International Journal of Social Sciences and Management Review

Volume: 06, Issue: 02 March - April 2023

ISSN 2582-0176

SUSTAINABLE INNOVATIVE MATERIALS AS A CRITICAL SUCCESS FACTOR FOR RENEWABLE ENERGY DEPLOYMENT IN THE CURRENT ENERGY TRANSITION

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https://doi.org/10.37602/IJSSMR.2023.6207

ABSTRACT

The world is racing towards a climatic tipping point unless very urgent steps are taken to force the global agenda of limiting the atmospheric temperature to within 1.5o C above the preindustrial level. While certain opportunities are associated with renewable energy sources such as energy security, energy access, social and economic development, climate change mitigation, and reduction of environmental and health impacts, nonetheless, some challenges such as market failures, lack of information, access to raw materials for future renewable resource deployment, and our daily carbon footprint continue to plague the sustainability of renewable energy sources towards climate change mitigation. Also, the paper identified other distinct societal issues besides energy, such as health and housing that are materials-centric that will play a critical role to guarantee a sustainable future on Earth. Consequently, the survival and sustainability of this energy transition will depend heavily on innovative materials science and technologies that can engineer and produce sustainable materials that will overcome those challenges such as intermittency, lower conversion efficiencies, and higher production costs, and guarantee cleaner and more eco-friendly utilization of renewable energy sources, while also meeting other material based social needs. The paper thus recommended full collaboration amongst the public and private sectors within the academics, government, businesses, and entrepreneurial nonprofit organizations to accelerate clean production and sustainable materials usage. Such innovative collaborations will provide data-driven tools that will enhance the decision process in identifying and selecting inherently safer chemicals and sustainable materials for a healthy renewable energy economy. Also, there is an urgent need to retool and reskill the existing skillsets required by these new technologies and infrastructures. The world should also pay closer attention to the usual geopolitics that is associated with such massive global trade and commercialization, and finally, while renewables are clearer and more environment friendly, it is imperative that the total life cycle from cradle to consumption, and its impact in each stage on the environment and man be taken seriously, in order to avoid the build-up of any environmental hazardous chemicals in due course.

Keywords: Sustainable Energy, Innovative Materials, Energy Transition, Renewable Energy Sources, Carbon Neutrality, Net Zero Emissions, Life Cycle

1.0 INTRODUCTION

Humanity's survival and development have been hinged on the discovery and innovation of materials as early as history has recorded. Consequently, literally, every facet of life has been greatly influenced and anchored on one material or the other, such as in transportation, housing, clothing, communication, recreation, and food production. The advancement of society and humanity thus rests on their ability to produce and manipulate materials to fill their needs, which in some respect has also defined the historical era of civilization by the dominant material in that period such as the Stone Age, the Bronze Age, and the Iron Age. (Callister and Rethwisch, 2010). Ferguson, 2007, showed that many civilizations were already developing under one material specie or another other such as Asia Minor, now Turkey, around 1500 BC that were experimenting with iron, while Mesopotamia, now Iraq, was working under the Bronze Age. About this time, Ferguson reported that the Europeans, Palestinians, and Egyptians were in operating under the Copper and early Bronze Age, while the Chinese were well advanced in the use of bronze, and had already begun to melt iron. The Spaniards and Portuguese were operating in the overlap of the Stone Age and the copper age, also referred to as the Chalcolithic period, whilst North Africa was in their late Stone Age. At about the same time, the Americas were also still under the Chalcolithic period, with beautiful artifacts of gold, silver, and copper - metals that they found naturally. So while several natural materials, though limited, such as stone, wood, clay, skins, mineral ores, existed, and with time man was able to manipulate these materials through innovative techniques to produce several other materials with properties that are superior to their natural progenitors. As science and technology developed, especially in the 18th and 19th centuries, scientists also came to understand the relationships between the structural elements of materials and their properties, which has catalyzed the development of tens of thousands of different materials with specialized characteristics, such as metals, plastics, glasses, and fibers. (Callister and Rethwisch, 2010). Ferguson, 2007 added that this explosive development led to the Metallurgic Age, which also saw the development of the Industrial Revolution in Britain that completely transformed that agrarian society into an industrial economy. Ferguson, 2007, thus quoting Cahn, R.W as stated that a modern industrial economy is no better than its best materials and has thus led to the evolution and the current revolution of material science and engineering, as a separate discipline, as all previous historic materials discoveries and developments were carried out by innovators and inventors who have applied knowledge and skills developed in other materials specialisms, other sciences, or engineering. Present material evolution is thus driven mostly by the forces of technological innovation, environmental concerns, geopolitical dynamics, changes in demand and supply patterns, and national and global policy shifts. (World Economic Forum Insight Report, 2018).

2.0 ENERGY TRANSITION

Energy is broadly categorized as Renewable and Non-Renewable sources, with non-renewables as those sources that are non-self-replenishing, and constantly depleting with products such as fossil fuels - coal, crude oil, gas, and nuclear energy from uranium sources. (IEA, 2019). Renewables are self-regenerative, and energy sources that are derived and also in abundance in nature such as sunlight, waves, ocean tides, geothermal, hydropower, bioenergy from biomass, and hydrogen. Fossil fuels are fuels formed from decayed organic matter buried over millions of years under the actions of pressure and temperature. (Kolhe and Khot, 2014). While conventional natural resources, such as wind, solar, and hydro are classified under renewable energy sources, another important renewable energy source is Bioenergy, which is an energy source that generates electricity and the production of gases and liquid fuel, and chemicals from the direct combustion of fuel wood and other biomass residues. (Bhatia, 2014).

Other renewable sources such as geothermal energy which is from the internal heat from the earth's crust are used in power generation to space heating and/or air conditioning. Figures 1, and 2 present charts of the global trend of renewable sources from 1965 to 2019 as reported by Ritchie and Roser (2019). Renewable technologies contribute about 11% of the global primary energy source in 2019.

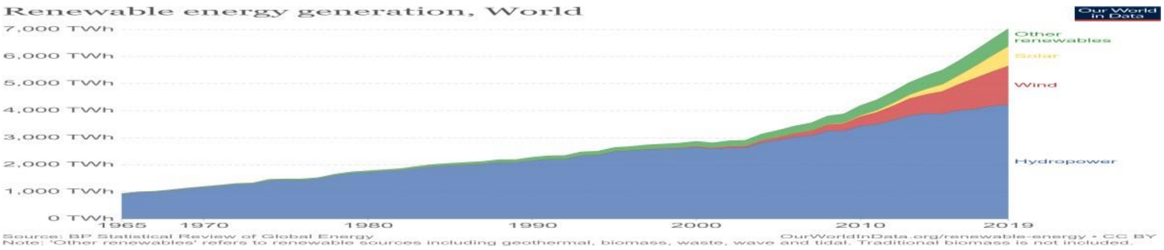


Figure 1: Renewable Energy Generation, by Sources. After Ritchie and Roser (2019)

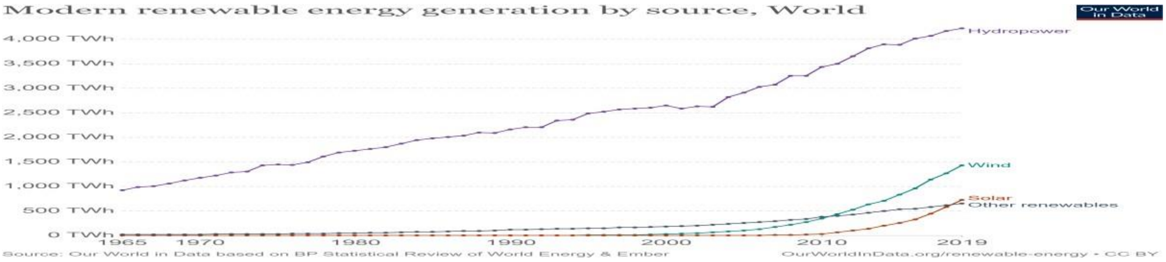


Figure 2: Modern Renewable Energy Generation by Source, World. After Ritchie and Roser, (2019)

The IEA in its 2020 report showed that while global energy demand declined by 3.8% in the first quarter of 2020, during the COVID19 lockdowns across the globe, especially in Europe, North America, renewables, as can be seen in figure 3, held strong amongst the other energy sources, showing its resilience in terms of energy security.

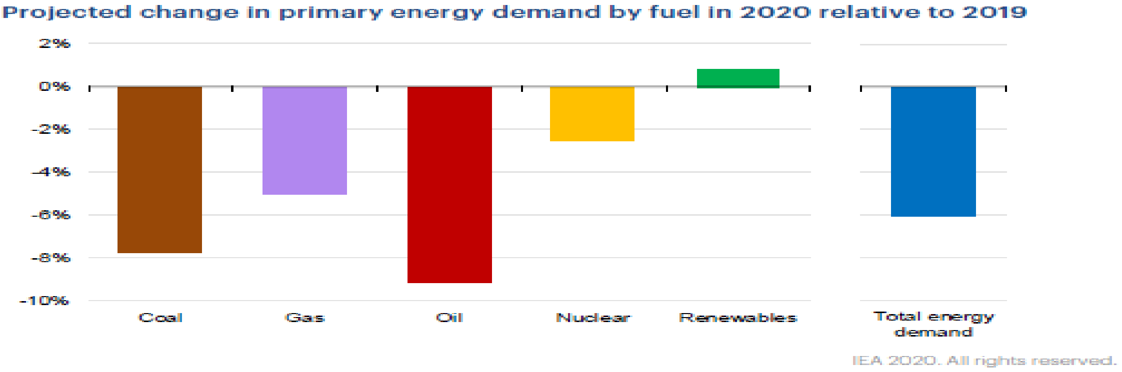


Figure 3: Projected change in primary energy demand by fuel in 2020 relative to 2019. Source IEA, 2020.

