Solar Energy as a Sustainable Energy for Power Generation

Moses Jeremiah Barasa Kabeyi
Industrial Engineering Department, Durban University of Technology, Durban South Africa
moseskabeyi@yahoo.com

Oludolapo Akanni. Olanrewaju
Industrial Engineering Department, Durban University of Technology, Durban South Africa
oludolapoo@dut.ac.za

Abstract

Solar energy has been the most renewable type of energy-producing electrical power from 2013 to date. Solar PV and concentrating solar-thermal power (CSTP) are the two primary forms of solar energy technology . The generation of electricity from both types of solar energy has witnessed a significant increase compared to any other renewable source, with new installations totaling up to an estimated 130 GW by the end of last year. Solar photovoltaic (PV) systems, are effective measures to reduce the greenhouse gas emissions related to the generation of power. However, the large exploitation of solar PV modules, leads to undesirable waste accu-mulation, impacting the environment. Solar PV waste management research is an emerging field which has received more attention recently, affected by the increase volume of solar PV disposal.

Keywords
Solar Energy, Sustainable energy, and Power generation.

1. Introduction
Grid-connected utility-scale solar PV has emerged as a potential pathway to ensure deep decarbonization of electricity in regions with fossil fuel-dominated energy mixes. Research on utility-scale solar PV projects mainly focuses on assessing technical or economic feasibility. Environmental performance assessments of large-scale solar applications are scarce. There is limited information on the greenhouse gas (GHG) emissions and energy footprints of utility-scale solar energy systems. Earlier studies conducted on small-scale solar systems have limited application in the grid system (Mehedi, 2022).

Photovoltaics is a renewable source of energy that converts solar radiation to electricity, which provides a perfect alternative to tradi-tional fossil fuels as the world transitions to a renewable energy-based economy. The application of this technology has been in existence since the 1980s, but the 1990s has been recorded as the year of the first appreciable application of power from solar photovoltaics (Padoan et al., 2019; Tao and Yu, 2015). Solar energy is non-polluting, efficient, reliable and safe. There is a global interest recently in solar energy particularly PV technology. This has seen the use of solar PV modules climb sharply because of government's effort to achieve clean energy globally. PV technology is to become one of the main energy sources worldwide because of its expectation to significantly produce a portion of the world's energy consumption (Al Shetwi, 2022).

2. Solar Power Generation
Solar power generation involves converting energy from the sun into electricity. Heat and electricity are the two forms of energy generated from the sun use. Energy is generated by means of solar panels, which vary in size from residential rooftops to 'solar farms' spread over large land space. The global commitment to reduce greenhouse gas emissions while achieving significant cost reductions, have generated demand for solar electricity making it one of the fastest growing renewable energy resources. The global solar power deployment increased from 40 GW in the year 2010 to 586 GW in the year 2019 (Wu et al. 2022).

Power fluctuations cover short and mid-term power variations in a timescale from seconds to hours. Intermittency is deemed to cover long-term power variations in the timescale from hours and days to years. Intermitence for solar energy is considered more challenging than power fluctuations. It is the deterministic astronomical diurnal and seasonal cycles, and the optical transmissivity of clouds and aerosols following atmospheric circulation patterns that determine the solar radiation reaching the Earth's surface. For this reason, the intermittency of solar power is in timescale of hours up to months because of diurnal and seasonal cycles, and this adversely affect the reliability and stability of power grids. In Great Britain (GB) energy the cost of backup capacity for solar is expected to increase from £2.5/MWh in 2016 to about £4.5/MWh by 2030, implying that high penetration of solar requires more backup procured through the capacity market and will increase capacity payments to incentivize entry as the while higher levels of solar lowers daytime power prices. Measures to accommodate high photovoltaic (PV) penetration, include proactive curtailment, energy storage and demand response to take advantage of the spatial diversity by spreading PV farms over a large geographical area

