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Analysis of Photovoltaic System Under Different Environmental Conditions and Optimizing The Energy Self-Consumption

A Thesis Submitted to the Council of College of EngineeringUniversity of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

وَٱلشَّمۡسُ تَجۡرِي لِمُسۡتَقَرّٖ لَّهَاۚ ذَٰلِكَ تَقۡدِيرُ ٱلۡعَزِيزِ
ٱلۡعَلِيمِ ٣٨

صدق الله العظيم

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Dedication

The current study is dedicated to my great teacher and messenger, Muhammad (*Peace and Blessings of Allah be upon him*)

In memory of those who passed away my father and my mother

All righteous and loyal people wherever they are in the world. My beautiful country Iraq

Gufran Adnan Jendar 2022

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ABSTRACT

Among the types of solar systems, the photovoltaic (PV) systems become more widely used and widespread. However, there are some factors and requirements must be taken into account when installing and operating these systems. The temperature, dust and shade are considered the most important factors that negatively on the power production of PV system. While, increasing the self-consumption of solar energy to reach the self-sufficiency for PV system is the main goal in achieving the optimal use of the PV systems. Therefore, this study was divided into two parts. The first part was dealt with an experimental investigation to studay the effect of temperature and dust on the PV module by fabricating two twin PV systems. While, HOMMER software was used in the second part to increase the self-consumption of solar energy to reach the self-sufficiency for PV system by sizing the number of batteries and by suggesting fuel cell (FC) as another storage unit. The experimental results showed that the maximum temperature of the dirty PV module was recorded 46.5 °C at 28th February as compared with the clean module that recorded 49 °C. The influence of accumulating the dust on the PV module results decreasing its energy production by 9%. On the other side, the results of HOMMER software showed that the self-sufficiency was achieved in third of June 2021, first of October 2021 and first of April 2022 at four battery number, while in first of January 2022 at eight battery number respectively with self-consumption about 14,13 kWh, 9.88 kWh, 21.28 kWh and 13.72 kWh. In addition, the largest energy provided by FC was recorded 29% from the required load. Furthermore, the self-consumption of energy was increase from 77.64% to 98.72% when the capacity of FC changed from 0.5 kW to 2.5 kW.

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LIST of SYMBOLS

Symbol	Description	Unit
EL_L	Electrolyzer power	kWh
E_{PV}	PV array energy	kWh
E_{FC}	FC energy	kWh
E_L	Electrical energy consumption	kWh
EFed	Grid energy delivered to the grid	kWh
EFrom	Grid energy taken from the grid	kWh
E_{tot}	Total annual required energy	kWh
E_{ren}	Total annual renewable energy production	kWh
$H_{T,STC}$	Solar irradiance at STC	kW/m^2
H_T	Solar irradiance	kW/m^2
I_{EL}	Current of the electrolyzer	A
I_{FC}	FC current	A
$P_{FC,t}$	Instantaneous FC system power	kW
$P_{Grid,t}$	Instantaneous power taken from grid	kW
$P_{Load,t}$	Electrical power	kW
$P_{PV,t}$	Instantaneous PV system power	kW
PV_C	PV system rated capacity	kW
PV_η	PV system derating factor	%
R_f	Renewable energy fraction	---
T_a	Ambient temperature	°C
$T_{C, STC}$	PV cell temperature at standard test condition	°C
T_C	PV cell temperature	°C
V_{FC}	FC voltage	V
G	Solar radiation	kW/m^2
R^2	The coefficient of Determination	---
$A\alpha_P$	PV cell temperature coefficient of power	%/°C
k	Rosse coefficient	Km^2/W
n	Number of simulation iterations	--------

Greek Symbols

Symbol	Description	Unit
β	PV module tilt angle	Degree
γ	PV module azimuth	Degree

LIST of ABBREVIATIONS

Abbreviations	Explanation
BT	Battery
BTU	British Thermal Unit
EIA	Energy Information Administration
TWh	Terawatt hour
GW	Gigawatt
AC	Alternating current
DC	Direct Current
PV	Photovoltaic
HVAC	Heating, Ventilating and Air Conditioning
G	Solar radiation
H_2	Hydrogen
HT	Hydrogen Tank
SC	Self-consumption
SS	Self-sufficiency
STC	Standard Test Conditions
R^2	The coefficient of Determination
RE	Renewable Energy
S-Q	Shockley-Queisser
FC	Fuel Cell