Figure 4 pictures the historical energy transition since 1750, with the increasing impact of renewables in the energy mix.

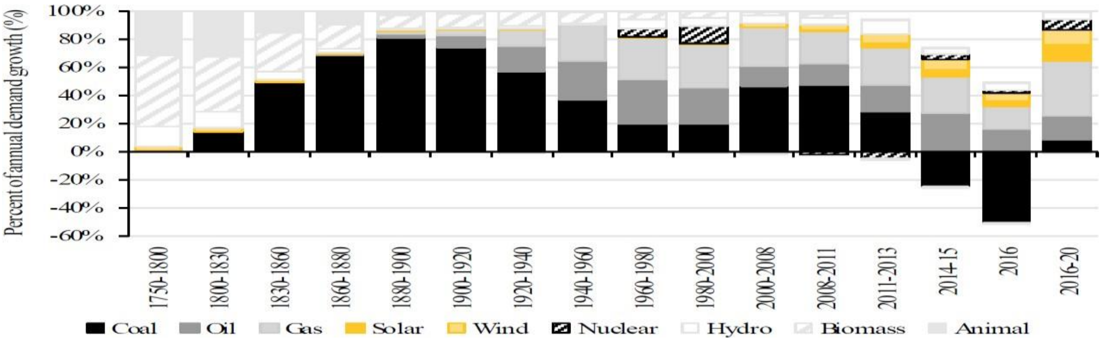


Fig. 4: Global Energy Supply by Source (percent). Source: Fattouh et al 2018. (Oxford Institute of Energy Studies)

Energy transition according to International Renewable Energy Agency (IRENA) is a pathway toward the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century. However, Sovacool, 2017, defined energy transition as ‘a particularly significant set of changes to the patterns of energy use in society, potentially affecting resources, carriers, converters, and services. In this definition lies the idea that energy transition refers to the time between the first introduction of a new source of primary energy or prime mover, to the time when it captures a significant or controlling share in the energy mix. This elapsed time according to Sovacool (2017) could either be protracted or quick as held by two varying schools of thought. One group viewed energy transition as an inclusive system that involves not only the national sources of energy supply and their compositional changes, but also viewed energy transitions as involving different things such as the use of fuels, services, and end-use devices that have occurred quite quickly, within a few years. The second group however, holds that sustainable energy transition generally takes much longer time, far beyond a decade, as to them, energy transitions are prolonged affairs that take decades to accomplish, and the greater the scale of prevailing uses and conversions, the longer the substitutions will take. They viewed that fast transition only occurs as anomalies and mostly in countries with small populations or under unique circumstances that can hardly be replicated elsewhere. The first energy transition from wood to coal occurred around the 1600s in Europe due to the scarcity of wood to meet the increasing energy demand with coal becoming the dominant energy source in the 1780s. The use of coal soon expanded with the invention of the first coal-fired power plant in the world by the French in 1875. (Zou et al 2016). In the United States, though wood was being used side by side with coal, the demand for coal across the country quadrupled between 1880 and 1918 as large amounts of coal were needed in the production of iron and steel as well as in the railroad industry. (NDSU). Coal soon began to pose environmental challenges at the onset of the 20th century, a condition that gradually paved way for a more qualitative energy source – petroleum in oil and gas. Petroleum was found to be more flexible and adaptable than coal, as kerosene that was refined from crude became more reliable and relatively inexpensive compared to “coal oils” and whale oil for fueling lamps. Naturally, with these better qualities, and with innovative technologies in the 20th century, the second energy transition occurred with petroleum crude oil taking over from coal as the preferred fuel to power the global economy. Oil also became a strategic energy source and critical military asset in its role during World War 1 in powering ships, trucks and tanks, and military airplanes. (EKT Interactive, 2020, Oil 101). Ague and Oristaglio (2017), added that petroleum products actually became prominent as an alternative fuel during World War I due to the invention and use of more advanced war fares.

2.1 The Current Energy Transition

The current energy transition is driven primarily to arrest the rising global temperature, which has resulted to extreme global warming and weather conditions due mainly to high carbon and methane, and other greenhouse gas (GHG) emissions into the atmosphere. The transition to renewables is limit the global average temperature within 1.5OC by the end of the century as agreed at the 2015 Paris Climate Summit (or COP21). The gases, five in number that are responsible for total global warming are:

1. Carbon dioxide (CO2): a by-product of fossil fuel, deforestation, and the production of cement and other materials contributes about 52% of all global warming. Technically, about 80% of CO2 emissions remain active for about 200 years while the balance 20% can take up to 30,000 years before its impact disappears.
2. Methane is a Shortlived Climate Pollutant (SLCP) that only remains effective for about 12 years in the atmosphere. It is produced from multiple sources such as livestock production, agriculture, sewage treatment, natural gas and oil production and consumption, and coal mining, and is also given off from wastes. Though methane contributes only 15% of global warming, it is about 84 times more potent than Carbon Dioxide in the first two decades in the atmosphere.
3. Halogenated compounds such as CFCs, HCFCs, HFCs, PFCs, SF6, and NF3 contribute only 11 % of global warming. These are chemical products from diverse sources such as refrigeration, air conditioning, electrical and electronic equipment, medicine, metallurgy, etc., these compounds can last from a few months to tens of thousands of years in the atmosphere depending on its constituent compound. The CFCs, HCFCs, HFCs, and PFCs have been banned in much of the world because they have heat-trapping potential thousands of times greater than CO2
4. Tropospheric ozone are gases produced from reactions between carbon monoxide (CO), nitrogen dioxide (NO_2), and VOCs (Volatile Organic Compounds), during the burning of fossil fuels. They contribute about 11% of global warming and only last for a few months in the atmosphere.
5. Finally, nitrous oxide, a product from the use of fertilizers, fuel use, chemical production, and sewage treatment, contributes around 11% to global warming and can last for about 114 years in the atmosphere. Nitrous oxide is 264 times more powerful than CO2. (Acciona, 2019).

3.0 BRIEF CLASSIFICATION OF RENEWABLE ENERGY SOURCES

Eight types of renewable energy sources are known which are solar, wind, geothermal, hydropower, biomass, tidal power, wave power, and fuel cells. (New World Encyclopedia, 2018). This section presents a brief on each of these sources.

3.1 Solar Energy

Solar energy is the primary energy source available to the earth and the ecosystem, as it is the main life supporting energy source that drives the photosynthesis reaction. As a matter of fact, the sun drives all sectors of the energy system besides that from from nuclear energy, geothermal energy and tidal power. Solar energy is the source of all bioenergy from biomass on the surface of the earth, and by extension also the origin of fossil fuels, which is actually formed through the process of millions of years of photosynthesis under the action of burial, heat and temperature in the earth surface. It is also responsible for the world's winds; it evaporates the water which is responsible for rain; waves and ocean thermal power are both a result of insolation. (Bhatia, 2014). Solar radiation can be converted directly as electricity through Photovoltaic (PV) devices or solar cells, or indirectly through solar thermal or electric power systems using concentrated or as chemical energy into solar fuel (Jager et al (2014).

3.2 Wind Power

Wind energy comes from the uneven heating of the atmosphere by the sun due to the irregularities of the earth's surface, and rotation of the earth (Bhatia, 2014). The heat is more intense near the earth's equator than near the North and South Poles. This heating translate into about 1 to 2% of the solar energy as wind energy, and this is about 50 to 100 times more than the energy converted into biomass by all plants on Earth. (Salameh, 2014). This is what made wind a renewable energy source, since it depends on sunshine, while the terms 'wind energy' or 'wind power' describe the process by which the wind is converted into mechanical power or electricity. As a renewable energy, wind is in natural abundance, widely distributed, clean, and produces no greenhouse gas emissions during operation. Such conversion uses wind turbines to make electricity, windmills for mechanical power, wind pumps for water pumping or drainage, or used as wind sails to propel ships.

3.3 Geothermal Energy

A geothermal resource is simply a reservoir inside the Earth that generates heat both in the solid rock and in the fluids contained in the fractures and pore spaces of the rock that can be extracted safely and economically, and utilized either for generating electric power or used for other domestic or industrial and agricultural application. It follows from this, that not all subsurface reservoirs are geothermal resources, as the essential requirements for a geothermal system to exist are (1) a large source of heat, (2) a reservoir to accumulate heat, and (3) a barrier to hold the accumulated heat. There is a suite of geological conditions that could result in a variety of geothermal systems. Consequently, all geothermal fields differ from one another. (Breeze, P et al (2009)

Figure 5: Geothermal Explained, Source: EIA, 2019

3.4 Hydropower

The earth's surface is approximately covered with 70 percent of water, a resource that has been exploited for many centuries. Many tens of thousands of watermills were in regular use across

Asia and Europe by the 18th century, mostly for milling grain). Hydroelectric power is generated by taking advantage of the kinetic energy and pressure freed by falling water of rivers, canals, streams and water networks. The rushing water drives a turbine, which converts the water's pressure and motion into mechanical energy, converted into electricity by a generator. The power of the scheme is proportional to the head (the difference between up- and downstream water levels), as shown in figure 9, the discharge (the quantity of water which goes through the turbines in a given unit of time) and the efficiency of the turbine. (European Renewable Energy Council, 2010).