3. Global Status of solar Power

Solar energy has been the most renewable type of energy-producing electrical power from 2013 to date. Solar PV and concentrating solar-thermal power (CSTP) are the two primary forms of solar energy technology (Oteng et al., 2021). The generation of electricity from both types of solar energy has witnessed a significant increase compared to any other renewable source, with new installations totaling up to an estimated 130 GW by the end of last year. The remarkable growth of solar power generated during the previous ten years is illustrated in Figure 1 (International Renewable Energy Agency, 2021)

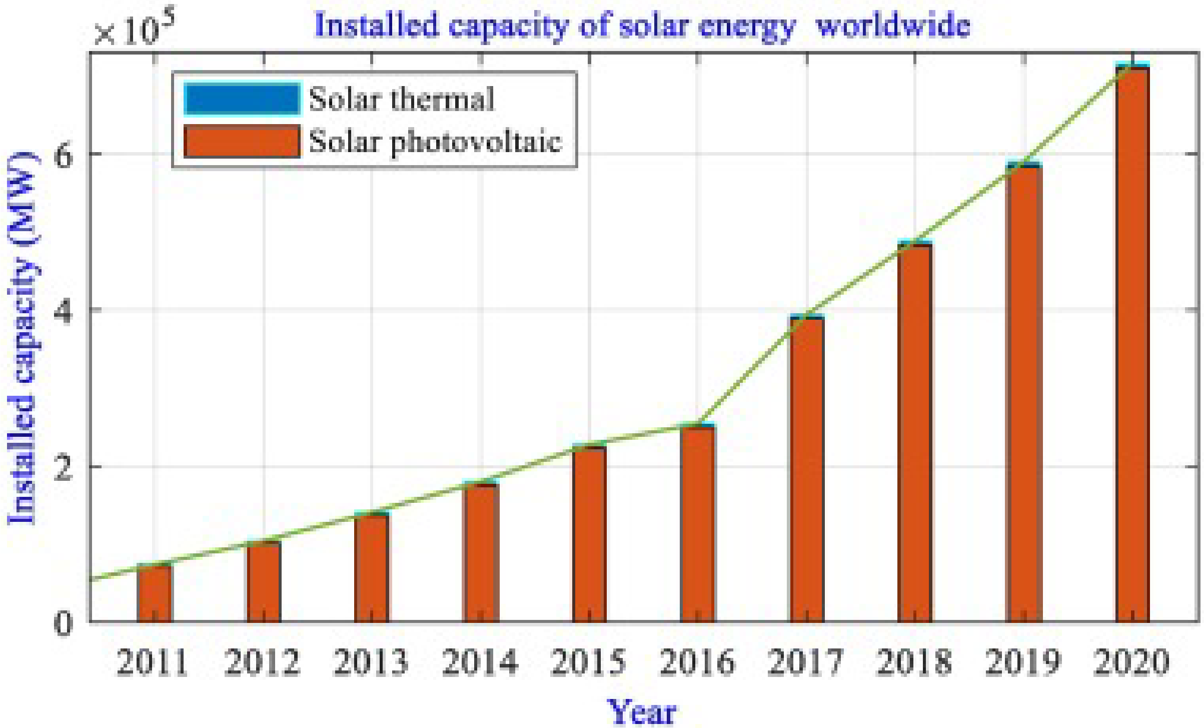


Figure 1. Power generated from solar energy during the last few years.

Solar PV is becoming increasingly popular and in demand as it becomes more competitive than other options for electricity generation. It is attracting interest in a wider range of places, both for commercial and residential purposes as well as for utility-scale projects (Choudhary and Srivastava, 2019). The number of nations with at least 1 GW of newly added solar PV capacity rose from 18 countries in 2019 to 20 countries in 2020, and all regions contributed significantly to the global expansion. Overall, at least 42 countries have reached a cumulative GW capacity of 1 by the end of 2020. Solar PV plays a meaningful role in electricity generation in a growing number of countries. By the end of 2020, at least 15 countries had enough capacity in operation to meet at least 5% of their electricity demand with solar PV. Solar PV accounted for around 11.2% of annual generation in Honduras and for notable shares also in Germany, Greece, Australia, Chile, Italy, and Japan by 10.5%, 10.4%, 9.9%, 9.8%, 9.4%, 8.5%, respectively of their annual generation (Global Status Report, 2021; Madsen and Hansen, 2019).

