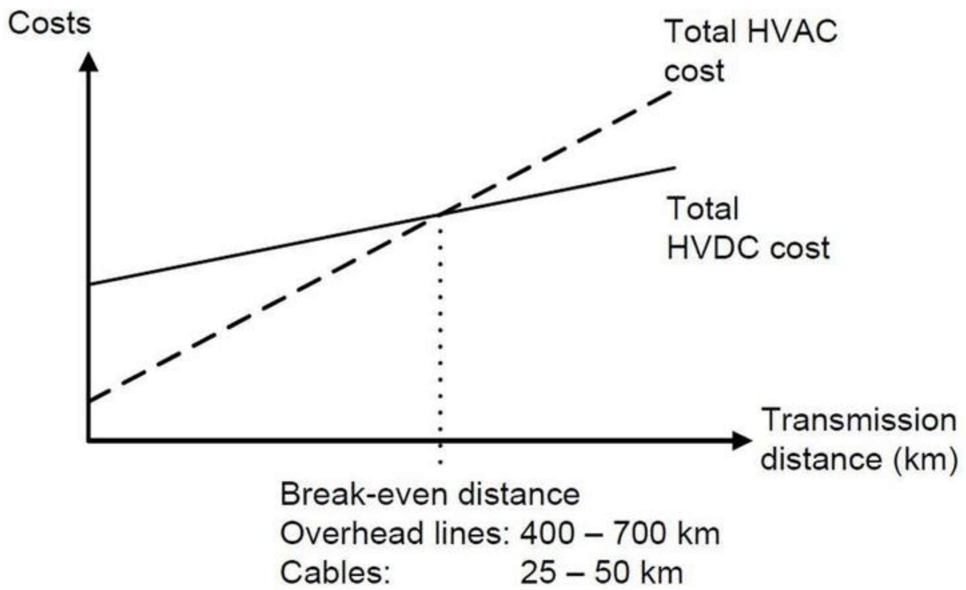

Figure 9: Cost against transmission distance for HVDC and HVAC systems [Source:(Kalair,A., 2015)]

infrastructure in North Africa and the Middle East (Desertec, 2022). Fifty-five billion was set aside to expand transmission capacity in the Mediterranean region, with this investment going toward both high-voltage AC transmission over shorter distances and high-voltage DC transmission over longer distances (EIA, 2018).

As figure 9 shows, there is a critical distance at which the transmission of high-voltage alternating current does not make sense.

DC loses less energy per kilometer than AC, but expensive transformers and converters are needed to convert a regional AC grid to DC. Instead, as in Figure 9, we can compare the distance to the investment cost, seeing that the breakeven point for both DC and AC lines is around the 600 km mark. At this point, DC becomes more cost-effective, making transmission lines, such as those from Morocco to Spain, with a span of only twenty-eight kilometers, unsuitable for high-voltage DC. In contrast, longer lines connecting Tunisia to Italy are likely to be high-voltage DC lines. Transmission losses for direct high-voltage current are about 3% per thousand kilometers, and many major cities would be within this range (EIA, 2018).

The transmission of electricity with so much investment money is feasible, and the technologies exist, but the problems of the Desertec project are in the generation of electricity.

Desert Tech was formulated around the idea of concentrated solar power (CSP), which works very differently than photovoltaic solar panels. Concentrated solar power plants would be distributed along the Sahara and Arabian deserts borders, whereby one such plant already exists in Morocco. It is the largest CSP plant globally, consisting of three separate sections, Noor 1, 2, and 3, whereby slightly different variants of concentrated solar power are used in each (Laaroussi, et al., 2021).

Noor 1 and 2, which have a combined capacity of 510 megawatts, are both trough systems that use parabolic mirrors with a tube at the mirror's focal point. The tube contains synthetic oil that collects heat from the 500 000 parabolic mirrors over 300 000 square meters. The oil becomes extremely hot, up to 400°C, allowing it to boil water and power a steam turbine that provides electricity for the grid. The 400°C oil is also hot enough to melt salt in a molten salt heat storage system. Noor 1's molten salt heat storage system can store enough heat to keep the plant running for three hours, while Noor 2 has a storage capacity of seven hours (Desertec, 2022).

However since this salt solidifies at 110°C and this would cause the power plant to shut down, Noor 1 and 2 need a fossil fuel backup to maintain the required minimum operating temperature (Laaroussi, et al., 2021).

In contrast, Noor 3 does not use parabolic mirrors but a tower system where mirrors are arranged in concentric circles around a central tower. Because of this design, Noor 3 does not require the oil, plumbing, and pumps of Noor 1 and 2, as the mirrors are controlled to focus the light on a single point on the tower. This directly heats the molten salt, which is the working fluid, rather than the oil-based system, allowing the solar concentration to reach much higher temperatures (Laaroussi, et al., 2021).

Noor 3 is the world's only operating tower-based concentrated molten salt solar energy system, following the shutdown of the Crescent Dunes facility in Nevada in 2019. The Crescent Dunes plant was shut down in 2019 after only four years of operation after it failed to meet performance requirements and experienced maintenance issues and leaks in the molten salt storage system (Boretti & Castelleto, 2021).

Even when fully operational, the plant's electricity costs $135 per megawatt-hour, compared to $30 per megawatt-hour for a nearby photovoltaic plant (Gauché, et al., 2017).

This is precisely the sticking point for concentrated solar power. The cost of CSP per megawatt was highly competitive with photovoltaics in 2009, but in the last decade, PV has become obscenely cheap (IPCC, 2021). Concentrated solar power cannot compete in a market like this, which is true for Noor 1, 2, and 3. With the rise of cheap solar panels, Desertec concentrated solar projects could no longer compete in the market, and future projects like those of Noor 1, 2, and 3 are likely doomed to fail.

Apart from the economic obstacles, the amount of water needed is also an argument against such projects in arid regions. The water needed to cool the plant and clean the mirrors alone is almost 3 billion liters per year for the Desertec project in Morocco. The water is taken from a nearby dam, and this, even though Morocco is already prone to droughts, further deprives the local area of little available water (Samus, et al., 2013).

If we want to scale this form of power generation, some technological improvements would be needed to reduce water consumption. The plants could be linked to desalination plants and use the extra water produced.