3.5 Tidal Power

Bhatia, 2014 also described tidal power as a form of hydropower that converts tidal energy into electricity. Tidal power are products of ocean or sea tides that originate from the periodic movement of seawater due to the interactions of the gravitational fields of the earth, moon and sun. Tidal power is converted to tidal energy through one of these three ways; tidal streams, barrages, and tidal lagoons. A tidal stream is a fast-moving water body that turns a turbine placed in the stream to generate electricity. (National Geographic, 2011). On the other hand, a tidal barrage consists of a large, dam-like structure built across the mouth of a bay or an estuary in an area with a large tidal range. Lastly, tidal lagoons are either a body of ocean water that is partly enclosed by a natural or manmade barrier, or estuaries, and can thus operate like a barrage. Unlike barrages, tidal lagoons are mostly constructed along the natural coastline

3.6 Biomass

Biomass are non-fossil organic materials that include a broad variety of raw materials such as plants, animals, and animals waste, wood, and by-products of wood processing, agricultural crops, agricultural and forest industries, manure, biodegradable organic residues from industrial or municipal wastes and the organic matter of waste streams. Constituting the fourth largest energy source, starting with coal, oil, and natural gas. Biomass is also categorized as woody and nonwoody with forests as the main source of woody materials, while agricultural products form the bulk of the nonwoody biomass. (Jawaid et al, 2017). Bioenergy on the other hand is the final energy in the form of heat, electricity and biofuels derived from biomass using various technologies and technological systems (European Renewable Energy Council, (2010). Four basic biomass conversion technologies have been reported and these are direct combustion, thermo-chemical conversion processes (pyrolysis, gasification); biochemical processes (anaerobic digestion, fermentation); and physical- chemical (the route to biodiesel).

3.7 Fuel Cells

Fuel cell converts chemical potential energy into electrical energy, and this can be readily done by either biological or chemical fuel cells. Chemical fuel cells produce electricity by running a chemical reaction. Usually, heat supplies the initial energy to get the process underway. Chemical fuel cells offer the advantage of serving as a power generator without the need for fossil fuels. In many cases, these fuel cells do not emit hazardous emissions. But fuel cell technology has also been held back by high costs, high operation temperatures, and inefficiency caused by impurities in the reaction cell. Biological fuel cells are another emerging technology in energy generation with an, as yet, unknown future. Biological fuels cells use microbes and their enzymes to act on fuels such as methanol or hydrogen for producing electricity. Biological systems hold advantages over chemical fuel cells because biological systems require no acids or other potentially harmful chemicals, and they run at room temperature. Biological fuel cells contain one or more components from nature, and enzymes control their reactions rather than high temperature. Carbon fuel cells react a carbon compound with oxygen to generate an electron flow. Though this type of fuel cell can use carbon-containing wastes as fuel, it also produces CO2 as its end product. In a carbon fuel cell, the same chemical reactions occur as in combustion, but the entire process runs more efficiently than combustion and generates more energy per unit of fuel. Fuel cell technology has advanced from small reactors, such as that invented by Grove, to high-voltage generators for two main purposes: transportation and electric power production plants. The intended future of large and small fuel cells is to accomplish the following tasks: replace gas turbines in power plants replace gasoline engines in vehicles replace batteries in computers and electronics. (Maczulak, 20010)

3.8 Wave Power

Wave power, also called ocean wave energy, is electrical energy generated by exploiting the up-and-down movement of ocean waves. The energy is produced by floating turbine platforms or buoys that rise and fall with the wave movements. It can also be generated by harnessing the changes in air pressure occurring in wave capture chambers that face the sea or changes in wave pressure on the ocean floor. Generally, the areas of greatest potential for wave energy development are in the latitudes with the highest winds (latitudes 40°– 60° N and S) on the eastern shores of the world’s oceans (which border the western edges of the continents) (Britannica, 2018). While wind and solar power have made significant in road into the renewable clean energy road map even as costs of installation continue to go down, that cannot be said of wave power. This is despite the fact that numerous studies have concluded that wave power, and its sister power source, tidal power could contribute massive amounts to the overall energy transition journey, but sadly, both sources remains decades behind other forms of renewables, as large amounts of money and research are required to bring its relevance in the energy transition trajectory. (Levitan, 2014). According to Levitan, 2014, the central challenge in fully harnessing wave power is that difficulties experienced in operating in the ocean, and the associated costs. For instance, building offshore wind installations is significantly more expensive than constructing wind farms onshore. Also the saltwater environment is hostile to some devices, while the waves pose their own challenge as they not only roll past a device but also bob up and down or converge from all sides in confused seas. This has led to a host of designs, including writhing snake-like attenuators, bobbing buoys, even devices mounted discreetly on the ocean floor that work by exploiting differences in pressure as a wave passes by. Some devices generate electricity on the spot and transmit it via undersea cables to shore, while others pass the mechanical energy of the wave along to land before turning it into electrical energy. Which of these drastically divergent concepts might emerge as a winner is far from clear. (Levitan, 2014).

4.0 SUSTAINABLE DEVELOPMENT AND RENEWABLE ENERGY SOURCES

Mensah (2019) in his work on sustainable development, cited the works of Ben-Eli (2015), who sees sustainability as ensuring a dynamic equilibrium between the people and the environment without producing irreversible adverse effects on the carrying capacity of the environment. He also cited the view of (Thomas, 2015) who held that sustainability ensures that humans, in their attempt to satisfy their needs do not deplete or exhaust the productive resources at their disposal. Mensah (2019) also captured the work of DESA-UN (2018) which stated that sustainability is to work towards ensuring an equilibrium in the ecosystem-man, economy and the environment in an evolving regenerative capacity of the planet's life-supporting systems. This according to Mensah (2019), is also the basis of the United Nations Conference on Sustainable Development (UNCSD) or Rio+ 20 held in 2012, green economy sustainable development framework. This plus the frequent climatic and environmental challenges has reinforced the context of green economy as the principal driver of the renewable energy transition. Tarner (2019) in his work, using data from 40 developed and 73 developing countries found that renewable energy has a positive and statistically significant effect on sustainable development both in developed countries and in developing countries. He established that as the quantum of renewable energy increases in the energy mix, the level of sustainable development increases, which directly follows that as more countries deploy renewable energy in their energy mix, the globe will easily achieve sustainability of development and the 2030 Sustainable Development Goals. Salvarli and Salvarli (2020) in their paper viewed sustainable development as an all-encompassing phenomenon that covers the use of renewable energy, energy security, energy pricing, energy policy, renewable energy applications and smart grid technologies. This is in view of the increasing environmental pollution due to rapid industrialization and human activities. To them, the success of any new technology will be on how cost-effective it is in ensuring a cleaner environment, and this is where renewable energy comes to the rescue in the pursuit to attain sustainable development. Salvarli and Salvarli (2020) added that achieving global energy sustainability will require frantic actions in the areas of energy diversity, efficiency, supply reliability, public trust, market-sensitive interventions, market-based climate change responses, cost reflective prices, technological innovation, and development of regional integration of energy systems. Global energy sustainability will also require climate compatibility, sparing use of resources, low risks, social equity, and public acceptance. All of these, they said, will be premised on technology innovation and improvement of new high technology level that belong to industrialization and commercialization. Since renewable energy sources are readily available, to guarantee the energy and environmental sustainability will require extensive research and investment in technologies that can improve on the materials and the processes of conversion of these natural resources into sustainable energy sources.

