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Permanent transfer of power from fossil energy to renewable energy sources Investigating the importance of ((Renewable Energy)) In achieving ((Sustainable Development))

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Abstract

Renewable energy is energy that is collected from renewable resources that are naturally replenished on a human timescale. It includes sources such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy stands in contrast to fossil fuels, which are being used far more quickly than they are being replenished. Although most renewable energy sources are sustainable, some are not. For example, some biomass sources are considered unsustainable at current rates of exploitation. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services. About 20% of humans' global energy consumption is renewables, including almost 30% of electricity. About 8% of energy consumption is traditional biomass, but this is declining. Over 4% of energy consumption is heat energy from modern renewables, such as solar water heating, and over 6% electricity. Globally there are over 10 million jobs associated with the renewable energy industries, with solar photovoltaics being the largest renewable employer. Renewable energy systems are rapidly becoming more efficient and cheaper, and their share of total energy consumption is increasing, with a large majority of worldwide newly installed electricity capacity being renewable. In most countries, photovoltaic solar or onshore wind are the cheapest new-build electricity. Sustainable development is an organizing principle for meeting human development goals while also sustaining the ability of natural systems to provide the natural resources and ecosystem services on which the economy and society depend. The desired result is a state of society where living conditions and resources are used to continue to meet human needs without undermining the integrity and stability of the natural system. Sustainable development can be defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. While the modern concept of sustainable development is derived mostly from the 1987 Brundtland Report, it is also rooted in earlier ideas about sustainable forest management and 20th-century environmental concerns. As the concept of sustainable development developed, it has shifted its focus more towards the economic development, social development and environmental protection for future generations. The UN-level Sustainable Development Goals (2015-2030) address global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice. Energy experts believe that renewable energy should replace conventional energy sources such as oil and gas in the 21st century to reduce the wasteful use of hydrocarbon products and that future energy use depends on a structure in which carbon-free energy sources such as solar energy. Or wind to be used. A way to overcome the energy crisis and the time bomb that seems to be tuned to announce the end of energy at any moment. In the book in front of you, chapter by chapter, the types of renewable energy are examined and finally its advantages and even disadvantages are expressed! In fact, we should listen to the proposal of the Saudi Minister of Energy in the 1970s, who said: "The Stone Age did not end because the stone ran out. The age of oil must end much sooner than the oil runs out." So, Ladies and gentlemen! Welcome to the age of new Energies.

Keywords: Energy; Renewable Energy; Green Energy; Solar Energy; Hydrogen Energy; Wind Energy; Fossil Energy; Oil; Gas; Development; Sustainable Development

Introduction

Objective of study

Reduction of greenhouse gases (GHG) emissions is a target for every country as an effective factor for reducing the negative effects of climate change and global warming. Energy generation and consumption is responsible for two third of these emissions. Low carbon energy production and energy efficiency are the two main solutions for reduction of GHG. United Nation's Framework

Convention on Climate Change (UNFCCC) actions in the Paris agreement have become the cornerstone of this movement. Based on the commitments in this conference, members should increase their share of renewable energy from 15% in 2015 to 65% in 2050. The transition to renewable resources, associated with energy innovation, new market design, new financing and business models, new policies and technology transfer, might be a pathway for cutting emissions. Long term policies such as: efficient renewable energy subsidies, carbon pricing and increasing the investment in the sector are also required for the transition process. Iran, one of the biggest owners of fossil fuels, committed to reduce its emissions up to 12% by 2030, but it is not the only motive for the transition of the energy sector. In Iran's sixth 5-year National Development Plan (NDP), as a part a 30-year plan, the growth in the share of renewable resources is targeted to be up to 5000MW. Additionally, the decreasing cost trend of renewable resources, the converging fossil fuels costs and the attractiveness of the foreign investment in Iran's renewable energy sector, constitute further motivations for this transition (OECD/IEA&IRENA, 2017). Identifying Iran's energy sector structure, its potential and its role players on one side, and its methods and institutions on the other, would be helpful to develop a pattern and respective policies for transition of Iran to renewable energy.

Method and Sample

This research is conducted based on a qualitative method. The first part of it is based on the analysis of secondary data on the energy sector, particularly electric power, including: actual and potential capacity, consumption and generation, the cost comparison and the share of the renewable resources versus fossil fuels in the energy supply. Also, primary data has been collected through a semi-conducted interview with companies that have recently participated in renewable energy projects in the country and its renewable energy organization (SATBA). The results of these interviews are collected, categorized and analyzed in order to highlight both the main drivers of Iran's renewable energy market development, and the identification of the policies, methods and patterns the country implemented in this regard.

Outline of Thesis

In this research, we first try to summarize the main theories and approaches of a sustainable transition to renewable resources in order to highlight its main drivers and barriers. Socio-technical approaches, such as socio-technical transition and energy development blocks, help us identify the structure of Iran's electricity power sector and the possible scenarios for its transition to renewable resources. For this regard we apply the mentioned theories to our data set in order to identify the characteristics and possibilities of Iran's electricity sector for a sustainable transition. Finally, based on the conducted analysis, some policies and methods will be proposed. The structure and the share of primary energy resources constitute effective information for clarifying the country's development blocks and socio-technical elements. Reserves, production levels, costs and the share of production of different energy resources will be analyzed to further this discussion. Economic incentives, such as cost and institutional drivers and environmental concerns will be studied in order to find the possible methods or policies for transition. What we discuss mainly in this study is changing the primary carriers rather than the end service (Kander et al. 2013: 383). Since the necessary technology shift is difficult, pinpointing the barriers for development of renewable resources, such as low price of fossil fuels, technology limitations, path dependency and investment deficiency in the energy sector will be discussed (Kander et al. 2013). Finally, some applicable methods regarding to the drivers and barriers of transition of the country's energy sector to renewable resources will be proposed [1-10].

Research Question

Despite of domestic (high potentials for power generation and determined share of renewable energy resources in the national development plan) and international motives (UNFCCC commitments and decreasing renewable cost trend) the share of renewable resources in electricity generation is very small. Resources, such as hydropower, solar and wind power can play an effective role in increasing the share of renewable energy in the country. Although there are considerable natural and institutional potentials for the development and transition to renewable resources, the low cost of fossil fuels and lack of infrastructures for the renewable energy resources, as a high-tech industry, are mentioned as the main obstacles for the growth of the renewable energy industry. On the other hand, recent domestic and foreign investments in renewable energy projects, particularly solar and wind energy power units show the tendency for investment in this sector. Investment of 51,725,000 EUR and the construction of 5 solar PV power units with a generation capacity of 44 MW in last 12 months show the increasing attractiveness of this industry. The country previously used to generate less than 1 MW of this kind and the recent investment in renewable energy sector continues. The above discussions about drivers, potentials for transition and recent investments in Iran's electricity energy sector, raise the following research questions:

- Based on Iran's electricity power generation, consumption and potentials, is it feasible for the country to transit to renewable resources?
- Which methods/patterns are helpful to overcome these barriers? Is it applicable to other oil producers with cheap fossil fuel resources?

Theory and Literature Review

Theoretical Context

The theoretical context of this thesis, like any case study, is a framework for categorizing and analyzing the case based on the developed theories and conducted research. Regarding the

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research questions and context, we use a theoretical perspective to analyze Iran's energy sector's barriers and drivers of transition to renewable energy resources, as well as the respective methods and patterns for this transition. Sustainable energy approach is helpful to identify drivers, barriers and potentials of energy sector for the transition process. Energy development blocks theory defines the share of different energy carriers and their respective innovations by analyzing supply and demand, energy efficiency and price trends as a result of market mechanisms. Since the transition process includes different technical and social aspects, the socio-technical transition theories are helpful to identify different barriers and drivers of energy transition in Iran. After analyzing the energy sector policy-oriented approaches, such as carbon pricing or energy subsidy, a pathway can be proposed for the energy sector transition.

Sustainable Energy and Drivers of transition

The MacKay's perspective Sustainable Energy (2009) reviews the motivation and the feasibility of transitioning to renewable energy resources. Although countries like Iran own abundant and cheap fossil fuel resources, even these big reserves are limited and will be depleted in the coming years. Thus, the country should plan for the substitution of these resources and use them for other purposes with added value. Investment of the income earned by selling these added value products, or using them as input in a production process, would increase the GDP and boost up the economic growth. Another motivation is energy security. Although fossil fuels might seem a secure option in the short term, as they will vanish in the near future, they are not a secure option in the long run. Also, the proved adverse effect of fossil fuel consumption, which tends to environmental disasters and climate change, needs to be taken into consideration (MacKay, 2009: 5). In order to analyze sustainable energy theory, we review the different potential and reserves of various available energy resources in Iran to address the energy security motive .This aspect of transition is already considered in Iran's National Development Plan which we will discuss later. Price trend comparison of fossil fuel and renewable energy resources will show to what extent the current cheap fuels are reliable and long lasting. Finally, the country's concern about GHG emissions and its commitment with the international community to cut them also shows to what extent the third major motivation and environmental issues matter for Iran.

Energy Transition Theories

Socio-Technical Transition of the Energy Sector

Socio-technical transition is a concept defined by Geels (2001) as one based on three major fields of evolutionary economics, sociology of technology and innovation studies. In fact, this theory addresses what Schumpeter discusses as non-economic forces in his theory of economic development. In the modern age, and after the industrial revolution, different technological innovations were created and diffused at a high pace. Technological transition is the process that explains how the innovation takes place and how it integrates in the society by studying social changes. The changes in infrastructures, regulations, user practices, industrial networks (production, supply, and distribution), culture and symbolic meaning of technology could be mentioned as major social factors in this process. A technological transition contains key alterations in the socio-technical structure, including substitution of technology, which starts from one element and transforms to others (Geels, 2002). Since the socio-technical systems and transition are complicated to understand, researchers created a model called Multi Level Perspective (MLP). MLP is a socio-economic approach which recently has been applied to different economic and social subjects. According to this theory, a sector such as energy could be considered as a socio-technical system. These systems consist of different elements including; actors (such as individuals or organizations), institutions (standards, regulations and norms), material and knowledge. The services provided to society are the result of interaction between the mentioned elements, which shows to what extent they are dependent on each other and interrelated together (Markard et al. 2012).

Institutional or fundamental change in these socio-technical systems can lead to socio-technical transition. The changes could be economic, political, institutional, technological, etc. These changes could result in new, complementary or in the substitution of services, products, organizations and business models. Socio-technical transition is not comparable with the technological transition as it is also accompanied with institutional structures, practice changes and non-technological innovations. If a socio-technical regime shift takes place in conformity between production and consumption, it would be a sustainable transition (Markard et al. 2012). Multi-level perspective is considered as an approach to analyze technology transition through interaction of elements at three levels, including: *niche*, *landscape* and *regime*.

The technological *niche* is a protected market, space or application so called "safe heaven" for the development of incremental innovation away from the pressure of the dominant regime (Markard etal. 2012). Niche is related to micro-level innovations and protects them from the pressure of the free market which regularly exists at regime level. Both producers and consumers in niche level create a protection for new technologies in two main parts of market and technological niches (Geels, 2002). The socio-technical *regime* is the product of the history and sociology of technology in combination with the concepts of evolutionary economics. In fact, this regime creates a direction for incremental socio-technical change in the development path already established (Markard et al., 2012). The regime level, which is concentrated on meso-level innovation, is a network of communities and social groups which are interconnected by a set of rules. Unlike the change in niche level, changes in regime level are incremental and slow. A technological regime also creates

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the trajectories and performs as a rule-set (Geels, 2002). Socio-technical Landscapes are the facilitators and opportunity makers for niche to step forward and play a role in fundamental shift or changes in regimes (Markard et al. 2012). Landscape level is connected to macro level innovation and is exogenous to regime and includes macro level dimensions of environmental issues, social trends and cultural values. It also consists of a set of rooted structural tendencies and modifications (Geels, 2002).

The MPL mechanism in summary operates as follows: a micro innovation at the niche level exerts a force by implementing price or performance improvement, learning processes and receiving support from powerful communities. This movement transforms the landscape level and puts pressure on the regime. The pressure on the regime destabilizes this level and creates an opportunity for niche innovation to move to the next level (Geels & Schot, 2007). Technological transitions have common characteristics, including: transitions are co-evolutionary and multi-dimensional; they include multi-actors; it happens at multiple levels; and it is a long-time process which is radical and non-linear (Geels et al. 2008).

Path Dependency and Development Blocks

Development Block is a Schumpeterian rooted concept which was first developed by Erik Dahmén. He identified a group of closely interrelated and inter-reliant elements in industrial development while conducting a study about Sweden Industrial economy. This process shows the indicators of price, cost or emerging markets made by entrepreneurial events. According to this concept, transformation is located between two severe conditions resulting from new methods of production or providing services, market, and sources of energy. A development block might be completed by a group of entrepreneurs and through uncoordinated events. The diffusion of technology and transition might face several issues, such as narrow market and the excess of capacity as a result of failing to find new markets. This could be solved by implementing marketing and sales promotion. Subsidiaries and expanding interests are two other solutions to this problem. Development blocks are wide socio-economic networks made of cumulative components (Dahmén, 1989). Although Dahmén defined the concept of development blocks for the technological and industrial sector, Kander et al. 2015 developed this concept for the energy sector. The first step for identifying energy development blocks is pinpointing the contribution of energy to the economy. The role of energy in economic growth, drivers of energy transition and the role of energy in the economic efficiency are the main contributions of energy to the economy and development blocks (Kander et al. 2013: 7) [11-20].

The price, cost, environmental effects, technological progress and share of energy in the economy are some variables which are determinant in economic growth. Price of energy carrier is a key variable in the economy since it affects production, economic growth and, ultimately, development. For instance, the cheapness of energy is not necessarily an unimportant sign, as it might show some qualitative progress in infrastructures that result in increased production and cost reduction. On the other hand, price of energy, as the core of development block, affects fundamental parts of economy, such as infrastructures, design and transportation. In a general perspective, development blocks formulate the economy, but they themselves are dependent on energy carriers and these carriers are accompanied with particular technologies. This concept is known as path dependency and shows why the cost of energy transition is high since it affects the whole economy (Kander et al. 2013: 7). Although the energy sector transition is expensive for the economy, the drivers for transition in this sector always exist. Like the industrial sector, energy development blocks follow the same pattern of complementarity between energy carriers and associated technology. Since development blocks consist of different elements other than technology, such as energy sources, institutions and infrastructures, transition takes time. In fact, development blocks are made of discontinuous phases resulting from the lag between innovations and their wide spread use, which shows the necessity of transformation in all the components of the energy sector (Kander et al. 2013: 8).

Another contribution of energy to the economy is the energy efficiency. In simple terms, energy efficiency is a measurement for showing the required unit of energy for one unit of production. Energy efficiency in development blocks could be discussed in two major categories of energy saving and energy expansion. Capital deepening, expansion of the service sector and modification of the economic structure in modern economies are signs of an increase in energy efficiency (Kander et al.2013: 10). Core innovations, which are the macro innovation of a development block, could be considered to be a General Purpose Technology (GPT) in case of a widespread application. Market suction and market widening, are important regarding to the complementary innovation and diffusion of new technology. While market suction oversees the relation between innovation and its own requirements as complementary drivers for diffusion, market widening considers the process as a result of lower prices of energy carriers, particularly in relation to the prices of transport and communication (Kander et al. 2013: 30). Based on the mentioned contributions of energy to the economy, three modern development blocks, including Oil- Internal Combustion Engine (ICE), Electricity and ICT Development Blocks could be mentioned (Kander et al. 2013: 15). The Oil- ICE development block formed around the internal combustion engine has the oil as the carrier and is mainly used by the transportation sector (Kander et al. 2013: 290). While pipelines and tankers performed as market suction mechanism of this block by reducing the oil prices, ICE was the core of the market widening mechanism (Kander et al. 2013:259).

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The electricity development block holds the electrical motor, generators and transformers as the core innovations inside. The flexibility of electricity as a secondary energy in generation and consumption were the main advantages of this block (Kander et al.2013: 266). The balance between generation and consumption in this energy carrier is very crucial due to the characteristics of electricity. As a result, system expansion played an important role in the market widening of this block. The need for higher energy efficiency, flexibility of electricity power, and the oil crisis in 1970s were some of the drivers of transition to electricity block. However, electricity is difficult and expensive to store, and it needs a big financial power to run (Kander et al. 2013: 310).

The ICT development block is the result of communication technology and microelectronic invention. ICT, as the most energy saving development block, benefited from expansion of higher education and the requirement for stored and accessible codified data inside machines (Kander et al. 2013: 318). Considerable increase in efficiency, a decreasing trend in computers prices and dematerialization are the characteristics of this block (Kander et al. 2013: 326). While large computers acted as the market suction mechanism of ICT-Block, Internet, PC and cell phones are the markets widening facilitators of this block. Information and communication society, which was created by the ICT-Block, is more focused on energy saving (Kander et al. 2013: 331).

As mentioned earlier the costs of energy carriers, either social or private, are really vital to development blocks and transition. While private costs are usually reflected in the energy carriers' price, the social costs such as environmental or health costs are not captured (Kander et al. 2013: 20). Development block and path dependency are two important concepts in energy transition theories. The transition or change in the energy sector is directly connected with economic growth and the development of a country. Although the transition to fossil fuels was one of the most important in the 20th century, it was not the only. The new transition wave is more concentrated on the electricity production, which has no strong substitution despite changes in the level and forms of electricity generation. There are always a complementary relationship between new technologies and energy carriers, but the transition of the energy sector is a regime change that requires a shift in organizations and infrastructure developments in addition to a shift in the technology. In fact, it is not only a matter of process change, but also the infrastructures (Kander et al. 2013: 8). Applying the development blocks concept to energy sector is helpful to identify the role of different blocks in the transition and diffusion of new technologies, as well as the mechanisms of market suction and widening (Kander et al. 2013: 295). This theoretical framework could be used to pinpoint the path dependency, trajectory and the possible effects of choices for Iran's energy sector (Kander et al., p375). The concept of path dependency tries to illustrate that decisions made in the past have an influence on the path taken in the future (Kander et al. 2013: 367).

Comparison between Socio-Technical Transition and Development Blocks

Path dependency in the energy sector could be either the result of a relative price of energy carriers such as cheap fossil fuels, or a result of the plans and infrastructures that play a critical role in economic growth. In fact path dependency could be studied in order to find the patterns of development and answer the question posited: will the economies find an efficient and sustainable pattern for their energy sector or follow the conventional trajectories? Path dependency and cumulativeness are two major issues for socio-technical regimes. In modern economic development, patterns and particularly the energy sector quality is as important as quantity. It means that the convergence in environmental issues and energy intensity in relation to growth is as important as the convergence of growth, structure and productivity (Berkout et al. 2009). The performance and characteristics of a socio-technical system have a close similarity to development blocks as they both consider the transition in the energy sector with technology innovation as their core, and both are associated with other social, institutional and infrastructure elements. The sustainability challenges are coupled with strong path-dependencies and lock-ins we observe in the existing sectors (Markard et al. 2012). As Macro-innovations diffuse, they change the society and economy and they tend to form new development blocks. These macro-innovations necessarily need niche market, micro and meso innovation and complementary innovation for diffusion and wider implementation. In addition to technology innovation, capital investment, new infrastructures and institutional activities are required for a wider socio-technical transition. Complementary institution, infrastructure and products are essential for the diffusion of new technology (Kander et al. 2013: 28).

CO2 Pricing Methods

We mentioned the climate change and particularly the UNFCCC Paris agreement in 2015 as a motivation for a transition to renewable energy for Iran's economy. One major contributor to the recent climate change is the burning of fossil fuels their resulting GHG emissions, including carbon dioxide. These negative external effects that are caused by these emissions are regularly not included in these carrier's prices. The method for calculating these costs in energy price is so called "carbon pricing". In fact it is the extra cost charged for the emission of CO_2 to the atmosphere. The carbon pricing methods try to reflect benefits of clean resources and costs of fossil fuels in the energy market (Moomaw et al. 2017). Sustainable development includes three main components: the economy, environment and society, and carbon pricing can play an important role in this process. The latter is a handy tool for the Intergovernmental Panel on Climate Change's agreements targeted to control global warming. Flexible economic transition and green economic growth are some of the aims of this method, which motivates all the consumers to reduce their emissions by shifting to cleaner energy carriers, as well as to

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the development of innovations to increase efficiency (Moomaw et al. 2017). The two major methods of carbon pricing are carbon tax and Emission Trading System (ETS). Carbon taxing is a tax which is directly charged on GHG emissions at a specific rate. ETS is a trading system of emissions with supply and demand mechanisms for determining the GHG emission price. In this system the trade between different economies is based on the level of emissions (Moomaw et al. 2017).

Carbon pricing is experiencing an increasing trend of diffusion as 40 countries, averaging 12 percent of the global emissions, are currently using this system. It is a 7 billion tons carbon dioxide that is worth around USD 50 billion (Moomaw et al., 2017). Private companies are also role players of carbon pricing method as they have their internal system called "shadow carbon price". This is a method that 453 global companies implemented to identify their corporate risks regarding to the climate change. This method helps companies prioritize investments on both renewable energy and energy efficiency (Moomaw et al. 2017). The movement for global carbon pricing started as a result of the Kyoto protocol (1997) on climate change but failed as it did not included major emitters. UNFCCC Paris agreement on climate change grounded the intended nationally determined contributions (INDCs) as well as the proposals of 162 countries for carbon pricing in 2016. This movement targeted to expand carbon pricing 25 percent by 2020 and by 50 percent by 2030, thus deepening carbon pricing and enhancing international cooperation. The main difference of the recent agreement from Kyoto agreement is that it covers the majority of emitters (61% global GHG emissions), including six main world leaders. Although there is doubt about the future of the global carbon pricing trend, particularly in relation to the US, other main leaders like China are developing their plans for national ETS (Moomaw et al. 2017).

There is an ongoing debate about subsidizing renewable energy called the green paradox. In general, taxation of fossil fuels and subsidizing the renewable energy sector policies target the demand side and not supply side with an announced time plan. The mentioned policies will make fossil fuels suppliers extract more and invest the income in the capital market. These higher volumes of extractions contradict the environmental policies that were set to provide a greener environment (Konrad et al. 1994). Contemporary climate change includes both global warming and its impacts on Earth's weather patterns. There have been previous periods of climate change, but the current changes are distinctly more rapid and not due to natural causes. Instead, they are caused by the emission of greenhouse gases, mostly carbon dioxide (CO_2) and methane. Burning fossil fuels for energy use creates most of these emissions. Agriculture, steelmaking, cement production, and forest loss are additional sources. Greenhouse gases are transparent to sunlight, allowing it through to heat the Earth's surface. When the Earth emits that heat as infrared radiation the gases absorb it, trapping the heat near the Earth's surface. As the planet heats up it causes changes like the loss of sunlight-reflecting snow cover, amplifying global warming.

On land, temperatures have risen about twice as fast as the global average. Deserts are expanding, while heat waves and wildfires are becoming more common. Increased warming in the Arctic has contributed to melting permafrost, glacial retreat and sea ice loss. Higher temperatures are also causing more intense storms and other weather extremes. Rapid environmental change in mountains, coral reefs, and the Arctic is forcing many species to relocate or become extinct. Climate change threatens people with food and water scarcity, increased flooding, extreme heat, more disease, and economic loss. Human migration and conflict can be a result. The World Health Organization calls climate change the greatest threat to global health in the 21st century. Even if efforts to minimize future warming are successful, some effects will continue for centuries. These include sea level rise, and warmer, more acidic oceans. Many of these impacts are already felt at the current level of warming (1.2 °C). Additional warming will increase these impacts and may trigger tipping points, such as the melting of the Greenland ice sheet. Under the 2015 Paris Agreement, nations collectively agreed to keep warming "well under 2 °C". However, with pledges made under the Agreement, global warming would still reach about 2.7 °C by the end of the century. Limiting warming to 1.5 °C will require halving emissions by 2030 and achieving net-zero emissions by 2050. Making deep cuts in emissions will require switching away from burning fossil fuels and towards using electricity generated from low-carbon sources. This includes phasing out coal-fired power plants, vastly increasing use of wind and solar power, switching to electric vehicles, switching to heat pumps in buildings, and taking measures to conserve energy. Carbon can also be removed from the atmosphere, for instance by increasing forest cover. While communities may adapt to climate change through efforts like better coastline protection, they cannot avert the risk of severe, widespread, and permanent impacts.

Terminology

Climate change is driven by rising greenhouse gas levels in the atmosphere. This strengthens the greenhouse effect which traps heat in Earth's climate system. Before the 1980s, it was unclear whether warming by increased greenhouse gases would dominate aerosol-induced cooling. Scientists then often used the term inadvertent climate modification to refer to the human impact on the climate. In the 1980s, the terms global warming and climate change were popularized. The former refers only to increase surface warming, the latter describes the full effect of greenhouse gases on the climate. Global warming became the most popular term after NASA climate scientist James Hansen used it in his 1988 testimony in the U.S. Senate. In the 2000s, the term climate change increased in popularity. Global warming usually refers to human-induced warming of the Earth system, whereas climate change can refer to natural or anthropogenic change. The two terms are often used interchangeably. Various scientists, politicians and media figures have adopted the terms

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climate crisis or climate emergency to talk about climate change, and global heating instead of global warming. The policy editor-in-chief of The Guardian said they included this language in their editorial guidelines "to ensure that we are being scientifically precise, while also communicating clearly with readers on this very important issue". In 2019, Oxford Languages chose climate emergency as its word of the year, defining it as "a situation in which urgent action is required to reduce or halt climate change and avoid potentially irreversible environmental damage resulting from it".

Observed Temperature Rise

Global surface temperature reconstruction over the last 2000 years using proxy data from tree rings, corals, and ice cores in blue. Directly observed data is in red. Multiple independent instrumental datasets show that the climate system is warming. The 2011-2020 decade warmed to an average 1.09 °C [0.95-1.20 °C] compared to the pre-industrial baseline (1850-1900). Surface temperatures are rising by about 0.2 °C per decade, with 2020 reaching a temperature of 1.2 °C above the pre-industrial era. Since 1950, the number of cold days and nights has decreased, and the number of warm days and nights has increased. There was little net warming between the 18th century and the mid-19th century. Climate information for that period comes from climate proxies, such as trees and ice cores. Thermometer records began to provide global coverage around 1850. Historical patterns of warming and cooling, like the Medieval Climate Anomaly and the Little Ice Age, did not occur at the same time across different regions. Temperatures may have reached as high as those of the late-20th century in a limited set of regions. There have been prehistorically episodes of global warming, such as the Paleocene-Eocene Thermal Maximum. However, the modern observed rise in temperature and CO_2 concentrations has been so rapid that even abrupt geophysical events in Earth›s history do not approach current rates.

Evidence of warming from air temperature measurements are reinforced with a wide range of other observations. There has been an increase in the frequency and intensity of heavy precipitation, melting of snow and land ice, and increased atmospheric humidity. Flora and fauna are also behaving in a manner consistent with warming; for instance, plants are flowering earlier in spring. Another key indicator is the cooling of the upper atmosphere, which demonstrates that greenhouse gases are trapping heat near the Earth's surface and preventing it from radiating into space. Regions of the world warm at differing rates. The pattern is independent of where greenhouse gases are emitted, because the gases persist long enough to diffuse across the planet. Since the pre-industrial period, the average surface temperature over land regions has increased almost twice as fast as the global-average surface temperature. This is because of the larger heat capacity of oceans, and because oceans lose more heat by evaporation. The thermal energy in the global climate system has grown with only brief pauses since at least 1970, and over 90% of this extra energy has been stored in the ocean. The rest has heated the atmosphere, melted ice, and warmed the continents. The Northern Hemisphere and the North Pole have warmed much faster than the South Pole and Southern Hemisphere. The Northern Hemisphere not only has much more land, but also more seasonal snow cover and sea ice. As these surfaces flip from reflecting a lot of light to being dark after the ice has melted, they start absorbing more heat. Local black carbon deposits on snow and ice also contribute to Arctic warming. Arctic temperatures are increasing at over twice the rate of the rest of the world. Melting of glaciers and ice sheets in the Arctic disrupts ocean circulation, including a weakened Gulf Stream, further changing the climate.

Drivers of recent temperature rise

Drivers of climate change from 1850-1900 to 2010-2019. There was no significant contribution from internal variability or solar and volcanic drivers. The climate system experiences various cycles on its own which can last for years (such as the El Niño-Southern Oscillation), decades or even centuries. Other changes are caused by an imbalance of energy that is "external" to the climate system, but not always external to the Earth. Examples of external forcings include changes in the concentrations of greenhouse gases, solar luminosity, volcanic eruptions, and variations in the Earth's orbit around the Sun. To determine the human contribution to climate change, known internal climate variability and natural external forcing need to be ruled out. A key approach is to determine unique "fingerprints" for all potential causes, then compare these fingerprints with observed patterns of climate change. For example, solar forcing can be ruled out as a major cause. Its fingerprint would be warming in the entire atmosphere. Yet, only the lower atmosphere has warmed, consistent with greenhouse gas forcing. Attribution of recent climate change shows that the main driver is elevated greenhouse gases, but that aerosols also have a strong effect.

Greenhouse Gases

The Earth absorbs sunlight, then radiates it as heat. Greenhouse gases in the atmosphere absorb and reemit infrared radiation, slowing the rate at which it can pass through the atmosphere and escape into space. Before the Industrial Revolution, naturally-occurring amounts of greenhouse gases caused the air near the surface to be about 33 °C warmer than it would have been in their absence. While water vapor (~50%) and clouds (~25%) are the biggest contributors to the greenhouse effect, they increase as a function of temperature and are therefore feedbacks. On the other hand, concentrations of gases such as CO_2 (~20%), tropospheric ozone, CFCs and nitrous oxide are not temperature-dependent, and are therefore external forcings. Human activity since the Industrial Revolution, mainly extracting and burning fossil fuels (coal, oil, and natural gas), has increased the amount of greenhouse gases in the atmosphere, resulting in a radiative imbalance. In 2019, the concentrations of CO_2 and methane had

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increased by about 48% and 160%, respectively, since 1750. These CO_2 levels are higher than they have been at any time during the last 2 million years. Concentrations of methane are far higher than they were over the last 800,000 years. The Global Carbon Project shows how additions to CO_2 since 1880 have been caused by different sources ramping up one after another. Global anthropogenic greenhouse gas emissions in 2018, excluding those from land use change, were equivalent to 52 billion tons of CO_2. Of these emissions, 72% was CO_2, 19% was methane, 6% was nitrous oxide, and 3% was fluorinated gases. CO_2 emissions primarily come from burning fossil fuels to provide energy for transport, manufacturing, heating, and electricity.

Additional CO_2 emissions come from deforestation and industrial processes, which include the CO_2 released by the chemical reactions for making cement, steel, aluminum, and fertilizer. Methane emissions come from livestock, manure, rice cultivation, landfills, wastewater, and coal mining, as well as oil and gas extraction. Nitrous oxide emissions largely come from the microbial decomposition of fertilizer. From a production standpoint, the primary sources of global greenhouse gas emissions are estimated as: electricity and heat (25%), agriculture and forestry (24%), industry and manufacturing (21%), transport (14%), and buildings (6%). Despite the contribution of deforestation to greenhouse gas emissions, the Earth's land surface, particularly its forests, remain a significant carbon sink for CO_2. Natural processes, such as carbon fixation in the soil and photosynthesis, more than offset the greenhouse gas contributions from deforestation. The land-surface sink is estimated to remove about 29% of annual global CO_2 emissions. The ocean also serves as a significant carbon sink via a two-step process. First, CO_2 dissolves in the surface water. Afterwards, the ocean›s overturning circulation distributes it deep into the ocean›s interior, where it accumulates over time as part of the carbon cycle. Over the last two decades, the world›s oceans have absorbed 20 to 30% of emitted CO_2.

Aerosols and Clouds

Air pollution, in the form of aerosols, not only puts a large burden on human health, but also affects the climate on a large scale. From 1961 to 1990, a gradual reduction in the amount of sunlight reaching the Earth's surface was observed, a phenomenon popularly known as global dimming, typically attributed to aerosols from biofuel and fossil fuel burning. Globally, aerosols have been declining since 1990, meaning that they no longer mask greenhouse gas warming as much. Aerosols scatter and absorb solar radiation. They also have indirect effects on the Earth's radiation budget. Sulfate aerosols act as cloud condensation nuclei and lead to clouds that have more and smaller cloud droplets. These clouds reflect solar radiation more efficiently than clouds with fewer and larger droplets. They also reduce the growth of raindrops, which makes clouds more reflective to incoming sunlight. Indirect effects of aerosols are the largest uncertainty in radiative forcing. While aerosols typically limit global warming by reflecting sunlight, black carbon in soot that falls on snow or ice can contribute to global warming. Not only does this increase the absorption of sunlight, but it also increases melting and sea-level rise. Limiting new black carbon deposits in the Arctic could reduce global warming by 0.2 °C by 2050.

Changes of the Land Surface

The rate of global tree cover loss has approximately doubled since 2001, to an annual loss approaching an area the size of Italy. Humans change the Earth's surface mainly to create more agricultural land. Today, agriculture takes up 34% of Earth's land area, while 26% is forests, and 30% is uninhabitable (glaciers, deserts, etc.). The amount of forested land continues to decrease, largely due to conversion to cropland in the tropics. This deforestation is the most significant aspect of land surface change affecting global warming. The main causes of deforestation are: permanent land-use change from forest to agricultural land producing products such as beef and palm oil (27%), logging to produce forestry/forest products (26%), short term shifting cultivation (24%), and wildfires (23%). Land use changes not only affect greenhouse gas emissions. The type of vegetation in a region affects the local temperature. It impacts how much of the sunlight gets reflected back into space (albedo), and how much heat is lost by evaporation. For instance, the change from a dark forest to grassland makes the surface lighter, causing it to reflect more sunlight. Deforestation can also affect temperatures by modifying the release of chemical compounds that influence clouds, and by changing wind patterns. In tropic and temperate areas, the net effect is to produce significant warming, while at latitudes closer to the poles a gain of albedo (as forest is replaced by snow cover) leads to a cooling effect. Globally, these effects are estimated to have led to a slight cooling, dominated by an increase in surface albedo.

Solar and Volcanic Activity

Physical climate models are unable to reproduce the rapid warming observed in recent decades when taking into account only variations in solar output and volcanic activity. As the Sun is the Earth's primary energy source, changes in incoming sunlight directly affect the climate system. Solar irradiance has been measured directly by satellites, and indirect measurements are available from the early 1600s onwards. There has been no upward trend in the amount of the Sun's energy reaching the Earth. Further evidence for greenhouse gases causing global warming comes from measurements that show a warming of the lower atmosphere (the troposphere), coupled with a cooling of the upper atmosphere (the stratosphere). If solar variations were responsible for the observed warming, the troposphere and stratosphere would both warm. Explosive volcanic eruptions represent the largest natural forcing over the industrial era. When the eruption is sufficiently strong (with sulfur dioxide reaching the stratosphere), sunlight can be partially blocked for a couple of years. The temperature signal lasts about twice as long. In the industrial era, volcanic

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activity has had negligible impacts on global temperature trends. Present-day volcanic CO_2 emissions are equivalent to less than 1% of current anthropogenic CO_2 emissions.

Climate Change Feedback

Sea ice reflects 50% to 70% of incoming solar radiation while the dark ocean surface only reflects 6%, so melting sea ice is self-reinforcing feedback. The response of the climate system to an initial forcing is modified by feedback: increased by self-reinforcing feedbacks and reduced by balancing feedbacks. The main reinforcing feedback is the water- vapor feedback, the ice-albedo feedback, and probably the net effect of clouds. The primary balancing mechanism is radiative cooling, as Earth's surface gives off more heat to space in response to rising temperature. In addition to temperature feedbacks, there are feedbacks in the carbon cycle, such as the fertilizing effect of CO_2 on plant growth. Uncertainty over feedbacks is the major reason why different climate models project different magnitudes of warming for a given amount of emissions. As air gets warmer, it can hold more moisture. After initial warming due to emissions of greenhouse gases, the atmosphere will hold more water. Water vapor is a potent greenhouse gas, so this further heats the atmosphere. If cloud cover increases, more sunlight will be reflected back into space, cooling the planet. If clouds become higher and thinner, they act as an insulator, reflecting heat from below back downwards and warming the planet. Overall, the net cloud feedback over the industrial era has probably exacerbated temperature rise. The reduction of snow cover and sea ice in the Arctic reduces the albedo of the Earth›s surface. More of the Sun›s energy is now absorbed in these regions, contributing to amplification of Arctic temperature changes. Arctic amplification is also melting permafrost, which releases methane and CO_2 into the atmosphere. Around half of human-caused CO_2 emissions have been absorbed by land plants and by the oceans. On land, elevated CO_2 and an extended growing season have stimulated plant growth. Climate change increases droughts and heat waves that inhibit plant growth, which makes it uncertain whether this carbon sink will continue to grow in the future. Soil contains large quantities of carbon and may release some when they heat up. As more CO_2 and heat are absorbed by the ocean, it acidifies, its circulation changes and phytoplankton take up less carbon, decreasing the rate at which the ocean absorbs atmospheric carbon. Climate change can increase methane emissions from wetlands, marine and freshwater systems, and permafrost.

Future warming and the carbon budget

Future warming depends on the strengths of climate feedback and on emissions of greenhouse gases. The former are often estimated using climate models, developed by multiple scientific institutions. A climate model is a representation of the physical, chemical, and biological processes that affect the climate system. Models include changes in the Earth's orbit, historical changes in the Sun's activity, and volcanic forcing. Computer models attempt to reproduce and predict the circulation of the oceans, the annual cycle of the seasons, and the flows of carbon between the land surface and the atmosphere. Models project different future temperature rises for given emissions of greenhouse gases; they do not fully agree on the strength of different feedbacks on climate sensitivity and magnitude of inertia of the climate system. The physical realism of models is tested by examining their ability to simulate contemporary or past climates. Past models have underestimated the rate of Arctic shrinkage and underestimated the rate of precipitation increase. Sea level rise since 1990 was underestimated in older models, but more recent models agree well with observations. The 2017 United States-published National Climate Assessment notes that "climate models may still be underestimating or missing relevant feedback processes". A subset of climate models add societal factors to a simple physical climate model. These models simulate how population, economic growth, and energy use affect - and interact with - the physical climate. With this information, these models can produce scenarios of future greenhouse gas emissions. This is then used as input for physical climate models to generate climate change projections. In some scenarios emissions continue to rise over the century, while others have reduced emissions. Fossil fuel resources are too abundant for shortages to be relied on to limit carbon emissions in the 21st century. Emissions scenarios can be combined with modelling of the carbon cycle to predict how atmospheric concentrations of greenhouse gases might change in the future. According to these combined models, By 2100 the atmospheric concentration of CO_2 could be as low as 380 or as high as 1400 ppm, depending on the socioeconomic scenario and the mitigation scenario.

The IPCC Sixth Assessment Report projects that global warming is very likely to reach 1.0 °C to 1.8 °C by the late 21st century under the very low GHG emissions scenario. In an intermediate scenario global warming would reach 2.1 °C to 3.5 °C, and 3.3 °C to 5.7 °C under the very high GHG emissions scenario. These projections are based on climate models in combination with observations. The remaining carbon budget is determined by modelling the carbon cycle and the climate sensitivity to greenhouse gases. According to the IPCC, global warming can be kept below 1.5 °C with a two-thirds chance if emissions after 2018 do not exceed 420 or 570 Giga tons of CO_2. This corresponds to 10 to 13 years of current emissions. There are high uncertainties about the budget. For instance, it may be 100 Giga tons of CO_2 smaller due to methane release from permafrost and wetlands.

Impacts

Physical Environment

The environmental effects of climate change are broad and far-reaching, affecting oceans, ice, and weather. Changes may occur

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gradually or rapidly. Evidence for these effects comes from studying climate change in the past, from modelling, and from modern observations. Since the 1950s, droughts and heat waves have appeared simultaneously with increasing frequency. Extremely wet or dry events within the monsoon period have increased in India and East Asia. The rainfall rate and intensity of hurricanes and typhoons is likely increasing. Frequency of tropical cyclones has not increased as a result of climate change. However, a study review article published in 2021 in Nature Geoscience concluded that the geographic range of tropical cyclones will probably expand poleward in response to climate warming of the Hadley circulation. Historical sea level reconstruction and projections up to 2100 published in 2017 by the U.S. Global Change Research Program. Global sea level is rising as a consequence of glacial melt, melt of the ice sheets in Greenland and Antarctica, and thermal expansion. Between 1993 and 2020, the rise increased over time, averaging 3.3 ± 0.3 mm per year. Over the 21st century, the IPCC projects that in a very high emissions scenario the sea level could rise by 61-110 cm. Increased ocean warmth is undermining and threatening to unplug Antarctic glacier outlets, risking a large melt of the ice sheet and the possibility of a 2-meter sea level rise by 2100 under high emissions. Climate change has led to decades of shrinking and thinning of the Arctic sea ice. While ice-free summers are expected to be rare at 1.5 °C degrees of warming, they are set to occur once every three to ten years at a warming level of 2 °C. Higher atmospheric CO_2 concentrations have led to changes in ocean chemistry. An increase in dissolved CO_2 is causing oceans to acidify. In addition, oxygen levels are decreasing as oxygen is less soluble in warmer water. Dead zones in the ocean, regions with very little oxygen, are expanding too [21-30].

Tipping points and Long-Term Impacts

The greater the amount of global warming, the greater the risk of passing through 'tipping points', thresholds beyond which certain impacts can no longer be avoided even if temperatures are reduced. An example is the collapse of West Antarctic and Greenland ice sheets, where a temperature rise of 1.5 to 2 °C may commit the ice sheets to melt, although the time scale of melt is uncertain and depends on future warming. Some large-scale changes could occur over a short time period, such as a collapse of certain ocean currents. Of particular concern is a shutdown of the Atlantic Meridional Overturning Circulation, which would trigger major climate changes in the North Atlantic, Europe, and North America. The long-term effects of climate change include further ice melt, ocean warming, sea level rise, and ocean acidification. On the timescale of centuries to millennia, the magnitude of climate change will be determined primarily by anthropogenic CO_2 emissions. This is due to CO_2's long atmospheric lifetime. Oceanic CO_2 uptake is slow enough that ocean acidification will continue for hundreds to thousands of years. These emissions are estimated to have prolonged the current interglacial period by at least 100,000 years. Sea level rise will continue over many centuries, with an estimated rise of 2.3 meters per degree Celsius (4.2 ft/°F) after 2000 years.

Nature and Wildlife

Recent warming has driven many terrestrial and freshwater species poleward and towards higher altitudes. Higher atmospheric CO_2 levels and an extended growing season have resulted in global greening. However, heat waves and drought have reduced ecosystem productivity in some regions. The future balance of these opposing effects is unclear. Climate change has contributed to the expansion of drier climate zones, such as the expansion of deserts in the subtropics. The size and speed of global warming is making abrupt changes in ecosystems more likely. Overall, it is expected that climate change will result in the extinction of many species.

The oceans have heated more slowly than the land, but plants and animals in the ocean have migrated towards the colder poles faster than species on land. Just as on land, heat waves in the ocean occur more frequently due to climate change, harming a wide range of organisms such as corals, kelp, and seabirds. Ocean acidification makes it harder for organisms such as mussels, barnacles and corals to produce shells and skeletons; and heat waves have bleached coral reefs. Harmful algal blooms enhanced by climate change and eutrophication lower oxygen levels, disrupt food webs and cause great loss of marine life. Coastal ecosystems are under particular stress. Almost half of global wetlands have disappeared due to climate change and other human impacts.

Humans

The IPCC Sixth Assessment Report (2021) projects that extreme weather will be progressively more common as the Earth warms. The effects of climate change on humans have been detected worldwide. They are mostly due to warming and shifts in precipitation. Impacts can now be observed on all continents and ocean regions, with low-latitude, less developed areas facing the greatest risk. Continued warming has potentially "severe, pervasive and irreversible impacts" for people and ecosystems. The risks are unevenly distributed but are generally greater for disadvantaged people in developing and developed countries.

Food and health

The WHO has classified climate change as the greatest threat to global health in the 21st century. Extreme weather leads to injury and loss of life, and crop failures to under nutrition. Various infectious diseases are more easily transmitted in a warmer climate, such as dengue fever and malaria. Young children are the most vulnerable to food shortages. Both children and older people are vulnerable to extreme heat. The World Health Organization (WHO) has estimated that between 2030 and 2050, climate change would cause around 250,000 additional deaths per year. They assessed deaths from heat exposure in elderly people, increases in diarrhea, malaria, dengue, coastal flooding, and childhood

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under nutrition. Over 500,000 more adult deaths are projected yearly by 2050 due to reductions in food availability and quality. Climate change is affecting food security. It has caused reduction in global yields of maize, wheat, and soybeans between 1981 and 2010. Future warming could further reduce global yields of major crops. Crop production will probably be negatively affected in low-latitude countries, while effects at northern latitudes may be positive or negative. Up to an additional 183 million people worldwide, particularly those with lower incomes, are at risk of hunger as a consequence of these impacts. Climate change also impacts fish populations. Globally, less will be available to be fished. Regions dependent on glacier water, regions that are already dry, and small islands have a higher risk of water stress due to climate change.

Livelihoods

Economic damages due to climate change may be severe and there is a chance of disastrous tail-risk events. Climate change has likely already increased global economic inequality, and this trend is projected to continue. Most of the severe impacts are expected in sub-Saharan Africa and South-East Asia. The World Bank estimates that climate change could drive over 120 million people into poverty by 2030. Current inequalities between men and women, between rich and poor, and between different ethnicities have worsened due to climate variability and climate change. An expert elicitation concluded that the role of climate change in armed conflict has been small compared to factors such as socio-economic inequality and state capabilities, but that future warming will bring increasing risks. Low-lying islands and coastal communities are threatened by sea level rise, which makes flooding more common. Sometimes, land is permanently lost to the sea. This could lead to statelessness for people in island nations, such as the Maldives and Tuvalu. In some regions, the rise in temperature and humidity may be too severe for humans to adapt to. With worst-case climate change, models project that almost one-third of humanity might live in extremely hot and uninhabitable climates, similar to the current climate found in the Sahara. These factors can drive environmental migration, both within and between countries. More people are expected to be displaced because of sea level rise, extreme weather and conflict from increased competition over natural resources. Climate change may also increase vulnerability, leading to "trapped populations" who are not able to move due to a lack of resources.

Responses

Mitigation

Scenarios of global greenhouse gas emissions. If all countries achieve their current Paris Agreement pledges, average warming by 2100 would still significantly exceed the maximum 2 °C target set by the Agreement. Climate change can be mitigated by reducing greenhouse gas emissions and by enhancing sinks that absorb greenhouse gases from the atmosphere. In order to limit global warming to less than 1.5 °C with a high likelihood of success, global greenhouse gas emissions need to be net-zero by 2050, or by 2070 with a 2 °C target. This requires far-reaching, systemic changes on an unprecedented scale in energy, land, cities, transport, buildings, and industry. The United Nations Environment Program estimates that countries need to triple their pledges under the Paris Agreement within the next decade to limit global warming to 2 °C. An even greater level of reduction is required to meet the 1.5 °C goal. With pledges made under the Agreement as of October 2021, global warming would still have a 66% chance of reaching about 2.7 °C (range: 2.2-3.2 °C) by the end of the century. Although there is no single pathway to limit global warming to 1.5 or 2 °C, most scenarios and strategies see a major increase in the use of renewable energy in combination with increased energy efficiency measures to generate the needed greenhouse gas reductions. To reduce pressures on ecosystems and enhance their carbon sequestration capabilities, changes would also be necessary in agriculture and forestry, such as preventing deforestation and restoring natural ecosystems by reforestation. Other approaches to mitigating climate change have a higher level of risk. Scenarios that limit global warming to 1.5 °C typically project the large-scale use of carbon dioxide removal methods over the 21st century. There are concerns, though, about over-reliance on these technologies, and environmental impacts. Solar radiation management (SRM) is also a possible supplement to deep reductions in emissions. However, SRM would raise significant ethical and legal issues, and the risks are poorly understood.

Clean Energy

Renewable energy is key to limiting climate change. Fossil fuels accounted for 80% of the world's energy in 2018. The remaining share was split between nuclear power and renewables (including solar and wind power, bioenergy, geothermal energy, and hydropower). That mix is projected to change significantly over the next 30 years. Solar and wind have seen substantial growth and progress over the last few years. Solar panels and onshore wind are the cheapest forms of adding new power generation capacity in most countries. Renewables represented 75% of all new electricity generation installed in 2019, nearly all solar and wind. Meanwhile, nuclear power share remains the same but costs are increasing. Nuclear power generation is now several times more expensive per megawatt-hour than wind and solar. To achieve carbon neutrality by 2050, renewable energy would become the dominant form of electricity generation, rising to 85% or more by 2050 in some scenarios. The use of electricity for heating and transport, would rise to the point where electricity becomes the largest form of energy. Investment in coal would be eliminated and coal use nearly phased out by 2050. In transport, emissions can be reduced fast by a switch to electric vehicles. Public transport and active transport (cycling and walking) also produce less CO_2. For shipping and flying, low-carbon fuels can be used to reduce emissions. Heating would be increasingly decarbonized with technologies like heat pumps.

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There are obstacles to the continued rapid growth of renewables. For solar and wind power, a key challenge is their intermittency and seasonal variability. Traditionally, hydro dams with reservoirs and conventional power plants have been used when variable energy production is low. Intermittency is further countered by expanding battery storage and matching energy demand and supply. Long-distance transmission can smooth variability of renewable output across wider geographic areas. There can be environmental and land use concerns with large solar and wind projects, while bioenergy is often not carbon-neutral and may have negative consequences for food security. Hydropower growth has been slowing and is set to decline further due to concerns about social and environmental impacts. Low-carbon energy improves human health by minimizing climate change. It also has the near-term benefit of reducing air pollution deaths, which were estimated at 7 million annually in 2016. Meeting the Paris Agreement goals that limit warming to a 2 °C increase could save about a million of those lives per year by 2050, whereas limiting global warming to 1.5 °C could save millions and simultaneously increase energy security and reduce poverty.

Energy Efficiency

Reducing energy demand is another major aspect of reducing emissions. If less energy is needed, there is more flexibility for clean energy development. It also makes it easier to manage the electricity grid and minimizes carbon-intensive infrastructure development. Major increases in energy efficiency investment will be required to achieve climate goals, comparable to the level of investment in renewable energy. Several COVID-19 related changes in energy use patterns, energy efficiency investments, and funding have made forecasts for this decade more difficult and uncertain. Strategies to reduce energy demand vary by sector. In transport, passengers and freight can switch to more efficient travel modes, such as buses and trains, or use electric vehicles. Industrial strategies to reduce energy demand include improving heating systems and motors, designing less energy-intensive products, and increasing product lifetimes. In the building sector the focus is on better design of new buildings, and higher levels of energy efficiency in retrofitting. The use of technologies like heat pumps can also increase building energy efficiency.

Agriculture and Industry

Agriculture and forestry face a triple challenge of limiting greenhouse gas emissions, preventing the further conversion of forests to agricultural land, and meeting increases in world food demand. A set of actions could reduce agriculture and forestry-based emissions by two thirds from 2010 levels. These include reducing growth in demand for food and other agricultural products, increasing land productivity, protecting and restoring forests, and reducing greenhouse gas emissions from agricultural production. Steel and cement production, responsible for about 13% of industrial CO_2 emissions, present particular challenges. In these industries, carbon-intensive materials such as coke and lime play an integral role in the production, so reducing CO_2 emissions requires research into alternative chemistries.

Carbon Sequestration

Most CO_2 emissions have been absorbed by carbon sinks, including plant growth, soil uptake, and ocean uptake (2020 Global Carbon Budget). Natural carbon sinks can be enhanced to sequester significantly larger amounts of CO_2 beyond naturally occurring levels. Reforestation and tree planting on non-forest lands are among the most mature sequestration techniques, although the latter raises food security concerns. Soil carbon sequestration and coastal carbon sequestration are less understood options. The feasibility of land-based negative emissions methods for mitigation are uncertain; the IPCC has described mitigation strategies based on them as risky. Where energy production or CO_2-intensive heavy industries continue to produce waste CO_2, the gas can be captured and stored instead of released to the atmosphere. Although its current use is limited in scale and expensive, carbon capture and storage (CCS) may be able to play a significant role in limiting CO_2 emissions by mid-century. This technique, in combination with bio-energy (BECCS) can result in net negative emissions: CO_2 is drawn from the atmosphere. It remains highly uncertain whether carbon dioxide removal techniques, such as BECCS, will be able to play a large role in limiting warming to 1.5 °C. Policy decisions that rely on carbon dioxide removal increase the risk of global warming rising beyond international goals.

Adaptation

Adaptation is "the process of adjustment to current or expected changes in climate and its effects". Without additional mitigation, adaptation cannot avert the risk of "severe, widespread and irreversible" impacts. More severe climate change requires more transformative adaptation, which can be prohibitively expensive. The capacity and potential for humans to adapt is unevenly distributed across different regions and populations, and developing countries generally have less. The first two decades of the 21st century saw an increase in adaptive capacity in most low- and middle-income countries with improved access to basic sanitation and electricity, but progress is slow. Many countries have implemented adaptation policies. However, there is a considerable gap between necessary and available finance. Adaptation to sea level rise consists of avoiding at-risk areas, learning to live with increased flooding and protection. If that fails, managed retreat may be needed. There are economic barriers for tackling dangerous heat impact. Avoiding strenuous work or having air conditioning is not possible for everybody. In agriculture, adaptation options include a switch to more sustainable diets, diversification, erosion control and genetic improvements for increased tolerance to a changing climate. Insurance allows for risk-sharing, but is often difficult to get for people on lower incomes. Education, migration and early warning systems can reduce climate vulnerability.

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Ecosystems adapt to climate change, a process that can be supported by human intervention. By increasing connectivity between ecosystems, species can migrate to more favorable climate conditions. Species can also be introduced to areas acquiring a favorable climate. Protection and restoration of natural and semi-natural areas helps build resilience, making it easier for ecosystems to adapt. Many of the actions that promote adaptation in ecosystems, also help humans adapt via ecosystem-based adaptation. For instance, restoration of natural fire regimes makes catastrophic fires less likely, and reduces human exposure. Giving rivers more space allows for more water storage in the natural system, reducing flood risk. Restored forest acts as a carbon sink, but planting trees in unsuitable regions can exacerbate climate impacts. There are synergies and trade-offs between adaptation and mitigation. Adaptation often offer short-term benefits, whereas mitigation has longer-term benefits. Increased use of air conditioning allows people to better cope with heat, but increases energy demand. Compact urban development may lead to reduced emissions from transport and construction. At the same time, it may increase the urban heat island effect, leading to higher temperatures and increased exposure. Increased food productivity has large benefits for both adaptation and mitigation.