Nevertheless, not only the costs decline of PV systems is competing with concentrated solar farms, but also the fact that CSP requires mirrors which need a lot of space to maintain the minimum operating temperature. Solar panels do not face this problem and can be installed on roofs, facades, or nearby farmland. No vast plots of land are required to operate them, and because they are so cheap, it is feasible to build smaller PV solar farms even in countries without large areas, thereby avoiding transmission losses (Creutzig, et al., 2017).

In addition, it avoids the massive financial risk of investing billions in a foreign country, especially since many of them are often politically and socially volatile.

The idea of specifically European countries pulling natural resources out of Africa to support their own economies undeniably has some disturbing historical parallels. Some supply guarantees for Europe will accompany any foreign investment like this. Such cross-border collaborations are inherently difficult to implement, precisely when the country where these plants are located needs the power for its own economy or simply wants to stabilize its grid for current needs.

The idea of transforming barren deserts into energy production centers must come as a grassroots movement rather than new-age imperialist megaprojects that come with a series of guarantees for the investment of nearly half a trillion dollars. North Africa is one of the regions of the world most affected by climate change, with desertification and water scarcity becoming a severe problem (IPCC, 2021). Despite its seemingly good intentions, the Desertec plan would exploit these countries to meet European needs, and we do not have to look far to prove that this was their intention. The plan was abandoned when the technology was developed to the point where European countries could meet their own renewable energy needs within their own borders.

Nevertheless, these countries in North Africa have the natural resources to benefit from solar energy, and Morocco is in the best position to lead by example. Its proximity to Spain allows relatively short interconnections to the European grid (Escribano, 2019). Its government is relatively stable compared to its North African neighbors such as Algeria, Tunisia, Libya, and Egypt. While Morocco has abundant solar resources, it also benefits from consistent desert winds along its coast. Morocco has the potential to invest in its own energy needs while exporting access to Europe by setting a good example and slowly transitioning from a net fossil fuel importer to an energy exporter. The technologies to facilitate cross-border energy trade already exist, and investments, such as the third interconnector, are being made to increase the capacity to trade between Morocco and Spain, funded by both sides equally (Escribano, 2019).

The lowest prices for CSP are now competitive with the more expensive fossil fuels, although average CSP costs are higher than fossil fuels (IPCC, 2021). Other data sources put current CSP costs at $120 MWh-1, which is in the middle of the fossil range (Tröndle, et al., 2020). If the pace of change since AR5 continues, CSP will become competitive with fossil fuels in sunny locations, although it will be difficult for CSP to compete with PV and even hybrid PV-battery systems. Even though CSP electricity may be more valuable because CSP systems can store heat longer than PV battery systems, PV is likely to dominate the solar market in the future. Higher efficiency, further decreasing costs, and better storage possibilities must be provided to lead to the rapid expansion of capacities in the way the planet needs it (IPCC, 2021).

4. 100% Renewable Energy Systems

The literature identifies two frameworks when discussing 100% renewable energy systems, namely 100% renewable electricity supply and 100% renewable supply for the entire energy sector, including heavy industry, transportation, and heating (IPCC, 2021). The discussion of whether 100% renewables are feasible and or even desirable under either framework takes a prominent role and is often associated with regional projects. To date, the technical implementation of very high shares of renewables, especially wind and solar, can be projected with high confidence to be technically feasible. While wind and solar are highly likely to play an integral role in the energy generation of the future, this does not imply that 100% demand will be satisfied by these technologies, as economic and operational challenges increase nonlinearly with increasing shares of VRE (Rogelj, et al., 2018). While there is no theoretical technical upper limit on renewable capacity additions, high penetration of solar and wind, and their temporally, spatially, and non-synchronously variable power generation characteristics, however, pose not only technical but also economic challenges. The economic value of additional VRE decreases with increased penetration making 100% RE less attractive and a possible deployment less likely (Tröndle, et al., 2020).

The regional annual generation above 75% is already achievable in many places, whereby factors have to be taken into account, such as geographic location, political stability, social acceptance, and, of course, the level of development of the region/country (IPCC, 2021).

While these challenges can be mitigated by new integration policy options and market designs, other factors must be considered and supplemented to enable a 100% renewable energy future. The challenges are more far-reaching concerning energy systems that seek to power not only 100% electricity but the entire energy sector with 100% renewable energy. Once the technological, regulatory, and market challenges have been solved and the entire electricity grid is powered by carbon-free/low-carbon energy, more zero-carbon energy carriers will be required for end-use applications such as aviation, heavy transport, and heavy industry.

Whether it is 100% in the electricity or the entire energy sector, far-reaching and intensifying electrification of the existing system is needed, and further R&D is required. An increase of the final energy share from electricity by renewable energy sources to at least 30% and up to 80% by 2050 is indicated by the IAE and IPCC, with the light transport sector, passenger transportation (rail, buses), heating and cooling of buildings offering great potential (IEA, 2021) (IPCC, 2021). As an example, the electrification of buildings will primarily rely on heat pumps, thereby reducing emissions through improved efficiency and reduced thermal requirements. Moreover, the electrification of light-duty vehicles (LDV) and buses will likely experience a substantial increase in the upcoming years (Brauner, 2016) (Cole, et al., 2021).

Electrification and decarbonization will take place in different ways depending on local, regional, national, and international circumstances. Regions with strong wind or solar potential will increasingly rely on these technologies. In contrast, countries with high shares of domestic fossil fuels or other liquid fuels will electrify more slowly, especially in challenging sectors, like steel and cement production (IPCC, 2021). Concerning the latter, electrified cement kilns already exist as a lower-emission alternative to current

