DEVELOPMENT OF SUSTAINABLE ENERGIES FROM SOLAR

by

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A Directed Research Project

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science in Engineering Technology

School of Engineering Technology

West Lafayette, Indiana

November 30, 2020

THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

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ACKNOWLEDGMENTS

I would like to express my sincere appreciation and gratitude to my advisor and Committee Chair, Professor John Dickey, M.A., D.H.L, for his guidance and support during the course of the study and research. The research paper would not have been possible without the exceptional support of Professor Dickey. Professor Dickey's knowledge, enthusiasm, and exacting attention to detail have been a courage and inspiration and kept my study on track from my Day One. I would like to extend my gratitude and special thanks to the Head of the Graduate Program, Dr. Duane Dunlap, for his guidance and contribution to my education and research. I am grateful for the insightful comments offered by both Professor Dickey and Dr. Dunlap. The generosity and expertise of them and all have improved my research study in innumerable ways and saved me from errors. Their eternal motivation and optimism have made my journey at Purdue University unforgettable and enjoyable.

My deepest and most sincere appreciation goes to my loving parents and my wife for the life-long love, support, and encouragement.

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LIST OF ABBREVIATIONS

ADSDI - Abu-Dhabi Spatial Data Infrastructure

AOT - Aerosol Optical Thickness

CSP - Concentrated Solar Power

DEM - Digital Elevation Model

DHI - Diffuse Horizontal Irradiance

DNI - Direct Normal Irradiance

DOE - Department of Energy

ECMWF - European Centre for Medium-Range Weather Forecasts

EIA - Energy Information Administration

GaAs - Gallium Arsenide

GHI - Global Horizontal Irradiance

GW - Gigawatts

kWh/m^2 - Kilowatt-hours per square meter

MW - Megawatts

NAE - National Academy of Engineering

NASA - National Aeronautics and Space Administration

NDVI - Normalized Difference Vegetation Index

Non-OECD - Non-Organization for Economic Cooperation and Development

NREL - National Renewable Energy Laboratory

PV – Photovoltaic

ReCREMA - Research Center for Renewable Energy Mapping and Assessment

RH - Relative Humidity

ROI - Return on Investment

Si - Silicon

UAE - United Arab Emirates

UN - United Nations

GLOSSARY

Direct Normal Irradiance (DNI): The technology mainly considered for concentrated solar energy application which uses Concentrated Solar Power (CSP) to indirectly generate heat and then electricity (Gherboudj & Ghedira, 2016).

Dust deposition: The important issue causes a decrease in the performance of the solar energy system in arid areas. Dust deposition attenuates the incoming solar irradiance on solar cells and changes the dependence on the angle of the solar radiation (Gherboudj & Ghedira, 2016).

Global Horizontal Irradiance (GHI): The technology mainly considered for photovoltaic (PV) applications which directly converts total solar energy falling on the earth's surface into electricity (Gherboudj & Ghedira, 2016).

Relative humidity (RH): Expressed as the ratio of the actual water vapor pressure to the saturated vapor pressure at a given temperature (Hachicha, Al-Sawafta, & Said, 2019).

Solar radiation: The radiant energy emitted by the sun from fusion reaction that created the electromagnetic energy (Sengupta, Xie, Lopez, Habte, Maclaurin, and Shelby, 2018).

ABSTRACT

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Degree Received: December 2020
Title: Development of Sustainable Energies from Solar
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Energy occupies a pivotal position in the development and progress of today's society. From the daily lives of residents to international transportation, the limited non-renewable energy resources on the earth are being exhausted. With increasing world energy demand and the shortage of fossil fuels, solar energy has become a key technology to solve energy problems. Compared with the serious pollution caused by fossil fuels, solar energy is clean and free. Nowadays, countries around the world are rapidly developing solar energy technology to alleviate the crisis caused by energy shortages. As a major oil producer and exporter, the United Arab Emirates (UAE) attached great importance to develop and utilize solar energy. The directed project investigated the feasibility and sustainability of developing solar energy in the UAE. The unique geographical location of the UAE gives it an absolute advantage in solar energy harvesting. However, the environment in the desert also affects the utilization of solar panels to a certain extent. The research performed data analysis on solar radiation and environmental factors to discuss the development prospects of solar energy in the UAE. Although the research has existing limitations, the strategic goal of sustainable development of solar energy never changes. Based on data and cost-effectiveness analysis, the directed research made recommendations to accept or decline the project.

Keywords: energy, sustainability, solar, radiation, environment

CHAPTER 1. INTRODUCTION

The progress and development of human society are inseparable from energy consumption. As a necessity for human lives, limited energy maintains the industrial production, transportation, commodity circulation, and daily lives of the world. Bilgen (2014) stated that energy is a crucial parameter that controls growth and determines aspects of human activity. Relying on conventional energy alone no longer met the energy needs of today's world (Lundgren et al., 2016). Along with the shortage of fossil fuel energy and increasing environmental pollution, human beings are paying extreme attention to the development and utilization of renewable energy. Fossil fuels dominate the energy supply of power generation and transport systems, accounting for three-quarters of total anthropogenic carbon dioxide emissions (Zeppini & Van Den Bergh, 2020).

Solar power generation is one of the key technologies to solve the energy shortage problem. According to the National Academy of Engineering (NAE, n.d.), as long-term and sustainable energy, solar power offers an attractive alternative. Therefore, solar energy has an essential meaning in implementing the sustainable development strategy of the power industry. According to Department of Energy (DOE, 2016) the solar industry is experiencing unprecedented growth and rapid change. The solar energy industry also gradually became a new energy industry in the contemporary era (DOE, 2016).

1.1 Problem Statement

According to Sabir (2012), global energy demand is expected to be 30 percent higher in 2040 than in 2010. Thus far, the dominant position of fossil energy represented by coal, oil, and natural gas in energy consumption is still unshakable. However, due to global climate change and the development of new technologies, the future energy structure underwent significant changes. According to Bilgen (2014), the economic growth of the developing countries has led to a rapid increase in energy consumption in the last decades.

Increased energy consumption affect people's lifestyles (Lundgren et al., 2016). Unsustainable development and consumption was the main causes of global environmental degradation, including pollutions and the excessive exploitation of renewable resources (Leonard et al., 2018). Bilgen (2014) stated that the rapid depletion of nonrenewable resources has led to uncertainties with the future availability of fossil fuels. Global energy demand is facing uncertainties, such as natural disasters, technological issues, and wars (Bilgen, 2014). According to Leonard, E. Michaelides, and D. Michaelides (2018), energy demand continued to increase with the growth of the world economy.

1.2 Problem Impact

India Energy News (2014) claimed, 3.5 billion people lack sufficient energy, and over four million die each year due to energy poverty. Since the consumption of fossil fuels continues to increase, human beings are facing an increasing energy crisis and environmental damage. Global warming has become a hot spot of international concern. According to Pretorius, Piketh, and Burger (2015), the energy crisis is characterized by reduced or insufficient electricity reserves. Electricity reserves represent the level of infrastructure construction in a country or city. Energy crisis or insufficient power reserves lead to lagging living standards, inconvenient transportation, and medical and education problems.

According to India Energy News (2014), half of the world's seven billion people lack sufficient access to energy, including 1.2 billion children. Therefore, the energy crisis not only affected the development and progress of society but also threatened the safety of human lives. Developed countries also face the problems of the energy crisis and power shortage. Since 1999, the energy emergency conditions of California have increased significantly that in some cases have necessitated rotating blackouts (Energy Information Administration [EIA], n.d.). The development of clean energy is vital for energy security, environmental protection, and sustainable development in the context of the energy crisis.

1.3 Problem Measure

The problem was measured by quantitatively evaluating that 4.4% of the world's electricity was from solar while 68.2% was from non-renewable sources (United Nations, 2019). The utilization of renewable energy is not exactly the same in today's energy system. The ability of different energy formations to convert from fossil fuels to renewable energy varies. Thus, renewable energy is not able to completely replace fossil fuels (Leonard et al., 2018). Carbon capture and storage is a solution that meets current needs and gives time for the development of alternative energy sources. However, the development of new renewable energy is imperative and urgent.

Figure 1.1 on page four (4) shows the United States primary energy consumption by energy source in 2019 (EIA, 2020). In 2019, 11% of United States energy consumption comes from renewable resources, of which solar energy contributes nine percent (EIA, 2020). Solar energy accounts for one percent of the total energy consumption, nevertheless, solar energy has great potential to gradually occupy market shares (EIA, 2020). According to DOE (2016), the amount of solar power installed in the United States has increased more than 23 times from 2008 to 2015. Therefore, solar energy increasingly became an economic energy choice for households or enterprises (Hayat et al., 2019). National Academy of Engineering (NAE, n.d.) stated that, globally, solar power generation is a growing multi-billion dollar industry.

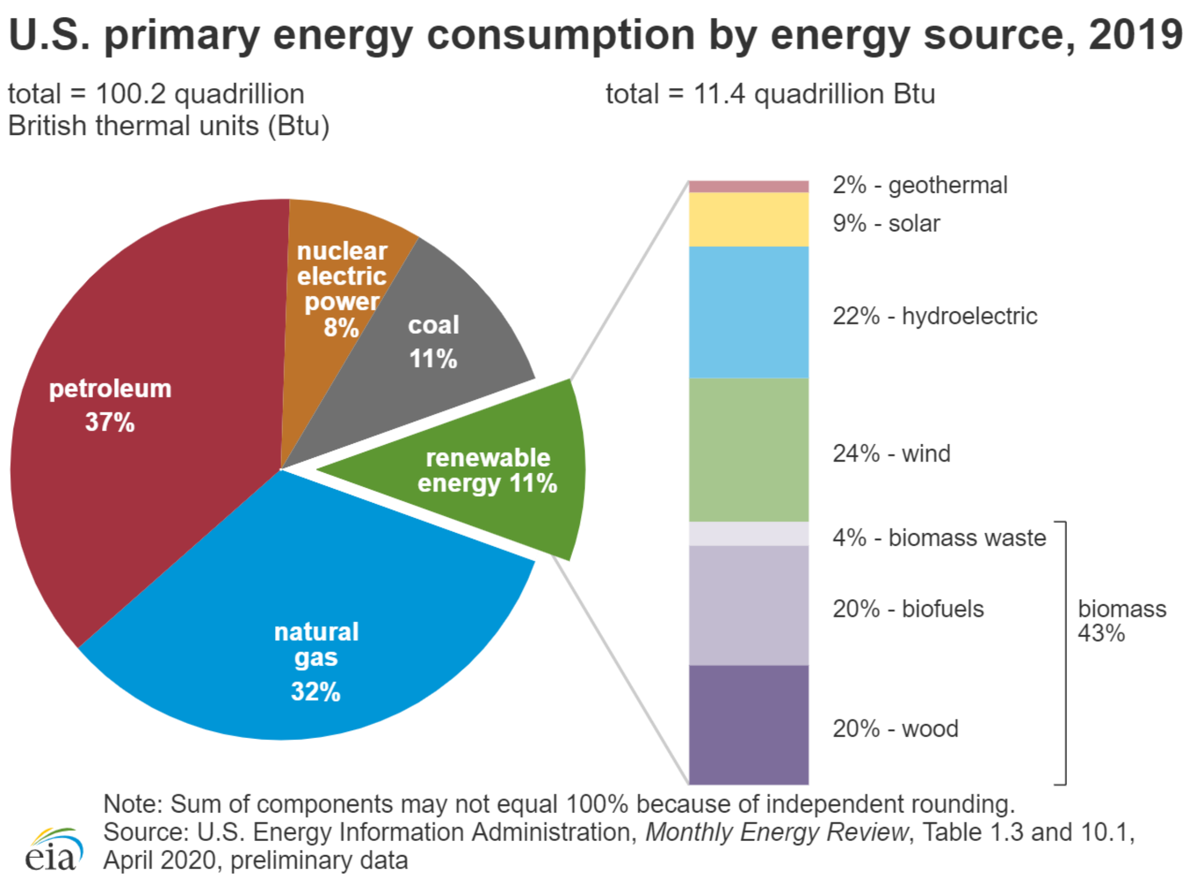


Figure 1.1 United States Primary Energy Consumption by Energy Source in 2019

1.4 Global Grand Challenge Connection

National Academy of Engineering (NAE, n.d.) claimed, developing sustainable energies from solar can replace fossil fuels while reducing greenhouse gas emissions by Carbon

Sequestration. Addressing climate change is a major task in the sustainable development agenda. The continuous emergence and advancement of new technologies have added confidence and hope for the energy system to achieve the goals. The response of the fossil fuel market to implement mitigation measures have essential impacts on the cost and acceptability of emission reduction (Bauer et al., 2015).