CHAPTER ONE

INTRODUCTION

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INTRODUCTION

1.1 Background

Energy is the ability of a physical system to do work (Lehrman, 1973). From this point, modern civilization has grown because individuals have learned to transform energy into different forms; electricity is one of these types. Therefore, primary energy which used in production of electricity can be splintered into (non-renewable and renewable) resources (Djellouli et al,. 2022). The first type includes nuclear and fossil energy such as: oil, coal, and natural gas while, the second kind compines wind, solar, geothermal and hydroelectric energy (Aboagyea et al., 2021).

Figure 1.1 compares the global demand for energy resources with its types by forecasting world energy consumption by 2050 (EIA, 2021).

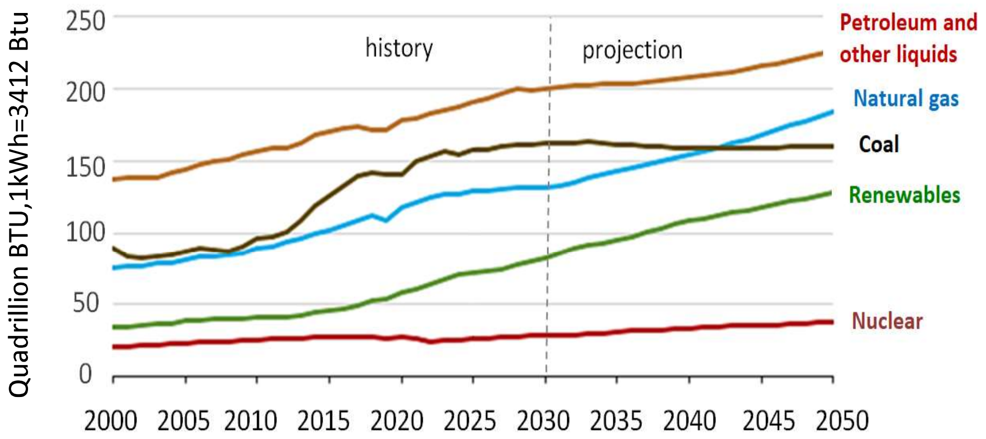

Figure 1.1 World energy consumption by sources to 2050, (EIA, 2021)

Despite the diversity of the primary sources of energy and their differences, an oil remains the main source for producing the various types of energy. World consumption is estimated at 100 million barrels of oil per day (Hacquard et al,2019). In addition, the recent studies indicate that this number may rise to 123 million barrels per day by 2025 (Abas, 2015). The consequences of burning these fossil fuels include pollution of the environment, changes in the climate, and global warming (Perera, 2018). With this rapid pace of civilization growth and increasing its requirements, it helps to run out of fossil fuels. Therefore, it is necessary to know the amount of consumption to find the required solutions. That help to eliminate the negatives of burning fuel and maximizing the use of renewable energy with the highest self-consumption of energy (Bilgen, 2014).

1.2 Global Energy Demands

Global energy needs to increase the utilisation of natural resources derived from all fossil fuels. So, scientists must create new methods for monitoring and reducing greenhouse gas emissions, and energy consumption must be more environmentally friendly. In this case, since electricity will be the primary source of increase in energy demand. Figure 1.2 shows the projected global energy demand from 1980 to 2050 (EIA, 2021).

