ENERGY TRANSITION: TECHNOLOGICAL DIMENSIONS OF THE ZERO-CARBON PATHWAY

Muhammad Asif, King Fahd University of Petroleum and Minerals Dhahran, KSA
Email: asifm@kfupm.edu.sa, Mob: 00966540649188

ABSTRACT

Energy is a vital commodity for the advancement of modern socitey. In the twenty-first century, the global energy landscape is going through an unprecedented transition. The energy transition is a response to challenges like rising energy demand, depleting fossil fuel reserves, soaring energy prices, and most importantly, climate change. The energy transition, also regarded as low-carbon or zero-carbon energy transition, requires robust and persistent advancements on multiple fronts. This paper presents the concept of energy transition pathway. It also examines the key technological dimensions of energy transition pathways. It provides an overview of a range of technological that need play an active role in propelling zero-carbon energy transition. It also classifies these technologies under four major categories: decarbonization, decreasing use of energy, decentralization, and digitalization.

Keywords: Energy transition, climate change, renewable energy, distributed generation, digitalization, energy efficiency

1. INTRODUCTION

Energy has attained the status of an indispensable commodity to propel the functioning of modern world. Since the 18th century industrial revolution the significance of energy is ever growing. All sector - i.e. industry, transportation, household, agriculture, trade and commerce, education and healthcare – require refined energy resources to operate. Availability of adequate, reliable and affordable energy is also critical for socio-economic development [1]. Energy as a commodity is also intricately linked to national and global security. Nations across the world strive to ensure a secure and reliable energy supply to sustain their economies, protect the well-being of their citizens [2]. Energy is also vital for safeguarding national security and geostrategic interests as access to diverse and affordable energy sources is critical for reducing dependence on foreign entities and mitigating vulnerabilities to supply disruptions. Since the middle of the 20th century, on a global scale, energy plays a significant role in geopolitical dynamics, as nations compete for access to energy resources and seek to secure favorable energy trade agreements. Thus, the availability, affordability, and efficient management of energy resources are of paramount importance for both national stability and international relations [1].

The global energy scenario faces a daunting challenge of meeting the rapidly growing energy demand caused by factors such as the growing population, economic and infrastructure development, and urbanization. The Energy Information Administration (EIA) projects that the global energy demand will rise by 50% between 2018 and 2050 [1]. For sizable segments of the population in developing countries, access to refined energy supplies continues to be a major concern. Contributing to climate change is a significant aspect of human energy use. GHS emissions that go unchecked contribute to global warming. The greatest threat the world is currently facing is climate change, which is a result of global warming. Fossil fuels in particular, but all forms of energy, contribute to greenhouse gas (GHG) emissions. Fossil fuels are thought to be the main cause of anthropogenic carbon dioxide (CO_2) emissions; the industrial revolution of the 18th century is thought to have sparked the sharp increase in greenhouse gas emissions [2].

The environment and energy use are intimately related [3, 4]. According to estimates, CO_2 emissions from energy and industry have increased by 60% since the United Nations Framework Convention on Climate Change (UNFCCC) was signed in 1992, despite the commitments and efforts made by the international community to combat climate change. Seasonal disorder, a rise in sea level, and a trend toward more frequent and powerful weather-related disasters such flooding, droughts, heat waves, wildfires, and storms are all effects of climate change that are currently present. The issue necessitates an immediate paradigm shift for the entire energy industry.

The human use of energy has evolved through the course of history. Availability of refined and efficient energy resources has played a decisive role in the advancement of societies. In the 21st century, the international energy scenario is experiencing a profound transition as the world increasingly embraces a trend away from fossil fuels. In the recorded history, there have been two major energy transitions. The first one was a shift from wood and biomass to coal during the 18th century industrial revolution and the second one was the 20th century transition from coal to oil and gas. With the beginning of the 21st century the world is witnessing dawning of the 3rd energy transition [5-7].

The energy energy transition is experiencing rapid advancements on the technological as well as policy fronts. Renewable and low-carbon technologies are leading the technological drive of the energy transition. This paper examines the key technogical dimensions of the energy transition in etrms of zero-carbon pathways. It discusses the concept of energy transition pathways. It also highlights main points of prominent zero-carbon pathways. The paper also provides an overvirw of the important technologies being counted on to accomplish the energy transition.