Policies and Politics

Countries that are most vulnerable to climate change have typically been responsible for a small share of global emissions. This raises questions about justice and fairness. Climate change is strongly linked to sustainable development. Limiting global warming makes it easier to achieve sustainable development goals, such as eradicating poverty and reducing inequalities. The connection is recognized in Sustainable Development Goal 13 which is to “take urgent action to combat climate change and its impacts”. The goals on food, clean water and ecosystem protection have synergies with climate mitigation. The geopolitics of climate change is complex. It has often been framed as a free-rider problem, in which all countries benefit from mitigation done by other countries, but individual countries would lose from switching to a low-carbon economy themselves. This framing has been challenged. For instance, the benefits of a coal phase-out to public health and local environments exceed the costs in almost all regions. Furthermore, net importers of fossil fuels win economically from switching to clean energy, causing net exporters to face stranded assets: fossil fuels they cannot sell.

Policy Options

A wide range of policies, regulations, and laws are being used to reduce emissions. As of 2019, carbon pricing covers about 20% of global greenhouse gas emissions. Carbon can be priced with carbon taxes and emissions trading systems. Direct global fossil fuel subsidies reached $319 billion in 2017, and $5.2 trillion when indirect costs such as air pollution are priced in. Ending these can cause a 28% reduction in global carbon emissions and a 46% reduction in air pollution deaths. Subsidies could be used to support the transition to clean energy instead. More direct methods to reduce greenhouse gases include vehicle efficiency standards, renewable fuel standards, and air pollution regulations on heavy industry. Several countries require utilities to increase the share of renewables in power production. Policy designed through the lens of climate justice tries to address human rights issues and social inequality. For instance, wealthy nations responsible for the largest share of emissions would have to pay poorer countries to adapt. As the use of fossil fuels is reduced, jobs in the sector are being lost. To achieve a just transition, these people would need to be retrained for other jobs. Communities with many fossil fuel workers would need additional investments.

International Climate Agreements

Nearly all countries in the world are parties to the 1994 United Nations Framework Convention on Climate Change (UNFCCC). The goal of the UNFCCC is to prevent dangerous human interference with the climate system. As stated in the convention, this requires that greenhouse gas concentrations are stabilized in the atmosphere at a level where ecosystems can adapt naturally to climate change, food production is not threatened, and economic development can be sustained. The UNFCCC does not itself restrict emissions but rather provides a framework for protocols that do. Global emissions have risen since the UNFCCC was signed. Its yearly conferences are the stage of global negotiations. The 1997 Kyoto Protocol extended the UNFCCC and included legally binding commitments for most developed countries to limit their emissions. During the negotiations, the G77 (representing developing countries) pushed for a mandate requiring developed countries to “[take] the lead” in reducing their emissions, since developed countries contributed most to the accumulation of greenhouse gases in the atmosphere. Per-capita emissions were also still relatively low in developing countries and developing countries would need to emit more to meet their development needs. The 2009 Copenhagen Accord has been widely portrayed as disappointing because of its low goals and was rejected by poorer nations including the G77. Associated parties aimed to limit the global temperature rise to below 2 °C. The Accord set the goal of sending $100 billion per year to developing countries for mitigation and adaptation by 2020 and proposed the founding of the Green Climate Fund. As of 2020, the fund has failed to reach its expected target, and risks a shrinkage in its funding. In 2015 all UN countries negotiated the Paris Agreement, which aims to keep global warming well below 2.0 °C and contains an aspirational goal of keeping warming under 1.5 °C. The agreement replaced the Kyoto Protocol. Unlike Kyoto, no binding emission targets were set in the Paris Agreement. Instead, a set of procedures was made binding. Countries have to regularly set ever more ambitious goals and reevaluate these goals every five years. The Paris Agreement restated that developing countries must be financially supported. As of October 2021, 194 states and the European Union have signed the treaty and 191 states and the EU have ratified or acceded to the agreement. The 1987 Montreal

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Protocol, an international agreement to stop emitting ozone-depleting gases, may have been more effective at curbing greenhouse gas emissions than the Kyoto Protocol specifically designed to do so. The 2016 Kigali Amendment to the Montreal Protocol aims to reduce the emissions of hydrofluorocarbons, a group of powerful greenhouse gases which served as a replacement for banned ozone-depleting gases. This made the Montreal Protocol a stronger agreement against climate change [31-40].

National Responses

In 2019, the United Kingdom parliament became the first national government to declare a climate emergency. Other countries and jurisdictions followed suit. That same year, the European Parliament declared a "climate and environmental emergency". The European Commission presented its European Green Deal with the goal of making the EU carbon-neutral by 2050. Major countries in Asia have made similar pledges: South Korea and Japan have committed to become carbon-neutral by 2050, and China by 2060. In 2021, the European Commission released its "Fit for 55" legislation package, which contains guidelines for the car industry; all new cars on the European market must be zero-emission vehicles from 2035. While India has strong incentives for renewables, it also plans a significant expansion of coal in the country. As of 2021, based on information from 48 national climate plans, which represent 40% of the parties to the Paris Agreement, estimated total greenhouse gas emissions will be 0.5% lower compared to 2010 levels, below the 45% or 25% reduction goals to limit global warming to 1.5 °C or 2 °C, respectively.

Scientific Consensus and Society

There is a near-complete scientific consensus that the climate is warming and that this is caused by human activities. Agreement in recent literature reached over 99%. No scientific body of national or international standing disagrees with this view. Consensus has further developed that some form of action should be taken to protect people against the impacts of climate change. National science academies have called on world leaders to cut global emissions. Scientific discussion takes place in journal articles that are peer-reviewed. Scientists assess these every few years in the Intergovernmental Panel on Climate Change reports. The 2021 IPCC Assessment Report stated that it is "unequivocal" that climate change is caused by humans.

Denial and Misinformation

Public debate about climate change has been strongly affected by climate change denial and misinformation, which originated in the United States and has since spread to other countries, particularly Canada and Australia. The actors behind climate change denial form a well-funded and relatively coordinated coalition of fossil fuel companies, industry groups, conservative think tanks, and contrarian scientists. Like the tobacco industry, the main strategy of these groups has been to manufacture doubt about scientific data and results. Many who deny, dismiss, or hold unwarranted doubt about the scientific consensus on anthropogenic climate change are labelled as "climate change skeptics", which several scientists have noted is a misnomer. There are different variants of climate denial: some deny that warming takes place at all, some acknowledge warming but attribute it to natural influences, and some minimize the negative impacts of climate change. Manufacturing uncertainty about science later developed into a manufactured controversy: creating the belief that there is significant uncertainty about climate change within the scientific community in order to delay policy changes. Strategies to promote these ideas include criticism of scientific institutions and questioning the motives of individual scientists. An echo chamber of climate-denying blogs and media has further fomented misunderstanding of climate change.

Public Awareness and Opinion

Climate change came to international public attention in the late 1980s. Due to media coverage in the early 1990s, people often confused climate change with other environmental issues like ozone depletion. In popular culture, the climate fiction movie The Day After Tomorrow (2004) and the Al Gore documentary An Inconvenient Truth (2006) focused on climate change. Significant regional, gender, age and political differences exist in both public concern for, and understanding of, climate change. More highly educated people, and in some countries, women and younger people, were more likely to see climate change as a serious threat. Partisan gaps also exist in many countries, and countries with high CO_2 emissions tend to be less concerned. Views on causes of climate change vary widely between countries. Concern has increased over time, to the point where in 2021 a majority of citizens in many countries express a high level of worry about climate change or view it as a global emergency. Higher levels of worry are associated with stronger public support for policies that address climate change.

Protests and Lawsuits

Climate protests have risen in popularity in the 2010s. These protests demand that political leaders take action to prevent climate change. They can take the form of public demonstrations, fossil fuel divestment, lawsuits and other activities. Prominent demonstrations include the School Strike for Climate. In this initiative, young people across the globe have been protesting since 2018 by skipping school on Fridays, inspired by Swedish teenager Greta Thunberg. Mass civil disobedience actions by groups like Extinction Rebellion have protested by disrupting roads and public transport. Litigation is increasingly used as a tool to strengthen climate action from public institutions and companies. Activists also initiate lawsuits which target governments and demand that they take ambitious action or enforce existing laws on climate change. Lawsuits against fossil-fuel companies generally seek compensation for loss and damage.

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Discovery

Tyndall's ratio spectrophotometer (drawing from 1861) measured how much infrared radiation was absorbed and emitted by various gases filling its central tube. In the 1820s, Joseph Fourier proposed the greenhouse effect to explain why Earth's temperature was higher than the sun's energy alone could explain. Earth's atmosphere is transparent to sunlight, so sunlight reaches the surface where it is converted to heat. However, the atmosphere is not transparent to heat radiating from the surface and captures some of that heat which warms the planet. In 1856 Eunice Newton Foote demonstrated that the warming effect of the sun is greater for air with water vapor than for dry air, and the effect is even greater with carbon dioxide. She concluded that "An atmosphere of that gas would give to our earth a high temperature..." Starting in 1859, John Tyndall established that nitrogen and oxygen-together totaling 99% of dry air-are transparent to radiated heat. However, water vapor and some gases (in particular methane and carbon dioxide) absorb radiated heat and re-radiate that heat within the atmosphere. Tyndall proposed that changes in the concentrations of these gases may have caused climatic changes in the past, including the ice ages. Svante Arrhenius noted that water vapor in air continuously varied, but the CO_2 concentration in air was influenced by long-term geological processes. At the end of an ice age, warming from increased CO_2 levels would increase the amount of water vapor, amplifying warming in a feedback loop. In 1896, he published the first climate model of its kind, showing that halving of CO_2 levels could have produced the drop in temperature initiating the ice age. Arrhenius calculated the temperature increase expected from doubling CO_2 to be around 5-6 °C. Other scientists were initially sceptical and believed the greenhouse effect to be saturated so that adding more CO_2 would make no difference. They thought climate would be self-regulating. From 1938 onwards Guy Stewart Callendar published evidence that climate was warming and CO_2 levels rising, but his calculations met the same objections. In the 1950s, Gilbert Plass created a detailed computer model that included different atmospheric layers and the infrared spectrum. This model predicted that increasing CO_2 levels would cause warming. Around the same time, Hans Suess found evidence that CO_2 levels had been rising, and Roger Revelle showed that the oceans would not absorb the increase. The two scientists subsequently helped Charles Keeling to begin a record of continued increase, which has been termed the "Keeling Curve". Scientists alerted the public, and the dangers were highlighted at James Hansen's 1988 Congressional testimony. The Intergovernmental Panel on Climate Change, set up in 1988 to provide formal advice to the world's governments, spurred interdisciplinary research.

Causes of Climate Change

Humans are increasingly influencing the climate and the earth's temperature by burning fossil fuels, cutting down forests and farming livestock. This adds enormous amounts of greenhouse gases to those naturally occurring in the atmosphere, increasing the greenhouse effect and global warming. Greenhouse gases. The main driver of climate change is the greenhouse effect. Some gases in the Earth's atmosphere act a bit like the glass in a greenhouse, trapping the sun's heat and stopping it from leaking back into space and causing global warming. Many of these greenhouse gases occur naturally, but human activity is increasing the concentrations of some of them in the atmosphere, in particular:

- Carbon Dioxide (CO_2)
- Methane
- Nitrous Oxide
- Fluorinated Gases

CO_2 produced by human activities is the largest contributor to global warming. By 2020, its concentration in the atmosphere had risen to 48% above its pre-industrial level (before 1750). Other greenhouse gases are emitted by human activity in smaller quantities. Methane is a more powerful greenhouse gas than CO_2 but has a shorter atmospheric lifetime. Nitrous oxide, like CO_2, is a long-lived greenhouse gas that accumulates in the atmosphere over decades to centuries. Natural causes, such as changes in solar radiation or volcanic activity are estimated to have contributed less than plus or minus 0.1°C to total warming between 1890 and 2010.

Causes for Rising Emissions

- Burning coal, oil and gas produces carbon dioxide and nitrous oxide.
- Cutting down forests (deforestation). Trees help to regulate the climate by absorbing CO_2 from the atmosphere. When they are cut down, that beneficial effect is lost and the carbon stored in the trees is released into the atmosphere, adding to the greenhouse effect.
- Increasing livestock farming. Cows and sheep produce large amounts of methane when they digest their food.
- Fertilisers containing nitrogen produce nitrous oxide emissions.
- Fluorinated gases are emitted from equipment and products that use these gases. Such emissions have a very strong warming effect, up to 23 000 times greater than CO_2.

2011-2020 was the warmest decade recorded, with global average temperature reaching 1.1°C above pre-industrial levels in 2019. Human-induced global warming is presently increasing at a rate of 0.2°C per decade.

An increase of 2°C compared to the temperature in pre-industrial times is associated with serious negative impacts on to the natural environment and human health and wellbeing,

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including a much higher risk that dangerous and possibly catastrophic changes in the global environment will occur. For this reason, the international community has recognized the need to keep warming well below 2°C and pursue efforts to limit it to 1.5°C. Global warming, the phenomenon of increasing average air temperatures near the surface of Earth over the past one to two centuries. Climate scientists have since the mid-20th century gathered detailed observations of various weather phenomena (such as temperatures, precipitation, and storms) and of related influences on climate (such as ocean currents and the atmosphere's chemical composition). These data indicate that Earth's climate has changed over almost every conceivable timescale since the beginning of geologic time and that human activities since at least the beginning of the Industrial Revolution have a growing influence over the pace and extent of present-day climate change. Giving voice to a growing conviction of most of the scientific community, the Intergovernmental Panel on Climate Change (IPCC) was formed in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). The IPCC's Sixth Assessment Report (AR6), published in 2021, noted that the best estimate of the increase in global average surface temperature between 1850 and 2019 was 1.07 °C (1.9 °F). An IPCC special report produced in 2018 noted that human beings and their activities have been responsible for a worldwide average temperature increase between 0.8 and 1.2 °C (1.4 and 2.2 °F) since preindustrial times, and most of the warming over the second half of the 20th century could be attributed to human activities. AR6 produced a series of global climate predictions based on modeling five greenhouse gas emission scenarios that accounted for future emissions, mitigation (severity reduction) measures, and uncertainties in the model projections. Some of the main uncertainties include the precise role of feedback processes and the impacts of industrial pollutants known as aerosols, which may offset some warming. The lowest-emissions scenario, which assumed steep cuts in greenhouse gas emissions beginning in 2015, predicted that the global mean surface temperature would increase between 1.0 and 1.8 °C (1.8 and 3.2 °F) by 2100 relative to the 1850-1900 average. This range stood in stark contrast to the highest-emissions scenario, which predicted that the mean surface temperature would rise between 3.3 and 5.7 °C (5.9 and 10.2 °F) by 2100 based on the assumption that greenhouse gas emissions would continue to increase throughout the 21st century. The intermediate-emissions scenario, which assumed that emissions would stabilize by 2050 before declining gradually, projected an increase of between 2.1 and 3.5 °C (3.8 and 6.3 °F) by 2100.

Many climate scientists agree that significant societal, economic, and ecological damage would result if the global average temperature rose by more than 2 °C (3.6 °F) in such a short time. Such damage would include increased extinction of many plant and animal species, shifts in patterns of agriculture, and rising sea levels. By 2015 all but a few national governments had begun the process of instituting carbon reduction plans as part of the Paris Agreement, a treaty designed to help countries keep global warming to 1.5 °C (2.7 °F) above preindustrial levels in order to avoid the worst of the predicted effects. Whereas authors of the 2018 special report noted that should carbon emissions continue at their present rate, the increase in average near-surface air temperature would reach 1.5 °C sometime between 2030 and 2052, authors of the AR6 report suggested that this threshold would be reached by 2041 at the latest. The AR6 report also noted that the global average sea level had risen by some 20 cm (7.9 inches) between 1901 and 2018 and that sea level rose faster in the second half of the 20th century than in the first half. It also predicted, again depending on a wide range of scenarios, that the global average sea level would rise by different amounts by 2100 relative to the 1995-2014 average. Under the report's lowest-emission scenario, sea level would rise by 28-55 cm (11-21.7 inches), whereas, under the intermediate emissions scenario, sea level would rise by 44-76 cm (17.3-29.9 inches). The highest-emissions scenario suggested that sea level would rise by 63-101 cm (24.8-39.8 inches) by 2100.

The scenarios referred to above depend mainly on future concentrations of certain trace gases, called greenhouse gases that have been injected into the lower atmosphere in increasing amounts through the burning of fossil fuels for industry, transportation, and residential uses. Modern global warming is the result of an increase in magnitude of the so-called greenhouse effect, a warming of Earth's surface and lower atmosphere caused by the presence of water vapor, carbon dioxide, methane, nitrous oxides, and other greenhouse gases. In 2014 the IPCC first reported that concentrations of carbon dioxide, methane, and nitrous oxides in the atmosphere surpassed those found in ice cores dating back 800,000 years. Of all these gases, carbon dioxide is the most important, both for its role in the greenhouse effect and for its role in the human economy. It has been estimated that, at the beginning of the industrial age in the mid-18th century, carbon dioxide concentrations in the atmosphere were roughly 280 parts per million (ppm). By the end of 2021 they had risen to 416 ppm, and, if fossil fuels continue to be burned at current rates, they are projected to reach 550 ppm by the mid-21st century essentially, a doubling of carbon dioxide concentrations in 300 years. A vigorous debate is in progress over the extent and seriousness of rising surface temperatures, the effects of past and future warming on human life, and the need for action to reduce future warming and deal with its consequences. This article provides an overview of the scientific background and public policy debate related to the subject of global warming. It considers the causes of rising near-surface air temperatures, the influencing factors, the process of climate research and forecasting, the possible ecological and social impacts of rising temperatures, and the public policy developments since the mid-20th century. For a detailed description of Earth's climate, its processes, and the responses of living things to its changing nature, see climate.

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For additional background on how Earth's climate has changed throughout geologic time, see climatic variation and change. For a full description of Earth's gaseous envelope, within which climate change and global warming occur, see the atmosphere.

Climatic variation since the last glaciation

Global warming is related to the more general phenomenon of climate change, which refers to changes in the totality of attributes that define climate. In addition to changes in air temperature, climate change involves changes to precipitation patterns, winds, ocean currents, and other measures of Earth's climate. Normally, climate change can be viewed as the combination of various natural forces occurring over diverse timescales. Since the advent of human civilization, climate change has involved an "anthropogenic," or exclusively human-caused, element, and this anthropogenic element has become more important in the industrial period of the past two centuries. The term global warming is used specifically to refer to any warming of near-surface air during the past two centuries that can be traced to anthropogenic causes. To define the concepts of global warming and climate change properly, it is first necessary to recognize that the climate of Earth has varied across many timescales, ranging from an individual human life span to billions of years. This variable climate history is typically classified in terms of "regimes" or "epochs." For instance, the Pleistocene glacial epoch (about 2,600,000 to 11,700 years ago) was marked by substantial variations in the global extent of glaciers and ice sheets. These variations took place on timescales of tens to hundreds of millennia and were driven by changes in the distribution of solar radiation across Earth's surface. The distribution of solar radiation is known as the insolation pattern, and it is strongly affected by the geometry of Earth's orbit around the Sun and by the orientation, or tilt, of Earth's axis relative to the direct rays of the Sun.

Worldwide, the most recent glacial period, or ice age, culminated about 21,000 years ago in what is often called the Last Glacial Maximum. During this time, continental ice sheets extended well into the middle latitude regions of Europe and North America, reaching as far south as present-day London and New York City. Global annual mean temperature appears to have been about 4-5 °C (7-9 °F) colder than in the mid-20th century. It is important to remember that these figures are a global average. In fact, during the height of this last ice age, Earth's climate was characterized by greater cooling at higher latitudes (that is, toward the poles) and relatively little cooling over large parts of the tropical oceans (near the Equator). This glacial interval terminated abruptly about 11,700 years ago and was followed by the subsequent relatively ice-free period known as the Holocene Epoch. The modern period of Earth's history is conventionally defined as residing within the Holocene. However, some scientists have argued that the Holocene Epoch terminated in the relatively recent past and that Earth currently resides in a climatic interval that could justly be called the Anthropocene Epoch-that is, a period during which humans have exerted a dominant influence over climate. Though less dramatic than the climate changes that occurred during the Pleistocene Epoch, significant variations in global climate have nonetheless taken place over the course of the Holocene. During the early Holocene, roughly 9,000 years ago, atmospheric circulation and precipitation patterns appear to have been substantially different from those of today. For example, there is evidence for relatively wet conditions in what is now the Sahara Desert. The change from one climatic regime to another was caused by only modest changes in the pattern of insolation within the Holocene interval as well as the interaction of these patterns with large-scale climate phenomena such as monsoons and El Niño/Southern Oscillation (ENSO).

During the middle Holocene, some 5,000-7,000 years ago, conditions appear to have been relatively warm-indeed, perhaps warmer than today in some parts of the world and during certain seasons. For this reason, this interval is sometimes referred to as the Mid-Holocene Climatic Optimum. The relative warmth of average near-surface air temperatures at this time, however, is somewhat unclear. Changes in the pattern of insolation favored warmer summers at higher latitudes in the Northern Hemisphere, but these changes also produced cooler winters in the Northern Hemisphere and relatively cool conditions year-round in the tropics. Any overall hemispheric or global mean temperature changes thus reflected a balance between competing seasonal and regional changes. In fact, recent theoretical climate model studies suggest that global mean temperatures during the middle Holocene were probably 0.2-0.3 °C (0.4-0.5 °F) colder than average late 20th-century conditions. Over subsequent millennia, conditions appear to have cooled relative to middle Holocene levels. This period has sometimes been referred to as the "Neoglacial." In the middle latitudes this cooling trend was associated with intermittent periods of advancing and retreating mountain glaciers reminiscent of (though far more modest than) the more substantial advance and retreat of the major continental ice sheets of the Pleistocene climate epoch.

Causes of Global Warming

The Greenhouse Effect

The amount of solar radiation absorbed by Earth's surface is only a small fraction of the total solar radiation entering the atmosphere. For every 100 units of incoming solar radiation, roughly 30 units are reflected back to space by either cloud, the atmosphere, or reflective regions of Earth's surface. This reflective capacity is referred to as Earth's planetary albedo, and it need not remain fixed over time, since the spatial extent and distribution of reflective formations, such as clouds and ice cover, can change. The 70 units of solar radiation that are not reflected may be absorbed by the atmosphere, clouds, or the surface. In the absence of further complications, in order to maintain thermodynamic equilibrium, Earth's surface and atmosphere must radiate these same 70 units

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back to space. Earth's surface temperature (and that of the lower layer of the atmosphere essentially in contact with the surface) is tied to the magnitude of this emission of outgoing radiation according to the Stefan-Boltzmann law. Earth's energy budget is further complicated by the greenhouse effect. Trace gases with certain chemical properties -the so-called greenhouse gases, mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) - absorb some of the infrared radiation produced by Earth's surface. Because of this absorption, some fraction of the original 70 units does not directly escape to space. Because greenhouse gases emit the same amount of radiation they absorb and because this radiation is emitted equally in all directions (that is, as much downward as upward), the net effect of absorption by greenhouse gases is to increase the total amount of radiation emitted downward toward Earth's surface and lower atmosphere. To maintain equilibrium, Earth's surface and lower atmosphere must emit more radiation than the original 70 units. Consequently, the surface temperature must be higher. This process is not quite the same as that which governs a true greenhouse, but the end effect is similar. The presence of greenhouse gases in the atmosphere leads to a warming of the surface and lower part of the atmosphere (and a cooling higher up in the atmosphere) relative to what would be expected in the absence of greenhouse gases.

It is essential to distinguish the "natural," or background, greenhouse effect from the "enhanced" greenhouse effect associated with human activity. The natural greenhouse effect is associated with surface warming properties of natural constituents of Earth's atmosphere, especially water vapor, carbon dioxide, and methane. The existence of this effect is accepted by all scientists. Indeed, in its absence, Earth's average temperature would be approximately 33°C (59 °F) colder than today, and Earth would be a frozen and likely uninhabitable planet. What has been subject to controversy is the so-called enhanced greenhouse effect, which is associated with increased concentrations of greenhouse gases caused by human activity. In particular, the burning of fossil fuels raises the concentrations of the major greenhouse gases in the atmosphere, and these higher concentrations have the potential to warm the atmosphere by several degrees.

Radiative Forcing

In light of the discussion above of the greenhouse effect, it is apparent that the temperature of Earth's surface and lower atmosphere may be modified in three ways: (1) through a net increase in the solar radiation entering at the top of Earth's atmosphere, (2) through a change in the fraction of the radiation reaching the surface, and (3) through a change in the concentration of greenhouse gases in the atmosphere. In each case the changes can be thought of in terms of "radiative forcing." As defined by the IPCC, radiative forcing is a measure of the influence a given climatic factor has on the amount of downward-directed radiant energy impinging upon Earth's surface. Climatic factors are divided between those caused primarily by human activity (such as greenhouse gas emissions and aerosol emissions) and those caused by natural forces (such as solar irradiance); then, for each factor, so-called forcing values are calculated for the time period between 1750 and the present day. "Positive forcing" is exerted by climatic factors that contribute to the warming of Earth's surface, whereas "negative forcing" is exerted by factors that cool Earth's surface. On average, about 342 watts of solar radiation strike each square meter of Earth's surface per year, and this quantity can in turn be related to a rise or fall in Earth's surface temperature. Temperatures at the surface may also rise or fall through a change in the distribution of terrestrial radiation (that is, radiation emitted by Earth) within the atmosphere. In some cases, radiative forcing has a natural origin, such as during explosive eruptions from volcanoes where vented gases and ash block some portion of solar radiation from the surface. In other cases, radiative forcing has an anthropogenic, or exclusively human, origin. For example, anthropogenic increases in carbon dioxide, methane, and nitrous oxide are estimated to account for 2.3 watts per square meter of positive radiative forcing. When all values of positive and negative radiative forcing are taken together and all interactions between climatic factors are accounted for, the total net increase in surface radiation due to human activities since the beginning of the Industrial Revolution is 1.6 watts per square meter.

The Influences of Human Activity on Climate

Human activity has influenced global surface temperatures by changing the radiative balance governing the Earth on various timescales and at varying spatial scales. The most profound and well-known anthropogenic influence is the elevation of concentrations of greenhouse gases in the atmosphere. Humans also influence climate by changing the concentrations of aerosols and ozone and by modifying the land cover of Earth's surface.

Greenhouse Gases

As discussed above, greenhouse gases warm Earth's surface by increasing the net downward long wave radiation reaching the surface. The relationship between atmospheric concentration of greenhouse gases and the associated positive radiative forcing of the surface is different for each gas. A complicated relationship exists between the chemical properties of each greenhouse gas and the relative amount of long wave radiation that each can absorb. What follows is a discussion of the radiative behavior of each major greenhouse gas.

Water Vapor

Water vapor is the most potent of the greenhouse gases in Earth's atmosphere, but its behavior is fundamentally different from that of the other greenhouse gases. The primary role of water vapor is not as a direct agent of radiative forcing but rather as climate feedback that is, as a response within the climate system that influences the system's continued activity. This distinction arises from the fact that the amount of water vapor in the atmosphere cannot, in general, be directly modified by human

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behavior but is instead set by air temperatures. The warmer the surface, the greater the evaporation rate of water from the surface. As a result, increased evaporation leads to a greater concentration of water vapor in the lower atmosphere capable of absorbing long wave radiation and emitting it downward.

Carbon Dioxide

Of the greenhouse gases, carbon dioxide (CO_2) is the most significant. Natural sources of atmospheric CO_2 include outgassing from volcanoes, the combustion and natural decay of organic matter, and respiration by aerobic (oxygen-using) organisms. These sources are balanced, on average, by a set of physical, chemical, or biological processes, called "sinks," that tend to remove CO_2 from the atmosphere. Significant natural sinks include terrestrial vegetation, which takes up CO_2 during the process of photosynthesis.

Carbon Cycle

Carbon is transported in various forms through the atmosphere, the hydrosphere, and geologic formations. One of the primary pathways for the exchange of carbon dioxide (CO_2) takes place between the atmosphere and the oceans; there a fraction of the CO_2 combines with water, forming carbonic acid (H_2CO_3) that subsequently loses hydrogen ions (H^+) to form bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. Mollusk shells or mineral precipitates that form by the reaction of calcium or other metal ions with carbonate may become buried in geologic strata and eventually release CO_2 through volcanic outgassing. Carbon dioxide also exchanges through photosynthesis in plants and through respiration in animals. Dead and decaying organic matter may ferment and release CO_2 or methane (CH_4) or may be incorporated into sedimentary rock, where it is converted to fossil fuels. Burning of hydrocarbon fuels returns CO_2 and water (H_2O) to the atmosphere. The biological and anthropogenic pathways are much faster than the geochemical pathways and, consequently, have a greater impact on the composition and temperature of the atmosphere. A number of oceanic processes also act as carbon sinks. One such process, called the "solubility pump," involves the descent of surface seawater containing dissolved CO_2. Another process, the "biological pump," involves the uptake of dissolved CO_2 by marine vegetation and phytoplankton (small free-floating photosynthetic organisms) living in the upper ocean or by other marine organisms that use CO_2 to build skeletons and other structures made of calcium carbonate ($CaCO_3$). As these organisms expire and fall to the ocean floor, the carbon they contain is transported downward and eventually buried at depth. A long-term balance between these natural sources and sinks leads to the background, or natural, level of CO_2 in the atmosphere [41-50].

In contrast, human activities increase atmospheric CO_2 levels primarily through the burning of fossil fuels -principally oil and coal and secondarily natural gas, for use in transportation, heating, and the generation of electrical power- and through the production of cement. Other anthropogenic sources include the burning of forests and the clearing of land. Anthropogenic emissions currently account for the annual release of about 7 Giga tons (7 billion tons) of carbon into the atmosphere. Anthropogenic emissions are equal to approximately 3 percent of the total emissions of CO_2 by natural sources, and this amplified carbon load from human activities far exceeds the offsetting capacity of natural sinks (by perhaps as much as 2-3 Giga tons per year). CO_2 consequently accumulated in the atmosphere at an average rate of 1.4 ppm per year between 1959 and 2006 and roughly 2.0 ppm per year between 2006 and 2018. Overall, this rate of accumulation has been linear (that is, uniform over time). However, certain current sinks, such as the oceans, could become sources in the future. This may lead to a situation in which the concentration of atmospheric CO_2 builds at an exponential rate (that is, its rate of increase is also increasing).

The natural background level of carbon dioxide varies on timescales of millions of years because of slow changes in outgassing through volcanic activity. For example, roughly 100 million years ago, during the Cretaceous Period (145 million to 66 million years ago), CO_2 concentrations appear to have been several times higher than they are today (perhaps close to 2,000 ppm). Over the past 700,000 years, CO_2 concentrations have varied over a far smaller range (between roughly 180 and 300 ppm) in association with the same Earth orbital effects linked to the coming and going of the Pleistocene ice age. By the early 21st century CO_2 levels had reached 384 ppm, which is approximately 37 percent above the natural background level of roughly 280 ppm that existed at the beginning of the Industrial Revolution. Atmospheric CO_2 levels continued to increase, and by 2021 they had reached 416 ppm. Such levels are believed to be the highest in at least 800,000 years according to ice core measurements and may be the highest in at least 5 million years according to other lines of evidence.

Radiative forcing caused by carbon dioxide varies in an approximately logarithmic fashion with the concentration of that gas in the atmosphere. The logarithmic relationship occurs as the result of a saturation effect wherein it becomes increasingly difficult, as CO_2 concentrations increase, for additional CO_2 molecules to further influence the "infrared window" (a certain narrow band of wavelengths in the infrared region that is not absorbed by atmospheric gases). The logarithmic relationship predicts that the surface warming potential will rise by roughly the same amount for each doubling of CO_2 concentration. At current rates of fossil fuel use, a doubling of CO_2 concentrations over preindustrial levels is expected to take place by the middle of the 21st century (when CO_2 concentrations are projected to reach 560 ppm). A doubling of CO_2 concentrations would represent an increase of roughly 4 watts per square meter of radiative forcing. Given typical estimates of "climate sensitivity" in the absence of any offsetting factors, this energy increase would lead to a warming of 2 to 5 °C (3.6 to 9 °F) over preindustrial times. The total radiative forcing by anthropogenic CO_2 emissions since the

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beginning of the industrial age is approximately 1.66 watts per square meter.

Methane

Methane (CH_4) is the second most important greenhouse gas. CH_4 is more potent than CO_2 because the radiative forcing produced per molecule is greater. In addition, the infrared window is less saturated in the range of wavelengths of radiation absorbed by CH_4, so more molecules may fill in the region. However, CH_4 exists in far lower concentrations than CO_2 in the atmosphere, and its concentrations by volume in the atmosphere are generally measured in parts per billion (ppb) rather than ppm. CH_4 also has a considerably shorter residence time in the atmosphere than CO_2 (the residence time for CH_4 is roughly 10 years, compared with hundreds of years for CO_2). Natural sources of methane include tropical and northern wetlands, methane-oxidizing bacteria that feed on organic material consumed by termites, volcanoes, seepage vents of the seafloor in regions rich with organic sediment, and methane hydrates trapped along the continental shelves of the oceans and in polar permafrost. The primary natural sink for methane is the atmosphere itself, as methane reacts readily with the hydroxyl radical (·OH) within the troposphere to form CO_2 and water vapor (H_2O). When CH_4 reaches the stratosphere, it is destroyed. Another natural sink is soil, where methane is oxidized by bacteria. As with CO_2, human activity is increasing the CH_4 concentration faster than it can be offset by natural sinks. Anthropogenic sources currently account for approximately 70 percent of total annual emissions, leading to substantial increases in concentration over time. The major anthropogenic sources of atmospheric CH_4 are rice cultivation, livestock farming, and the burning of coal and natural gas, the combustion of biomass, and the decomposition of organic matter in landfills. Future trends are particularly difficult to anticipate. This is in part due to an incomplete understanding of the climate feedbacks associated with CH_4 emissions. In addition, it is difficult to predict how, as human populations grow, possible changes in livestock raising, rice cultivation, and energy utilization will influence CH_4 emissions.

It is believed that a sudden increase in the concentration of methane in the atmosphere was responsible for a warming event that raised average global temperatures by 4-8 °C (7.2-14.4 °F) over a few thousand years during the so-called Paleocene-Eocene Thermal Maximum, or PETM. This episode took place roughly 55 million years ago, and the rise in CH4 appears to have been related to a massive volcanic eruption that interacted with methane-containing flood deposits. As a result, large amounts of gaseous CH_4 were injected into the atmosphere. It is difficult to know precisely how high these concentrations were or how long they persisted. At very high concentrations, residence times of CH_4 in the atmosphere can become much greater than the nominal 10-year residence time that applies today. Nevertheless, it is likely that these concentrations reached several ppm during the PETM. Methane concentrations have also varied over a smaller range (between roughly 350 and 800 ppb) in association with the Pleistocene ice age cycles. Preindustrial levels of CH4 in the atmosphere were approximately 700 ppb, whereas levels exceeded 1,876 ppb in late 2021. (These concentrations are well above the natural levels observed for at least the past 650,000 years.) The net radiative forcing by anthropogenic CH_4 emissions is approximately 0.5 watt per square meter or roughly one-third the radiative forcing of CO_2.

Surface-Level Ozone and Other Compounds

The next most significant greenhouse gas is surface, or low-level, ozone (O_3). Surface O_3 is a result of air pollution; it must be distinguished from naturally occurring stratospheric O_3, which has a very different role in the planetary radiation balance. The primary natural source of surface O_3 is the subsidence of stratospheric O_3 from the upper atmosphere. In contrast, the primary anthropogenic source of surface O_3 is photochemical reactions involving the atmospheric pollutant carbon monoxide (CO). The best estimates of the natural concentration of surface O_3 are 10 ppb, and the net radiative forcing due to anthropogenic emissions of surface O_3 is approximately 0.35 watt per square meter. Ozone concentrations can rise above unhealthy levels (that is, conditions where concentrations meet or exceed 70 ppb for eight hours or longer) in cities prone to photochemical smog.

Nitrous Oxides and Fluorinated Gases

Additional trace gases produced by industrial activity that have greenhouse properties include nitrous oxide (N_2O) and fluorinated gases (halocarbons), the latter including sulfur hexafluoride, hydrofluorocarbons (HFCs), and per-fluorocarbons (PFCs). Nitrous oxide is responsible for 0.16 watt per square meter radiative forcing, while fluorinated gases are collectively responsible for 0.34 watt per square meter. Nitrous oxides have small background concentrations due to natural biological reactions in soil and water, whereas the fluorinated gases owe their existence almost entirely too industrial sources.

Aerosols

The production of aerosols represents an important anthropogenic radiative force of climate. Collectively, aerosols block -that is, reflect and absorb- a portion of incoming solar radiation, and this creates a negative radiative forcing. Aerosols are second only to greenhouse gases in relative importance in their impact on near-surface air temperatures. Unlike the decade-long residence times of the “well-mixed” greenhouse gases, such as CO_2 and CH_4, aerosols are readily flushed out of the atmosphere within days, either by rain or snow (wet deposition) or by settling out of the air (dry deposition). They must therefore be continually generated in order to produce a steady effect on radiative forcing.

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Aerosols have the ability to influence climate directly by absorbing or reflecting incoming solar radiation, but they can also produce indirect effects on climate by modifying cloud formation or cloud properties. Most aerosols serve as condensation nuclei (surfaces upon which water vapor can condense to form clouds); however, darker-colored aerosols may hinder cloud formation by absorbing sunlight and heating up the surrounding air. Aerosols can be transported thousands of kilometers from their sources of origin by winds and upper-level circulation in the atmosphere. Perhaps the most important type of anthropogenic aerosol in radiative forcing is sulfate aerosol. It is produced from sulfur dioxide (SO_2) emissions associated with the burning of coal and oil. Since the late 1980s, global emissions of SO_2 have decreased from about 151.5 million tons (167.0 million tons) to less than 100 million tons (110.2 million tons) of sulfur per year.

Nitrate aerosol is not as important as sulfate aerosol, but it has the potential to become a significant source of negative forcing. One major source of nitrate aerosol is smog (the combination of ozone with oxides of nitrogen in the lower atmosphere) released from the incomplete burning of fuel in internal-combustion engines. Another source is ammonia (NH_3), which is often used in fertilizers or released by the burning of plants and other organic materials. If greater amounts of atmospheric nitrogen are converted to ammonia and agricultural ammonia emissions continue to increase as projected, the influence of nitrate aerosols on radiative forcing is expected to grow. Both sulfate and nitrate aerosols act primarily by reflecting incoming solar radiation, thereby reducing the amount of sunlight reaching the surface. Most aerosols, unlike greenhouse gases, impart a cooling rather than warming influence on Earth's surface. One prominent exception is carbonaceous aerosols such as carbon black or soot, which are produced by the burning of fossil fuels and biomass. Carbon black tends to absorb rather than reflect incident solar radiation, and so it has a warming impact on the lower atmosphere, where it resides. Because of its absorptive properties, carbon black is also capable of having an additional indirect effect on climate. Through its deposition in snowfall, it can decrease the albedo of snow cover. This reduction in the amount of solar radiation reflected back to space by snow surfaces creates a minor positive radiative forcing.

The Paris Agreement (Accord de Paris), often referred to as the Paris Accords or the Paris Climate Accords, is an international treaty on climate change, adopted in 2015. It covers climate change mitigation, adaptation, and finance. The Agreement was negotiated by 196 parties at the 2015 United Nations Climate Change Conference near Paris, France. The Paris Agreement was opened for signature on 22 April 2016 (Earth Day) at a ceremony in New York. After the European Union ratified the agreement, sufficient countries had ratified the Agreement responsible for enough of the world's greenhouse gases for the Agreement to enter into force on 4 November 2016. As of November 2021, 193 members of the United Nations Framework Convention on Climate Change (UNFCCC) are parties to the agreement. Of the four UNFCCC member states which have not ratified the agreement, the only major emitter is Iran. The United States withdrew from the Agreement in 2020 but rejoined in 2021. The Paris Agreement's long-term temperature goal is to keep the rise in mean global temperature to well below 2 °C (3.6 °F) above pre-industrial levels, and preferably limit the increase to 1.5 °C (2.7 °F), recognizing that this would substantially reduce the effects of climate change. Emissions should be reduced as soon as possible and reach net-zero by the middle of the 21st century. To stay below 1.5 °C of global warming, emissions need to be cut by roughly 50% by 2030. This is an aggregate of each country's nationally determined contributions.

It aims to increase the ability of parties to adapt to climate change effects and mobilize sufficient finance. Under the Agreement, each country must determine, plan, and regularly report on its contributions. No mechanism forces a country to set specific emissions targets, but each target should go beyond previous targets. In contrast to the 1997 Kyoto Protocol, the distinction between developed and developing countries is blurred, so that the latter also have to submit plans for emission reductions. The Agreement was lauded by world leaders, but criticized as insufficiently binding by some environmentalists and analysts. There is debate about the effectiveness of the Agreement. While current pledges under the Paris Agreement are insufficient for reaching the set temperature goals, there is a mechanism of increased ambition. The Paris Agreement has been successfully used in climate litigation forcing countries and an oil company to strengthen climate action.

Development

The UN Framework Convention on Climate Change (UNFCCC), adopted at the 1992 Earth Summit is one of the first international treaties on the topic. It stipulates that parties should meet regularly to address climate change, at the Conference of Parties or COP. It forms the foundation to future climate agreements. The Kyoto Protocol, adopted in 1997, regulated greenhouse gas reductions for a limited set of countries from 2008 to 2012. The protocol was extended until 2020 with the Doha Amendment in 2012. The United States decided not to ratify the Protocol, mainly because of its legally-binding nature. This, and distributional conflict, led to failures of subsequent international climate negotiations. The 2009 negotiations were intended to produce a successor treaty of Kyoto, but the negotiations collapsed and the resulting Copenhagen Accord was not legally binding and did not get adopted universally. The Accord did lay the framework for bottom-up approach of the Paris Agreement. Under the leadership of UNFCCC executive secretary Christiana Figures, negotiation regained momentum after Copenhagen's failure. During the 2011 United Nations Climate Change Conference, the Durban Platform was established to negotiate a legal instrument governing climate change mitigation measures from 2020. The resulting agreement was to be adopted in 2015.

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Negotiations and Adoption

Negotiations in Paris took place over a two week span, and continued throughout the three final nights. Various drafts and proposals had been debated and streamlined in the preceding year. According to one commentator two ways in which the French increased the likelihood of success were: firstly to ensure that INDCs were completed before the start of the negotiations, and secondly to invite leaders just for the beginning of the conference. The negotiations almost failed because of a single word when the US legal team realized at the last minute that "shall" had been approved, rather than "should", meaning that developed countries would have been legally obliged to cut emissions: the French solved the problem by changing it as a "typographical error". At the conclusion of COP21 (the 21st meeting of the Conference of the Parties), on 12 December 2015, the final wording of the Paris Agreement was adopted by consensus by the 195 UNFCCC participating member states and the European Union. Nicaragua indicated they had wanted to object to the adoption as they denounced the weakness of the Agreement, but were not given a chance. In the Agreement the members promised to reduce their carbon output "as soon as possible" and to do their best to keep global warming "to well below 2 degrees C" (3.6 °F).

Signing and Entry into Force

The Paris Agreement was open for signature by states and regional economic integration organizations that are parties to the UNFCCC (the Convention) from 22 April 2016 to 21 April 2017 at the UN Headquarters in New York. Signing of the Agreement is the first step towards ratification, but it is possible to accede to the Agreement without signing. It binds parties to not act in contravention of the goal of the treaty. On 1 April 2016, the United States and China, which represent almost 40% of global emissions confirmed they would sign the Paris Climate Agreement. The Agreement was signed by 175 parties (174 states and the European Union) on the first day it was opened for signature. As of March 2021, 194 states and the European Union have signed the Agreement. The Agreement would enter into force (and thus become fully effective) if 55 countries that produce at least 55% of the world's greenhouse gas emissions (according to a list produced in 2015) ratify or otherwise join the treaty. After ratification by the European Union, the Agreement obtained enough parties to enter into effect on 4 November 2016. Both the EU and its member states are individually responsible for ratifying the Paris Agreement. A strong preference was reported that the EU and its 28 member states ratify at the same time to ensure that they do not engage themselves to fulfilling obligations that strictly belong to the other, and there were fears by observers that disagreement over each member state's share of the EU-wide reduction target, as well as Britain's vote to leave the EU might delay the Paris pact. However, the EU deposited its instruments of ratification on 5 October 2016, along with seven EU member states.

Parties

The Indian Prime Minister, Narendra Modi greeting the President of Brazil, Dilma Rousseff, at the COP21 Summit on 30 November 2015. The EU and 192 states, totaling over 98% of anthropogenic emissions, have ratified or acceded to the Agreement. The only countries which have not ratified are some greenhouse gas emitters in the Middle East: Iran with 2% of the world total being the largest. Eritrea, Libya and Yemen have also not ratified the agreement. Iraq is the latest country to ratify the agreement, on 1 November 2021. Article 28 enables parties to withdraw from the Agreement after sending a withdrawal notification to the depositary. Notice can be given no earlier than three years after the Agreement goes into force for the country. Withdrawal is effective one year after the depositary is notified.

United States Withdrawal and Readmittance

On 4 August 2017, the Trump administration delivered an official notice to the United Nations that the United States, the second largest emitter of greenhouse gases, intended to withdraw from the Paris Agreement as soon as it was eligible to do so. The notice of withdrawal could not be submitted until the Agreement was in force for three years for the US, on 4 November 2019. The U.S. government deposited the notification with the Secretary General of the United Nations and officially withdrew one year later on 4 November 2020. President Joe Biden signed an executive order on his first day in office, 20 January 2021, to re-admit the United States into the Paris Agreement. Following the 30-day period set by Article 21.3, the U.S. was readmitted to the Agreement. United States Climate Envoy John Kerry took part in virtual events, saying that the US would "earn its way back" into legitimacy in the Paris process. United Nations Secretary-General António Guterres welcomed the return of the United States as restoring the "missing link that weakened the whole".

Content

The Paris Agreement is a short agreement with 16 introductory paragraphs and 29 articles. It contains procedural (e.g., the criteria for entry into force) and operational articles (mitigation, adaptation and finance). It is a binding agreement, but many of its articles do not imply obligations or are there to facilitate international collaboration. It covers most greenhouse gas emissions, but does not apply to international aviation and shipping, which fall under the responsibility of the International Civil Aviation Organization and the International Maritime Organization, respectively.

Aims

The aim of the agreement, as described in Article 2, is to have a stronger response to the danger of climate change; it seeks to enhance the implementation of the United Nations Framework Convention on Climate Change through:

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A. Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change

B. Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;

C. Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development. Countries furthermore aim to reach "global peaking of greenhouse gas emissions as soon as possible."

Nationally Determined Contributions

Countries determine themselves what contributions they should make to achieve the aims of the treaty. As such, these plans are called nationally determined contributions (NDCs). Article 3 requires NDCs to be "ambitious efforts" towards "achieving the purpose of this Agreement" and to "represent a progression over time". The contributions should be set every five years and are to be registered by the UNFCCC Secretariat. Each further ambition should be more ambitious than the previous one, known as the principle of 'progression'. Countries can cooperate and pool their nationally determined contributions. The Intended Nationally Determined Contributions pledged during the 2015 Climate Change Conference are converted to NDCs when a country ratifies the Paris Agreement, unless they submit an update. The Paris Agreement does not prescribe the exact nature of the NDCs. At a minimum, they should contain mitigation provisions, but they may also contain pledges on adaptation, finance, technology transfer, capacity building and transparency. Some of the pledges in the NDCs are unconditional, but others are conditional on outside factors such as getting finance and technical support, the ambition from other parties or the details of rules of the Paris Agreement that are yet to be set. Most NDCs have a conditional component. While the NDCs themselves are not binding, the procedures surrounding them are. These procedures include the obligation to prepare, communicate and maintain successive NDCs, set a new one every five years, and provide information about the implementation. There is no mechanism to force a country to set a NDC target by a specific date, nor to meet their targets. There will be only a name and shame system or as János Pásztor, the former U.N. assistant secretary-general on climate change, stated, a "name and encourage" plan.

Global Stock Take

Under the Paris Agreement, countries must increase their ambition every five years. To facilitate this, the Agreement established the Global Stocktake, which assesses progress, with the first evaluation in 2023. The outcome is to be used as input for new nationally determined contributions of parties. The Talanoa Dialogue in 2018 was seen as an example for the global stocktake. After a year of discussion, a report was published and there was a call for action, but countries did not increase ambition afterwards. The stocktake works as part of the Paris Agreement's effort to create a "ratcheting up" of ambition in emissions cuts. Because analysts agreed in 2014 that the NDCs would not limit rising temperatures below 2 °C, the global stocktake reconvenes parties to assess how their new NDCs must evolve so that they continually reflect a country's "highest possible ambition". While ratcheting up the ambition of NDCs is a major aim of the global stocktake, it assesses efforts beyond mitigation. The 5-year reviews will also evaluate adaptation, climate finance provisions, and technology development and transfer.

Structure

The Paris Agreement has been described as having a bottom-up structure, as its core pledge and review mechanism allows nations to set their own NDCs, rather than having targets imposed top down. Unlike its predecessor, the Kyoto Protocol, which sets commitment targets that have legal force, the Paris Agreement, with its emphasis on consensus building, allows for voluntary and nationally determined targets. The specific climate goals are thus politically encouraged, rather than legally bound. Only the processes governing the reporting and review of these goals are mandated under international law. This structure is especially notable for the United States-because there are no legal mitigation or finance targets, the Agreement is considered an "executive agreement rather than a treaty". Because the UNFCCC treaty of 1992 received the consent of the US Senate, this new agreement does not require further legislation. Another key difference between the Paris Agreement and the Kyoto Protocol is their scope. The Kyoto Protocol differentiated between Annex-I, richer countries with a historical responsibility for climate change, and non-Annex-I countries, but this division is blurred in the Paris Agreement as all parties are required to submit emissions reduction plans. The Paris Agreement still emphasizes the principle of Common but Differentiated Responsibility and Respective Capabilities -the acknowledgement that different nations have different capacities and duties to climate action- but it does not provide a specific division between developed and developing nations.

Mitigation Provisions and Carbon Markets

Article 6 has been flagged as containing some of the key provisions of the Paris Agreement. Broadly, it outlines the cooperative approaches that parties can take in achieving their nationally determined carbon emissions reductions. In doing so, it helps establish the Paris Agreement as a framework for a global carbon market. Article 6 is the only important part of the Agreement yet to be resolved; negotiations in 2019 did not produce a result. The topic is now expected to be settled during

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the 2021 negotiations in Glasgow [51-60].

Linkage of Carbon Trading Systems

A framework to govern the international transfer of mitigation outcomes (ITMOs). The Agreement recognizes the rights of parties to use emissions reductions outside of their own borders toward their NDC, in a system of carbon accounting and trading. This provision requires the "linkage" of carbon emissions trading systems-because measured emissions reductions must avoid "double counting", transferred mitigation outcomes must be recorded as a gain of emission units for one party and a reduction of emission units for the other. Because the NDCs, and domestic carbon trading schemes, are heterogeneous, the ITMOs will provide a format for global linkage under the auspices of the UNFCCC. The provision thus also creates pressure for countries to adopt emissions management systems -if a country wants to use more cost-effective cooperative approaches to achieve their NDCs, they will have to monitor carbon units for their economies.

Sustainable Development Mechanism

Establish a mechanism "to contribute to the mitigation of greenhouse gases and support sustainable development". Though there is no official name for the mechanism as yet, it has been referred to as the Sustainable Development Mechanism or SDM. The SDM is considered to be the successor to the Clean Development Mechanism, a mechanism under the Kyoto Protocol by which parties could collaboratively pursue emissions reductions. The SDM is set to largely resemble the Clean Development Mechanism, with the dual goal of contributing to global GHG emissions reductions and supporting sustainable development. Though the structure and processes governing the SDM are not yet determined, certain similarities and differences from the Clean Development Mechanisms have become clear. A key difference is that the SDM will be available to all parties as opposed to only Annex-I parties, making it much wider in scope. The Clean Development Mechanism of the Kyoto Protocol was criticized for failing to produce either meaningful emissions reductions or sustainable development benefits in most instances and for its complexity. It is possible that the SDM will see difficulties.

Adaptation Provisions

Adaptation garnered more focus in Paris negotiations than in previous climate treaties. Collective, long-term adaptation goals are included in the Agreement, and countries must report on their adaptation actions, making it a parallel component with mitigation. The adaptation goals focus on enhancing adaptive capacity, increasing resilience, and limiting vulnerability.

Ensuring Finance

Developed countries reaffirmed the commitment to mobilize $100 billion a year in climate finance by 2020, and agreed to continue mobilizing finance at this level until 2025.The money is for supporting mitigation and adaptation in developing countries. It includes finance for the Green Climate Fund, which is a part of the UNFCCC, but also for a variety of other public and private pledges. The Paris Agreement states that a new commitment of at least $100 billion per year has to be agreed before 2025. Though both mitigation and adaptation require increased climate financing, adaptation has typically received lower levels of support and has mobilized less action from the private sector. A report by the OECD found that 16% of global climate finance was directed toward climate adaptation in 2013-2014, compared to 77% for mitigation. The Paris Agreement called for a balance of climate finance between adaptation and mitigation, and specifically increasing adaptation support for parties most vulnerable to the effects of climate change, including least developed countries and Small Island Developing States. The Agreement also reminds parties of the importance of public grants, because adaptation measures receive less investment from the public sector. Some specific outcomes of the elevated attention to adaptation financing in Paris include the G7 countries' announcement to provide US$420 million for climate risk insurance, and the launching of a Climate Risk and Early Warning Systems (CREWS) Initiative. The largest donors to multilateral climate funds, which includes the Green Climate Fund, are the United States, the United Kingdom, Japan, Germany, France and Sweden.

Loss and Damage

It is not possible to adapt to all effects of climate change: even in the case of optimal adaptation, severe damage may still occur. The Paris Agreement recognizes loss and damage of this kind. Loss and damage can stem from extreme weather events, or from slow-onset events such as the loss of land to sea level rise for low-lying islands. Previous climate agreements classified loss and damage as a subset of adaptation. The push to address loss and damage as a distinct issue in the Paris Agreement came from the Alliance of Small Island States and the Least Developed Countries, whose economies and livelihoods are most vulnerable to the negative effects of climate change. The Warsaw Mechanism, established two years earlier during COP19 and set to expire in 2016, categorizes loss and damage as a subset of adaptation, which was unpopular with many countries. It is recognized as a separate pillar of the Paris Agreement. The United States argued against this, possibly worried that classifying the issue as separate from adaptation would create yet another climate finance provision. In the end, the Agreement calls for "averting, minimizing, and addressing loss and damage" but specifies that it cannot be used as the basis for liability. The Agreement adopts the Warsaw Mechanism, an institution that will attempt to address questions about how to classify, address, and share responsibility for loss.

Transparency

The parties are legally bound to have their progress tracked by technical expert review to assess achievement toward the NDC and to determine ways to strengthen ambition. Article 13

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of the Paris Agreement articulates an “enhanced transparency framework for action and support” that establishes harmonized monitoring, reporting, and verification (MRV) requirements. Both developed and developing nations must report every two years on their mitigation efforts, and all parties will be subject to technical and peer review. While the enhanced transparency framework is universal, the framework is meant to provide “built-in flexibility” to distinguish between developed and developing countries’ capacities. The Paris Agreement has provisions for an enhanced framework for capacity building, recognizes the varying circumstances of countries, and notes that the technical expert review for each country consider that country’s specific capacity for reporting. Parties to the Agreement send their first Biennial Transparency Report (BTR), and greenhouse gas inventory figures to the UNFCCC by 2024 and every two years after that. Developed countries submit their first BTR in 2022 and inventories annually from that year. The Agreement also develops a Capacity-Building Initiative for Transparency to assist developing countries in building the necessary institutions and processes for compliance. Flexibility can be incorporated into the enhanced transparency framework via the scope, level of detail, or frequency of reporting, tiered based on a country’s capacity. The requirement for in-country technical reviews could be lifted for some less developed or small island developing countries. Ways to assess capacity include financial and human resources in a country necessary for NDC review.