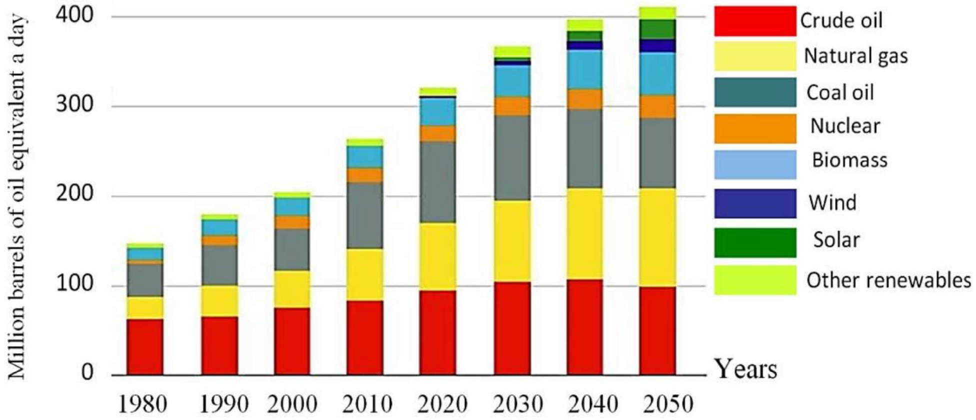

Figure 1.2 Global energy demand projected to 2050, (EIA, 2021)

In 2020, global electricity demand fell by about 1% because of the COVID-19 pandemic (EIA, 2021). In 2021, electricity demand was exected to rise by 4.5%, thanks to a rebounding economy and rapid growth in major emerging economies like China (Jiang et al., 2021). So, to reduce dependence on fossil fuels, research contributions should be directed into two fields: the first field deals with discovering new energy sources, and the other fields work to improve the use of the available renewable energies and find the best ways to help energy generation's stability.

1.3 Global Electricity Demand and Generation

The growth of renewable energy demand is outpacing global power consumption. That resulted in a dramatic increase in conventional energy usage and in recording levels of carbon dioxide emissions from the electricity sector (Vigoya et al., 2020). Figure 1.3 illustrates the rise in electricity produced by fossil fuels, which will account for about 45% of world demand in 2021 and about 40% in 2022(EIA, 2021).

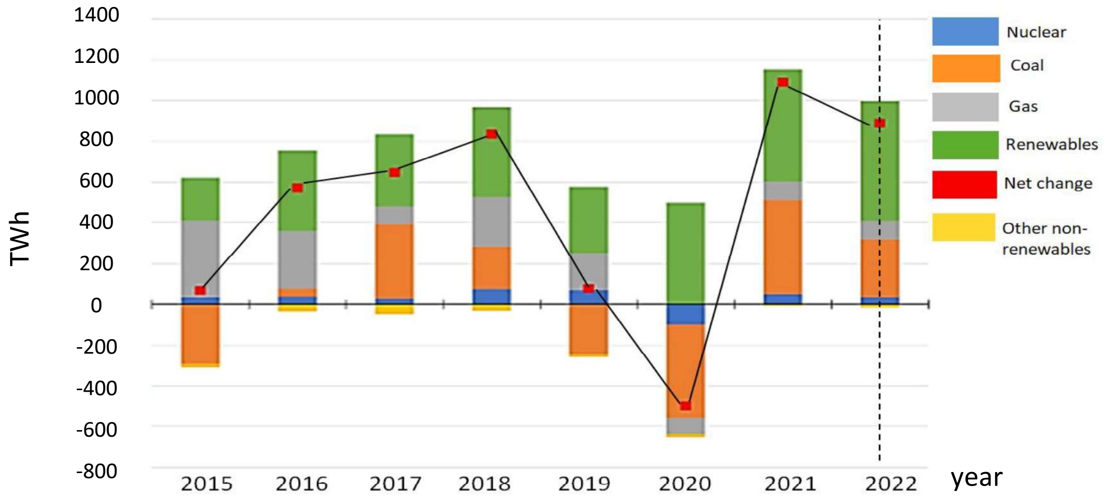

Figure 1.3 Global changes in electricity generation to 2022, (EIA, 2021)

The International Energy Agency study also predicted a rise in energy consumption by around 5% in 2021 and 4% in 2022. Asia and the Pacific, notably China and India, account for 9% of global growth (EIA, 2021). Global projections indicate that power output from renewable energy sources such as hydroelectric, wind, and solar energy will grow by 8% in 2021 and 6% in 2022. Despite this rise, renewable energy sources are estimated to supply around 50% of worldwide power consumption (Mastoi et al., 2022). Due to the consequences of the COVID-19 epidemic, renewable energy-generated power output declined by about 1% in 2020

(Naderipour et al., 2020). Iraq is pursuing a path consistent with global policies toward renewable energy generation.