2. ENERGY TRANSITION PATHWAYS

The energy transition unfolding in the 21st century is fundamentally a sustainability-driven energy pathway with the focus on decarbonization of the energy sector by shifting away from fossil fuels. Against the backdrop of Paris Agreement to rally the global fight against climate change, decarbonization of energy sector is the most critical dimension of energy transition, as the united nations (UN) calls upon the international community to decarbonize energy sector by 2050. Subsequently, leading economies and economic blocks including USA, European Union (EU), UK, and China are targeting to become zero-carbon between 2050 and 2060 [6]. The major decarbonization avenues include renewable energy, hydrogen and fuel cells, electric mobility, carbon capture and storage, and nuclear power. Holistically, however, the ongoing energy transition is not just about going low carbon or a shift away from fossil fuels. It is rather much more dynamic, thanks to the enormous changes and developments on the fronts of energy resources and their consumption, technological advancements, socio-economic and political response, and evolving policy-landscape. Technologically, this energy transition has four key dimensions: decarbonization, decentralization/distributed generation, digitalization, and decreasing use of energy through energy conservation and management [5].

An energy transition pathway refers to a strategic framework that guides energy transition. It is a strategic and planned approach to accomplish energy transition in terms of shifting from the current fossil fuels dominant energy system to a more sustainable and low-carbon energy system. Energy transition pathways encompass a set of policies, strategies, and actions to achieve specific energy transition goals. It typically encompass multiple dimensions, including decarbonization, renewable energy deployment, energy efficiency, technological innovation, and supportive policy frameworks, all aimed at achieving environmental sustainability and addressing the challenges of climate change. Some of the critical foundational blocks energy transition pathways incorporate include:

- Sustainability: An energy transition pathway is primarily driven by the goal of achieving a sustainable energy system. It strives to minimize environmental impacts, reduce carbon emissions, promote social equity, and foster economic development and stability.

- Decarbonization: Energy transition pathways aim to decarbonize the energy sector through reduction or elimination of carbon dioxide and other greenhouse gas emissions associated with energy system, from production to consumption.

- Renewable Energy Deployment: Arguably, central to an energy transition pathways is effective utilization of renewable energy sources, such as solar, wind, hydropower, and biomass.
- Energy Efficiency: Energy conservation and management is an important part of an energy transition pathway.
- Technological Innovation: Research and development (R&D) to develop and deploy new technological measures is an integral part of an energy transition pathway. Research and development efforts contribute to improving the efficiency, performance, and cost-effectiveness of clean energy solutions.
- Policy and Regulatory Frameworks: Supportive policies and regulatory measures is imperative to facilitate energy transition. Examples could include setting renewable energy targets, implementing carbon pricing mechanisms, providing financial incentives and subsidies, enacting regulations and standards, and fostering collaboration among governments, businesses, and other stakeholders.

While an energy transition pathway should involve a combination of technological, economic, policy, and societal changes, different organiztaions have proposed these pathways. Some of the prominent organizations to have proposed pathways include International energy Agency (IEA), International Renewable Energy Agency (IRENA), and the Organization of Petroleum Exporting Countries (OPEC) . These pathways can vary depending on factors such as regional resources, infrastructure, policy frameworks, and societal priorities as the United Nations recognizes that the energy transition is not a uniform, one-size-fits-all process. It reflects diverse priorities and entails a combination of abilities, technologies, policies, finance and resources. While the specific path to the end goal depends on individual circumstances, the destination is common [8, 10].

3. TECHNOLOGICAL DIMENSIONS OF ENERGY TRANSITION

3.1. Decarbonization

Since reducing CO2 and other GHG emissions is essential in the fight against climate change, decarbonization of the energy sector is at the core of the energy transition. A variety of technologies and strategies, including renewable energy, electric vehicles (EVs), hydrogen and fuel cells, carbon capture and storage (CCS), and the phase-out of fossil fuels, can help the energy sector become carbon-free. The decarbonization effort's most important element is renewable energy.