If the current ratio of fossil fuels remains unchanged, carbon emissions continued to increase and the energy crisis became increasingly serious (Leonard et al., 2018). Therefore, developing emerging technologies such as solar and fusion to produce energy to replace fossil fuels is imperative. Breyer, Bogdanov, Aghahosseini, Gulagi, Child, Oyewo, Farfan, Sadovskaia, and Vainikka (2018) stated that Solar Photovoltaic (PV) is a key technology for future energy transformation. Solar energy has broad market prospects but also faces technical and economic challenges. Therefore, solar energy is one of the fourteen Grand Engineering Challenges of the twenty-first century proposed by NAE.

1.5 Methodology

Solar became the main energy source in the future market in view of the increasing demand and impact of global energy (Assouline et al., 2017). Although the proportion of solar energy in the global energy market is relatively small compared to fossil fuels, it has great potential (DOE, 2016). Therefore, the research project investigated the existing energy market, collected and analyzed the data. All studies are based on global long-term models, including detailed energy sector representatives and academic references. The study considered the differences between solar energy and traditional fossil fuels in order to conduct case analysis. For example, how solar energy's contribution to environmental protection has a positive impact on the future. The research project studied the data of solar power generation, price, growth trend, and other related data through quantitative analysis.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Global Energy Demand

The world's energy supply has increased substantially in the past decades, however, the warning of the energy crisis has not been lifted (Lundgren et al., 2016). As long as the global economy continues to grow, the demand for energy in countries around the world continues to increase. Sabir (2012) stated that the non-Organization for Economic Cooperation and Development (non-OECD) energy demand grew by 60%. Therefore, energy demand became a global problem and challenge.

Figure 2.1 on page eight (8) shows the global energy demand by types of energy by 2040 (Pipeline and Gas Journal, 2015). According to the forecast described in Figure 2.1, fossil fuels still were the most demanded energy sources (Pipeline and Gas Journal, 2015). However, clean energy such as solar energy and wind energy has the highest growth rate, reaching 5.8% (Pipeline and Gas Journal, 2015). Pipeline and Gas Journal (2015) stated that the growth in global energy demand projected at 35% by 2040.

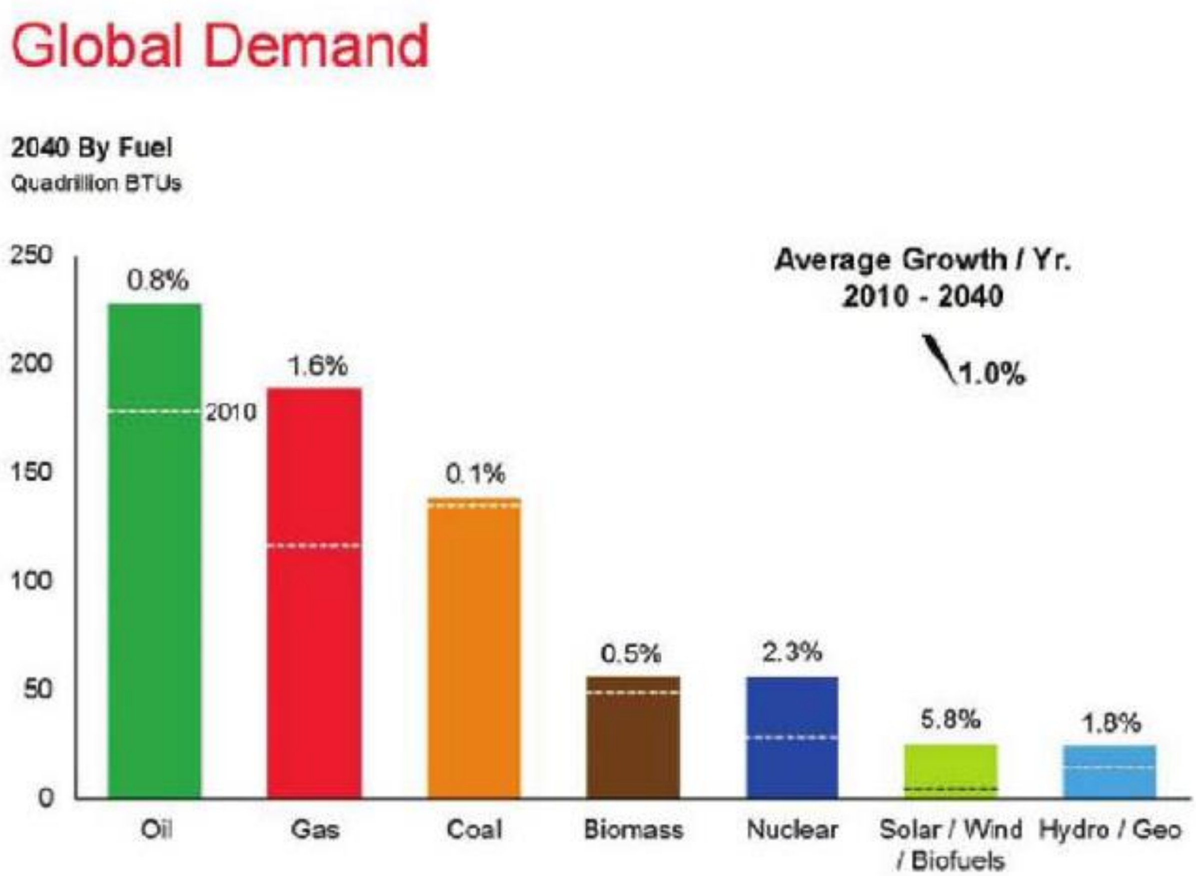


Figure 2.1 Global Energy Demand by Type of Energy

However, a question worth considering is whether existing non-renewable resources reserves can meet future demands by 2040 or beyond. According to NAE (n.d.), the fossil fuel supply did not keep up with growing global energy demand. Obviously, the development and utilization of renewable resources is the theme of future energy demand. According to Addison (2016), by 2040, renewable and nuclear energies will account for 40% of the growth in energy demand. The availability of solar energy as the first choice for clean energy exceeds any imaginable future energy demands.

2.2 Energy Crisis Impact

As long as global energy demand continues to rise, the risk of an energy crisis is also increasing. The energy crisis caused energy prices to rise, thereby affecting the stability of the world economy or even an economic crisis (Askari, 2020). Wholesale electricity prices increased on average 270 percent over the same period in 1999 from June 2000 through July 2000 in California (Energy Information Administration [EIA], n.d.). Figure 2.2, below, shows California's declared staged power emergencies between 1998 and 2001 (EIA, n.d.). Intermittent power shortages have caused California must limit residents' electricity consumption and even blackouts in emergency situations.

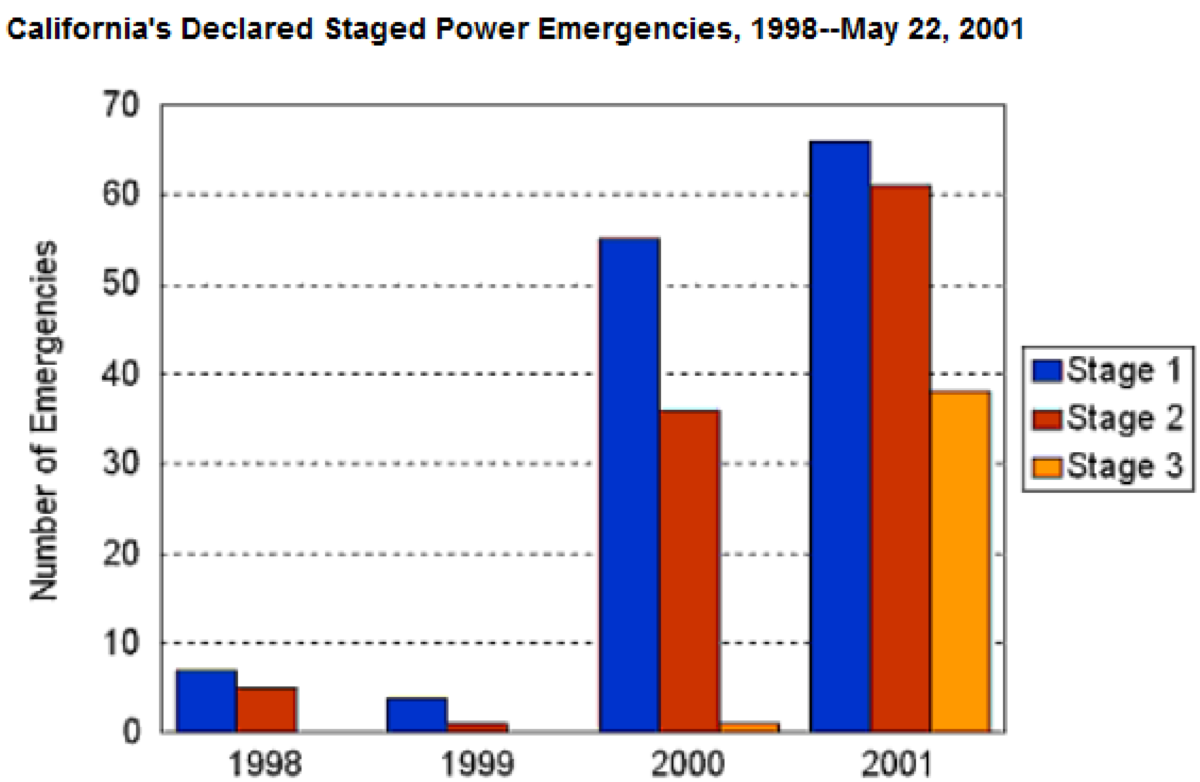


Figure 2.2 California's Declared Staged Power Emergencies

Wars and conflicts caused by energy crisis and energy plunder continue to occur in the Middle East and Africa (Askari, 2020). According to Askari (2020), tensions and disputes between countries regarding global oil and gas prices continue to occur frequently in the Middle East. Figure 2.3, below, shows data of selected energy and growth variables in regions from 2010 to 2012 (Qureshi et al., 2016). According to Figure 2.3, Sub-Saharan Africa has low electrification rates and capacity growth has stagnated from 2010 to 2012 (Qureshi et al., 2016). The power production capacity of Sub-Saharan Africa is less than other regions in the world, such as Asia, Europe, and Latin America (Qureshi et al., 2016). Qureshi et al. (2016) stated that less than 30 percent of people in sub-Saharan Africa have access to electricity, compared with 65 percent in South Asia.