Implementation and Effectiveness

The Paris Agreement is implemented via national policy. It would involve improvements to energy efficiency to decrease the energy intensity of the global economy. Implementation also requires fossil fuel burning to be cut back and the share of sustainable energy to grow rapidly. Emissions are being reduced rapidly in the electricity sector, but not in the building, transport and heating sector. Some industries are difficult to decarbonize, and for those carbon dioxide removal may be necessary to achieve net-zero emissions. To stay below 1.5 °C of global warming, emissions need to be cut by roughly 50% by 2030. This is an aggregate of each country’s nationally determined contributions. By mid-century, CO_2 emissions would need to be cut to zero, and total greenhouse gases would net to be net-zero just after mid-century. There are barriers to implementing the Agreement. Some countries struggle to attract the finance often considered necessary for investments in decarburization. Climate finance is fragmented, further complicating investments. Another issue is the lack of capabilities in government and other institutions to implement policy. Clean technology and knowledge is often not transferred to countries or places that need it. [96] In December 2020, the former chair of the COP 21, Laurent Fabius, argued that the implementation of the Paris Agreement could be bolstered by the adoption of a Global Pact for the Environment. The latter would define the environmental rights and duties of states, individuals and businesses.

Effectiveness of Mitigation

The effectiveness of the Paris Agreement to reach its climate goals is under debate, with most experts saying it is insufficient for it’s more ambitious goal of keeping global temperature rise under 1.5 °C. Many of the exact provisions of the Paris Agreement have yet to be straightened out, so that it may be too early to judge effectiveness. According to the 2020 United Nations Environment Program (UNEP), with the current climate commitments of the Paris Agreement, global mean temperatures will likely rise by more than 3 °C by the end of the 21st century. Newer net-zero commitments were not included in the NDCs, and may bring down temperatures a further 0.5 °C. With initial pledges by countries inadequate, faster and more expensive future mitigation would be needed to still reach the targets. Furthermore, there is a gap between pledges by countries in their NDCs and implementation of these pledges; one third of the emission gap between the lowest-costs and actual reductions in emissions would be closed by implementing existing pledges. A pair of studies in Nature found that as of 2017 none of the major industrialized nations were implementing the policies they had pledged, and none met their pledged emission reduction targets, and even if they had, the sum of all member pledges (as of 2016) would not keep global temperature rise “well below 2 °C”. In 2021, a study using a probabilistic model concluded that the rates of emissions reductions would have to increase by 80% beyond NDCs to likely meet the 2 °C upper target of the Paris Agreement, that the probabilities of major emitters meeting their NDCs without such an increase is very low. It estimated that with current trends the probability of staying below 2 °C of warming is 5% - and 26% if NDCs were met and continued post-2030 by all signatories.

Effectiveness of Capacity Building and Adaptation

As of 2020, there is little scientific literature on the topics of the effectiveness of the Paris Agreement on capacity building and adaptation, even though they feature prominently in the Paris Agreement. The literature available is mostly mixed in its conclusions about loss and damage, and adaptation.

International Response

The Agreement was lauded by French President François Hollande, UN Secretary General Ban Ki-moon and Christiana Figueres, Executive Secretary of the UNFCCC. The president of Brazil, Dilma Rousseff, called the Agreement “balanced and long-lasting”, and India’s Prime Minister Narendra Modi commended the Agreement’s climate justice. When the Agreement achieved the required signatures in October 2016, US President Barack Obama said that “Even if we meet every target, we will only get to part of where we need to go.” He also stated “this agreement will help delay or avoid some of the worst consequences of climate change [and] will help other nations ratchet down their emissions over time.” Some environmentalists and analysts reacted cautiously, acknowledging the “spirit of Paris” in bringing together countries,

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but expressing less optimism about the pace of climate mitigation and how much the Agreement could do for poorer countries. James Hansen, a former NASA scientist and leading climate change expert, voiced anger that most of the Agreement consists of "promises" or aims and not firm commitments and called the Paris talks a fraud with "no action, just promises". Criticism on the Agreement from those arguing against climate action has been diffuse, which may be due to the weakness of the Agreement. This type of criticism typically focusses on national sovereignty and ineffectiveness of international action.

Litigation

The Paris Agreement has become a focal point of climate change litigation. One of the first major cases in this area was State of the Netherlands v. Urgenda Foundation, which was raised against the Netherlands' government after it had reduced its planned emissions reductions goal for 2030 prior to the Paris Agreement. After an initial ruling against the government in 2015 that required it to maintain its planned reduction, the decision was upheld on appeals through the Supreme Court of the Netherlands in 2019, ruling that the Dutch government failed to uphold human rights under Dutch law and the European Convention on Human Rights by lowering its emission targets. The 2 °C temperature target of the Paris Agreement provided part of the judgment's legal basis. The Agreement, whose goals are enshrined in German law, also formed part of the argumentation in Neubauer et al. v. Germany, where the court ordered Germany to reconsider its climate targets. In a case that was the first of its kind, the district court of The Hague ruled against oil company Royal Dutch Shell in May 2021 in Milieudefensie et al v Royal Dutch Shell. The court ruled that it must cut its global emissions by 45% from 2019 levels by 2030, as it was in violation of human rights. This lawsuit was considered the first major application of the Paris Agreement towards a corporation. Sustainable development is an organizing principle for meeting human development goals while also sustaining the ability of natural systems to provide the natural resources and ecosystem services on which the economy and society depend. The desired result is a state of society where living conditions and resources are used to continue to meet human needs without undermining the integrity and stability of the natural system. Sustainable development can be defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. While the modern concept of sustainable development is derived mostly from the 1987 Brundtland Report, it is also rooted in earlier ideas about sustainable forest management and 20th-century environmental concerns. As the concept of sustainable development developed, it has shifted its focus more towards the economic development, social development and environmental protection for future generations. The UN-level Sustainable Development Goals (2015-2030) address the global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

Definition

Sustainable development can be defined as the practice of maintaining productivity by replacing used resources with resources of equal or greater value without degrading or endangering natural biotic systems. Sustainable development binds together concern for the carrying capacity of natural systems with the social, political and economic challenges faced by humanity. Sustainability science is the study of the concepts of sustainable development and environmental science. There is an emphasis on the present generations' responsibility to regenerate, maintain and improve planetary resources for use by future generations.

Development of the Concept

Origins

Sustainable development has its roots in ideas about sustainable forest management, which were developed in Europe during the 17th and 18th centuries. In response to a growing awareness of the depletion of timber resources in England, John Evelyn argued, in his 1662 essay Sylva that "sowing and planting of trees had to be regarded as a national duty of every landowner, in order to stop the destructive over-exploitation of natural resources." In 1713, Hans Carl von Carlowitz, a senior mining administrator in the service of Elector Frederick Augustus I of Saxony published Sylvicultura economics, a 400-page work on forestry. Building upon the ideas of Evelyn and French minister Jean-Baptiste Colbert, von Carlowitz developed the concept of managing forests for sustained yield. His work influenced others, including Alexander von Humboldt and Georg Ludwig Hartig, eventually leading to the development of the science of forestry. This, in turn, influenced people like Gifford Pinchot, the first head of the US Forest Service, whose approach to forest management was driven by the idea of wise use of resources, and Aldo Leopold whose land ethic was influential in the development of the environmental movement in the 1960s. Following the publication of Rachel Carson's Silent Spring in 1962, the developing environmental movement drew attention to the relationship between economic growth and environmental degradation. Kenneth E. Boulding, in his influential 1966 essay The Economics of the Coming Spaceship Earth, identified the need for the economic system to fit itself to the ecological system with its limited pools of resources. Another milestone was the 1968 article by Garrett Hardin that popularized the term "tragedy of the commons". One of the first uses of the term sustainable in the contemporary sense was by the Club of Rome in 1972 in its classic report on the Limits to Growth, written by a group of scientists led by Dennis and Donella Meadows of the Massachusetts Institute of Technology. Describing the desirable "state of global equilibrium", the authors wrote: "We are searching for a model output that

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represents a world system that is sustainable without sudden and uncontrolled collapse and capable of satisfying the basic material requirements of all of its people."

In 1980, the International Union for Conservation of Nature published a world conservation strategy that included one of the first references to sustainable development as a global priority and introduced the term "sustainable development". Two years later, the United Nations World Charter for Nature raised five principles of conservation by which human conduct affecting nature is to be guided and judged. In 1987, the United Nations World Commission on Environment and Development released the report Our Common Future, commonly called the Brundtland Report. The report included what is now one of the most widely recognized definitions of sustainable development. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains Within it two key concepts: The concept of 'needs', in particular, the essential needs of the world's poor, to which overriding priority should be given; and The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs. Since the Brundtland Report, the concept of sustainable development has developed beyond the initial intergenerational framework to focus more on the goal of "socially inclusive and environmentally sustainable economic growth". In 1992, the UN Conference on Environment and Development published the Earth Charter, which outlines the building of a just, sustainable, and peaceful global society in the 21st century. The action plan Agenda 21 for sustainable development identified information, integration, and participation as key building blocks to help countries achieve development that recognizes these interdependent pillars. It emphasizes that in sustainable development, everyone is a user and provider of information. It stresses the need to change from old sector-centered ways of doing business to new approaches that involve cross-sectoral co-ordination and the integration of environmental and social concerns into all development processes. Furthermore, Agenda 21 emphasizes that broad public participation in decision making is a fundamental prerequisite for achieving sustainable development.

Under the principles of the United Nations Charter the Millennium Declaration identified principles and treaties on sustainable development, including economic development, social development and environmental protection. Broadly defined, sustainable development is a systems approach to growth and development and to manage natural, produced, and social capital for the welfare of their own and future generations. The term sustainable development as used by the United Nations incorporates both issues associated with land development and broader issues of human development such as education, public health, and standard of living. A 2013 study concluded that sustainability reporting should be reframed through the lens of four interconnected domains: ecology, economics, politics and culture.

Reception

The concept of sustainable development has been, and still is, subject to criticism, including the question of what is to be sustained in sustainable development. It has been argued that there is no such thing as a sustainable use of a non-renewable resource, since any positive rate of exploitation will eventually lead to the exhaustion of earth's finite stock; this perspective renders the Industrial Revolution as a whole unsustainable.

The sustainable development debate is based on the assumption that societies need to manage three types of capital (economic, social, and natural), which may be non-substitutable and whose consumption might be irreversible. Leading ecological economist and steady-state theorist Herman Daly, for example, points to the fact that natural capital can not necessarily be substituted by economic capital. While it is possible that we can find ways to replace some natural resources, it is much more unlikely that they will ever be able to replace eco-system services, such as the protection provided by the ozone layer, or the climate stabilizing function of the Amazonian forest. In fact natural capital, social capital and economic capital are often complementarities. A further obstacle to substitutability lies also in the multi-functionality of many natural resources. Forests, for example, not only provide the raw material for paper but they also maintain biodiversity, regulate water flow, and absorb CO_2.

Requirements

Six interdependent capacities are deemed to be necessary for the successful pursuit of sustainable development. These are the capacities to measure progress towards sustainable development; promote equity within and between generations; adapt to shocks and surprises; transform the system onto more sustainable development pathways; link knowledge with action for sustainability; and to devise governance arrangements that allow people to work together in exercising the other capacities.

Dimensions

Sustainable development can be thought of in terms of three spheres, dimensions, domains or pillars: the environment, the economy and society. The three-sphere framework has also been worded as "economic, environmental and social" or "ecology, economy and equity". This has been expanded by some authors to include a fourth pillar of culture, institutions or governance, or alternatively reconfigured as four domains of the social - ecology, economics, politics and culture, thus bringing economics back inside the social, and treating ecology as the intersection of the social and the natural [61-70].

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Sustainable Development Goals

The Sustainable Development Goals (SDGs) or Global Goals are a collection of 17 interlinked global goals designed to be a "blueprint to achieve a better and more sustainable future for all". The SDGs were set up in 2015 by the United Nations General Assembly (UN-GA) and are intended to be achieved by the year 2030. They are included in a UN-GA Resolution called the 2030 Agenda or what is colloquially known as Agenda 2030. The SDGs were developed in the Post-2015 Development Agenda as the future global development framework to succeed the Millennium Development Goals which ended in 2015.

Pathways

Deforestation and increased road-building in the Amazon rainforest are a concern because of increased human encroachment upon wilderness areas, increased resource extraction and further threats to biodiversity. The ecological stability of human settlements is part of the relationship between humans and their natural, social and built environments. Also termed human ecology, this broadens the focus of sustainable development to include the domain of human health. Fundamental human needs such as the availability and quality of air, water, food and shelter are also the ecological foundations for sustainable development; addressing public health risk through investments in ecosystem services can be a powerful and transformative force for sustainable development which, in this sense, extends to all species. Environmental sustainability concerns the natural environment and how it endures and remains diverse and productive. Since natural resources are derived from the environment, the state of air, water, and the climate is of particular concern. The IPCC Fifth Assessment Report outlines current knowledge about scientific, technical and socio-economic information concerning climate change, and lists options for adaptation and mitigation. Environmental sustainability requires society to design activities to meet human needs while preserving the life support systems of the planet. This, for example, entails using water sustainably, using renewable energy and sustainable material supplies (e.g., harvesting wood from forests at a rate that maintains the biomass and biodiversity). An unsustainable situation occurs when natural capital (the total of nature's resources) is used up faster than it can be replenished. Sustainability requires that human activity only uses nature's resources at a rate at which they can be replenished naturally. The concept of sustainable development is intertwined with the concept of carrying capacity. Theoretically, the long-term result of environmental degradation is the inability to sustain human life. Such degradation on a global scale should imply an increase in human death rate until population falls to what the degraded environment can support Table 1. Pollution of the public resources is not a different action, it is just a reverse tragedy of the commons, in that instead of taking something out, and something is put into the commons. When the costs of polluting the commons are not calculated into the cost of the items consumed, then it becomes only natural to pollute, as the cost of pollution is external to the cost of the goods produced and the cost of cleaning the waste before it is discharged exceeds the cost of releasing the waste directly into the commons. One of the ways to mitigate this problem is by protecting the ecology of the commons by making it, through taxes or fines, more costly to release the waste directly into the commons than would be the cost of cleaning the waste before discharge.

Table 1: The long-term result of environmental degradation is the inability to sustain human life.

Consumption of Natural Resources	State of the Environment	Sustainability
More than nature's ability to replenish	Environmental degradation	Not sustainable
Equal to nature's ability to replenish	Environmental equilibrium	Steady state economy
Less than nature's ability to replenish	Environmental renewal	Environmentally sustainable

Land Use Changes, Agriculture and Food

Alterations in the relative proportions of land dedicated to urbanization, agriculture, forest, woodland, grassland and pasture have a marked effect on the global water, carbon and nitrogen biogeochemical cycles and this can impact negatively on both natural and human systems. On the local human scale, major sustainability benefits accrue from sustainable parks and gardens and green cities. Feeding almost eight billion human bodies takes a heavy toll on the Earth's resources. This begins with the appropriation of about 38% of the Earth's land surface and about 20% of its net primary productivity. Added to this are the resource -hungry activities of industrial agribusiness- everything from the crop needs for irrigation water, synthetic fertilizers and pesticides to the resource costs of food packaging, transport (now a major part of global trade) and retail. Environmental problems associated with industrial agriculture and agribusiness are now being addressed through such movements as sustainable agriculture, organic farming and more sustainable business practices. The most cost-effective mitigation options include afforestation, sustainable forest management, and reducing deforestation. The environmental effects of different dietary patterns depend on many factors, including the proportion of animal and plant foods consumed and the method of food production. At the global level

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the environmental impact of agribusiness is being addressed through sustainable agriculture and organic farming. At the local level there are various movements working towards sustainable food systems which may include local food production, slow food, sustainable gardening, and organic gardening.

Materials and Waste

As global population and affluence have increased, so has the use of various materials increased in volume, diversity, and distance transported. Included here are raw materials, minerals, synthetic chemicals (including hazardous substances), manufactured products, food, living organisms, and waste. By 2050, humanity could consume an estimated 140 billion tons of minerals, ores, fossil fuels and biomass per year (three times its current amount) unless the economic growth rate is decoupled from the rate of natural resource consumption. Developed countries' citizens consume an average of 16 tons of those four key resources per capita per year, ranging up to 40 or more tons per person in some developed countries with resource consumption levels far beyond what is likely sustainable. By comparison, the average person in India today consumes four tons per year. Sustainable use of materials has targeted the idea of dematerialization, converting the linear path of materials (extraction, use, disposal in landfill) to a circular material flow that reuses materials as much as possible, much like the cycling and reuse of waste in nature. Dematerialization is being encouraged through the ideas of industrial ecology, eco design and ecolabelling. The use of sustainable biomaterials that come from renewable sources and that can be recycled is preferred to the use on non-renewables from a life cycle standpoint. This way of thinking is expressed in the concept of circular economy, which employs reuse, sharing, repair, refurbishment, remanufacturing and recycling to create a closed-loop system, minimizing the use of resource inputs and the creation of waste, pollution and carbon emissions. The European Commission has adopted an ambitious Circular Economy Action Plan in 2020, which aims at making sustainable products the norm in the EU.

Improving On Economic and Social Aspects

It has been suggested that because of rural poverty and overexploitation, environmental resources should be treated as important economic assets, called natural capital. Economic development has traditionally required a growth in the gross domestic product. This model of unlimited personal and GDP growth may be over. Sustainable development may involve improvements in the quality of life for many but may necessitate a decrease in resource consumption. According to ecological economist Malte Faber, ecological economics is defined by its focus on nature, justice, and time. Issues of intergenerational equity, irreversibility of environmental change, uncertainty of long-term outcomes, and sustainable development guide ecological economic analysis and valuation. As early as the 1970s, the concept of sustainability was used to describe an economy "in equilibrium with basic ecological support systems". Scientists in many fields have highlighted The Limits to Growth, and economists have presented alternatives, for example a 'steady-state economy', to address concerns over the impacts of expanding human development on the planet. In 1987, the economist Edward Barbier published the study The Concept of Sustainable Economic Development, where he recognized that goals of environmental conservation and economic development are not conflicting and can be reinforcing each other. A World Bank study from 1999 concluded that based on the theory of genuine savings, policymakers have many possible interventions to increase sustainability, in macroeconomics or purely environmental. Several studies have noted that efficient policies for renewable energy and pollution are compatible with increasing human welfare, eventually reaching a golden-rule steady state.

However, Gilbert Rist says that the World Bank has twisted the notion of sustainable development to prove that economic development need not be deterred in the interest of preserving the ecosystem. He writes: "From this angle, 'sustainable development' looks like a cover-up operation... The thing that is meant to be sustained is really 'development', not the tolerance capacity of the ecosystem or of human societies." The World Bank, a leading producer of environmental knowledge, continues to advocate the win-win prospects for economic growth and ecological stability even as its economists express their doubts. Herman Daly, an economist for the Bank from 1988 to 1994, writes: When authors of WDR '92 [the highly influential 1992 World Development Report that featured the environment] were drafting the report, they called me asking for examples of "win-win" strategies in my work. What could I say? None exists in that pure form; there are trade-offs, not "win-wins." But they want to see a world of "win-wins" based on articles of faith, not fact. I wanted to contribute because WDRs are important in the Bank, [because] task managers read [them] to find philosophical justification for their latest round of projects. But they did not want to hear about how things really are, or what I find in my work. A Meta review in 2002 looked at environmental and economic valuations and found a lack of "sustainability policies". A study in 2004 asked if humans consume too much. A study concluded in 2007 that knowledge, manufactured and human capital (health and education) has not compensated for the degradation of natural capital in many parts of the world. It has been suggested that intergenerational equity can be incorporated into sustainable development and decision making, as has become common in economic valuations of climate economics. A Meta review in 2009 identified conditions for a strong case to act on climate change, and called for more work to fully account of the relevant economics and how it affects human welfare. According to John Baden, a free-market environmentalist, "the improvement of environment quality depends on the market economy and the existence of legitimate and protected property rights". They enable the effective practice of personal

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responsibility and the development of mechanisms to protect the environment. The State can in this context "create conditions which encourage the people to save the environment"

Environmental Economics

The total environment includes not just the biosphere of Earth, air, and water, but also human interactions with these things, with nature, and what humans have created as their surroundings. As countries around the world continue to advance economically, they put a strain on the ability of the natural environment to absorb the high level of pollutants that are created as a part of this economic growth. Therefore, solutions need to be found so that the economies of the world can continue to grow, but not at the expense of the public good. In the world of economics, the amount of environmental quality must be considered as limited in supply and therefore is treated as a scarce resource. This is a resource to be protected. One common way to analyze possible outcomes of policy decisions on the scarce resource is to do a cost-benefit analysis. This type of analysis contrasts different options of resource allocation and, based on an evaluation of the expected courses of action and the consequences of these actions, the optimal way to do so in the light of different policy goals can be elicited. Further complicating this analysis are the interrelationships of the various parts of the environment that might be impacted by the chosen course of action. Sometimes, it is almost impossible to predict the various outcomes of a course of action, due to the unexpected consequences and the number of unknowns that are not accounted for in the benefit-cost analysis.

Management of Human Consumption and Impacts

The environmental impact of a community or humankind as a whole depends both on population and impact per person, which in turn depends in complex ways on what resources are being used, whether or not those resources are renewable, and the scale of the human activity relative to the carrying capacity of the ecosystems involved. Careful resource management can be applied at many scales, from economic sectors like agriculture, manufacturing and industry, to work organizations, the consumption patterns of households and individuals, and the resource demands of individual goods and services. The underlying driver of direct human impacts on the environment is human consumption. This impact is reduced by not only consuming less but also making the full cycle of production, use, and disposal more sustainable. Consumption of goods and services can be analyzed and managed at all scales through the chain of consumption, starting with the effects of individual lifestyle choices and spending patterns, through to the resource demands of specific goods and services, the impacts of economic sectors, through national economies to the global economy. Analysis of consumption patterns relates resource use to the environmental, social and economic impacts at the scale or context under investigation. The ideas of embodied resource use (the total resources needed to produce a product or service), resource intensity, and resource productivity are important tools for understanding the impacts of consumption. Key resource categories relating to human needs are food, energy, raw materials and water. In 2010, the International Resource Panel published the first global scientific assessment on the impacts of consumption and production. The study found that the most critical impacts are related to ecosystem health, human health and resource depletion. From a production perspective, it found that fossil-fuel combustion processes, agriculture and fisheries have the most important impacts. Meanwhile, from a final consumption perspective, it found that household Consumption related to mobility, shelter, food, and energy-using products causes the majority of life-cycle impacts of consumption. According to the IPCC Fifth Assessment Report, human consumption, with current policy, by the year 2100 will be seven times bigger than in the year 2010.

Biodiversity and Ecosystem Services

In 2019, a summary for policymakers of the largest, most comprehensive study to date of biodiversity and ecosystem services was published by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. It recommended that human civilization will need a transformative change, including sustainable agriculture, reductions in consumption and waste, fishing quotas and collaborative water management.

Technology

Before flue-gas desulfurization was installed, the air-polluting emissions from this power plant in New Mexico contained excessive amounts of sulfur dioxide. A sewage treatment plant that uses solar energy, located at Santuari de Lluc monastery, Majorca. One of the core concepts in sustainable development is that technology can be used to assist people to meet their developmental needs. Technology to meet these sustainable development needs is often referred to as appropriate technology, which is an ideological movement (and its manifestations) originally articulated as intermediate technology by the economist E. F. Schumacher in his influential work Small Is Beautiful and now covers a wide range of technologies. Both Schumacher and many modern-day proponents of appropriate technology also emphasise the technology as people centered. Today appropriate technology is often developed using open-source principles, which have led to open-source appropriate technology (OSAT) and thus many of the plans of the technology can be freely found on the Internet. OSAT has been proposed as a new model of enabling innovation for sustainable development.

Business

The most broadly accepted criterion for corporate sustainability constitutes a firm's efficient use of natural capital. This eco-efficiency is usually calculated as the economic value added by a firm in relation to its aggregated ecological impact.

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This idea has been popularized by the World Business Council for Sustainable Development (WBCSD) under the following definition: "Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's carrying capacity" (DeSimone and Popoff, 1997: 47). Similar to the eco-efficiency concept but so far less explored is the second criterion for corporate sustainability. Socio-efficiency describes the relation between a firm's value added and its social impact. Whereas, it can be assumed that most corporate impacts on the environment are negative (apart from rare exceptions such as the planting of trees) this is not true for social impacts. These can be either positive (e.g., corporate giving, creation of employment) or negative (e.g., work accidents, human rights abuses). Both eco-efficiency and socio-efficiency are concerned primarily with increasing economic sustainability. In this process they instrumentalize both natural and social capital aiming to benefit from win-win situations. Some point towards eco-effectiveness, socio-effectiveness, sufficiency, and eco-equity as four criteria that need to be met if sustainable development is to be reached [71-80].

Architecture and Construction

In sustainable architecture the recent movements of New Urbanism and New Classical architecture promote a sustainable approach towards construction that appreciates and develops smart growth, architectural tradition and classical design. This in contrast to modernist and International Style architecture, as well as opposing to solitary housing estates and suburban sprawl, with long commuting distances and large ecological footprints. The global design and construction industry is responsible for approximately 39 percent of greenhouse gas emissions. Green building practices that avoid emissions or capture the carbon already present in the environment, allow for reduced footprint of the construction industry, for example, use of hempcrete, cellulose fiber insulation, and landscaping.

Sustainable Development

Sustainable development is the overarching paradigm of the United Nations. The concept of sustainable development was described by the 1987 Bruntland Commission Report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." There are four dimensions to sustainable development - society, environment, culture and economy - which are intertwined, not separate. Sustainability is a paradigm for thinking about the future in which environmental, societal and economic considerations are balanced in the pursuit of an improved quality of life. For example, a prosperous society relies on a healthy environment to provide food and resources, safe drinking water and clean air for its citizens. One might ask, what is the difference between sustainable development and sustainability? Sustainability is often thought of as a long-term goal (i.e., a more sustainable world), while sustainable development refers to the many processes and pathways to achieve it (e.g. sustainable agriculture and forestry, sustainable production and consumption, good government, research and technology transfer, education and training, etc.).

What are the Sustainable Development Goals?

The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. The 17 SDGs are integrated-they recognize that action in one area will affect outcomes in others, and that development must balance social, economic and environmental sustainability. Countries have committed to prioritize progress for those who're furthest behind. The SDGs are designed to end poverty, hunger, AIDS, and discrimination against women and girls. The creativity, knowhow, technology and financial resources from all of society is necessary to achieve the SDGs in every context.

Goal 1

No Poverty

Eradicating poverty in all its forms remains one of the greatest challenges facing humanity. While the number of people living in extreme poverty dropped by more than half between 1990 and 2015, too many are still struggling for the most basic human needs. As of 2015, about 736 million people still lived on less than US$1.90 a day; many lack food, clean drinking water and sanitation. Rapid growth in countries such as China and India has lifted millions out of poverty, but progress has been uneven. Women are more likely to be poor than men because they have less paid work, education, and own less property. Progress has also been limited in other regions, such as South Asia and sub-Saharan Africa, which account for 80 percent of those living in extreme poverty. New threats brought on by climate change, conflict and food insecurity, mean even more work is needed to bring people out of poverty. The SDGs are a bold commitment to finish what we started, and end poverty in all forms and dimensions by 2030. This involves targeting the most vulnerable, increasing basic resources and services, and supporting communities affected by conflict and climate-related disasters.

Goal 2

Zero Hunger

Unfortunately, extreme hunger and malnutrition remain a huge barrier to development in many countries. There are 821 million people estimated to be chronically undernourished as of 2017, often as a direct consequence of environmental degradation, drought and biodiversity loss. Over 90 million children under five

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are dangerously underweight. Undernourishment and severe food insecurity appear to be increasing in almost all regions of Africa, as well as in South America. The SDGs aim to end all forms of hunger and malnutrition by 2030, making sure all people-especially children-have sufficient and nutritious food all year. This involves promoting sustainable agricultural, supporting small-scale farmers and equal access to land, technology and markets. It also requires international cooperation to ensure investment in infrastructure and technology to improve agricultural productivity.

Goal 3

Good Health and Well-Being

We have made great progress against several leading causes of death and disease. Life expectancy has increased dramatically; infant and maternal mortality rates have declined, we've turned the tide on HIV and malaria deaths have halved. Good health is essential to sustainable development and the 2030 Agenda reflects the complexity and interconnectedness of the two. It takes into account widening economic and social inequalities, rapid urbanization, threats to the climate and the environment, the continuing burden of HIV and other infectious diseases, and emerging challenges such as non-communicable diseases. Universal health coverage will be integral to achieving SDG 3, ending poverty and reducing inequalities. Emerging global health priorities not explicitly included in the SDGs, including antimicrobial resistance, also demand action. But the world is off-track to achieve the health-related SDGs. Progress has been uneven, both between and within countries. There's a 31-year gap between the countries with the shortest and longest life expectancies. And while some countries have made impressive gains, national averages hide that many are being left behind. Multisectoral, rights-based and gender-sensitive approaches are essential to address inequalities and to build good health for all.

Goal 4

Quality Education

Since 2000, there has been enormous progress in achieving the target of universal primary education. The total enrollment rate in developing regions reached 91 percent in 2015, and the worldwide number of children out of school has dropped by almost half. There has also been a dramatic increase in literacy rates, and many more girls are in school than ever before. These are all remarkable successes. Since 2000, there has been enormous progress in achieving the target of universal primary education. The total enrollment rate in developing regions reached 91 percent in 2015, and the worldwide number of children out of school has dropped by almost half. There has also been a dramatic increase in literacy rates, and many more girls are in school than ever before. These are all remarkable successes. Progress has also been tough in some developing regions due to high levels of poverty, armed conflicts and other emergencies. In Western Asia and North Africa, ongoing armed conflict has seen an increase in the number of children out of school. This is a worrying trend. While Sub-Saharan Africa made the greatest progress in primary school enrollment among all developing regions - from 52 percent in 1990, up to 78 percent in 2012 - large disparities still remain. Children from the poorest households are up to four times more likely to be out of school than those of the richest households. Disparities between rural and urban areas also remain high. Achieving inclusive and quality education for all reaffirms the belief that education is one of the most powerful and proven vehicles for sustainable development. This goal ensures that all girls and boys complete free primary and secondary schooling by 2030. It also aims to provide equal access to affordable vocational training, to eliminate gender and wealth disparities, and achieve universal access to a quality higher education.

Goal 5

Gender Equality

Ending all discrimination against women and girls is not only a basic human right, it's crucial for sustainable future; it's proven that empowering women and girls helps economic growth and development. UNDP has made gender equality central to its work and we've seen remarkable progress in the past 20 years. There are more girls in school now compared to 15 years ago, and most regions have reached gender parity in primary education. But although there are more women than ever in the labor market, there are still large inequalities in some regions, with women systematically denied the same work rights as men. Sexual violence and exploitation, the unequal division of unpaid care and domestic work, and discrimination in public office all remain huge barriers. Climate change and disasters continue to have a disproportionate effect on women and children, as do conflict and migration. It is vital to give women equal rights land and property, sexual and reproductive health, and to technology and the internet. Today there are more women in public office than ever before, but encouraging more women leaders will help achieve greater gender equality.

Goal 6

Clean Water and Sanitation

Water scarcity affects more than 40 percent of people, an alarming figure that is projected to rise as temperatures do. Although 2.1 billion people have improved water sanitation since 1990, dwindling drinking water supplies are affecting every continent. More and more countries are experiencing water stress, and increasing drought and desertification are already worsening these trends. By 2050, it is projected that at least one in four people will suffer recurring water shortages. Safe and affordable drinking

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water for all by 2030 requires we invest in adequate infrastructure, provide sanitation facilities, and encourage hygiene. Protecting and restoring water-related ecosystems is essential. Ensuring universal safe and affordable drinking water involves reaching over 800 million people who lack basic services and improving accessibility and safety of services for over two billion. In 2015, 4.5 billion people lacked safely managed sanitation services (with adequately disposed or treated excreta) and 2.3 billion lacked even basic sanitation.

Goal 7

Affordable and Clean Energy

Between 2000 and 2018, the number of people with electricity increased from 78 to 90 percent, and the numbers without electricity dipped to 789 million. Yet as the population continues to grow, so will the demand for cheap energy, and an economy reliant on fossil fuels is creating drastic changes to our climate. Investing in solar, wind and thermal power, improving energy productivity, and ensuring energy for all is vital if we are to achieve SDG 7 by 2030. Expanding infrastructure and upgrading technology to provide clean and more efficient energy in all countries will encourage growth and help the environment.

Goal 8

Decent Work and Economic Growth

Over the past 25 years the number of workers living in extreme poverty has declined dramatically, despite the lasting impact of the 2008 economic crisis and global recession. In developing countries, the middle class now makes up more than 34 percent of total employment - a number that has almost tripled between 1991 and 2015. However, as the global economy continues to recover, we are seeing slower growth, widening inequalities, and not enough jobs to keep up with a growing labor force. According to the International Labor Organization, more than 204 million people were unemployed in 2015. The SDGs promote sustained economic growth, higher levels of productivity and technological innovation. Encouraging entrepreneurship and job creation are key to this, as are effective measures to eradicate forced labor, slavery and human trafficking. With these targets in mind, the goal is to achieve full and productive employment, and decent work, for all women and men by 2030.

Goal 9

Industry, Innovation and Infrastructure

Investment in infrastructure and innovation are crucial drivers of economic growth and development. With over half the world population now living in cities, mass transport and renewable energy are becoming ever more important, as are the growth of new industries and information and communication technologies. Technological progress is also key to finding lasting solutions to both economic and environmental challenges, such as providing new jobs and promoting energy efficiency. Promoting sustainable industries, and investing in scientific research and innovation, are all important ways to facilitate sustainable development. More than 4 billion people still do not have access to the Internet, and 90 percent are from the developing world. Bridging this digital divide is crucial to ensure equal access to information and knowledge, as well as foster innovation and entrepreneurship.

Goal 10

Reduced Inequalities

Income inequality is on the rise the richest 10 percent have up to 40 percent of global income whereas the poorest 10 percent earn only between 2 to 7 percent. If we take into account population growth inequality in developing countries, inequality has increased by 11 percent. Income inequality has increased in nearly everywhere in recent decades, but at different speeds. It's lowest in Europe and highest in the Middle East. These widening disparities require sound policies to empower lower income earners, and promote economic inclusion of all regardless of sex, race or ethnicity. Income inequality requires global solutions. This involves improving the regulation and monitoring of financial markets and institutions, encouraging development assistance and foreign direct investment to regions where the need is greatest. Facilitating the safe migration and mobility of people is also key to bridging the widening divide.

Goal 11

Sustainable Cities and Communities

More than half of us live in cities. By 2050, two-thirds of all humanity -6.5 billion people- will be urban. Sustainable development cannot be achieved without significantly transforming the way we build and manage our urban spaces. The rapid growth of cities -a result of rising populations and increasing migration has led to a boom in mega-cities, especially in the developing world, and slums are becoming a more significant feature of urban life. Making cities sustainable means creating career and business opportunities, safe and affordable housing, and building resilient societies and economies. It involves investment in public transport, creating green public spaces, and improving urban planning and management in participatory and inclusive ways [81-90].

Goal 12

Responsible Consumption and Production

Achieving economic growth and sustainable development requires that we urgently reduce our ecological footprint by changing the way we produce and consume goods and resources. Agriculture is the biggest user of water worldwide, and irrigation now claims close to 70 percent of all freshwater for human use.

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The efficient management of our shared natural resources, and the way we dispose of toxic waste and pollutants, are important targets to achieve this goal. Encouraging industries, businesses and consumers to recycle and reduce waste is equally important, as is supporting developing countries to move towards more sustainable patterns of consumption by 2030. A large share of the world population is still consuming far too little to meet even their basic needs. Halving the per capita of global food waste at the retailer and consumer levels is also important for creating more efficient production and supply chains. This can help with food security and shift us towards a more resource efficient economy.

Goal 13

Climate Action

There is no country that is not experiencing the drastic effects of climate change. Greenhouse gas emissions are more than 50 percent higher than in 1990. Global warming is causing long-lasting changes to our climate system, which threatens irreversible consequences if we do not act. The annual average economic losses from climate-related disasters are in the hundreds of billions of dollars. This is not to mention the human impact of geo-physical disasters, which are 91 percent climate-related, and which between 1998 and 2017 killed 1.3 million people and left 4.4 billion injured. The goal aims to mobilize US$100 billion annually by 2020 to address the needs of developing countries to both adapt to climate change and invest in low-carbon development. Supporting vulnerable regions will directly contribute not only to Goal 13 but also to the other SDGs. These actions must also go hand in hand with efforts to integrate disaster risk measures, sustainable natural resource management, and human security into national development strategies. It is still possible, with strong political will, increased investment, and using existing technology, to limit the increase in global mean temperature to two degrees Celsius above pre-industrial levels, aiming at 1.5°C, but this requires urgent and ambitious collective action.

Goal 14

Life below Water

The world's oceans - their temperature, chemistry, currents and life - drive global systems that make the Earth habitable for humankind. How we manage this vital resource is essential for humanity as a whole, and to counterbalance the effects of climate change. Over three billion people depend on marine and coastal biodiversity for their livelihoods. However, today we are seeing 30 percent of the world's fish stocks overexploited, reaching below the level at which they can produce sustainable yields. Oceans also absorb about 30 percent of the carbon dioxide produced by humans, and we are seeing a 26 percent rise in ocean acidification since the beginning of the industrial revolution. Marine pollution, an overwhelming majority of which comes from land-based sources, is reaching alarming levels, with an average of 13,000 pieces of plastic litter to be found on every square kilometer of ocean. The SDGs aim to sustainably manage and protect marine and coastal ecosystems from pollution, as well as address the impacts of ocean acidification. Enhancing conservation and the sustainable use of ocean-based resources through international law will also help mitigate some of the challenges facing our oceans.

Goal 15

Life on Land

Human life depends on the earth as much as the ocean for our sustenance and livelihoods. Plant life provides 80 percent of the human diet, and we rely on agriculture as an important economic resource. Forests cover 30 percent of the Earth's surface, provide vital habitats for millions of species, and important sources for clean air and water, as well as being crucial for combating climate change. Every year, 13 million hectares of forests are lost, while the persistent degradation of dry lands has led to the desertification of 3.6 billion hectares, disproportionately affecting poor communities. While 15 percent of land is protected, biodiversity is still at risk. Nearly 7,000 species of animals and plants have been illegally traded. Wildlife trafficking not only erodes biodiversity, but creates insecurity, fuels conflict, and feeds corruption. Urgent action must be taken to reduce the loss of natural habitats and biodiversity which are part of our common heritage and support global food and water security, climate change mitigation and adaptation, and peace and security.

Goal 16

Peace, Justice and Strong Institutions

We cannot hope for sustainable development without peace, stability, human rights and effective governance, based on the rule of law. Yet our world is increasingly divided. Some regions enjoy peace, security and prosperity, while others fall into seemingly endless cycles of conflict and violence. This is not inevitable and must be addressed. Armed violence and insecurity have a destructive impact on a country's development, affecting economic growth, and often resulting in grievances that last for generations. Sexual violence, crime, exploitation and torture are also prevalent where there is conflict, or no rule of law, and countries must take measures to protect those who are most at risk The SDGs aim to significantly reduce all forms of violence, and work with governments and communities to end conflict and insecurity. Promoting the rule of law and human rights are key to this process, as is reducing the flow of illicit arms and strengthening the participation of developing countries in the institutions of global governance.

Goal 17

Partnerships for the Goals

The SDGs can only be realized with strong global partnerships and cooperation. Official Development Assistance remained

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steady but below target, at US$147 billion in 2017. While humanitarian crises brought on by conflict or natural disasters continue to demand more financial resources and aid. Many countries also require Official Development Assistance to encourage growth and trade. The world is more interconnected than ever. Improving access to technology and knowledge is an important way to share ideas and foster innovation. Coordinating policies to help developing countries manage their debt, as well as promoting investment for the least developed, is vital for sustainable growth and development. The goals aim to enhance North-South and South-South cooperation by supporting national plans to achieve all the targets. Promoting international trade and helping developing countries increase their exports is all part of achieving a universal rules-based and equitable trading system that is fair and open and benefits all.

Renewable Energy

Renewable energy is energy that is collected from renewable resources that are naturally replenished on a human timescale. It includes sources such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy stands in contrast to fossil fuels, which are being used far more quickly than they are being replenished. Although most renewable energy sources are sustainable, some are not. For example, some biomass sources are considered unsustainable at current rates of exploitation. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services. About 20% of humans' global energy consumption is renewables, including almost 30% of electricity. About 8% of energy consumption is traditional biomass, but this is declining. Over 4% of energy consumption is heat energy from modern renewables, such as solar water heating, and over 6% electricity.

Globally there are over 10 million jobs associated with the renewable energy industries, with solar photovoltaics being the largest renewable employer. Renewable energy systems are rapidly becoming more efficient and cheaper and their share of total energy consumption is increasing, with a large majority of worldwide newly installed electricity capacity being renewable. In most countries, photovoltaic solar or onshore wind are the cheapest new-build electricity. Many nations around the world already have renewable energy contributing more than 20% of their energy supply, with some generating over half their electricity from renewables. National renewable energy markets are projected to continue to grow strongly in the 2020s and beyond. A few countries generate all their electricity using renewable energy. Renewable energy resources exist over wide geographical areas, in contrast to fossil fuels, which are concentrated in a limited number of countries. Deployment of renewable energy and energy efficiency technologies is resulting in significant energy security, climate change mitigation, and economic benefits. However renewables are being hindered by hundreds of billions of dollars of fossil fuel subsidies. In international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power.

Renewable energy technology projects are typically large-scale, but they are also suited to rural and remote areas and developing countries, where energy is often crucial in human development. As most of the renewable energy technologies provide electricity, renewable energy is often deployed together with further electrification, which has several benefits: electricity can be converted to heat, can be converted into mechanical energy with high efficiency, and is clean at the point of consumption. In addition, electrification with renewable energy is more efficient and therefore leads to significant reductions in primary energy requirements. In 2021, China accounted for almost half of the increase in renewable electricity. In 2021, Norway, known for its production of hydroelectricity, consumed hydro energy worth 45% of its total energy supply. Renewable power is booming, as innovation brings down costs and starts to deliver on the promise of a clean energy future. American solar and wind generation are breaking records and being integrated into the national electricity grid without compromising reliability. This means that renewables are increasingly displacing "dirty" fossil fuels in the power sector, offering the benefit of lower emissions of carbon and other types of pollution. But not all sources of energy marketed as "renewable" are beneficial to the environment. Biomass and large hydroelectric dams create difficult tradeoffs when considering the impact on wildlife, climate change, and other issues. Here's what you should know about the different types of renewable energy sources and how you can use these emerging technologies at your own home [81-90].

What Is Renewable Energy?

Renewable energy, often referred to as clean energy, comes from natural sources or processes that are constantly replenished. For example, sunlight or wind keep shining and blowing, even if their availability depends on time and weather. While renewable energy is often thought of as a new technology, harnessing nature's power has long been used for heating, transportation, lighting, and more. Wind has powered boats to sail the seas and windmills to grind grain. The sun has provided warmth during the day and helped kindle fires to last into the evening. But over the past 500 years or so, humans increasingly turned to cheaper, dirtier energy sources such as coal and fracked gas. Now that we have increasingly innovative and less-expensive ways to capture and retain wind and solar energy, renewables are becoming a more important power source, accounting for more than one-eighth of U.S. generation. The expansion in renewables is also happening at scales large and small, from rooftop solar panels on homes that can sell power back to the grid to giant offshore wind farms. Even some entire rural communities rely on renewable energy for heating and lighting. As renewable use continues to grow, a key goal will be to modernize America's electricity grid, making it smarter, more secure, and better integrated across regions.

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Dirty Energy

Nonrenewable, or "dirty," energy includes fossil fuels such as oil, gas, and coal. Nonrenewable sources of energy are only available in limited amounts and take a long time to replenish. When we pump gas at the station, we're using a finite resource refined from crude oil that's been around since prehistoric times. Nonrenewable energy sources are also typically found in specific parts of the world, making them more plentiful in some nations than others. By contrast, every country has access to sunshine and wind. Prioritizing nonrenewable energy can also improve national security by reducing a country's reliance on exports from fossil fuel-rich nations. Many nonrenewable energy sources can endanger the environment or human health. For example, oil drilling might require strip-mining Canada's boreal forest, the technology associated with fracking can cause earthquakes and water pollution, and coal power plants foul the air. To top it off, all these activities contribute to global warming.

Overview

Coal, oil, and natural gas remain the primary global energy sources even as renewables have begun rapidly increasing. Planet Solar, the world's largest solar-powered boat and the first ever solar electric vehicle to circumnavigate the globe (in 2012). Renewable energy flows involve natural phenomena such as sunlight, wind, tides, plant growth, and geothermal heat, as the International Energy Agency explains: Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources. Renewable energy resources and significant opportunities for energy efficiency exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency, and technological diversification of energy sources, would result in significant energy security and economic benefits. It would also reduce environmental pollution such as air pollution caused by the burning of fossil fuels, and improve public health, reduce premature mortalities due to pollution and save associated health costs that could amount to trillions of dollars annually. Multiple analyses of decarbonization strategies have found that quantified health benefits can significantly offset the costs of implementing these strategies. Renewable energy sources, that derive their energy from the sun, either directly or indirectly, such as hydro and wind, are expected to be capable of supplying humanity energy for almost another 1 billion years, at which point the predicted increase in heat from the Sun is expected to make the surface of the Earth too hot for liquid water to exist.

Climate change and global warming concerns, coupled with the continuing fall in the costs of some renewable energy equipment, such as wind turbines and solar panels, are driving increased use of renewables. New government spending, regulation and policies helped the industry weather the global financial crisis better than many other sectors. As of 2019, however, according to the International Renewable Energy Agency, renewables overall share in the energy mix (including power, heat and transport) needs to grow six times faster, in order to keep the rise in average global temperatures "well below" 2.0 °C (3.6 °F) during the present century, compared to pre-industrial levels. As of 2011, small solar PV systems provide electricity to a few million households, and micro-hydro configured into mini-grids serves many more. Over 44 million households use biogas made in household-scale digesters for lighting and/or cooking, and more than 166 million households rely on a new generation of more-efficient biomass cook stoves. United Nations' eighth Secretary-General Ban Ki-moon has said that renewable energy has the ability to lift the poorest nations to new levels of prosperity. At the national level, at least 30 nations around the world already have renewable energy contributing more than 20% of energy supply. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond, and some 120 countries have various policy targets for longer-term shares of renewable energy, including a 20% target of all electricity generated for the European Union by 2020. Some countries have much higher long-term policy targets of up to 100% renewables. Outside Europe, a diverse group of 20 or more other countries targets renewable energy shares in the 2020-2030 time frame that range from 10% to 50%. Renewable energy often displaces conventional fuels in four areas: electricity generation, hot water/space heating, transportation, and rural (off-grid) energy services:

- Power generation

By 2040, renewable energy is projected to equal coal and natural gas electricity generation. Several jurisdictions, including Denmark, Germany, the state of South Australia and some US states have achieved high integration of variable renewables. For example, in 2015 wind power met 42% of electricity demand in Denmark, 23.2% in Portugal and 15.5% in Uruguay. Interconnectors enable countries to balance electricity systems by allowing the import and export of renewable energy. Innovative hybrid systems have emerged between countries and regions.

- Heating

Solar water heating makes an important contribution to renewable heat in many countries, most notably in China, which now has 70% of the global total (180 GWth). Most of these systems are installed on multi-family apartment buildings and meet a portion of the hot water needs of an estimated 50-60 million households in China. Worldwide, total installed solar water heating systems meet a portion of the water heating needs of over 70 million households. The use of biomass for heating continues to grow as well. In Sweden, national use of biomass energy has surpassed that of oil. Direct geothermal for heating is also growing

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rapidly. The newest addition to heating is from geothermal heat pumps which provide both heating and cooling, and also flatten the electric demand curve and are thus an increasing national priority.

- Transportation

Bioethanol is an alcohol made by fermentation, mostly from carbohydrates produced in sugar or starch crops such as corn, sugarcane, or sweet sorghum. Cellulosic biomass, derived from non-food sources such as trees and grasses is also being developed as a feedstock for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form, but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Bioethanol is widely used in the USA and in Brazil. Biodiesel can be used as a fuel for vehicles in its pure form, but it is usually used as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons from diesel-powered vehicles. Biodiesel is produced from oils or fats using trans-esterification and is the most common biofuel in Europe. A solar vehicle is an electric vehicle powered completely or significantly by direct solar energy. Usually, photovoltaic (PV) cells contained in solar panels convert the sun's energy directly into electric energy. The term "solar vehicle" usually implies that solar energy is used to power all or part of a vehicle's propulsion. Solar power may be also used to provide power for communications or controls or other auxiliary functions. Solar vehicles are not sold as practical day-to-day transportation devices at present but are primarily demonstration vehicles and engineering exercises, often sponsored by government agencies. High-profile examples include Planet Solar and Solar Impulse. However, indirectly solar-charged vehicles are widespread and solar boats are available commercially.

History

Prior to the development of coal in the mid-19th century, nearly all energy used was renewable. The oldest known use of renewable energy, in the form of traditional biomass to fuel fires, dates from more than a million years ago. The use of biomass for fire did not become commonplace until many hundreds of thousands of years later. Probably the second oldest usage of renewable energy is harnessing the wind in order to drive ships over water. This practice can be traced back some 7000 years, to ships in the Persian Gulf and on the Nile. From hot springs, geothermal energy has been used for bathing since Paleolithic times and for space heating since ancient Roman times. Moving into the time of recorded history, the primary sources of traditional renewable energy were human labor, animal power, water power, and wind, in grain crushing windmills, and firewood, a traditional biomass. In the 1860s and 1870s, there were already fears that civilization would run out of fossil fuels and the need was felt for a better source. In 1873 Augustin Mouchot wrote: The time will arrive when the industry of Europe will cease to find those natural resources, so necessary for it. Petroleum springs and coal mines are not inexhaustible but are rapidly diminishing in many places. Will man, then, return to the power of water and wind?

Or will he emigrate where the most powerful source of heat sends its rays to all? History will show what will come. 1885, Werner von Siemens, commenting on the discovery of the photovoltaic effect in the solid state, wrote: In conclusion, I would say that however great the scientific importance of this discovery may be, its practical value will be no less obvious when we reflect that the supply of solar energy is both without limit and without cost, and that it will continue to pour down upon us for countless ages after all the coal deposits of the earth have been exhausted and forgotten. Max Weber mentioned the end of fossil fuel in the concluding paragraphs of his Die protestantische Ethik und der Geist des Kapitalismus (The Protestant Ethic and the Spirit of Capitalism), published in 1905. Development of solar engines continued until the outbreak of World War I. The importance of solar energy was recognized in a 1911 Scientific American article: "in the far distant future, natural fuels having been exhausted [solar power] will remain as the only means of existence of the human race". The theory of peak oil was published in 1956. In the 1970s environmentalists promoted the development of renewable energy both as a replacement for the eventual depletion of oil, as well as for an escape from dependence on oil, and the first electricity-generating wind turbines appeared. Solar had long been used for heating and cooling, but solar panels were too costly to build solar farms until 1980. Since the 21st century, many parts of the world have transitioned to sources of renewable energy from fossil fuels.

Mainstream Technologies

Hydropower

Since water is about 800 times denser than air, even a slow flowing stream of water, or moderate sea swell, can yield considerable amounts of energy. There are many forms of water energy: Historically, hydroelectric power came from constructing large hydroelectric dams and reservoirs, which are still popular in developing countries. The largest of them are the Three Gorges Dam (2003) in China and the Itaipu Dam (1984) built by Brazil and Paraguay. Small hydro systems are hydroelectric power installations that typically produce up to 50 MW of power. They are often used on small rivers or as a low-impact development on larger rivers. China is the largest producer of hydroelectricity in the world and has more than 45,000 small hydro installations. Run-of-the-river hydroelectricity plants derive energy from rivers without the creation of a large reservoir. The water is typically conveyed along the side of the river valley (using channels, pipes and/or tunnels) until it is high above the valley floor, whereupon it can be allowed to fall through a penstock to drive a turbine. This style of generation may still produce a large amount of electricity, such as the Chief Joseph Dam on the Columbia River in the United States. Many run-of-the-river hydro power plants are micro hydro or pico hydro plants. Hydropower is produced in 150

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countries, with the Asia-Pacific region generating 32 percent of global hydropower in 2010. Of the top 50 countries by percentage of electricity generated from renewables, 46 are primarily hydroelectric. China is the largest hydroelectricity producer, with 721 terawatt-hours of production in 2010, representing around 17 percent of domestic electricity use. There are now three hydroelectricity stations larger than 10 GW: the Three Gorges Dam in China, Itaipu Dam across the Brazil/Paraguay border, and Guri Dam in Venezuela.

Wave power, which captures the energy of ocean surface waves, and tidal power, converting the energy of tides, are two forms of hydropower with future potential; however, they are not yet widely employed commercially. According to the Energy Information Administration, the theoretical annual energy potential of waves off the coasts of the United States is estimated to be as much as 2.64 trillion kilowatthours, or the equivalent of about 66% of U.S. electricity generation in 2020. A demonstration project operated by the Ocean Renewable Power Company on the coast of Maine, and connected to the grid, harnesses tidal power from the Bay of Fundy, location of the world's highest tidal flow. Ocean thermal energy conversion, which uses the temperature difference between cooler deep and warmer surface waters, currently has no economic feasibility. Air flow can be used to run wind turbines. Modern utility-scale wind turbines range from around 600 kW to 9 MW of rated power. The power available from the wind is a function of the cube of the wind speed, so as wind speed increases, power output increases up to the maximum output for the particular turbine. Areas where winds are stronger and more constant, such as offshore and high-altitude sites, are preferred locations for wind farms. Typically, full load hours of wind turbines vary between 16 and 57 percent annually but might be higher in particularly favorable offshore sites. Wind-generated electricity met nearly 4% of global electricity demand in 2015, with nearly 63 GW of new wind power capacity installed. Wind energy was the leading source of new capacity in Europe, the US and Canada, and the second largest in China. In Denmark, wind energy met more than 40% of its electricity demand while Ireland, Portugal and Spain each met nearly 20%. Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production, or 40 times current electricity demand, assuming all practical barriers needed were overcome. This would require wind turbines to be installed over large areas, particularly in areas of higher wind resources, such as offshore. As offshore wind speeds average ~90% greater than that of land, so offshore resources can contribute substantially more energy than land-stationed turbines.

Types of Renewable Energy

What is a renewable energy source?