3.1.1. Renewable Energy

The main route toward a low- or zero-carbon energy sector is renewable energy. In terms of scientific advancements and economic maturity during the past couple of decades, renewable technologies, particularly solar PV and wind turbines, have made significant strides. In 2021, renewable energy installed capacity increased globally by 257GW, reaching to 3064GW. Over the last few years renewable energy has increased power generation capacity more than fossil fuels and nuclear power put together. For instance, more than 83% of all new power generation capacity installed globally in 2022 came from renewable sources as shown in Figure 1 [11].

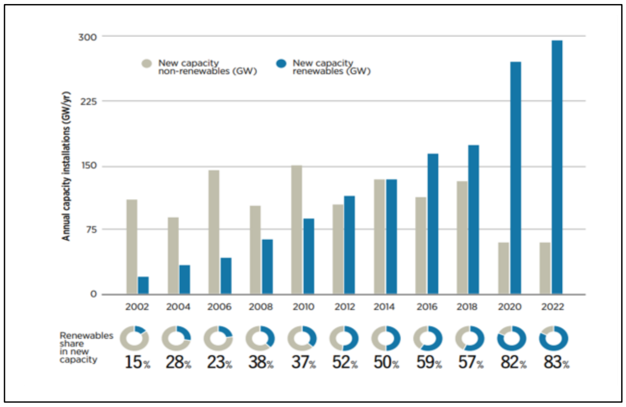

Figure 1: Growth of renewable energy in the power generation capacity

The development of technology, economies of scale, and supportive policies have contributed to the success of renewable energy sources. The development in science and engineering has had a significant positive impact on the solar and wind power industries. For instance, solar PV cells are improving in terms of efficiency and dependability. Concentrated solar PV cells have over 40% efficiency rates. The development of renewable technologies, particularly solar energy systems, is greatly aided by the expansion of their application fields. Solar PV and solar water heating systems have found extensive use in the construction industry.

3.1.2. Electric Vehicles

The transportation sector's attempts to reduce carbon emissions are being led by electric automobiles. Because they have fewer moving parts, electric cars are quiet to drive, convenient for city use, and environmentally friendly. Numerous policies are helping to promote the use of electric vehicles. Standards (such as requiring a specific percentage of clean vehicles or setting limits for the fleet's average emissions intensity) are included, as are purchase price subsidies (such as tax exemptions or tax credits); incentives encouraging the use of clean vehicles (such as free parking, zero-low road tax, and bus lane usage); pricing of externalities (such as carbon pricing); and scrappage policies that target emitting vehicles. Additionally, important in this regard are active support for R&D and infrastructure development. Electric vehicles (EVs) are making steep rise in car market share. The global electric vehicle market saw a 65% YoY growth in 2022 as EV sales climbed over 10.2 million units. EVs accounted for over 14% of the world’s passenger vehicle sales in 2022, compared to 9% in 2021[12].

3.1.3. Hydrogen

Hydrogen has excellent fuel characteristics. When compared to other frequently used fuels, it has the highest calorific value and produces no toxic emissions during use. The simplest and one of the most common elements in the universe is hydrogen. Despite its abundance, hydrogen does not exist alone; rather, it is bound to other elements and can be found in compounds like water, hydrocarbons, and carbohydrates. Both renewable and fossil fuels can be used to make hydrogen. In the first scenario, hydrogen can be created in a variety of ways, including coal gasification, natural gas reformation, and partial oxidation of heavy fossil fuels. However, since fossil fuels account for the production of over 90% of the world's hydrogen supplies. The environmentally friendly method of producing hydrogen is electrolysis, which includes using electricity to divide water into hydrogen and oxygen. In an ideal world, the electricity needed for electrolysis would come from renewable sources, creating "clean hydrogen," also known as "green hydrogen." Through a variety of technologies, hydrogen can be transported, stored, and used for energy applications.