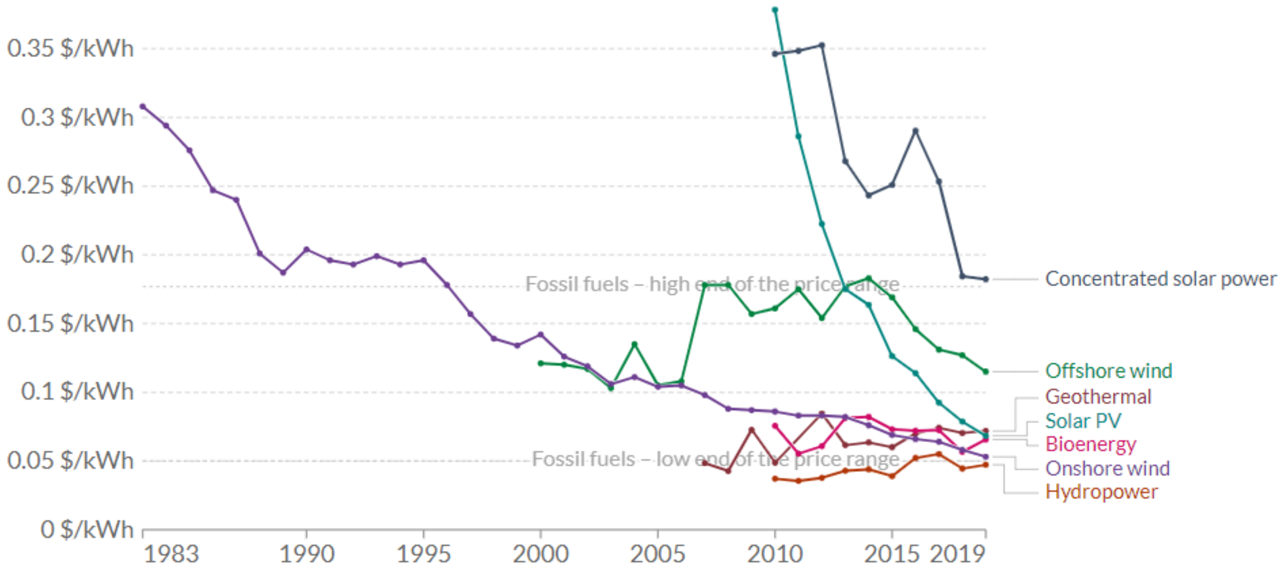

Figure 10: Global Levelized cost of energy by technology [Source: (OurWorldInData,2022)]

production methods. However, the cost is still significantly higher, and the question arises as to whether the electricity is generated sustainably.

For sectors that are difficult to electrify, alternative carbon-free fuels will be needed to replace fossil fuels. Methane, petroleum, and various alcohols but primarily hydrogen, can be used in sectors that are not amenable to electricity without using fossil fuels for their production. While biofuels are predicted to have great potential in the future their expansion is controversial given their life-cycle carbon emissions, ecological footprint and land use (food vs. fuels), and most importantly, their cost (Cole, et al., 2021).

On the other hand, hydrogen faces fewer of these challenges, which are described in more detail in the next chapter. However, this type of fuel requires infrastructure changes, cost reductions, and improvements in production efficiencies (Brauner, 2022).

The term efficiency has a fundamental role in future low-carbon energy systems, despite the lack of a precise definition of energy efficiency to date, which presents challenges in measuring efficiency. On a consumer base, strategies based on energy efficiency allow the same output level to be achieved while consuming less energy. At the macroeconomic level, primary energy per capita or GDP indicators can be applied and serve as a proxy for energy efficiency (IPCC, 2021).

Energy-efficient measures have already led to a significant reduction in energy demand, and the median total energy demand in the OECD+EU countries has decreased over the past decade. Significant efficiency improvements have been achieved in the industry, yet these systems are gradually approaching their thermodynamic limits (Brauner, 2022).

Nevertheless, global energy consumption is expected to increase in all scenarios in IPCC’s AR6 report due to population growth and development, and further efficiency improvement will be required to tackle new circumstances (IPCC, 2021).

The increasing demand for electricity and VRE integration will pose challenges for the existing power grid, which will have to be met by high investment costs and a smart planning design. In terms of infrastructure, the main focus will be on creating storage capacities, automation, smart control mechanisms, and the renewal of cables and high-voltage pylons. Electricity utilities and operators must implement a coordinated network that responds flexibly, quickly, and reliably to fluctuating generation. A combination of fuels across the spectrum will be required, especially for those difficult or infeasible systems to electrify (Brauner, 2022) (Brauner, 2016).

The list of necessities for a future close to 100% renewable energy supply is long but already largely feasible, especially from a technological point of view. The challenges facing the integration, implementation, and scaling for a green future are outlined and discussed in the following chapter.

5. Challenges

Due to the complexity of a rapid and successful energy transition, numerous obstacles must be overcome to reduce CO_2 emissions and mitigate climate warming.

Science has put forward many proposals on how to reduce GHG emissions to reach the 1.5° or 2° target. The concept of "negative emissions" is increasingly receiving attention and carbon capture and storage (CCS) technologies on the rise. CO_2 is taken out of the atmosphere through natural sinks or removal technologies and stored in underground storage facilities or other storage alternatives. As the IPCC AR5 report states, measures to remove CO_2 from the atmosphere can in no way replace decarbonization, but effective removal of CO_2 from the atmosphere is essential to achieve our climate goals and will need to be used complementary to sustainable energy generation technologies. CCS technologies already exist and are successfully deployed, but this technology remains to be market competitive.

Wind and solar energy are widely seen as the flagship technologies in the fight against climate change, but their technological progress is also limited. Both technologies are mature and often constrained by space, size, and social challenges. Many countries are already generating their electricity from these renewables, although operational, technological, economic, regulatory, and social challenges remain (IPCC, 2021).

Solar and wind capacities have increased significantly in recent years, but their share still remains very small compared to other energy sources. This share is even smaller when looking at both technologies, not only in the electricity sector but also in the primary energy sector.

The electrification with renewable energies of the energy sector is essential, not only because the sector is the biggest emitter of CO_2 but also because a reduction is crucial to reach the climate target of less than 1,5°C or 2°C warmings. Except for the pandemic year 2020, global greenhouse gas emissions have risen steadily over the last decade, and emissions have not peaked yet, especially in the energy sector.

To increase the share of renewable energy, especially VRE, in the global energy system, it is necessary to increase their capacities and provide reliable and cost-efficient storage possibilities. A fundamental issue facing energy storage technologies, is the public interest, knowledge, and the areas of application of these technologies. Many people assume that large-scale electricity storage is already taking place or do not consider the issue of power system flexibility to be significant (Jones, et al., 2018). Besides storage technologies, which will mainly be based on batteries and hydrogen, the grid infrastructure and socio-political factors are crucial and will be discussed in the following.