A renewable energy source means energy that is sustainable - something that can't run out, or is endless, like the sun. When you hear the term 'alternative energy' it's usually referring to renewable energy sources too. It means sources of energy that are alternative to the most commonly used non-sustainable sources - like coal [91-100].

What is zero-carbon or low-carbon energy?

Nuclear-generated electricity isn't renewable but its zero-carbon, which means its generation emits low levels or almost no CO_2, just like renewable energy sources. Nuclear energy has a stable source, which means it's not dependent on the weather and will play a big part in getting Britain to net zero status.

- Solar energy
- Wind energy
- Hydro energy
- Geothermal energy
- Biomass energy
- **Solar energy**

Solar energy, radiant light and heat from the sun, is harnessed using a range of ever-evolving technologies such as solar heating, photovoltaics, concentrated solar power (CSP), concentrator photovoltaics (CPV), solar architecture and artificial photosynthesis. Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert, and distribute solar energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air. Active solar technologies encompass solar thermal energy, using solar collectors for heating, and solar power, converting sunlight into electricity either directly using photovoltaics (PV), or indirectly using concentrated solar power (CSP). A photovoltaic system converts light into electrical direct current (DC) by taking advantage of the photoelectric effect. Solar PV has turned into a multi-billion, fast-growing industry, continues to improve its cost-effectiveness, and has the most potential of any renewable technologies together with CSP. Concentrated solar power (CSP) systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. Commercial concentrated solar power plants were first developed in the 1980s. CSP-Stirling has by far the highest efficiency among all solar energy technologies.

In 2011, the International Energy Agency said that "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise.

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These advantages are global. Hence the additional costs of the incentives for early deployment should be considered learning investments; they must be wisely spent and need to be widely shared". Solar power accounts for 505 GW annually, which is about 2% of the world's electricity. Solar energy can be harnessed anywhere that receives sunlight; however, the amount of solar energy that can be harnessed for electricity generation is influenced by weather conditions, geographic location and time of day. Australia has the largest proportion of solar electricity in the world, supplying 9.9% of the country's electrical demand in 2020.

- **Bioenergy**

Biomass is biological material derived from living, or recently living organisms. It most often refers to plants or plant-derived materials which are specifically called lignocellulosic biomass. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel. Conversion of biomass to biofuel can be achieved by different methods which are broadly classified into: thermal, chemical, and biochemical methods. Wood was the largest biomass energy source as of 2012; examples include forest residues - such as dead trees, branches and tree stumps -, yard clippings, wood chips and even municipal solid waste. In the second sense, biomass includes plant or animal matter that can be converted into fibers or other industrial chemicals, including biofuels. Industrial biomass can be grown from numerous types of plants, including miscanthus, switchgrass, hemp, corn, poplar, willow, sorghum, sugarcane, bamboo and a variety of tree species, ranging from eucalyptus to oil palm (palm oil).Plant energy is produced by crops specifically grown for use as fuel that offer high biomass output per hectare with low input energy. The grain can be used for liquid transportation fuels while the straw can be burned to produce heat or electricity. Plant biomass can also be degraded from cellulose to glucose through a series of chemical treatments, and the resulting sugar can then be used as a first-generation biofuel. Biomass can be converted to other usable forms of energy such as methane gas or transportation fuels such as ethanol and biodiesel. Rotting garbage, and agricultural and human waste, all release methane gas - also called landfill gas or biogas. Crops, such as corn and sugarcane, can be fermented to produce the transportation fuel, ethanol. Biodiesel, another transportation fuel, can be produced from left-over food products such as vegetable oils and animal fats. Also, biomass to liquids (BTLs) and cellulosic ethanol are still under research. There is a great deal of research involving algal fuel or algae-derived biomass due to the fact that it is a non-food resource and can be produced at rates 5 to 10 times those of other types of land-based agriculture, such as corn and soy. Once harvested, it can be fermented to produce biofuels such as ethanol, butanol, and methane, as well as biodiesel and hydrogen.

The biomass used for electricity generation varies by region. Forest by-products, such as wood residues, are common in the United States. Agricultural waste is common in Mauritius (sugar cane residue) and Southeast Asia (rice husks). Animal husbandry residues, such as poultry litter, are common in the United Kingdom. Biofuels include a wide range of fuels which are derived from biomass. The term covers solid, liquid, and gaseous fuels. Liquid biofuels include bioalcohols, such as bioethanol, and oils, such as biodiesel. Gaseous biofuels include biogas, landfill gas and synthetic gas. Bioethanol is an alcohol made by fermenting the sugar components of plant materials and it is made mostly from sugar and starch crops. These include maize, sugarcane and, more recently, sweet sorghum. The latter crop is particularly suitable for growing in dryland conditions, and is being investigated by International Crops Research Institute for the Semi-Arid Tropics for its potential to provide fuel, along with food and animal feed, in arid parts of Asia and Africa. With advanced technology being developed, cellulosic biomass, such as trees and grasses, are also used as feedstocks for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form, but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Bioethanol is widely used in the United States and in Brazil. The energy costs for producing bio-ethanol are almost equal to, the energy yields from bio-ethanol. However, according to the European Environment Agency, biofuels do not address global warming concerns. Biodiesel is made from vegetable oils, animal fats or recycled greases. It can be used as a fuel for vehicles in its pure form, or more commonly as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons from diesel-powered vehicles. Biodiesel is produced from oils or fats using trans-esterification and is the most common biofuel in Europe. Biofuels provided 2.7% of the world's transport fuel in 2010. Biomass, biogas and biofuels are burned to produce heat/power and in doing so harm the environment. Pollutants such as sulphurous oxides (SOx), nitrous oxides (NOx), and particulate matter (PM) are produced from the combustion of biomass. The World Health Organization estimates that 3.7 million prematurely died from outdoor air pollution in 2012 while indoor pollution from biomass burning effects over 3 billion people worldwide.

- **Geothermal Energy**

High temperature geothermal energy is from thermal energy generated and stored in the Earth. Thermal energy is the energy that determines the temperature of matter. Earth's geothermal energy originates from the original formation of the planet and from radioactive decay of minerals (in currently uncertain but possibly roughly equal proportions). The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. The adjective geothermal originates from the Greek roots geo, meaning earth, and thermos, meaning heat. The heat that is used for geothermal energy can be from deep within the Earth, all the way down to Earth's core - 4,000 miles (6,400 km) down. At the core, temperatures may reach over 9,000 °F (5,000 °C). Heat conducts from the core to the surrounding rock. Extremely

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high temperature and pressure cause some rock to melt, which is commonly known as magma. Magma convects upward since it is lighter than the solid rock. This magma then heats rock and water in the crust, sometimes up to 700 °F (371 °C). Low temperature geothermal refers to the use of the outer crust of the Earth as a thermal battery to facilitate renewable thermal energy for heating and cooling buildings, and other refrigeration and industrial uses. In this form of geothermal, a geothermal heat pump and ground-coupled heat exchanger are used together to move heat energy into the Earth (for cooling) and out of the Earth (for heating) on a varying seasonal basis. Low-temperature geothermal (generally referred to as "GHP") is an increasingly important renewable technology because it both reduces total annual energy loads associated with heating and cooling, and it also flattens the electric demand curve eliminating the extreme summer and winter peak electric supply requirements. Thus, low temperature geothermal/GHP is becoming an increasing national priority with multiple tax credit support and focus as part of the ongoing movement toward net zero energy.

Emerging Technologies

There are also other renewable energy technologies that are still under development, including cellulosic ethanol, hot-dry-rock geothermal power, and marine energy. These technologies are not yet widely demonstrated or have limited commercialization. Many are on the horizon and may have potential comparable to other renewable energy technologies, but still depend on attracting sufficient attention and research, development and demonstration (RD&D) funding. There are numerous organizations within the academic, federal, and commercial sectors conducting large-scale advanced research in the field of renewable energy. This research spans several areas of focus across the renewable energy spectrum. Most of the research is targeted at improving efficiency and increasing overall energy yields. Multiple federally supported research organizations have focused on renewable energy in recent years. Two of the most prominent of these labs are Sandia National Laboratories and the National Renewable Energy Laboratory (NREL), both of which are funded by the United States Department of Energy and supported by various corporate partners. Sandia has a total budget of $2.4 billion while NREL has a budget of $375 million.

Enhanced Geothermal System

Enhanced geothermal systems (EGS) are a new type of geothermal power technology that does not require natural convective hydrothermal resources. The vast majority of geothermal energy within drilling reach is in dry and non-porous rock. EGS technologies "enhance" and/or create geothermal resources in this "hot dry rock (HDR)" through hydraulic fracturing. EGS and HDR technologies, such as hydrothermal geothermal, are expected to be baseload resources that produce power 24 hours a day like a fossil plant. Distinct from hydrothermal, HDR and EGS may be feasible anywhere in the world, depending on the economic limits of drill depth. Good locations are over deep granite covered by a thick (3-5 km) layer of insulating sediments which slow heat loss. There are HDR and EGS systems currently being developed and tested in France, Australia, Japan, Germany, the U.S., and Switzerland. The largest EGS project in the world is a 25 megawatt demonstration plant currently being developed in the Cooper Basin, Australia. The Cooper Basin has the potential to generate 5,000-10,000 MW.

Cellulosic Ethanol

Several refineries that can process biomass and turn it into ethanol are built by companies such as Iogen, POET, and Abengoa, while other companies such as the Verenium Corporation, Novozymes, and Dyadic International are producing enzymes which could enable future commercialization. The shift from food crop feedstocks to waste residues and native grasses offers significant opportunities for a range of players, from farmers to biotechnology firms, and from project developers to investors.

Marine Energy

Marine energy (also sometimes referred to as ocean energy) is the energy carried by ocean waves, tides, salinity, and ocean temperature differences. The movement of water in the world's oceans creates a vast store of kinetic energy, or energy in motion. This energy can be harnessed to generate electricity to power homes, transport and industries. The term marine energy encompasses both wave power - power from surface waves, and tidal power - obtained from the kinetic energy of large bodies of moving water. Reverse electro-dialysis (RED) is a technology for generating electricity by mixing fresh river water and salty sea water in large power cells designed for this purpose; as of 2016, it is being tested at a small scale (50 kW). Offshore wind power is not a form of marine energy, as wind power is derived from the wind, even if the wind turbines are placed over water. The oceans have a tremendous amount of energy and are close to many if not most concentrated populations. Ocean energy has the potential of providing a substantial amount of new renewable energy around the world.

Solar Energy

Solar energy is radiant light and heat from the Sun that is harnessed using a range of technologies such as solar power to generate electricity, solar thermal energy including solar water heating, and solar architecture. It is an essential source of renewable energy, and its technologies are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy or convert it into solar power. Active solar techniques include the use of photovoltaic systems, concentrated solar power, and solar water heating to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or

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light-dispersing properties, and designing spaces that naturally circulate air. The large magnitude of solar energy available makes it a highly appealing source of electricity. Solar energy has been cheaper than fossil fuels since 2021. In 2011, the International Energy Agency said that "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible, and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating global warming... These advantages are global."

Potential

Average insolation. The theoretical area of the small black dots is sufficient to supply the world's total energy needs of 18 TW with solar power. The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. Most of the world's population live in areas with insolation levels of 150-300 watts/m2, or 3.5-7.0 kWh/m2 per day. Solar radiation is absorbed by the Earth's land surface, oceans - which cover about 71% of the globe - and atmosphere. Warm air containing evaporated water from the oceans rises, causing atmospheric circulation or convection. When the air reaches a high altitude, where the temperature is low, water vapor condenses into clouds, which rain onto the Earth's surface, completing the water cycle. The latent heat of water condensation amplifies convection, producing atmospheric phenomena such as wind, cyclones and anticyclones. Sunlight absorbed by the oceans and land masses keeps the surface at an average temperature of 14 °C. By photosynthesis, green plants convert solar energy into chemically stored energy, which produces food, wood and the biomass from which fossil fuels are derived.

The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. In 2002, this was more energy in one hour than the world used in one year. Photosynthesis captures approximately 3,000 EJ per year in biomass. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined. The potential solar energy that could be used by humans differs from the amount of solar energy present near the surface of the planet because factors such as geography, time variation, cloud cover, and the land available to humans limit the amount of solar energy that we can acquire. In 2021, Carbon Tracker Initiative estimated the land area needed to generate all our energy from solar alone was 450,000 km2- or about the same as the area of Sweden, or the area of Morocco, or the area of California (0.3% of the Earth's total land area).

Geography affects solar energy potential because areas that are closer to the equator have a higher amount of solar radiation. However, the use of photovoltaics that can follow the position of the Sun can significantly increase the solar energy potential in areas that are farther from the equator. Time variation effects the potential of solar energy because during the nighttime, there is little solar radiation on the surface of the Earth for solar panels to absorb. This limits the amount of energy that solar panels can absorb in one day. Cloud cover can affect the potential of solar panels because clouds block incoming light from the Sun and reduce the light available for solar cells. Besides, land availability has a large effect on the available solar energy because solar panels can only be set up on land that is otherwise unused and suitable for solar panels. Roofs are a suitable place for solar cells, as many people have discovered that they can collect energy directly from their homes this way. Other areas that are suitable for solar cells are lands that are not being used for businesses where solar plants can be established. Solar technologies are characterized as either passive or active depending on the way they capture, convert and distribute sunlight and enable solar energy to be harnessed at different levels around the world, mostly depending on the distance from the equator. Although solar energy refers primarily to the use of solar radiation for practical ends, all renewable energies, other than geothermal power and Tidal power, derive their energy either directly or indirectly from the Sun.

Active solar techniques use photovoltaics, concentrated solar power, solar thermal collectors, pumps, and fans to convert sunlight into useful outputs. Passive solar techniques include selecting materials with favorable thermal properties, designing spaces that naturally circulate air, and referencing the position of a building to the Sun. Active solar technologies increase the supply of energy and are considered supply side technologies, while passive solar technologies reduce the need for alternate resources and are generally considered demand-side technologies. In 2000, the United Nations Development Programme, UN Department of Economic and Social Affairs, and World Energy Council published an estimate of the potential solar energy that could be used by humans each year that took into account factors such as insolation, cloud cover, and the land that is usable by humans. The estimate found that solar energy has a global potential of 1,600 to 49,800 exajoules (4.4×1014 to 1.4×1016 kWh) per year.

Solar Energy Developments

Experimental Solar Power

Concentrated photovoltaics (CPV) systems employ sunlight concentrated onto photovoltaic surfaces for the purpose of electricity generation. Thermoelectric, or "thermovoltaic" devices convert a temperature difference between dissimilar materials into an electric current.

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Floating Solar Arrays

Floating solar arrays are PV systems that float on the surface of drinking water reservoirs, quarry lakes, irrigation canals or remediation and tailing ponds. A small number of such systems exist in France, India, Japan, South Korea, the United Kingdom, Singapore, and the United States. The systems are said to have advantages over photovoltaics on land. The cost of land is more expensive, and there are fewer rules and regulations for structures built on bodies of water not used for recreation. Unlike most land-based solar plants, floating arrays can be unobtrusive because they are hidden from public view. They achieve higher efficiencies than PV panels on land, because water cools the panels. The panels have a special coating to prevent rust or corrosion. In May 2008, the Far Niente Winery in Oakville, California, pioneered the world's first floatovoltaic system by installing 994 solar PV modules with a total capacity of 477 kW onto 130 pontoons and floating them on the winery's irrigation pond. Utility-scale floating PV farms are starting to be built. Kyocera will develop the world's largest, a 13.4 MW farm on the reservoir above Yamakura Dam in Chiba Prefecture using 50,000 solar panels. Salt-water resistant floating farms are also being constructed for ocean use. The largest so far announced floatovoltaic project is a 350 MW power station in the Amazon region of Brazil.

Perovskite Solar Cells

A perovskite solar cell (PSC) is a type of solar cell which includes a perovskite-structured compound, most commonly a hybrid organic-inorganic lead or tin halide-based material, as the light-harvesting active layer. Perovskite materials, such as methylammonium lead halides and all-inorganic cesium lead halide, are cheap to produce and simple to manufacture. Solar cell efficiencies of laboratory-scale devices using these materials have increased from 3.8% in 2009 to 25.7% in 2021 in single-junction architectures, and, in silicon-based tandem cells, to 29.8%, exceeding the maximum efficiency achieved in single-junction silicon solar cells. Perovskite solar cells have therefore been the fastest-advancing solar technology as of 2016. With the potential of achieving even higher efficiencies and very low production costs, perovskite solar cells have become commercially attractive. Core problems and research subjects include their short- and long-term stability.

Solar-Assisted Heat Pump

A heat pump is a device that provides heat energy from a source of heat to a destination called a "heat sink". Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. A solar-assisted heat pump represents the integration of a heat pump and thermal solar panels in a single integrated system. Typically, these two technologies are used separately (or only placing them in parallel) to produce hot water. In this system the solar thermal panel performs the function of the low temperature heat source and the heat produced is used to feed the heat pump's evaporator. The goal of this system is to get high COP and then produce energy in a more efficient and less expensive way. It is possible to use any type of solar thermal panel (sheet and tubes, roll-bond, heat pipe, thermal plates) or hybrid (mono/polycrystalline, thin film) in combination with the heat pump. The use of a hybrid panel is preferable because it allows covering a part of the electricity demand of the heat pump and reduces the power consumption and consequently the variable costs of the system.

Solar Aircraft

An electric aircraft is an aircraft that runs on electric motors rather than internal combustion engines, with electricity coming from fuel cells, solar cells, ultracapacitors, power beaming, or batteries. Currently, flying manned electric aircraft are mostly experimental demonstrators, though many small unmanned aerial vehicles are powered by batteries. Electrically powered model aircraft have been flown since the 1970s, with one report in 1957. The first man-carrying electrically powered flights were made in 1973. Between 2015 and 2016, a manned, solar-powered plane, Solar Impulse 2, completed a circumnavigation of the Earth.

1.1. Solar Updraft Tower

A solar updraft tower is a renewable-energy power plant for generating electricity from low-temperature solar heat. Sunshine heats the air beneath a very wide greenhouse-like roofed collector structure surrounding the central base of a very tall chimney tower. The resulting convection causes a hot air updraft in the tower by the chimney effect. This airflow drives wind turbines placed in the chimney updraft or around the chimney base to produce electricity. Plans for scaled-up versions of demonstration models will allow significant power generation and may allow the development of other applications, such as water extraction or distillation, and agriculture or horticulture. A more advanced version of a similarly themed technology is the Vortex engine which aims to replace large physical chimneys with a vortex of air created by a shorter, less-expensive structure.

Space-Based Solar Power

For either photovoltaic or thermal systems, one option is to loft them into space, particularly geosynchronous orbit. To be competitive with Earth-based solar power systems, the specific mass (kg/kW) times the cost to loft mass plus the cost of the parts needs to be $2400 or less. I.e., for a parts cost plus rectenna of $1100/kW, the product of the $/kg and kg/kW must be $1300/kW or less. Thus for 6.5 kg/kW, the transport cost cannot exceed $200/kg. While that will require a 100 to one reduction, SpaceX is targeting a ten to one reduction, Reaction Engines may make a 100 to one reduction possible.

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Artificial Photosynthesis

Artificial photosynthesis uses techniques including nanotechnology to store solar electromagnetic energy in chemical bonds by splitting water to produce hydrogen and then using carbon dioxide to make methanol. Researchers in this field are striving to design molecular mimics of photosynthesis that use a wider region of the solar spectrum, employ catalytic systems made from abundant, inexpensive materials that are robust, readily repaired, non-toxic, stable in a variety of environmental conditions and perform more efficiently allowing a greater proportion of photon energy to end up in the storage compounds, i.e., carbohydrates (rather than building and sustaining living cells). However, prominent research faces hurdles, Sun Catalytix a MIT spin-off stopped scaling up their prototype fuel-cell in 2012, because it offers few savings over other ways to make hydrogen from sunlight.

Thermal Energy

Solar thermal technologies can be used for water heating, space heating, and space cooling and process heat generation.

Early Commercial Adaptation

In 1878, at the Universal Exposition in Paris, Augustin Mouchot successfully demonstrated a solar steam engine, but couldn't continue development because of cheap coal and other factors. In 1897, Frank Shuman, a US inventor, engineer and solar energy pioneer built a small demonstration solar engine that worked by reflecting solar energy onto square boxes filled with ether, which has a lower boiling point than water and were fitted internally with black pipes which in turn powered a steam engine. In 1908 Shuman formed the Sun Power Company with the intent of building larger solar power plants. He, along with his technical advisor A.S.E. Ackermann and British physicist Sir Charles Vernon Boys, developed an improved system using mirrors to reflect solar energy upon collector boxes, increasing heating capacity to the extent that water could now be used instead of ether. Shuman then constructed a full-scale steam engine powered by low-pressure water, enabling him to patent the entire solar engine system by 1912. Shuman built the world's first solar thermal power station in Maadi, Egypt, between 1912 and 1913. His plant used parabolic troughs to power a 45-52 kilowatts (60-70 hp) engine that pumped more than 22,000 litres (4,800 imp gal; 5,800 US gal) of water per minute from the Nile River to adjacent cotton fields. Although the outbreak of World War I and the discovery of cheap oil in the 1930s discouraged the advancement of solar energy, Shuman's vision, and basic design were resurrected in the 1970s with a new wave of interest in solar thermal energy. In 1916 Shuman was quoted in the media advocating solar energy's utilization, saying: "We have proved the commercial profit of sun power in the tropics and have more particularly proved that after our stores of oil and coal are exhausted the human race can receive unlimited power from the rays of the Sun."

Water Heating

Solar hot water systems use sunlight to heat water. In middle geographical latitudes (between 40 degrees north and 40 degrees south), 60 to 70% of the domestic hot water use, with water temperatures up to 60 °C (140 °F), can be provided by solar heating systems. The most common types of solar water heaters are evacuated tube collectors (44%) and glazed flat plate collectors (34%) generally used for domestic hot water; and unglazed plastic collectors (21%) used mainly to heat swimming pools. As of 2015, the total installed capacity of solar hot water systems was approximately 436 thermal gigawatt (GWth), and China is the world leader in their deployment with 309 GWth installed, taken up 71% of the market. Israel and Cyprus are the per capita leaders in the use of solar hot water systems with over 90% of homes using them. In the United States, Canada, and Australia, heating swimming pools is the dominant application of solar hot water with an installed capacity of 18 GWth as of 2005.

Heating, Cooling and Ventilation

In the United States, heating, ventilation and air conditioning (HVAC) systems account for 30% (4.65 EJ/yr) of the energy used in commercial buildings and nearly 50% (10.1 EJ/yr) of the energy used in residential buildings. Solar heating, cooling and ventilation technologies can be used to offset a portion of this energy. Use of solar for heating can roughly be divided into passive solar concepts and active solar concepts, depending on whether active elements such as sun tracking and solar concentrator optics are used. Thermal mass is any material that can be used to store heat-heat from the Sun in the case of solar energy. Common thermal mass materials include stone, cement, and water. Historically they have been used in arid climates or warm temperate regions to keep buildings cool by absorbing solar energy during the day and radiating stored heat to the cooler atmosphere at night. However, they can be used in cold temperate areas to maintain warmth as well. The size and placement of thermal mass depend on several factors such as climate, day lighting, and shading conditions. When duly incorporated, thermal mass maintains space temperatures in a comfortable range and reduces the need for auxiliary heating and cooling equipment.

A solar chimney (or thermal chimney, in this context) is a passive solar ventilation system composed of a vertical shaft connecting the interior and exterior of a building. As the chimney warms, the air inside is heated, causing an updraft that pulls air through the building. Performance can be improved by using glazing and thermal mass materials in a way that mimics greenhouses. Deciduous trees and plants have been promoted as a means of controlling solar heating and cooling. When planted on the southern side of a building in the northern hemisphere or the northern side in the southern hemisphere, their leaves provide shade during the summer, while the bare limbs allow light to pass during the winter. Since bare, leafless trees shade 1/3 to 1/2 of

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incident solar radiation, there is a balance between the benefits of summer shading and the corresponding loss of winter heating. In climates with significant heating loads, deciduous trees should not be planted on the Equator-facing side of a building because they will interfere with winter solar availability. They can, however, be used on the east and west sides to provide a degree of summer shading without appreciably affecting winter solar gain.

Cooking

Solar cookers use sunlight for cooking, drying, and pasteurization. They can be grouped into three broad categories: box cookers, panel cookers, and reflector cookers. The simplest solar cooker is the box cooker first built by Horace de Saussure in 1767. A basic box cooker consists of an insulated container with a transparent lid. It can be used effectively with partially overcast skies and will typically reach temperatures of 90-150 °C (194-302 °F). Panel cookers use a reflective panel to direct sunlight onto an insulated container and reach temperatures comparable to box cookers. Reflector cookers use various concentrating geometeries (dish, trough, Fresnel mirrors) to focus light on a cooking container. These cookers reach temperatures of 315 °C (599 °F) and above but require direct light to function properly and must be repositioned to track the Sun.

Process Heat

Solar concentrating technologies such as parabolic dish, trough and Scheffler reflectors can provide process heat for commercial and industrial applications. The first commercial system was the Solar Total Energy Project (STEP) in Shenandoah, Georgia, US where a field of 114 parabolic dishes provided 50% of the process heating, air conditioning and electrical requirements for a clothing factory. This grid-connected cogeneration system provided 400 kW of electricity plus thermal energy in the form of 401 kW steam and 468 kW chilled water, and had a one-hour peak load thermal storage. Evaporation ponds are shallow pools that concentrate dissolved solids through evaporation. The use of evaporation ponds to obtain salt from seawater is one of the oldest applications of solar energy. Modern uses include concentrating brine solutions used in leach mining and removing dissolved solids from waste streams. Clothes lines, clotheshorses, and clothes racks dry clothes through evaporation by wind and sunlight without consuming electricity or gas. In some states of the United States legislation protects the “right to dry” clothes. Unglazed transpired collectors (UTC) are perforated sun-facing walls used for preheating ventilation air. UTCs can raise the incoming air temperature up to 22 °C (40 °F) and deliver outlet temperatures of 45-60 °C (113-140 °F). The short payback period of transpired collectors (3 to 12 years) makes them a more cost-effective alternative than glazed collection systems. As of 2003, over 80 systems with a combined collector area of 35,000 square meters (380,000 sq ft) had been installed worldwide, including an 860 m2 (9,300 sq ft) collector in Costa Rica used for drying coffee beans and a 1,300 m2 (14,000 sq ft) collector in Coimbatore, India, used for drying marigolds.

Water Treatment

Solar distillation can be used to make saline or brackish water potable. The first recorded instance of this was by 16th-century Arab alchemists. A large-scale solar distillation project was first constructed in 1872 in the Chilean mining town of Las Salinas. The plant, which had solar collection area of 4,700 m2 (51,000 sq ft), could produce up to 22,700 L (5,000 imp gal; 6,000 US gal) per day and operate for 40 years. Individual still designs include single-slope, double-slope (or greenhouse type), vertical, conical, inverted absorber, multi-wick, and multiple effect. These stills can operate in passive, active, or hybrid modes. Double-slope stills are the most economical for decentralized domestic purposes, while active multiple effect units are more suitable for large-scale applications. Solar water disinfection (SODIS) involves exposing water-filled plastic polyethylene terephthalate (PET) bottles to sunlight for several hours. Exposure times vary depending on weather and climate from a minimum of six hours to two days during fully overcast conditions. It is recommended by the World Health Organization as a viable method for household water treatment and safe storage. Over two million people in developing countries use this method for their daily drinking water. Solar energy may be used in a water stabilization pond to treat waste water without chemicals or electricity. A further environmental advantage is that algae grow in such ponds and consume carbon dioxide in photosynthesis, although algae may produce toxic chemicals that make the water unusable.

Molten Salt Technology

Molten salt can be employed as a thermal energy storage method to retain thermal energy collected by a solar tower or solar trough of a concentrated solar power plant so that it can be used to generate electricity in bad weather or at night. It was demonstrated in the Solar Two project from 1995 to 1999. The system is predicted to have an annual efficiency of 99%, a reference to the energy retained by storing heat before turning it into electricity, versus converting heat directly into electricity. The molten salt mixtures vary. The most extended mixture contains sodium nitrate, potassium nitrate and calcium nitrate. It is non-flammable and non-toxic, and has already been used in the chemical and metals industries as a heat-transport fluid. Hence, experience with such systems exists in non-solar applications. The salt melts at 131 °C (268 °F). It is kept liquid at 288 °C (550 °F) in an insulated “cold” storage tank. The liquid salt is pumped through panels in a solar collector where the focused irradiance heats it to 566 °C (1,051 °F). It is then sent to a hot storage tank. This is so well insulated that the thermal energy can be usefully stored for up to a week. When electricity is needed, the hot salt is pumped to a conventional steam-generator to produce superheated steam for a turbine/generator as used in any conventional coal,

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oil, or nuclear power plant. A 100-megawatt turbine would need a tank about 9.1 meters (30 ft) tall and 24 meters (79 ft) in diameter to drive it for four hours by this design. Several parabolic trough power plants in Spain and solar power tower developer SolarReserve use this thermal energy storage concept. The Solana Generating Station in the U.S. has six hours of storage by molten salt. The María Elena plant is a 400 MW thermo-solar complex in the northern Chilean region of Antofagasta employing molten salt technology.

Electricity Production

Solar power is the conversion of renewable energy from sunlight into electricity, either directly using photovoltaics (PV), indirectly using concentrated solar power, or a combination. Concentrated solar power systems use lenses or mirrors and solar tracking systems to focus a large area of sunlight into a small beam. Photovoltaic cells convert light into an electric current using the photovoltaic effect. Photovoltaics were initially solely used as a source of electricity for small and medium-sized applications, from the calculator powered by a single solar cell to remote homes powered by an off-grid rooftop PV system. Commercial concentrated solar power plants were first developed in the 1980s. Since then, as the cost of solar electricity has fallen, grid-connected solar PV systems have grown more or less exponentially. Millions of installations and gigawatt-scale photovoltaic power stations have been and are being built. Solar PV has rapidly become an inexpensive, low-carbon technology. The International Energy Agency said in 2021 that under its "Net Zero by 2050" scenario solar power would contribute about 20% of worldwide energy consumption, and solar would be the world's largest source of electricity. China has the most solar installations. In 2020, solar power generated 3.5% of the world's electricity, compared to under 3% the previous year. In 2020 the unsubsidised levelized cost of electricity for utility-scale solar power was around $36/MWh and installation cost about a dollar per DC watt.

Photovoltaics

Photovoltaics (PV) is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. The photovoltaic effect is commercially utilized for electricity generation and as photosensors. A photovoltaic system employs solar modules, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop-mounted, wall-mounted or floating. The mount may be fixed or use a solar tracker to follow the sun across the sky. Some hope that photovoltaic technology will produce enough affordable sustainable energy to help mitigate global warming caused by CO_2. Solar PV has specific advantages as an energy source: once installed, its operation generates no pollution and no greenhouse gas emissions, it shows simple scalability in respect of power needs and silicon has large availability in the Earth's crust, although other materials required in PV system manufacture such as silver will eventually constrain further growth in the technology. Other major constraints identified are competition for land use and lack of labor in making funding applications. The use of PV as a main source requires energy storage systems or global distribution by high-voltage direct current power lines causing additional costs, and also has a number of other specific disadvantages such as unstable power generation and the requirement for power companies to compensate for too much solar power in the supply mix by having more reliable conventional power supplies in order to regulate demand peaks and potential undersupply. Production and installation does cause pollution and greenhouse gas emissions and there are no viable systems for recycling the panels once they are at the end of their lifespan after 10 to 30 years.

Photovoltaic systems have long been used in specialized applications as stand-alone installations and grid-connected PV systems have been in use since the 1990s. Photovoltaic modules were first mass-produced in 2000, when German environmentalists and the Eurosolar organization received government funding for a ten thousand roof program. Decreasing costs has allowed PV to grow as an energy source. This has been partially driven by massive Chinese government investment in developing solar production capacity since 2000, and achieving economies of scale. Much of the price of production is from the key component polysilicon, and most of the world supply is produced in China, especially in Xinjiang. Beside the subsidies, the low prices of solar panels in the 2010s has been achieved through the low price of energy from coal and cheap labour costs in Xinjiang, as well as improvements in manufacturing technology and efficiency. Advances in technology and increased manufacturing scale have also increased the efficiency of photovoltaic installations. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries. Panel prices dropped by a factor of 4 between 2004 and 2011. Module prices dropped 90% of over the 2010s, but began increasing sharply in 2021. In 2019, worldwide installed PV capacity increased to more than 635 gigawatts (GW) covering approximately two percent of global electricity demand. After hydro and wind powers, PV is the third renewable energy source in terms of global capacity. In 2019 the International Energy Agency expected a growth by 700 - 880 GW from 2019 to 2024. In some instances, PV has offered the cheapest source of electrical power in regions with a high solar potential, with a bid for pricing as low as 0.01567 US$/kWh in Qatar in 2020.

Concentrated Solar Power

Concentrating Solar Power (CSP) systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated heat is then used as a heat source

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for a conventional power plant. A wide range of concentrating technologies exists; the most developed are the parabolic trough, the concentrating linear Fresnel reflector, the Stirling dish, and the solar power tower. Various techniques are used to track the Sun and focus light. In all of these systems, a working fluid is heated by the concentrated sunlight, and is then used for power generation or energy storage. Designs need to account for the risk of a dust storm, hail, or another extreme weather event that can damage the fine glass surfaces of solar power plants. Metal grills would allow a high percentage of sunlight to enter the mirrors and solar panels while also preventing most damage.

Architecture and Urban Planning

Darmstadt University of Technology, Germany, won the 2007 Solar Decathlon in Washington, DC with this passive house designed for humid and hot subtropical climate. Sunlight has influenced building design since the beginning of architectural history. Advanced solar architecture and urban planning methods were first employed by the Greeks and Chinese, who oriented their buildings toward the south to provide light and warmth. The common features of passive solar architecture are orientation relative to the Sun, compact proportion (a low surface area to volume ratio), selective shading (overhangs) and thermal mass. When these features are tailored to the local climate and environment, they can produce well-lit spaces that stay in a comfortable temperature range. Socrates' Megaron House is a classic example of passive solar design. The most recent approaches to solar design use computer modeling tying together solar lighting, heating and ventilation systems in an integrated solar design package. Active solar equipment such as pumps, fans, and switchable windows can complement passive design and improve system performance. Urban heat islands (UHI) are meteropolitan areas with higher temperatures than that of the surrounding environment. The higher temperatures result from increased absorption of solar energy by urban materials such as asphalt and concrete, which have lower albedos and higher heat capacities than those in the natural environment. A straightforward method of counteracting the UHI effect is to paint buildings and roads white and to plant trees in the area. Using these methods, a hypothetical "cool communities" program in Los Angeles has projected that urban temperatures could be reduced by approximately 3 °C at an estimated cost of US$1 billion, giving estimated total annual benefits of US$530 million from reduced air-conditioning costs and healthcare savings [101-110].

Agriculture and Horticulture

Agriculture and horticulture seek to optimize the capture of solar energy to optimize the productivity of plants. Techniques such as timed planting cycles, tailored row orientation, staggered heights between rows and the mixing of plant varieties can improve crop yields. While sunlight is generally considered a plentiful resource, the exceptions highlight the importance of solar energy to agriculture. During the short growing seasons of the Little Ice Age, French and English farmers employed fruit walls to maximize the collection of solar energy. These walls acted as thermal masses and accelerated ripening by keeping plants warm. Early fruit walls were built perpendicular to the ground and facing south, but over time, sloping walls were developed to make better use of sunlight. In 1699, Nicolas Fatio de Duillier even suggested using a tracking mechanism which could pivot to follow the Sun. Applications of solar energy in agriculture aside from growing crops include pumping water, drying crops, brooding chicks and drying chicken manure. More recently the technology has been embraced by vintners, who use the energy generated by solar panels to power grape presses. Greenhouses convert solar light to heat, enabling year-round production and the growth (in enclosed environments) of specialty crops and other plants not naturally suited to the local climate. Primitive greenhouses were first used during Roman times to produce cucumbers year-round for the Roman emperor Tiberius. The first modern greenhouses were built in Europe in the 16th century to keep exotic plants brought back from explorations abroad. Greenhouses remain an important part of horticulture today. Plastic transparent materials have also been used to similar effect in polytunnels and row covers.

Transport

Development of a solar-powered car has been an engineering goal since the 1980s. The World Solar Challenge is a biannual solar-powered car race, where teams from universities and enterprises compete over 3,021 kilometers (1,877 mi) across central Australia from Darwin to Adelaide. In 1987, when it was founded, the winner's average speed was 67 kilometers per hour (42 mph) and by 2007 the winner's average speed had improved to 90.87 kilometers per hour (56.46 mph). The North American Solar Challenge and the planned South African Solar Challenge are comparable competitions that reflect an international interest in the engineering and development of solar powered vehicles. Some vehicles use solar panels for auxiliary power, such as for air conditioning, to keep the interior cool, thus reducing fuel consumption. In 1975, the first practical solar boat was constructed in England. By 1995, passenger boats incorporating PV panels began appearing and are now used extensively. In 1996, Kenichi Horie made the first solar-powered crossing of the Pacific Ocean, and the Sun21 catamaran made the first solar-powered crossing of the Atlantic Ocean in the winter of 2006-2007. There were plans to circumnavigate the globe in 2010. In 1974, the unmanned AstroFlight Sunrise airplane made the first solar flight. On 29 April 1979, the Solar Riser made the first flight in a solar-powered, fully controlled, man-carrying flying machine, reaching an altitude of 40 ft (12 m). In 1980, the Gossamer Penguin made the first piloted flights powered solely by photovoltaics. This was quickly followed by the Solar Challenger which crossed the English Channel in July 1981. In 1990 Eric Scott Raymond in 21 hops flew from California to North Carolina using solar power.

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Developments then turned back to unmanned aerial vehicles (UAV) with the Pathfinder (1997) and subsequent designs, culminating in the Helios which set the altitude record for a non-rocket-propelled aircraft at 29,524 meters (96,864 ft) in 2001. The Zephyr, developed by BAE Systems, is the latest in a line of record-breaking solar aircraft, making a 54-hour flight in 2007, and month-long flights were envisioned by 2010. As of 2016, Solar Impulse, an electric aircraft, is currently circumnavigating the globe. It is a single-seat plane powered by solar cells and capable of taking off under its own power. The design allows the aircraft to remain airborne for several days. A solar balloon is a black balloon that is filled with ordinary air. As sunlight shines on the balloon, the air inside is heated and expands, causing an upward buoyancy force, much like an artificially heated hot air balloon. Some solar balloons are large enough for human flight, but usage is generally limited to the toy market as the surface-area to payload-weight ratio is relatively high.

Fuel Production

Solar chemical processes use solar energy to drive chemical reactions. These processes offset energy that would otherwise come from a fossil fuel source and can also convert solar energy into storable and transportable fuels. Solar induced chemical reactions can be divided into thermochemical or photochemical. A variety of fuels can be produced by artificial photosynthesis. The multielectron catalytic chemistry involved in making carbon-based fuels (such as methanol) from reduction of carbon dioxide is challenging; a feasible alternative is hydrogen production from protons, though use of water as the source of electrons (as plants do) requires mastering the multielectron oxidation of two water molecules to molecular oxygen. Some have envisaged working solar fuel plants in coastal meteropolitan areas by 2050 - the splitting of seawater providing hydrogen to be run through adjacent fuel-cell electric power plants and the pure water by-product going directly into the municipal water system. Hydrogen production technologies have been a significant area of solar chemical research since the 1970s. Aside from electrolysis driven by photovoltaic or photochemical cells, several thermochemical processes have also been explored. One such route uses concentrators to split water into oxygen and hydrogen at high temperatures (2,300-2,600 °C or 4,200-4,700 °F). Another approach uses the heat from solar concentrators to drive the steam reformation of natural gas thereby increasing the overall hydrogen yield compared to conventional reforming methods. Thermochemical cycles characterized by the decomposition and regeneration of reactants present another avenue for hydrogen production. The Solzinc process under development at the Weizmann Institute of Science uses a 1 MW solar furnace to decompose zinc oxide (ZnO) at temperatures above 1,200 °C (2,200 °F). This initial reaction produces pure zinc, which can subsequently be reacted with water to produce hydrogen.

Energy Storage Methods

Thermal mass systems can store solar energy in the form of heat at domestically useful temperatures for daily or interseasonal durations. Thermal storage systems generally use readily available materials with high specific heat capacities such as water, earth and stone. Well-designed systems can lower peak demand, shift time-of-use to off-peak hours and reduce overall heating and cooling requirements. Phase change materials such as paraffin wax and Glauber's salt are another thermal storage medium. These materials are inexpensive, readily available, and can deliver domestically useful temperatures (approximately 64 °C or 147 °F). The "Dover House" (in Dover, Massachusetts) was the first to use a Glauber's salt heating system, in 1948. Solar energy can also be stored at high temperatures using molten salts. Salts are an effective storage medium because they are low-cost, have a high specific heat capacity, and can deliver heat at temperatures compatible with conventional power systems. The Solar Two project used this method of energy storage, allowing it to store 1.44 terajoules (400,000 kWh) in its 68 m^3 storage tank with an annual storage efficiency of about 99%. Off-grid PV systems have traditionally used rechargeable batteries to store excess electricity. With grid-tied systems, excess electricity can be sent to the transmission grid, while standard grid electricity can be used to meet shortfalls. Net metering programs give household systems credit for any electricity they deliver to the grid. This is handled by 'rolling back' the meter whenever the home produces more electricity than it consumes. If the net electricity use is below zero, the utility then rolls over the kilowatt-hour credit to the next month. Other approaches involve the use of two meters, to measure electricity consumed vs. electricity produced. This is less common due to the increased installation cost of the second meter. Most standard meters accurately measure in both directions, making a second meter unnecessary. Pumped-storage hydroelectricity stores energy in the form of water pumped when energy is available from a lower elevation reservoir to a higher elevation one. The energy is recovered when demand is high by releasing the water, with the pump becoming a hydroelectric power generator.

Development, Deployment and Economics

Beginning with the surge in coal use, which accompanied the Industrial Revolution, energy consumption has steadily transitioned from wood and biomass to fossil fuels. The early development of solar technologies starting in the 1860s was driven by an expectation that coal would soon become scarce. However, development of solar technologies stagnated in the early 20th century in the face of the increasing availability, economy, and utility of coal and petroleum. The 1973 oil embargo and 1979 energy crisis caused a reorganization of energy policies around the world. It brought renewed attention to developing

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solar technologies. Deployment strategies focused on incentive programs such as the Federal Photovoltaic Utilization Program in the US and the Sunshine Program in Japan. Other efforts included the formation of research facilities in the US (SERI, now NREL), Japan (NEDO), and Germany (Fraunhofer Institute for Solar Energy Systems ISE). Commercial solar water heaters began appearing in the United States in the 1890s. These systems saw increasing use until the 1920s but were gradually replaced by cheaper and more reliable heating fuels. As with photovoltaics, solar water heating attracted renewed attention as a result of the oil crises in the 1970s, but interest subsided in the 1980s due to falling petroleum prices. Development in the solar water heating sector progressed steadily throughout the 1990s, and annual growth rates have averaged 20% since 1999. Although generally underestimated, solar water heating and cooling is by far the most widely deployed solar technology with an estimated capacity of 154 GW as of 2007. The International Energy Agency has said that solar energy can make considerable contributions to solving some of the most urgent problems the world now faces: The development of affordable, inexhaustible, and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible, and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise. These advantages are global. Hence the additional costs of the incentives for early deployment should be considered learning investments; they must be wisely spent and need to be widely shared. In 2011, a report by the International Energy Agency found that solar energy technologies such as photovoltaics, solar hot water, and concentrated solar power could provide a third of the world's energy by 2060 if politicians commit to limiting climate change and transitioning to renewable energy. The energy from the Sun could play a key role in de-carbonizing the global economy alongside improvements in energy efficiency and imposing costs on greenhouse gas emitters. "The strength of solar is the incredible variety and flexibility of applications, from small scale to big scale".

Wind Power

Wind power or wind energy is the use of wind turbines to generate electricity. Wind power is a popular, sustainable, renewable energy source that has a much smaller impact on the environment than burning fossil fuels. Wind farms consist of many individual wind turbines, which are connected to the electric power transmission network. In 2020, wind supplied almost 1600 TWh of electricity, which was over 5% of worldwide electrical generation and about 2% of energy consumption. With over 100 GW added during 2020, mostly in China, global installed wind power capacity reached more than 730 GW. To help meet the Paris Agreement goals to limit climate change, analysts say it should expand much faster - by over 1% of electricity generation per year. New onshore (on-land) wind farms are cheaper than new coal or gas plants, but expansion of wind power is being hindered by fossil fuel subsidies. Onshore wind farms have a greater visual impact on the landscape than other power stations, as they need to be spread over more land and need to be built in rural areas. Small onshore wind farms can feed some energy into the grid or provide power to isolated off-grid locations. Offshore wind farms provide a steadier and stronger source of energy and have less visual impact. Although there is less offshore wind power at present and construction and maintenance costs are higher, it is expanding. Wind power is variable renewable energy, so power-management techniques are used to match supply and demand, such as: wind hybrid power systems, hydroelectric power or other dispatchable power sources, excess capacity, geographically distributed turbines, exporting and importing power to neighboring areas, or grid storage. As the proportion of wind power in a region increases the grid may need to be upgraded. Weather forecasting allows the electric-power network to be readied for the predictable variations in production that occur.

Wind Energy

Wind power in an open-air stream is thus proportional to the third power of the wind speed; the available power increases eightfold when the wind speed doubles. Wind turbines for grid electric power, therefore, need to be especially efficient at greater wind speeds. Wind is the movement of air across the surface of the Earth, driven by areas of high and low pressure. The global wind kinetic energy averaged approximately 1.50 MJ/m2 over the period from 1979 to 2010, 1.31 MJ/m2 in the Northern Hemisphere with 1.70 MJ/m2 in the Southern Hemisphere. The atmosphere acts as a thermal engine, absorbing heat at higher temperatures, releasing heat at lower temperatures. The process is responsible for the production of wind kinetic energy at a rate of 2.46 W/m2 thus sustaining the circulation of the atmosphere against friction. Through wind resource assessment it is possible to estimate wind power potential globally, by country or region, or for a specific site. The Global Wind Atlas provided by the Technical University of Denmark in partnership with the World Bank provides a global assessment of wind power potential. Unlike 'static' wind resource atlases which average estimates of wind speed and power density across multiple years, tools such as Renewables. Ninja provides time-varying simulations of wind speed and power output from different wind turbine models at an hourly resolution. More detailed, site-specific assessments of wind resource potential can be obtained from specialist commercial providers, and many of the larger wind developers have in-house modeling capabilities. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. The strength of wind varies, and an average value for a given location does not alone indicate the amount of

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energy a wind turbine could produce there. To assess prospective wind power sites a probability distribution function is often fit to the observed wind speed data. Different locations will have different wind speed distributions. The Weibull model closely mirrors the actual distribution of hourly/ten-minute wind speeds at many locations. The Weibull factor is often close to 2 and therefore a Rayleigh distribution can be used as a less accurate, but simpler model.

Wind Farm

Wind farm is a group of wind turbines in the same location. A large wind farm may consist of several hundred individual wind turbines distributed over an extended area. The land between the turbines may be used for agricultural or other purposes. For example, Gansu Wind Farm, the largest wind farm in the world, has several thousand turbines. A wind farm may also be located offshore. Almost all large wind turbines have the same design - a horizontal axis wind turbine having an upwind rotor with 3 blades, attached to a nacelle on top of a tall tubular tower. In a wind farm, individual turbines are interconnected with a medium voltage (often 34.5 kV) power collection system and communications network. In general, a distance of 7D (7 times the rotor diameter of the wind turbine) is set between each turbine in a fully developed wind farm. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system.

Generator Characteristics and Stability

Induction generators, which were often used for wind power projects in the 1980s and 1990s, require reactive power for excitation, so electrical substations used in wind-power collection systems include substantial capacitor banks for power factor correction. Different types of wind turbine generators behave differently during transmission grid disturbances, so extensive modeling of the dynamic electromechanical characteristics of a new wind farm is required by transmission system operators to ensure predictable stable behavior during system faults. In particular, induction generators cannot support the system voltage during faults, unlike steam or hydro turbine-driven synchronous generators. Induction generators are not used in current turbines. Instead, most turbines use variable speed generators combined with either a partial or full-scale power converter between the turbine generator and the collector system, which generally have more desirable properties for grid interconnection and have low voltage ride through-capabilities. Modern turbines use either doubly fed electric machines with partial-scale converters or squirrel-cage induction generators or synchronous generators (both permanently and electrically excited) with full-scale converters. Transmission systems operators will supply a wind farm developer with a grid code to specify the requirements for interconnection to the transmission grid. This will include the power factor, the constancy of frequency, and the dynamic behavior of the wind farm turbines during a system fault. The world's second full-scale floating wind turbine (and first to be installed without the use of heavy-lift vessels), Wind Float, operating at rated capacity (2 MW) approximately 5 km offshore of Póvoa de Varzim, Portugal. Offshore wind power is wind farms in large bodies of water, usually the sea. These installations can utilize the more frequent and powerful winds that are available in these locations and have less visual impact on the landscape than land-based projects. However, the construction and maintenance costs are considerably higher. Siemens and Vestas are the leading turbine suppliers for offshore wind power. Ørsted, Vattenfall, and E.ON are the leading offshore operators. As of November 2021, the Hornsea Wind Farm in the United Kingdom is the largest offshore wind farm in the world at 1,218 MW.

Collection and Transmission Network

In a wind farm, individual turbines are interconnected with a medium voltage (usually 34.5 kV) power collection system and communications network. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system. A transmission line is required to bring the generated power to (often remote) markets. For an offshore station, this may require a submarine cable. Construction of a new high voltage line may be too costly for the wind resource alone, but wind sites may take advantage of lines already installed for conventional fuel generation. Wind power resources are not always located near to high population density. As transmission lines become longer the losses associated with power transmission increase, as modes of losses at lower lengths are exacerbated and new modes of losses are no longer negligible as the length is increased, making it harder to transport large loads over large distances. When the transmission capacity does not meet the generation capacity, wind farms are forced to produce below their full potential or stop running altogether, in a process known as curtailment. While this leads to potential renewable generation left untapped, it prevents possible grid overload or risk to reliable service. One of the biggest current challenges to wind power grid integration in some countries is the necessity of developing new transmission lines to carry power from wind farms, usually in remote lowly populated areas due to availability of wind, to high load locations, usually on the coasts where population density is higher. Any existing transmission lines in remote locations may not have been designed for the transport of large amounts of energy. In particular geographic regions, peak wind speeds may not coincide with peak demand for electrical power, whether offshore or onshore. A possible future option may be to interconnect widely dispersed geographic areas with an HVDC super grid.

Wind Power Capacity and Production

In 2020, wind supplied almost 1600 TWh of electricity, which was over 5% of worldwide electrical generation and about 2%

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of energy consumption. With over 100 GW added during 2020, mostly in China, global installed wind power capacity reached more than 730 GW. But to help meet Paris Agreement goals to limit climate change analysts say it should expand much faster by over 1% of electricity generation per year. Expansion of wind power is being hindered by fossil fuel subsidies. The actual amount of electric power that wind can generate is calculated by multiplying the nameplate capacity by the capacity factor, which varies according to equipment and location. Estimates of the capacity factors for wind installations are in the range of 35% to 44%.Capacity factor since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the capacity factor. Online data is available for some locations, and the capacity factor can be calculated from the yearly output. For example, the German nationwide average wind power capacity factor overall of 2012 was just under 17.5% (45,867 GW·h/yr / (29.9 GW × 24 × 366) = 0.1746) and the capacity factor for Scottish wind farms averaged 24% between 2008 and 2010. Unlike fueled generating plants, the capacity factor is affected by several parameters, including the variability of the wind at the site and the size of the generator relative to the turbine's swept area. A small generator would be cheaper and achieve a higher capacity factor but would produce less electric power (and thus less profit) in high winds. Conversely, a large generator would cost more but generate little extra power and, depending on the type, may stall out at low wind speed.

Thus an optimum capacity factor of around 40-50% would be aimed for. Wind energy penetration is the fraction of energy produced by wind compared with the total generation. Wind power's share of worldwide electricity usage in 2021 was almost 7%, up from 3.5% in 2015. There is no generally accepted maximum level of wind penetration. The limit for a particular grid will depend on the existing generating plants, pricing mechanisms, capacity for energy storage, demand management, and other factors. An interconnected electric power grid will already include reserve generating and transmission capacity to allow for equipment failures. This reserve capacity can also serve to compensate for the varying power generation produced by wind stations. Studies have indicated that 20% of the total annual electrical energy consumption may be incorporated with minimal difficulty. These studies have been for locations with geographically dispersed wind farms, some degree of dispatchable energy or hydropower with storage capacity, demand management, and interconnected to a large grid area enabling the export of electric power when needed. Beyond the 20% level, there are few technical limits, but the economic implications become more significant. Electrical utilities continue to study the effects of large-scale penetration of wind generation on system stability and economics. A wind energy penetration figure can be specified for different durations of time but is often quoted annually. To obtain 100% from wind annually requires substantial long-term storage or substantial interconnection to other systems that may already have substantial storage. On a monthly, weekly, daily, or hourly basis -or less- wind might supply as much as or more than 100% of current use, with the rest stored, exported or curtailed. The seasonal industry might then take advantage of high wind and low usage times such as at night when wind output can exceed normal demand. Such industry might include the production of silicon, aluminum, steel, or natural gas, and hydrogen, and using future long-term storage to facilitate 100% energy from variable renewable energy. Homes can also be programmed to accept extra electric power on demand, for example by remotely turning up water heater thermostats.

Variability

Wind power is variable, and during low wind periods, it must be replaced by other power sources. Transmission networks presently cope with outages of other generation plants and daily changes in electrical demand, but the variability of intermittent power sources such as wind power is more frequent than those of conventional power generation plants which, when scheduled to be operating, may be able to deliver their nameplate capacity around 95% of the time. Electric power generated from wind power can be highly variable at several different timescales: hourly, daily, or seasonally. Annual variation also exists but is not as significant. Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, this variability can present substantial challenges to incorporating large amounts of wind power into a grid system. Intermittency and the non-dispatchable nature of wind energy production can raise costs for regulation, incremental operating reserve, and (at high penetration levels) could require an increase in the already existing energy demand management, load shedding, storage solutions, or system interconnection with HVDC cables. Fluctuations in load and allowance for the failure of large fossil-fuel generating units require operating reserve capacity, which can be increased to compensate for the variability of wind generation. Presently, grid systems with large wind penetration require a small increase in the frequency of usage of natural gas spinning reserve power plants to prevent a loss of electric power if there is no wind. At low wind power penetration, this is less of an issue. Utility-scale batteries are often used to balance hourly and shorter timescale variation, but car batteries may gain ground from the mid-2020s. Wind power advocates argue that periods of low wind can be dealt with by simply restarting existing power stations that have been held in readiness, or interlinking with HVDC. Electrical grids with slow-responding thermal power plants and without ties to networks with hydroelectric generation may have to limit the use of wind power. Conversely, on particularly windy days, even with penetration levels of 16%, wind power generation can surpass all other electric power sources in a country. In Denmark, which had a power market penetration of 30% in 2013, over

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90 hours, wind power generated 100% of the country's power, peaking at 122% of the country's demand at 2 am on 28 October. The combination of diversifying variable renewables by type and location, forecasting their variation, and integrating them with dispatchable renewables, flexible fueled generators, and demand response can create a power system that has the potential to meet power supply needs reliably. Integrating ever-higher levels of renewables is being successfully demonstrated in the real world:

In 2009, eight American and three European authorities, writing in the leading electrical engineers' professional journal, didn't find "a credible and firm technical limit to the amount of wind energy that can be accommodated by electric power grids". In fact, not one of more than 200 international studies, nor official studies for the eastern and western U.S. regions, nor the International Energy Agency, has found major costs or technical barriers to reliably integrating up to 30% variable renewable supplies into the grid, and in some studies much more. Seasonal cycle of capacity factors for wind and photovoltaics in Europe under idealized assumptions. The figure illustrates the balancing effects of wind and solar energy at the seasonal scale (Kaspar et al., 2019). Solar power tends to be complementary to wind. On daily to weekly timescales, high-pressure areas tend to bring clear skies and low surface winds, whereas low-pressure areas tend to be windier and cloudier. On seasonal timescales, solar energy peaks in summer, whereas in many areas wind energy is lower in summer and higher in winter. Thus the seasonal variation of wind and solar power tend to cancel each other somewhat. Wind hybrid power systems are becoming more popular.