3.1.4. Nuclear Power

There were 442 nuclear power plants in the world as of 2021, with a gross capacity of roughly 394 GWe, and an additional 57 power plants, with a total capacity of 60 GWe, were under construction [13]. As more than 8 GW of reactors were retired in 2021, there was a 3 GW reduction in the world's nuclear power capacity. While the majority of these lengthy shutdowns took place in G7 members Germany, the United Kingdom, and the United States, all of the additional capacity was in emerging market and developing economies. To maintain nuclear power through 2030, the world's nuclear capacity would need to grow by about 10 GW annually. G7 members should give lifetime extensions top priority in order to maximize new nuclear capacity and fortify the current low-emissions infrastructure. The goals embodied in net zero targets have fostered the development of novel nuclear power technologies, including as small modular reactors (SMRs), which have a reduced size of under 300 MW per reactor, down to 10 MW. SMRs have the potential to be more affordable, easier, and quicker to build than conventional large reactors. More than 70 designs are currently being worked on. SMRs might be produced in a factory and shipped to the ultimate destination, reducing financial requirements and accelerating project deadlines. With the decarbonization of power systems and the rise in the proportion of solar and wind energy, SMRs could be an important part of solving the increased flexibility required in power generation. They can also be used to produce hydrogen and heat. Expanding nuclear power is necessary to balance off the need for fossil fuels and enhanced renewable energy generation in order to realize the Net Zero Scenario. Nuclear power has reduced the need for coal, natural gas, and oil since it has been used to produce electricity for more than 50 years, which has led to a reduction of 66 Gt of CO2 emissions globally [14].

3.2. Distributed Generation

Energy produced around the site of use is referred to as decentralized or distributed generation, as seen in Figure 9. By avoiding or minimizing transmission and distribution setup, decentralized generating (DG) reduces costs and losses. In comparison to big, centralized generation systems, it offers better efficiency, flexibility, and economy. Depending on the project type and application, DG systems can utilize a variety of energy technologies. DG technologies can be divided into two categories, renewables-based systems and non-renewables-based systems, depending on the type of energy resource being used. Technologies like solar energy, wind energy, hydropower, biomass, and geothermal energy are used in renewables-based DG systems. Systems based on renewable energy have a number of advantages, including cheaper operating and maintenance costs and a reduction in greenhouse gas emissions. However, because these systems are frequently erratic, they require energy storage to provide dependable solutions. Internal combustion (IC) engines, combined heat & power (CHP), gas turbines, micro-turbines, Stirling engines, and fuel cells are just a few examples of the numerous non-renewable based DG technologies that are accessible. Different kinds of fossil fuels can be used by these technologies.

Solar and wind energy technologies are dominating the DG landscape. DG is giving workable solutions for addressing contemporary energy needs and supporting the livelihoods of hundreds of millions of people who still lack access to electricity or clean cooking options, and is thus playing a significant part in the global electrification initiatives.

3.3. Digitalization

The fourth industrial revolution, also known as digitalization, is what is causing the necessary fundamental transition in the energy sector, which is upending established market actors. In the context of the energy sector, digitalization is a general word. The gathering and analysis of energy data is a crucial aspect of digitalization in order to optimize energy demand and supply and achieve system performance and cost effectiveness. While the energy sector is being transformed by decarbonization, decentralization, and decreased energy use, digitalization—which is being facilitated by the proliferation of sensors, computing, communication, and predictive & control techniques—is also expected to alter how energy services are realized and provided. A variety of established and developing technologies, most notably artificial intelligence (AI), are used to do this. The fourth industrial revolution, often known as digitalization, is what is causing the energy sector to undergo the necessary fundamental change while upsetting established market actors [15]. In the context of the energy sector, the term "digitalization" is broad. The gathering and analysis of energy data to optimize energy demand and supply, increase system efficiency, and reduce costs is a crucial aspect of digitalization. While decarbonization, decentralization, and reduced energy use are changing the energy sector, digitalization—which is being facilitated by the proliferation of sensors, computing, communication, and predictive & control techniques—is also expected to alter how energy services are realized and provided. In particular, artificial intelligence (AI) is used to do this through a variety of established and developing technologies.

