1

Introduction to the Four-Dimensional Energy Transition

Muhammad Asif

Department of Architectural Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

1.1 Energy: Resources and Conversions

Growing human dependence on energy is one of the defining characteristics of the modern age. Historically, the increasingly extensive and efficient utilization of energy has been pivotal in the evolution of societies. However, the eighteenth/nineteenth-century industrial revolution has been a turning point in human-energy interaction. Energy has attained the status of a prerequisite for all crucial aspects of societies, i.e. mobility, agriculture, industry, health, education, and trade and commerce [1]. Energy resources exist in many physical states, harnessing and capitalizing through various technologies. They can be broadly classified into two categories: renewables and non-renewables. Renewable energy resources are naturally replenished or renewed.

Examples of renewable resources include solar energy, wind power, hydropower, and wave and tidal power. Energy resources that are finite and exhaustible are non-renewable such as coal, oil, and natural gas. In terms of resources, energy can also be classified into two types: primary resources and secondary resources. Primary energy resources consist of natural or unrefined resources such as raw fossil fuel, biomass, solar radiation, wind, and flowing water. These resources can be extracted or harnessed directly from nature. Secondary energy resources are refined/converted from primary resources. For example, electricity is a secondary energy resource that can be produced by transforming different primary resources. Figure 1.1 shows examples of primary and secondary energy resources.

Energy can be classified in different forms, typically through several conversion and transformation processes in their usable life cycle. Different forms of energy include chemical energy, thermal energy, mechanical energy, electrical energy, light energy, and sound energy. The four commonly used forms of energy and their mutual transformations are shown in Figure 1.2. It also highlights the associated energy resources.

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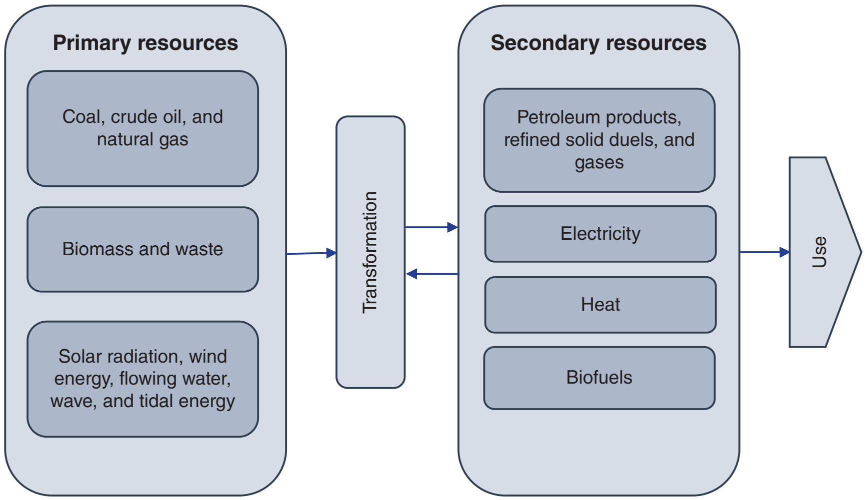

Figure 1.1 Primary and secondary energy resources.

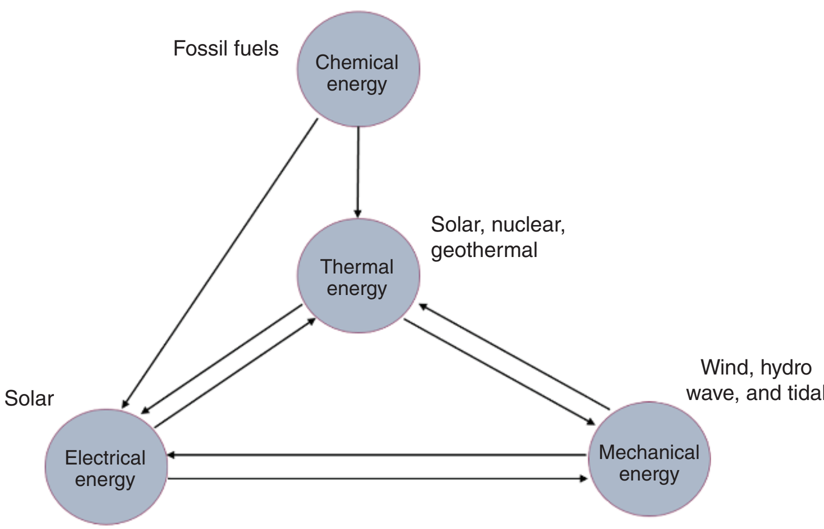

Figure 1.2 Energy resources and transformations.