Country name	Series name	2010	2011	2012
East Asia & Pacific	Access to electricity (% of population)	95.06841	96.0142	96.5241
East Asia & Pacific	Electric power consumption (kWh)	6.7E+12	7.18E+12	7.45E+12
East Asia & Pacific	GDP per unit of energy use (PPP $ per kg of oil equivalent)	6.065636	6.264103	6.412
Latin America & Caribbean	Access to electricity (% of population)	94.85068	95.012	95.325
Latin America & Caribbean	Electric power consumption (kWh)	1.15E+12	1.22E+12	1.28E+12
Latin America & Caribbean	GDP per unit of energy use (PPP $ per kg of oil equivalent)	9.859509	10.4058	10.9254
Europe & Central Asia	Access to electricity (% of population)	99.97975	99.989	98.698
Europe & Central Asia	Electric power consumption (kWh)	4.9E+12	4.88E+12	4.91E+12
Europe & Central Asia	GDP per unit of energy use (PPP $ per kg of oil equivalent)	7.765854	8.281519	8.852
South Asia	Access to electricity (% of population)	74.45614	74.895	75.214
South Asia	Electric power consumption (kWh)	9.02E+11	9.67E+11	9.85E+11
South Asia	GDP per unit of energy use (PPP $ per kg of oil equivalent)	7.876018	8.274102	8.652
Sub-Saharan Africa	Access to electricity (% of population)	31.81943	32.014	32.422
Sub-Saharan Africa	Electric power consumption (kWh)	3.42E+11	3.55E+11	3.64E+11
Sub-Saharan Africa	GDP per unit of energy use (PPP $ per kg of oil equivalent)	5.217636	5.467267	5.685

Figure 2.3 Data of Selected Energy and Growth Variables

Energy shortages and crises not only have a serious impact on the world economy but also cause harm to human survival (Lundgren et al., 2016). According to Qureshi et al. (2016), consistent and reasonable power and energy supply is essential for economic strengthening. The causes of the energy crisis vary. For the form of energy, over-reliance on fossil fuels is bound to cause a global energy shortage (Lundgren et al., 2016). Therefore, the development of renewable energy is an effective way to solve the energy shortage and crisis.

2.3 Solar Energy

The vast expanse of solar energy provides humanity with inexhaustible energy (Hayat et al., 2019). DOE (2016) stated that 173,000 terawatts of solar energy strikes the Earth continuously, which is more than 10,000 times the world's total energy use. Solar energy plays a vital role in achieving the sustainable development of human society and nature (Hayat et al., 2019). Thus, the industry formed by solar energy will become a new growth point for the development of the world economy.

Table 2.1, below, shows a table of world electricity capacity by type from United Nations (United Nations, 2019). From 1990 to 2016, the non-renewable energy capacity index increased from 100 to 219. The solar energy capacity index increased from 100 to 84,604 in the past 26 years. The current solar power generation capacity is still low compared to non-renewable energy, however, solar energy has a trend of rapid growth.

Table 2.1 World Electricity Capacity by Type

Type	1990	2000	2010	2016	% 2016
Non-renewable *of which*	100	126	185	219	68.2%
- Thermal (non-ren.)	100	129	197	237	62.0%
- Nuclear	100	108	116	121	6.0%
Renewable *of which*	100	125	197	318	31.8%
- Thermal (ren.)	100	153	352	546	1.5%
- Hydro	100	122	159	194	18.6%
- Wind	100	728	7,664	20,152	7.1%
- Solar	100	342	11,333	84,604	4.4%
Total	**100**	**126**	**188**	**243**	**100.0%**

Figure 2.4 on page 12 shows annual average electricity production growth rate by source in the Middle East in 2011 (Askari, 2020). The days when the Middle East countries were heavily dependent on non-renewable energy have become history (Askari, 2020). The annual

growth rate of solar power generation reached 112 percent in 2011(Askari, 2020). The growth rate of fossil fuels is only six percent (Askari, 2020). Additionally, the annual growth rate of other renewable and clean energy generation is also higher than the growth rate of fossil fuels (Askari, 2020).

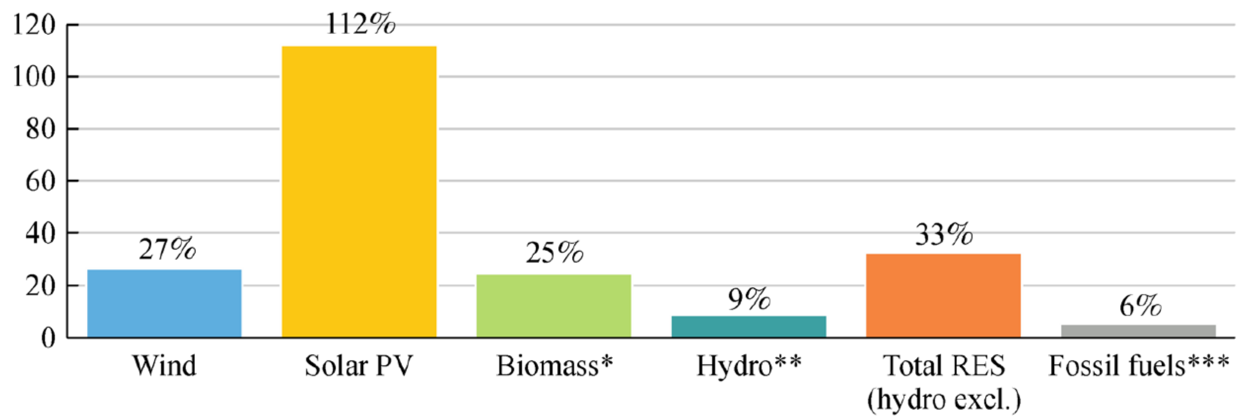


Figure 2.4 Annual Average Growth Rate of Electricity Production by Source in the Middle East in 2011

Turning from the Middle East to the United States, one of the countries with the most solar power generation in the world. Figure 2.5 on page 13 shows the United States electricity generation from renewable energy sources from 1950 to 2019 (EIA, 2020). Photovoltaic (PV) and solar-thermal power are the two main solar electricity generation technologies used in the United States. According to EIA (2020), solar provided 1.82 billion kilowatt-hours of electricity in 2011, accounting for 0.35% of the total US electricity. Solar technology is continuously improving and the installation costs are getting lower. Solar energy is becoming an economic energy choice for homeowners and enterprises in the United States (EIA, 2020). DOE (2016) stated that the world's largest solar thermal power plant in California has a total installed capacity of 392 MW. The strong power reserve and supply provide people with reliable solar energy options. According to Figure 2.4 (Askari, 2020), the growth rate of solar energy in the Middle

East countries in 2011 was higher than fossil fuels. However, during the same period, the United States had far more access to fossil fuels than solar energy (EIA, 2020). The UAE is one of the most outstanding countries in the development and application of solar energy in the Middle East (Askari, 2020).

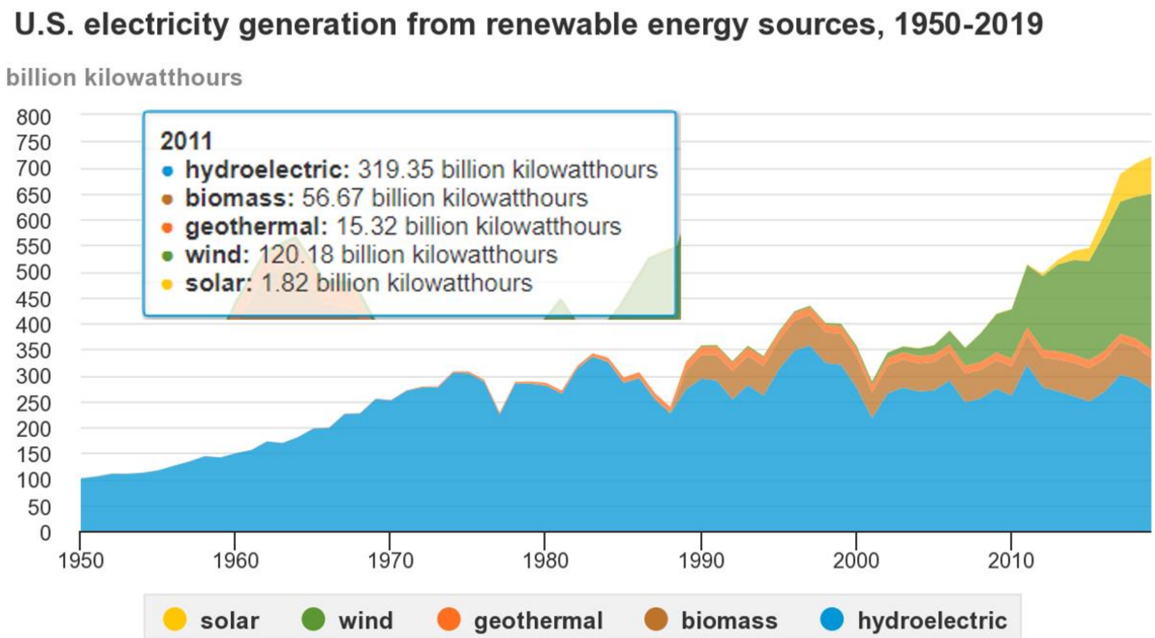


Figure 2.5 United States Power Generation from Renewable Energy Sources, 1950 - 2019

Figure 2.6 on page 14 shows a 100 megawatt-hour battery energy storage system paired with a solar photovoltaic system (DOE, n.d.). Obtaining power from solar energy requires achievement by solar cells for photoelectric conversion. According to DOE (n.d.), storage helps solar energy contribute to electricity supply even when the sun is not shining. To make solar power truly reach the practical level, it is necessary to improve the solar photovoltaic conversion efficiency and reduce its cost. According to NAE (n.d.), the efficiency of commercial solar cells to convert solar into electrical energy is ten to twenty percent. The breakthrough in cell material technology will have a profound impact on the cost and widespread implementation of solar energy. Engineers must find ways to increase battery efficiency and reduce manufacturing costs to make solar energy economically competitive. Eventually, both residential and commercial customers and large solar operators will benefit from solar systems.

Figure 2.6 Solar Panels

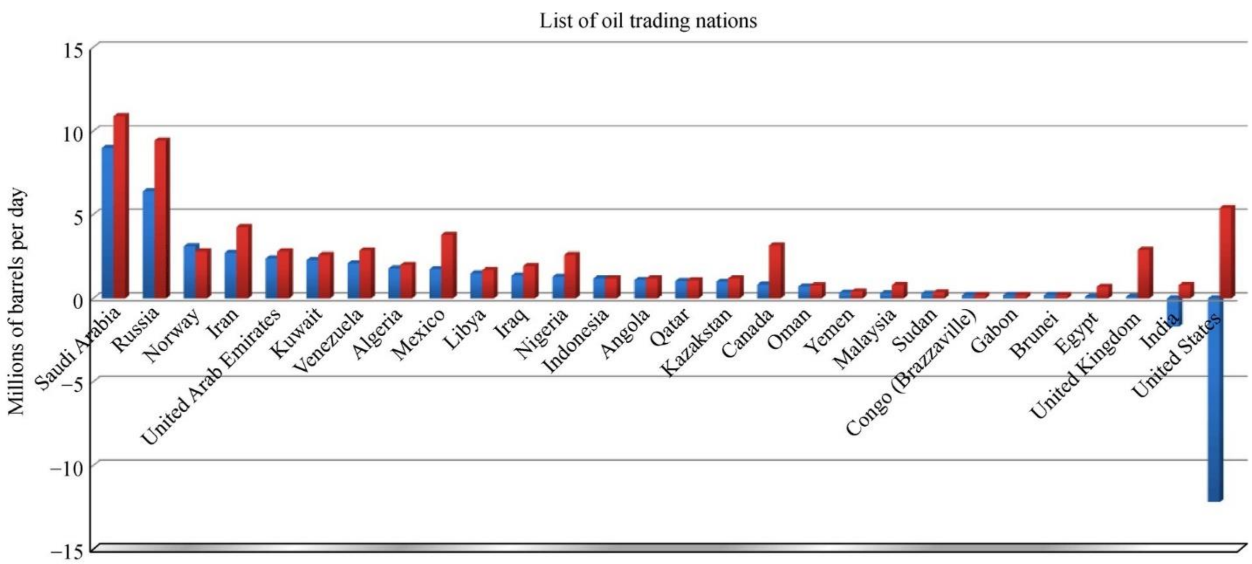
The application of solar power generation is wide, including commercial, residential, transportation, aerospace. The combination of solar energy and buildings will greatly reduce energy costs and environmental pollution (NAE, n.d.). Today, various technologies for achieving solar energy conversion already exist. NAE (n.d.) stated that the solar energy conversion efficiency through the nanocrystal method reached 60%. Therefore, the prospect of improving solar efficiency is encouraging. Solar energy, as renewable and clean energy, plays an essential role in the sustainable development strategy.