1.4 Conventional Energy

Due to their scarcity, conventional energy sources are referred to as non-renewable energy. Additionally, it may be classified as commercial or non-commercial energy. Fossil fuels are no longer viable energy sources for meeting growing energy demand and ensuring a developed civilization due to their decline and significant environmental effects (Al-Obaidi & Nguyenhuynh, 2018). When these energy sources are depleted, they are difficult to recycle and cannot be replenished at the same rate they are utilized (Wills., 2020). Fossil fuels are the most extensive conventional energy source (Brockway et al., 2019).

Petroleum, coal, natural gas, and derivatives are just a few examples of those possessing a high carbon concentration due to their origins in carbon-based creatures. Conventional energy involves the production of power in many forms but within certain limits. Generally, the advantages and disadvantages of these energies can be summarized as follows:

1. The negative impact on the environment includes (waste pollution, thermal pollution, and carbon dioxide emission into the atmosphere).
2. The spread of thermal power plants creates the greenhouse effect due to the production of large amounts of ash, soot, sulfur oxides, and nitrogen oxides that cause acid rain.

1.5 Renewable Energy

Renewable energy is a new energy that is naturally replenished and does not fade with time. Still, they are limited in the energy available per unit of time (Quaschning, 2019). Renewable energy technologies provide clean energy from the sun, wind, geothermal, and biomass. It is expected that the coming years will see new growth paths for the renewable energy industry (Deshmukh et al., 2021). It will be backed by supportive policies from an administration concerned with addressing climate change. However, some challenges remain because of the increasing global demand for electrical energy. New technologies, business models, policies, and investments can help address these challenges and accelerate future growth in the renewable energy industry. In 2020, electricity generation from these sources reached the highest level globally and approached 29%, with a future increase of up to 12% from 2021-2030 compared to the period between 2011-2020 (Twidell, 2021). In general, renewable energy grew by 7.1%, equal to 505 TWh, to meet the (net-zero-carbon) level (Lennon et al., 2022). The advantages and disadvantages (Ariane et al., 2020) of the primary sources of renewable energies like solar, wind, geothermal and biomass can be summarized as follows:

1. The advantages of solar energy are it's an infinite source and environmentally friendly, while the disadvantages lie in its expensive and need for ample space.
2. Wind energy is characterized by rapid growth and low operational costs but is limited by environmental issues and noise problems.
3. The advantage of geothermal energy is potentially infinite, and the limited area is the most problematic.
4. Furthermore, the advantages of biomass lie in carbon neutral and cost-effective, while disadvantages are summarized as it is expensive and requires ample space.

Iraq may be regarded as a modern nation concerning developing renewable energy sources and joining the worldwide trend of reducing fossil fuel usage by 2024 via wind and solar energy (Niyonteze, 2020). The degree to which renewable energy is used in the Middle East, including Iraq, is seen in Figure 1.5 (Sisodia et al., 2020).

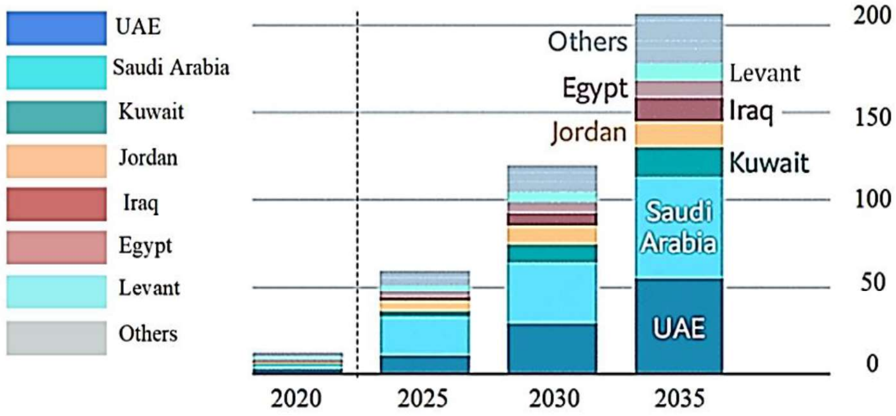

Figure 1.4 Middle East projects solar capacity (GW), (Sisodia et al., 2020)