4.1 Sustainable Energy

There is an increasing need for energy and its related services to satisfy humanity socio-economic development, welfare and health in the face of ever-increasing population and human development needs. This is coupled with the damaging effects of the continuous use of fossil derived fuels on the environment and increasingly unsustainable global ecosystem. This has thus paved the way for renewable energy sources to mitigate the climatic and environmental degradation while also providing more sustainable energy sources to meet the increasing energy demand of future generations. Owusu & Asumadu-Sarkodie (2016) in their study noted that there are certain opportunities that are associated with renewable energy sources which includes: energy security, energy access, social and economic development, climate change mitigation, and reduction of environmental and health impacts.They also noted that, despite these opportunities, some challenges such as market failures, lack of information, access to raw materials for future renewable resource deployment, and our daily carbon footprint, have been observed to hinder the sustainability of renewable energy sources towards climate change mitigation. Sustainable energy according to Tester (2005) as cited by Owusu & Asumadu-Sarkodie (2016) is “a dynamic harmony between the equitable availability of energy- intensive goods and services to all people and preservation of the earth for future generations”. Unfortunately, fossil fuel from coal to petroleum crude oil and gas, which have powered the global economy have become problematic due to depletion of fossil fuel reserves, greenhouse gas emissions and other environmental concerns, geopolitical and military conflicts, and the continual fuel price fluctuations. Owusu & Asumadu-Sarkodie (2016) viewed these problems as causing unsustainable energy supplies, with the potential of causing irreversible threat to human societies. Therefore the shift towards renewable energy sources has become imperative for sustainable development, since all economies rely on sustainable and reliable energy sources for heating, lighting, industrial equipment, transport, etc. Owusu & Asumadu- Sarkodie (2016) added that though renewable energy sources are abundant in nature, for renewable energy to be sustainable, it must provide non-harmful delivery of environmental goods and services. In their contribution to the subject matter, Chu et al, 2017, stated that research in materials science has significantly pushed the frontiers towards a sustainable future that is based on clean energy generation, transmission, and distribution, the storage of electrical and chemical energy, energy efficiency, and better energy management systems. They stated that while material science continues to create innovative materials for sustainable renewable energy, it will be proper that the public sector plays the leading role in such research and development, due to relatively long gestation period, something that may discourage private investors. Rajan etal 2020 also reiterated the need for holistic approach that will assess the full environmental and human health impacts across the entire life cycle of renewable sources, which in the case of solar energy, should begin from mining, manufacturing, use, decommissioning and recycling of materials required for solar cells production across the critical stages in the production process. Assessing the life cycle of renewable sources was one of the core assignment undertaken by CoRE, the Collaboratory for a Regenerative Environment created by the Department of Materials Design and Innovation at the University of Buffalo, Clean Production Action, and Niagara Share in 2017. The collaboration is to bring academic experts in materials design with entrepreneurial nonprofit organizations to accelerate clean production and sustainable materials in the renewable energy economy. CoRE is to adopt innovative collaborations and data-driven tools that will enhance decision process of business, government, and nonprofit leaders to identify and select inherently safer chemicals and sustainable materials for a healthy renewable energy economy. According to Rajan etal, CoRE’s major objective is to adopt systemic changes in the design and development of renewable energy technologies that can accelerate the discovery of safer materials without compromising performance. This is because, many renewable energy industries, including solar energy, depend on hazardous chemicals and novel materials to reduce costs and optimize efficiencies, that are unsafe for the environment and human health. They therefore recommended for a simultaneous and integrated consideration of technical, environmental, and social factors when designing, developing and in the adoption of renewable energy technologies. One major challenge with the materials for sustainable renewable energy, according to Finley, 2019, is that not all the countries are endowed with these special materials as production of inputs to some of these energy sources are highly concentrated in a few countries which will also create future energy security problems. For instance, China dominates the global production of rare earth metals (an important component for batteries), solar power panels, and batteries for electric vehicles, while two-thirds of the world’s cobalt production (another battery, solar panel, and wind turbine component) is concentrated in the Democratic Republic of Congo, a country with a history of human rights abuses and corruption. Also, the expected growth in renewable energy and batteries will also require an unprecedented increase in the mining and refining of ores. Now since it takes a rather long time to develop new mines, coupled with the environmental and social issues that come with mining and refining of these rare ores, such growth poses a risk of future supply shocks. Moreover, both the US and Europe are highly dependent on ores that are mined and refined outside of their borders.

5.0 APPLICATION OF MATERIALS SCIENCE AND ENGINEERING IN ENERGY SUSTAINABILITY

Though humanity knowledge of materials were limited at the beginning, however, development in science and technology have since expanded the structures and properties of materials into far more superior properties, in order to meet their ever-increasing quest for growth. Consequently, any technological and or industrial development have always rested on the advancement and understanding of innovative material science and technology, which is clearly seen in modern automobiles, phones, sophisticated electronics devices, and computing and communicating equipment, all of which are products of inexpensive steel or some other comparable substitute, and innovative semiconducting materials. (Callister, 2001). Technically, materials are defined in terms of structures and properties. The structure describes the internal arrangements of each component of the material, such as in subatomic, atomic, and microscopic, and finally structures that can be viewed with the naked eyes as in macroscopic in nature. The subatomic structure describes the arrangements of electrons within the individual atoms and interactions with their nuclei, while the atomic and microscopic structures define the arrangements of atoms and molecules, and which can be subject to direct observation using some type of microscope. Properties of a material describes how the material response to a specific imposed stimulus, independent of shape and size. (Callister, 2001). Callister, 2001 further stated that properties of solid materials are generally of six categories, which are mechanical, electrical, thermal, magnetic, optical, and deteriorative, each of which has a characteristic type of stimulus capable of provoking different responses. Besides the structure and properties, materials are also measured in terms of its ease of processing into useable form and how it finally performs. In terms of relationships, the structure of a material depends on how it is processed, while the properties determine its performance, which makes the interrelationship between processing, structure, properties, and performance as linear.

5.1 Classification of Materials

Solid materials are further classified as metal, ceramics and polymers based on their atomic structures and chemical makeups. Metallic materials have large numbers of nonlocalized electrons, that are free and not bound to any atom, which is why metals are extremely good conductors of both electricity and heat. Also, metals are opaque and thus are not transparent to visible light, though a polished metal surface has a lustrous appearance. Metals, though quiet strong are also malleable, which gives them the property that accounts for their extensive use in structural applications. Ceramics, which are mostly oxides, nitrides, and carbides, are compounds that fall between metallic and nonmetallic elements. Ceramics are composed of clay minerals, cement, and glass, and therefore insulators to both electricity and heat, but can withstand high temperatures and harsh environments than metals and polymers. In terms of mechanical behavior, ceramics are hard but very brittle. Finally, polymers are organic compounds based on carbon, hydrogen, and other non-metallic elements with very large molecular structures, and low densities and can be very flexible. Examples include plastics and rubber materials. (Callister, 2001). Materials are also further classified as composites, semiconductors, and biomaterials. Composite materials are engineered materials containing more than one material type, as in fiberglass, which is a composite of glass fibers embedded within a polymeric material. As engineered materials, the intention is to combine materials of best properties into a composite structure, such that the composite materials now display the best of both components. This is seen in fiberglass which has the strength of glass and the flexibility of polymer. Semiconductors fall between electrical conductors and insulators, and thus very sensitive to even minute concentrations of impurities. Semiconductors are the backbones of integrated circuitry that globally drives the electronics and computing and communication industries over the past two decades. Finally, biomaterials are used as implants in human body for replacement of diseased or damaged body parts, and as such must be toxic free and compatible with body tissues (i.e., must not cause adverse biological reactions). Any of the earlier classes of materials, metals, ceramics, polymers, composites, and semiconductors are useable as as biomaterials. (Callister, 2001). Besides these classification, Callister, 2001, also reported additional classes of materials known as advanced materials, used mainly in high-technology (or high-tech), and relatively intricate and sophisticated applications such as electronic equipment (VCRs, CD players, etc.), computers, fibreoptic systems, spacecraft, aircraft, and military rocketry. These advanced materials are either engineered materials with enhanced properties, or newly developed, high-performance materials, and can also be derived from any of the known material types (e.g., metals, ceramics, and polymers). They are also relatively expensive.

5.2 Materials for Sustainable Energy Development

Sustainable energy development in this context refers to the ability of the materials to meet economic expectation of the manufacturers and producers, in order to ensure a going concern process, the materials durability and generative capacity, and such as not to pollute and harm the environment. It is important to know about and understand economic issues simply because the producer or manufacturer must realize a profit from the products it manufactures. Materials engineering decisions have economic consequences, with regard to both material and production costs, as it is also important that the manufactured product must be offered for sale at a price that is attractive to the consumer, and, in addition, return a suitable profit to the company. Callister, 2001 pointed out that the cost of the product is determined by three main factors, they are (1) component design, (2) the material(s) used, and (3) the manufacturing technique(s) that are employed, and all these are within the control of the materials engineer. For example, the direct conversion of solar into electrical energy has been demonstrated. Solar cells employ some rather complex and expensive materials. To ensure a viable technology, materials that are highly efficient in this conversion process yet less costly must be developed. Furthermore, Callister, 2001 stated that, environmental quality depends on our ability to control air and water pollution. Pollution control techniques employ various materials. In addition, materials processing and refinement methods need to be improved so that they produce less environmental degradation, that is, less pollution and less despoilage of the landscape from the mining of raw materials. Also, in some materials manufacturing processes, toxic substances are produced, and the ecological impact of their disposal must be considered. Many materials that we use are derived from resources that are nonrenewable, that is, not capable of being regenerated. These include polymers, for which the prime raw material is oil, and some metals. These nonrenewable resources are gradually becoming depleted, which necessitates: 1) the discovery of additional reserves, 2) the development of new materials having comparable properties with less adverse environmental impact, and/or 3) increased recycling efforts and the development of new recycling technologies. Recycling of used products rather than disposing of them as waste is a desirable approach for several reasons. First, using recycled material obviates the need to extract raw materials from the earth, and thus conserves natural resources and eliminates any associated ecological impact from the extraction phase. Second, energy requirements for the refinement and processing of recycled materials are normally less than for their natural counterparts; for example, approximately 28 times as much energy is required to refine natural aluminum ores than to recycle aluminum beverage can scrap. And, finally, there is no need to dispose of recycled materials. Correcting any environmental problems associated with manufacturing will influence product price. That is, manufacturing cost is normally greater for a ‘‘green’’ (or ‘‘environmentally friendly’’) product than for its equivalent that is produced under conditions wherein environmental issues are minimized. Thus, a company must confront the dilemma of this potential economic- environmental trade-off and then decide the relative importance of economics and of environmental impact. One approach that is being implemented by industry to improve the environmental performance of products is termed life cycle analysis/assessment. With this approach to product design, consideration is given to the cradle-to-grave environmental assessment of the product, from material extraction to product manufacture to product use, and, finally, to recycling and disposal; sometimes this approach is also labelled as ‘‘green design.’’ One important phase of this approach is to quantify the various inputs (e.g., materials and energy) and outputs (e.g., wastes) for each phase of the life cycle as shown in figure 6 below:

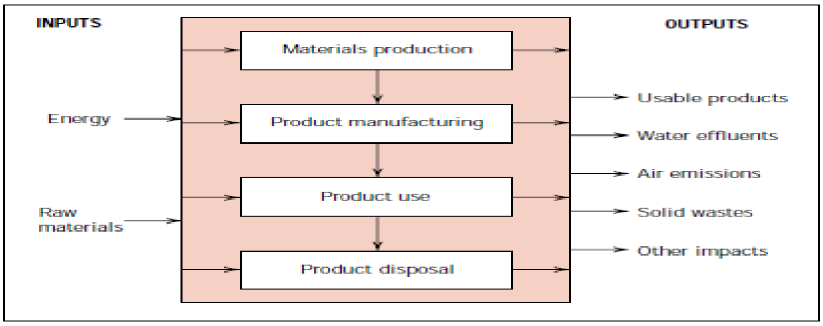


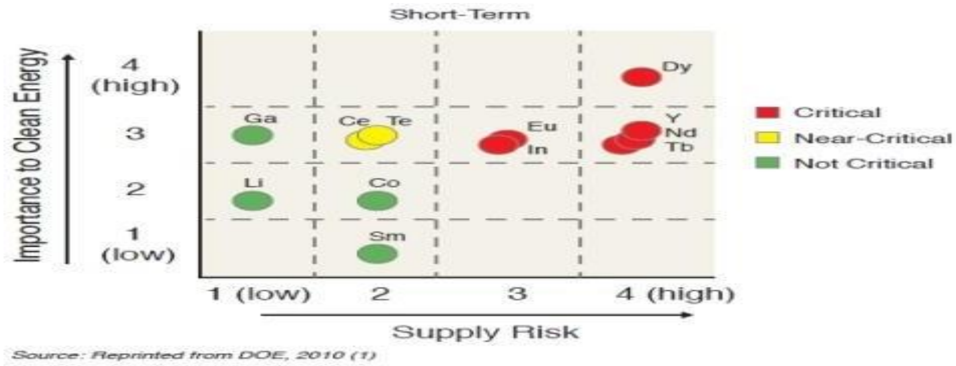
Figure 6: Representation of the input/output inventory for the life cycle of a product. Source: Callister, 2001.

5.3 Innovative Materials Science for Sustainable Energy Transition

The 21st century has a major theme in its sustainable development agenda, and that is on how to provide sustainable and cost-efficient energy resources that can power its ever-increasing development needs, as the economic growth that occurred in developing countries over the past two decades has been unprecedented. This is where evolution and revolution in materials science and engineering (MSE) innovations become pivotal as an enabling resource to address these sustainable development needs. Apelian, 2012, stated that material consumption in the 21st century, is at an all-time high and that given the comparatively small amounts of material recovered and recycled in the overall system, there is much room for improvement. He also mentioned the issue of increasing use of scarce elements in the production system, such as the use of more than 50 elements in the production of the average smartphone. However, few programs now exist that ensure that these rare elements are recovered and recycled at the end of a component's useful life, in view of the price volatilities of rare-earth materials which have increased dramatically even since the beginning of 2010. Apelin, 2012 further outlined five distinct societal issues that are materials-centric that will play a critical role to guarantee a sustainable future on Earth, and these are, energy, transportation, health, housing and materials resources. Considering the ongoing energy transition from fossil fuel to a cleaner renewable source, the survival and sustainability of this transition will greatly depend on innovative materials science and technologies that will engineer and produce sustainable materials. For instance, there are efforts to engineer nanostructured materials and advanced photovoltaic materials such as nanocrystalline-silicon thin films and novel chalcogenides, to guarantee solar power reliability and sustainability. Fuel cells and bio-derived liquid fuels are also not left out, as there are also new materials developments in the areas of advanced catalysts with more accessible surface area, nanostructured catalyst supports, and membranes. Wind turbines also require innovative technologies to create high-strength non-rare earth-based permanent magnets for compact, low-maintenance generators, while, "next-generation" nuclear energy can become a potential carbon-free baseload energy source, from a cost perspective, as nuclear power offers advantages over other non-fossil-based energy sources as being the lowest-cost producer of baseload electricity. (Apelin, 2012). Contributing to the discourse on material science and sustainable energy, the former US Secretary of Energy Steven Chu, Yi Cui, and Nian Liu, in their paper in Nature Materials, agreed that, innovative research in materials science has significantly helped the push for sustainable energy generation, transmission and distribution, energy efficiency and better energy management systems including the quest for durable and higher capacity storage devices for electrical and chemical energy. They considered materials science as an enabler in the race for a successful transition to sustainable energy. This is in view of the numerous advances in the past decades, with the occasional accidental discovery of a major source of new materials. There has also been empirical trials on finding innovative materials through a deeper understanding of their physics and chemistry, so as to measure and fabricate these materials at both molecular and nanoscale levels. (Chu et al 2017).

5.4 Critical Materials Selection

The sustainable energy technologies of focus include wind, photovoltaics, solar fuel generation, fuel cells, electric and hybrid vehicles, and lighting, and the materials of critical concerns include silver, platinum, indium, tellurium and of course the rare earth elements. Others include lithium or even copper, all of which will be needed in high demand to propel the desired disruptive growth in the clean energy sector, which currently constitute about 20% of global consumption of these technology metals. While the world's energy economy is built upon a base of metals, and the sustainable energy economy is more critically dependent on a wider array of metals than the current one, it has rather become imperative that the materials necessary to implement these potentially game-changing technologies are readily available to drive the various industrial sectors in the economy. Consequently, defining the criticality of a material is very time-dependent and hinges conceptually on the "eye of the beholder." The entire process of determining material critically revolves around the materials producers and speculators, which inadvertently, has created an atmosphere of paranoia and hype that is also counter-productive to finding viable solutions. Resolving these challenges, according to Fromer etal, 2011, led to the model of determining the criticality of materials. Critical Material is defined in terms of its importance to the clean energy economy and risk of supply disruption. Generally, according to Fromer etal, 2011, a material's criticality is because that material has one or more properties that can be physically essential for the performance of the system, and some uncertainty or risk exists in the supply of that material. Criticality assessment can therefore be performed for any material or application, to analyze the importance of the materials for the technology in question, and to also analyze the supply risk for the material. Figure 7 thus shows the Criticality Matrix which is a plot of the importance of the materials to clean energy and the supply risk.

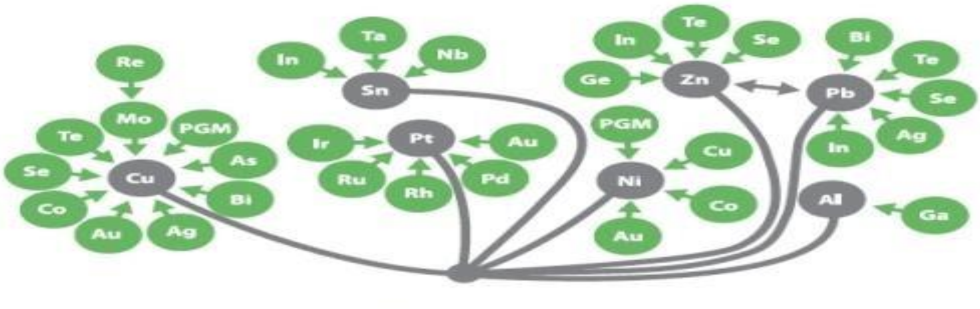


Source: Reprinted from DOE, 2010 (1)

Figure 7: Criticality Matrix. Source: Fromer etal, 2011

5.6 Supply Risk

The supply risk poses more challenges to the assessment of the criticality of the material as some materials are rare in the earth's crust, while some do not occur commonly in single deposits with significant concentrations. Some other materials are very expensive to mine from the earth's crust, while some groups of materials, referred to as technology metals are by-products of other primary production metals such as copper, lead, and zinc as shown in figure 8. These technology metals require significant capital investment to extract as by-products, as they are usually produced in smaller quantities compared to base metals. A second economic reason is that technology metals face larger uncertainty in demand and thus in their market price. An example is tellurium, Te, made as a by-product from Copper, that while the copper market is fairly stable and predictable, the market for tellurium is much harder to predict for the long term, and hence it's pricing. This has made investing in facilities to produce more tellurium a riskier proposition for a producer.