CHAPTER 3. RESEARCH METHODOLOGY

Global energy demand continues to grow, and non-renewable energy still dominates (Leonard et al., 2018). However, the reserves of non-renewable energy sources are steadily decreasing, and environmental problems are increasingly serious (Bilgen, 2014). The sustainable development strategy of the world requires further development and application of renewable energy. The use of renewable energy reduced emissions of air pollutants and greenhouse gases (Hosenuzzaman et al., 2015). Solar energy, as an inexhaustible source of clean energy, became the main energy source in the future market (Leonard et al., 2018). The chapter described the research methodology, plan, and analytical approach deciphering the application of solar energy within the Middle East marketplace. The study selected the United Arab Emirates (UAE) as the research location with sufficient daylight to conduct the research study. Considering the future promotion and application of solar energy, the research project also discussed the environmental impact.

3.1 Research Environment

The Middle East countries are the potential locations for solar power plants, including the United Arab Emirates (Najafi et al., 2015). The section examines the potentials and development of energy production from solar power in the United Arab Emirates. Figure 3.1 on page 16 shows the net production and export of oil in Middle East countries in 2014 (Askari, 2020). According to Najafi et al., (2015), the United Arab Emirates is one of the major oil suppliers in the world. Following the trend, uncontrolled exploitation will lead to the evacuation of oil resources and a serious energy crisis (Najafi et al., 2015). The other factor of over-exploitation is the competition between countries for more sales and oil prices (Najafi et al., 2015). Additionally, the over-exploitation of fossil fuels has resulted in higher carbon dioxide emissions in the United Arab Emirates (Askari, 2020). Therefore, the United Arab Emirates has initiated various green power plans. The UAE initiated Masdar City in 2006, and Sheikh Zayed solar park in 2013, to lower the country's dependence on fossil fuel (Gherboudj & Ghedira, 2016).



Net exports	9	6.4	3.1	2.721	2.4	2.3	2.1	1.8	1.756	1.5	1.367	1.3	1.2	1.1	1.04	1	0.832	0.714	0.333	0.3	0.25	0.2	0.2	0.2	0.1	0.1	−1.7	−12.2
Production	10.9	9.44	2.8	4.259	2.8	2.6	2.855	2	3.791	1.7	1.942	2.6	1.2	1.2	1.08	1.2	3.151	0.781	0.41	0.8	0.36	0.2	0.2	0.2	0.7	2.9	0.8	5.4

Figure 3.1 Net Production and Export of Oil in Middle East Countries in 2014

Figure 3.2 on page 17 shows carbon dioxide emissions in the Middle East countries in 2009 (Askari, 2020). Power generation is one of the most major factors causing environmental pollution in the Middle East. According to Askari (2020), 96 percent of power generation capacity in the Middle East depends on fossil fuels (Askari). In 2009, the United Arab Emirates produced a total of 147 million tons of carbon dioxide emissions (Askari, 2020). The UAE is one of the countries with the highest carbon dioxide emissions in the Middle East (Askari, 2020). Therefore, the research project focuses on solar energy use in the United Arab Emirates. Compared to the recommended Global Horizontal Irradiance (GHI) threshold 1,600 kilowatt-hours per square meter, the average GHI in UAE is 2,100 (Hachicha et al., 2019). Therefore, the high GHI values make UAE a suitable place for the implementation of solar energy plants and facilities (Hachicha et al., 2019).

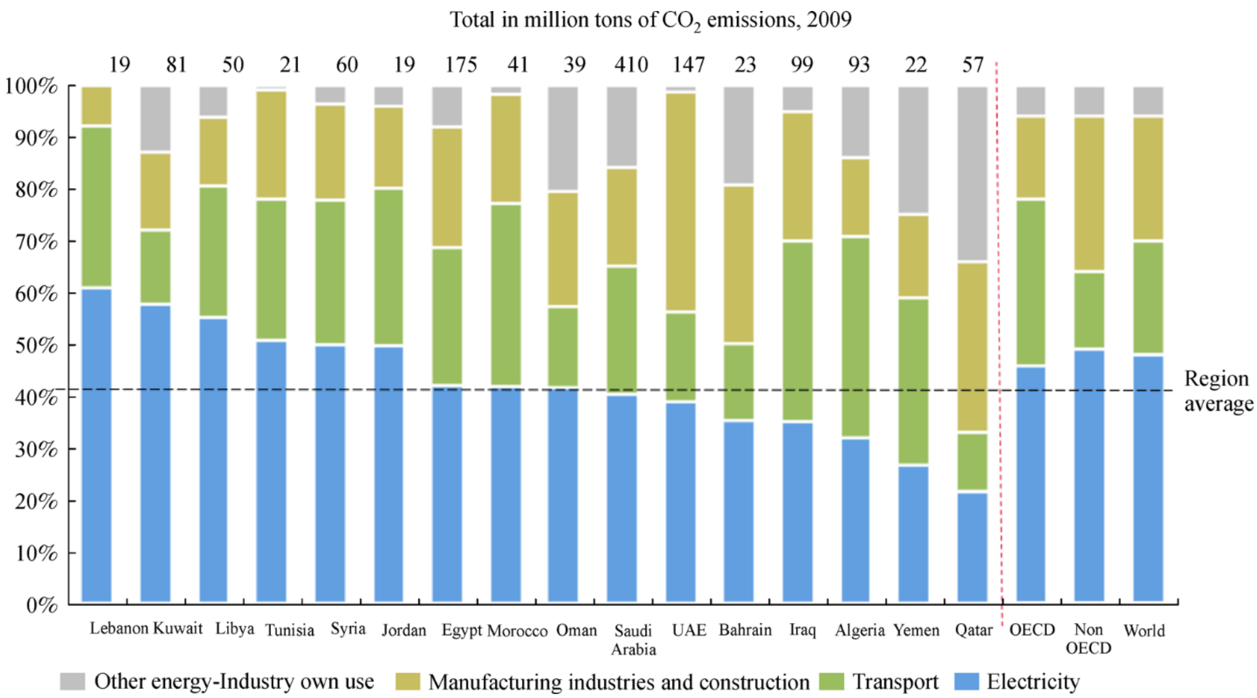


Figure 3.2 Carbon Dioxide Emissions in the Middle East Countries

3.2 Variables

The geographical location factor is one of the essential variable indicators. The Middle East countries are located in desert areas, and the annual exposure time under the sunshine is relatively longer. Longer sunshine exposure time is conducive to the collection of solar energy. For example, Iran has a high solar energy potential since the annual sunshine is longer than in other countries. According to Askari (2020), over 90 percent of Iran's land has a minimum of 280 days of sunshine per year. The global mean of solar radiation is 1800–2200 kilowatt-hours per square meter (kWh/m^2) per year (Askari, 2020). Therefore, the amount of solar radiation in Iran is higher than the global mean. Due to the geographical location, the United Arab Emirates is also always under the sunshine. However, due to seasonal changes in solar irradiance and degradation of solar energy systems, the power generation from solar is still limited (Gherboudj & Ghedira, 2016). For example, the solar irradiance is proportional to the insolation factor, which depends on the topography, season, and weather conditions (Gherboudj & Ghedira, 2016). Therefore, even in countries with sufficient sunlight like the UAE, solar power still faces variables and challenges. Additionally, long time high-temperature irradiation is not completely beneficial to solar panels. Rising air temperature reduced the solar system power output by affecting the cell voltage and the condensation efficiency of the collector (Askari, 2020). When the solar photovoltaic (PV) module temperature increases from 38°C to 48°C, the PV efficiency reduced by 11% (Gherboudj & Ghedira, 2016).

Another variable factor in the desert is the dust particles in the air. High humidity dust particles in the desert caused the penetration and dilution intensity of solar radiation to decrease. However, the total installed solar capacity of the Middle East and North Africa countries still reached 562.24 Mega Watts (Askari, 2020). The low night temperature in desert caused dew to form on solar panel surfaces and trap dust particles in the air (Hachicha et al., 2019). As the temperature rises and the dew evaporates, a layer of dust forms on the surface of the solar panels. According to Hachicha et al. (2019), due to dust accumulation, the maximum power reduced by ten percent within five weeks. Therefore, dust deposition is one of the main variables and challenges affecting solar power generation in the UAE. Without cleaning in six months, the solar system can reduce electricity by more than 50% (Hachicha et al., 2019). The accumulation of atmospheric dust in the desert reduces the efficiency of solar energy. Therefore, solar equipment in the Middle East and North Africa countries need to consider additional cleaning costs. However, increasing solar power generation brings environmental and economic returns on investment to the region.

Figure 3.3 on page 20 shows the solar installations in the United Arab Emirates (Askari, 2020). The coastal area has less wind and sand than the center of the desert (Askari, 2020). The settlement and transmission reduction of dust is strongly depending on weather conditions and the inclination angle of solar panels (Gherboudj & Ghedira, 2016). The wind sweeps dust particles on the surface of the solar panel, and the best panel installation angle is 30 degrees (Hachicha et al., 2019). Therefore, according to Askari (2020), the dust cleaning cost of solar systems installed in coastal areas is lower.

The main variables of this research study are geographical location factors and dust particles in the air. Therefore, the research studied the development of solar energy in the UAE based on the above variables.