1.6 Solar Energy Systems

Humanity has known solar energy as a form of energy since time immemorial. History records that the "ASSYRIANS" used solar radiation to dry the clay used for writing tablets (Robson, 2019). Then the uses varied and increased day after day. Solar energy is a significant, cheap, and inexhaustible source of energy. The Earth's energy from the sun is approximately 1.8×1011 MW (Sukhatme & Nayak, 2017). It's much more than a thousand times the current energy consumption rate in the world. In principle, solar energy can continuously supply all current and future energy needs, making it one of the most renewable energy types with remarkable growth. Referring to the Agency for Renewable Energy (IRENA) data and stats, solar energy will overtake 30% of green energy production by 2050 (IRENA, 2019). In addition, solar energy also has some problems, especially related to its use, including being a reduced energy source even in the generality of the hottest regions on Earth. Besides, the available solar radiation flux rarely exceeds 1 kWh/m^2, and the total radiation throughout the day is, at best, about 7 kWh/m2 (Benatiallah et al., 2019).Numerous methods, including solar electricity and thermal systems, aid is dedicated to converting solar radiation into valuable types of energy. However, these systems are subject to various variables that affect the amount of solar energy received, including time, weather, geographic location, and angle of incidence (Ramli et al., 2016). Researchers and engineers are attempted to provide the most efficient solutions to these issues to maxim the efficiency of systems.

However, these systems may now be considered acceptable due to their reliance on renewable energy and worldwide availability. Any spot on the Earth's surface where sunlight hits is a possible location for solar energy production (Brock, 1981). On the other side, hybrid solar energy systems (PV/thermal) that use sunshine to create heat and light are considered crucial solar energy systems from a practical and economic standpoint (Kuo et al., 2019). It combines heat exchangers that transform solar energy into heat and power for valuable purposes through a moving fluid medium (often air, water, or oil) (Tyagi et al., 2012).

1.7 Photovoltaic (PV) Technique

Photovoltaic is a subject of science and study concerned with using solar cells to generate energy directly from the sun's energy. The latter refers to how light (photons) is converted to electricity (voltage). Solar cells are PV devices that convert sunlight directly to power via semi-conducting materials. When these materials absorb sunlight, electrons move across them, creating electric currents. Solar cells generate direct current electricity (DC). The PV module can be defined as several solar cells connected in series to generate more voltage. At the same time, several modules connected in series, parallel, or hybrid can form a PV array or generator. These PV arrays are named PV systems that work with grid-connected and stand-alone applications (Goel & Shamanrma, 2017). The PV systems can be classified as shown in Figure 1.6.