Source: Hagelüken and Meskers, 2010 (21)

Figure 8: Technology Metals Produced as Byproducts of Base Metals. Source: Fromer etal, 2011

The Criticality Matrix has further provided another platform for the assessment of the materials supply risk in order to ensure the availability of sustainable materials for the clean energy segments of the energy mix.

Figure 9: Materials Criticality Solutions Assessment. Source: Fromer etal, 2011

One of the solutions of resolving the criticality matrix is to deal with both sides of the matrix- the application (demand) side and in the risk of availability (supply). Solutions for the supply side include developing new sourcing strategies, end of life recycling, and increasing production of the material through either new mining operations or processing yield improvements as shown in figure 9. The demand side can be improved through materials and manufacturing optimization, material substitution and system substitution. Some of the strategic approaches on the supply side includes finding more material, improving process yields, and reducing waste.

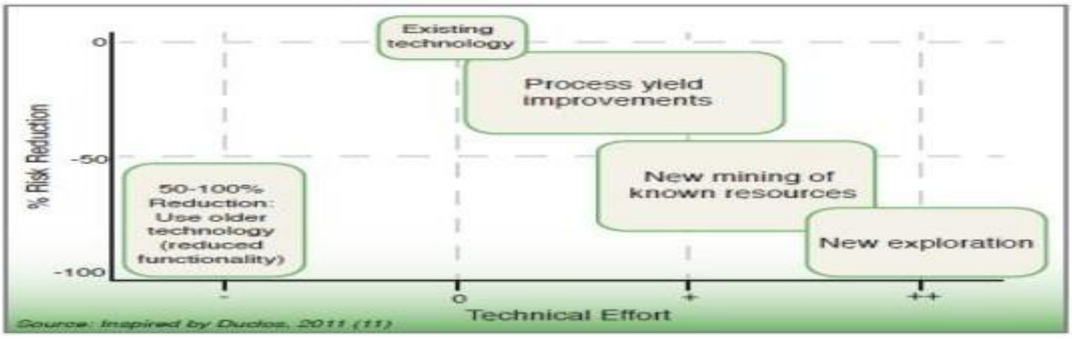


Figure 10: Option Space for Supply Side Criticality Reduction. Source: Fromer etal, 2011

One other supply-side improvement strategy is to breakdown the extraction and manufacturing processes, into component steps to identify bottlenecks and remove them to improve efficiencies, and the yields. Fromer etal, 2011 also stated that improving four steps each by 20% in a multistep extraction and purification process, will double the production. One of the major challenges in achieving maximum yield through the improvement process according to Fromer etal, 2011, is the variability from material to material and differences in the composition of the ore, and unless the workforce is technically knowledgeable, this will really slow down the improvement process. There are also cases when some improvement techniques could be borrowed from other industries, provided there was support to test these ideas without exposing producers to excessive risk to develop the technology. (Fromer, etal 2011).

6.0 SOLAR ENERGY MATERIALS

As presented in earlier section, the sun's radiation provides the principal source of energy for solar power generation, and as also mentioned earlier, the solar radiation can be converted into useful energy, either directly as electricity through Photovoltaic (PV) devices or solar cells, or indirectly through solar thermal or electric power systems using concentrated or as chemical energy into solar fuel (Jager et al (2014). PV cells can generate as little as microwatts to as much as megawatts, and so, are used in several standalone and mobile devices such as hand calculators, wrist watches, water pumping, in remote buildings, communications, satellites and space vehicles, and also in megawatt-scale power plants. (Goswami, 2015).

Solar energy, which is the third-largest renewable energy source after hydropower and wind, has emerged as a clean, sustainable, and powerful alternative to fossil fuels. As at 2019, solar electricity contributed about 2.2% of global electricity generation, with outputs growing from 585 TWh in 2018 to 720 TWh in 2019, while it is projected to reach 1940 TWh by 2025. (Mukhopadhyay, 2020). Mukhopadhyay, 2020 also mentioned that, research and development (R&D) on innovative solar energy materials has helped to push for maximum solar-to-electricity efficiency at much lower cost. This has produced innovative semiconducting materials such as crystalline Si, thin films, and the next-generation perovskite solar cells (PSCs). Technically, Piebalgs and Potocnik, 2009, stated that the PV solar cell forms the primary building block in the photovoltaic technology. These individual cells can be connected electrically to each other to create a 'photovoltaic module'. Several modules can also be wired together to a form a PV array. All PV solar cells only produce direct-current electricity either in series or parallel electrical arrangements. Photovoltaic (PV) cells are constructed from semiconductors such as silicon (Si), Cadmium Sulfide (CdS), cuprous sulfide (Cu2S), and gallium arsenide (GaAs). Semiconductors are materials that only moderately conduct electricity (Kalogirou, 2014). Most of current solar cells are made from silicon that absorbs the sun's photons. As shown in figure 11, the silicon wafers are doped so as to enable the electrical contacts to connect the solar cells together to form a complete circuit, which forms a silicon disks. This disk is then coated with anti-reflective coating to prevent loss of solar radiation. This is then further encapsulated and placed in an aluminium frame as shown in the figure.

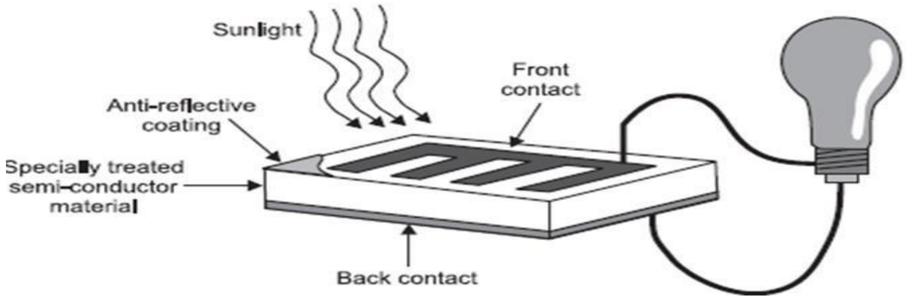


Figure 11: Typical solar cell. Source: Bhatia, 2014

Most commercial solar cells use silicon as the semiconducting layer, even though silicon does not represent the optimum solar absorber, it has the advantage of being relatively easy to work with, extremely abundant and cheap. It also has the added advantage of being used in other industries in the manufacture of transistors and microchips, and so, has a wealth of experience, unless other semiconducting materials. Silicon, therefore, may still play significant role in the PV industry for some time, irrespective of the appearance of other semiconducting materials such as cadmium telluride, and copper indium selenide, and gallium arsenide in the PV solar cell industry. Silicon can be used various forms, as a single crystal silicon, that has shown best performance in terms of electrical conversion efficiencies of up to 24%. They are also durable, but are expensive as well, which has made room for the use of polycrystalline silicon, cut out from several tiny individual crystals as opposed to one large crystal. Polycrystalline though cheaper to make, has proved less efficient than the single crystal material with only 18% conversion efficiency. Next is the amorphous silicon, which initially had serious degradation problem when exposed to light, an effect which reduced efficiencies by 20–40%. However, this problem has been minimized with extensive redesign leading to only 20% degradation with cell efficiencies of around 13%. The amorphous noncrystalline silicon has also been transformed through several innovations into a stack consisting of three cells one on top of the other, to absorb blue, then green, and finally red lights in that order. This three-cell design offers the potential for higher efficiency than a single cell absorbing the whole spectrum. (Breeze, P et al (2009). Generally, semiconductors come in two forms, the pure ones, or the intrinsic semiconductors, and doped ones, also called extrinsic semiconductors. The extrinsic semiconductors are doped with small amounts of impurities to modify their conductivity. The Pure or Intrinsic Semiconductors are materials that have both an outermost electron, called a valence band that are partly filled and intermediate band gaps (≤3 eV). The valence band determines how an atom interreacts with its neighboring atom, and thus can be excited and escape from the nucleus to form a conductor band, which makes the material a conductor of both heat and electricity. The band gap on the other hand, refers to the energy difference between the valence band and the innermost subshell of the conduction band. As shown in figure 12, insulators are materials that have full valence bands and high band gaps (>3 eV), while conductors have relatively empty valence bands and may have some electrons in the conduction band.

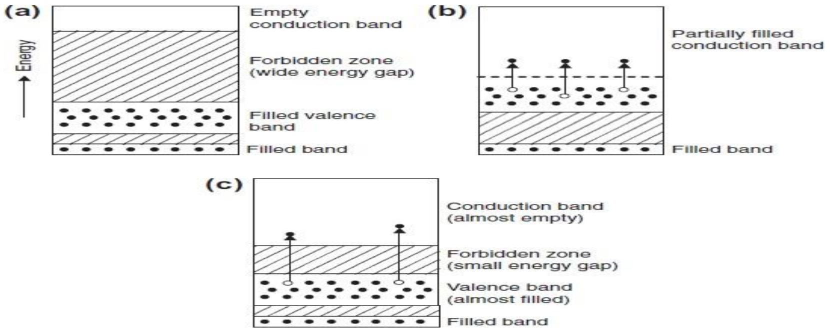


Figure 12. Schematic diagrams of energy bands for typical materials. (a) Insulator. (b) Conductor (metal).

(c) Semiconductor. Source: Kalogirou, 2014.