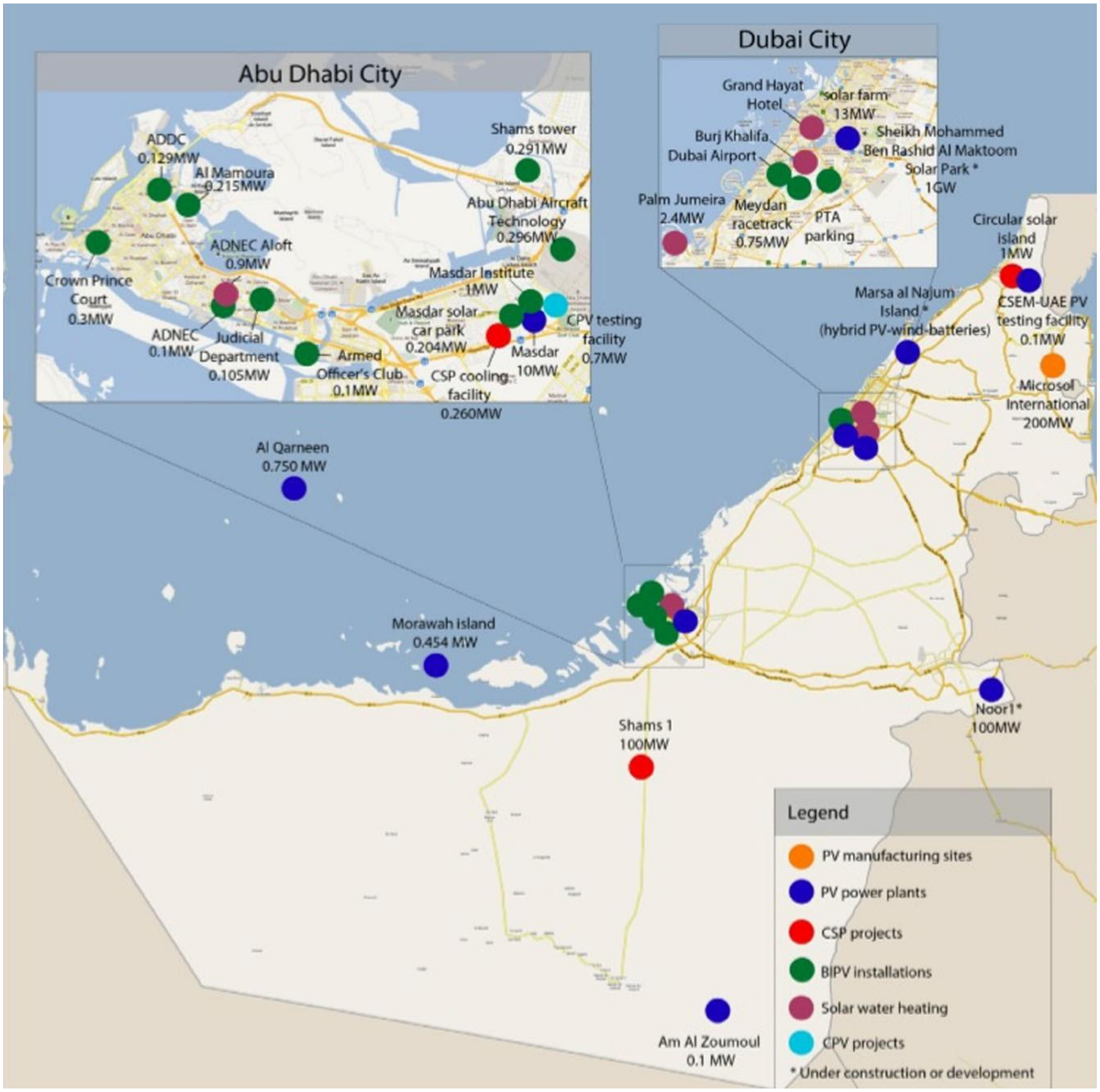


Figure 3.3 Solar Installations in the United Arab Emirates (UAE)

3.3 Sample Size

The main research sample is from the United Arab Emirates (UAE). The UAE is located at the southeastern tip of the Arabian Peninsula desert on the Arabian Gulf (Askari, 2020). Table

3.1 on page 22 shows the capacity of Solar Photovoltaics (PV) and Concentrated Solar Power (CSP) in five Middle East countries (Askari, 2020). The total solar power capacity in Iran, Egypt, Lebanon, Saudi Arabia, and the United Arab Emirates reached 186.8 Megawatts (MW). The solar PV capacity in the UAE accounts for 45% of the five countries' total, while the CSP capacity has reached 73%. The UAE has an arid climate that is exposed to ocean effects due to the geographical location (Gherboudj & Ghedira, 2016). The UAE has low rainfall, 120 millimeters per year on average from 1970 to 2001 (Hachicha et al., 2019). The extremely high temperatures in the UAE rose to 48°C during summer months (Gherboudj & Ghedira, 2016). According to National Renewable Energy Laboratory (NREL, 2019), at the end of 2018, the total installed solar capacity worldwide was 509 Gigawatt. The installed capacity of solar energy in the United Arab Emirates is relatively small. However, in areas with sufficient sunshine, the selection of the sample and the participants are optimal for the research study. Most of the areas in the UAE are well lit, however, sand and dust storms often occur (Askari, 2020). Therefore, the most ideal regions for implementing solar systems in the UAE are located in densely populated coastal cities (Askari, 2020). Abu Dhabi and Dubai are the most representative samples for studying the development of solar energy in the UAE (Askari, 2020). The research collectted sample data through the Research Center for Renewable Energy Mapping and Assessment (ReCREMA, 2020). The research obtained supplemental data through Abu-Dhabi Spatial Data Infrastructure (ADSDI, 2020).

Table 3.1 Capacity of Solar Energy in Five Middle East Countries, Units in Megawatts (MW)

Country	Capacity of Solar Photovoltaics (PV) in Megawatts	Capacity of Concentrated Solar Power (CSP) in Megawatts	Year
Iran	4.3	17	2011
Egypt	15	20	2012
Lebanon	1	0	2012
Saudi Arabia	7	0	2013
United Arab Emirates	22.5	100	2013
Total	49.8	137	

3.4 Statistical Measures and Data Analysis

The implementation of solar systems in the UAE depends on two constraints, geography and environment (Gherboudj & Ghedira, 2016). Geographical restrictions depend largely on the amount of solar radiation reaching the ground. Environmental restrictions are mainly related to climate and weather conditions. Table 3.2 on page 23 shows the description of the considered datasets of the research project in the UAE (Gherboudj & Ghedira, 2016). The study utilized the measurement units in Table 3.2 to analyze and research the solar environment in the UAE. To reach the research objective, the statistical measures considered include Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). Atmospheric variables and climatic factors affect the collection of solar energy from solar systems located in the UAE (Askari, 2020). Therefore, the main data collection also includes atmospheric temperature, airborne dust loading, relative humidity, wind speed, etc (Hachicha et al., 2019). Variable factors have a dual impact on the solar irradiance reaching the surface and the performance of the solar system (Gherboudj & Ghedira, 2016).

Table 3.2 Description of the Considered Datasets

Constraint	**Atmospheric variable**	**Acronym**	**Units**	**Dataset**	**Resolution**
Seasonal variability of the solar irradiances	Global horizontal irradiance	GHI	kW h/m2	ReCREMA	3 km
	Direct normal irradiance	DNI			
Dust deposition	Dust loading: aerosol optical thickness	AOT	–	ReCREMA	3 km
	Particle size: angstrom component	α500/870			
	Wind speed at 10 m	WS10 m	m/s	ReCREMA/3TIER	500 m
Weather variables	Relative humidity at 2 m	RH	%	ReCREMA/3TIER	500 m
	Air temperature at 2 m	Tair/2 m	K	ReCREMA/3TIER	500 m
	Atmospheric water vapor content	WV	cm	ECMWF	75 km
Land constraints/use	Digital elevation model	DEM	m	ADSDI	30 m
	Normalized difference vegetation index	NDVI	%	NASA	250 m

Figure 3.4, below, shows adopted methodology to identify the sustainability plan based on the geographical constraints and the environmental constraints. The geographical constraints include the annual sum of global horizontal irradiance and the annual sum direct horizontal irradiance. The environmental constraints include dust deposition, weather variables, and land constraints. First of all, the research identified the potential areas for solar energy applications based on the average annual sum of solar irradiances. Then, the research identified the weather conditions based on data collection of wind speed, air temperature, and relative humidity. Finally, based on the data measurement and analysis, the study drew a conclusion regarding the UAE's solar energy implementation plan.

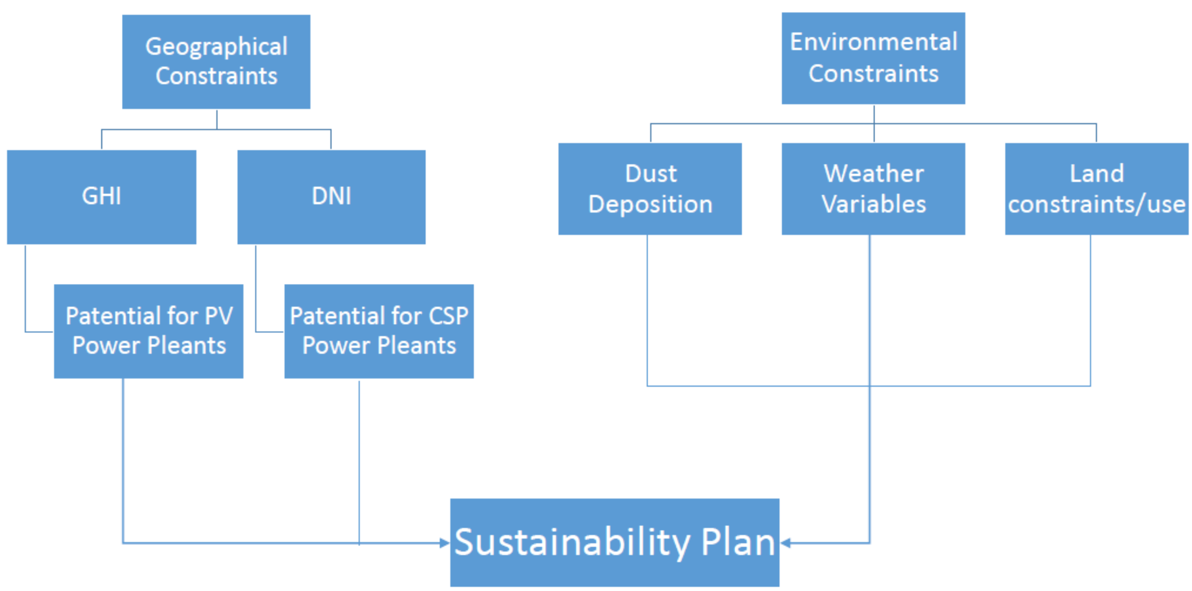


Figure 3.4 Adopted Methodology to Identify the Sustainability Plan Based On the Geographical Constraints and Environmental Constraints

Figure 3.5 on page 25 shows the cumulative capacity of global solar installations in 2018 (NREL, 2019). From 2006 to 2012, the global installed solar capacity increased from 6.9 GW to

102.2 GW, a nearly 15 times increase. The measurement increased to 509 GW, a five-time growth in the following six years from 2012 to 2018. The solar capacity growth has slowed down, however, the global capacity kept increasing and more countries begun to implement solar energy. According to NREL (2019), the total solar capacity of Middle East countries is still lower than in other countries as of 2018 (NREL). Coyle and Simmons (2016) estimated, by 2050, solar power could account for eleven percent of global electricity generation (Coyle & Simmons). The UAE is aimed to derive five percent of the total national electricity production from solar energy in 2021 (Gherboudj & Ghedira, 2016).

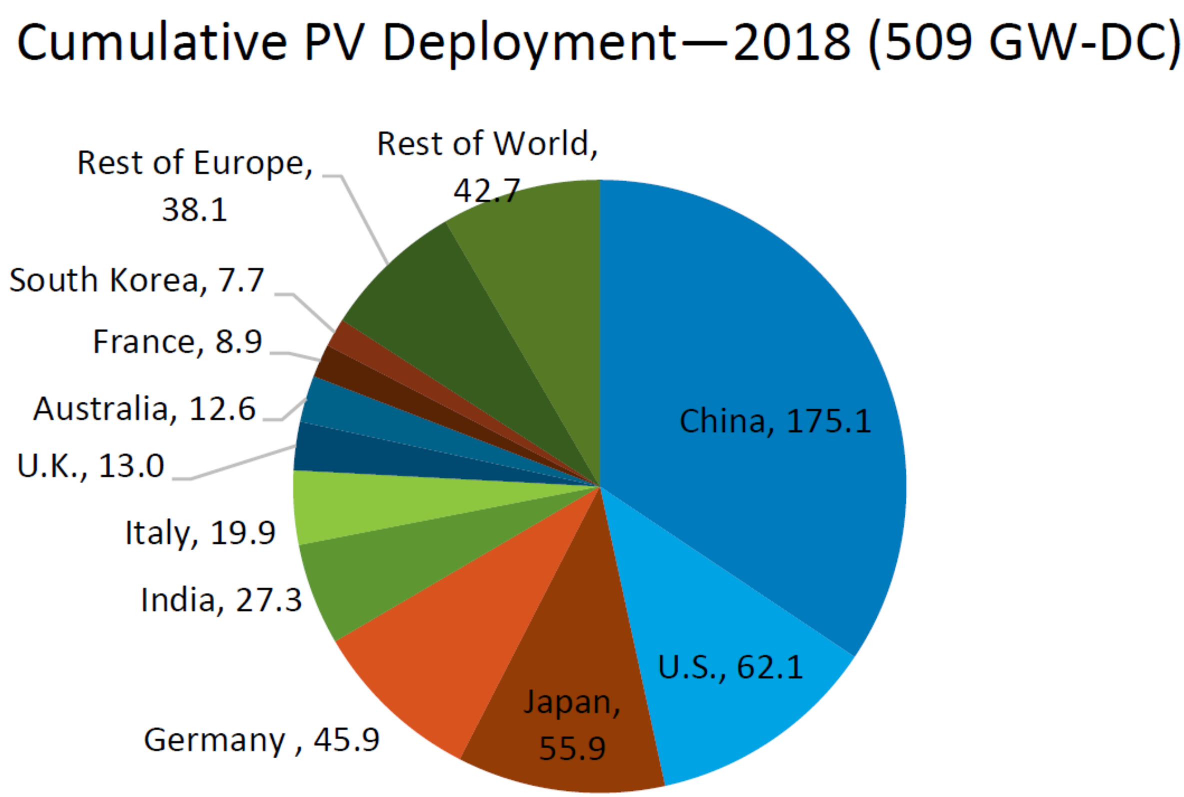


Figure 3.5 Cumulative Capacity of Global Solar PV Development, 2018

3.5 Research Instruments and Tools

Research Instruments are designed to obtain data on the topic from research subjects. The instruments and tools used for the research include published surveys, articles, books, and government reports. The study cited the research instruments and tools from Purdue University Library and government websites. Cited resources are included in the list of references at the end of the research.