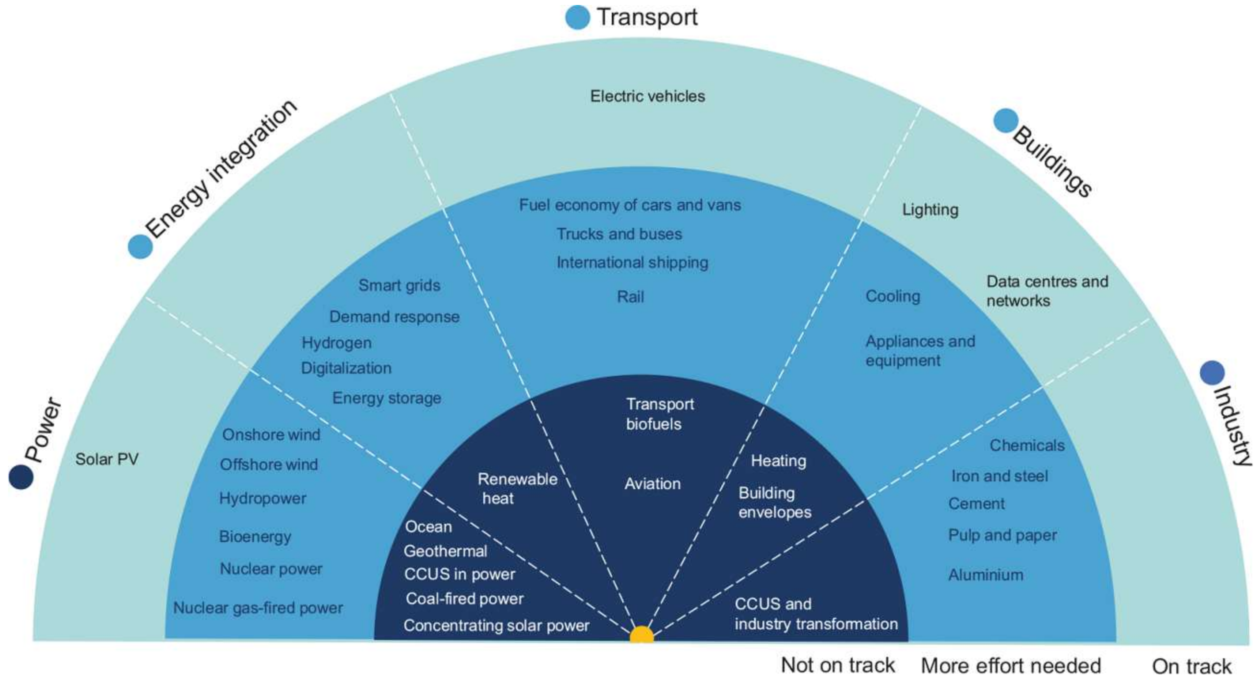

Figure 11: IEA radar of energy technology areas [Source:(IEA, Energy Technology Perspectives, 2018)]

5.1. Batteries in Energy Storage

In 2019, 90% of energy was stored in pumped hydro storage plants. However, batteries and hydrogen have become increasingly important in recent years and have accounted for 90% of new storage capacity since 2015 (IPCC, 2021). Besides the high installation costs, the problem with pumped hydro plants is that they require a significant amount of space. Their construction has a significant impact on the ecology of the environment. Water scarcity is also becoming an increasing problem in many regions (Botelhoa, et al., 2017). In recent decades, investments and advances have been made in the research and development of various batteries, especially lithium-ion batteries (LIB), which have successfully penetrated the market. The costs of these batteries has decreased by 97% in the last three decades and by 90% in the last decade alone, which has favored their commercialization and use in the energy and transport sectors (Staffel & Rustomji, 2016). The energy storage capabilities offered by lithium-ion technology are playing an increasingly important role in the electricity sector with a high percentage of variable renewable energy, providing flexibility to the grid and opening possibilities for decentralized market options. Given the variable nature of renewable power generation, especially from wind and solar, the fast response time of batteries can be used to support voltage and frequency regulation in the power grid. LIB allows low weight and volume storage options and can provide the most power services, with seasonal storage exception (Staffel & Rustomji, 2016) (IPCC, 2021).

Disadvantages often associated with lithium-ion batteries are the relatively short life span, the decrease in storage capacity even when the battery is not in use, the susceptibility of the battery to extreme temperatures, the associated risk of ignition, and the hazardous materials themselves, and the issue of sustainable resource extraction (Staffel & Rustomji, 2016). Lithium is primarily extracted in Australia and Chile, raising the question of long-term resource availability and an undesirable dependence of the state community on these two countries.

Nevertheless, LIB will, with high probability, continue to dominate the market in the medium term due to its properties and cost competitiveness (Brauner, 2022). However, research into future batteries is necessary and already in progress.

All-solid-state batteries are a promising future candidate, as they would bypass the fluid and highly reactive components of LIBs and offer improved safety features.

Apart from improved safety, all-solid-state batteries are also expected to offer longer life spans and improved energy density. A shift away from lithium batteries is also being pursued, with sodium and sulfur-based batteries seen as a possible future option (IPCC, 2021) (Ahmadi, et al., 2017).

A common obstacle all batteries are still facing nowadays is the topic of safe disposal. The disposal of old batteries and their hazardous materials is one of the biggest challenges, and recycling is still a cost-intensive choice. Lithium-ion batteries contain many different materials in minimal quantities, making many steps necessary for recycling. In addition, there are no international standards for LIBs, and recycling companies have to deal with many different manufacturers, which further hinders the process. Thereby, in many cases, the recovery of metals is feasible but economically nor ecologically viable (Ahmadi, et al., 2017).

When the traction batteries in electric vehicles have reached 70 to 80% efficiency, they are usually discarded but can still be used for other purposes. There are theoretical approaches to reusing old EV batteries, such as additional storage for variable renewable energy, but infrastructural and grid-related obstacles remain to be solved (IPCC, 2021).

The technological advances and affordability of Li-ion batteries will make them a key element in the future energy system, though several other energy storage options are also being considered. Liquid air energy storage (LAES), compressed air energy storage (CAES), thermal energy storage (TES), supercapacitors, or double-layer capacitors (SCAP) are being considered and researched. However, hydrogen and reversible hydrogen fuel cells (RHFC) are currently the most promising and discussed energy carriers (IPCC, 2021).

5.2. Hydrogen

Hydrogen can be produced by the electrolysis of water, i.e., its electrochemical splitting into hydrogen (H_2) and oxygen (O_2), and stored in aboveground pressurized or liquefied gas storage facilities, in metal hydride storage facilities, or suitable underground caverns. Alternatively, to a certain extent, also injected into and transported through the natural gas grid (Brauner, 2022).