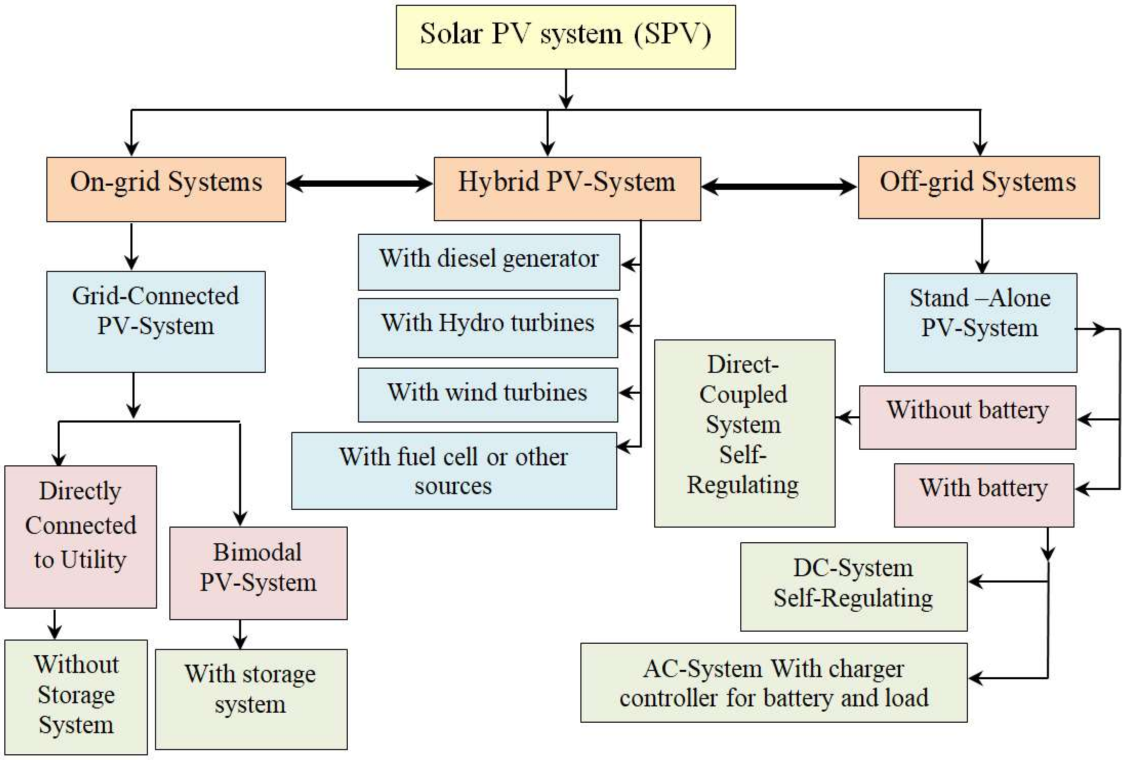

Figure 1.5 Classification of solar PV systems (Goel & Shamanrma, 2017)

Despite the simplicity of solar cells and their ability to generate electricity, they are considered low efficiency (Abu Talip et al., 2020). Suppose it is used to provide electric power on a large scale, which requires large areas. Furthermore, that is reflected when considering it is the only renewable source capable of producing electricity worldwide. Accordingly, numerous experiments and research were conducted to increase the efficiency of the PV systems by improving their design to supply the required load with appropriate energy storage to integrate with PV systems (Yang et al., 2018). Nowadays, double-sided solar became the most PV modules used to absorb the reflected energy from the ground (AL-Rousan et al., 2018). Using single-axis tracking technology with PV systems leads to an average increase in energy production by 35% compared to fixed single-PV panels (Rodríguez-Gallegos et al., 2020), causing a reduction in the average cost of electricity by 16%. On the other hand, practical efforts focus on enhancing the power production of PV cells via studying the influence of weather conditions and other environmental factors such as: (temperature and dust) or by tracking the inclination angle of PV modules.

1.8 Stand-Alone Solar Energy System (Off-Grid)

A stand-alone PV system is particularly effective in rural sites where access to the grid is limited or restricted. In such a system, the available electrical power mainly depends on the solar radiation and the capabilities of the PV array and the battery. Several attempts are tried to develop and optimize an off-grid residential PV system. Small-scale off-grid renewable energy systems are being increased significantly in areas with an electricity shortage or for small communities. Figure 1.6 (a) shows the diagram of the Off-grid PV system.

1.9 Grid-connected Solar Energy System (On-Grid)

Today, having the intermittent characteristics of PV, its integration with the power system may cause certain uncertainties (voltage fluctuations, harmonics in output waveforms, etc.), leading to reliability and stability issues (Khan et al., 2020). An on-grid PV system can be defined as a solar system which connects to the grid by a special meter, and its components do not differ from the components of the Off-grid system. Figure 1.6 (b) shows the diagram of an On-grid PV system.