The energy contained in fossil fuels – coal, oil, and natural gas – contributing to almost 80% of the world's total primary energy supplies is chemical energy. Nuclear power and geothermal energy enter the usable energy equation in the form of thermal energy. Wind power, hydropower, and wave and tidal power are capitalized as mechanical energy, while solar energy can be harnessed in the form of thermal energy and electrical energy. The most common energy requirements in day-to-day life include heat, electricity, and mechanized mobility. Heat is primarily acquired through fossil fuels, making it a chemical to thermal energy conversion process. Useable heat can also be directly acquired from solar energy, geothermal energy, and nuclear power. One of the most common energy transformation pathways is to convert chemical energy into mechanical energy. The first stage in this transformation process involves converting fossil fuel's chemical energy into thermal energy, usually in the form of steam, hot water, or hot gases, through boilers, rotating turbines, or internal combustion engines. In the second stage, thermal energy is converted to mechanical energy through internal combustion engines and rotary turbines. The produced mechanical energy is used in many applications, such as running machinery and transportation. This mechanical energy can also be used to produce electricity with the help of generators. Electricity can be produced through various transformation routes, including chemical–thermal–mechanical–electrical, thermal–mechanical–electrical, and mechanical–electrical.

1.2 Climate Change in Focus

Climate change is arguably the biggest challenge the world faces today. It is widely regarded as a consequence of global warming. The gradual warming of the Earth's atmospheric temperature as a small fraction of the solar radiation is entrapped by greenhouse gases. Greenhouse gases are part of the Earth's atmosphere. Human activities such as burning fossil fuels, transportation, power generation, and industrial and agricultural processes increase the concentration of these gases in the atmosphere. The eighteenth-century industrial revolution is considered to have triggered the rapid growth in the release of greenhouse gases. For example, the atmosphere's carbon dioxide (CO_2) concentration has increased from the pre-industrial age level of 280 parts-per-million (ppm) to 415 ppm. The acceleration in the growth of CO_2 concentration can be gauged from the fact that almost 100 ppm of the total 135 ppm increment has occurred since 1960. Commonly known greenhouse gases include water vapor, carbon dioxide, nitrous oxide, methane, chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs). The impact of a greenhouse gas depends on various factors such as their level of concentration or abundance, lifetime (duration of stay in the atmosphere), and ability to trap radiation (radiative efficiency). Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities and has been adopted as a reference index to represent the concentration of greenhouse gases. Accordingly, the global warming potential (GWP) – an index to compare the global warming impact of different greenhouse gases – of CO_2 has been regarded as one.

Due to numerous involved factors and their dynamic and complex interrelationship, it is difficult to precisely predict the nature and extent of the implications of climate change. However, based on the expert interpretations of the available data and scientific models, certain weather-related incidents are attributed to climate change with a great degree of confidence. Accordingly, climate change leads to many challenges, including seasonal disorder, a pattern of intense and more frequent weather-related events such as floods, droughts, storms, heat waves and wildfires, financial loss, and health problems [2]. Climate change also exacerbates water and food crises in many parts of the world. In recent decades, the global focus on climate change has increased exponentially. Extreme weather events and natural disasters such as floods, storms, hurricanes, wildfires, and droughts have played a vital role. Since 1880, the atmospheric temperature has increased by 1.23 °C (2.21 °F). The rising temperature is driven largely by increased anthropogenic greenhouse gas emissions. According to the US National Aeronautics and Space Administration (NASA), most atmospheric warming has occurred over the last four decades [3]. Warmer temperatures are increasing the sea level due to the melting of glaciers. During the twentieth century, the global sea level rose by around 20 cm. The rise in sea level has been accelerating every year – over the last two decades. It has almost doubled that of the last century [3]. Glaciers are shrinking worldwide, including the Himalayas, Alps, Alaska, Rockies, and Africa.