Public perception of hydrogen is generally positive, and it is seen as a modern, clean, and green energy storage option. Nonetheless, there are legitimate concerns about hydrogen's safety, storage capabilities, and energy efficiency (Eitan & Fischhendler, 2021).

As an energy vector-like electricity, hydrogen has a variety of potential applications. It can be used for long-term energy storage and, in particular, as an energy carrier in the industry. hydrogen could be used to produce steel and other non-metallic materials and as a fuel for land, water, and air vehicles. If hydrogen were to replace coal in blast furnaces, around 95% of CO_2 emissions could be saved, according to the German Energy Agency (DENA, 2017).

Due to its versatility and carbon-free end-product, hydrogen is likely to play an integral role in the future. Large-scale application, which is currently not competitive, is expected to be possible in the future, and with the anticipated economy of scale, costs in this sector will also drop. However, hydrogen faces several obstacles, mainly in the area of production and infrastructure. In order to use existing gas infrastructures, new equipment and technologies will be needed, which are currently very capital intensive, such as new compressor stations. So far, liquefied hydrogen cannot be used for stable combustion in gas turbines because of its lower flammability. However, there have been advances where the hydrogen content in gas turbines could be increased, and further advances could lead to turbines running on 100% hydrogen by 2030 (IPCC, 2021).

To ensure hydrogen purity, existing pipeline projects will have to be reconsidered and future ones redesigned to avoid, for example, the escape of the highly explosive mixture in combination with oxygen. The large surface area required for hydrogen pipelines is also a problem that should not be underestimated, especially in terms of social acceptance. The delivery infrastructure is also an expensive and cost-intensive challenge. Hydrogen has so far primarily been transported in liquid form, and the condensation and pressurization of the gas are highly cost and energy-intensive since temperatures of -253ºc are required. The liquefied gas must be re-gasified for further use, which causes additional costs and infrastructure requirements. At the same volumes, compressed hydrogen provides only one-third of the energy that could otherwise be obtained from natural gas, increasing the need for storage capacities and a challenge to the security of supply (Brauner, 2022) (Cole, et al., 2021).

When it comes to offshore wind farms, deploying infrastructure and transport capabilities is often complicated and, above all, cost-intensive. Therefore, hydrogen could also be produced and stored directly at the plants and transported onshore by ships instead of pipelines (IPCC, 2021).

One possible application of hydrogen may be in the form of ammonia or other liquid organic hydrogen carriers (LOHCs). These have petroleum-like properties and could be integrated into the existing oil infrastructure. The higher energy density and lower temperatures of -33°C needed make ammonia also advantageous in terms of transportation. A disadvantage of LOHCs is the high emission of nitrogen oxides produced during high-temperature combustion which poses a threat to human health, air quality, and the climate (IPCC, 2021).

5.3. Grid infrastructure

The power grid's infrastructural development, improvement, and international coordination will provide the necessary backbone to implement a future low-carbon energy system. Electricity systems and their management will face economic and technical challenges with the integration of large amounts of renewable energy, and smart digitization of the grid will be necessary to ensure real-time balancing of supply and demand (Brauner, 2016).

Unlike energy sources such as solar and wind, traditional large-scale power plants do not simply generate electricity but also provide a range of so-called system services. These are measures that ensure the power grid's high stability and fault resistance. As

decentralized generation plants displace the large power plants, the system service obligations are transferred to the decentralized energy producers (Cole, et al., 2021).
The example of so-called short-circuit power can be used to illustrate one aspect of the changed requirements: If a short circuit occurs in a power grid dominated by large producers, it can be solar and wind (Brauner, 2021). While addressing critical performance challenges, including the shortage of system inertia, voltage, frequency, and black-start control, these converters will significantly reduce or eliminate the necessity to use conventional electricity generation (IPCC, 2021).
However, regardless of future outcomes, the grid network and producers depend on improving storage capabilities, without which long-term use of renewables in the grid becomes infeasible. Storage technologies such as batteries or hydrogen can act as both demand and generation sources, helping to balance the system, like transmission or distribution assets, or as network management tools.
Apart from infrastructure improvements and coordination at the national level, international cooperation will also be necessary to improve the balancing of VRE's fluctuating power generation. Several studies (Bloom, et al., 2020) (Halawa, et al., 2018) (Newbery, et al., 2013) indicate that the interconnection of countries and regions leads to improved cost benefits for all parties involved. In the short run, however, costs may be higher for certain involved actors, slowing down the overall interconnectivity. In order to better cross-border coordinate transmission and allocate investment costs and revenues proportionally according to the benefits to market participants, a policy framework and appropriate market designs are required to address a wide range of geopolitical and socio-techno-economic challenges. New business models may be needed to expand and improve generation and transport options and encourage a more positive public perception of VRE (Brauner, 2016).

5.4. Socio-politics

"*The feasibility challenges associated with mitigation pathways are predominantly institutional and economic rather than technological and geophysical* (IPCC, 2021, TS-138)*.",* whereby mitigation models and calculations often do not emphasize societal aspects. Increasing the percentage of renewable energies in the energy system or even raising it to 100% will depend on technological factors and rather be a socio-political challenge. The relations and cooperation of stakeholders like politics, institutions, industry, consumers, electricity producers, grid companies, etc., will be crucial to achieving a green future.

Capacity expansion of renewable energy sources is often seen as straightforward. However, the biggest challenge of our energy transition is probably social acceptance and willingness for change. This change will take on various dimensions and will undoubtedly lead to hardened fronts in society and politics, which will inevitably pose an obstacle to global decarbonization. For climate mitigation attempts to be successful, demand-side measures, especially in the field of efficiency, will be essential to reduce energy demand (Brauner, 2022). This can be achieved by reducing overall energy demand for non-essential purposes, smart and more efficient household appliances, and building-based thermal energy storage. The term "energy demand reduction" is thereby attracting much attention, and especially already industrialized countries are addressed. They have been able to rely on fossil fuels as energy sources to create their prosperity, and steady economic growth is still the dogma today. The idea that economic growth and prosperity can also exist separately and that degrowth, post-growth, and post-development could represent a sustainable opportunity for society has to be debated and further researched. Whereby once again, Here again, efficiency measures will be decisive if mitigation pathways succeed, and therefore a change in how we heat and cool our houses, light our homes, cook our food, and how we produce goods and services is imminent (IPCC, 2021). In any case, the debate on sustainable growth/degrowth will eventually intensify, especially in light of the demographic development of the world's population, which foresees an increase to 10 billion people by 2050 (OurWorldInData, 2019). Currently, increasing energy demand is not correlated with the added low-carbon energy sources. Increasing demand could further deepen this gap if actions are not taken rapidly, if not instantaneously.