3.6 Processes

The research project identified and developed the research topic, and development of sustainable energies from solar. The research first determined the problem statement, and then introduce the impact of the problem. Next, the research determined the method to measure the problem and associate it with one of the Grand Engineering Challenges. The research project conducted a preliminary search for information and data. Purdue University Library and government reports provide valuable academic references, resources, and materials for the research project. Therefore, the study evaluated the academic sources and materials and then conduct the outline of the study. The study introduced the current status of global energy demand and the future development direction, namely sustainable development strategy. Through the analysis of energy demand, the study explored the significance and prospects of solar energy for sustainable development strategies. The study selected the UAE as a sample of research. The research studied and analyze the development of solar energy in the UAE, including limitations, current status, opportunities, and challenges. The research obtained research results through data collection, measurement, and analysis. The research project collected, sorted, analyzed, and studied the data through the above resources by utilizing the Microsoft Excel tool. Then, the study summarized the results and reiterated the importance of solar energy for the sustainable development of global energy. Finally, the research project wrote the research paper and correctly cite the sources and references.

3.7 Limitations and De-limitations

Limitations:

1. The research is aimed at the global energy crisis and the sustainable development of solar energy. However, the sample size limited the comprehensiveness of the research geography to the United Arab Emirates.
2. The study analyzed the UAE's energy consumption, solar energy potential and development, and limitations.
3. Due to the unique geographic location and energy reserves of the UAE, the research has limitations to global energy sustainable development.
4. Weather factors such as dust, wind, vapor, and rain limited the development of the solar energy industry in the UAE.
5. Adequate sunlight is conducive to the collection of solar energy, but high temperatures affected the power output of solar systems. Therefore, in the UAE, excessively high temperatures also became a limitation and challenge for solar systems.
6. Limitations of insufficient resources. The research resources were mainly from Purdue University Library and government reports.

De-limitations:

1. The research topics revolved around the global energy crisis and the prospect of solar energy replacing fossil fuels.
2. The goal of the research was to demonstrate the potential of solar energy and provide more energy to the world in the future.
3. The variables of the study were the impact of the region and environment on solar output and installed capacity.

3.8 Presentation of Data

The United Arab Emirates (UAE) is a Middle East country. The UAE is located between 51° and 56°25′ east longitudes and between 22° 30′ and 26° 10′ north latitudes (Hachicha et al., 2019). The location gives the UAE good solar energy exposure and average Global Horizontal Irradiance (GHI) between 1900 and 2300 kilowatt-hours per square meter (Hachicha et al., 2019). The spatiotemporal variability of solar resources includes Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). The weather conditions include the measurements of dust deposition, weather variables, and land constraints.

Figure 3.6 on page 29 shows the average annual sum of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) estimates. The average annual sum of GHI and DNI are fundamental and decisive factors for the analysis (Gherboudj & Ghedira, 2016). The horizontal axis in Figure 3.6 a1 and a2 represents the average annual sum of GHI and DNI. The horizontal axis in Figure 3.6 b1 and b2 represents the scale value corresponding to the average annual sum of GHI and DNI. The scaled values between 0 and 1 where 0.5 corresponds respectively to the threshold annual sum of GHI (1600 kWh/m2) and DNI (1900 kWh/m2) (Gherboudj & Ghedira, 2016). Appropriate areas for both PV and CSP applications had threshold annual sum of GHI greater than 1,000 kilowatt-hours per square meter (Gherboudj & Ghedira, 2016). Therefore, according to the data in Figure 3.6, the UAE has potential areas for implementing solar energy applications.

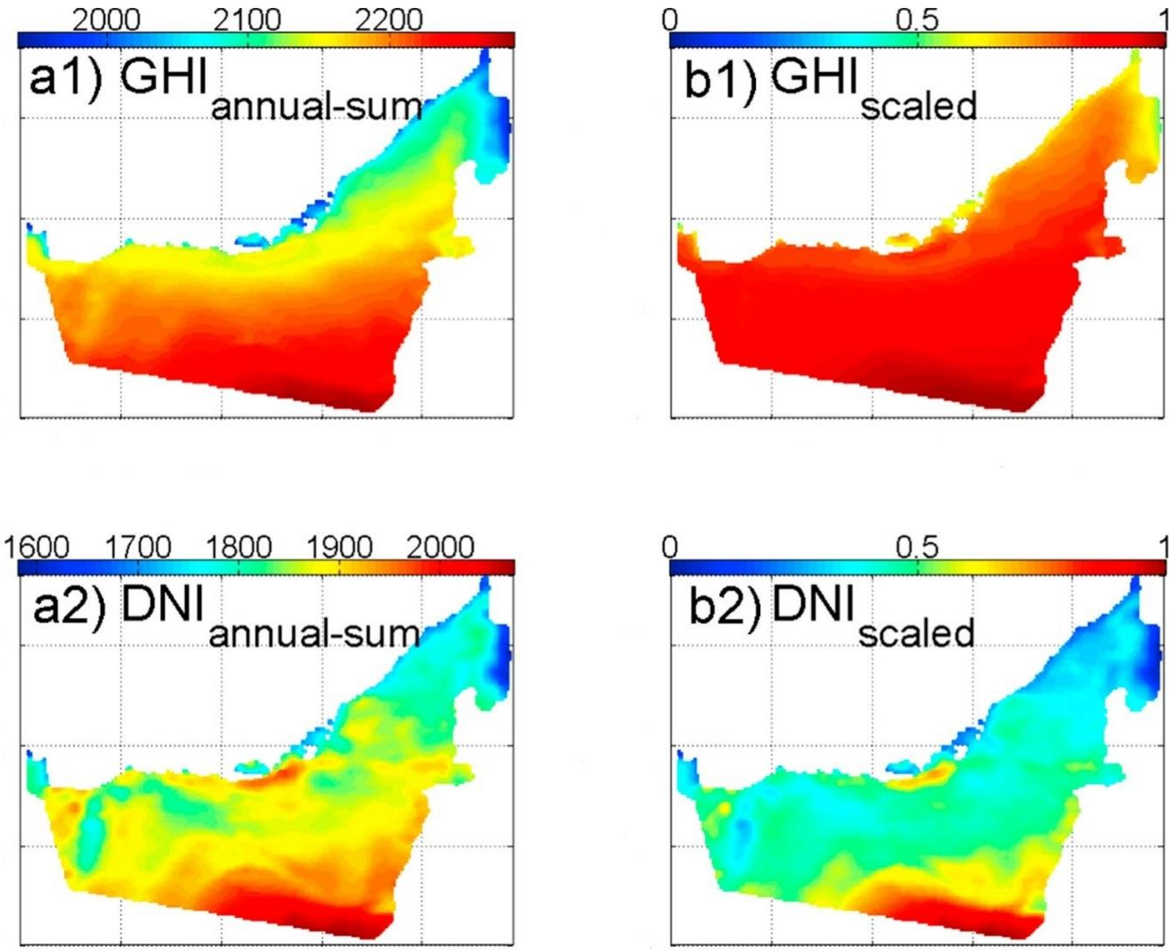


Figure 3.6 UAE Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) Solar Irradiance Maps

3.9 Return of Investment

The investment in solar energy mainly comes from energy conversion and storage. Solar power is growing rapidly, and emerging research in nanotechnology is providing broader assistance. Coyle and Simmons (2016) stated that 88 percent of the primary energy consumed worldwide is wasted in the form of heat. Improving the conversion of future thermal energy into electrical energy is vital in order to reduce the consumption of fossil fuels. Therefore, nanotechnology is an essential method to improve the energy storage and transmission of solar cells. Figure 3.7 on page 31 shows the solar PV value chain spot pricing trend (NREL, 2019). The prices of solar system modules and module components have continued to decline over a period of 16 months. Electrical efficiency depends on the length and intensity of sunlight and cell materials and components (Hosenuzzaman et al., 2015). The decline in the price of major solar module components is conducive to promotion worldwide. The solar system maximized the value at a lower price with the return on investment to the world.

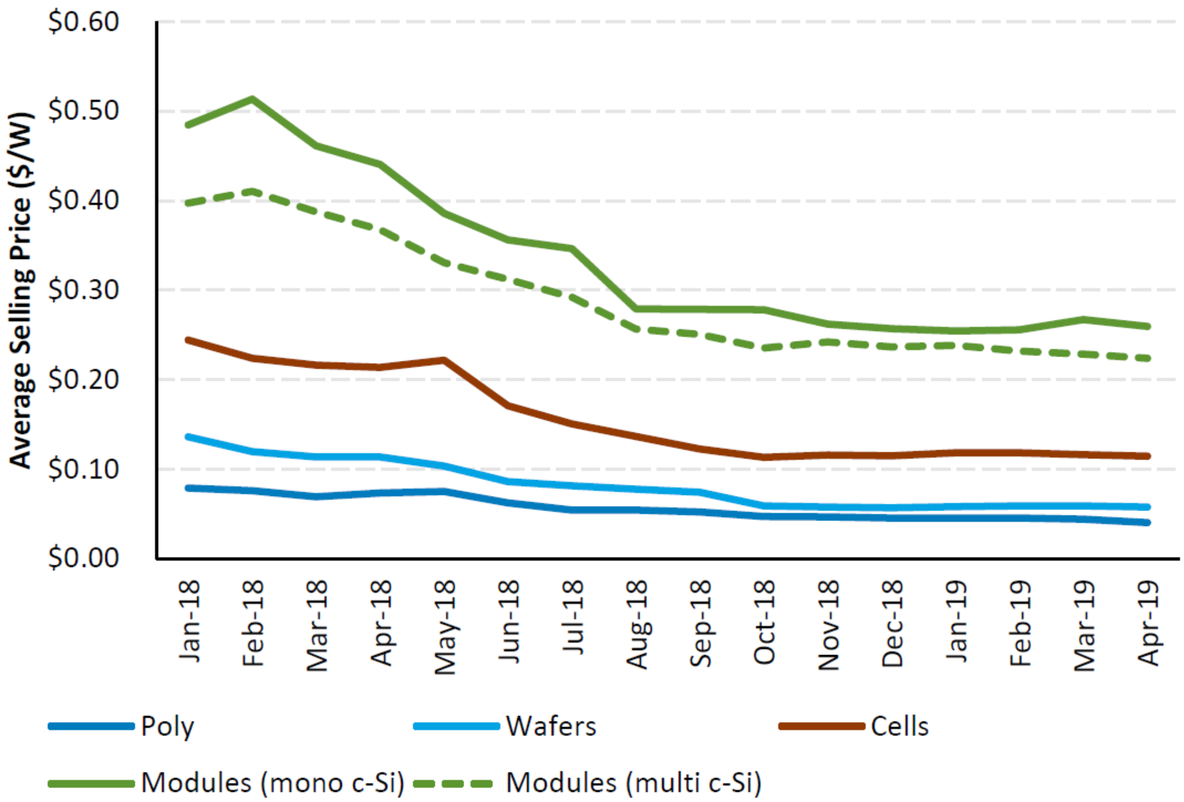


Figure 3.7 PV Value Chain Spot Pricing Trend

The best way in the context of the energy crisis is to increase solar energy development to gradually replace fossil fuels (Qureshi et al., 2016). The direct return on investment for the sustainable development of solar energy is to reduce environmental pollution and greenhouse gas emissions. Qureshi et al. (2016) stated, greenhouse gas emissions have severe impact on energy demand, which exacerbates unpredictable changes in the global climate. Solar energy is clean and transmitted from the sun to the earth without cost. Solar energy does not need to establish long-distance high-voltage transmission lines for power transmission when supplying power for small grid. Therefore, Jahangiri, Ghaderi, Haghani, and Nematollahi (2016) stated, solar energy saves the cost of the transmission network for the local power grid. Therefore, regardless of environmental protection or return on investment, solar is one of the top choices for sustainable development.