3.4. Decreasing Use of Energy

The whole energy value chain is under pressure due to the rapidly increasing global demand for energy. When the planet is already almost 70% over its bio-capacity, a one-dimensional approach of matching the rising energy demands with corresponding capacity addition is not a sustainable solution. Energy consumption reduction through energy efficiency initiatives must be the first step in a sustainable energy pathway that aims to meet global energy demands while safeguarding the environment. In comparison to expanding capacity, energy efficiency is thought to be a more effective way to address energy shortages. Energy efficiency benefits industrial and commercial organizations economically, environmentally, and competitively.

Energy efficiency is regarded to be the starting point of a sustainable energy transition program. It is also called as the first fuel for sustainable energy transition. The important role energy efficiency has to play in energy transition is described in Figure 2 [16]. The usage of energy can be decreased in all significant industries, including buildings, business, and transportation. Over one-third of the world's energy is consumed by buildings. Several energy efficiency techniques can be used to lower the energy consumption of buildings. Building energy-saving options can be broadly categorized as either active or passive energy-saving techniques . The type of building, site conditions, regional climate, desired comfort levels, and financial status all influence the energy efficiency solutions that are chosen. Energy demand in new and existing buildings can be decreased by 30% to 80% with energy efficiency techniques.

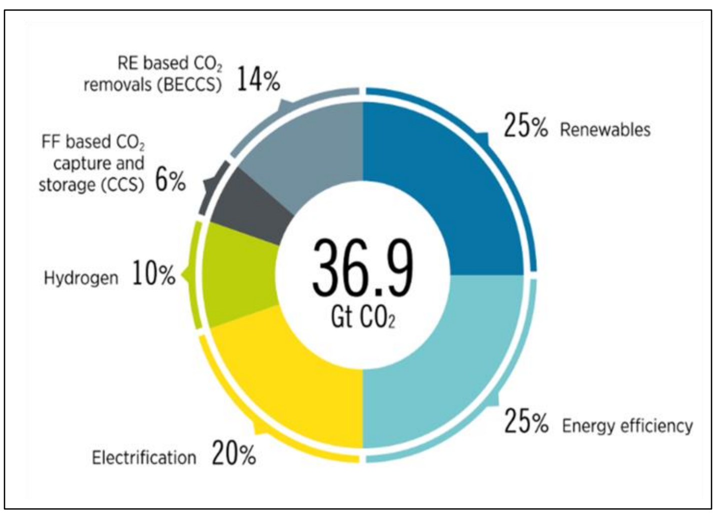

Figure 2: Decarbonization avenues

5. CONCLUSIONS

The 21st century energy transition is much more vibrant and multidimensional as compared to the 19th and 20th century energy transitions thanks to the enormous changes and advancements on the fronts of energy resources and their consumption, technological advancements, socio-economic and political response, and evolving policy-landscape. This energy transition is driven by the global pursuit for sustainable development having energy and environmental sustainability at its heart.

Energy transition pathways are strategic frameworks that guides energy transition. An energy transition athway presents a strategic and planned approach to accomplish energy transition in terms of shifting from the current fossil fuels dominant energy system to a more sustainable and low-carbon energy system. Some of the prominent organizations to have proposed pathways include International energy Agency (IEA), International Renewable Energy Agency (IRENA), and the Organization of Petroleum Exporting Countries (OPEC). While energy transition pathways can vary depending on factors such as regional resources, infrastructure, policy frameworks, and societal priorities, they all typically encompass multiple dimensions, including decarbonization, renewable energy deployment, energy efficiency, technological innovation, and supportive policy frameworks, all aimed at achieving environmental sustainability and addressing the challenges of climate change.. In terms of technology, the present energy transition has four broader dimensions: decarbonisation, decreased use, decentralisation, and digitalisation. Decarbonisation of the energy sector is led by solutions like renewable and low-carbon technologies, electric mobility, carbon capture and storage, and hydrogen and fuel cells. Decreased use of energy through energy conservation and management (ECM) is critical to energy sustainability. ECM is a widely established and techno-economically viable strategy across all major energy consuming sectors. Distributed generation or decentralised energy systems are becoming popular around the world to help cost effective and efficient supplies of energy. Digitalisation of energy systems is also deemed to be an important aspect of future energy systems. The International Energy Agency (IEA), regards energy digitalisation as important to help improve productivity, accessibility, cost-effectiveness, and overall sustainability of future energy systems.

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