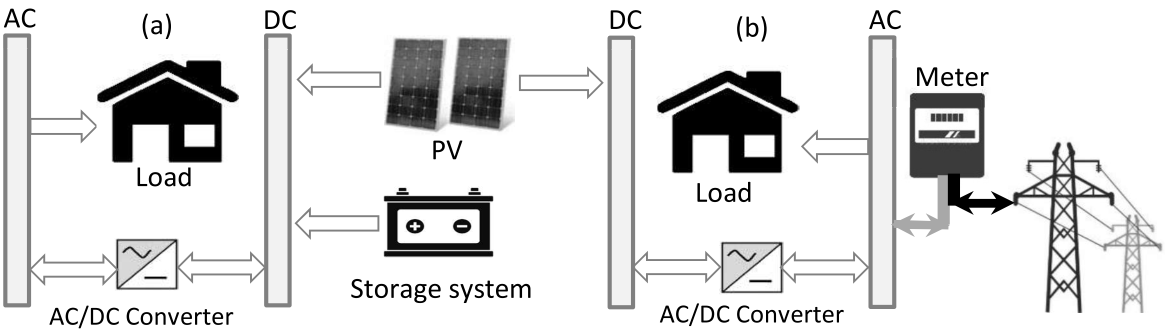

Figure 1.6 Solar PV-connected systems (Khan et al., 2020)

1.10 Fuel cell

Fuel cell technology is a promising way to provide energy for rural areas without access to the public grid or with a massive cost of wiring and transferring electricity. Fuel cells generate electricity and heat during an electrochemical reaction between oxygen and hydrogen to form water (Mekhilef et al., 2012).

1.11 Problem Statement

The current study intends to forecast the future competitiveness of Iraq's local energy systems. Solar energy is considered the most prominent renewable energy source in the world. Due to restricted PV panel availability or non-technical limits and restrictions, not all PV models are usable. This work develops a strategy for the optimal approach to constructing grid-connected photovoltaic storage systems in urban residences in Diyala-Iraq at the highest self-sustainability. The outcomes indicate that the highest level of used renewable energy as a function of self-sustainability (self-sufficiency and self-consumption) can be achieved depending on the capacity of the storage unit (batteries and fuel cells) used and the amount of energy consumed.

1.12 Objectives

The main aim of this study is to assess the degradation in voltage, current and power of PV modules under the influence of temperature and dust based on one year of measurements. To reach this aim of the thesis, two main objectives can be summarized as:

1. Design two twin PV solar systems to investigate an experimental study about the effect of dust and temperature on the power production of PV systems.
2. Using HOMMER software (version 2.68) to size the number of batteries in the PV systems (2, 4, 6, 8 and 10) and to suggest

another storage unit (fuel cell) to balance the exceeded power of the PV system and then used to equip the load at peak period or at night or at cloudy days.

1.13 Thesis Organization

This thesis results from research work sponsored by Diyala University/ College of Engineering. The significance and objectives of this project are disclosed in the current chapter. Additional information is discussed in the balance of this thesis to achieve its objectives. This thesis is divided into six technical chapters, each of one specialized to describe a specific topic of research activities as follows:

Chapter II describes the literature review for this thesis. The topics are divided into five main sections. The first section provides a brief overview of PV solar applications and the weather condition in Iraq. Also, parameter that effect on performance of PV system. Secondly, the influence of temperature on the performance of PV solar systems is presented. Furthermore, the third section deals with the impact of accumulated dust on the production of PV energy. In contrast, the fourth section was concerned with studying energy self-consumption and self-sufficiency. Finally, the effect of the volume of self-consumption on PV energy was also reviewed.

Chapter III presents the mathematical methodology that was used to achieve the calculations and analysis of this thesis. Generally, the equation of power distribution from PV modules, batteries, and the electrical grid is first defined. The equation of power production of a PV module is expressed and represented. In addition, the temperature of the PV module under the influence of solar radiation, ambient temperature, and wind speed is also mentioned. Furthermore, the soiling (dust) to energy metric ratio is expressed. Finally, the governing equations are those used in HOMMER software (version 2.68) to analyze the performance of hydrogen that is produced by the electrolyzer.

Chapter IV deals with the materials and project description, including research requirements and system descriptions. The measurements, instrumentations, and data acquisition are described in detail. This chapter also includes an experimental setup.

Chapter V discusses simulations and experimental outcomes. In addition, a comparison is made between the outcomes of the current research and those of previously published studies.

The outcomes of the thesis are summarized in Chapter VI, along with recommendations for future research in this subject to enhance and expand the approaches used in this study.