Predictability

Wind power forecasting methods are used, but the predictability of any particular wind farm is low for short-term operation. For any particular generator, there is an 80% chance that wind output will change less than 10% in an hour and a 40% chance that it will change 10% or more in 5 hours. In summer 2021 wind power in the United Kingdom fell due to the lowest winds in seventy years- smoothing peaks by producing hydrogen may help in future when wind has a larger share of generation. While the output from a single turbine can vary greatly and rapidly as local wind speeds vary, as more turbines are connected over larger and larger areas the average power output becomes less variable and more predictable. Weather forecasting permits the electric-power network to be readied for the predictable variations in production that occur. Wind power hardly ever suffers major technical failures, since failures of individual wind turbines have hardly any effect on overall power, so that the distributed wind power is reliable and predictable, whereas conventional generators, while far less variable, can suffer major unpredictable outages.

Energy Storage

Typically, conventional hydroelectricity complements wind power very well. When the wind is blowing strongly, nearby hydroelectric stations can temporarily hold back their water. When the wind drops they can, provided they have the generation capacity, rapidly increase production to compensate. This gives a very even overall power supply and virtually no loss of energy and uses no more water. Alternatively, where a suitable head of water is not available, pumped-storage hydroelectricity or other forms of grid energy storage such as compressed air energy storage and thermal energy storage can store energy developed by high-wind periods and release it when needed. The type of storage needed depends on the wind penetration level -low penetration requires daily storage, and high penetration requires both short- and long-term storage - as long as a month or more. Stored energy increases the economic value of wind energy since it can be shifted to displace higher-cost generation during peak demand periods. The potential revenue from this arbitrage can offset the cost and losses of storage. Although pumped-storage power systems are only about 75% efficient, and have high installation costs, their low running costs and ability to reduce the required electrical base-load can save both fuel and total electrical generation costs.

Fuel Savings and Energy Payback

According to the American Wind Energy Association, production of wind power in the United States in 2015 avoided consumption of 280 million cubic meters (73 billion US gallons) of water and reduced CO_2 emissions by 132 million meteric tons, while providing US$ 7.3 billion in public health savings. The energy needed to build a wind farm divided into the total output over its life, Energy Return on Energy Invested, of wind power varies but averages about 20-25. Thus, the energy payback time is typically around a year.

Economics

Onshore wind cost per kilowatt-hour between 1983 and 2017. Onshore wind is an inexpensive source of electric power, cheaper than coal plants and new gas plants. According to Business Green, wind turbines reached grid parity (the point at which the cost of wind power matches traditional sources) in some areas of Europe in the mid-2000s, and in the US around the same time. Falling prices continue to drive the Levelized cost down and it has been suggested that it has reached general grid parity in Europe in 2010, and will reach the same point in the US around 2016 due to an expected reduction in capital costs of about 12%. In 2021 the CEO of Siemens Gamesa warned that increased demand for low-cost wind turbines combined with high input costs and high costs of steel result in increased pressure on the manufacturers and decreasing profit margins.

Electric Power Cost and Trends

A turbine blade convoy passing through Edenfield in the U.K. (2008). Even longer 2-piece blades are now manufactured, and then assembled on-site to reduce difficulties in transportation. Wind power is capital intensive but has no fuel costs. The price

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of wind power is therefore much more stable than the volatile prices of fossil fuel sources. However, the estimated average cost per unit of electric power must incorporate the cost of construction of the turbine and transmission facilities, borrowed funds, return to investors (including the cost of risk), estimated annual production, and other components, and averaged over the projected useful life of the equipment, which may be more than 20 years. Energy cost estimates are highly dependent on these assumptions so published cost figures can differ substantially. The presence of wind energy, even when subsidized, can reduce costs for consumers (€5 billion/year in Germany) by reducing the marginal price, by minimizing the use of expensive peaking power plants. The cost has decreased as wind turbine technology has improved. There are now longer and lighter wind turbine blades, improvements in turbine performance, and increased power generation efficiency. Also, wind project capital expenditure costs and maintenance costs have continued to decline. In 2021 at Lazard study of unsubsidized electricity said that wind power levelized cost of electricity continues to fall but more slowly than before. The study estimated new wind-generated electricity cost from $26 to $50/MWh, compared to new gas power from $45 to $74/MWh. The median cost of fully depreciated existing coal power was $42/MWh, nuclear $29/MWh and gas $24/MWh. The study estimated offshore wind at around $83/MWh. Compound annual growth rate was 4% per year from 2016 to 2021, compared to 10% per year from 2009 to 2021.

Incentives and Community Benefits

Turbine prices have fallen significantly in recent years due to tougher competitive conditions such as the increased use of energy auctions, and the elimination of subsidies in many markets. As of 2021 subsidies are still often given to offshore wind. But they are generally no longer necessary for onshore wind in countries with even a very low carbon price such as China, provided there are no competing fossil fuel subsidies. Secondary market forces provide incentives for businesses to use wind-generated power, even if there is a premium price for the electricity. For example, socially responsible manufacturers pay utility companies a premium that goes to subsidize and build new wind power infrastructure. Companies use wind-generated power, and in return, they can claim that they are undertaking strong "green" efforts. Wind projects provide local taxes, or payments in place of taxes and strengthen the economy of rural communities by providing income to farmers with wind turbines on their land.

Small-Scale Wind Power

A small Quietrevolution QR5 Gorlov type vertical axis wind turbine on the roof of Colston Hall in Bristol, England. Measuring 3 m in diameter and 5 m high, it has a nameplate rating of 6.5 kW. Small-scale wind power is the name given to wind generation systems with the capacity to produce up to 50 kW of electrical power. Isolated communities that may otherwise rely on diesel generators may use wind turbines as an alternative. Individuals may purchase these systems to reduce or eliminate their dependence on grid electric power for economic reasons, or to reduce their carbon footprint. Wind turbines have been used for household electric power generation in conjunction with battery storage over many decades in remote areas. Examples of small-scale wind power projects in an urban setting can be found in New York City, where, since 2009, several building projects have capped their roofs with Gorlov-type helical wind turbines. Although the energy they generate is small compared to the buildings' overall consumption, they help to reinforce the building's 'green' credentials in ways that "showing people your high-tech boiler" cannot, with some of the projects also receiving the direct support of the New York State Energy Research and Development Authority. Grid-connected domestic wind turbines may use grid energy storage, thus replacing purchased electric power with locally produced power when available. The surplus power produced by domestic microgenerators can, in some jurisdictions, be fed into the network and sold to the utility company, producing a retail credit for the microgenerators' owners to offset their energy costs. Off-grid system users can either adapt to intermittent power or use batteries, photovoltaic, or diesel systems to supplement the wind turbine. Equipment such as parking meters, traffic warning signs, street lighting, or wireless Internet gateways may be powered by a small wind turbine, possibly combined with a photovoltaic system, which charges a small battery replacing the need for a connection to the power grid. Distributed generation from renewable resources is increasing as a consequence of the increased awareness of climate change. The electronic interfaces required to connect renewable generation units with the utility system can include additional functions, such as active filtering to enhance the power quality.

Impact on Environment and Landscape

The environmental impact of wind power is minor compared to that of fossil fuels. According to the IPCC, in assessments of the life-cycle greenhouse-gas emissions of energy sources, wind turbines have a median value of 12 and 11 (gCO_2eq/kWh) for offshore and onshore turbines, respectively. Compared with other low carbon power sources, wind turbines have some of the lowest global warming potential per unit of electricity generated. Onshore (on-land) wind farms can have a significant visual impact and impact on the landscape. Due to a very low surface power density and spacing requirements, wind farms typically need to be spread over more land than other power stations. Their network of turbines, access roads, transmission lines, and substations can result in "energy sprawl"; although land between the turbines and roads can still be used for agriculture. They also need to be built away from urban areas, which can lead to "industrialization of the countryside". Some wind farms are opposed for potentially spoiling protected scenic areas, archaeological landscapes and heritage sites. A report by the Mountaineering Council of Scotland concluded that wind farms harmed tourism in areas known for natural landscapes and panoramic views. Habitat loss

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and fragmentation are the greatest potential impacts on wildlife of onshore wind farms. But the worldwide ecological impact is minimal. Wind farm construction near wetlands has been linked to several bog landslides in Ireland that have polluted rivers, such as at Derrybrien (2003) and Meenbog (2020).Such incidents could be prevented with stricter planning procedures and siting guidelines. Thousands of birds and bats, including rare species, have been killed by wind turbine blades, though wind turbines are responsible for far fewer bird deaths than fossil-fueled power stations. This can be mitigated with proper wildlife monitoring. Many wind turbine blades are made of fiberglass and only have a lifetime of 10 to 20 years. Previously, there was no market for recycling these old blades, and they are commonly disposed of in landfills. Because blades are hollow, they take up a large volume compared to their mass. Since 2019, some landfill operators have begun requiring blades to be crushes before being landfilled. Wind turbines also generate noise. At a distance of 300 meters (980 ft) this may be around 45 dB, which is slightly louder than a refrigerator. At 1.5 km (1 mi) distance they become inaudible. There are anecdotal reports of negative health effects on people who live very close to wind turbines. Peer-reviewed research has generally not supported these claims. The United States Air Force and Navy have expressed concern that siting large wind turbines near bases "will negatively impact radar to the point that air traffic controllers will lose the location of aircraft".

Politics

Nuclear power and fossil fuels are subsidized by many governments, and wind power and other forms of renewable energy are also often subsidized. It has been suggested that a subsidy shift would help to level the playing field and support growing energy sectors, namely solar power, wind power, and biofuels. History shows that no energy sector was developed without subsidies. According to the International Energy Agency (IEA) (2011), energy subsidies artificially lower the price of energy paid by consumers, raise the price received by producers or lower the cost of production. "Fossil fuels subsidies costs generally outweigh the benefits. Subsidies to renewables and low-carbon energy technologies can bring long-term economic and environmental benefits". Following the 2011 Japanese nuclear accidents, Germany's federal government is working on a new plan for increasing energy efficiency and renewable energy commercialization, with a particular focus on offshore wind farms. Under the plan, large wind turbines will be erected far away from the coastlines, where the wind blows more consistently than it does on land, and where the enormous turbines won't bother the inhabitants. The plan aims to decrease Germany's dependence on energy derived from coal and nuclear power plants.

Public opinion

Surveys of public attitudes across Europe and in many other countries show strong public support for wind power. In 2008, surveys found about 80% of EU citizens supported wind power. Bakker et al. (2012) found in their study that residents who did not want turbines built near them suffered significantly more stress than those who "benefited economically from wind turbines". Although wind power is a popular form of energy generation, onshore or near offshore wind farms are sometimes opposed for their impact on the landscape (especially scenic areas, heritage areas and archaeological landscapes), as well as noise, and impact on tourism. In a 2007 survey of wind power in Canada, 89% of respondents said that using renewable energy sources like wind or solar power was positive for Canada because these sources were better for the environment. Only 4 percent considered using renewable sources as negative since they could be unreliable and expensive. Another 2007 survey concluded that wind power was the alternative energy source most likely to gain public support for future development in Canada, with only 16% opposed to this type of energy. By contrast, 3 out of 4 Canadians opposed nuclear power developments. In other cases, there is direct community ownership of wind farms. The hundreds of thousands of people who have become involved in Germany's small and medium-sized wind farms demonstrate such support there. A 2010 Harris Poll found strong support for wind power in Germany, other European countries, and the United States. In China, Shen et al. (2019) found that Chinese city-dwellers may be resistant to building wind turbines in urban areas, with a surprisingly high proportion of people citing an unfounded fear of radiation as driving their concerns. Also, the study finds that like their counterparts in OECD countries, urban Chinese respondents are sensitive to direct costs and wildlife externalities. Distributing relevant information about turbines to the public may alleviate resistance.

Community

Wind turbines such as these, in Cumbria, England, have been opposed for a number of reasons, including aesthetics, by some sectors of the population. Many wind power companies work with local communities to reduce environmental and other concerns associated with particular wind farms. In other cases there is direct community ownership of wind farm projects. Appropriate government consultation, planning and approval procedures also help to minimize environmental risks. Some may still object to wind farms but The Australia Institute says their concerns should be weighed against the need to address the threats posed by climate change and the opinions of the broader community. In the US, wind power projects are reported to boost local tax bases, helping to pay for schools, roads, and hospitals, and to revitalize the economies of rural communities by providing steady income to farmers and other landowners. In the UK, both the National Trust and the Campaign to Protect Rural England have expressed concerns about the effects on the rural landscape caused by inappropriately sited wind turbines and wind farms. Some wind farms have become tourist attractions. The Whitelee Wind Farm Visitor Centre has an exhibition room, a learning hub, a café with

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a viewing deck and also a shop. It is run by the Glasgow Science Centre. In Denmark, a loss-of-value scheme gives people the right to claim compensation for loss of value of their property if it is caused by proximity to a wind turbine. The loss must be at least 1% of the property's value. Despite this general support for the concept of wind power in the public at large, local opposition often exists and has delayed or aborted a number of projects. As well as concerns about the landscape, there are concerns that some installations can negatively affect TV and radio reception and Doppler weather radar, as well as produce excessive sound and vibration levels leading to a decrease in property values. Potential broadcast-reception solutions include predictive interference modeling as a component of site selection. A study of 50,000 home sales near wind turbines found no statistical evidence that prices were affected. While aesthetic issues are subjective and some find wind farms pleasant and optimistic, or symbols of energy independence and local prosperity, protest groups are often formed to attempt to block some wind power stations for various reasons. Some opposition to wind farms is dismissed as NIMBYism, but research carried out in 2009 found that there is little evidence to support the belief that residents only object to wind farms because of a "Not in my Back Yard" attitude [111-130].

Geopolitics

It has been argued that expanding the use of wind power will lead to increasing geopolitical competition over critical materials for wind turbines such as rare earth elements neodymium, praseodymium, and dysprosium. But this perspective has been criticized for failing to recognize that most wind turbines do not use permanent magnets and for underestimating the power of economic incentives for expanded production of these minerals.

Turbine Design

Wind turbines are devices that convert the wind's kinetic energy into electrical power. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of horizontal axis and vertical axis types. The smallest turbines are used for applications such as battery charging for auxiliary power. Slightly larger turbines can be used for making small contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, have become an increasingly important source of renewable energy and are used in many countries as part of a strategy to reduce their reliance on fossil fuels. Wind turbine design is the process of defining the form and specifications of a wind turbine to extract energy from the wind. A wind turbine installation consists of the necessary systems needed to capture the wind's energy, point the turbine into the wind, convert mechanical rotation into electrical power, and other systems to start, stop, and control the turbine. In 1919 the German physicist Albert Betz showed that for a hypothetical ideal wind-energy extraction machine, the fundamental laws of conservation of mass and energy allowed no more than 16/27 (59%) of the kinetic energy of the wind to be captured. This Betz limit can be approached in modern turbine designs, which may reach 70 to 80% of the theoretical Betz limit. The aerodynamics of a wind turbine are not straightforward. The airflow at the blades is not the same as the airflow far away from the turbine. The very nature of how energy is extracted from the air also causes air to be deflected by the turbine. This affects the objects or other turbines downstream, which is known as Wake effect. Also, the aerodynamics of a wind turbine at the rotor surface exhibit phenomena that are rarely seen in other aerodynamic fields. The shape and dimensions of the blades of the wind turbine are determined by the aerodynamic performance required to efficiently extract energy from the wind, and by the strength required to resist the forces on the blade. In addition to the aerodynamic design of the blades, the design of a complete wind power system must also address the design of the installation's rotor hub, nacelle, tower structure, generator, controls, and foundation.

History

Wind power has been used as long as humans have put sails into the wind. King Hammurabi's Codex (reign 1792 - 1750 BC) already mentioned windmills for generating mechanical energy. Wind-powered machines used to grind grain and pump water, the windmill and wind pump, were developed in what is now Iran, Afghanistan, and Pakistan by the 9th century. Wind power was widely available and not confined to the banks of fast-flowing streams, or later, requiring sources of fuel. Wind-powered pumps drained the polders of the Netherlands, and in arid regions such as the American mid-west or the Australian outback, wind pumps provided water for livestock and steam engines. The first windmill used for the production of electric power was built in Scotland in July 1887 by Prof James Blyth of Anderson's College, Glasgow (the precursor of Strathclyde University). Blyth's 10 meters (33 ft) high cloth-sailed wind turbine was installed in the garden of his holiday cottage at Marykirk in Kincardineshire, and was used to charge accumulators developed by the Frenchman Camille Alphonse Faure, to power the lighting in the cottage, thus making it the first house in the world to have its electric power supplied by wind power. Blyth offered the surplus electric power to the people of Marykirk for lighting the main street, however, they turned down the offer as they thought electric power was "the work of the devil."

Although he later built a wind turbine to supply emergency power to the local Lunatic Asylum, Infirmary, and Dispensary of Montrose, the invention never really caught on as the technology was not considered to be economically viable. Across the Atlantic, in Cleveland, Ohio, a larger and heavily engineered machine was designed and constructed in the winter of 1887-1888 by Charles F. Brush. This was built by his engineering company at his home and operated from 1886 until 1900. The Brush wind turbine had a rotor 17 meters (56 ft) in diameter and was mounted on an 18

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meters (59 ft) tower. Although large by today's standards, the machine was only rated at 12 kW. The connected dynamo was used either to charge a bank of batteries or to operate up to 100 incandescent light bulbs, three arc lamps, and various motors in Brush's laboratory. With the development of electric power, wind power found new applications in lighting buildings remote from centrally generated power. Throughout the 20th century parallel paths developed small wind stations suitable for farms or residences. The 1973 oil crisis triggered the investigation in Denmark and the United States that led to larger utility-scale wind generators that could be connected to electric power grids for remote use of power. By 2008, the U.S. installed capacity had reached 25.4 gigawatts, and by 2012 the installed capacity was 60 gigawatts. Today, wind-powered generators operate in every size range between tiny stations for battery charging at isolated residences, up to gigawatt-sized offshore wind farms that provide electric power to national electrical networks.

Advantages of Wind Power

- Wind power is cost-effective. Land-based utility-scale wind is one of the lowest-priced energy sources available today, costing 1-2 cents per kilowatt-hour after the production tax credit. Because the electricity from wind farms is sold at a fixed price over a long period of time (e.g., 20+ years) and its fuel is free, wind energy mitigates the price uncertainty that fuel costs add to traditional sources of energy.

- Wind creates jobs. The U.S. wind sector employs more than 100,000 workers, and wind turbine technician is one of the fastest growing American jobs. According to the Wind Vision Report, wind has the potential to support more than 600,000 jobs in manufacturing, installation, maintenance, and supporting services by 2050.

- Wind enables U.S. industry growth and U.S. competitiveness. New wind projects account for annual investments of over $10 billion in the U.S. economy. The United States has a vast domestic resource and a highly-skilled workforce, and can compete globally in the clean energy economy.

- It's a clean fuel source. Wind energy doesn't pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas, which emit particulate matter, nitrogen oxides, and sulfur dioxide-causing human health problems and economic damages. Wind turbines don't produce atmospheric emissions that cause acid rain, smog, or greenhouse gases.

- Wind is a domestic source of energy. The nation's wind supply is abundant and inexhaustible. Over the past 10 years, U.S. wind power capacity has grown 15% per year, and wind is now the largest source of renewable power in the United States.

- It's sustainable. Wind is actually a form of solar energy. Winds are caused by the heating of the atmosphere by the sun, the rotation of the Earth, and the Earth's surface irregularities. For as long as the sun shines and the wind blows, the energy produced can be harnessed to send power across the grid.

- Wind turbines can be built on existing farms or ranches. This greatly benefits the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land, providing landowners with additional income.

Challenges of Wind Power

- Wind power must still compete with conventional generation sources on a cost basis. Even though the cost of wind power has decreased dramatically in the past several decades, wind projects must be able to compete economically with the lowest-cost source of electricity, and some locations may not be windy enough to be cost competitive.

- Good land-based wind sites are often located in remote locations, far from cities where the electricity is needed. Transmission lines must be built to bring the electricity from the wind farm to the city. However, building just a few already-proposed transmission lines could significantly reduce the costs of expanding wind energy.

- Wind resource development might not be the most profitable use of the land. Land suitable for wind-turbine installation must compete with alternative uses for the land, which might be more highly valued than electricity generation.

- Turbines might cause noise and aesthetic pollution. Although wind power plants have relatively little impact on the environment compared to conventional power plants, concern exists over the noise produced by the turbine blades and visual impacts to the landscape.

- Wind plants can impact local wildlife. Birds have been killed by flying into spinning turbine blades. Most of these problems have been resolved or greatly reduced through technological development or by properly siting wind plants. Bats have also been killed by turbine blades, and research is ongoing to develop and improve solutions to reduce the impact of wind turbines on these species. Like all energy sources, wind projects can alter the habitat on which they are built, which may alter the suitability of that habitat for certain species.

How Do Wind Turbines Work?

Wind turbines work on a simple principle: instead of using electricity to make wind -like a fan- wind turbines use wind to make electricity. Wind turns the propeller-like blades of a turbine around a rotor, which spins a generator, which creates electricity.

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Explore a Wind Turbine

Wind is a form of solar energy caused by a combination of three concurrent events:

1. The sun unevenly heating the atmosphere
2. Irregularities of the earth's surface

The rotation of the earth.

Wind flow patterns and speeds vary greatly across the United States and are modified by bodies of water, vegetation, and differences in terrain. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity. The terms "wind energy" and "wind power" both describe the process by which the wind is used to generate mechanical power or electricity. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity. A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin. The rotor connects to the generator, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity. Types of Wind Turbines

The majority of wind turbines fall into two basic types:

- Horizontal-axis turbines
- Vertical-axis turbines

Wind turbines can be built on land or offshore in large bodies of water like oceans and lakes. The U.S. Department of Energy is currently funding projects to facilitate offshore wind deployment in U.S. waters.

Hydrogen Fuel

Hydrogen fuel is a zero-carbon fuel burned with oxygen; provided it is created in a zero-carbon way. It can be used in fuel cells or internal combustion engines (see HICEV). Regarding hydrogen vehicles, hydrogen has begun to be used in commercial fuel cell vehicles, such as passenger cars, and has been used in fuel cell buses for many years. It is also used as a fuel for spacecraft propulsion. In the early 2020s, most hydrogen is produced by steam methane reforming of fossil gas. Only a small quantity is made by alternative routes such as biomass gasification or electrolysis of water or solar thermochemistry, a solar fuel with no carbon emissions. Hydrogen is found in the first group and the first period in the periodic table, i.e., it is the lightest and first element of all. Since the weight of hydrogen is less than air, it rises in the atmosphere and is therefore rarely found in its pure form, H_2. In a flame of pure hydrogen gas, burning in air, the hydrogen (H_2) reacts with oxygen (O_2) to form water (H_2O) and releases energy.

$$2H2\ (g) + O2\ (g) \rightarrow 2H2O\ (g) + \text{energy}$$

If carried out in atmospheric air instead of pure oxygen, as is usually the case, hydrogen combustion may yield small amounts of nitrogen oxides, along with the water vapor. The energy released enables hydrogen to act as a fuel. In an electrochemical cell, that energy can be used with relatively high efficiency. If it is used simply for heat, the usual thermodynamics limits on the thermal efficiency apply. Hydrogen is usually considered an energy carrier, like electricity, as it must be produced from a primary energy source such as solar energy, biomass, electricity (e.g., in the form of solar PV or via wind turbines), or hydrocarbons such as natural gas or coal. Conventional hydrogen production using natural gas induces significant environmental impacts; as with the use of any hydrocarbon, carbon dioxide is emitted. At the same time, the addition of 20% of hydrogen (an optimal share that does not affect gas pipes and appliances) to natural gas can reduce CO_2 emissions caused by heating and cooking.

Production

Because pure hydrogen does not occur naturally on Earth in large quantities, it usually requires a primary energy input to produce on an industrial scale. Hydrogen fuel can be produced from methane or by electrolysis of water. As of 2020, the majority of hydrogen (~95%) is produced from fossil fuels by steam reforming or partial oxidation of methane and coal gasification with only a small quantity by other routes such as biomass gasification or electrolysis of water. Steam-methane reforming, the current leading technology for producing hydrogen in large quantities, extracts hydrogen from methane. However, this reaction releases fossil carbon dioxide and carbon monoxide into the atmosphere which is greenhouse gases exogenous to the natural carbon cycle, and thus contribute to climate change. In electrolysis, electricity is run through water to separate the hydrogen and oxygen atoms. This method can use wind, solar, geothermal, hydro, fossil fuels, biomass, nuclear, and many other energy sources. Obtaining hydrogen from this process is being studied as a viable way to produce it domestically at a low cost. The world's largest facility for producing hydrogen fuel is claimed to be the Fukushima Hydrogen Energy Research Field (FH2R), a 10MW-class hydrogen production unit, inaugurated on 7 March 2020, in Namie, Fukushima Prefecture. The site occupies 180,000 square meters of land, much of which is occupied by a solar array; but power from the grid is also used to conduct electrolysis of water to produce hydrogen fuel. Production is usually classed in terms of colour; 'grey hydrogen' is produced as a by-product of an industrial process, 'blue hydrogen' is produced through a

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production process where CO_2 is also produced then subsequently captured via CCS, and finally 'green hydrogen' is produced entirely from renewable sources.

Energy

Hydrogen is locked up in enormous quantities in water, hydrocarbons, and other organic matter. One of the challenges of using hydrogen as a fuel comes from being able to extract hydrogen efficiently from these compounds. Now, steam reforming, which combines high-temperature steam with natural gas, accounts for the majority of the hydrogen produced. This method of hydrogen production occurs at temperatures between 700-1100 °C, and has a resultant efficiency of between 60-75%. Hydrogen can also be produced from water through electrolysis, which is less carbon-intensive if the electricity used to drive the reaction does not come from fossil-fuel power plants but rather renewable or nuclear energy instead. The efficiency of water electrolysis is between about 70-80%, with a goal set to reach 82-86% efficiency by 2030 using proton exchange membrane (PEM) electrolyzers. Once produced, hydrogen can be used in much the same way as natural gas - it can be delivered to fuel cells to generate electricity and heat, used in a combined cycle gas turbine to produce larger quantities of centrally produced electricity or burned to run a combustion engine; all methods producing no carbon or methane emissions. In each case hydrogen is combined with oxygen to form water. This is also one of its most important advantages as hydrogen fuel is environmentally friendly. The heat in a hydrogen flame is a radiant emission from the newly formed water molecules. The water molecules are in an excited state on the initial formation and then transition to a ground state; the transition releasing thermal radiation. When burning in air, the temperature is roughly 2000 °C (the same as natural gas). Historically, carbon has been the most practical carrier of energy, as hydrogen and carbon combined are more volumeterically dense, although hydrogen itself has three times the energy density per mass as methane or gasoline. Although hydrogen is the smallest element and thus has a slightly higher propensity to leak from venerable natural gas pipes such as those made from iron, leakage from plastic (polyethylene PE100) pipes is expected to be very low at about 0.001%. The reason steam methane reforming has traditionally been favored over electrolysis is that whereas methane reforming directly uses natural gas, electrolysis requires electricity. As the cost of producing electricity (via wind turbines and solar PV) falls below the cost of natural gas, electrolysis becomes cheaper than SMR.

Uses

Hydrogen fuel can provide motive power for liquid-propellant rockets, cars, trucks, trains, boats and airplanes, portable fuel cell applications or stationary fuel cell applications, which can power an electric motor. Hydrogen is considered as the primary sustainable source of renewable energy and is "highly required for advanced energy conversion systems." The problems of using hydrogen fuel in cars arise from the fact that hydrogen is difficult to store in either a high-pressure tank or a cryogenic tank. Alternative storage media such as within complex metal hydrides are in development. In general batteries are more suitable for vehicles the size of cars or smaller, but hydrogen may be better for larger vehicles such as heavy Lorries, because hydrogen energy storage offers longer range and faster refueling time. Hydrogen fuel can also be used to power stationary power generation plants or provide an alternative to natural gas for heating applications.

Fuel Cells

Fuel cells present the most attractive choice for energy conversion from hydrogen directly towards electricity, due to their high efficiency, low noise, and a limited number of moving parts. Fuel cells are of interest for both stationary and mobile power generation from hydrogen. Fuel cells are often considered as part of a vehicle propulsion system. Using a fuel cell to power an electrified powertrain including a battery and an electric motor is two to three times more efficient than using a combustion engine, although some of this benefit is related to the electrified powertrain (i.e., including regenerative braking). This means that much greater fuel economy is available using hydrogen in a fuel cell, compared to that of a hydrogen combustion engine.

Internal Combustion Engine Conversions to Hydrogen

Alongside mono-fuel hydrogen combustion, combustion engines in commercial vehicles have the potential to be converted to run on a hydrogen-diesel mix. This has been demonstrated in prototypes in the UK, where up to 40% of CO_2 emissions have been reduced during normal driving conditions. This dual-fuel flexibility eliminates range anxiety as the vehicles can alternatively fill up only on diesel when no hydrogen refueling is available. Relatively minor modifications are needed to the engines, as well as the addition of hydrogen tanks at a compression of 350 bars. Trials are also underway to test the efficiency of the 100% conversion of a Volvo FH16 heavy-duty truck to use only hydrogen. The range is expected to be 300 km/17 kg; which means an efficiency better than a standard diesel engine (where the embodied energy of 1 gallon of gasoline is equal to 1 kilogram of hydrogen). Compared to conventional fuels, if a low-cost price for hydrogen (€5/kg), significant fuel savings could be made via such a conversion in Europe or the UK. A lower price would be needed to compete with diesel/gasoline in the US, since these fuels are not exposed to high taxes at the pump. Combustion engines using hydrogen are of interest since the technology offers a less substantial change to the automotive industry, and potentially a lower up-front cost of the vehicle compared to fully electric or fuel cell alternatives. However, the non -zero emission nature of the engine means it will not be able to operate in city zero emission zones, unless it is part of a hybrid powertrain.

Drawbacks

Hydrogen has a high energy content per unit mass. However, at room temperature and atmospheric pressure, it has a very low energy content per unit volume, compared to liquid fuels or even

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to natural gas. For this reason, it is usually either compressed or liquefied by lowering its temperature to less than 33 K. High-pressure tanks weigh much more than the hydrogen they can hold. For example, in 2014 Toyota Mirai, a full tank contains only 5.7% hydrogen, the rest of the weight being the tank. Hydrogen fuel is hazardous because of the low ignition energy and high combustion energy of hydrogen, and because it tends to leak easily from tanks. Explosions at hydrogen filling stations have been reported. Hydrogen fueling stations generally receive deliveries of hydrogen by truck from hydrogen suppliers. An interruption at a hydrogen supply facility can shut down multiple hydrogen fueling stations.

Hydrogen Storage

Hydrogen storage is a term used for any of several methods for storing hydrogen for later use. These methods encompass mechanical approaches such as high pressures and low temperatures, or chemical compounds that release H2 upon demand. While large amounts of hydrogen are produced, it is mostly consumed at the site of production, notably for the synthesis of ammonia. For many years hydrogen has been stored as compressed gas or cryogenic liquid, and transported as such in cylinders, tubes, and cryogenic tanks for use in industry or as propellant in space programs. Interest in using hydrogen for on-board storage of energy in zero-emissions vehicles is motivating the development of new methods of storage, more adapted to this new application. The overarching challenge is the very low boiling point of H_2: it boils around 20.268 K (-252.882 °C or -423.188 °F). Achieving such low temperatures requires significant energy.

Established Technologies

Compressed Hydrogen

Compressed hydrogen is a storage form whereby hydrogen gas is kept under pressure to increase the storage density. Compressed hydrogen in hydrogen tanks at 350 bar (5,000 psi) and 700 bar (10,000 psi) is used for hydrogen tank systems in vehicles, based on type IV carbon-composite technology. Car manufacturers have been developing this solution, such as Honda or Nissan.

Liquefied Hydrogen

Liquid hydrogen tanks for cars, producing for example the BMW Hydrogen 7. Japan has a liquid hydrogen (LH2) storage site in Kobe port. Hydrogen is liquefied by reducing its temperature to -253 °C, similar to liquefied natural gas (LNG) which is stored at -162 °C. A potential efficiency loss of only 12.79% can be achieved, or 4.26 kW·h/kg out of 33.3 kW·h/kg.

Chemical Storage

Hydrogen gravimeteric capacity of proposed storage materials for hydrogen fuel as a function of hydrogen release temperature. The targets have since been lowered. Chemical storage could offer high storage performance due to the high storage densities. For example, supercritical hydrogen at 30 °C and 500 bar only has a density of 15.0 mol/L while methanol has a density of 49.5 mol H2/L methanol and saturated dimethyl ether at 30 °C and 7 bar has a density of 42.1 mol H_2/L dimethyl ether. Regeneration of storage material is problematic. A large number of chemical storage systems have been investigated. H_2 release can be induced by hydrolysis reactions or catalyzed dehydrogenation reactions. Illustrative storage compounds are hydrocarbons, boron hydrides, ammonia, and alane etc. The most promising chemical approach is electrochemical hydrogen storage, as the release of hydrogen can be controlled by applied electricity. Most of the materials listed below can be directly used for electrochemical hydrogen storage. As shown before, nanomaterials offer advantages for hydrogen storage systems. Nanomaterials offer an alternative that overcomes the two major barriers of bulk materials, rate of sorption and release temperature.

Enhancement of sorption kinetics and storage capacity can be improved through nanomaterial-based catalyst doping, as shown in the work of the Clean Energy Research Center in the University of South Florida. This research group studied LiBH4 doped with nickel nanoparticles and analyzed the weight loss and release temperature of the different species. They observed that an increasing amount of nano catalyst lowers the release temperature by approximately 20 °C and increases the weight loss of the material by 2-3%. The optimum amount of Ni particles was found to be 3 mol%, for which the temperature was within the limits established (around 100 °C) and the weight loss was notably greater than the undoped species. The rate of hydrogen sorption improves at the nanoscale due to the short diffusion distance in comparison to bulk materials. They also have favorable surface-area-to-volume ratio. The release temperature of a material is defined as the temperature at which the desorption process begins. The energy or temperature to induce release affects the cost of any chemical storage strategy. If the hydrogen is bound too weakly, the pressure needed for regeneration is high, thereby cancelling any energy savings. The target for onboard hydrogen fuel systems is roughly <100 °C for release and <700 bar for recharge (20-60 kJ/mol H_2). A modified van't Hoff equation, relates temperature and partial pressure of hydrogen during the desorption process. The modifications to the standard equation are related to size effects at the nanoscale. Where pH2 is the partial pressure of hydrogen, ΔH is the enthalpy of the sorption process (exothermic), ΔS is the change in entropy, R is the ideal gas constant, T is the temperature in Kelvin, Vm is the molar volume of the metal, r is the radius of the nanoparticle and γ is the surface free energy of the particle. From the above relation we see that the enthalpy and entropy change of desorption processes depend on the radius of the nanoparticle. Moreover, a new term is included that takes into account the specific surface area of the particle and it can be mathematically proven that a decrease in particle radius leads to a decrease in the release temperature for a given partial pressure.

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Hydrogenation of CO2

CO_2 emission is causing an unclouded carbon cycle. Climate change and related issue requires immediate attention. The current approach to reduce CO_2 includes capturing and storing from facilities across the world. However, storage posts technical and economic barriers preventing global scale application. To utilize CO_2 at the point source, CO_2 hydrogenation is a realistic and practical approach. Conventional hydrogenation reduces saturated organic compounds by addition of H_2. One pathway of CO_2 hydrogenation is CO_2 to methanol pathway. Methanol can be used to produce long chain hydrocarbons. Some barriers of CO_2 hydrogenation includes purification of captured CO_2, H_2 source from splitting water and energy inputs for hydrogenation. To overcome these barriers, we can further develop green H_2 technology and encourage catalyst research at industrial and academic level. For industrial applications, CO_2 is often converted to methanol. Till now, much progress has been made for CO_2 to C1 molecules. However, CO_2 to high value molecules still face many roadblocks and the future of CO_2 hydrogenation depends on the advancement of catalytic technologies.

Metal Hydrides

Metal hydrides, such as MgH_2, $NaAlH_4$, $LiAlH_4$, LiH, $LaNi_5H_6$, $TiFeH_2$, ammonia borane, and palladium hydride represent sources of stored hydrogen. Again, the persistent problems are the % weight of H_2 that they carry and the reversibility of the storage process. Some are easy-to-fuel liquids at ambient temperature and pressure, whereas others are solids which could be turned into pellets. These materials have good energy density, although their specific energy is often worse than the leading hydrocarbon fuels. An alternative method for lowering dissociation temperatures is doping with activators. This strategy has been used for aluminium hydride, but the complex synthesis makes the approach unattractive. Proposed hydrides for use in a hydrogen economy include simple hydrides of magnesium or transition metals and complex metal hydrides, typically containing sodium, lithium, or calcium and aluminium or boron. Hydrides chosen for storage applications provide low reactivity (high safety) and high hydrogen storage densities. Leading candidates are lithium hydride, sodium borohydride, and Lithium Aluminium hydride and ammonia borane. A French company McPhy Energy is developing the first industrial product, based on magnesium hydride, already sold to some major clients such as Iwatani and ENEL. Reversible hydrogen storage is exhibited by frustrated Lewis pair, which produces a borohydride. The phosphino-borane on the left accepts one equivalent of hydrogen at one atmosphere and 25 °C and expels it again by heating to 100 °C. The storage capacity is 0.25 wt%.

Aluminium

Hydrogen can be produced using aluminium by reacting it with water. To react with water, however, aluminium must be stripped of its natural oxide layer, a process which requires pulverization, chemical reactions with caustic substances, or alloys. The byproduct of the reaction to create hydrogen is aluminum oxide, which can be recycled back into aluminium with the Hall-Héroult process, making the reaction theoretically renewable. However, this requires electrolysis, which consumes a large amount of energy

Magnesium

Mg-based hydrogen storage materials can be generally fell into three categories, i.e., pure Mg, Mg-based alloys, and Mg-based composites. Particularly, more than 300 sorts of Mg-based hydrogen storage alloys have been receiving extensive attention because of the relatively better overall performance. Nonetheless, the inferior hydrogen absorption/desorption kinetics rooting in the overly undue thermodynamic stability of metal hydride make the Mg-based hydrogen storage alloys currently not appropriate for the real applications, and therefore, massive attempts have been dedicated to overcoming these shortages. Some sample preparation methods, such as smelting, powder sintering, diffusion, mechanical alloying, hydrating combustion synthesis method, surface treatment, and heat treatment, etc., have been broadly employed for altering the dynamic performance and cycle life of Mg-based hydrogen storage alloys. Besides, some intrinsic modification strategies, including alloying, nano structuring, doping by catalytic additives, and acquiring nanocomposites with other hydrides, etc., have been mainly explored for intrinsically boosting the performance of Mg-based hydrogen storage alloys. Of the primary hydrogen storage alloys progressed formerly, Mg and Mg-based hydrogen storage materials are believed to provide the remarkable possibility of the practical application, on account of the advantages as following: 1) the resource of Mg is plentiful and economical. Mg element exists abundantly and accounts for ~2.35% of the earth's crust with the rank of the eighth; 2) low density of merely 1.74 g cm-3; 3) superior hydrogen storage capacity. The theoretical hydrogen storage amounts of the pure Mg is 7.6 wt % (weight percent), and the Mg_2Ni is 3.6 wt%, respectively.

Alanates Based-Systems

Sodium Alanate ($NaAlH_4$) is a complex hydride for H_2 storage. The crystal structure was first determined through a single crystal X-ray diffraction study in 1979. The atomic structure consisted of isolated $[AlH4]^-$ tetrahedra in which the Na atoms are surrounded by eight [AlH4]- tetrahedra in a distorted square. Hydrogen release from NaAlH4 is known since the 1950's. In 1997, Bogdanovic discovered that Tio2 doping of materials makes the process reversible at modest temperature and pressure. TiO2-doped materials are reversible in hydrogen storage, $NaAlH_4$ is currently the state of the art reversible solid state hydrogen storage material which can be used in low temperature and has 5.6 wt. % hydrogen contained. The chemical reaction is, $3NaAlH_4$

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← catalyst → Na_3AlH_6 + 2Al + $3H_2$ ← catalyst → 3NaH + Al + $3/2H_2$. The heat required to change from $NaAlH_4$ to Na_3AlH_6 is 37 kJ/mol. The heat required to change from Na_3AlH_6 to NaH is 47 kJ/mol. In principle, the first step of $NaAlH_4$ releases 3.7 wt. % hydrogen at about 190 °C and the second step releases 1.8 wt. % hydrogen at about 225 °C upon heating. Further dehydrogenation of NaH occurs only at temperature higher than 400 °C. This temperature is too high for technical applications, therefore, can't be used in a fuel cell vehicle. Lithium alanate (LiAlH4) was synthesized for the first time in 1947 by dissolution of lithium hydride in an ether solution of aluminum chloride. $LiAlH_4$ has a theoretical gravimeteric capacity of 10.5 wt %H2 and dehydrogenates in the following three steps:

$3LiAlH_4 \leftrightarrow Li_3AlH_6 + 3H_2 + 2Al$ (423-448 K; 5.3 wt %H_2; ΔH = -10 kJ·mol^{-1} H_2)

$Li_3AlH_6 \leftrightarrow 3LiH + Al + 3/2H_2$ (453-493 K; 2.6 wt %H_2; ΔH = 25 kJ·mol^{-1} H_2)

$3LiH + 3Al \leftrightarrow 3LiAl + 3/2H_2$ (>673 K; 2.6 wt %H_2; ΔH = 140 kJ·mol^{-1} H_2)

The first two steps lead to a total amount of hydrogen released equal to 7.9 wt. %, which could be attractive for practical applications, but the working temperatures and the desorption kinetics are still far from the practical targets. Several strategies have been applied in the last few years to overcome these limits, such as ball-milling and catalysts additions. Potassium Alanate ($KAlH_4$) was first prepared by Ashby et al. by one-step synthesis in toluene, tetrahydrofuran, and diglyme. Concerning the hydrogen absorption and desorption properties, this alanate was only scarcely studied. Morioka et al., by temperature programmed desorption (TPD) analyses, proposed the following dehydrogenation mechanism: $3KAlH_4 \rightarrow K_3AlH_6 + 2Al + 3H_2$ (573 K, ΔH = 55 kJ·mol^{-1} H_2; 2.9 wt %H_2), $K_3AlH_6 \rightarrow 3KH + Al + 3/2H_2$ (613 K, ΔH = 70 kJ·mol^{-1} H2; 1.4 wt %H_2), $3KH \rightarrow 3K + 3/2H_2$ (703 K, 1.4 wt %H2). These reactions were demonstrated reversible without catalysts addition at relatively low hydrogen pressure and temperatures. The addition of TiCl3 was found to decrease the working temperature of the first dehydrogenation step of 50 K, but no variations were recorded for the last two reaction steps.

Organic Hydrogen Carriers

Unsaturated organic compounds can store huge amounts of hydrogen. These Liquid Organic Hydrogen Carriers (LOHC) are hydrogenated for storage and dehydrogenated again when the energy/hydrogen is needed. Using LOHCs relatively high gravimeteric storage densities can be reached (about 6 wt- %) and the overall energy efficiency is higher than for other chemical storage options such as producing methane from hydrogen. Both hydrogenation and dehydrogenation of LOHCs require catalysts. It was demonstrated that replacing hydrocarbons by hetero atoms, like N, O etc. improves reversible de/hydrogenation properties.

Cycloalkanes

Research on LOHC was concentrated on cycloalkanes at an early stage, with its relatively high hydrogen capacity (6-8wt %) and production of CO_x-free hydrogen. Heterocyclic aromatic compounds (or N-Heterocycles) are also appropriate for this task. A compound featuring in LOHC research is N-Ethylcarbazole (NEC), but many others do exist. Dibenzyltoluene, which is already used as a heat transfer fluid in industry, was identified as potential LOHC. With a wide liquid range between -39 °C (melting point) and 390 °C (boiling point) and a hydrogen storage density of 6.2 wt% dibenzyltoluene is ideally suited as LOHC material. Formic acid has been suggested as a promising hydrogen storage material with a 4.4wt% hydrogen capacity. Cycloalkanes reported as LOHC include cyclohexane, methyl-cyclohexane and decalin. The dehydrogenation of cycloalkanes is highly endothermic (63-69 kJ/mol H_2), which means this process requires high temperature. Dehydrogenation of decalin is the most thermodynamically favored among the three cycloalkanes, and methyl-cyclohexane is second because of the presence of the methyl group. Research on catalyst development for dehydrogenation of cycloalkanes has been carried out for decades. Nickel (Ni), Molybdenum (Mo) and Platinum (Pt) based catalysts are highly investigated for dehydrogenation. However, coking is still a big challenge for catalyst's long-term stability. The addition of second metal such as W, Ir, Re, Rh and Pd etc. and/or promoter (such as Ca) and selection of suitable support (such as CNF and Al_2O_3) are effective against coking. For cyclohexane, there are two dehydrogenation mechanisms, the sextet mechanism and the doublet mechanism. The difference between the two mechanisms lies in whether they are intermediate products during dehydrogenation. In the sextet mechanism, cyclohexane overlies on the catalyst surface and undergoes dehydrogenation directly to benxzene. In contrast, in the double mechanism, hydrogen will be released step by step because of the C=C double bound.

N-Heterocycles

The temperature required for hydrogenation and dehydrogenation drops significantly for heterocycles vs simple carbocycles. Among all the N-heterocycles, the saturated-unsaturated pair of dodecahydro-N-ethylcarbazole (12H-NEC) and NEC has been considered as a promising candidate for hydrogen storage with a fairly large hydrogen content (5.8wt%). The figure on the top right shows dehydrogenation and hydrogenation of the 12H-NEC and NEC pair. The standard catalyst for NEC to 12H-NEC is Ru and Rh based. The selectivity of hydrogenation can reach 97% at 7 MPa and 130 °C-150 °C. Although N-Heterocyles can optimize the unfavorable thermodynamic properties of cycloalkanes, a lot of issues remain unsolved, such as high cost, high toxicity and kinetic barriers etc. The imidazolium ionic liquids such alkyl(aryl)-

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3-methylimidazolium N-bis(trifluoromethanesulfonyl)imidate salts can reversibly add 6-12 hydrogen atoms in the presence of classical Pd/C or Ir0 nanoparticle catalysts and can be used as alternative materials for on-board hydrogen-storage devices. These salts can hold up to 30 g L-1 of hydrogen at atmospheric pressure.

Formic Acid

Formic acid is a highly effective hydrogen storage material, although its H_2 density is low. Carbon monoxide free hydrogen has been generated in a very wide pressure range (1-600 bar). A homogeneous catalytic system based on water-soluble ruthenium catalysts selectively decomposes HCOOH into H_2 and CO_2 in aqueous solution. This catalytic system overcomes the limitations of other catalysts (e.g., poor stability, limited catalytic lifetimes, and formation of CO) for the decomposition of formic acid making it a viable hydrogen storage material. And the co-product of this decomposition, carbon dioxide, can be used as hydrogen vector by hydrogenating it back to formic acid in a second step. The catalytic hydrogenation of CO_2 has long been studied and efficient procedures have been developed. Formic acid contains 53 g L-1 hydrogen at room temperature and atmospheric pressure. By weight, pure formic acid stores 4.3 wt% hydrogen. Pure formic acid is a liquid with a flash point 69 °C (cf. gasoline -40 °C, ethanol 13 °C). 85% of formic acid is not flammable.

Carbohydrates

Carbohydrates (polymeric $C_6H_{10}O_5$) release H_2 in a bioreformer mediated by the enzyme cocktail-cell-free synthetic pathway biotransformation. Carbohydrate provides high hydrogen storage densities as a liquid with mild pressurization and cryogenic constraints: It can also be stored as a solid powder. Carbonhydrates are the most abundant renewable bioresource in the world. Polysaccharides ($C_6H_{10}O_5$) has a reaction of $C_6H_{10}O_5 + {}_7H_2O \rightarrow 12H_2 + 6CO_2$. As a result, hydrogen storage density in polysaccharides is 14.8 mass%. Carbonhydrates are much less costly than other carriers. Hydrogen generation from arbonhydrates can be implemented at mild conditions of 30~80 °C and about 1 atm, the process does not need any costly high-pressure reactor, and high purity hydrogen mixed with CO_2 is generated, making extra product purification unnecessary. Under mild reaction conditions, separation of gaseous products and aqueous reaction is easy and nearly no cost. Moreover, renewable corbonhydrates are nearly inflammable and not toxic at all. Carbonhydrates may be an appealing hydrogen carrier. Compared to other hydrogen carriers, carbonhydrates are very appealing due to their low cost, renewable source, high purity hydrogen generated, and so on.

Ammonia and Related Compounds

Ammonia

Ammonia (NH_3) releases H_2 in an appropriate catalytic reformer. Ammonia provides high hydrogen storage densities as a liquid with mild pressurization and cryogenic constraints: It can also be stored as a liquid at room temperature and pressure when mixed with water. Ammonia is the second most commonly produced chemical in the world and a large infrastructure for making, transporting, and distributing ammonia exists. Ammonia can be reformed to produce hydrogen with no harmful waste or can mix with existing fuels and under the right conditions burn efficiently. Since there is no carbon in ammonia, no carbon by-products are produced; thereby making this possibility a "carbon neutral" option for the future. Pure ammonia burns poorly at the atmospheric pressures found in natural gas fired water heaters and stoves. Under compression in an automobile engine, it is a suitable fuel for slightly modified gasoline engines. Ammonia is a suitable alternative fuel because it has 18.6 MJ/kg energy density at NTP and carbon-free combustion byproducts.

Ammonia has several challenges to widespread adaptation as a hydrogen storage material. Ammonia is a toxic gas with a potent odor at standard temperature and pressure. Additionally, advances in the efficiency and scalability of ammonia decomposition are needed for commercial viability, as fuel cell membranes are highly sensitive to residual ammonia and current decomposition techniques have low yield rates. A variety of transition metals can be used to catalyze the ammonia decomposition reaction, the most effective being ruthenium. This catalysis works through chemisorption, where the adsorption energy of N2 is less than the reaction energy of dissociation. Hydrogen purification can be achieved in several ways. Hydrogen can be separated from unreacted ammonia using a permeable, hydrogen-selective membrane. It can also be purified through the adsorption of ammonia, which can be selectively trapped due to its polarity. In September 2005 chemists from the Technical University of Denmark announced a method of storing hydrogen in the form of ammonia saturated into a salt tablet. They claim it will be an inexpensive and safe storage method.

Hydrazine

Hydrazine breaks down in the cell to form nitrogen and hydrogen/Silicon hydrides and germanium hydrides are also candidates of hydrogen storage materials, as they can subject to energetically favored reaction to form covalently bonded dimers with loss of a hydrogen molecule.

Chemical Hydrides

Chemical hydride is an irreversible hydrogen storage material. The reaction of hydrogen releasing from chemical hydrides are usually exothermic, which makes regeneration of the fuel energy-intensive. $NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 + 300$ kJ. The chemical reaction gives potential for high density storage, but current systems produce much lower effective density. The $NaBH_4$ has a theoretical effective density of 10.8 wt. %, however there is only 1.1 wt. % of effective density in reality. Examples of chemical hydride reactions: $NaBH_4$ (20~35% solution, stabilized with 1~3% NaOH) + $2H_2O$ (from fuel cell exhaust) → $NaBO_2$ (Borax

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in NaOH) + $4H_2$. $2LiH + 2H_2O \rightarrow 2LiOH + 2H_2$. A leading chemical hydride is NH3BH3, which is a waxy solid at room temperature with a melting point of 90 °C. Hydrogen will be released from NH3BH3 around 90 °C because of thermal decomposition. NH3BH3 is a promising material for hydrogen storing because it has one of the highest theoretical hydrogen weight percentages at 19.6% and also the highest hydrogen volume density at 151 kg H_2 per volume. Hydrogen release from NH3BH3 occurs stepwise, where the onset temperature for the first equivalent is 90 °C, the temperature for second equivalent is 150 $_{°C}$. The remaining hydrogen will be released at a temperature higher than 150 °C.

Amine Boranes

Prior to 1980, several compounds were investigated for hydrogen storage including complex borohydrides, or aluminohydrides, and ammonium salts. These hydrides have an upper theoretical hydrogen yield limited to about 8.5% by weight. Amongst the compounds that contain only B, N, and H (both positive and negative ions), representative examples include: amine boranes, boron hydride ammoniates, hydrazine-borane complexes, and ammonium octahydrotriborates or tetrahydroborates. Of these, amine boranes (and especially ammonia borane) have been extensively investigated as hydrogen carriers. During the 1970s and 1980s, the U.S. Army and Navy funded efforts aimed at developing hydrogen/deuterium gas-generating compounds for use in the HF/DF and HCl chemical lasers, and gas dynamic lasers. Earlier hydrogen gas-generating formulations used amine boranes and their derivatives. Ignition of the amine borane(s) forms boron nitride (BN) and hydrogen gas. In addition to ammonia borane (H_3BNH_3), other gas-generators include diborane diammoniate, $H_2B(NH_3)_2BH_4$.

Physical Storage

In this case hydrogen remains in physical forms, i.e., as gas, supercritical fluid, adsorbate, or molecular inclusions. Theoretical limitations and experimental results are considered concerning the volumeteric and gravimeteric capacity of glass microvessels, microporous, and nanoporous media, as well as safety and refilling-time demands.

Porous or Layered Carbon

Activated carbons are highly porous amorphous carbon materials with a high apparent surface area. Hydrogen physisorption can be increased in these materials by increasing the apparent surface area and optimizing pore diameter to around 7 Å. These materials are of particular interest due to the fact that they can be made from waste materials, such as cigarette butts which have shown great potential as precursor materials for high-capacity hydrogen storage materials. Graphene can store hydrogen efficiently. The H_2 adds to the double bonds giving graphane. The hydrogen is released upon heating to 450 °C.