Extreme weather conditions and climate abnormalities are becoming more frequent. The situation is already widely dubbed as the climate crisis. With the recorded acceleration in the accumulation of greenhouse gases and consequent increase in atmospheric temperature, climate change-driven weather-related disasters are becoming more intense and recurrent. The recent seven years have been the warmest since records began, while 2016 and 2020 are reportedly tied for the hottest year on record [3]. July 2021 witnessed heat waves, wildfires, storms, and floods worldwide. North America particularly faced intense heat waves, besides record high temperatures and massive wildfires. California's Death Valley recorded a temperature of 54.4 °C (130 °F), potentially the highest ever temperature recorded on the planet, and British Columbia witnessed a temperature of 49.6 °C, obliterating Canada's previous national temperature record by 8 °C [4]. While the heat wave killed over 500 people in Canada alone, Europe and Asia were hit by unprecedented flooding. High temperatures, heat waves, and droughts are also causing record-breaking wildfires. The 2019–2020 wildfire in Australia burnt around 19 million ha, resulting in an economic loss of over AU$ 100 billion that became the costliest natural disaster in national history [5]. The year 2021 has also witnessed heat waves fueling massive wildfires in Australia, North America, and Europe. Extreme wildfires are now becoming a new normal as experts predict more fires and higher degrees of devastation as each fire season comes.

1.3 The Unfolding Energy Transition

The global energy scenario experiences a string of challenges such as climate change, rapid growth in energy demand, depletion of fossil fuel reserves, volatile energy prices, and lack of universal access to energy. The post-industrial revolution energy scenario is closely linked to global warming as fossil fuels are responsible for the bulk of greenhouse gas emissions. Due to surging population, economic and infrastructural development, and urbanization, fast growth in the global energy demand is adding pressures on the energy supply chain. According to the Energy Information Administration (EIA), between 2018 and 2050, the world energy requirements are projected to increase by 50% [6]. Most of this growth in demand is associated with developing countries.

Energy use is closely linked to the environment. It is estimated that despite the pledges and efforts by the global community to tackle climate change, 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 [7]. Climate change is already there with its implications like seasonal disorder, rising sea level, a trend of more frequent and intense weather-driven disasters such as flooding, droughts, heat waves, wildfires, storms, and associated financial losses [8, 9]. The situation calls for an urgent paradigm shift in the energy sector. As a response to the challenges, the global energy sector is going through a transition to ensure a supply of energy compatible with the demands of a sustainable future for the planet. The International Renewable Energy Agency (IRENA) defines the energy transition as "a pathway toward the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century." The ongoing energy transition is needed to reduce energy-related CO_2 emissions to limit climate change [10].

Through the Paris Agreement, the world has adopted the first-ever universally legally binding global climate deal to avoid the dangers of climate change by limiting global warming to below 2 °C. However, the Intergovernmental Panel on Climate Change (IPCC) warns that the world is seriously overshooting this target, heading toward a higher temperature rise, asking for major changes in four global systems: energy, land use, cities, and industry. The energy sector is where the greatest challenges and opportunities exist [11].

Following the Paris Agreement, many major economies and economic blocks – such as the US, China, the EU, and the UK – have committed to net-zero carbon emissions. The US, EU, and the UK are targeting net-zero emissions by 2050, while China by 2060. Each country or economic block is developing its plans for incrementally achieving its goals, but they will all require a transformation of the energy sector [11]. For example, the EU has decided to reduce emissions by 55% from the 1990 level by 2030 to go net-zero by 2050. The US has announced to cut emissions by 40–43% by 2030. Some of the notable initiatives include having 30 GW of new offshore wind projects and cutting the cost of solar energy further by 60% over the next decade to achieve 100% renewable electricity by 2035 [12]. China targets emissions to peak by 2030 to reach carbon neutrality by 2060. Similarly, the UK has plans to cut emissions by 68% by 2030 to reach the target by 2050. A landmark decision the UK has made in shifting away from fossil fuels is closing down all coal power plants by 2024, which means the country reduces its reliance on coal for power generation from around one-third to zero within a decade. It is a major step the UK has taken toward the transition away from fossil fuels and decarbonization of the power sector to eliminate contributions to climate change by 2050 [13].