The second type of semiconductor or the extrinsic is modified by doping external impurities into it to increase its conductivities, such as when a silicon-based semiconductor, with 4 valance electrons is modified by doping it with phosphorus with 5 valence electrons on one side, which donates valence electrons to silicon to make it negative, or n-donor, and doping it with boron with 3 valences on the other side to create a greater affinity than silicon and thus making it positive or p-donor to the semiconductor. (European Commission, 2009). PV solar cells are also either wafer-based silicon cells or thin-filmed solar cells, of which about 90% of the global PV cells are of the wafer type. The wafer types, which are also called mono-crystalline or multi-crystalline are either produced from a single crystal rod or from a block composed of many crystals. Wafer-based silicon solar cells are approximately 200 µm thick. (Piebalgs and Potocnik, 2009). The next important solar cells are the thin-films, which are approximately 1-2 µm thick and that they require much less semiconducting material to produce. They are produced by depositing layers of semiconducting material onto an insulating substrate, such as glass or flexible plastic. They also have the advantage of low production cost, and hence can be produced in large quantities, with the potential of capturing greater portion of the PV market in the near future. One limitation is that thin-films are less efficient in terms of electrical conversion than the wafer based silicon cells, and to make it competitive would require more exposure surface and material for the installation. (Piebalgs and Potocnik, 2009). Thin films can be made from amorphous silicon (α-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe), out of which the α-Si has the lowest conversion efficiency plus light-induced degradation. The CIGS and CdTe technologies can compete favourably in conversion efficiencies with crystalline solar cells, that has more than 55% of the global market share. Thin film cells therefore stand a great chance to provide the needed sustainable energy for the future, only that they must guarantee longevity, reliability, consumer confidence and greater investments in order to become sustainable in the energy transition to renewables. (Lee et al, 2017).

6.1 Silicon Photovoltaic (PV) cells

Silicon photovoltaic (PV) cells are made from rare materials and are also found in abundance in the form of silicon dioxide as beach sand. Typically, silicon dioxide is purified in an electrode arc furnace at temperatures between 1500–2000 degrees Celsius, making the process rather very expensive, coupled with the emissions of greenhouse gases. Schmalensee, R etal (2015) also pointed out the low intrinsic light absorption capacity of wafer-type silicon, due to its indirect bandgap, the manufacturing process thus requires that the wafer is thickened, and this also comes with additional production cost. Carbeck, 2016 showed that the thickening of the silicon, makes them to be rigid and heavy, while a typical silicon PV cell should be flat and housed in large heavy panels for better efficiency. These rigids and heavy panels are the reason for the very expensive large-scale use of PV cells in places other than rooftops and in big solar farms. Goswami, 2015, also identified the problem of low flux density, which will require that large surfaces are used to collect solar energy for large-scale utilization, and this also translate into higher costs. There are other technical challenges inherent with crystalline-Si such as the need to thoroughly remove all impurities, the large for large volume material consumption, restricted module form factor, relatively low throughput due to its rather slow batch production process, and module integration processes. Zendehdel etal, 2020 stated these challenges notwithstanding, Gallium Arsenide (GaAs) wafer type technology, has very strong absorption capacity with a direct bandgap that matches well in the solar spectrum, coupled with its very low non-radiative energy loss. Also, the III-V multijunction (MJ) which is a stack of two or more single-junction cells with different band gaps, absorbs solar irradiation with minimum thermalization losses. The the III-V multijunction (MJ) stacks can be formed from the V (N, P, As, Sb) and group III (Al, Ga, In) of semiconducting compounds with variable band energies, that yield power conversion efficiencies, of 35.5, 44.4, and 46.0% for record 4-junction (2 J), 3 J, and 4 J cells, respectively, under concentrated illumination.

6.2 Thin Film Solar Cells

For photovoltaic power to bridge the global energy mix, it requires a dramatic lowering of photovoltaic cell material cost and the use of inexpensive, abundant materials and low-cost fabrication strategies. Zendehdel etal, 2020, stated that besides these requirements, photovoltaic must also meet the environmental challenges efficiently in their value chains to become sustainable. This has led to the evolution of Thin Film PVs, and though crystalline wafer type Si currently dominates the global PV market, they rely mostly on indirect band gap absorber material which will require them to be produced in thick layers to absorb more fractions of the incident solar radiations. This will result in higher cost of production, in addition to extra cost needed in creating perfect crystals that will guarantee higher efficiency solar modules. (Suryawanshi etal, 2013). Thin- film solar cells, according to Mukhopadhyay, 2020 are classified as second-generation solar cells, with greater promises in the evolution of sustainable PV technologies due their narrow design, about 350 times smaller light- absorbing layers when compared to standard Si-panels. They are light weight, flexible, and easy to install, and constituting about 10% of the global PV module market, thin-film cells, are made by additive fabrication processes, with cheaper manufacturing cost and material usage. Zendehdel etal, 2020, further reported that thin film technologies can utilize both conventional inorganic semiconductors and emerging nanostructured materials. Three thin film PV technologies are already in commercial phase: (i) hydrogenated amorphous silicon (a-Si:H), (ii) cadmium telluride (CdTe) and (iii) copper indium gallium diselenide (CuInxGa1−xSe2, or CIGS). Amorphous silicon, thin film PV is produced by the process of plasma-enhanced chemical vapor deposition (PECVD) at low substrate temperatures of 150–300°C. This process while it creates a larger band gap (1.7–1.8 eV, compared to 1.12 eV for c-Si), produces a higher absorptive amorphous silicon surface than crystalline wafer type-Si. Also, the amorphous Si (a-Si:H) with 300 nm film thickness can absorb about 90% of band gap photons in a single pass, establishing the benefit of the thin-film to create lightweight and flexible panels. Finally, amorphous silicon can safely combine with nanocrystalline silicon (nc-Si) or amorphous silicon-germanium (a-SiGe) alloys to form a multijunction cell without lattice-matching requirements. The next thin-film is made from Cadmium telluride (CdTe), which according to Zendehdel etal, 2020 is the leading thin-film PV in the present global market with a direct band gap of 1.45 eV. It also has a strong solar spectrum absorption, with conversion efficiencies of 22.1% for the lab-scale cells with continuous improvement in commercial efficiencies. One of the limitations of the CdTe technologies, regardless of its high throughput deposition processes, and lowest module costs of any PV technology, is its relatively high processing temperatures of about 500°C. This plus the toxicity of elemental cadmium, and the scarcity of tellurium, has caused more research on alternative material systems. The last thin film technology is Copper indium gallium diselenide (CIGS), used mostly in building-integrated and other unconventional PV applications. CIGS is fabricated from a variety of solution- and vapor-phase techniques using polyimide substrates or flexible metals, to produce a direct band gap of 1.1–

1.2 eV. It also exhibits high radiation resistance, with a concentrator cell efficiency of 23.3%, making it very suitable for mandatory space applications. One of the limitation of CIGS is the rarity of the indium element that has capacity to absorb solar radiation about 10-100 times more than silicon. It also has other technological challenges such as: (i) high variability in film stoichiometry and physical properties, (ii) limited knowledge of the grain boundaries activity, (iii) low open-circuit voltage due to structural and electronic inhomogeneity, (iv) engineering of higher-band gap alloys to enable multijunction devices. Figure 13, shows a chart from the National Renewable Energy Laboratory (NREL) on the growth in efficiencies of thin film solar cells.

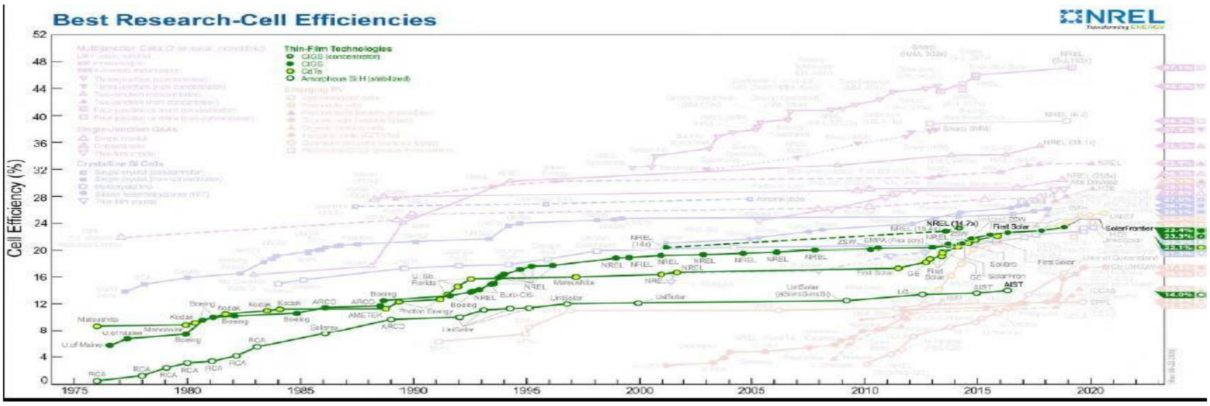


Figure 13: Growth in the efficiencies of the various thin film solar cell technologies. Source: NREL, 2020