Carbon Nanotubes

Hydrogen carriers based on nanostructured carbon (such as carbon buckyballs and nanotubes) have been proposed. However, hydrogen content amounts up to ≈3.0-7.0 wt% at 77K which is far from the value set by US Department of Energy (6 wt% at nearly ambient conditions). To realize carbon materials as effective hydrogen storage technologies, carbon nanotubes (CNTs) have been doped with MgH_2. The metal hydride has proven to have a theoretical storage capacity (7.6 wt.%) that fulfills the United States Department of Energy requirement of 6 wt% but has limited practical applications due to its high release temperature. The proposed mechanism involves the creation of fast diffusion channels by CNTs within the MgH_2 lattice. Fullerene is another carbonaceous nanomaterial that has been tested for hydrogen storage in this center. Fullerene molecules are composed of a C_60 close-caged structure, which allows for hydrogenation of the double bonded carbons leading to a theoretical C_60H_60 isomer with a hydrogen content of 7.7 wt%. However, the release temperature in these systems is high (600 °C).

Metal-Organic Frameworks

Metal-organic frameworks represent another class of synthetic porous materials that store hydrogen and energy at the molecular level. MOFs are highly crystalline inorganic-organic hybrid structures that contain metal clusters or ions (secondary building units) as nodes and organic ligands as linkers. When guest molecules (solvent) occupying the pores are removed during solvent exchange and heating under vacuum, porous structure of MOFs can be achieved without destabilizing the frame and hydrogen molecules will be adsorbed onto the surface of the pores by physisorption. Compared to traditional zeolites and porous carbon materials, MOFs have a very high number of pores and surface area which allow higher hydrogen uptake in a given volume. Thus, research interests on hydrogen storage in MOFs have been growing since 2003 when the first MOF-based hydrogen storage was introduced. Since there are infinite geometric and chemical variations of MOFs based on different combinations of SBUs and linkers, many researches explore what combination will provide the maximum hydrogen uptake by varying materials of metal ions and linkers.

Factors Influencing Hydrogen Storage Ability

Temperature, pressure and composition of MOFs can influence their hydrogen storage ability. The adsorption capacity of MOFs is lower at higher temperatures and higher at lower temperatures. With the rising of temperature, physisorption decreases and chemisorption increases. For MOF-519 and MOF-520, the isosteric heat of adsorption decreased with pressure increase. For MOF-5, both gravimeteric and volumeteric hydrogen uptake increased with increase in pressure. The total capacity may not be consistent with the usable capacity under pressure

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swing conditions. For instance, MOF-5 and IRMOF-20, which have the highest total volumeteric capacity, show the least usable volumeteric capacity. Absorption capacity can be increased by modification of structure. For example, the hydrogen uptake of PCN-68 is higher than PCN-61. Porous aromatic frameworks (PAF-1), which is known as a high surface area material, can achieve a higher surface area by doping.

Modification of MOFs

There are many different ways to modify MOFs, such as MOF catalysts, MOF hybrids, MOF with metal centers and doping. MOF catalysts have high surface area, porosity and hydrogen storage capacity. However, the active metal centers are low. MOF hybrids have enhanced surface area, porosity, loading capacity and hydrogen storage capacity. Nevertheless, they are not stable and lack active centers. Doping in MOFs can increase hydrogen storage capacity, but there might be steric effect and inert metals have inadequate stability. There might be formation of interconnected pores and low corrosion resistance in MOFs with metal centers, while they might have good binding energy and enhanced stability. These advantages and disadvantages for different kinds of modified MOFs show that MOF hybrids are more promising because of the good controllability in selection of materials for high surface area, porosity and stability. In 2006, chemists achieved hydrogen storage concentrations of up to 7.5 wt% in MOF-74 at a low temperature of 77 K. In 2009, researchers reached 10 wt% at 77 bar (1,117 psi) and 77 K with MOF NOTT-112. Most articles about hydrogen storage in MOFs report hydrogen uptake capacity at a temperature of 77K and a pressure of 1 bar because these conditions are commonly available and the binding energy between hydrogen and the MOF at this temperature is large compared to the thermal vibration energy. Varying several factors such as surface area, pore size, catenation, ligand structure, and sample purity can result in different amounts of hydrogen uptake in MOFs. In 2020, researchers reported that NU-1501-Al, an ultraporous metal-organic framework (MOF) based on metal trinuclear clusters, yielded "impressive gravimeteric and volumeteric storage performances for hydrogen and methane", with a hydrogen delivery capacity of 14.0% w/w, 46.2 g/litre.

Cryo-Compressed

Cryo-compressed storage of hydrogen is the only technology that meets 2015 DOE targets for volumeteric and gravimeteric efficiency. Furthermore, another study has shown that cryo-compressed exhibits interesting cost advantages: ownership cost (price per mile) and storage system cost (price per vehicle) are actually the lowest when compared to any other technology. For example, a cryo-compressed hydrogen system would cost $0.12 per mile (including cost of fuel and every associated other cost), while conventional gasoline vehicles cost between $0.05 and $0.07 per mile. Like liquid storage, cryo-compressed uses cold hydrogen (20.3 K and slightly above) in order to reach a high energy density. However, the main difference is that, when the hydrogen would warm-up due to heat transfer with the environment ("boil off"), the tank is allowed to go to pressures much higher (up to 350 bars versus a couple of bars for liquid storage). As a consequence, it takes more time before the hydrogen has to vent, and in most driving situations, enough hydrogen is used by the car to keep the pressure well below the venting limit. Consequently, it has been demonstrated that a high driving range could be achieved with a cryo-compressed tank: more than 650 miles (1,050 km) were driven with a full tank mounted on a hydrogen-fueled engine of Toyota Prius. Research is still underway to study and demonstrate the full potential of the technology. As of 2010, the BMW Group has started a thorough component and system level validation of cryo-compressed vehicle storage on its way to a commercial product.

Clathrate Hydrates

H2 caged in a clathrate hydrate was first reported in 2002, but requires very high pressures to be stable. In 2004, researchers showed solid H2-containing hydrates could be formed at ambient temperature and 10s of bar by adding small amounts of promoting substances such as THF. These clathrates have a theoretical maximum hydrogen densities of around 5 wt% and 40 kg/m3.

Glass Capillary Arrays

A team of Russian, Israeli and German scientists have collaboratively developed an innovative technology based on glass capillary arrays for the safe infusion, storage and controlled release of hydrogen in mobile applications. The C.En technology has achieved the United States Department of Energy (DOE) 2010 targets for on-board hydrogen storage systems. DOE 2015 targets can be achieved using flexible glass capillaries and cryo-compressed method of hydrogen storage.

Glass Microspheres

Hollow glass microspheres (HGM) can be utilized for controlled storage and release of hydrogen. HGMs with a diameter of 1 to 100 μm, a density of 1.0 to 2.0 gm/cc and a porous wall with openings of 10 to 1000 angstroms are considered for hydrogen storage. The advantages of HGMs for hydrogen storage are that they are nontoxic, light, cheap, recyclable, reversible, easily handled at atmospheric conditions, capable of being stored in a tank, and the hydrogen within is non-explosive. Each of these HGMs is capable of containing hydrogen up to 150 MPa without the heaviness and bulk of a large, pressurized tank. All of these qualities are favorable in vehicular applications. Beyond these advantages, HGMs are seen as a possible hydrogen solution due to hydrogen diffusivity having a large temperature dependence. At room temperature, the diffusivity is very low, and the hydrogen is trapped in the HGM. The disadvantage of HGMs is that to fill and outgas hydrogen effectively the temperature must be at

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least 300 °C which significantly increases the operational cost of HGM in hydrogen storage. The high temperature can be partly attributed to glass being an insulator and having a low thermal conductivity; this hinders hydrogen diffusivity and therefore requiring a higher temperature to achieve the desired output. To make this technology more economically viable for commercial use, research is being done to increase the efficiency of hydrogen diffusion through the HGMs. One study done by Dalai et al. sought to increase the thermal conductivity of the HGM through doping the glass with cobalt. In doing so they increased the thermal conductivity from 0.0072 to 0.198 W/m-K at 10 wt% Co. Increases in hydrogen adsorption though were only seen up to 2 wt% Co (0.103 W/m-K) as the metal oxide began to cover pores in the glass shell. This study concluded with a hydrogen storage capacity of 3.31 wt% with 2 wt% Co at 200 °C and 10 bar.

A study done by Rapp and Shelby sought to increase the hydrogen release rate through photo-induced outgassing in doped HGMs in comparison to conventional heating methods. The glass was doped with optically active metals to interact with. The high-intensity infrared light. The study found that 0.5 wt% Fe_3O_4 doped 7070 borosilicate glass had hydrogen release increase proportionally to the infrared lamp intensity. In addition to the improvements to diffusivity by infrared alone, reactions between the hydrogen and iron-doped glass increased the Fe^{2+}/Fe^{3+} ratio which increased infrared absorption therefore further increasing the hydrogen yield. As of 2020, the progress made in studying HGMs has increased its efficiency, but it still falls short of Department of Energy targets for this technology. The operation temperatures for both hydrogen adsorption and release are the largest barrier to commercialization.

Stationary Hydrogen Storage

Unlike mobile applications, hydrogen density is not a huge problem for stationary applications. As for mobile applications, stationary applications can use established technology:

- Compressed hydrogen (CGH_2) in a hydrogen tank
- Liquid hydrogen in a (LH_2) cryogenic hydrogen tank
- Slush hydrogen in a cryogenic hydrogen tank

Underground Hydrogen Storage

Underground hydrogen storage is the practice of hydrogen storage in caverns, salt domes and depleted oil and gas fields. Large quantities of gaseous hydrogen have been stored in caverns by ICI for many years without any difficulties. The storage of large quantities of liquid hydrogen underground can function as grid energy storage. The round-trip efficiency is approximately 40% (vs. 75-80% for pumped hydro (PHES)), and the cost is slightly higher than pumped hydro, if only a limited number of hours of storage is required. Another study referenced by a European staff working paper found that for large scale storage, the cheapest option is hydrogen at €140/MWh for 2,000 hours of storage using an electrolyser, salt cavern storage and combined-cycle power plant. The European project Hyunder indicated in 2013 that for the storage of wind and solar energy an additional 85 caverns are required as it cannot be covered by PHES and CAES systems. A German case study on storage of hydrogen in salt caverns found that if the German power surplus (7% of total variable renewable generation by 2025 and 20% by 2050) would be converted to hydrogen and stored underground, these quantities would require some 15 caverns of 500,000 cubic meters each by 2025 and some 60 caverns by 2050 - corresponding to approximately one third of the number of gas caverns currently operated in Germany. In the US, Sandia Labs are conducting research into the storage of hydrogen in depleted oil and gas fields, which could easily absorb large amounts of renewably produced hydrogen as there are some 2.7 million depleted wells in existence.

Power To Gas

Power to gas is a technology which converts electrical power to gas fuel. There are two methods: the first is to use the electricity for water splitting and inject the resulting hydrogen into the natural gas grid; the second, less efficient method is used to convert carbon dioxide and hydrogen to methane, (see natural gas) using electrolysis and the Sabatier reaction. A third option is to combine the hydrogen via electrolysis with a source of carbon (either carbon dioxide or carbon monoxide from biogas, from industrial processes or via direct air-captured carbon dioxide) via biomethanation, where biomethanogens (archaea) consume carbon dioxide and hydrogen and produce methane within an anaerobic environment. This process is highly efficient, as the archaea are self-replicating and only require low-grade (60 °C) heat to perform the reaction. Another process has also been achieved by SoCalGas to convert the carbon dioxide in raw biogas to methane in a single electrochemical step, representing a simpler method of converting excess renewable electricity into storable natural gas.

The UK has completed surveys and is preparing to start injecting hydrogen into the gas grid as the grid previously carried 'town gas' which is a 50% hydrogen-methane gas formed from coal. Auditors KPMG found that converting the UK to hydrogen gas could be £150bn to £200bn cheaper than rewiring British homes to use electric heating powered by lower-carbon sources. Excess power or off peak power generated by wind generators or solar arrays can then be used for load balancing in the energy grid. Using the existing natural gas system for hydrogen, Fuel cell maker Hydrogenics and natural gas distributor Enbridge have teamed up to develop such a power to gas system in Canada. Pipeline storage of hydrogen where a natural gas network is used for the storage of hydrogen. Before switching to natural gas, the German gas networks were operated using towngas, which for the most part (60-65%) consisted of hydrogen. The storage capacity

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of the German natural gas network is more than 200,000 GW·h which is enough for several months of energy requirement. By comparison, the capacity of all German pumped storage power plants amounts to only about 40 GW·h. The transport of energy through a gas network is done with much less loss (<0.1%) than in a power network (8%). The use of the existing natural gas pipelines for hydrogen was studied by Natural Hydrogen.

Automotive Onboard Hydrogen Storage

Portability is one of the biggest challenges in the automotive industry, where high density storage systems are problematic due to safety concerns. High-pressure tanks weigh much more than the hydrogen they can hold. For example, in the 2014 Toyota Mirai, a full tank contains only 5.7% hydrogen, the rest of the weight being the tank. The US Department of Energy has set targets for onboard hydrogen storage for light vehicles. The list of requirements include parameters related to gravimeteric and volumeteric capacity, operability, durability and cost. These targets have been set as the goal for a multiyear research plan expected to offer an alternative to fossil fuels. The Freedom CAR Partnership, which was established under U.S. President George W. Bush, set targets for hydrogen vehicle fuel systems. The 2005 targets were not reached. The targets were revised in 2009 to reflect new data on system efficiencies obtained from fleets of test cars. In 2017 the 2020 and ultimate targets were lowered, with the ultimate targets set to 65 g H_2 per kg total system weight, and 50 g H_2 per liter of system. It is important to note that these targets are for the hydrogen storage system, not the hydrogen storage material such as hydride. System densities are often around half those of the working material, thus while a material may store 6 wt% H_2, a working system using that material may only achieve 3 wt% when the weight of tanks, temperature and pressure control equipment, etc., is considered. In 2010, only two storage technologies were identified as having the potential to meet DOE targets: MOF-177 exceeds 2010 target for volumeteric capacity, while cryo-compressed H_2 exceeds more restrictive 2015 targets for both gravimeteric and volumeteric capacity. The target for fuel cell powered vehicles is to provide a driving range of over 300 miles. A long-term goal set by the US Fuel Cell Technology Office involves the use of nanomaterials to improve maximum range.

Fuel Cells and Storage

Due to its clean-burning characteristics, hydrogen is a clean fuel alternative for the automotive industry. Hydrogen-based fuel could significantly reduce the emissions of greenhouse gases such as CO_2, SO_2 and NOx. Three problems for the use of hydrogen fuel cells (HFC) are efficiency, size, and safe onboard storage of the gas. Other major disadvantages of this emerging technology involve cost, operability and durability issues, which still need to be improved from the existing systems. To address these challenges, the use of nanomaterials has been proposed as an alternative option to the traditional hydrogen storage systems. The use of nanomaterials could provide a higher density system and increase the driving range towards the target set by the DOE at 300 miles. Carbonaceous materials such as carbon nanotube and metal hydrides are the main focus of research. They are currently being considered for onboard storage systems due to their versatility, multi-functionality, mechanical properties and low cost with respect to other alternatives.

Other Advantages of Nanomaterials in Fuel Cells

The introduction of nanomaterials in onboard hydrogen storage systems may be a major turning point in the automotive industry. However, storage is not the only aspect of the fuel cell to which nanomaterials may contribute. Different studies have shown that the transport and catalytic properties of Nafion membranes used in HFCs can be enhanced with TiO_2/SnO_2 nanoparticles. The increased performance is caused by an improvement in hydrogen splitting kinetics due to catalytic activity of the nanoparticles. Furthermore, this system exhibits faster transport of protons across the cell which makes HFCs with nanoparticle composite membranes a promising alternative. Another application of nanomaterials in water splitting has been introduced by a research group at Manchester Metropolitan University in the UK using screen-printed electrodes consisting of a graphene-like material. Similar systems have been developed using photoelectrochemical techniques.

Hydrogen Storage Now and in the Future

The Hydrogen Storage Materials research field is vast, having tens of thousands of published papers. According to Papers in the 2000 to 2015 period collected from Web of Science and processed in VantagePoint® bibliometeric software, a scientometeric review of research in hydrogen storage materials was constituted. According to the literature, hydrogen energy went through a hype-cycle type of development in the 2000's. Research in Hydrogen Storage Materials grew at increasing rates from 2000 to 2010. Afterwards, growth continued but at decreasing rates, and a plateau was reached in 2015. Looking at individual country output, there is a division between countries that after 2010 inflected to a constant or slightly declining production, such as the European Union countries, the US and Japan, and those whose production continued growing until 2015, such as China and South Korea. The countries with most publications were China, the EU and the USA, followed by Japan. China kept the leading position throughout the entire period and had a higher share of hydrogen storage materials publications in its total research output.

Among materials classes, Metal-Organic Frameworks were the most researched materials, followed by Simple Hydrides. Three typical behaviors were identified:

1. New materials, researched mainly after 2004, such as MOFs and Borohydrides;

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2. Classic materials, present through the entire period with growing number of papers, such as Simple Hydrides, and

3. Materials with stagnant or declining research through the end of the period, such as AB5 alloys and Carbon Nanotubes.

However, current physisorption technologies are still far from being commercialized. Experimental studies are executed for small samples less than 100 g. The described technologies require high pressure and/or low temperatures as a rule. Therefore, we consider these techniques at their current state of the art not as a separate novel technology but as a type of valuable add-on to current compression and liquefaction methods.

Physisorption processes are reversible since no activation energy is involved and the interaction energy is very low. In materials such as metal-organic frameworks, porous carbons, zeolites, clathrates, and organic polymers, hydrogen is physisorbed on the surface of the pores. In these classes of materials, the hydrogen storage capacity mainly depends on the surface area and pore volume. The main limitation of use of these sorbents as H2storage materials is weak van der Waals interaction energy between hydrogen and the surface of the sorbents. Therefore, many of the physisorption based materials have high storage capacities at liquid nitrogen temperature and high pressures, but their capacities become very low at ambient temperature and pressure. LOHC, liquid organic hydrogen storage systems are a promising technique for future hydrogen storage. LOHC are organic compounds that can absorb and release hydrogen through chemical reactions. These compounds are characterized by the fact that they can be loaded and unloaded with considerable amounts of hydrogen in a cyclic process. In principle, every unsaturated compound (organic molecules with C-C double or triple bonds) can take up hydrogen during hydrogenation. This technique ensures that the release of compounds into the atmosphere is entirely avoided in hydrogen storage. Therefore, LOHCs are an attractive way to provide wind and solar energy for mobility applications in the form of liquid energy carrying molecules of similar energy storage densities and manageability as today's fossil fuels.

Fuel Cell Vehicle

A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is an electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat. As compared with internal combustion vehicles, hydrogen vehicles centralize pollutants at the site of the hydrogen production, where hydrogen is typically derived from reformed natural gas. Transporting and storing hydrogen may also create pollutants.

Fuel cells have been used in various kinds of vehicles including forklifts, especially in indoor applications where their clean emissions are important to air quality, and in space applications. The first commercially produced hydrogen fuel cell automobile, the Hyundai ix35 FCEV, was introduced in 2013, Toyota Mirai followed in 2015 and then Honda entered the market. Fuel cells are being developed and tested in trucks, buses, boats, motorcycles and bicycles, among other kinds of vehicles. As of December 2020, 31,225 passenger FCEVs powered with hydrogen had been sold worldwide. As of 2021, there were only two models of fuel cell cars publicly available in select markets: the Toyota Mirai (2014-) and the Hyundai Nexo (2018-). The Honda Clarity was produced from 2016 to 2021, when it was discontinued. As of 2020, there was limited hydrogen infrastructure, with fewer than fifty hydrogen fueling stations for automobiles publicly available in the U.S. Critics doubt whether hydrogen will be efficient or cost-effective for automobiles, as compared with other zero emission technologies, and in 2019, The Motley Fool opined "what is tough to dispute is that the hydrogen fuel cell dream is all but dead for the passenger vehicle market."

Description and Purpose of Fuel Cells in Vehicles

All fuel cells are made up of three parts: an electrolyte, an anode and a cathode. In principle, a hydrogen fuel cell functions like a battery, producing electricity, which can run an electric motor. Instead of requiring recharging, however, the fuel cell can be refilled with hydrogen. Different types of fuel cells include polymer electrolyte membrane (PEM) Fuel Cells, direct methanol fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, reformed methanol fuel cells and Regenerative Fuel Cells.

History

1966 GM Electrovan

The concept of the fuel cell was first demonstrated by Humphry Davy in 1801, but the invention of the first working fuel cell is credited to William Grove, a chemist, lawyer, and physicist. Grove's experiments with what he called a "gas voltaic battery" proved in 1842 that an electric current could be produced by an electrochemical reaction between hydrogen and oxygen over a platinum catalyst. English engineer Francis Thomas Bacon expanded on Grove's work, creating and demonstrating variousalkaline fuel cells from 1939 to 1959. The first modern fuel cell vehicle was a modified Allis-Chalmers farm tractor, fitted with a 15 kilowatt fuel cell, around 1959. The Cold War Space Race drove further development of fuel cell technology. Project Gemini tested fuel cells to provide electrical power during manned space missions. Fuel cell development continued with the Apollo Program. The electrical power systems in the Apollo capsules and lunar modules used alkali fuel cells. In 1966, General Motors developed the first fuel cell road vehicle, the Chevrolet Electrovan. It had a PEM fuel cell, a range of 120 miles and a top speed of 70mph. There were only two seats, as the fuel cell stack and large tanks of hydrogen and oxygen took up the rear portion of the van.

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Only one was built, as the project was deemed cost-prohibitive. General Electric and others continued working on PEM fuel cells in the 1970s. Fuel cell stacks were still limited principally to space applications in the 1980s, including the Space Shuttle. However, the closure of the Apollo Program sent many industry experts to private companies. By the 1990s, automobile manufacturers were interested in fuel cell applications, and demonstration vehicles were readied. In 2001, the first 700 bar (10000 PSI) hydrogen tanks were demonstrated, reducing the size of the fuel tanks that could be used in vehicles and extending the range.

Applications

There are fuel cell vehicles for all modes of transport. The most prevalent fuel cell vehicles are cars, buses, forklifts and material handling vehicles.

Automobiles

The Honda FCX Clarity concept car was introduced in 2008 for leasing by customers in Japan and Southern California and discontinued by 2015. From 2008 to 2014, Honda leased a total of 45 FCX units in the US. Over 20 other FCEV prototypes and demonstration cars were released in that time period, including the GM HydroGen4, and Mercedes-Benz F-Cell. The Hyundai ix35 FCEV Fuel Cell vehicle was available for lease from 2014 to 2018, when 54 units were leased. In 2018, Hyundai introduced the Nexo. Sales of the Toyota Mirai to government and corporate customers began in Japan in December 2014. Pricing started at ¥6,700,000 (~US$57,400) before taxes and a government incentive of ¥2,000,000 (~US$19,600). Former European Parliament President Pat Cox estimated that Toyota initially would lose about $100,000 on each Mirai sold. As of December 2017, global sales totaled 5,300 Mirais. The top selling markets were the U.S. with 2,900 units, Japan with 2,100 and Europe with 200. The Honda Clarity Fuel Cell was produced from 2016 to 2021. The 2017 Clarity had the highest combined and city fuel economy ratings among all hydrogen fuel cell cars rated by the EPA that year, with a combined city/highway rating of 67 miles per gallon gasoline equivalent (MPGe), and 68 MPGe in city driving.] In 2019, Katsushi Inoue, the president of Honda Europe, stated, "Our focus is on hybrid and electric vehicles now. Maybe hydrogen fuel cell cars will come, but that's a technology for the next era." By 2017, Daimler phased out its FCEV development, citing declining battery costs and increasing range of EVs, and most of the automobile companies developing hydrogen cars had switched their focus to battery electric vehicles. By 2020, only three car makers were still manufacturing, or had active manufacturing programs for hydrogen cars.

Hydrogen Infrastructure

Eberle and Rittmar von Helmolt stated in 2010 that challenges remain before fuel cell cars can become competitive with other technologies and cite the lack of an extensive hydrogen infrastructure in the U.S.: As of July 2020, there were 43 publicly accessible hydrogen refueling stations in the US, 41 of which were located in California. In 2013, Governor Jerry Brown signed AB 8, a bill to fund $20 million a year for 10 years to build up to 100 stations. In 2014, the California Energy Commission funded $46.6 million to build 28 stations. Japan got its first commercial hydrogen fueling station in 2014. By March 2016, Japan had 80 hydrogen fueling stations, and the Japanese government aims to double this number to 160 by 2020. In May 2017, there were 91 hydrogen fueling stations in Japan. Germany had 18 public hydrogen fueling stations in July 2015. The German government hoped to increase this number to 50 by end of 2016, but only 30 were open in June 2017.

Geothermal Energy

Geothermal energy is the thermal energy in the Earth's crust which originates from the formation of the planet and from radioactive decay of materials in currently uncertain but possibly roughly equal proportions. The high temperature and pressure in Earth's interior cause some rock to melt and solid mantle to behave plastically. This results in parts of the mantle convecting upward since it is lighter than the surrounding rock. Temperatures at the core-mantle boundary can reach over 4000 °C (7200 °F). Geothermal heating, using water from hot springs, for example, has been used for bathing since Paleolithic times and for space heating since ancient Roman times. More recently geothermal power, the term used for generation of electricity from geothermal energy, has gained in importance. It is estimated that the earth's geothermal resources are theoretically more than adequate to supply humanity's energy needs, although only a very small fraction is currently being profitably exploited, often in areas near tectonic plate boundaries. As a result of government assisted research and industry experience, the cost of generating geothermal power decreased by 25% over the 1980s and 1990s. More recent technological advances have dramatically reduced costs and thereby expanded the range and size of viable resources. In 2021, the U.S. Department of Energy estimates that geothermal energy from a power plant "built today" costs about $0.05/kWh. In 2019, 13,900 megawatts (MW) of geothermal power were available worldwide. An additional 28 Gigawatts of direct geothermal heating capacity has been installed for district heating, space heating, spas, industrial processes, desalination and agricultural applications as of 2010. Forecasts for the future of geothermal power depend on assumptions about technology, energy prices, subsidies, plate boundary movement and interest rates. Pilot programs like EWEB's customer opt in Green Power Program show that customers would be willing to pay a little more for a renewable energy source like geothermal. About 100 thousand people are employed in the industry. The adjective geothermal originates from the Greek roots γῆ (gê), meaning Earth, and θερμός (thermós), meaning hot.

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History

Hot springs have been used for bathing at least since Paleolithic times. The oldest known spa is a stone pool on China's Lisan Mountain built in the Qin Dynasty in the 3rd century BCE, at the same site where the Huaqing Chi palace was later built. In the first century CE, Romans conquered Aquae Sulis, now Bath, Somerset, England, and used the hot springs there to feed public baths and underfloor heating. The admission fees for these baths probably represent the first commercial use of geothermal power. The world's oldest geothermal district heating system in Chaudes-Aigues, France, has been operating since the 15th century. The earliest industrial exploitation began in 1827 with the use of geyser steam to extract boric acid from volcanic mud in Larderello, Italy. In 1892, America's first district heating system in Boise, Idaho was powered directly by geothermal energy, and was copied in Klamath Falls, Oregon in 1900. The first known building in the world to utilize geothermal energy as its primary heat source was the Hot Lake Hotel in Union County, Oregon, whose construction was completed in 1907. A deep geothermal well was used to heat greenhouses in Boise in 1926, and geysers were used to heat greenhouses in Iceland and Tuscany at about the same time. Charlie Lieb developed the first downhole heat exchanger in 1930 to heat his house. Steam and hot water from geysers began heating homes in Iceland starting in 1943. Global geothermal electric capacity. The upper red line is installed capacity; lower green line is realized production. In the 20th century, demand for electricity led to the consideration of geothermal power as a generating source. Prince Piero Ginori Conti tested the first geothermal power generator on 4 July 1904, at the same Larderello dry steam field where geothermal acid extraction began. It successfully lit four light bulbs. Later, in 1911, the world's first commercial geothermal power plant was built there. It was the world's only industrial producer of geothermal electricity until New Zealand built a plant in 1958. In 2012, it produced some 594 megawatts.

In 1960, Pacific Gas and Electric began operation of the first successful geothermal electric power plant in the United States at The Geysers in California. The original turbine lasted for more than 30 years and produced 11 MW net power. The binary cycle power plant was first demonstrated in 1967 in the USSR and later introduced to the US in 1981.This technology allows the generation of electricity from much lower temperature resources than previously. In 2006, a binary cycle plant in Chena Hot Springs, Alaska, came on-line, producing electricity from a record low fluid temperature of 57 °C (135 °F).

Resources

Outside of the seasonal variations, the geothermal gradient of temperatures through the crust is 25-30 °C (45-54 °F) per km of depth in most of the world. The conductive heat flux averages 0.1 MW/km^2. These values are much higher near tectonic plate boundaries where the crust is thinner. They may be further augmented by fluid circulation, either through magma conduits, hot springs, hydrothermal circulation or a combination of these. The thermal efficiency and profitability of electricity generation is particularly sensitive to temperature. The most demanding applications receive the greatest benefit from a high natural heat flux, ideally from using a hot spring. The next best option is to drill a well into a hot aquifer. If no adequate aquifer is available, an artificial one may be built by injecting water to hydraulically fracture the bedrock. This last approach is called hot dry rock geothermal energy in Europe or enhanced geothermal systems in North America. Much greater potential may be available from this approach than from conventional tapping of natural aquifers. Estimates of the potential for electricity generation from geothermal energy vary sixfold, from 0.035 to 2TW depending on the scale of investments. Upper estimates of geothermal resources assume enhanced geothermal wells as deep as 10 kilometers (6 mi), whereas existing geothermal wells are rarely more than 3 kilometers (2 mi) deep. Wells of this depth are now common in the petroleum industry. The deepest research well in the world, the Kola superdeep borehole, is 12 kilometers (7 mi) deep.

Geothermal Power

Geothermal power is electrical power generated from geothermal energy. Technologies in use include dry steam power stations, flash steam power stations and binary cycle power stations. Geothermal electricity generation is currently used in 26 countries, while geothermal heating is in use in 70 countries. As of 2019, worldwide geothermal power capacity amounts to 15.4 gigawatts (GW), of which 23.86 percent or 3.68 GW are installed in the United States. International markets grew at an average annual rate of 5 percent over the three years to 2015, and global geothermal power capacity is expected to reach 14.5-17.6 GW by 2020. Based on current geologic knowledge and technology the GEA publicly discloses, the Geothermal Energy Association (GEA) estimates that only 6.9 percent of total global potential has been tapped so far, while the IPCC reported geothermal power potential to be in the range of 35 GW to 2 TW. Countries generating more than 15 percent of their electricity from geothermal sources include El Salvador, Kenya, the Philippines, Iceland, New Zealand, and Costa Rica. Geothermal power is considered to be a sustainable, renewable source of energy because the heat extraction is small compared with the Earth's heat content. The greenhouse gas emissions of geothermal electric stations are on average 45 grams of carbon dioxide per kilowatt-hour of electricity, or less than 5 percent of that of conventional coal-fired plants. As a source of renewable energy for both power and heating, geothermal has the potential to meet 3-5% of global demand by 2050. With economic incentives, it is estimated that by 2100 it will be possible to meet 10% of global demand.

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Geothermal electric plants were traditionally built exclusively on the edges of tectonic plates where high-temperature geothermal resources are available near the surface. The development of binary cycle power plants and improvements in drilling and extraction technology enable enhanced geothermal systems over a much greater geographical range. Demonstration projects are operational in Landau-Pfalz, Germany, and Soultz-sous-Forêts, France, while an earlier effort in Basel, Switzerland, was shut down after it triggered earthquakes. Other demonstration projects are under construction in Australia, the United Kingdom, and the United States of America. In Myanmar over 39 locations capable of geothermal power production and solme of these hydrothermal reservoirs lie quite close to Yangon which is a significant underutilized resource.

Geothermal Heating

Geothermal heating is the direct use of geothermal energy for some heating applications. Humans have taken advantage of geothermal heat this way since the Paleolithic era. Approximately seventy countries made direct use of a total of 270 PJ of geothermal heating in 2004. As of 2007, 28 GW of geothermal heating capacity is installed around the world, satisfying 0.07% of global primary energy consumption. Thermal efficiency is high since no energy conversion is needed, but capacity factors tend to be low (around 20%) since the heat is mostly needed in the winter. Geothermal energy originates from the heat retained within the Earth since the original formation of the planet, from radioactive decay of minerals, and from solar energy absorbed at the surface. Most high temperature geothermal heat is harvested in regions close to tectonic plate boundaries where volcanic activity rises close to the surface of the Earth. In these areas, ground and groundwater can be found with temperatures higher than the target temperature of the application. However, even cold ground contains heat, below 6 meters (20ft) the undisturbed ground temperature is consistently at the Mean Annual Air Temperature, and it may be extracted with a ground source heat pump.

Types

Geothermal energy comes in either vapor-dominated or liquid-dominated forms. Larderello and The Geysers are vapor-dominated. Vapor-dominated sites offer temperatures from 240 to 300 °C that produce superheated steam.

Liquid-Dominated Plants

Liquid-dominated reservoirs (LDRs) are more common with temperatures greater than 200 °C (392 °F) and are found near young volcanoes surrounding the Pacific Ocean and in rift zones and hot spots. Flash plants are the common way to generate electricity from these sources. Pumps are generally not required, powered instead when the water turns to steam. Most wells generate 2-10 MW of electricity. Steam is separated from a liquid via cyclone separators, while the liquid is returned to the reservoir for reheating/reuse. As of 2013, the largest liquid system is Cerro Prieto in Mexico, which generates 750 MW of electricity from temperatures reaching 350 °C (662 °F). The Salton Sea field in Southern California offers the potential of generating 2000 MW of electricity.

Lower-temperature LDRs (120-200 °C) require pumping. They are common in extensional terrains, where heating takes place via deep circulation along faults, such as in the Western US and Turkey. Water passes through a heat exchanger in a Rankine cycle binary plant. The water vaporizes an organic working fluid that drives a turbine. These binary plants originated in the Soviet Union in the late 1960s and predominate in new US plants. Binary plants have no emissions.

Enhanced Geothermal Systems

Enhanced geothermal systems (EGS) actively inject water into wells to be heated and pumped back out. The water is injected under high pressure to expand existing rock fissures to enable the water to freely flow in and out. The technique was adapted from oil and gas extraction techniques. However, the geologic formations are deeper, and no toxic chemicals are used, reducing the possibility of environmental damage. Drillers can employ directional drilling to expand the size of the reservoir. Small-scale EGS have been installed in the Rhine Graben at Soultz-sous-Forêts in France and at Landau and Insheim in Germany.

Economics

Geothermal power requires no fuel (except for pumps) and is therefore immune to fuel cost fluctuations. However, capital costs are significant. Drilling accounts for over half the costs, and exploration of deep resources entails significant risks. A typical well doublet (extraction and injection wells) in Nevada can support 4.5 megawatts (MW) and costs about $10 million to drill, with a 20% failure rate.

A Power Plant at the Geysers

As noted above, drilling cost is a major component of a geothermal power plant's budget and is one of the key barriers to wider development of geothermal resources. A power plant must have production wells to bring the hot fluid (steam or hot water) to the surface and must also have injection wells to pump the liquid back into the reservoir after it has passed through the power plant. Drilling geothermal wells is more expensive than drilling oil and gas wells of comparable depth for several reasons:

- Geothermal reservoirs are usually in igneous or metamorphic rock, which is harder than the sedimentary rock of hydrocarbon reservoirs.
- The rock is often fractured, which causes vibrations that are damaging to bits and other drilling tools.
- The rock is often abrasive, with high quartz content, and

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sometimes contains highly corrosive fluids.

- The formation is, by definition, hot, which limits use of downhole electronics.

- Casing in geothermal wells must be cemented from top to bottom, to resist the casing's tendency to expand and contract with temperature changes. Oil and gas wells are usually cemented only at the bottom.

- Because the geothermal well produces a low-value fluid (steam or hot water) its diameter is considerably larger than typical oil and gas wells.

In total, electrical plant construction and well drilling cost about €2-5 million per MW of electrical capacity, while the break-even price is 0.04-0.10 € per kW.h. Enhanced geothermal systems tend to be on the high side of these ranges, with capital costs above $4 million per MW and break-even above $0.054 per kW.h in 2007. The capital cost of one such district heating system in Bavaria was estimated at somewhat over 1 million € per MW. Direct systems of any size are much simpler than electric generators and have lower maintenance costs per kW.h, but they must consume electricity to run pumps and compressors. Some governments subsidize geothermal projects. Geothermal power is highly scalable: from a rural village to an entire city, making it a vital part of the renewable energy transition. The most developed geothermal field in the United States is The Geysers in Northern California. Geothermal projects have several stages of development. Each phase has associated risks. At the early stages of reconnaissance and geophysical surveys, many projects are canceled, making that phase unsuitable for traditional lending. Projects moving forward from the identification, exploration and exploratory drilling often trade equity for financing.

Environmental Effects

Plant construction can adversely affect land stability. Subsidence has occurred in the Wairakei field in New Zealand. In Staufen im Breisgau, Germany, tectonic uplift occurred instead, due to a previously isolated anhydrite layer coming in contact with water and turning into gypsum, doubling its volume. Enhanced geothermal systems can trigger earthquakes as part of hydraulic fracturing. The project in Basel, Switzerland was suspended because more than 10,000 seismic events measuring up to 3.4 on the Richter scale occurred over the first 6 days of water injection. Geothermal has minimal land and freshwater requirements. Geothermal plants use 3.5 square kilometers (1.4 sq mi) per gigawatt of electrical production (not capacity) versus 32 square kilometers (12 sq mi) and 12 square kilometers (4.6 sq mi) for coal facilities and wind farms respectively. They use 20 liters (5.3 US gal) of freshwater per MW·h versus over 1,000 liters (260 US gal) per MW·h for nuclear, coal, or oil.

Production

According to the Geothermal Energy Association (GEA) installed geothermal capacity in the United States grew by 5%, or 147.05 MW, since the last annual survey in March 2012. This increase came from seven geothermal projects that began production in 2012. GEA also revised its 2011 estimate of installed capacity upward by 128 MW, bringing current installed U.S. geothermal capacity to 3,386 MW.

Legal Frameworks

Some of the legal issues raised by geothermal energy resources include questions of ownership and allocation of the resource, the grant of exploration permits, exploitation rights, royalties, and the extent to which geothermal energy issues have been recognized in existing planning and environmental laws. Other questions concern overlaps between geothermal and mineral or petroleum tenements. Broader issues concern the extent to which the legal framework for encouragement of renewable energy assists in encouraging geothermal industry innovation and development.

Geothermal Energy Comes from Deep Inside the Earth!

The slow decay of radioactive particles in the earth's core, a process that happens in all rocks, produces geothermal energy. The earth has four major parts or layers:

- An inner core of solid iron that is about 1,500 miles in diameter

- An outer core of hot molten rock called magma that is about 1,500 miles thick.

- A mantle of magma and rock surrounding the outer core that is about 1,800 miles thick

- A crust of solid rock that forms the continents and ocean floors that is 15 to 35 miles thick under the continents and 3 to 5 miles thick under the oceans

Scientists have discovered that the temperature of the earth's inner core is about 10,800 degrees Fahrenheit (°F), which is as hot as the surface of the sun. Temperatures in the mantle range from about 392°F at the upper boundary with the earth's crust to approximately 7,230°F at the mantle-core boundary. The earth's crust is broken into pieces called tectonic plates. Magma comes close to the earth's surface near the edges of these plates, which is where many volcanoes occur. The lava that erupts from volcanoes is partly magma. Rocks and water absorb heat from magma deep underground. The rocks and water found deeper underground have the highest temperatures.

Where Does Geothermal Energy Come from?

Geothermal energy is the heat that comes from the sub-surface of the earth. It is contained in the rocks and fluids beneath

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the earth's crust and can be found as far down to the earth's hot molten rock, magma. To produce power from geothermal energy, wells are dug a mile deep into underground reservoirs to access the steam and hot water there, which can then be used to drive turbines connected to electricity generators. There are three types of geothermal power plants; dry steam, flash and binary. Dry steam is the oldest form of geothermal technology and takes steam out of the ground and is used to directly drive a turbine. Flash plants use high-pressure hot water into cool, low-pressure water whilst binary plants pass hot water through a secondary liquid with a lower boiling point, which turns to vapor to drive the turbine.

Where It's Used

Geothermal energy is used in over 20 countries. The United States is the largest producer of geothermal energy in the world, and hosts the largest geothermal field. Known as "The Geysers" in California, the field is spread over 117 square kilometers and formed of 22 power plants, with an installed capacity of over 1.5GW. The energy source is also prevalent in Iceland, where it has been used since 1907. Describing itself as a 'pioneer' of geothermal power, the country produces 25% of its energy from five geothermal power plants. This is due to the 600 hot springs and 200 volcanoes in the country.

Pros and Cons of Geothermal Energy

The British Geological Survey describes geothermal energy as a "carbon-free, renewable, sustainable form of energy that provides a continuous, uninterrupted supply of heat that can be used to heat homes and office buildings and to generate electricity." Geothermal energy only produces one-sixth of the CO_2 produced by a natural gas plant and is not an intermittent source of energy like wind or solar. Its potential production could reach at least 35GW and as high as 2TW. However, there are some drawbacks to the energy source. Despite low CO_2 production geothermal has been associated with other emissions like sulphur dioxide and hydrogen sulphide. Similar to fracking, geothermal power plants have been the cause of mini tremors in the area they operate in and also have a high initial cost to build. It is also described as "the most location-specific energy source known to man" due to its activity being along the tectonic plates of the earth's crust. As such, it is limited to countries such as the aforementioned US and Iceland, alongside Kenya and Indonesia.

Bioenergy

Bioenergy is energy made from biomass or biofuel. Biomass is any organic material which has absorbed sunlight and stored it in the form of chemical energy. Examples are wood, energy crops and waste from forests, yards, or farms. Since biomass technically can be used as a fuel directly (e.g., wood logs), some people use the terms biomass and biofuel interchangeably. More often than not, the word biomass simply denotes the biological raw material the fuel is made of. The word biofuel is usually reserved for liquid or gaseous fuels, used for transportation. The U.S. Energy Information Administration (EIA) follows this naming practice. The IPCC (Intergovernmental Panel on Climate Change) defines bioenergy as a renewable form of energy. Researchers have disputed that the use of forest biomass for energy is carbon neutral.

Biomass

Wood and wood residues are the largest biomass energy source today. Wood can be used as a fuel directly or processed into pellet fuel or other forms of fuels. Other plants can also be used as fuel, for instance corn, switchgrass, miscanthus and bamboo. The main waste feedstocks are wood waste, agricultural waste, municipal solid waste, and manufacturing waste. Upgrading raw biomass to higher grade fuels can be achieved by different methods, broadly classified as thermal, chemical, or biochemical: Thermal conversion processes use heat as the dominant mechanism to upgrade biomass into a better and more practical fuel. The basic alternatives are torrefaction, pyrolysis, and gasification, these are separated mainly by the extent to which the chemical reactions involved are allowed to proceed (mainly controlled by the availability of oxygen and conversion temperature). Many chemical conversions are based on established coal-based processes, such as The Fischer-Tropsch synthesis. Like coal, biomass can be converted into multiple commodity chemicals. Biochemical processes have developed in nature to break down the molecules of which biomass is composed, and many of these can be harnessed. In most cases, microorganisms are used to perform the conversion. The processes are called anaerobic digestion, fermentation, and composting.

Biofuel

Based on the source of biomass, biofuels are classified broadly into two major categories: First-generation biofuels are made from food sources grown on arable lands, such as sugarcane and corn. Sugars present in this biomass are fermented to produce bioethanol, an alcohol fuel which serves as an additive to gasoline, or in a fuel cell to produce electricity. Bioethanol is made by fermentation, mostly from carbohydrates produced in sugar or starch crops such as corn, sugarcane, or sweet sorghum. Bioethanol is widely used in the United States and in Brazil. Biodiesel is produced from oils, for instance rapeseed or sugar beets and is the most common biofuel in Europe. Second-generation biofuels utilize non-food-based biomass sources such as perennial energy crops and agricultural residues/waste. The feedstock used to make the fuels either grow on arable land but are byproducts of the main crop, or they are grown on marginal land. Waste from industry, agriculture, forestry and households can also be used for second-generation biofuels, using e.g., anaerobic digestion to produce biogas, gasification to produce syngas or by direct combustion. Cellulosic biomass, derived from

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non-food sources, such as trees and grasses, is being developed as a feedstock for ethanol production, and biodiesel can be produced from left-over food products like vegetable oils and animal fats.

Power Production Compared to Other Renewables

To calculate land use requirements for different kinds of power production, it is essential to know the relevant surface power production densities. Vaclav Smil estimates that the average lifecycle surface power densities for biomass, wind, hydro and solar power production are 0.30 W/m^2, 1 W/m^2, 3 W/m^2 and 5 W/m^2, respectively (power in the form of heat for biomass, and electricity for wind, hydro and solar). Lifecycle surface power density includes land used by all supporting infrastructure, manufacturing, mining/harvesting and decommissioning. Van Zalk et al. estimates 0.08 W/m^2 for biomass, 0.14 W/m^2 for hydro, 1.84 W/m^2 for wind, and 6.63 W/m^2 for solar (median values, with none of the renewable sources exceeding 10 W/m^2). Fossil gas has the highest surface density at 482 W/m^2 while nuclear power at 240 W/m^2 is the only high-density and low-carbon energy source. The average human power consumption on ice-free land is 0.125 W/m^2 (heat and electricity combined), although rising to 20 W/m^2 in urban and industrial areas. Generally, bioenergy expansion fell by 50% in 2020. China and Europe are the only two regions that reported significant expansion in 2020, adding 2 GW and 1.2 GW of bioenergy capacity, respectively. Plants with low yields have lower surface power density compared to plants with high yields. Additionally, when the plants are only partially utilized, surface density drops even lower. This is the case when producing liquid fuels. For instance, ethanol is often made from sugarcane's sugar content or corn's starch content, while biodiesel is often made from rapeseed and soybean's oil content.

Eucalyptus Plantation in India

Combusting solid biomass is more energy efficient than combusting liquids, as the whole plant is utilized. For instance, corn plantations producing solid biomass for combustion generate more than double the amount of power per square meter compared to corn plantations producing for ethanol, when the yield is the same: 10 t/ha generates 0.60 W/m^2 and 0.26 W/m^2 respectively. Oven dry biomass in general, including wood, miscanthus and Napier grass, have a calorific content of roughly 18 GJ/t. When calculating power production per square meter, every t/ha of dry biomass yield increases a plantation's power production by 0.06 W/m^2. Consequently, Smil estimates the following:

- Large-scale plantations with pines, acacias, poplars and willows in temperate regions 0.30-0.90 W/m^2 (yield 5-15 t/ha)
- Large scale plantations with eucalyptus, acacia, leucaena, pinus and dalbergia in tropical and subtropical regions 1.20-1.50 W/m^2 (yield 20-25 t/ha)

In Brazil, the average yield for eucalyptus is 21 t/ha (1.26 W/m^2), but in Africa, India and Southeast Asia, typical eucalyptus yields are below 10 t/ha (0.6 W/m^2). FAO (Food and Agriculture Organization of the United Nations) estimate that forest plantation yields range from 1 to 25 m^3 per hectare per year globally, equivalent to 0.02-0.7 W/m^2 (0.4-12.2 t/ha):

- Pine (Russia) 0.02-0.1 W/m^2 (0.4-2 t/ha or 1-5 m^3)
- Eucalyptus (Argentina, Brazil, Chile and Uruguay) 0.5-0.7 W/m^2 (7.8-12.2 t/ha or 25 m^3)
- Poplar (France, Italy) 0.2-0.5 W/m^2 (2.7-8.4 t/ha or 25 m^3)

Smil estimate that natural temperate mixed forests yield on average 1.5-2 dry tons per hectare (2-2,5 m^3, equivalent to 0.1 W/m^2), ranging from 0.9 m^3 in Greece to 6 m^3 in France). IPCC provides average net annual biomass growth data for natural forests globally. Net growth varies between 0.1 and 9.3 dry tons per hectare per year, with most natural forests producing between 1 and 4 tons, and with the global average at 2.3 tons. Average net growth for plantation forests varies between 0.4 and 25 tons, with most plantations producing between 5 and 15 tons, and with the global average at 9.1 tons.

As mentioned above, Smil estimates that the world average for wind, hydro and solar power production is 1 W/m^2, 3 W/m^2 and 5 W/m^2 respectively. In order to match these surface power densities, plantation yields must reach 17 t/ha, 50 t/ha and 83 t/ha for wind, hydro and solar respectively. This seems achievable for the tropical plantations mentioned above (yield 20-25 t/ha) and for elephant grasses, e.g., miscanthus (10-40 t/ha), and Napier (15-80 t/ha), but unlikely for forest and many other types of biomass crops. To match the world average for biofuels (0.3 W/m2), plantations need to produce 5 tons of dry mass per hectare per year. Instead of using the Van Zalk estimates for hydro, wind and solar (0.14, 1.84, and 6.63 W/m2 respectively), plantation yields must reach 2 t/ha, 31 t/ha and 111 t/ha in order to compete. Only the first two of those yields seem achievable, however.

Yields need to be adjusted to compensate for the amount of moisture in the biomass (evaporating moisture in order to reach the ignition point is usually wasted energy). The moisture of biomass straw or bales varies with the surrounding air humidity and eventual pre-drying measures, while pellets have a standardized (ISO-defined) moisture content of below 10% (wood pellets) and below 15% (other pellets). Likewise, for wind, hydro and solar, power line transmission losses amount to roughly 8% globally and should be accounted for. If biomass is to be utilized for electricity production rather than heat production, note that yields have to be roughly tripled in order to compete with wind, hydro and solar, as the current heat to electricity conversion efficiency is only 30-40%. When simply comparing surface

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power density without regard for cost, this low heat to electricity conversion efficiency effectively pushes at least solar parks out of reach of even the highest yielding biomass plantations, surface power density wise.

Carbon Neutrality for Forest Biomass

GHG emissions from wood pellet production and transport (Hanssen et al. 2017). IEA defines carbon neutrality and carbon negativity like so: "Carbon neutrality, or 'net zero,' means that any CO_2 released into the atmosphere from human activity is balanced by an equivalent amount being removed. Becoming carbon negative requires a company, sector or country to remove more CO_2 from the atmosphere than it emits." The actual carbon intensity of biomass varies with production techniques and transportation lengths. According to the EU, typical greenhouse gas emissions savings when replacing fossil fuels with wood pellets from forest residues is 77% when the transport distance is between 0 and 500 km, also 77% when the transport distance is between 500 and 2500 km, 75% when the distance is between 2500 and 10 000 km, and 69% when the distance is above 10 000 km. When stemwood is used, the savings change only marginally from between 70 and 77%. When wood industry residues are used, savings increase to between 79 and 87%. Likewise, Hanssen et al. argue that greenhouse gas emissions savings from wood pellets produced in the US southeast and shipped to the EU is between 65 and 75%, compared to fossil fuels. They estimate that average net GHG emissions from wood pellets imported from the USA and burnt for electricity in the EU amounts to approximately 0.2 kg CO_2 equivalents per kWh, while average emissions from the mix of fossil fuels that is currently burnt for electricity in the EU amounts to 0.67 kg CO_2-eq per kWh (see chart on the right). Ocean transport emissions amounts to 7% of the fossil fuel mix emissions per produced kWh (equivalent to 93 kg CO_2-eq/t vs 1288 kg CO_2/t). IEA Bioenergy estimates that in a scenario where Canadian wood pellets are used to totally replace coal use in a European coal plant, the specific emissions originating from ocean transport of the pellets, going from Vancouver to Rotterdam, amounts to approximately 2% of the plant's total coal-related emissions.

More CO2 from Wood Combustion than Coal Combustion

When combusted in combustion facilities with the same heat-to-electricity conversion efficiency, oven dry wood emits slightly less CO_2 per unit of heat produced, compared to oven dry coal. However, many biomass combustion facilities are relatively small and inefficient, compared to the typically much larger coal plants. Further, raw biomass can have higher moisture content compared to some common coal types. When this is the case, more of the wood's inherent energy must be spent solely on evaporating moisture, compared to the drier coal, which means that the amount of CO_2 emitted per unit of produced heat will be higher.

Coal Port in Russia

Some research groups (e.g. Chatham House) therefore argue that "[...] the use of woody biomass for energy will release higher levels of emissions than coal [...]." How much "extra" CO_2 that is released depends on local factors? Some research groups estimate relatively low extra emissions. IEA Bioenergy for instance estimates 10%.The bioenergy consultant group Future Metrics argue that wood pellets with 6% moisture content emits 22% less CO_2 for the same amount of produced heat, compared to sub-bituminous coal with 15% moisture, when both fuels are combusted in facilities with the same conversion efficiency (here 37%). Likewise, they state that "[...] dried wood at MC's [moisture content] below 20% have the same or less CO_2 emission per MMBTU [million British thermal units] as most coal. Wood pellets at under 10% MC result in less CO_2 emission than any coal under otherwise equal circumstances."(Moisture content in wood pellets is usually below 10%, as defined in the ISO standard 17225-2:2014.) However, when raw wood chips are used instead (45% moisture content), this wood biomass emits 9% more CO_2 than coal in general, for the same amount of produced heat. According to Indiana Center for Coal Technology Research, the coal type anthracite typically contains below 15% moisture, while bituminous contains 2-15%, sub-bituminous 10-45%, and lignite 30-60%. The most common coal type in Europe is lignite.

Other research groups estimate relatively high extra emissions. The Manomet Center for Conservation Sciences for instance, argues that for smaller scale utilities, with 32% conversion efficiency for coal, and 20-25% for biomass, coal emissions are 31% less than for wood chips. Assumed moisture content for wood chips is 45%, as above. The assumed moisture content for coal is not provided. The IPCC (Intergovernmental Panel on Climate Change) put their "extra CO_2" estimates for biomass at roughly 16% extra for wood over coal in general, somewhere in the middle compared to the estimates above. Is the extra CO_2 from biomass a problem? IPCC argues that focusing on gross emissions misses the point, what counts is the net effect of emissions and absorption taken together: "Estimating gross emissions only creates a distorted representation of human impacts on the land sector carbon cycle. While forest harvest for timber and fuel wood and land-use change (deforestation) contribute to gross emissions, to quantify impacts on the atmosphere, it is necessary to estimate net emissions, that is, the balance of gross emissions and gross removals of carbon from the atmosphere through forest regrowth [...]."