CHAPTER 4. RESULTS

Uncontrolled exploitation led to the evacuation of oil resources and a serious energy crisis in the world (Najafi et al., 2015). As one of the major oil suppliers in the world, the United Arab Emirates (UAE) is also facing the problem of energy shortage (Najafi et al., 2015). Although the UAE as the sample of this study is not enough to explain the trend of global solar energy development, the conclusion is still vital. Due to geographical and environmental factors, the amount of solar energy collected in each country or region is relatively different (Gherboudj & Ghedira, 2016). The UAE has relatively sufficient sunlight, which is conducive to collecting solar energy. The countries in tropical rain forests or areas with plenty of rain face the problem of insufficient sunlight (Hachicha et al., 2019). However, the UAE, which is located in a desert, is also faced with restrictive factors brought by dust and wind (Gherboudj & Ghedira, 2016). Although the limitations of research still exist, the strategic goal of sustainable development of solar energy never shakes.

As an inexhaustible source of clean energy, the UAE government considered solar as the main source of energy in the future (Gherboudj & Ghedira, 2016). The UAE's integrated energy strategy is aimed to derive five percent of the total electricity production from solar energy in 2021 (Gherboudj & Ghedira, 2016). Geography and environment are the two constraints that impact the implementation of solar systems in the UAE (Gherboudj & Ghedira, 2016). Geographical restrictions depend largely on the amount of solar radiation reaching the ground. Environmental restrictions are mainly related to climate and weather conditions. The Chapter Four mainly conducted data collection and analysis based on the geographical and environmental factors of the UAE. Additionally, the chapter discussed the results to conduct research analysis and answer research questions by analyzing data. The main purpose of the research study was to discuss and demonstrate the potential and sustainability of solar energy. Therefore, the discussion in the chapter proved the prospect and feasibility of replacing fossil fuels with solar energy in the UAE.

4.1 Research Data Collection Strategy

The research study introduced data collection through four aspects: data capture time, location, format, and storage. Global Horizontal Irradiance (GHI) is the total amount of shortwave radiation received from above on a surface horizontal ground. GHI is particularly meaningful for photovoltaic installations and includes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). Therefore, to reach the research objective, the statistical measures considered include GHI and DNI. Data collection started on September 14, 2020, and ended on September 20, 2020. Atmospheric variables and climatic factors affect the collection of solar energy from solar systems located in the UAE (Askari, 2020). Therefore, the data collection also included air temperature, dust loading, and relative humidity in 2017 in the UAE.

The major sources of data were Research Center for Renewable Energy Mapping and Assessment (ReCREMA) and European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset comprised the UAE monthly solar irradiance (GHI and DNI), dust deposition, and weather variables. ReCREMA is founded by the UAE Directorate of Energy and Climate Change, Dubai Supreme Council of Energy, and Environment Agency of Abu Dhabi (ReCREMA, n.d.). ReCREMA has been recording and providing relevant environmental data in the UAE since 2012. The monthly GHI and DNI data from ReCREMA included the solar zenith angle and solar time, day number, and eccentricity correction (Gherboudj & Ghedira, 2016). The accuracy of the data from ReCREMA was satisfactory with relative root mean square errors of 12.4% and 26.1% for GHI and DNI components (Gherboudj & Ghedira, 2016). European Centre for Medium-Range Weather Forecasts is a research institute that has one of the largest meteorological data archives in the world (ECMWF, 2020). European Centre for Medium-Range Weather Forecasts produces global numerical weather predictions and other data (ECMWF, 2020).

Insolation is a measure of solar radiation energy received on a given surface area in a given time. Therefore, the seasonal variability of the solar irradiances was measured in kilowatt-hours per square meter (kWh/m2) with a resolution of three kilometers. The dust deposition was measured in Aerosol Optical Thickness (AOT) with a resolution of three kilometers. The weather variable dataset consisted of relative humidity in percentage and air temperature in Fahrenheit and both with a resolution of 500 meters. All data had a scale of two in precision.

The data of the research project were recorded and kept using Microsoft Excel. Excel provides the necessary functions for data collection and processing and facilitates later data analysis. Purdue University provides students with free Microsoft 365 applications, including cloud storage service. Therefore, all data from the research project were saved in the Microsoft OneDrive cloud storage service in real-time. Additionally, for safety reasons, the data were synchronized to a local computer for a daily backup.

4.2 Data Analysis and Findings

Atmospheric variables such as airborne dust loading, atmospheric water content, air temperature, relative humidity, and wind speed impact the desert climate (Gherboudj & Ghedira, 2016). However, the interaction of atmospheric variables has vital impact on solar irradiance reaching the surface and the performance of the solar system (Gherboudj & Ghedira, 2016). The research collected data from Research Center for Renewable Energy Mapping and Assessment (ReCREMA) and European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset comprised the monthly solar irradiance, including both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) in Dubai and Abu Dhabi.

Table 4.1 on page 37 shows the irradiation values (GHI and DNI) of each month in Dubai and Abu Dhabi in 2017. According to the data from Table 4.1, the increase in the GHI values starts in spring (March) to reach the maximum values in summer (May). The decrease starts in autumn (September) to reach the minimum values in winter (December) season. In contrast to the GHI component, the DNI component shows mainly higher values during the spring (April to May) and autumn (September to November) seasons. The lower values are observed during summer and winter seasons.

Table 4.1 Monthly Irradiation Values (kWh/m^2) in 2017

Month	GHI in Dubai	DNI in Dubai	GHI in Abu Dhabi	DNI in Abu Dhabi
January	126.1	152.8	129.1	158.9
February	109.6	85.8	109.8	84.4
March	154.2	110.3	158.3	120.8
April	203.8	173.4	202	176.1
May	217.9	183.3	212.8	179.6
June	211.5	166.7	210.6	171.9
July	208.4	142.6	207.2	145.6
August	202.9	156.6	202.9	163.3
September	184.2	174	187	181.9
October	171.7	203.7	175.8	213.9
November	134.4	177.6	137.7	187
December	121.6	168.4	123.8	169.6
Total in 2017	**2046.3**	**1895.2**	**2057**	**1953**

Figure 4.1 on page 38 shows the irradiation values chart in Dubai and Abu Dhabi in 2017. Throughout the summer, GHI values in Dubai and Abu Dhabi stabilized, while DNI values decreased in July. As presented in Figure 4.1, the temporal variability of GHI is notably higher than DNI.

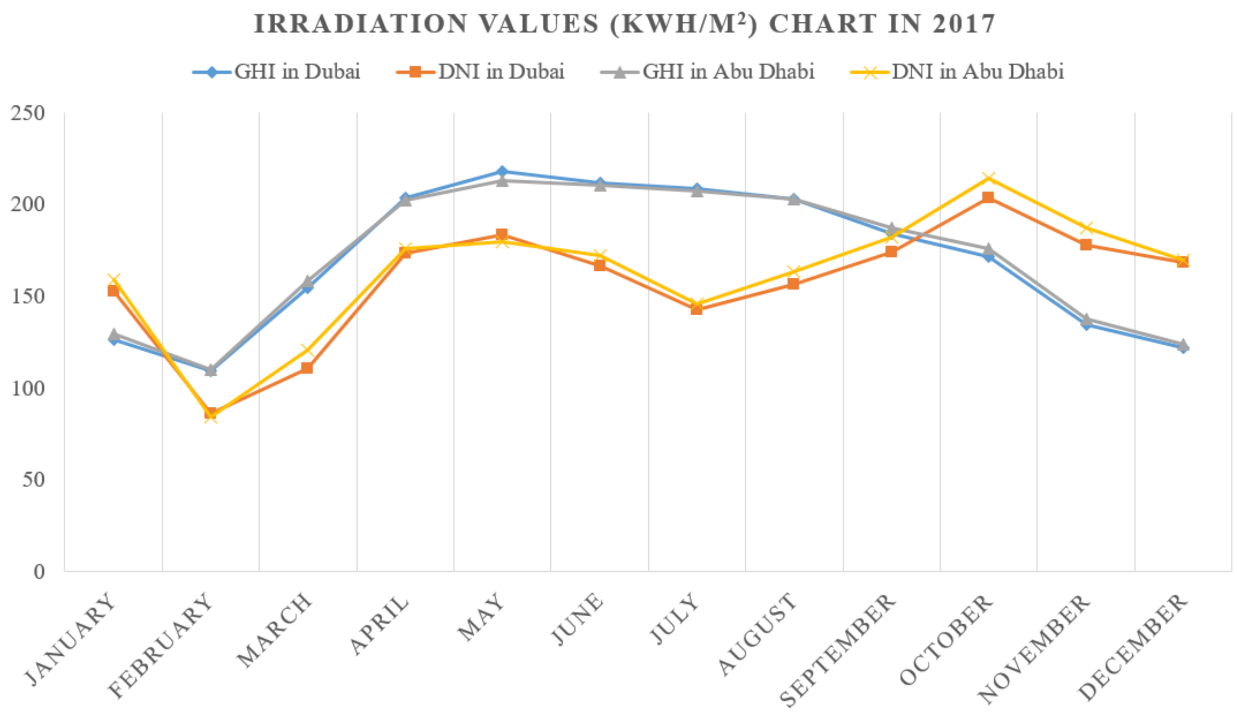


Figure 4.1 Irradiation Values Chart in 2017

Table 4.2 below shows the yearly irradiation values in Dubai and Abu Dhabi from 2015 to 2017. Appropriate areas for photovoltaic applications had a threshold annual sum of GHI greater than 1,000 kWh/m2 indicates the potential for solar applications (Gherboudj & Ghedira, 2016). According to the data from Table 4.2, both Dubai and Abu Dhabi have potential areas for implementing solar energy applications.