Although the wealthiest 10% of the world's population is currently responsible for 36-45% of global greenhouse gas emissions, additional energy demand will occur primarily in rapidly developing countries. Population growth and the establishment of new middle classes in high-population countries like Bangladesh, India, China, and Sub-Saharan Africa will further drive demand (IPCC, 2021).

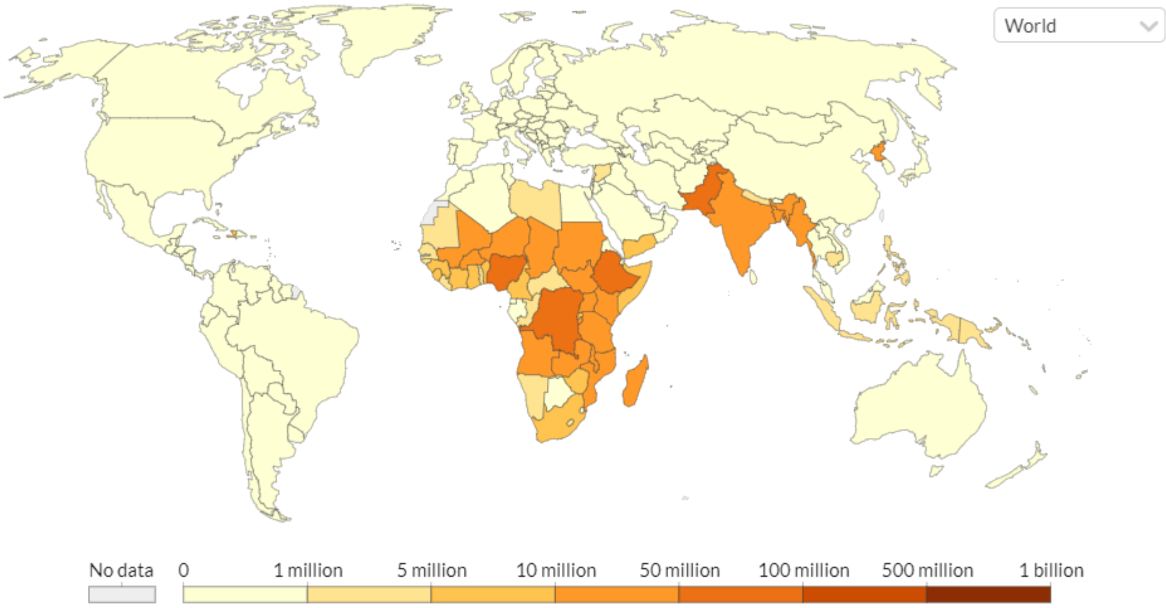

Figure 12: Number of people without access to electricity, 2019 [Source:(OurWorldInData,2019)]

Today, nearly 600 million people in Sub-Saharan Africa alone are without access to electricity, and this number has been stagnating for years as the population has grown. Approximately 1.14 billion inhabitants in the region are predicted to more than double by 2050 and almost triple by the end of the century (Gu, et al., 2021). Before providing access to energy, billions of capital will have to be invested in renewing, structuring, and creating new grid infrastructure. SDG Goal 6, which includes the ability to access energy, is a desirable future scenario. Yet, it should not be forgotten that access to electricity is likely to increase demand for it, as seen in Asia's developing countries. After access to energy was expanded, the energy demand doubled in less than two decades. The energy supply mainly came from fossil fuels, and the expansion of renewable energies failed to keep up with the demand pace (IPCC, 2021).

It will be political and social decision-making in these fast-growing countries will enable climate change mitigation on a global scale. Fast-growing cities in these countries could benefit from sustainable and efficient development, but institutional barriers have remained the limiting factor. Resource scarcity, limited access to modern technology and labor, or social division are equally important factors that prevent sustainable and equitable development in developing countries. However, they may also pose a challenge to developed countries.

Governance and institutional capacity, behavior and lifestyles, finance, international cooperation, and innovation will be crucial factors in mitigating climate change also in developed countries (Allen, et al., 2018). As today's global democracies are under pressure, a possible bloc formation in the face of the Ukraine war is likely, and an expectable global financial crisis does not stand as a good sign for the international community to create an efficient and rapid energy transition. Also, on a national level, one can be intrigued by how an intensifying energy debate will develop and which, even political, role renewable energies will possibly take.

Multilateral cooperation may be jeopardized in some cases by national developments such as growing populism, nationalism, and protectionism (Abrahamsen, et al., 2017), as seen under the Trump administration when the US even resigned from the Paris Agreement. Internal as well as international coordination can lead to a highly polarized discussion that would block further political actions. At the same time, public and private entities across the spectrum might attempt to gain as much benefit from these efforts as possible, perhaps even overthrowing governments.

In order to advance global decarbonization and make mitigation efforts of global warming succeed, a joint global social and political effort will be required, which must be given absolute priority. Although the urgency of our climate situation has been pointed out for years, international leaders have made only half-hearted attempts to deal with the crisis. The most important of the numerous international efforts to address global warming is the Paris Agreement, signed by 195 countries and entered into force in 2016. The agreement aims to create a framework to reduce greenhouse gases for keeping *"the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.* (UNFCCC, 2015).*"*

Although the Paris Agreement is a milestone in the climate change debate, its effectiveness is limited because it cannot impose sanctions on parties that do not comply with their nationally determined contributions (NDC). Furthermore, important terminology such as "global average temperature," "pre-industrial," and the term "1.5 degrees" are not well defined and leave room for interpretation. A flaw in the terminology can be claimed that it is not precisely explained whether 1.5°C refers to total warming or only to human-induced warming (Allen, et al., 2018).