Renewable energy is the backbone of the energy sector's transition toward zero carbon emissions. Over the last few decades, renewable technologies, especially solar photovoltaic (PV) and wind turbines, have made significant technological and economic progress. The global installed capacity of renewables increased from 2581 GW in 2019 to 2838 GW in 2020, exceeding expansion in the previous year by almost 50%. For several years, renewable energy is adding more power generation capacity than fossil fuels and nuclear power combined. In 2020, renewables contributed to more than 80% of all new power generation capacity added worldwide. The renewable sector's growth is propelled by solar and wind power, with the two technologies accounting for 91% of the new renewables added [14]. There was over US$ 303 billion invested in renewable energy projects during the year [15]. The upward scale of the renewable developments can be gauged from China's first 100 GW phase of solar and wind power buildout. The initiative will likely be expanded to several hundreds of GW in capacity as China aims to develop 1200 GW of renewables by 2030 [16]. The renewables growth trends are projected to continue as the annual capacity addition of solar and wind power is set to grow fourfold between 2020 and 2030 [11].

Renewables-based decentralized or distributed generation systems are helping both urban and rural settings, providing several energy services. Solar PV is one of the most successful technologies, especially at small-scale and off-grid levels. Since 2010, over 180 million off-grid solar systems have been installed worldwide, including 30 million solar-home systems. In 2019, the market for off-grid solar systems grew by 13%, with sales totaling 35 million units. Renewable energy also supplied around half of the 19 000 mini-grids installed by the end of 2019 [15]. Efficient biomass systems, such as improved cooking stoves and biogas systems, are also helping with the global efforts to access clean energy [1, 17].

1.4 The Four Dimensions of the Twenty-First Century Energy Transition

The use of energy has evolved through the course of history. The availability of refined and efficient energy resources has played a decisive role in advancing societies, especially since the industrial revolution of the eighteenth century. In the twenty-first century, the international energy scenario is experiencing a profound transition as the world increasingly embraces a trend away from fossil fuels. In recorded history, there have been two major energy transitions. The first was a shift from wood and biomass to coal during the eighteenth-century industrial revolution, and the second was the twentieth century transition from coal to oil and gas. With the advent of the twenty-first century, the world is witnessing the dawn of the third energy transition.

The energy transition unfolding in the twenty-first century is unprecedented. It is much more vibrant, intriguing, and impactful than the earlier ones. It is fundamentally a sustainability-driven energy pathway focusing on decarbonizing the energy sector by shifting away from fossil fuels. Therefore, this energy transition can also be termed "sustainable energy transition" or "low-carbon energy transition." However, the ongoing energy transition is not just about reducing carbon or shifting away from fossil fuels. 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, it is much more dynamic. This energy transition has four key dimensions: decarbonization, decentralization, digitalization, and decreasing energy use.

1.4.1 Decarbonization

Decarbonization of the energy sector is the most important dimension of the ongoing energy transition. Reduction in CO_2 and other greenhouse gas (GHG) emissions is fundamental to the fight against climate change. The energy sector can be decarbonized through various technologies and solutions, including renewable energy, electric vehicles (EVs), hydrogen and fuel cells, carbon capture and storage (CCS), and phasing out of fossil fuels. The replacement of fossil fuels with renewable energy is the most critical part of the decarbonization drive. Renewable energy is already supplying 26% of the global electricity needs. According to International Energy Agency (IEA), to achieve net-zero emissions by 2050, almost 90% of the global electricity generation must be supplied from renewables. While some decarbonization solutions like hydrogen, fuel cells, and CCS are yet to have techno-economic maturity, electric vehicles are already making an impact. For example, in 2020, the worldwide sale of EVs increased by 41% despite the COVID-related economic downturn and a drop of 6% in the overall sale of vehicles. During the same year, Europe recorded the registration of new electric cars increase by 100%, and the number of electric car models available worldwide increased from 260 to 370 [18]. While electric mobility is also paving its way in the aviation and ship industry, the sale of electric cars is expected to increase from around 3.5 million in 2020 to over 55 million by 2030 [11].