Table 4.2 Yearly Irradiation Values (kWh/m^2) in 2015, 2016, and 2017

Year	GHI in Dubai	DNI in Dubai	GHI in Abu Dhabi	DNI in Abu Dhabi
2015	2044.3	1828.1	2063.1	1887.7
2016	2019	1852.1	2040.1	1903.3
2017	2046.3	1895.2	2057	1953

The dusty environment of the UAE is one of the biggest obstacles to the country's use of abundant solar resources (MENA Report, 2016). A beam of sunlight reaches the surface of the earth and bounces back between dust particles and other aerosols in the air (MENA Report, 2016). In other words, the dust and moisture on the surface of the solar panel impact the efficiency in receiving sunlight. Table 4.3 on page 40 shows the monthly coefficient of variation of weather variables and average air temperature in 2017. The seasonal and spatial variations of the aerosol optical thickness (AOT) have the most striking trend (Shahin, Topriska, Nour, & Gormley, 2020). The coefficient of variation of dust loading from April to August in 2017 is between eight percent and 19%. Therefore, the significant dust loading is mainly observed during late spring and summer monsoon bracketed from April to August. The wind in the desert caused high and heterogeneous spatial variability of the dust loading in the area (Gherboudj & Ghedira, 2016). The coefficient of variation value reached 20% in July.

The air relative humidity (RH) is inversely proportional to air temperature and coefficient of variation (Shahin et al., 2020). As the air temperature rises in summer, the relative humidity gradually decreases while the coefficient of variation increases. The maximum value of relative humidity is obtained in coastal cities such as Dubai and Abu Dhabi (Utilities Middle East, 2018). In fact, the summer temperatures in the UAE are often associated with higher relative humidity along the coasts than inland (Gherboudj & Ghedira, 2016).

Table 4.3 Monthly Coefficient of Variation of Weather Variables and Average Air Temperature in 2017

Year of 2017	Coefficient of Variation (%) - Aerosol Optical Thickness (AOT)	Coefficient of Variation (%) - Relative Humidity (RH)	Average Air Temperature (F)
January	3%	3%	67
February	5%	7%	70
March	6%	13%	75
April	8%	18%	82
May	9%	22%	90
June	10%	24%	93
July	20%	21%	97
August	8%	19%	98
September	6%	19%	93
October	3%	17%	87
November	2%	8%	79
December	3%	6%	71

4.3 Impact

Dust accumulation is one of the challenging issues encountered when operating solar photovoltaic systems under UAE weather conditions (Hachicha et al., 2019). During outdoor exposure, dust settling seriously affects the performance of solar equipment (Hachicha et al., 2019). The dust loading is the most essential variable in the desert climate, followed by the water vapor content in the atmosphere (Gherboudj & Ghedira, 2016). The variables greatly affect solar irradiance by reducing surface insolation. Dust particles scatter sunlight (namely, aerosol direct effect), which results to consequently a decrease in DNI values (Gherboudj & Ghedira, 2016). Due to the special climate of the UAE, a reduction in DNI leads to a reduction in the level of solar power generation (Shahin et al., 2020). The electrical conversion efficiency of the solar system reduced by half when dust and vapor cover the surface of the solar cell (MENA Report, 2016).

The increased rate of dust density and power soiling are not constant and largely depend on local weather conditions (Hachicha et al., 2019). Rainfall participates in the cleaning of the solar panels to reduce the pollution of the photovoltaic system. However, researchers from the Masdar Institute and the Massachusetts Institute of Technology (MIT) have found a way around dust difficulties in the UAE (MENA Report, 2016). The novel solar thermal energy conversion system can leverage the sunshine both direct and diffuse to generate steam in a simple, low-cost way (MENA Report, 2016). The steam system uses solar thermal radiation rather than the direct sunlight, which can be hindered by the aerosols (MENA Report, 2016). Therefore, the new technology is particularly suited for the dusty climate.

4.4 Summary

The variation of photovoltaic performance and dust accumulation are largely dependent on weather conditions, such as humidity, rainfall, and wind (Hachicha et al., 2019). Rainfall contributes to improve photovoltaic performance and reduce dust density. Weather conditions are uncontrollable factors and continue to affect the dust deposition on the photovoltaic surface. Therefore, further research is needed for the combined effects of dust and moisture, and to develop the cleaning technologies suitable for the UAE. However, relatively speaking, the coastal areas of the UAE are more suitable for the application and development of solar energy than inland (Gherboudj & Ghedira, 2016). In fact, the region has been selected as a solar power plant with multiple photovoltaic power plants. Masdar-City in Abu Dhabi, the largest solar power station in the Middle East, has an annual power generation of 10 megawatts (Gherboudj & Ghedira, 2016). Additionally, the orientation and tilt angle of the photovoltaic surface affects the dust deposition (Hachicha et al., 2019). 25 degrees tilt angle is favorable for a fixed photovoltaic system in the UAE location with the lower effect of dust accumulation (Hachicha et al., 2019). The availability of solar resources and the compatibility with regional power demand patterns are driving the development of the UAE's solar industry (Shahin et al., 2020). The total capacity of rooftop photovoltaic solar panels in Abu Dhabi doubled to reach six megawatts in 2018 (SyndiGate Media Inc., 2018). The rapid decline in the cost of solar system and growth in government support are bound to encourage the installation of new facilities in the region (Utilities Middle East, 2018).

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

The global energy crisis and the threat of climate change demand innovation in the energy sectors and responsible consumption for all countries (Phillips & Smith, n.d.). The proportion of fossil fuels in energy consumption is large, nevertheless, sustainable energy is the only option for the future (Phillips & Smith, n.d.). Developing sustainable energies from solar can replace fossil fuels while reducing greenhouse gas emissions by Carbon Sequestration (NAE, n.d.). Transformation requires more than converting energy, but also ensuring cost-effectiveness, sustainability, and benefit to development. Along with the continuous advancement of technology and the rise in production, the cost of solar energy systems has fallen accordingly (Ryan, 2016).

As a major oil producer and exporter, the UAE is one of the countries with the highest carbon dioxide emissions in the Middle East (Askari, 2020). However, the UAE is also one of the most outstanding countries in the development and application of solar energy in the Middle East (Askari, 2020). The sustainable development of solar energy is succeeding in the UAE. Although the desert climate has certain impacts on the efficiency of solar energy collection, the promotion of solar energy is energetically imperative. Cost reductions in the implementation of solar technologies made solar systems cost-competitiveness with fossil fuel-based power generation in mid to high latitudes (Phillips & Smith, n.d.).

5.2 Conclusions

Tropical and subtropical regions receive higher solar radiation throughout the year (Khan & Arsalan, 2016). Therefore, countries in tropical and subtropical regions have great potential to harness solar energy for electricity demand. The dust in the desert adhered to the solar panels and reduced the efficiency of solar energy collection. Additionally, the excessively high ambient temperature also affected the power output of the solar system. However, the use of new materials and cleaning equipment on solar panels can effectively reduce the impact of environmental factors. Innovative technologies are advancing every day and contributed to improving the sustainability and development of solar energy (Phillips & Smith, n.d.). Promoting the sustainable development of solar energy in the world's major crude oil-producing and exporting countries is revolutionary progress. Environmental constraints exist objectively, but the research results are encouraging. The development of affordable and clean solar technology innovation has long-term benefits as it enhances the world's power security and economic applicability (Khan & Arsalan, 2016). The prospect of solar energy replacing fossil fuels is exciting in the shadow of the global energy crisis.

5.2.1 Research Alignment with Current Literature

Energy is the essential factor in the economic development, and prosperity of any country and is directly related to the major global challenges. The world's energy supply has increased substantially in the past decades, nevertheless, the warning of the energy crisis has not been lifted (Lundgren, Marklund, & Zhang, 2016). The global energy situation dominated by fossil fuels has led to impacts on regional climate conditions, environmental degradation, and energy crisis (Khan & Arsalan, 2016). Energy demand becomes a global problem and challenge. The fossil fuel supply did not keep up with growing global energy demand (NAE, n.d.). Based on the world's latest technological innovations and extensive researches, naturally available solar energy has shown great potential to meet the world's energy demands in the future (Khan & Arsalan, 2016). Therefore, the availability of solar energy as the first choice for clean energy exceeds any imaginable future energy demands. Further, solar energy systems are relatively affordable and are suitable for developed, developing, and poverty-ridden regions (Khan & Arsalan, 2016).

5.2.2 Limitations of Research

While the findings demonstrated that the sustainable development of solar energy in the UAE has encouraging potential, the research has limitations. The primary restrictions include changes in geographic location, climate, and environmental factors, as well as regulations on solar energy in different countries. The research is aimed at the global energy crisis and the sustainable development of solar energy. However, the research project sample size limited the comprehensiveness of the research geography to the UAE. Weather factors such as dust, wind, vapor, and rain limited the efficiency of solar energy systems. Solar radiation is higher in tropical and subtropical regions, which is conducive to solar energy collection. However, in desert areas, weather and environmental constraints were prominent. In regions with less sunlight time throughout the year, the demand for solar systems will be higher to meet the needs.

The cost of the solar system will take into account the equipment and installation, as well as transportation and maintenance. The sustainable development plans and regulations of solar energy vary in different countries. The UAE government actively encourages and vigorously develops the solar energy industry. The United States has multiple incentive policies to encourage people to use solar energy systems. However, not all countries regard solar energy as part of a sustainable development strategy.

5.2.3 Interpretation and Implications of Findings

The impact of the desert climate on solar systems mainly comes from dust, wind, and steam. Additionally, in coastal areas where rainfall is relatively abundant, rainwater also cleans the surface of solar panels. The development and progress of science and technology effectively solve the constraints of environmental factors. For instance, the application of new materials reduced the adhesion of dust. The two common materials used to make solar panels are silicon (Si) and gallium arsenide (GaAs), however, both are expensive materials (Raebel, 2019). Scientists are committed to discovering and researching efficient and low-cost materials for application in solar energy systems. Perovskite is a naturally occurring mineral that can be found in the earth's crust and is a promising candidate (Raebel, 2019). Perovskite materials have reached efficiency ratings of as high as 27%, while the highest level ever reached by GaAs is 28.8% (Raebel, 2019). Perovskite materials stand up to the elements of the environment and make dust difficult to absorb on solar panel surfaces (Raebel, 2019). Therefore, new materials not only make progress in cost control of solar energy systems but also provides solutions to environmental issues.

The introduction of cleaning equipment effectively removes the dust attached to the surface of the solar panel. For example, acoustic cleaning technologies provide effective solutions for the self-cleaning of solar panels. The surface vibration formed by the piezoelectric actuator mounted on the surface of solar panels achieves an effective cleaning purpose (Alagoz & Apak, 2020). Acoustic cleaning technologies brought great benefits to solar panels installed in desert environments. The surface acoustic wave generated on the solar panel surface contributes to cleaning of large dust particles on the inclined solar panels (Alagoz & Apak, 2020).

Summarizing the interpretation and Implications of findings, new materials and cleaning technologies contribute to the fact that solar systems are effective. The research showed that technological progress and government encouragement are promoting the sustainable development of solar energy. Emerging technologies and materials have improved solar energy systems efficiency and provided environmentally friendly and sustainable options for world energy sources.

5.3 Recommendations for Future Work

The following areas, including but not limited, need further research to complement the findings of the current research project.

1. Cost analysis of adding solar panel cleaning equipment in a desert environment.
2. Due to changes in the angle and intensity of sunlight during the day, the prospect of designing and adopting automatically angle adjustable solar systems.
3. Comparison of solar energy harvesting efficiency between coastal areas and the center of the desert in a calendar year.
4. The impact of the application of new materials on the cost and promotion of solar equipment.
5. The development of solar energy systems from commercialization to residentialization in the UAE.
6. Equipment installation and maintenance, and labor cost accounting.

The sustainable development of solar energy is succeeding in the UAE. While current research has limitations, research provides a basis for the development of solar energy to replace fossil fuels. At present, the development of solar energy is making continuous progress, and advanced technology provides more choices. The economical and sustainable development plan of solar energy provides an effective solution to the global energy crisis.

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