That the political attempt in the form of the Paris Agreement has failed must finally be recognized on the international stage in order to be able to initiate appropriate measures of change and improvement. The latest IPCC report also highlights with high confidence that "*pathways following current NDCs until 2030 […] will make it impossible to limit warming to 1.5°C with no or limited overshoot and strongly increasing the challenge to likely limit warming to 2°C* (IPCC, 2021, TS-43)."

To reach the goals set by the Paris Agreement, especially by 2030, an immediate and drastic change in geophysical, environmental, technological, economic, socio-cultural, and institutional dimensions would be needed but is unlikely to happen (MCC, 2022). If we would immediately set anthropogenic emissions to zero, further warming to the 1°C we have already experienced would *"likely be less than 0.5°C over the next two to three decades, and also likely less than 0.5°C on a century time scale* (Allen, et al., 2018, 66)."

The fact that climate policy goals are still not being implemented conscientiously can be further exemplified by the continuous high subsidies for fossil fuels and the unmet demand for a carbon tax. Energy subsidies are policy measures to lower prices for consumers or producers and are likely to become even more significant in light of the Ukraine War and the upcoming winter. Fossil fuels have received twice the amount of subsidies or more than half of the world's total energy subsidies compared to greatly needed renewable energy subsidies with "*predominantly adverse environmental, economic, and social effects* (IPCC, 2021, 6-21)."

A national or global carbon tax would be the most effective way to collect revenue which could then be reallocated or used impartially, such as for green infrastructure or back to the taxpayers, which would increase public acceptance of such an undertaking (Jones, et al., 2018).

6. Future and Fusion

All the challenges described in the above chapter must be met to achieve the decarbonization of our future society. It is essential to keep in mind that unforeseeable challenges are highly likely to arise, further impeding a shift to a carbon-free society.

Particular attention must be given to the socio-political dimension, arguably the most challenging and will require national and international efforts of unprecedented magnitude.

In this context, the Russian invasion of Ukraine offers the opportunity to initiate a sustainable transformation of existing paradigms, especially in a European context. It offers the possibility to shift away from oil and gas dependency and further promote VRE, but increasing energy prices for fossil fuels can sustainably influence the social dimension. Whether the exporting countries of fossil fuels will commit themselves to a sustainable shift is uncertain, and above all, the pace of the phase-out of fossil fuels will be decisive in mitigating global warming (IPCC, 2021).

The rate at which we are currently reducing CO_2 emissions is far from sufficient, and the goal of reducing global warming to 1.5° is vanishingly tiny. Especially concerning the often-mentioned deadlines 2030 and 2050, various reports, first and foremost the IPCC reports, see almost no possibility of reaching our set goals without immediate, far-reaching changes (IPCC, 2021).

Since we will with high probability not reach 1.5° or 2° mitigation targets, we will have to live with the consequences. Further decarbonization should nevertheless be pursued because warming does not stop at 2°, and the intensity of the consequences will continue to increase.

Technological and socioeconomic progress must occur no matter how we want to continue our mitigation efforts. Technological progress will come in the form of increased efficiency, falling costs, and improved production processes. International economic and political frameworks will need to be established on the socioeconomic side (Allen, et al., 2018).

Wind and solar will lead the energy transition, but we should not solely rely on these technologies but also focus on new energy technologies, some of which are still undeveloped. The most promising and widely researched energy source is fusion energy in this context. While we can achieve the thermonuclear process fusion already today, it costs more energy to conduct the experiment than electricity is generated. Several technological breakthroughs have made the commercialization of fusion energy tangible in recent years. However, numerous obstacles still have to be overcome to harness "*the only primary energy source left in the universe* (Ball & Thompson, 2021, 363)" on our planet.

In contrast to the generation of energy through the fission of atoms, fusion involves the fusion of two atoms into a new element. The atoms used in this process need to get superheated so that the electrons are removed from the atoms, and plasma - a fluid state of matter comprising ionized atoms as well as other charged particles - is created in which the nuclei and electrons circulate freely (Classens, 2020). Since the nuclei are all positively charged, they repel each other. In order to overcome this repulsion, the particles must reach an extreme velocity, where very fast simultaneously means very hot. With more than 100 million degrees kelvin, the temperature in the reactor reaches higher temperatures than the center of the sun. Stars reach the millions of degrees celsius required for the fusion process with the help of their mass. The pressure created by their mass compresses and heats the nuclei until they fuse and merge into heavier nuclei, releasing energy in the process (Turrell, 2021). Scientists were able to achieve an uncontrolled release of this energy as early as 1952 in the form of the hydrogen bomb, but a lasting controlled reaction to generate electricity has not yet been achieved (Britannica, 2022).

This released energy scientists intend to harness in a new generation of power plants.

The technology still has a long way to go before it is commercially viable, but with advances in materials, research and computing "*nuclear fusion seems finally to be approaching commercial viability* (Ball & Thompson, 2021, 362)". If it came to pass, it would be so efficient that a single glass of seawater could generate as much energy as burning a barrel of oil without significant waste (Turrell, 2021).

Fusion reactors would use hydrogen or helium as fuel, and seawater is rich in hydrogen. However, not all hydrogen is suitable for a fusion process. Particular isotopes with extra neutrons, deuterium and tritium, are needed for the proper reactions. Deuterium is stable and can be found in abundance in seawater (Souers, 2020). Tritium, however, is somewhat more challenging to find and radioactive. It is estimated that only 20 kg of tritium exists globally, most of it in nuclear warheads, which makes it incredibly expensive (Pearson, et al., 2018). To ensure the long-term security of supply with fusionable elements, the rare tritium could be replaced by helium-3 isotopes for a fusion with deuterium. Unfortunately, helium-3 is also scarce on earth, but the moon could provide a reliable supply. Over billions of years, the solar wind could have built up vast deposits of helium-3, which we could extract from the lunar dust and thus supply the world for thousands of years (Glickman, 2021).

Since fusion is a thermonuclear reaction containing the term nuclear, safety concerns could influence the public's perception. Unlike fission reactors, which produce long-lived radioactive waste, a fusion reactor only produces short-lived neutrons. Fusion reactors are not comparable to a nuclear power plant, where a disastrous meltdown can occur if the containment fails. Should an incident such as a power outage, terrorist attack, or other event occur, the plasma would simply expand and cool, terminating the reaction. The release of radioactive fuel such as tritium could threaten the environment. In the process, escaping tritium could combine with oxygen to form radioactive water, which would, however, be quickly diluted due to the small amount of tritium in the reaction needed (Parisi & Ball, 2019).