6.3 Emerging Solar Energy Technologies

Though crystalline silicon solar cells hold more than 90% of the solar cell global market share, their conversion efficiency is significantly lower than the theoretical limit (~30%). This has led to several types of research, especially by the National Renewable Energy Laboratory (NREL) to drive the development of high-efficiency crystalline PVs, such as III-V multijunction materials (with target efficiency of >30%), hybrid tandem III-V/Si solar cells, and the six-junction III-V solar cells with capabilities for reaching efficiencies of 47.1% under concentrated light. Also, silicon-based bifacial technology has been tried to harvest solar energy from both sides of the panel, with 11% more efficiency compared to standard panels. ((Mukhopadhyay, 2020). There has also been several research into innovative materials and device engineering on thin-film solar system, which has resulted in the emergence of several new thin-film PV technologies. Zendehdel etal, 2020 thus recorded five of such key emerging thin-film PV technologies: (i) copper zinc tin sulfide (Cu2ZnSnS4, or CZTS), (ii) perovskite solar cells (PSCs), (iii) organic photovoltaics (OPV), (iv) dye-sensitized solar cells (DSCs) and (v) colloidal quantum dot photovoltaics (QDPV). CZTS is an earth-abundant alternative technology to CIGS, with similar processing challenges and strategies. Cu2ZnSnS4 (CZTS), with its kesterite structure, and suitable suitable direct band gap between 1.4 and 1.5 eV, is one of the most promising absorber layer candidates for low cost thin film solar cells. It also has large absorption coefficient, of over 104 cm21, and as an earth abundant and non-toxic element, it has the promise of significant price reductions in future. Regardless, it has the problems with uncontrolled Cu and Zn inter-substitution which can lead to point defects, blocking charge extraction and reduce the open-circuit voltage of the cell. Record certified cell efficiencies of CZTS cells have gained 12.6%. (Suryawanshi etal 2013). The other innovative thin film materials are perovskites, which is a three- dimensional crystal lattice formed when organic molecules, such as carbon and hydrogen, bind with a metal such as lead and a halogen such as chlorine. Liquid solutions of perovskites can be deposited virtually on any surface as thin films without any heat treatment in a furnace. Carbeck, 2016, added that perovskites film weighs very little, and thus can be made much more cheaply and with fewer emissions. They have also been reported to overcome the limitation of conversion efficiency of conventional solar cells which has been stuck at 25 percent for 15 years. Perovskite solar cells (PSCs), according to Zendehdel etal, 2020, can also be made from solid-state dye-sensitized solar cells with certified efficiencies of 24.2% in 3 years of development in lab-scale devices. The material can also be fabricated from various low temperature techniques involving solution or vapor deposition processes. Perovskites have certain structural/physical properties such as long diffusion lengths of charge carriers under low recombination reaction, low cost precursor materials, and wide band gap tunability.The perovskite type of significant promise is the hybrid organic–inorganic lead halide (MA and/or FA)Pb(I, Cl, Br)3, which has a high band gap tunability of 1.25– 3 eV by substituting cations or anions in the latticestructure. Next to this is the organic Photovoltaic (OPV), a group of organic small molecules or polymers that can easily combine with earth abundant materials and also scale-up the thin film structures through various deposition techniques. They are cheaper to fabricate than the conventional III-V MJs due to high defect tolerance and leisure deposition routes. (Zendehdel etal, 2020). Within the OPV group, the small-molecule cells can absorb light within the visible and near-infrared electromagnetic spectrum, while the polymer-based OPV cells works by donating electrons by long-chained molecular systems, and electron-accepting through their derivatives.(EERE). The OPV cells have recorded lab efficiencies as low as 15.6%, mainly due to their small exciton diffusion lengths and low carrier mobilities. Also, OPV modules have lesser lifetime than inorganic devices. (EERE). Some of the limitations of the OPV cells is the inefficient exciton transport, poor long-term stability, low large-area deposition yield, and low ultimate efficiency limits. The dye-sensitized thin film solar cells (DSC), is a hybrid organic- inorganic technology that uses small-molecule absorber dyes. The absorber is adsorbed onto a suitable electron-accepting material, such as titanium dioxide or zinc oxide, in the presence of an electrolyte to regenerate the dye. (EERE). The DSC type of thin film are photoelectrochemical, and rated as one of the matured nanomaterial-based PV technologies. They are made from inorganic scaffold anode such as nanoporous TiO2 or other n-type oxides of transition metals that is sensitized with light-absorbing dye molecules (ruthenium (Ru) complexes or organic dyes DSCs can achieve efficiencies upto 12.3% by utilizing liquid electrolyte that can transport ions to a counter electrode. DSC have some drawbacks such as limited long-term stability under high temperature illumination, low absorption in the near-infrared region, and low open-circuit voltages from interfacial recombination. The last of the thin film solar cell is Colloidal Quantum Dot Photovoltaics QDPV technologies, which are nanometer-scale semiconductor crystals capped with suffactant molecules dispersed in solution. They have recorded cell efficiencies of about 16.6% and are continuously improving. (Zendehdel etal, 2020). QDPV have created a platform for the development of other classes of solution-processed optoelectronic devices such as photovoltaic cells, photodetectors, and light-emission devices. In addition to enabling solution processing, a key advantage of colloidal quantum dots is the quantum confinement effect; optical and electrical properties are readily tuned by adjusting the size and shape of the nanoparticles. In photovoltaic devices, doped semiconductor CQD films are combined with a metal (Schottky junction cells) or with another semiconductor (CQD−CQD or CQD−titanium dioxide p−n junctions, CQD−CQD−zinc oxide p−i−n junctions), along with asymmetric electrodes, to form a complete functional device. (Carey et al, 2015). These emerging thin-film technologies which are based on nanostructured materials can easily be engineered to achieve desired electronic and optical properties, which will open great opportunities for large scale production and use of these emerging PV cells. However these excellent properties, such as transparency, light weight and flexibility, notwithstandingdespite the technology is yet to scale past the maturity test for commercial industrial production. (Zendehdel et al, 2020). Figure 18 is a chart showing the progressive improvement of these new thin-film systems over the period:

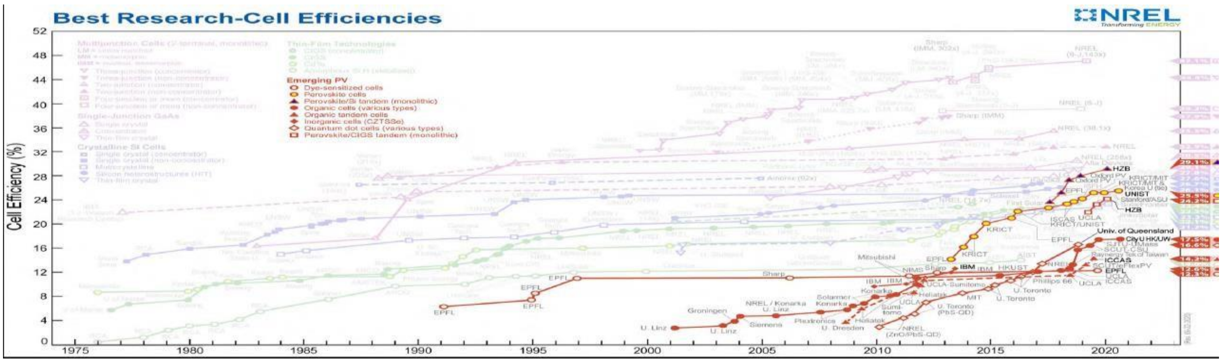


Figure 14: Chart showing progressive development of Thin Film PV cells technologies. Source: NREL, 2020.

7.0 RECOMMENDATIONS

There is no doubt that the world is at the stage of moving into another energy platform to safeguards its environment and for future generation. While the current transition efforts may not be as aggressive as is the environmental damage, it is important that the efforts be expedited if the world wants to remain sustainable. Changing the energy source from fossil fuel to renewable is not only capital intensive, but also comes with new skills, and total overhauling of infrastructure and skill sets. This is where there is urgent quickly develop the required skill sets at all levels since this will become the primary energy source from 2050 upwards. Just as was experienced in the geopolitics of fossil fuel, renewable energy will also have its share of geopolitics, and it will be proper for the global community to pay closer attention to these salient areas of ensuring sustainability. Finally, while renewables are clearer and more environment friendly, as discussed in this paper, the total life cycle from cradle to consumption, and its impact in each stage on the environment and man, must be taken seriously, as not to ignorantly build up more environmental hazardous chemicals in due course.

8.0 CONCLUSION

It has become rather urgent for the world to transit into cleaner and less carbon emission renewable energy sources to achieve the zero carbon by 2050 and 2060. However, though these renewable materials and resources are abundant in nature, the technology for efficient and sustainable conversions into energy are still evolving, especially for heating, cooling and transportation. However, research and development (R&D) in the areas of innovative materials especially in solar PV cells and storage facilities that can achieve higher conversion efficiencies, lower production costs, and guarantee cleaner and more eco-friendly are on the rise and very encouraging. It is, however, critical that, these R&D efforts are jointly undertaken by the public and private sectors for timely results. It is also important that the energy transition must run side by side with development of new skills for wider appreciation and application of the evolving technologies. Finally, though renewables have lesser environmental impacts, achieving the required sustainable energy transition requires that attention is paid on the entire life cycle of the processes from mining to fabrication to application of these new materials as not to build up more hazardous materials in the environment.

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