Wood Pellet Mill in Germany

IEA Bioenergy provides a similar argument: "It is incorrect to determine the climate change effect of using biomass for energy by comparing GHG emissions at the point of combustion. "They also argue that "[...] the misplaced focus on emissions at the point of combustion blurs the distinction between fossil and biogenic

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carbon, and it prevents proper evaluation of how displacement of fossil fuels with biomass affects the development of atmospheric GHG concentrations." IEA Bioenergy concludes that the additional CO_2 from biomass "[...] is irrelevant if the biomass is derived from sustainably managed forests." What are sustainable managed forests? The IPCC writes: "Sustainable Forest Management (SFM) is defined as 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems' [...]. This SFM definition was developed by the Ministerial Conference on the Protection of Forests in Europe and has since been adopted by the Food and Agriculture Organization [of the United Nations (FAO)]." Further, IPCC writes: "Sustainable Forest management can prevent deforestation, maintain and enhance carbon sinks and can contribute towards GHG emissions-reduction goals. Sustainable forest management generates socio-economic benefits, and provides fiber, timber and biomass to meet society's growing needs."

In the context of CO_2 mitigation, the key measure regarding sustainability is the size of the forest carbon stock. In a research paper for FAO, Reid Miner writes: "The core objective of all sustainable management programs in production forests is to achieve a long-term balance between harvesting and regrowth. [...] [T]he practical effect of maintaining a balance between harvesting and regrowth is to keep long-term carbon stocks stable in managed forests." Is the forest carbon stock stable? Globally, the forest carbon stock has decreased 0.9% and tree cover 4.2% between 1990 and 2020, according to FAO. IPCC states that there is disagreement about whether the global forest is shrinking or not, and quote research indicating that tree cover has increased 7.1% between 1982 and 2016. IPCC writes: "While above-ground biomass carbon stocks are estimated to be declining in the tropics, they are increasing globally due to increasing stocks in temperate and boreal forests [...]."

Forest Protection

Some research groups seem to want more than "just" sustainably managed forests, they want to realize the forests full carbon storage potential. For instance, EASAC writes: "There is a real danger that present policy over-emphasizes the use of forests in energy production instead of increasing forest stocks for carbon storage." Further, they argue that "[...] it is the older, longer-rotation forests and protected old-growth forests that exhibit the highest carbon stocks." Chatham House argues that old trees have a very high carbon absorption, and that felling old trees means that this large potential for future carbon absorption is lost. In addition they argue that there is a loss of soil carbon due to the harvest operations. Research show that old trees absorb more CO_2 than young trees, because of the larger leaf area in full grown trees. However, the old forest (as a whole) will eventually stop absorbing CO_2 because CO_2 emissions from dead trees cancel out the remaining living trees' CO_2 absorption. The old forest (or forest stands) are also vulnerable for natural disturbances that produces CO_2. The IPCC writes: "When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, the annual removal of CO_2 from the atmosphere declines towards zero, while carbon stocks can be maintained (high confidence). However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by disturbances such as flood, drought, fire, or pest outbreaks, or future poor management (high confidence)."Summing up, IPCC writes that "[...] landscapes with older forests have accumulated more carbon but their sink strength is diminishing, while landscapes with younger forests contain less carbon but they are removing CO_2 from the atmosphere at a much higher rate [...]."Regarding soil carbon, the IPCC writes: "Recent studies indicate, that effects of forest management actions on soil C [carbon] stocks can be difficult to quantify and reported effects have been variable and even contradictory (see Box 4.3a)." Because the "current scientific basis is not sufficient", the IPCC will not currently provide soil carbon emission factors for forest management.

Regarding the net climate effect of conversion from natural to managed forests, the IPCC argues that it can swing both ways: "SFM [sustainable forest management] applied at the landscape scale to existing unmanaged forests can first reduce average forest carbon stocks and subsequently increase the rate at which CO_2 is removed from the atmosphere, because net ecosystem production of forest stands is highest in intermediate stand ages (Kurz et al. 2013; Volkova et al. 2018; Tang et al. 2014). The net impact on the atmosphere depends on the magnitude of the reduction in carbon stocks, the fate of the harvested biomass (i.e. use in short - or long-lived products and for bioenergy, and therefore displacement of emissions associated with GHG-intensive building materials and fossil fuels), and the rate of regrowth. Thus, the impacts of SFM on one indicator (e.g., past reduction in carbon stocks in the forested landscape) can be negative, while those on another indicator (e.g., current forest productivity and rate of CO_2 removal from the atmosphere, avoided fossil fuel emissions) can be positive. Sustainably managed forest landscapes can have a lower biomass carbon density than unmanaged forest, but the younger forests can have a higher growth rate, and therefore contribute stronger carbon sinks than older forests (Trofymow et al. 2008; Volkova et al. 2018; Poorter et al. 2016)."

In other words, there is a tradeoff between the benefits of having a maximized forest carbon stock, not absorbing any more carbon, and the benefits of having a portion of that carbon stock "unlocked", and instead working as a renewable fossil fuel replacement tool. When put to work, this carbon is constantly replacing carbon in fossil fuels used in for instance heat production and baseload electricity production - sectors where it

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is uneconomical or impossible to use intermittent power sources like wind or solar. Being a renewable carbon source, the unlocked portion keeps cycling back and forth between forests and forest products like lumber and wood pellets. For each cycle it replaces more and more of the fossil-based alternatives, e.g., cement and coal. FAO researcher Reid Miner argues that the "competition" between locked-away and unlocked forest carbon is won by the unlocked carbon: "In the long term, using sustainably produced forest biomass as a substitute for carbon-intensive products and fossil fuels provides greater permanent reductions in atmospheric CO_2 than preservation does."

Plantation Forest in Hawaii

Summing up the above, IEA Bioenergy writes: "As the IPCC has pointed out in several reports, forests managed for producing sawn timber, bioenergy and other wood products can make a greater contribution to climate change mitigation than forests managed for conservation alone, for three reasons. First, the sink strength diminishes as conservation forests approach maturity. Second, wood products displace GHG-intensive materials and fossil fuels. Third, carbon in forests is vulnerable to loss through natural events such as insect infestations or wildfires, as recently seen in many parts of the world including Australia and California. Managing forests can help to increase the total amount of carbon sequestered in the forest and wood products carbon pools, reduce the risk of loss of sequestered carbon, and reduce fossil fuel use." The IPCC further suggest that the possibility to make a living out of forestry incentivize sustainable forestry practices: "[...] SFM [sustainable forest management] aimed at providing timber, fiber, biomass and non-timber resources can provide long-term livelihood for communities, reduce the risk of forest conversion to non-forest uses (settlement, crops, etc.), and maintain land productivity, thus reducing the risks of land degradation [...]." Further: "By providing long-term livelihoods for communities, sustainable forest management can reduce the extent of forest conversion to non-forest uses (e.g., cropland or settlements) (high confidence)."

The National Association of University Forest Resources Programs agrees: "Research demonstrates that demand for wood helps keep land in forest and incentivizes investments in new and more productive forests, all of which have significant carbon benefits. [...] Failing to consider the effects of markets and investment on carbon impacts can distort the characterization of carbon impacts from forest biomass energy." Favero et al. focus on the potential future increase in demand and argues: "Increased bioenergy demand increases forest carbon stocks thanks to afforestation activities and more intensive management relative to a no-bioenergy case [...] higher biomass demand will increase the value of timberland, incentivize additional investment in forest management and afforestation, and result in greater forest carbon stocks over time". Possibly strengthening the arguments above, data from FAO show that most wood pellets are produced in regions dominated by sustainably managed forests. Europe (including Russia) produced 54% of the world's wood pellets in 2019, and the forest carbon stock in this area increased from 158.7 to 172.4 Gt between 1990 and 2020. Likewise, North America produced 29% of the world's pellets in 2019, while forest carbon stock increased from 136.6 to 140 Gt in the same period. Carbon stock decreased from 94.3 to 80.9 Gt in Africa, 45.8 to 41.5 Gt in South and Southeast Asia combined, 33.4 to 33.1 Gt in Oceania, 5 to 4.1 Gt in Central America, and from 161.8 to 144.8 Gt in South America. Wood pellet production in these areas combined was 13.2% in 2019. Chatham House answers the above argument like so: "Forest carbon stock levels may stay the same or increase for reasons entirely unconnected with use for energy."

Carbon Payback Time

Some research groups still argue that even if the European and North American forest carbon stock is increasing, it simply takes too long for harvested trees to grow back. EASAC for instance argues that since the world is on track to pass by the agreed target of 1.5 degrees temperature increase already in a decade or so, CO_2 from burnt round wood, which resides in the atmosphere for many decades before being re-absorbed, make it harder to achieve this goal. They therefore suggest that the EU should adjust its sustainability criteria so that only renewable energy with carbon payback times of less than 10 years is defined as sustainable, for instance wind, solar, biomass from wood residues and tree thinning that would otherwise be burnt or decompose relatively fast, and biomass from short rotation coppicing (SRC). Chatham House agrees, and in addition argues that there could be tipping points along the temperature scale where warming accelerates. Chatham House also argues that various types of round wood (mostly pulpwood) is used in pellet production in the USA. Future Metrics argues that it makes no sense for foresters to sell sawlog-quality round wood to pellet mills, since they get a lot more money for this part of the tree from sawmills. Foresters make 80-90% of their income from sawlog-quality round wood (the lower and thicker straight part of the tree stem), and only 10-15% from pulpwood, defined as a.) The middle part of mature trees (the thinner part of the stem that often bends a little, plus branches) and b.) Tree thinning (small, young trees cleared away for increased productivity of the whole forest stand.) This low-value biomass is mainly sold to pulp mills for paper production, but in some cases also to pellet mills for pellet production. Pellets are typically made from sawmill residues in areas where there are sawmills, and from pulpwood in areas without sawmills.

Chatham House further argue that almost all available sawmill residue is already being utilized for pellet production, so there is no room for expansion. For the bioenergy sector to significantly expand in the future, more of the harvested pulpwood must go to pellet mills. However, the harvest of pulpwood (tree thinning) removes the possibility for these trees to grow old and therefore maximize their carbon holding capacity. Compared to pulpwood,

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sawmill residues have lower net emissions: “Some types of biomass feedstock can be carbon-neutral, at least over a period of a few years, including in particular sawmill residues. These are wastes from other forest operations that imply no additional harvesting, and if otherwise burnt as waste or left to rot would release carbon to the atmosphere in any case.” An important presupposition for the “tree regrowth is too slow” argument is the view that carbon accounting should start when trees from particular, harvested forest stands are combusted, and not when the trees in those stands start to grow.It is within this frame of thought it becomes possible to argue that the combustion event creates a carbon debt that has to be repaid through regrowth of the harvested stands. When instead assuming that carbon accounting should start when the trees start to grow, it becomes impossible to argue that the emitted carbon constitutes debt. Future Metrics for instance argue that the harvested carbon is not a debt but “[...] a benefit that was earned by 30 years of management and growth [...].” Other researchers however argue back that “[...] what is important to climate policy is understanding the difference in future atmospheric GHG levels, with and without switching to woody biomass energy. Prior growth of the forest is irrelevant to the policy question [...].”Undermining forester’s income may backfire however, see above for IPCC’s argument that forests which provide long-term livelihood for communities reduce the risk of forest conversion to non-forest uses.

Some researchers limit their carbon accounting to particular forest stands, ignoring the carbon absorption that takes place in the rest of the forest. In opposition to this single forest stand accounting practice, other researchers include the whole forest when doing their carbon accounting. Future Metrics for instance argue that the whole forest continually absorb CO_2 and therefore immediately compensate for the relatively small amounts of biomass that is combusted in biomass plants from day to day. Likewise, IEA Bioenergy criticizes EASAC for ignoring the carbon absorption of forests as a whole, noting that there is no net loss of carbon if annual harvest do not exceed the forest’s annual growth. IPCC argue along similar lines: “While individual stands in a forest may be either sources or sinks, the forest carbon balance is determined by the sum of the net balance of all stands. “IPCC also state that the only universally applicable approach to carbon accounting is the one that accounts for both carbon emissions and carbon removals (absorption) for the whole landscape. When the total is calculated, natural disturbances like fires and insect infestations are subtracted, and what remains is the human influence. In this way, the whole landscape works as a proxy for calculating specifically human GHG emissions: “In the AFOLU [Agriculture, Forestry and Other Land Use] sector, the management of land is used as the best approximation of human influence and thus, estimates of emissions and removals on managed land are used as a proxy for anthropogenic emissions and removals on the basis that the preponderance of anthropogenic effects occurs on managed lands. This allows for consistency, comparability, and transparency in estimation. Referred to as the Managed Land Proxy (MLP), this approach is currently recognized by the IPCC as the only universally applicable approach to estimating anthropogenic emissions and removals in the AFOLU sector (IPCC 2006, IPCC 2010).”

Hanssen et al. notes that when comparing continued wood pellet production to a potential policy change where the forest instead is protected, most researchers estimate a 20-50-year carbon parity (payback) time range for the burnt wood pellets. But when instead comparing continued pellet production to the more realistic alternative scenarios of 1.) Instead using all harvested biomass to produce paper, pulp or wood panels, 2.) quitting the thinning practice altogether (leaving the small trees alone, realizing more of their growth potential but at the same time reduce the growth potential of the bigger trees), and 3.) leaving the forest residue alone, so it is decomposed in the forest over time, rather than being burned almost immediately in power plants, the result is that carbon payback (parity) times for wood pellets drop to 0-21 years in all demand scenarios (see chart on the right). The estimate is based on the landscape rather than the individual forest stand carbon accounting practice.

Short-Term Vs Long-Term Climate Benefits

Researchers from both sides agree that in the short term, emissions might rise compared to a no-bioenergy scenario. IPCC for instance states that forest carbon emission avoidance strategies always give a short-term mitigation benefit, but argue that the long-term benefits from sustainable forestry activities are larger: Relative to a baseline, the largest short-term gains are always achieved through mitigation activities aimed at emission avoidance [...]. But once an emission has been avoided, carbon stocks on that forest will merely be maintained or increased slightly. [...] In the long term, sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual yield of timber, fibre, or energy from the forest, will generate the largest sustained mitigation benefit. Similarly, addressing the issue of climate consequences for modern bioenergy in general, IPCC states: “Life-cycle GHG emissions of modern bioenergy alternatives are usually lower than those for fossil fuels [...].”Consequently, most of IPCC’s GHG mitigation pathways include substantial deployment of bioenergy technologies. Limited or no bioenergy pathways lead to increased climate change or shifting bioenergy’s mitigation load to other sectors. In addition, mitigation costs increase.

IEA Bioenergy also prioritize the long-term benefits: “Concern about near-term emissions is not a strong argument for stopping investments that contribute to net emissions reduction beyond

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2030, be it the scaling-up of battery manufacturing to support electrification of car fleets, the development of rail infrastructure, or the development of biomass supply systems and innovation to provide bio-based products displacing fossil fuels, cement and other GHG-intensive products. We assert that it is critical to focus on the global emissions trajectory required to achieve climate stabilization, acknowledging possible trade-offs between short- and long-term emissions reduction objectives. A strong focus on short-term carbon balances may result in decisions that make long-term climate objectives more difficult to meet. "IEA states that "[...] the current rate of bioenergy deployment is well below the levels required in low carbon scenarios. Accelerated deployment is urgently needed to ramp up the contribution of sustainable bioenergy across all sectors [...]."They recommend a five-fold increase in sustainable bioenergy feedstock supply.

The National Association of University Forest Resources Programs agrees, and argues that a timeframe of 100 years is recommended in order to produce a realistic assessment of cumulative emissions: "Comparisons between forest biomass emissions and fossil fuel emissions at the time of combustion and for short periods thereafter do not account for long term carbon accumulation in the atmosphere and can significantly distort or ignore comparative carbon impacts over time. [...] The most common timeframe for measuring the impacts of greenhouse gases is 100 years, as illustrated by the widespread use of 100-year global warming potentials. This timeframe provides a more accurate accounting of cumulative emissions than shorter intervals."

Carbon Neutrality for Energy Crops

Like with forests, it is the total amount of CO_2 equivalent emissions and absorption together that determines if an energy crop project is carbon positive, carbon neutral or carbon negative. If emissions during agriculture, processing, transport and combustion are higher than what is absorbed, both above and below ground during crop growth, the project is carbon positive. Likewise, if total absorption over time is higher than total emissions, the project is carbon negative. Many first-generation biomass projects are carbon positive (have a positive GHG life cycle cost), especially if emissions caused by direct or indirect land use change are included in the GHG cost calculation. The IPCC states that indirect land use change effects are highly uncertain, though. Some projects have higher total GHG emissions than some fossil based alternatives. Transport fuels might be worse than solid fuels in this regard. During plant growth, ranging from a few months to decades, CO_2 is re-absorbed by new plants. While regular forest stands have carbon rotation times spanning many decades, short rotation forestry (SRF) stands have a rotation time of 8-20 years, and short rotation coppicing (SRC) stands 2-4 years. Perennial grasses like miscanthus or napier grass have a rotation time of 4-12 months. In addition to absorbing CO2 and storing it as carbon in its above-ground tissue, biomass crops also sequester carbon below ground, in roots and soil. Typically, perennial crops sequester more carbon than annual crops because the root buildup is allowed to continue undisturbed over many years. Also, perennial crops avoid the yearly tillage procedures (plowing, digging) associated with growing annual crops. Tilling helps the soil microbe populations to decompose the available carbon, producing CO_2.

Soil organic carbon has been observed to be greater below switchgrass crops than under cultivated cropland, especially at depths below 30 cm (12 in).A large meta-study of 138 individual studies, done by Harris et al., revealed that second generation perennial grasses (miscanthus and switchgrass) planted on arable land on average store five times more carbon in the ground than short rotation coppice or short rotation forestry plantations (poplar and willow). McCalmont et al. compared a number of individual European reports on Miscanthus x giganteus carbon sequestration, and found accumulation rates ranging from 0.42 to 3.8 tons per hectare per year, with a mean accumulation rate of 1.84 tonne (0.74 tons per acre per year), or 25% of total harvested carbon per year. When used as fuel, greenhouse gas (GHG) savings are large-even without considering the GHG effect of carbon sequestration, miscanthus fuel has a GHG cost of 0.4-1.6 grams CO_2-equivalents per megajoule, compared to 33 grams for coal, 22 for liquefied natural gas, 16 for North Sea gas, and 4 for wood chips imported to Britain from the USA.

Likewise, Whitaker et al. argue that a miscanthus crop with a yield of 10 tons per hectare per year sequesters so much carbon below ground that the crop more than compensates for both agriculture, processing and transport emissions. The chart on the right displays two CO_2 negative miscanthus production pathways, and two CO_2 positive poplar production pathways, represented in gram CO_2-equivalents per megajoule. The bars are sequential and move up and down as atmospheric CO_2 is estimated to increase and decrease. The grey/blue bars represent agriculture, processing and transport related emissions, the green bars represents soil carbon change, and the yellow diamonds represent total final emissions. Relationship between above-ground yield (diagonal lines), soil organic carbon (X axis), and soil's potential for successful/unsuccessful carbon sequestration (Y axis). Basically, the higher the yield, the more land is usable as a GHG mitigation tool (including relatively carbon-rich land). Successful sequestration depends on planting sites, as the best soils for sequestration are those that are currently low in carbon. The varied results displayed in the graph highlights this fact. For the UK, successful sequestration is expected for arable land over most of England and Wales, with unsuccessful sequestration expected in parts of Scotland, due to already carbon rich soils (existing woodland) plus lower yields. Soils already rich in carbon include peatland and mature forest. Milner et al. further argue that the most successful carbon sequestration in the UK takes place below improved grassland. However, Harris et al. notes that since the carbon content of grasslands vary considerably, so does the success rate of land use changes from grasslands to perennial.

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The bottom graphic displays the estimated yield necessary to achieve CO_2 negativity for different levels of existing soil carbon saturation. The higher the yield, the more likely CO_2 negativity becomes.

Environmental Impact

Biodiversity and Pollution

Gasparatos et al. reviews current research about the side effects of all kinds of renewable energy production, and argue that in general there is a conflict between "[...] site/local-specific conservation goals and national energy policy/climate change mitigation priorities [...]." The authors argue that for instance biodiversity should be seen as an equally "[...] legitimate goal of the Green Economy as curbing GHG emissions." Oil palm and sugar cane are examples of crops that have been linked to reduced biodiversity. Other problems are pollution of soil and water from fertiliser/pesticide use, and emission of ambient air pollutants, mainly from open field burning of residues. The authors note that the extent of the environmental impact "[...] varies considerably between different biomass energy options." For impact mitigation, they recommend "[...] adopting environmentally-friendly bioenergy production practices, for instance limiting the expansion of monoculture plantations, adopting wildlife-friendly production practices, installing pollution control mechanisms, and undertaking continuous landscape monitoring." They also recommend "[...] multi-functional bioenergy landscapes." Other measures include "[...] careful feedstock selection, as different feedstocks can have radically different environmental trade-offs. For example, US studies have demonstrated that 2nd generation feedstocks grown in unfertilized land could provide benefits to biodiversity when compared to monocultural annual crops such as maize and soy that make extensive use of agrochemicals." Miscanthus and switchgrass are examples of such crops.

Air Quality

The traditional use of wood in cook stoves and open fires produces pollutants, which can lead to severe health and environmental consequences. However, a shift to modern bioenergy contributes to improved livelihoods and can reduce land degradation and impacts on ecosystem services. According to the IPCC, there is strong evidence that modern bioenergy has "large positive impacts" on air quality. When combusted in industrial facilities, most of the pollutants originating from woody biomass reduce by 97-99%, compared to open burning. A study of the giant brown haze that periodically covers large areas in South Asia determined that two thirds of it had been principally produced by residential cooking and agricultural burning, and one third by fossil-fuel burning.

Benefits of a Robust Bioenergy Industry

Abundant and renewable bioenergy can contribute to a more secure, sustainable, and economically sound future by:

- Supplying domestic clean energy sources
- Reducing U.S. dependence on foreign oil
- Generating U.S. jobs
- Revitalizing rural economies.

The U.S. Department of Energy's 2016 billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy concluded that the United States has the potential to produce 1 billion dry tons of non-food biomass resources annually by 2040 and still meet demands for food, feed, and fiber. One billion tons of biomass could:

- Produce up to 50 billion gallons of biofuels
- Yield 50 billion pounds of bio-based chemicals and bioproducts
- Generate 85 billion kilowatt-hours of electricity to power 7 million households
- Contribute 1.1 million jobs to the U.S. economy
- Keep $260 billion in the United States.

Biomass is one type of renewable resource that can be converted into liquid fuels-known as biofuels-for transportation. Biofuels include cellulosic ethanol, biodiesel, and renewable hydrocarbon "drop-in" fuels. The two most common types of biofuels in use today are ethanol and biodiesel. Biofuels can be used in airplanes and most vehicles that are on the road. Renewable transportation fuels that are functionally equivalent to petroleum fuels lower the carbon intensity of our vehicles and airplanes.

Biopower: Energy for Heat and Electricity

Bio-power technologies convert renewable biomass fuels into heat and electricity using processes like those used with fossil fuels. There are three ways to harvest the energy stored in biomass to produce bio-power: burning, bacterial decay, and conversion to a gas or liquid fuel. Bio-power can offset the need for carbon fuels burned in power plants, thus lowering the carbon intensity of electricity generation. Unlike some forms of intermittent renewable energy, bio-power can increase the flexibility of electricity generation and enhance the reliability of the electric grid.

Bioproducts: Everyday Commodities Made from Biomass

Biomass is a versatile energy resource, much like petroleum. Beyond converting biomass to biofuels for vehicle use, it can also serve as a renewable alternative to fossil fuels in the manufacturing of bioproducts such as plastics, lubricants, industrial chemicals,

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and many other products currently derived from petroleum or natural gas. Mimicking the existing petroleum refinery model, integrated biorefineries can produce bioproducts alongside biofuels. This co-production strategy offers a more efficient, cost-effective, and integrated approach to the use of U.S. biomass resources. Revenue generated from bioproducts also offers added value, improving the economics of biorefinery operations and creating more cost-competitive biofuels.

Why is Renewable Energy Important?

We're now facing unprecedented heatwaves, polluted air, and unbelievable health issues caused by fossil fuels. In Addition to this issue, fossil fuels are about to run out if we continue to burn them uncontrollably. Renewable energy sources are our best chance to stop the current trend and make the world a better place to live. Therefore, governments are thinking of using renewable sources of energy to generate electric power. As a result, there is increasing usage of renewable energy for generating electricity in all countries. For example, the share of renewable energy in global electricity generation was increased to 29% in 2020. This is a success compared with a 27% share in electricity generation in 2019. Some advanced countries such as the UK have aimed for 100% renewable cities by 2050. Currently, around 43% of the UK's electricity is generated by renewables. In spite of many obstacles in the way towards 100% renewable energy, there are promising advantages to using renewable technologies. Overall, the advantages of using renewable energy sources outweigh the disadvantages. Although the initial cost of establishing a network of renewable technologies might be higher, over time, the expenses will be offset. Considering the lateral influencers of using renewable energy, postponing the process of shifting toward 100% renewable is not a wise course of action. Wind, geothermal, solar, hydro, tidal, hydrogen, and other renewable technologies are a widely popular source of energy throughout the world today. Countries, corporations, and individuals are adopting renewables for a number of great benefits. In this article, we'll dive into some of the advantages and disadvantages of renewable energy Table 2.

Table 2: Advantages and disadvantages of renewable energy.

Advantages	Disadvantages
Renewable energy won't run out	Renewable energy has high upfront costs
Renewable energy has lower maintenance requirements	Renewable energy is intermittent
Renewables save money	Renewables have limited storage capabilities
Renewable energy has numerous environmental benefits	Renewable energy sources have geographic limitations
Renewables lower reliance on foreign energy sources	Renewables aren't always 100% carbon-free
Renewable energy leads to cleaner water and air	
Renewable energy creates jobs	
Renewable energy can cut down on waste	

Advantages of Renewable Energy

Renewable energy has multiple advantages over fossil fuels. Here are some of the top benefits of going green:

- Renewable energy won't run out
- Renewable energy has lower maintenance requirements
- Renewables save money
- Renewable energy has numerous environmental benefits
- Renewables lower reliance on foreign energy sources
- Renewable energy leads to cleaner water and air
- Renewable energy creates jobs
- Renewable energy can cut down on waste

Renewable Energy Won't Run Out

Renewable energy technologies use resources straight from the environment to generate power. These energy sources include sunshine, wind, tides, and biomass, to name some of the more popular options. Renewable resources won't run out, which cannot be said for many types of fossil fuels - as we use fossil fuel resources, they will be increasingly difficult to obtain, likely driving up both the cost and environmental impact of extraction.

Maintenance Requirements are Lower for Renewable Energy

In most cases, renewable energy technologies require less overall maintenance than generators that use traditional fuel sources. This is because generating technology like solar panels and wind turbines either have few or no moving parts or don't rely on flammable, combustible fuel sources to operate. Fewer

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maintenance requirements translate to more time and money saved.

Renewables Save Money

Using renewable energy can help you save money in the long term. Not only will you save on maintenance costs, but on operating costs as well. When you're using a technology that generates power from the sun, wind, steam, or natural processes, you don't have to pay to refuel. The amount of money you will save using renewable energy can vary depending on a number of factors, including the technology itself. In most cases, transitioning to renewable energy means anywhere from hundreds to thousands of dollars in savings-find out how much you can save by switching to solar energy.

Renewable Energy has Numerous Environmental Benefits

Renewable energy generation sources emit little to no greenhouse gases or pollutants into the air. This means a smaller carbon footprint and an overall positive impact on the natural environment. During the combustion process, fossil fuels emit high amounts of greenhouse gases, which have been proven to exacerbate the rise of global temperatures and frequency of extreme weather events. The use of fossil fuels not only emits greenhouse gases but other harmful pollutants as well that lead to respiratory and cardiac health issues. With renewable energy, you're helping decrease the prevalence of these pollutants and contributing to an overall healthier atmosphere.

Renewables Lower Reliance on Foreign Energy Sources

With renewable energy technologies, you can produce energy locally. The more renewable energy you're using for your power needs, the less you'll rely on imported energy, and the more you'll contribute to U.S. energy independence as a whole. Renewable energy sources can help us minimize the geo-political risks associated with fossil fuels, from trade disputes to political instability to pricing wars, all of which are often rooted in access to oil.

Renewable Energy Leads to Cleaner Water and Air

When you burn fossil fuels to generate electricity, it contaminates the air and water we use. For example, coal power stations release high volumes of carbon dioxide and nitrous oxide, as well as harmful toxins like mercury, lead, and sulfur dioxide. Health problems from ingesting these elements can be dangerous, and even fatal in some cases. Investing in renewable energy is a great way to work against these risks, as renewables have a far lower negative impact on our air and water. The use of fossil fuels not only emits greenhouse gases but other harmful pollutants as well that lead to respiratory and cardiac health issues. With renewable energy, you're helping decrease the prevalence of these pollutants and contributing to an overall healthier environment.

Renewable Energy Creates New Jobs

While the U.S. shifts its focus to combat global warming, we're setting ambitious carbon-reduction goals that require labor to get the job done. Today, the renewable energy sector employs three times as many people as fossil fuels do in the U.S. That number is expected to rise over the next few years-and as a plus, these jobs tend to pay above average wages, making it a very attractive career option and an overall economic boom.

Renewable Energy Can Help Solve Our Waste Problem

Specifically, biomass energy can offer a big benefit in this way. Biomass generators consume used organic products like vegetable oil, corn and soybean byproducts, and even algae to generate energy. Because of this, using biomass as an energy source can reduce the amount of waste that goes into landfills, which helps cut down on carbon emissions and environmental contamination.

Disadvantages of Renewable Energy

Renewable energy has many benefits, but it's not always sunny when it comes to renewable energy. Here are some disadvantages to using renewables over traditional fuel sources:

- Renewable energy has high upfront costs
- Renewable energy is intermittent
- Renewables have storage capabilities
- Renewable energy sources have geographic limitations
- Renewables aren't always 100% carbon-free

Higher Upfront Cost

While you can save money by using renewable energy, the technologies are typically more expensive upfront than traditional energy generators. To combat this, there are often financial incentives, such as tax credits and rebates, available to help alleviate your initial costs of renewable technology.

Intermittency

Though renewable energy resources are available around the world, many of these resources aren't available 24/7, year-round. Some days may be windier than others, the sun doesn't shine at night, and droughts may occur for periods of time. There can be unpredictable weather events that disrupt these technologies. Fossil fuels are not intermittent and can be turned on or off at any given time. Wondering if you should make the switch to renewables? Find out if an energy source like solar power is a good fit for you.

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Storage Capabilities

Because of the intermittent of some renewable energy sources, there's a high need for energy storage. While there are storage technologies available today, they can be expensive, especially for large-scale renewable energy plants. It's worth noting that energy storage capacity is growing as the technology progresses, and batteries are becoming more affordable as time goes on.

Geographic Limitations

The United States has a diverse geography with varying climates, topographies, vegetation, and more. This creates a beautiful melting pot of landscapes but also means that there are some geographies that are more suitable for renewable technologies than others. For example, a large farm with open space may be a great place for a residential wind turbine or a solar energy system, while a townhome in a city covered in shade from taller buildings wouldn't be able to reap the benefits of either technology on their property. If your property isn't suitable for personal renewable energy technology, there are other options. If you're interested in solar but don't have a sunny property, you can often still benefit from renewable energy by purchasing green power or enrolling in a community solar option.

Not 100% Carbon-Free

Although solar panels and other forms of renewable energy drastically reduce carbon emissions, these resources aren't always completely clean. The manufacturing, transportation, and installation of renewable energy, like wind turbines, can create a carbon footprint since they're usually produced in factories that are powered by fossil fuels -not to mention the diesel and gasoline needed to fuel the transport trucks. As the U.S. becomes more and more electrified - from solar panels on factories, to electric transport trucks - carbon emissions associated with solar will continue to decrease.

Supply Chain Constraints

Renewables must have an effective distribution network created to transfer the energy where it's needed on a large scale. These networks need non-renewable energies to be generated, which offsets the benefits of renewable energy for a bit until it's paid back. Additionally, politics can play a factor in installing renewable energy if it's not a priority among local governments.

Renewable Energy has more Benefits than Drawbacks

When it comes to renewable energy, the positives outweigh the negatives. Transitioning to renewables on a personal, corporate, or governmental level will not only help you save money but also promote a cleaner, healthier environment for the future.

Installing solar panels is one of the easiest ways to go green. By signing up on the Energy Sage Solar Marketplace, you can compare multiple quotes from local, pre-screened installers to see what solar costs and savings for your property. The quotes will also include estimates of the amount of carbon dioxide emissions you will offset over 20 years, and what this equates to in both trees planted and gallons of gasoline burned. Geothermal power is considered to be renewable because any projected heat extraction is small compared to the Earth's heat content. The Earth has an internal heat content of 1031 joules (3·1015 TWh), approximately 100 billion times the 2010 worldwide annual energy consumption. About 20% of this is residual heat from planetary accretion; the remainder is attributed to past and current radioactive decay of naturally occurring isotopes. For example, a 5275 m deep borehole in United Downs Deep Geothermal Power Project in Cornwall, England, found granite with very high thorium content, whose radioactive decay is believed to power the high temperature of the rock.

Natural heat flows are not in equilibrium, and the planet is slowly cooling down on geologic timescales. Human extraction taps a minute fraction of the natural outflow, often without accelerating it. According to most official descriptions of geothermal energy use, it is currently called renewable and sustainable because it returns an equal volume of water to the area that the heat extraction takes place, but at a somewhat lower temperature. For instance, the water leaving the ground is 300 degrees, and the water returning is 200 degrees, the energy obtained is the difference in heat that is extracted. Current research estimates of impact on the heat loss from the Earth's core are based on a studies done up through 2012. However, if household and industrial uses of this energy source were to expand dramatically over coming years, based on a diminishing fossil fuel supply and a growing world population that is rapidly industrializing requiring additional energy sources, then the estimates on the impact on the Earth's cooling rate would need to be re-evaluated. Geothermal power is also considered to be sustainable thanks to its power to sustain the Earth's intricate ecosystems. By using geothermal sources of energy present generations of humans will not endanger the capability of future generations to use their own resources to the same amount that those energy sources are presently used. Further, due to its low emissions geothermal energy is considered to have excellent potential for mitigation of global warming.

Even though geothermal power is globally sustainable, extraction must still be monitored to avoid local depletion. Over the course of decades, individual wells draw down local temperatures and water levels until a new equilibrium is reached with natural flows. The three oldest sites, at Larderello, Wairakei, and the Geysers have experienced reduced output because of local depletion. Heat and water, in uncertain proportions, were extracted faster than they were replenished. If production is reduced and water is reinjected, these wells could theoretically recover their full potential. Such mitigation strategies have already been implemented at some sites. The long-term sustainability of geothermal energy has been demonstrated at the Lardarello field

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in Italy since 1913, at the Wairakei field in New Zealand since 1958, and at The Geysers field in California since 1960.

Falling electricity production may be boosted through drilling additional supply boreholes, as at Poihipi and Ohaaki. The Wairakei power station has been running much longer, with its first unit commissioned in November 1958, and it attained its peak generation of 173 MW in 1965, but already the supply of high-pressure steam was faltering, in 1982 being derated to intermediate pressure and the station managing 157 MW. Around the start of the 21st century it was managing about 150 MW, then in 2005 two 8 MW isopentane systems were added, boosting the station's output by about 14 MW. Detailed data are unavailable, being lost due to re-organisations. One such re-organisation in 1996 causes the absence of early data for Poihipi (started 1996), and the gap in 1996/7 for Wairakei and Ohaaki; half-hourly data for Ohaaki's first few months of operation are also missing, as well as for most of Wairakei's history.

Sustainable Development

Sustainable development is an organizing principle for meeting human development goals while also sustaining the ability of natural systems to provide the natural resources and ecosystem services on which the economy and society depend. The desired result is a state of society where living conditions and resources are used to continue to meet human needs without undermining the integrity and stability of the natural system. Sustainable development can be defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. While the modern concept of sustainable development is derived mostly from the 1987 Brundtland Report, it is also rooted in earlier ideas about sustainable forest management and 20th-century environmental concerns. As the concept of sustainable development developed, it has shifted its focus more towards economic development, social development and environmental protection for future generations. The UN-level Sustainable Development Goals (2015-2030) address global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

Definition

Sustainable development can be defined as the practice of maintaining productivity by replacing used resources with resources of equal or greater value without degrading or endangering natural biotic systems. Sustainable development binds together concern for the carrying capacity of natural systems with the social, political and economic challenges faced by humanity. Sustainability science is the study of the concepts of sustainable development and environmental science. There is an emphasis on the present generations' responsibility to regenerate, maintain and improve planetary resources for use by future generations.

Development of the Concept

Origins

Sustainable development has its roots in ideas about sustainable forest management, which were developed in Europe during the 17th and 18th centuries. In response to a growing awareness of the depletion of timber resources in England, John Evelyn argued, in his 1662 essay Sylva that "sowing and planting of trees had to be regarded as a national duty of every landowner, in order to stop the destructive over-exploitation of natural resources." In 1713, Hans Carl von Carlowitz, a senior mining administrator in the service of Elector Frederick Augustus I of Saxony published Sylvicultura economics, a 400-page work on forestry. Building upon the ideas of Evelyn and French minister Jean-Baptiste Colbert, von Carlowitz developed the concept of managing forests for sustained yield. His work influenced others, including Alexander von Humboldt and Georg Ludwig Hartig, eventually leading to the development of the science of forestry. This, in turn, influenced people like Gifford Pinchot, the first head of the US Forest Service, whose approach to forest management was driven by the idea of wise use of resources, and Aldo Leopold whose land ethic was influential in the development of the environmental movement in the 1960s. Following the publication of Rachel Carson's Silent Spring in 1962, the developing environmental movement drew attention to the relationship between economic growth and environmental degradation. Kenneth E. Boulding, in his influential 1966 essay The Economics of the Coming Spaceship Earth, identified the need for the economic system to fit itself to the ecological system with its limited pools of resources. Another milestone was the 1968 article by Garrett Hardin that popularized the term "tragedy of the commons". One of the first uses of the term sustainable in the contemporary sense was by the Club of Rome in 1972 in its classic report on the Limits to Growth, written by a group of scientists led by Dennis and Donella Meadows of the Massachusetts Institute of Technology. Describing the desirable "state of global equilibrium", the authors wrote: "We are searching for a model output that represents a world system that is sustainable without sudden and uncontrolled collapse and capable of satisfying the basic material requirements of all of its people."

In 1980, the International Union for Conservation of Nature published a world conservation strategy that included one of the first references to sustainable development as a global priority and introduced the term "sustainable development". Two years later, the United Nations World Charter for Nature raised five principles of conservation by which human conduct affecting nature is to be guided and judged. In 1987, the United Nations World Commission on Environment and Development released the report Our Common Future, commonly called the Brundtland Report. The report included what is now one of the most widely recognized definitions of sustainable development. Sustainable

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development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains

Within it two key concepts:

- The concept of 'needs', in particular, the essential needs of the world's poor, to which overriding priority should be given; and

- The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

Since the Brundtland Report, the concept of sustainable development has developed beyond the initial intergenerational framework to focus more on the goal of "socially inclusive and environmentally sustainable economic growth". In 1992, the UN Conference on Environment and Development published the Earth Charter, which outlines the building of a just, sustainable, and peaceful global society in the 21st century. The action plan Agenda 21 for sustainable development identified information, integration, and participation as key building blocks to help countries achieve development that recognizes these interdependent pillars. It emphasizes that in sustainable development, everyone is a user and provider of information. It stresses the need to change from old sector-centered ways of doing business to new approaches that involve cross-sectoral co-ordination and the integration of environmental and social concerns into all development processes. Furthermore, Agenda 21 emphasizes that broad public participation in decision making is a fundamental prerequisite for achieving sustainable development. Under the principles of the United Nations Charter the Millennium Declaration identified principles and treaties on sustainable development, including economic development, social development and environmental protection. Broadly defined, sustainable development is a systems approach to growth and development and to manage natural, produced, and social capital for the welfare of their own and future generations. The term sustainable development as used by the United Nations incorporates both issues associated with land development and broader issues of human development such as education, public health, and standard of living. A 2013 study concluded that sustainability reporting should be reframed through the lens of four interconnected domains: ecology, economics, politics and culture.

Reception

The concept of sustainable development has been, and still is, subject to criticism, including the question of what is to be sustained in sustainable development. It has been argued that there is no such thing as a sustainable use of a non-renewable resource, since any positive rate of exploitation will eventually lead to the exhaustion of earth's finite stock; this perspective renders the Industrial Revolution as a whole unsustainable.

The sustainable development debate is based on the assumption that societies need to manage three types of capital (economic, social, and natural), which may be non-substitutable and whose consumption might be irreversible. Leading ecological economist and steady-state theorist Herman Daly, for example, points to the fact that natural capital can not necessarily be substituted by economic capital. While it is possible that we can find ways to replace some natural resources, it is much more unlikely that they will ever be able to replace eco-system services, such as the protection provided by the ozone layer, or the climate stabilizing function of the Amazonian forest. In fact natural capital, social capital and economic capital are often complementarities. A further obstacle to substitutability lies also in the multi-functionality of many natural resources. Forests, for example, not only provide the raw material for paper but they also maintain biodiversity, regulate water flow, and absorb CO_2.

Requirements

Six interdependent capacities are deemed to be necessary for the successful pursuit of sustainable development. These are the capacities to measure progress towards sustainable development; promote equity within and between generations; adapt to shocks and surprises; transform the system onto more sustainable development pathways; link knowledge with action for sustainability; and to devise governance arrangements that allow people to work together in exercising the other capacities.

Dimensions

Sustainable development can be thought of in terms of three spheres, dimensions, domains or pillars: the environment, the economy and society. The three-sphere framework has also been worded as "economic, environmental and social" or "ecology, economy and equity". This has been expanded by some authors to include a fourth pillar of culture, institutions or governance, or alternatively reconfigured as four domains of the social - ecology, economics, politics and culture, thus bringing economics back inside the social, and treating ecology as the intersection of the social and the natural.

Sustainable Development Goals

The Sustainable Development Goals (SDGs) or Global Goals are a collection of 17 interlinked global goals designed to be a "blueprint to achieve a better and more sustainable future for all". The SDGs were set up in 2015 by the United Nations General Assembly (UN-GA) and are intended to be achieved by the year 2030. They are included in a UN-GA Resolution called the 2030 Agenda or what is colloquially known as Agenda 2030. The SDGs were developed in the Post-2015 Development Agenda as the future global development framework to succeed the Millennium Development Goals which ended in 2015.

Pathways

Deforestation and increased roadbuilding in the Amazon rainforest are a concern because of increased human encroachment

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upon wilderness areas, increased resource extraction and further threats to biodiversity. The ecological stability of human settlements is part of the relationship between humans and their natural, social and built environments. Also termed human ecology, this broadens the focus of sustainable development to include the domain of human health. Fundamental human needs such as the availability and quality of air, water, food and shelter are also the ecological foundations for sustainable development; addressing public health risk through investments in ecosystem services can be a powerful and transformative force for sustainable development which, in this sense, extends to all species.

Environmental sustainability concerns the natural environment and how it endures and remains diverse and productive. Since natural resources are derived from the environment, the state of air, water, and the climate is of particular concern. The IPCC Fifth Assessment Report outlines current knowledge about scientific, technical and socio-economic information concerning climate change, and lists options for adaptation and mitigation. Environmental sustainability requires society to design activities to meet human needs while preserving the life support systems of the planet. This, for example, entails using water sustainably, using renewable energy and sustainable material supplies (e.g., harvesting wood from forests at a rate that maintains the biomass and biodiversity).An unsustainable situation occurs when natural capital (the total of nature's resources) is used up faster than it can be replenished. Sustainability requires that human activity only uses nature's resources at a rate at which they can be replenished naturally. The concept of sustainable development is intertwined with the concept of carrying capacity. Theoretically, the long-term result of environmental degradation is the inability to sustain human life. Such degradation on a global scale should imply an increase in human death rate until population falls to what the degraded environment can support Table 3. Pollution of the public resources is not a different action, it is just a reverse tragedy of the commons, in that instead of taking something out, and something is put into the commons. When the costs of polluting the commons are not calculated into the cost of the items consumed, then it becomes only natural to pollute, as the cost of pollution is external to the cost of the goods produced and the cost of cleaning the waste before it is discharged exceeds the cost of releasing the waste directly into the commons. One of the ways to mitigate this problem is by protecting the ecology of the commons by making it, through taxes or fines, more costly to release the waste directly into the commons than would be the cost of cleaning the waste before discharge [131-141].

Table 3: The long-term result of environmental degradation is the inability to sustain human life.

Consumption of Natural Resources	State of the Environment	Sustainability
More than nature's ability to replenish	Environmental degradation	Not sustainable
Equal to nature's ability to replenish	Environmental equilibrium	Steady state economy
Less than nature's ability to replenish	Environmental renewal	Environmentally sustainable

Land Use Changes, Agriculture and Food

Alterations in the relative proportions of land dedicated to urbanization, agriculture, forest, woodland, grassland and pasture have a marked effect on the global water, carbon and nitrogen biogeochemical cycles and this can impact negatively on both natural and human systems. At the local human scale, major sustainability benefits accrue from sustainable parks and gardens and green cities. Feeding almost eight billion human bodies takes a heavy toll on the Earth's resources. This begins with the appropriation of about 38% of the Earth's land surface and about 20% of its net primary productivity. Added to this are the resource -hungry activities of industrial agribusiness- everything from the crop need for irrigation water, synthetic fertilizers and pesticides to the resource costs of food packaging, transport (now a major part of global trade) and retail. Environmental problems associated with industrial agriculture and agribusiness are now being addressed through such movements as sustainable agriculture, organic farming and more sustainable business practices. The most cost-effective mitigation options include afforestation, sustainable forest management, and reducing deforestation. The environmental effects of different dietary patterns depend on many factors, including the proportion of animal and plant foods consumed and the method of food production. At the global level the environmental impact of agribusiness is being addressed through sustainable agriculture and organic farming. At the local level there are various movements working towards sustainable food systems which may include local food production, slow food, sustainable gardening, and organic gardening.

Materials and Waste

As global population and affluence have increased, so has the use of various materials increased in volume, diversity, and distance transported. Included here are raw materials, minerals, synthetic chemicals (including hazardous substances), manufactured products, food, living organisms, and waste. By 2050, humanity could consume an estimated 140 billion tons of minerals, ores, fossil fuels and biomass per year (three times its current amount) unless the economic growth rate is decoupled from the rate of natural resource consumption. Developed countries' citizens consume an average of 16 tons of those four key resources per capita per year, ranging up to 40 or more tons per person in some developed countries with resource consumption levels far beyond what is likely sustainable. By comparison, the average person in India today consumes four tons per year. Sustainable

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use of materials has targeted the idea of dematerialization, converting the linear path of materials (extraction, use, disposal in landfill) to a circular material flow that reuses materials as much as possible, much like the cycling and reuse of waste in nature. Dematerialization is being encouraged through the ideas of industrial ecology, eco design and ecolabelling. The use of sustainable biomaterials that come from renewable sources and that can be recycled is preferred to the use on non-renewables from a life cycle standpoint. This way of thinking is expressed in the concept of circular economy, which employs reuse, sharing, repair, refurbishment, remanufacturing and recycling to create a closed-loop system, minimizing the use of resource inputs and the creation of waste, pollution and carbon emissions. The European Commission has adopted an ambitious Circular Economy Action Plan in 2020, which aims at making sustainable products the norm in the EU.

Improving on Economic and Social Aspects

It has been suggested that because of rural poverty and overexploitation, environmental resources should be treated as important economic assets, called natural capital. Economic development has traditionally required a growth in the gross domestic product. This model of unlimited personal and GDP growth may be over. Sustainable development may involve improvements in the quality of life for many but may necessitate a decrease in resource consumption. According to ecological economist Malte Faber, ecological economics is defined by its focus on nature, justice, and time. Issues of intergenerational equity, irreversibility of environmental change, uncertainty of long-term outcomes, and sustainable development guide ecological economic analysis and valuation. As early as the 1970s, the concept of sustainability was used to describe an economy "in equilibrium with basic ecological support systems". Scientists in many fields have highlighted The Limits to Growth, and economists have presented alternatives, for example a 'steady-state economy', to address concerns over the impacts of expanding human development on the planet. In 1987, the economist Edward Barbier published the study The Concept of Sustainable Economic Development, where he recognized that goals of environmental conservation and economic development are not conflicting and can be reinforcing each other.

A World Bank study from 1999 concluded that based on the theory of genuine savings, policymakers have many possible interventions to increase sustainability, in macroeconomics or purely environmental. Several studies have noted that efficient policies for renewable energy and pollution are compatible with increasing human welfare, eventually reaching a golden-rule steady state. However, Gilbert Rist says that the World Bank has twisted the notion of sustainable development to prove that economic development need not be deterred in the interest of preserving the ecosystem. He writes: "From this angle, 'sustainable development' looks like a cover-up operation. The thing that is meant to be sustained is really 'development', not the tolerance capacity of the ecosystem or of human societies." The World Bank, a leading producer of environmental knowledge, continues to advocate the win-win prospects for economic growth and ecological stability even as its economists express their doubts. Herman Daly, an economist for the Bank from 1988 to 1994, writes: When authors of WDR '92 [the highly influential 1992 World Development Report that featured the environment] were drafting the report, they called me asking for examples of "win-win" strategies in my work. What could I say? None exists in that pure form; there are trade-offs, not "win-wins." But they want to see a world of "win-wins" based on articles of faith, not fact. I wanted to contribute because WDRs are important in the Bank, [because] task managers read [them] to find philosophical justification for their latest round of projects. But they did not want to hear about how things really are, or what I find in my work.

A Meta review in 2002 looked at environmental and economic valuations and found a lack of "sustainability policies". A study in 2004 asked if humans consume too much. A study concluded in 2007 that knowledge, manufactured and human capital (health and education) has not compensated for the degradation of natural capital in many parts of the world. It has been suggested that intergenerational equity can be incorporated into sustainable development and decision making, as has become common in economic valuations of climate economics. A Meta review in 2009 identified conditions for a strong case to act on climate change, and called for more work to fully account of the relevant economics and how it affects human welfare. According to John Baden, a free-market environmentalist, "the improvement of environment quality depends on the market economy and the existence of legitimate and protected property rights". They enable the effective practice of personal responsibility and the development of mechanisms to protect the environment. The State can in this context "create conditions which encourage the people to save the environment"

Environmental Economics

The total environment includes not just the biosphere of Earth, air, and water, but also human interactions with these things, with nature, and what humans have created as their surroundings. As countries around the world continue to advance economically, they put a strain on the ability of the natural environment to absorb the high level of pollutants that are created as a part of this economic growth. Therefore, solutions need to be found so that the economies of the world can continue to grow, but not at the expense of the public goods. In the world of economics, the amount of environmental quality must be considered as limited in supply and therefore is treated as a scarce resource. This is a resource to be protected. One common way to analyze possible outcomes of policy decisions on the scarce resource is to do a

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cost-benefit analysis. This type of analysis contrasts different options of resource allocation and, based on an evaluation of the expected courses of action and the consequences of these actions, the optimal way to do so in the light of different policy goals can be elicited. Further complicating this analysis are the interrelationships of the various parts of the environment that might be impacted by the chosen course of action. Sometimes, it is almost impossible to predict the various outcomes of a course of action, due to the unexpected consequences and the number of unknowns that are not accounted for in the benefit-cost analysis.

Management of Human Consumption and Impacts

Waste Generation, Measured in Kilograms Per Person Per Day

The environmental impact of a community or humankind as a whole depends both on population and impact per person, which in turn depends in complex ways on what resources are being used, whether or not those resources are renewable, and the scale of the human activity relative to the carrying capacity of the ecosystems involved. Careful resource management can be applied at many scales, from economic sectors like agriculture, manufacturing and industry, to work organizations, the consumption patterns of households and individuals, and the resource demands of individual goods and services. The underlying driver of direct human impacts on the environment is human consumption. This impact is reduced by not only consuming less but also making the full cycle of production, use, and disposal more sustainable. Consumption of goods and services can be analyzed and managed at all scales through the chain of consumption, starting with the effects of individual lifestyle choices and spending patterns, through to the resource demands of specific goods and services, the impacts of economic sectors, through national economies to the global economy. Analysis of consumption patterns relates resource use to the environmental, social and economic impacts at the scale or context under investigation. The ideas of embodied resource use (the total resources needed to produce a product or service), resource intensity, and resource productivity are important tools for understanding the impacts of consumption. Key resource categories relating to human needs are food, energy, raw materials and water.

In 2010, the International Resource Panel published the first global scientific assessment on the impacts of consumption and production. The study found that the most critical impacts are related to ecosystem health, human health and resource depletion. From a production perspective, it found that fossil-fuel combustion processes, agriculture and fisheries have the most important impacts. Meanwhile, from a final consumption perspective, it found that household. Consumption related to mobility, shelter, food, and energy-using products causes the majority of life-cycle impacts of consumption. According to the IPCC Fifth Assessment Report, human consumption, with current policy, by the year 2100 will be seven times bigger than in the year 2010.

Biodiversity and Ecosystem Services

In 2019, a summary for policymakers of the largest, most comprehensive study to date of biodiversity and ecosystem services was published by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. It recommended that human civilization would need a transformative change, including sustainable agriculture, reductions in consumption and waste, fishing quotas and collaborative water management.

Technology

Before flue-gas desulfurization was installed, the air-polluting emissions from this power plant in New Mexico contained excessive amounts of sulfur dioxide. A sewage treatment plant that uses solar energy, located at Santuari de Lluc monastery, Majorca. One of the core concepts in sustainable development is that technology can be used to assist people to meet their developmental needs. Technology to meet these sustainable development needs is often referred to as appropriate technology, which is an ideological movement (and its manifestations) originally articulated as intermediate technology by the economist E. F. Schumacher in his influential work Small Is Beautiful and now covers a wide range of technologies. Both Schumacher and many modern-day proponents of appropriate technology also emphasise the technology as people centered. Today appropriate technology is often developed using open-source principles, which have led to open-source appropriate technology (OSAT) and thus many of the plans of the technology can be freely found on the Internet. OSAT has been proposed as a new model of enabling innovation for sustainable development.

Business

The most broadly accepted criterion for corporate sustainability constitutes a firm's efficient use of natural capital. This eco-efficiency is usually calculated as the economic value added by a firm in relation to its aggregated ecological impact. This idea has been popularized by the World Business Council for Sustainable Development (WBCSD) under the following definition: "Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's carrying capacity" (DeSimone and Popoff, 1997: 47). Similar to the eco-efficiency concept but so far less explored is the second criterion for corporate sustainability. Socio-efficiency describes the relation between a firm's value added and its social impact. Whereas, it can be assumed that most corporate impacts on the environment are negative (apart from rare exceptions such as the planting of trees) this is not true

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for social impacts. These can be either positive (e.g., corporate giving, creation of employment) or negative (e.g., work accidents, human rights abuses). Both eco-efficiency and socio-efficiency are concerned primarily with increasing economic sustainability. In this process they instrumentalize both natural and social capital aiming to benefit from win-win situations. Some point towards eco-effectiveness, socio-effectiveness, sufficiency, and eco-equity as four criteria that need to be met if sustainable development is to be reached.

Architecture and Construction

In sustainable architecture the recent movements of New Urbanism and New Classical architecture promote a sustainable approach towards construction that appreciates and develops smart growth, architectural tradition and classical design. This is in contrast to modernist and International Style architecture, as well as opposing to solitary housing estates and suburban sprawl, with long commuting distances and large ecological footprints. The global design and construction industry is responsible for approximately 39 percent of greenhouse gas emissions. Green building practices that avoid emissions or capture the carbon already present in the environment, allow for reduced footprint of the construction industry, for example, use of hempcrete, cellulose fiber insulation, and landscaping.