The great challenge of fusion energy is producing a stable and long-lasting reaction of the fusion elements. The electrically charged plasma undergoing fusion, the heat that is thereby generated, and the system's cooling represent critical obstacles to overcome (Glickman, 2021). There are several ways to start a fusion process, but scientists have primarily relied on two ways to make plasmas hot enough to fuse. These methods work on the concept of sophisticated magnets or shockwaves enclosing and levitating the plasma inside the reactor. The fusion process has to be maintained long enough to get more energy out of the reaction than what was fed in, but only short-term fusion reactions have been possible so far due to the unstable infernal fluid and the high temperatures.

In the last year, the EUROfusion consortium based in the UK has achieved a new record in its JET reactor, with a reaction over five seconds generating 11 MW of power (Clery, 2022). This outstanding performance has been an essential source of research for the planned commissioning of ITER in 2025, which differs from JET mainly in its size and the superconducting magnets used. With a price tag of over $22 billion and over 35 countries involved in the research, ITER, based in France, is nowadays a frontrunner in fusion technology. This magnetic confinement reactor uses superconducting electromagnets cooled with liquid helium to within a few degrees of absolute zero, thereby hosting some of the most significant temperature gradients in the known universe. The goal of ITER over the next decade is to generate, for the first time, more energy than is needed for the fusion reaction, with 50 MW input and 500 MW output (Classens, 2020) (ITER, 2022).

In the second type, inertial confinement, the plasma is compressed by shock pulses from high-power lasers to the density required for a fusion reaction. In this process, the plasma retains its form for a fraction of a second due to its inertia before the expansion of the plasma and energy release occurs. This fusion reactor design has existed since the 1950s but was not resumed until the introduction of computationally powerful supercomputers that could calculate the equations describing the plasma for this complex geometry (Parisi & Ball, 2019).

In August of last year, the US National Ignition Facility (NIF) reported that its latest laser achieved an energy output eight times greater than any design to date and recovered up to 70% of the energy needed for the reaction (Thoss, 2021).

A design that combines superconducting magnets and high-performance lasers is called magnetized target fusion. The Canadian company General Fusion (GF) has developed a reactor that compresses the plasma more slowly, prevents heat deviation due to magnetic confinement, and relies on reactions lasting seconds instead of long fusion reactions. the company has set ambitious goals, predicting that the first reactor will be online by 2025 and "*will be the first power-plant-relevant large-scale demonstration*. (Ball & Thompson, 2021, 363)"

There are also fusion concepts that do not use deuterium-tritium fuel, as the Californian company TAE Technologies is attempting to develop. This type of fusion reactor is still in the early stages, as temperatures in the billions are required to fuse the atoms. The temperature resistance of the outer walls and magnets is a general problem in all fusion reactions. Optimizing this problem will likely lead to rapid improvements in the technology (Turrell, 2021).

What speaks in favor of fusion energy as a possible carbon-free, sustainable energy source is the increasing appeal to private companies and investors who sense real prospects for a return on their money. In the past, fusion projects have been conducted solely by states or international projects, but the entry of private companies could create a boom similar to that in the space industry. More than $2.4 billion, much of it privately funded, has been raised by the 18 companies according to the Fusion Industry Association (FIA), and advances in materials and research herald a commercially lucrative reactor solution.

As private firms, such as GF, Google, and Goldman Sachs advance or invest in the fusion technology sector, synergies among companies can be generated, and diversification of approaches can be achieved (Ball & Thompson, 2021).

7. Conclusion

This paper shows that mitigating the climate crisis and the associated global warming is an absolute necessity to reduce weather extremes, social injustice, loss of biodiversity, and the overall impact on our environment. Climate change is highly likely to jeopardize the chance of reaching our Sustainable Development Goals (SDGs), as the climate has a ubiquitous impact on global development (IPCC, 2021).

Without rapid and deep reductions in CO_2 and other climate forcers, the goal of containing warming to 2°C by 2050 becomes even more distant.

While numerous reputable reports emphasize that we will most likely not reach 1.5°, global efforts to improve the situation still fall short. Experts have warned for years that our lifestyle and emissions will have severe consequences for future generations.

Even if we most likely fail our mitigation targets, we should try to increase the capacity of renewable energies further, improve our grids, and enhance smart-control technologies to prevent even faster warming.

In the discussion about the future energy transition, much hope is put on improving existing and inventing new technologies. Solar and wind have the technical capabilities and cost competitiveness to lead the energy transition, but their efficiency, scale, and deployment are limited by physical, material, and socio-political factors. Environmental issues and the supply of resources must also be taken into account.

This paper shows that an energy transition is possible with already existing technological possibilities. Obstacles, in the form of storage possibilities, grid infrastructure and electricity generation, can be overcome and mostly depend on economic factors. There is no need for a technological revolution. However, so far, challenges in the socio-political field represent the biggest obstacles that hamper the pace of the transition.

We can achieve an energy transition towards 100% renewable energy. However, we should stop referring to 1.5° or 2° and instead communicate our efforts against climate warming as a fight over life and death, which is exactly what it is! We must abolish the "not-in-my-backyard mentality" and see the expansion of renewable energies as a prioritized global goal, which socio-political obstacles, above all, should not restrain.

A rationalization of the debate on climate warming would be desirable, and new tactics by policymakers would be necessary to use the social component as a powerful weapon against climate warming. Countries should clearly communicate what capacity expansion, network investments, and national and international frameworks are needed

to achieve a successful energy transition, not by 2030 or 2050, but as soon as possible.
It must also be made clear to the public that other yet unexplored, sustainable energy sources exist that deserve increased attention. In the course of this work, I have often been struck by how few people have even the slightest idea about fusion energy. In the context of fusion energy, people commonly say that it will never be achieved or that it will never be feasible on a large scale. The reality is that it is feasible, we have already achieved it, but more research and investment are needed. With increased international cooperation and funding, these advances can be accelerated. Comparing the $2.4 billion in fusion energy funding with the $4.1 billion that Coca-Cola spent on advertising in one year, one can see that there is still plenty of room for improvement (Statista, 2021).
Until fusion power can power the world, we must continue to rely on renewable energy sources such as wind and solar, which can be considered transitional technologies, until the first viable fusion reactor is completed.

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