1.4.2 Decentralization

Decentralized or distributed generation is the energy generated close to the point of use. Decentralized generation (DG) avoids/minimizes transmission and distribution setup, saving costs and losses. It offers better efficiency, flexibility, and economy than large and centralized generation systems. DG systems can employ various energy resources and technologies and be grid-connected, off-grid, or stand-alone. Renewables like solar and wind power systems are leading the DG landscape. DG is leading in the global electrification efforts, presenting viable solutions for modern energy needs and enabling the livelihoods of hundreds of millions who still lack access to electricity or clean cooking solutions [4]. Solar PV is one of the most successful DG technologies, especially at small-scale and off-grid levels. It is estimated that since 2010, over 180 million off-grid solar systems have been installed, including 30 million solar-home systems. In 2019, the market for off-grid solar systems grew by 13%, with sales totaling 35 million units. Renewable energy also supplied around half of the 19 000 mini-grids installed worldwide by the end of 2019. Efficient biomass systems such as improved cooking stoves and biogas systems are also helping the global efforts toward clean energy access. In 2020, the installed capacity of off-grid DG systems grew by 365 MW to reach 10.6 GW. Solar systems alone added 250 MW to have a total installed capacity of 4.3 GW.

1.4.3 Digitalization

The digital revolution is also revamping the energy sector. Digitalization of the energy sector employs technologies like artificial intelligence, machine learning, big data and data analytics, Internet of Things, cloud computing, blockchain, and robotics and automation. These technologies are at various degrees of techno-economic maturity for their application in the energy sector. In general, digitalization is revolutionizing the energy sector by improving the productivity, safety, accessibility, and overall sustainability of energy systems. New, smarter modeling, monitoring, analyzing, and forecasting energy production and consumption are helping the sustainable energy transition. However, with its advantages, digitalization is also posing several challenges. Most importantly, digital transformation heavily relies on large datasets, which is increasingly exposing the utilities and energy industry to cyber security risks.

1.4.4 Decreasing Energy Use

Energy demand is rising worldwide, and it is estimated that between 2018 and 2050, global energy requirements will increase by 50%. A one-dimensional approach to matching the growing energy demand with corresponding capacity addition is not a sustainable solution, especially when the planet is already overshooting its bio-capacity by almost 70%. Any sustainable way to satisfy global energy requirements has to begin with decreasing energy use through energy efficiency (EE) measures. Energy efficiency is a better solution to address energy shortages than adding new capacity. A negawatt – a watt of energy not used through energy efficiency measures – is considered the cheapest watt of energy. Energy efficiency delivers economic and environmental gains to industrial and commercial entities, besides offering a competitive edge. With the available technologies, building and industrial sectors can reduce their energy consumption by 40–80% and 18–26% [19, 20].

1.5 Conclusions

The twenty-first century energy transition is fundamentally a sustainability-driven energy pathway. In the fight against climate change, the main focus of the energy transition is on decarbonization by shifting away from fossil fuel-based energy systems. The energy transition is perceived as a pathway toward the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century. Following the Paris Agreement, several major economies and economic blocks – including the US, the UK, and the European Union – have committed to net-zero carbon emissions by 2050, while China has targeted it for 2060. However, the ongoing energy transition is not just about reducing carbon or shifting away from fossil fuels. It is more vibrant and impactful, thanks to the enormous changes and developments on energy resources and their consumption, technological advancements, socio-economic and political response, and evolving policy landscape. This energy transition has four main and closely linked dimensions: decarbonization, decentralization, digitalization, and decreasing energy use. The energy sector can be decarbonized through various technologies and solutions, including renewable energy, electric vehicles (EVs), hydrogen and fuel cells, CCS, and phasing out of fossil fuels. Renewable energy has a pivotal role in decarbonizing the energy sector. Having accounted for over 80% of the worldwide newly added power generation capacity in 2020, renewable energy has already become an important stakeholder in the global energy sector. However, it may be challenging for the developed and industrialized nations to adjust to removing fossil fuels and other carbon-intensive processes from their economies. Energy transition will be harder for the developing nations that lack financial resources, infrastructure, policy measures, and technical know-how.

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