Iran Energy Sector

In order to analyze Iran's energy sector we first need to review the share of different resources in energy and particularly electricity generation and consumption. Next, we need to review share and potentials of energy resources in the country, as well their capacity trend in the recent years. Finally, we need to analyze Iran's energy sector's cost trends in the last years.. In this regard we have categorized resources as fossil fuels and renewable energy resources.

Iran Energy Reserves, Generation and Consumption

Iran is one of the biggest owners of fossil fuels in the whole world .These big reserves of fossil fuels are exceptional as the country is the largest owner of oil and gas resources worldwide. Despite their advantages, such as short term energy security, they might prove be insecure and instable in the long run. As the country relies on these abundant and usually cheap resources, any variation in the production, reserve or price of fossil fuels will affect the security of energy supply. While a more diversified primary energy structure could ensure this sector in the case of crisis, a dependent energy structure could have an adverse effect on the whole economy and in the economic growth as a result. Another issue for an owner of big reserves like Iran is the economy's dependence on the fossil fuels' export income. Reliance of economies on their exports of natural resources can cause a problem named "Dutch Disease". This is a theory originated in a historical event in the Netherlands connected to the natural gas fields discovered in Groningen region. This concept developed in the 1970's and relies on the connection of the increase in the development of one economic sector (a natural resource like oil) and its connection to other sectors (like industry). The mechanism makes income flow predominantly to the growing sector while making other sectors less competitive (The Economist, 1977). As long as a big share of the country's exports and revenues are dependent on one natural resource, any fluctuation in the price of the product can affect the economy. In an economy like Iran, which 90% of exports and 60% of revenues are based on oil, even higher revenue of the country could not compensate the budget deficit because of high subsidies in the energy sector (Farzanegan & Markwardth, 2009). Transition to renewable resources makes this sector more sustainable while reducing the dependability on fossil fuels and overcoming the Dutch Disease Figure 1.

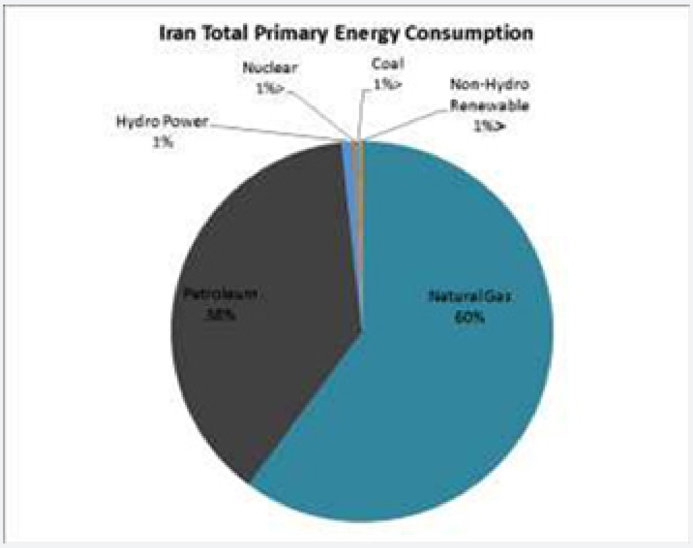

Figure 1: Iran total primary energy consumption (EIA, 013).

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Figure 1 indicates the share of different energy resources in primary energy consumption in Iran in 2013. As it is showed the majority of primary energy is supplied by fossil fuels. Although 60% of the energy share is provided by gas, which has the least volume of carbon emissions among fossil fuels, the small share of renewable resources is still notable. Fossil fuel consumption for energy generation is the major producer of GHG for which, energy efficiency and transition to renewable resources are two major suggested solutions. Crude oil, natural gas and coal are the main resources of fossil fuels in the country (Mohammadnejad et al. 2011). Referring to the development blocks theory the share of fossil fuels shows the dominance of ICE-Oil development block. A part of these fossil fuels are used for electricity generation. This fact shows the importance of the Electricity block but a small share of renewable resources might be the result of a minor ICT block Figure 2.

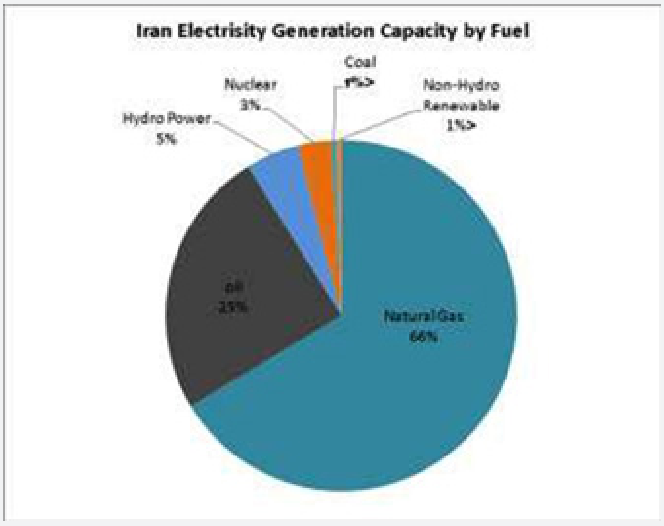

Figure 2: Iran electricity generation capacity by fuel (EIA, 013).

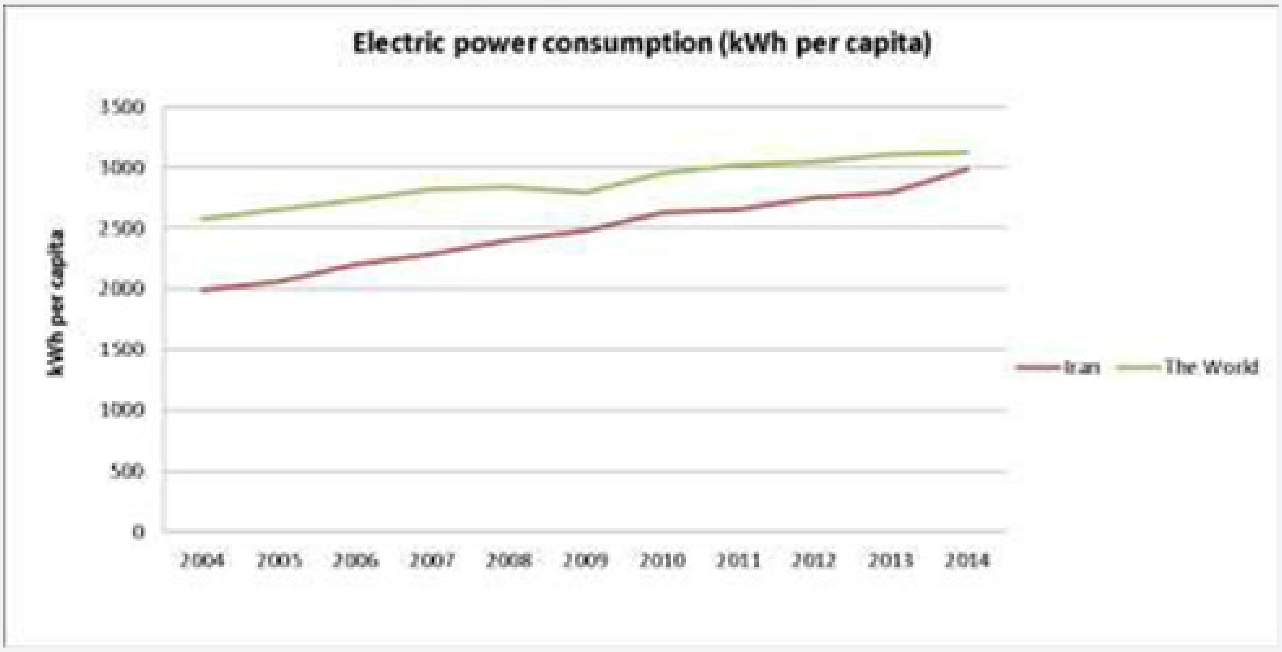

Figure 3: Electric power comparison- Iran and the world average (World Bank Data, 01).

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The dominance of fossil fuels is also considerable in electricity generation. As it is illustrated, around 93% of the country's electricity is generated by fossil fuels. This composition of resources shows that whole energy sector electricity generation is not diversified based on the carriers in accordance to the energy sector. Although the country owns big reserves of oil and gas, their big share in energy generation can cause insecurity and instability in some cases. Recently the increase in demand for energy, as a result of the increase in population and production, has raised the initiative to search for other potential energy resources. The electricity power sector is experiencing a 6.6% average growth in the last decades, and it provides energy service to 27.2 million consumers, of which 81.8% are residential (Tofighi & Abedian, 2016) Figure 3. As a result of this increase in energy consumption, in an energy sector which relies on a big share of fossil fuels, the demand and extraction of these types of energy carriers will drastically increase. The lower volume of energy consumption per capita in Iran, in comparison to the world's average, could be considered as one of a developing economy and lacking in technology and efficiency. It also means that still the ICT development block is not a dominant block in the country's development blocks and that the share of services compared to products is much lower. Otherwise, the trend of energy consumption would not be higher than average with an increasing trend Figure 4.

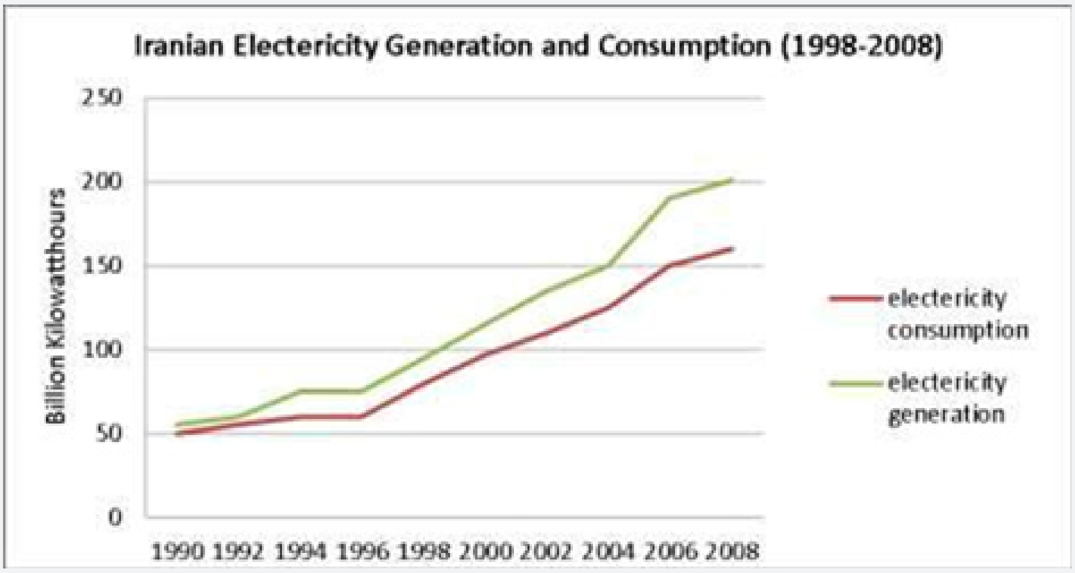

Figure 4: Iran electricity generation and consumption (EIA, 009).

Figure 4 also shows the electricity consumption and generation has experienced a high increase during recent years as consumption almost tripled in a decade from 1996-2006. This could both show the development of the electricity block and a lack of efficiency as the major sign of ICT block Figure 5. The transition relates more to the primary energy carrier as we cannot replace electricity. Hence, the country's power unit's composition and their capacity are relevant. In 2016 Iran added about 2324 MW (a 3.1% increase) to its electricity capacity and the total electricity capacity has reached to 76427 MW. However, the share of clean energies in the mentioned increase was only 94 MW, including 19 MW renewable and 75 MW hydroelectric resources Table 4. Table 4 illustrates that even if we count nuclear and hydro power as renewable energy resources, they present a low portion of electricity generation. Reviewing the mentioned nominal capacity also shows the highest increase in generation capacity belongs to the gas and combined cycle power plants, and that renewable power units (excluding hydro in 2015) did not experience a considerable increase. The growth rate of power units show a small number of renewable resources in comparison to thermal power plants, particularly gas and combined cycle in recent years. The only considerable growth rate in the renewable sector belongs to hydro power. Although hydro power is one of the cleanest and most efficient types of renewable resources, it is mostly dependent on dam construction and the water resources management sector, and therefore cannot be counted as an independent power unit Figure 6.

Figure 6 clearly shows the gap between renewable and thermal power plant capacity trends. It is obvious that the renewable resources graph located at the bottom of the figure is lagging behind. The thermal resources show an upward trend, particularly in the gas and combined cycle power plants as a result of the abundant and cheap gas reserves in the country.

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One important aspect and characteristic of development is sustainability which should be considered for every single element of this process. Energy can play an important role in a sustainable economic development by supplying secure, efficient and environment friendly supplies for economic growth. Compatibility of energy generation and consumption is also another sign of energy sustainability Variety of energy resources and energy supply diversity is also another important element for sustainability and getting away from monopoly (Bakhoda et al. 2012). In order to have a more comprehensive study of the energy sector and to further the analysis of sustainability transition, we must review the capacity and potential of Iran's major energy carriers for electricity generation in two major categories, fossil fuels and renewable resources.

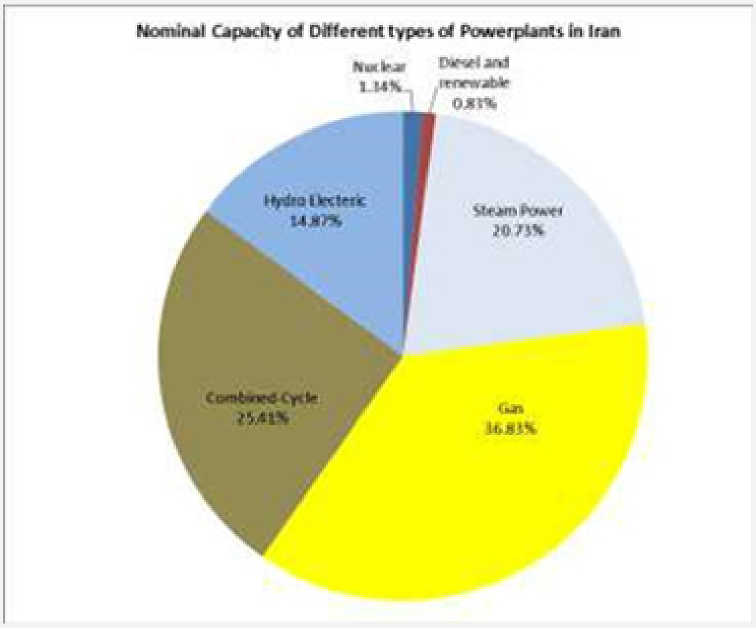

Figure 5: Iran electricity generation capacity by fuel (Iran Ministry of Energy).

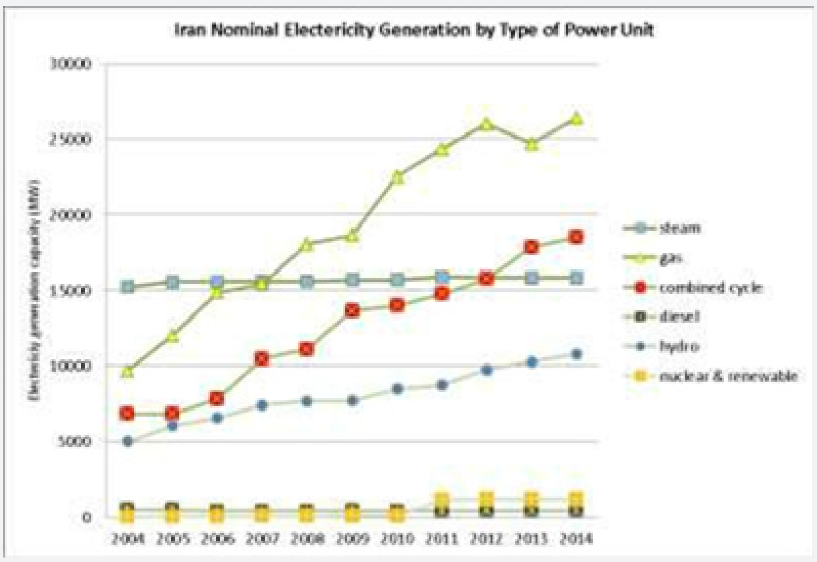

Figure 6: Iran electricity generation by type of power plant (Ministry of Energy, 01).

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Fossil Fuels in Iran

Oil

Iran ranked as the 4th largest oil reserves owner in the world. This amount is about 10% of the world and 13% of Organization of the Petroleum Exporting Countries (OPEC) oil reserves. About 70% of reserves are onshore which are mostly located on the south-west part of the country and the biggest offshore reserve is located at the Caspian Sea in the northern part of Iran. The country's production used to be 5.5 million b/d in 1970's and reached to 3.7 million in 2011 after lots of variation. The economic sanctions decreased the production to 2.7 million b/d in 2013 and even less afterwards. After sanctions being lifted in 2013 the country rises to gradually recover its production level (US energy Information administration, 2015). Based on current estimations, Iran's crude oil reserves will be depleted in the next 94 years as the country both exports and consumes this carrier (Abedian & Tofighi, 2016) Figure 7.

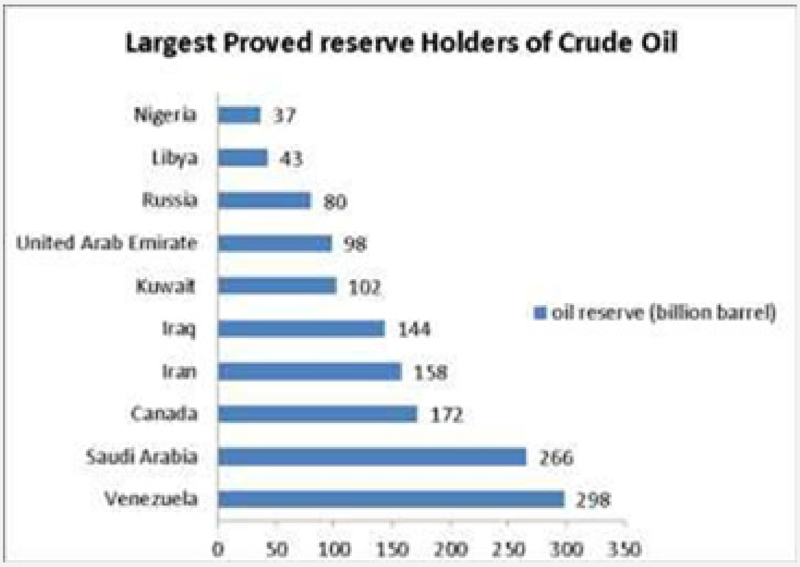

Figure 7: Largest holders of crude oil (billion barrel) (OECD/IEA and IRENA, 017).

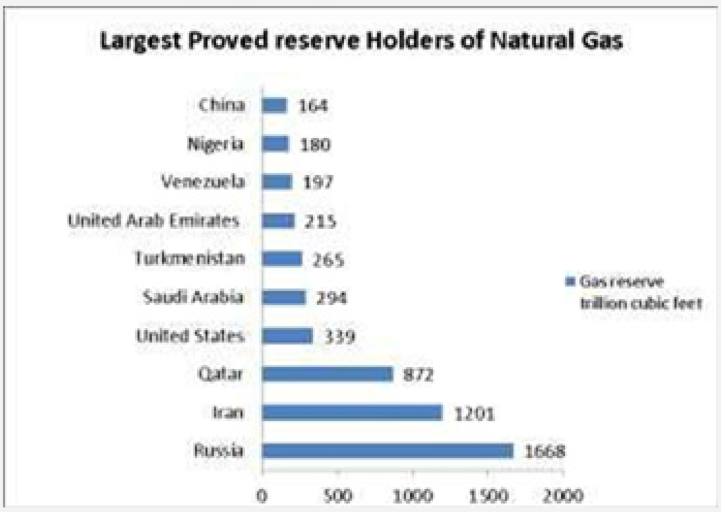

Figure 8: Largest holders of natural gas (trillion cubic feet) (OECD/IEA and IRENA, 017).

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Gas

Iran owns the 2nd gas reserves in the world with proved reserves of about 1201 trillion cubic feet (tcf), which is 17.5% of the world and one-third of OPEC's natural gas reserves. South Pars gas field is the country's biggest gas reserve (40%) and is located in the Persian Gulf, in southern Iran. The natural gas production of the country was 8.1 Tcf in 2013 (US energy Information administration, 2017). Gas reserves are estimated to be depleted in the next 53 years The share of natural gas in energy supply increased from 44.63% in 2001 to 54.93% in 2008 (Mohammadnejad et al. 2011) Figure 8.

Coal

This carrier accounts for a small portion of energy supply in Iran which is about 0.21% , but in comparison to renewable energy resources it is still a considerable amount. The country currently holds 2.73 million tons coal reserve (Mohammadnejad et al. 2011).

Renewable Energy Resources in Iran

Renewable energy resources are defined as those which can generate energy through a natural method and are not exhaustible such as fossil fuels or uranium (Mohammadnejad et al. 2011) Although Iran owns large reserves of fossil fuels such as oil and gas, the process of investment in renewable resource started several decades ago. Despite of the national will and its development plan regarding renewable energy, the share of renewable energy resources in the total energy supply is still less than 1%.

Solar Power

Thanks to the more efficient solar panels, solar power and particularly Photo Volcanic (PV) has experienced an increasing expansion trend. Iran is a country that, due to its location on the Sun Belt, has a high potential of solar power. It has been estimated that is could be up to 3200 hours per year in the central parts. The potential of electricity generation varies in different parts of the country between 250 W/m2 to 540 W/m2 in the day time. It has been estimated that Iran has 1.7 million hectares (1.1% of the total land) with 270 W/m2 and 28 million (17.3%) hectares with 250-270 w/m2 (Azadi et al. 2017). This capacity is up to 2.5 times more than the average capacity in European countries. Since the diffusion and implementation of solar power in EU countries, with a lower potential and less solar radiation was significant, it shows to what extent Iran can increase its solar power capacity. Currently the country produces around 26 MW from solar power and 24 MW of this number started up in 2017 (SATBA, 2017).

Wind Power

Iran owns many wind tunnels all around the country and the current electricity production is about 90 MW. By having the density of 275 W/m2 it has been estimated that the country has the potential of 6500 MW electricity generation from wind power. The main wind power stations in Iran are Kahak station located in Qazvin in upper center of the country with currently 55 MW, Manjil which located in northern part by the Caspian Sea with 71 MW and Binalood site located on the northeast, near Neyshabur with a capacity of 28.4 MW (SATBA, 2017). 2.1 million hectares of the country (1.3% of the Land) has 8m/s or more, which is suitable for electricity generation (Azadi et al. 2017). Following Iran's Ministry of Energy incentive policies and import of new technology of 2.5 MW wind turbines, the new projects have now turned into mega projects. In comparison to solar power wind power is more limited. Despite the country's 14000 MW capacity in this sector, the economic condition for wind energy generation has agglomerated the capacity in particular regions of the country. This condition is generally based on the existence of continuous wind with a speed of 6.1 to 21 meters per second. In addition the construction of wind power units takes more time, is more complex and requires a higher technology (SATBA, 2017).

Hydro Power

Hydro dam construction is rooted and advanced in Iran. In addition to water supply and management and flood control, dams have played an important role in electricity generation and reduction of GHG in the recent decades. The country has targeted to reach 30,000 MW of hydroelectric generation in the near future (Mohammadnejad et al. 2011). Comparing the capacity of hydro power with the country's total renewable generation capacity shows how large is the share of Hydro power. The hydro power technology is very environmental friendly with a high capacity of generation. However, the problem is that the initial capital investment of hydro power is very high since the facilities are usually located inside the dam structure. In fact this technology has a complementary relationship with dams and as a result has long construction period and requires high investment.

Nuclear Power

Although Iran faced many restrictions for development of nuclear power, it owns 3 nuclear power plants with the total capacity of 1400 MW. The biggest power plant is Bushehr, which is located in southern coast of Iran with 1000 MW capacity. It has been targeted for the country's nuclear sector to reach 7000 MW in the next 20 years (Tofighi & Abedian, 2016). Despite of its high electricity generation capacity, this technology has some proved adverse effects. Nuclear contaminations or explosions which sometimes turn into a disaster are a part of these issues. The disadvantages of nuclear power plants are doubled for Iran as the country deals with nuclear issues. Although the country has planned its network of nuclear power plants, the main issue is still providing them with nuclear fuel. The country owns some uranium mines but turning that to the fuel requires an enrichment process. Since enrichment process is very limited and under the

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IAEA supervision, the country faces issues to provide fuels with economic efficiency and reasonable price for the new units and even existing ones.

Worldwide and Iran Energy Price and Capacity Trend

Fossil fuels as the main resource of electricity power generation experienced many ups and downs in the price in the last decades. Oil, as one of the main role players in global energy price trends, was a part of these fluctuations. Although the oil price has been recently decreased considerably, they are still not very cheap comparing to some types of renewable energy resources. What's more, fossil fuels like crude oil are not secure resources. For oil importing countries it carries the risk of price fluctuation and of being depleted for oil reserve owners. Unlike the irregular trend of oil price in the last decade the price of renewable resources was more reliable Figure 9. Figure 9 illustrated the prices of wind and solar energy experienced a decreasing trend in recent years. Based on the data presented by the International Renewable Energy Association (IRENA), price of the wind power dropped to 40 USD/MWh in 2016, which is half of 2010, that used to be 80 USD/MWh. The price of solar power experienced a drastic decrease of one fifth and reached 50 USD/MWh in 2016. The two above figures 10 (a,b) show that the global prices for wind and solar power might be even cheaper in some countries depending on their different elements and potential. Due to the development blocks concept and the market widening mechanism, price is an important factor for diffusion of new carrier. Electricity as a secondary carrier is flexible regarding to the primary carrier. Price and efficiency are two major elements for the selection of electricity generation primary resources. As the price is not a comprehensive measure when comparing between different types of energy resources. In economic analysis, particularly comparison of different types or resources of energy, we need a measurement in order to make a fair and balanced assessment. The measure, which implements for the cost of different types of electricity generation is called "Levelized Cost of Electricity" (LCOE) .In fact, this measure considers other factors that affect the generation costs, such as operation and maintenance, initial investment, and capital and fuel cost.

Drivers, feasibility and Methods of sustainable Transition to Renewable Energy Resources

Drivers

Beside the role of market mechanisms and price, institutions and regulations take an undeniable part in any socio-technical transition. They could perform as driver, barrier or facilitator for the transition process based on their nature. Among various ratified laws and regulations the country's commitments to UNFCCC for cutting GHG emissions and Iran's National Development plan are the most effective and well known examples in this regard. The recent increase of investment in renewable energy, particularly through foreign finance, was also another motive for the development of this sector.

Iran National Development Plan [NDP]

Iran's National Development Plan (NDP) is the country's main roadmap for development. It is a comprehensive 30 years plan for Iran's development divided into smaller 5 years plans. Although DNP targeted to develop clean tech resources in the energy sector, the large share of fossil fuels is still a barrier for these policies. The current NDP is targeted to ascertain the country's commitment with environmental protection and the reduction of the GHG emissions.

Iran's Commitments to UNFCCC at Paris Conference 2015

Energy sector and the share of renewable and non-renewable resources are directly connected to the environment and economic sustainability. A problematic environment and an economy that relies on non-renewable energy resources are considered as an unsustainable condition that will never lead to economic development (Bakhoda et al. 2012). Iran's commitments to UNFCCC at the Paris climate change conference in 2015 to cut the GHG emissions between 4-12% shows the willingness of the country to favor the sustainable environment movement (United Nation Climate Change Conference, Paris 2015). As mentioned earlier increase in energy efficiency and implementation of renewable resources due to their low carbon emissions are two possible solutions for cutting the GHG emissions. Referring back to Iran's electricity sector, only 16% of electricity power generation belongs to renewable resources, of which the share of wind, solar and biomass is 0.2%, hydro-power 14.5%, and nuclear 1.3% (Iran Ministry of Energy detailed statistical report, 2016).

Foreign and Domestic Investment in Renewable Energy in Iran

Despite of Iran's energy sector infrastructure and design, few Iranian and foreign countries have invested in the country's renewable energy sector. These projects include a variety of renewable energy projects like solar or wind farms, as well as other type of projects in different parts of Iran.

Sustainable Transition of Iran Electricity Power to Renewable Resources

The review of Iran's energy sector, particularly electricity sector and the composition of primary energy resources, contrasts with the concept of energy sustainability. The high ratio of fossil fuels might cause insecurity and instability in the sector in the long run. By defining the gap between the country's electricity sector and sustainability, we will reach the first step of a transition to renewable resources, which is feasibility.

Feasibility of Sustainable Transition to Renewable Resources

The most important fact in energy sustainability is the conformity of consumption and generation of energy (McKay, 2009:103). The calculation for the energy generation capacity and

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feasibility are complex and require multi-dimensional scientific studies. In this part we will make some simple calculations based on the country's data and potential in order to show to what extent renewable energies can substitute the fossil fuel resources in case they reach their maximum potential capacity. Due to the high potentials of solar and wind energy in comparison to other renewable energy resources in Iran, we only focus on these two resources here as renewable options.

Wind

As mentioned earlier 1.3% of Iran's land including 26 regions (45 sites) is economic for wind energy generation. This potential is capable of creating 6500-14000 MW capacity of wind power which could cover 8.5-18% of the current electricity capacity (76427 MW).

Solar

The solar power potential is between 2.8 and 5.4 w/m^2 per day and the area per person is 18,350 square meters (1,483,375 km^2/ 80,836,699) so considering the minimum capacity per person/ m^2: $2.8W/m^2 \times 18{,}350m^2$ per person = 51.38 kWh/d per person Electricity consumption per capita is 2985 kWh per year or 8.15 kWh per day. If we consider the above calculated capacities the potentials are also enough for almost five times more consumption in the case of growth in electricity demand. In addition to the generation capacity, these potential seems enough for meeting the commitments of increasing the share of renewable resources to 65% and cutting emissions up to 12% to UNFCCC. Considering 28 million hectares with the minimum generation capacity of 2.8 w per m2, gives us the number of 784,000 MW as the capacity of the country for solar power generation. As the renewable energy experts state, PV power units with 100 km length and 100 km width of solar cells is enough to meet the country's electricity demand. This was just simple calculations to examine the capacity feasibility of transition of the electricity power generation to renewable resources while many other technical, economic and social factors are effective for this process.

Methods for Sustainable Transition of Electricity Sector

Carbon Pricing

One of the effective methods for making renewable energy resources competitive and facilitating renewable energy transition is carbon pricing. There are different opinions about the amount and trend of carbon taxation. While some economists argue that it should be a decreasing value, others state that due to the accumulation of carbon dioxide, it must increase up to a certain level and start to decrease at the time that fossil fuel reserves are about to exhaust. For instance, the model implemented in 1990's in European countries was charging $3 per barrel of oil and increase $1 annually until 2000 (Farzin & Tahvonen, 1996). Converting carbon pricing from an agreement into a law requires the intent of the countries' jurisdiction system. While some countries like Sweden are pioneer in carbon pricing methods like charging 126 USD/tCO_2e other recently joined economies such as Mexico are currently charging 1 USD/tCO_2e (World Carbon Price Watch, 2017) (Figure 11). The CO_2 emissions of different types of energy careers are different. It is proven that fossil fuels are the main sources of CO_2 emissions. For a better comparison of emissions of different energy carriers, we will consider their CO_2 volume of emission (grams) unit for every unit of energy (MJ). As can be seen below the CO_2 intensity varies for different sources of energy Table 5.

Table 5: Co emission factors for different fossil fuels, gram Co /MJ (Kander et al. 013: 78).

Coal	92
Oil	74
Natural gas	56

Carbon pricing systems are effective for emissions reduction by reducing the demand for energy and shifting the economy to clean energy resources. The major problem with ETS is price vitality as its allowance is determined in market based on the energy demand and supply mechanism. Since the carbon price volatility imposes costs to emission cutting programs, like carbon taxing, programs with fixed prices are more recommended when compared to cap and trade (ETS) methods. Carbon taxes are more effective environmentally comparing to cap and trade system. While taxes are additive and effective for mitigation plans, prices in cap and trade might have severe cap and become ineffective as a result (IMF, 2011). Carbon taxation not only carries the advantages of motivating the shift to alternative resources, but also helps the conservation of environment, increases government revenue and enhances socially efficient income. However, it also might cause some disadvantages such as a shift in production, imposing heavy administration costs, increasing the possibility of costs growth and supporting hidden operations (IMF, 2011). The table below shows that increasing the CO_2 pricing is one method for supporting the global agreement on emission reduction. This mechanism makes renewable resources competitive as it increases the cost of fossil fuels. This prediction also shows that the carbon prices are relatively low for Non-OECD and developing countries, like Iran, based on the nature of their economy and energy sectors. Iran has already established some legal articles regarding to pollution taxes in NDP but they do not seem binding. Additionally,

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the decision making reference in the mentioned articles are not a country wide system and decisions could be made by local judiciary. In fact, it is a penalty system rather than a carbon pricing system. Applying a real carbon pricing system requires localized scientific calculations based on in-depth studies. Recently, Iran's government has ratified a law named green tax. It is predicted that government charges 0.5-1.5% income taxes on polluting units which do not obey environmental standards (green tax and accounting).

Energy Subsidy

Iran's energy sector, which is controlled by a government monopoly, receives the highest subsidy amount in the world. This subsidy is worth around $82 billion and consists of 16% of the country's GDP (Tofighi & Abedian, 2016). In addition to the abundance of fossil fuel reserves, which keeps them at low prices in the market, the subsidy that the government assigned to them is making them even cheaper. This process takes the competitiveness of renewable resources away. In recent years, the government has planned to reduce the allocated subsidy of fossil fuels gradually and let the prices converge in their real level. For renewable energy promotion, factors such as the subsidy for equipment purchase, the reduction of interest rates, a subsidy for O&M, higher selling prices, or putting a constraint on energy supply mix could be used. One common subsidy tool economy use to make renewable energy sector more attractive with higher selling prices is feed in tariffs (FiTs). For conducting FiTs policies, Iran Renewable Energy Organization (SATBA) settled 20 years purchasing power agreement (PPA) with guaranteed tariffs and their annual adjustment for the money devaluation based on the Euro exchange rate and internal inflation. They established a system benefit charge (SBC) proposed by the World Bank in 2010 that is in the amount of 0.0015 USD per kWh (except rural consumers) charges on electricity bills. These charges were USD 334 million of which 50 % is assigned to the development of renewable energy. This is also mentioned in article no. 5 of support of electricity industry law. The factors they consider for FiTs are Internal Rate of Return (IRR) and payback period. If the investors use a low interest loan, SATBA will consider it as a subsidy and deduct it from their FiTs (SATBA, 2017).

Methods and policies for renewable transition are necessary as the matter of investment constraints and price implications. Even high economic potential for renewable energy generation is not a guarantee for the development of this sector. Based on some policy scenarios renewable resources should enter the market when the producers can at least cover their marginal production cost. They state solar power is independent from availability of oil. It might delay first entering the market, but once in, it gets to the same path as oil consumption, and later they will reach the same level of peak price. Through the transition process natural reserves coexist rather than override each other (Amigues et al. 2015).

Renewable Energy Tenders

The recently organized tender of different countries for constructing their new renewable energy projects is named "Auction". These auctions increased the global renewable energy installed capacity and reduced the prices. In solar power sector the capacity increased from 2 GW in 2012 to 222 GW in 2015 and the solar PV LCOE decreased 58% from 2010 to 2015. Prices decrease varies in different countries between 10-45% late 2016. The mentioned method is currently more common comparing to others such as feed- in tariffs and is based on particular determinants. A country's specific condition and finance accessibility, conductive environment and investor's confidence, its policies in support of renewable energy, and design factors for auction are the main determinants (IRENA, 2016). Auctions, like other transition methods, will affect the renewable energy price, which is effective on the supply and demand mechanisms.

Data & Method

Methodology

In order to conduct this research the qualitative method has been chosen as it is the best fit for complex social problems. As the focus of qualitative research approach is on the quality or meaning of experience, it is helpful for defining a socio-technical mechanism. The interpretivist approach and the aim of qualitative method for describing and discovering make it a proper method for a transition process that includes many complex elements. This flexible approach is also the best fit for an evolving or emerging concept like the aimed theoretical concept of our research. In addition, the main advantages of qualitative research are exploration, description and interpretation. Exploration is about the understanding of patterns, phenomena, while description completes this understanding. The interpretation tries to make sense what is going on. Case study is a suitable qualitative method to study a process and is also flexible for a research design. Case study is an empirical inquiry that investigates a contemporary phenomenon with its real life context, especially when the boundaries between phenomenon and context are not clearly evident (Yin, 2003 p 16).The interviews for gathering primary data, archive records and documents for organizing the analytical criteria, are the best instruments for conducting a case study research (Yin, 2003, p 87) The focused interview is a respondent interview for a short period of time and it is semi structured for giving some degree of freedom to the interviewee (Yin, 2003: 90).

The reason for picking Iran as the case study is that the country has big reserves of fossil fuels like other countries in the region. But the case would be more interesting when we focused on the country's solar power, which also has a very high potential and thus provides a high motive for studying a socio-technical transition in the energy sector. The aim of selecting three perspectives of the investor, contractor and the government side of the sector, is to find a more practical pattern for transition and validate the different perspectives at the same time. In order

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to create a high-quality case study research design, we should set the research based on 4 main principles. First, construct validity, which could be organized by implementing different sources or evidence, or a chain or collection of them. For internal validity of the research pattern matching, explanation building, and logic models have been used. External validity requires theory in single case research design and replication logic in multiple cases (Yin, 2003 p 29). For this regard, the same set of semis conducted questions have been asked to two CEOs of the investment companies in Iran's solar power industry, as well as to the head of strategic and economic studies department in Iran Renewable Energy and Energy Efficiency Organization (SATBA) to review the case from two different perspectives. Reliability could be built by a case study protocol (collection) or database. The lack of up-to-date data from valid resources, like IEA or IRENA, and the impossibility of conducting an interview with MAPNA, the biggest company in the wind power industry in Iran could be counted as the limitations of the project.

Data

The main sources of the data are as follows: Primary Data

Table 6: Specification of case studies.

Company/Organization Name	Type of Project	Number of Projects	Investment Value	Production Capacity
GEIC	Solar (PV)	١	١٢,٠٠٠,٠٠٠ EUR	١٠ MW
Mokran	Solar (PV)	١	٢٢,٧٢٥,٠٠٠ EUR	٢٠ MW
SATBA	Renewable Energy and Energy Efficiency Organi-zation- Ministry of Energy			

Results of the semi-structured interviews with investors in renewable energy sector (domestic and foreign) and a representative from SATBA, which is a part of Iran Ministry of Energy in charge of renewable resources, are the main data of this research. The protocol of semi-conducted interview is attached as appendix 1. As it is listed in the table 6 below, a number of companies have invested or participated in renewable energy projects built in the last 4 years (2013-2017). METKA is a Greek company that constructed and invested on a solar power unit in Isfahan in cooperation with Ghadir Energy Investment Company (GEIC), which is also the biggest of its kind in Iran. Mokran is a holding composed of two major companies, Tose-e Faragir Jask and Solar Energy Arka, which recently constructed two solar power units in Kerman, with the German technology of ADORE Co. and the investment of DURION from Switzerland. A part of the data has been gathered from the government's perspective, and for the validity of the data, the same set of questions have been asked to the head of strategic studies in the department of Renewable Energy and Energy Efficiency Organization- Ministry of Energy Table 6.

Secondary Data

- Iran Ministry of Energy statistics including: 48 years report of electricity industry (2014) and Iran electricity industry detailed statistics (2017).

- IRENA reports including: renewable capacity statistics (2017), renewable energy auctions (2016) and perspective of energy transition (2017).

General Information about Interviewee and Research Group

Article number 44 of Iran constitution is targeted to enhance the participation of private sector in the economic activities. Renewable Energy and Energy Organization (SATBA) as the government's representative is responsible to facilitate the privatization process in the renewable energy sector by developing respecting policies. The organization started the renewable energy development projects in 2004 by construction of pilot projects mentioned in the country's 4th NDP (article 25) to support renewable energy sector. In the following years based on the section "b" of article 133 of the 5th NDP the renewable energy resources considered as a part of electricity generation capacity in development plan. Recent FiTs in 2015 and SATBA's new policies attracted considerable non-governmental investments. SATBA as the representative of Iran Ministry of Energy binds purchasing power agreement (PPA). Coinciding policies for renewable resources promotion, the organization established some general conditions for these agreements including limitation of number (two power units at the same time) and capacity (less than 100 MW) of power units.

Cheap fossil fuel as an "unhelpful friend" was SATBA's primary barrier for development of renewable resources. For the first step ratification of "Electricity Industry Protection Law" which targeted on reduction of reliance on fossil fuels with priority of efficiency was an effective action. At the beginning, the government settled a unit price for all types of renewable energy electricity power. The benchmarking from other countries such as Germany and Turkey was helpful for solving this problem. Regardless of economic and

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potential differences, Iran patterned Germany's successful FiTs to create a comprehensive FiTs system with various tariffs based on the type and the capacity of power units. It is estimated that Iran has 150000 MW nominal, 40000 MW operational and 15000 MW economic capacities. SATBA currently has issued 15000 MW permit for generation units, of which about 1100 MW agreement resulted in agreements and about 400 MW (170 MW public and 230 MW private) are installed. GIEC started with wind power but the limited economic wind tunnels in Iran made the company to conduct a new study for solar power investment. During the study they analyzed the potential of solar power are economic for electricity generation and as a result they shifted to solar power and decided to invest in 50 MW solar power projects in Isfahan, Qom and Yazd. For their first phase including 5 EPC projects each with the capacity of 10 MW (EUR 12 million). The SATBA's feasible Feed in Tariffs (FiTs) for projects with the capacity of more than 10 MW was effective on their decision.

Mokran started the solar power business by conducting research studies and providing consultancy services to other companies. They constructed Kerman solar power unit as their first project in 2017 with the capacity of 20 MW (EUR 22 million) and recently started to construct a further 100 MW project in the region. Due to the type of the agreements with companies, SATBA plays a Sovereignty and affiliate role which does not intervene in the amount of capital invested and the equipment imported by them. However, the organization is working to design comprehensive instructions for import of equipment. Previously the affiliate role was more highlighted but due to the recent development and maturity of private sector, it has been turned to the Sovereignty role. They perform as policy maker, coordinator and accelerator.

Multi-Level Perspective [MLP] of Socio-Technical Transition in Energy Sector

Landscape Level

SATBA primarily objective was to participate in the renewable energy projects and constructed two large scale wind power units at the beginning of their foundation. They believed since the renewable sector was at its introduction stage the government's support was urgent. Currently the industry is about to mature so they are focused to act as a facilitator. The first unit tariff was established from 2004-2010. some improvement occurred in clause B of article 133 of 5th NDP but still with unit price and 5 year PPA. Finally, article 61 of the instruction specialized prices and extended agreement period to 20 years. The items for determining the FiTs rates are: energy saving, the volume of GHG emissions prevention and generation costs. GEIC had a positive picture of Iran's renewable energy sector as an investor due to the high rate of return and feasibility of the project. It was the same case for Mokran adding that for them high potential of solar power generation was effective in the mentioned positive picture. The financial feasibility of the project, reasonable purchasing price were the primary drivers for GEIC to participate in the project. The price was about 0.161 EUR/ kWh at the beginning but decreased to 0.133 EUR/ kWh when they finalized the contract with the ministry. The government also provided some exemption particularly custom and custom tariff exemption which motivated the company. The on time payments of generated electricity invoices by SATBA are a recently added motivation for the company. For Mokran, company's perspective about the future of energy sector in Iran and environment protection finding solution for clean energy and protection of the planet were more effective. SATBA had the same point of view with Mokran as they believed in maintaining reserves for future generation by implementing renewable resources. But the country's huge fossil fuel reserves and current energy security make this vision meaningless. Regarding to the mentioned facts the country planned for renewable industry development based on the studies conducted on their price trend. They did not start their large scale renewable power units like solar until the costs dropped considerably. Other effective drivers in national interest in the public sector perspective include: currency savings, fossil fuel saving and localization of the renewable energy industry.

SATBA did not consider abundance fossil fuels as the major determinant in their policies otherwise they could not start their new project. Mokran as a contractor believes fossil fuel era is over and Iran's capacity for renewable energy generation is capable to compete with the fossil fuel reserves For GEIC what matters is the price of oil not the abundance. It is because FiTs have positive correlation with fossil fuel reserves and decrease of fossil fuel prices result in decrease of tariffs. As mentioned earlier decreasing trend of renewable energy prices were really effective on SATBA's new policies and FiTs system. For instance cost of solar power installation in 2011 was USD 6000 per kWh which has been decreased to USD1000 per Kwh. Mokran as a contractor believes cost reduction including installation and generation cost is a big challenge and matters for the company and the cost reduction is important to them. For SATBA international commitments of Iran for cutting GHG emissions are good motives for establishing supportive policies in Iran renewable energy sector. They also the country's commitment to cut 4% of emissions is feasible. As an example in generation sector substitution of 5000MW renewable resources can result in 2% of emission cut. The organization believes high potentials in Iran renewable energy sector was really effective on their policies. Not only they have considered the natural and landscape potentials but also potentials in industry sector. For instance they have a new project so called waste heat recovery. According to this project factories like cement can generate power from their waste heat to generate electricity which government purchases USD 0.088 per kWh. They have 5 contracts currently which one is in operation with the capacity of 10 MW. For Mokran it was an effective factor but GEIC as an investor does not consider it as a direct variable in their decision for investment.

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While the country's national development plan which is targeted to increase the share of renewable resources was very effective for SATBA policies and for Mokran decision to participate in the project, it was not directly effective for GEIC as an investor. Based on SATBA perspective Comprehensive Plan of Action (JCPOA)1 was effective to some extent but did not meet their expectations. Since the interest rates are high domestic investments are not economic and foreign investment is really crucial for renewable energy sector. Mokran believes that there was a depression in renewable sector during the sanction's period and businesses started to move to betterment after the lifted. For GEIC the agreement was really effective on the investment particularly for providing the loan from METKA. JCPOA provided the opportunity for investment in the country that earlier no foreign company would take the risk. JCPOA facilitated foreign investment by accelerating monetary transaction and investment security. Thanks to the agreement METKA is now a business partner of GEIC for current and future projects. SATBA states currently there is not a particular contractual, banking or legal barrier for their PPA contract but for their surety and banking guarantees. Although Iran Investment Organization supports Iranian companies by providing Foreign Investment Promotion and Protection Act (FIIPA) license for them still there is uncertainty among foreign investor to invest in Iran market. In addition they count connection to the network, land ownership and environmental permit as other resolvable barriers. Mokran faced some barriers which were not complicated and could be solved easily. GEIC think insurance coverage for foreign investment from well recognized and international companies was a big issue at the beginning. But Greek companies like METKA took the risk to participate in the projects so they got their spot in the Iranian market and motivated other investors like German to come to the Iran renewable energy market. Previously German companies required 6 month to get the confirmation of insurance companies. He believes that they did not face any banking issue for financial transactions.

SATBA believes companies can minimize the technical and contractual risks by using consultancy services and currently most significant risk is about banking risks. Since the agreement is PPA and does not cover risks regarding to construction like capital adjustment companies have to deal it themselves. GEIC did not have a real risk but they had several issues with custom release of their equipment. Since the renewable energy projects were new the company had problem with custom organization to receive custom exemptions. This made delay in time plan and invaded extra costs such as stand-by charges from sub-contractors. But despite of all problems they finished the project less than 8 months. Mokran minimized their risk probability to zero by implementing risk management policies. GEIC thinks that support and commitment of government to their agreement is really crucial for their prospect projects. For Mokran barriers including monetary transaction, customs clearance and lack of

Niche level

SATBA considers the conditions provided for constructing the renewable energy power units as the most attractive part of the industry. According to the tariff geothermal and according to the potential solar are the most interesting types of renewable energies in Iran. Wind power is less attractive due to its high tech and geothermal excavation and assessment costs are high. For GEIC Financial feasibility of the project, shorter erection period of solar power units (less than 8 months) in comparison with thermal power plants (3 to 5 years) and shorter payback period were the most interesting incentive. The primary incentive for Mokran was environmental objectives and secondly company targeted to get a big share of renewable energy market in Iran and earn a profitable return.

GEIC believes we cannot find a direct connection between recent developments of renewable energy in Iran in relation with a country like Turkey as they do not have any considerable fossil fuel reserves like Iran. it was not very effective for Mokran's decision. SATBA as a member of IRENA used some useful policies of other members proposed by IRENA. The organization believes background of previous renewable projects in Iran was effective on their new policies. Considering the technology's life cycle it needs a substantial support in introduction and growth stages. 10 years ago at the introduction stage the organization had a different policy with supportive perspective to construct pilot renewable projects. Beside try and error it was for introduction of the technology to the society. They also designed an act for informing and promotion of industry in the society. Afterwards they started to study about market motivation mechanisms and formulated FiTs. But it was not so effective on Moran and GEICS' decision.

Regarding to investment guarantees SATBA believes some improvements in investment sector has happened in the renewable sector after JCPOA but still documents like FIPPA license is not convincing for some investors. The currency for payment of purchase by Iranian Rial transfers some risks to the investors as they might face several fluctuations. Some foreign insurance companies are willing cover the investment risks but with high premiums (3% in some cases). He believes Iranian banks have enough money to support these projects but the problem is their high interest. They have Sovereign Guarantee and the FIPPA license but the problem is the payment guarantee. But they believe PPA is a guarantee itself. GEIC states financial investment must be guaranteed by Iranian partner and since GEIC is a well - known company and owns assets they did not face problem to provide surety for their foreign investors. If Iran builds trust with foreign insurance companies and they accept to cover the renewable energy projects in Iran the risk will be transferred to them and it will facilitated. Mokran did not face any problem by having the FIPPA license.SATBA believes there is no significance competition in the renewable energy unless they start tenders.

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Germany as one of benchmarks started renewable FiTs in 2002 and they have started to organize tenders from 2016. It is because of scarcity of economic sites and maturity of industry. GEIC believes there is still a large gap between the countries targeted and actual capacity and Mokran see the market condition as a win-win situation for companies and the environment.

SATBA believes there is no significant barrier for investors in renewable energy sector, except items like currency fluctuation which is not under SATBA authority and cause loss for investors. Recent production of solar panels in Iran has caused the increase in custom tariffs for importing them. While Mokran did not face any legal barriers GEIC complains about bureaucratic process and several permits they should get. Companies must pay 9% tax according to article 132 of direct taxes but due to the location of their projects they are exempted from this tax for ten years. What is more they are exempted to pay custom tariff for products which have no domestic sample. Mokran and GEIC did not have any experience for investment or construction of renewable energy projects in other countries but SATBA previously conducted a comprehensive research about renewable energy market in oil producing countries. They were surprised why companies invest in the projects in countries like Saudi Arabia by 3.99 cents but not for 15 cents per kWh in Iran and found out they just bring a small portion of equity (10%) and the rest is financed by the government and it is more political rather than economic. They also did a benchmark of Norway but it is a completely different case. The big question regarding to renewable energy is: does the country need the industry (like Norway) or just the renewable energy generation (like Saudi Arabia)? The industry makes employment energy saving currency saving and also cuts the emission. While Persian Gulf region countries are looking for renewable electricity Iran is targeted to acquire renewable energy industry. Moving on technology life cycle stages and setting proper respective policies acknowledges this target. Pilot projects, prices trend studies and FiTs system are some parts of these policies at different stages. SATBA prefers energy efficiency as prevention over renewable energy as the cure. They proposes instead of big investment on renewable resources the country can construct efficient combined cycles and export the value added electricity to other countries. it might not It might not be economic any further in 20 years to generate electricity by gas. The country has more than 20000 MW reserve capacity.

Discussion and Implications

According to the present analysis, we found that, like other economics scarcities, resource limits, energy security in the long run, as well as environmental issues are the main drivers of Iran's transition to renewable resources. Although the country has an abundance of fossil fuel reserves, the use of them as an income resource will eventually deplete them. It would be a threat for the country's energy security in the long run. The related articles in the country's National Development Plan (NDP) for increasing the renewable resources share might confirm this fact. Iran's energy sector as a socio-technical system includes important actors like the Ministry of Energy and SATBA, institutions like NDP and different related material and knowledge. Iran's energy sector transition started in the first decade of 21st century with protected small size renewable power units as pilot units. This niche in the sector is still protected by the government by implementing different mechanisms such as FiTs, guarantees and exemptions. Landscapes such as Iran's high potential for renewable energy generation, NDP and commitments to UNFCCC are helping to niches to overcome barriers like low price and abundant fossil fuels. The mentioned niches by implementing the facilities of the landscape try to put pressure on the current regime, which is basically based on the fossil fuels for electricity generation to gradually transform it.At the macro level, the energy sector is dealing with three major development blocks. Since still a big portion of transportation and electricity generation consumes fossil fuels as the primary resource, ICE-Oil development block is still dominant in these sectors. Although ICE performed as the market suction tool, due to the country's big reserve of oil and gas, pipelines and oil tankers were not very effective for price decrease and its respective diffusion. But on the other side, an increase in the final service of energy generation as a secondary carrier shows that the electricity block has experienced a large growth. This sector benefited from a wide electricity network as the market suction and big power plants with high capacity and high voltage transformation functioned as market widening tools. The country's increasing trend of electricity consumption might show the ICE block is under development and is yet inefficient. In addition PC, Mobile and electric cars, as market widening mechanisms of this block, are not yet developed in the country.

Although the country has a high potential for transition of energy sector to renewable resources, the cheap fossil fuels and under developed infrastructures in electricity and ICT sector are big issues in this regard. Carbon pricing systems, subsidies and institutional support are reasonable methods for protection and development of the renewable sector in Iran. These methods take the environmental costs of fossil fuels in to the consideration and make fossil fuel prices competitive for consumption and feasible for generation. The country has already developed policies including: high selling prices such as FiTs or constraints on energy mix in NDP and other regulations, which benefit from legal authority and have resulted in the development of renewable energy sector, particularly in solar power. One big issue in the transition process is whether the country targeted to generate renewable energy or acquire renewable energy technology and industry. Based on the current policies of Iran's Ministry of Energy the country is targeted to localize the industry rather than just generating renewable electricity. Iranian model for energy sector transition is applicable to other oil producing countries with similar structure

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and potential, as long as they are willing to have renewable energy industry. Additionally, currently energy efficiency comes prior to renewable energy generation policies in the country.

Conclusion

Iran as a big owner of natural resources and a vast landscape, owns variable resources for energy production. Despite of these huge reserves, the country's development plan, international commitments for the reduction of GHG emissions and long term perspective of finite fossil fuels, provide the motivations for the transition to clean energy resources. Regardless of various plans and institutional support for renewable resources, the country's path dependency and trajectories for investment in the oil industry, the cheap resources of fossil fuels, the lack of infrastructures and technology are the main barriers for this transition. Decreasing price trend of renewable energy resources, CO_2 pricing, renewable energy subsidization and energy mix constraints are major.

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