4. Solar Photovoltaic

The Solar Photovoltaic (PV) System is currently the most visible, competitive and popular renewable energy resource in many countries, and is more preferred when compared with other renewable sources of energy like wind, biomass, geothermal and and Wave energy. The main compnents of a Solar PV consists of system are solar panels, inverters, photovoltaic mounting systems and multiple accessories. Solar PV uses photovoltaic to supply supply electric power (Okoye et al. 2019, US Energy Information Administration 2023)

Photovoltaic (PV) was first discovered in 1839 by Alexander Edmond Becquerel, in his experiment with a solid electrode in an electrolyte solution. Becquerel discovered that when light struck the electrode a viltage was established, that was called Beckerel effect. The first solar module was built by Charles Edgar Fritts, an American inventor in in 1883 by constructing solar modules by coating a copper plate with Selenium topped with a thin semitransparent layer of gold leaf. These modules generated an electric current that was 'continuous, constant and had considerable force. Werner von Siemen, a German scientist, after examining Fritts' Solar Panel, presented it before the Royal Academy of Prussia and declared that Fritts' panel marked the first direct conversion of sunlight energy into electricity and was regrded as the first solar photovoltaic process. Selenium (Se) is a non-metal produced commercially as a bye product of refined metal sulfide ores. and is a a semiconductor used in photocells. Selenium occurs as a major part or constituent of the Copper Indium Gallium Selenide cell (CIGS), which is a thin-film solar cell that converts sunlight to electricity. Advances in technology and increase in scale of manufacturing and sophistication levels have led to the decline in the cost of photovoltaics. Solar PV accounts for at least 1% of global electricity production.

1.) The Solar Photo Voltaic (PV)

Photovoltaic (PV) comprises a process where electricity is generated when a silicon crystal embedded in the Solar Panel is exposed to sunlight The Crystalline and Amorphous Silicon are modified silicon crystals, embedded materials that are for conversion of light to electricity. The Solar Photovoltaic Cell (Solar Cell) converts sunlight (photons) into electrons in form of a Direct Current (DC). Photo means light, while voltaic means electricity. The PV power system generates DC current that is not constant and fluctuates based on sunlight intensity or lack of. The DC is preferably converted to Alternating Current (AC) by Inverters at required freqiuency and voltage to comply with the appliances, electronics and other gadgets using the electricity. Since sunlight irradiance is not constant all the day round, solar energy saving devices like batteries are used to sytore or conserve the solar energy captured during the day, for use at night and times of low solar radiations **(Okoye et al. 2019)**

i.) Solar Panel

A Solar Panel consist of Photovoltaic Cells made from Silicon., which is the material responsible for converting sunlight into electricity. Solar PV cells have negative and positive films placed often under thin glass. The radiations fall on the glass and onto the PV cells, where sunlight photons knock the electrons off the Silicon. The free electrons are then attracted to one side of the Silicon cell creating an electric voltage and flow or electric current which is in the form of direct current (DC). The direct current is then conerted to Alternating Current (120 Volts AC) by the Inverter.

ii.) Solar PV Invertor

The inverter is an electrical device that combines mechanical and electronic circuitry in changing or converting the direct current from solar panels to altermatic current. The inverter controls and monitors the system to ensure that it operates at the correct temperature. The device should have some good conversion efficiency meaning of at least 95%. The inverter optimizes power regardless of solar radiation intensity (or not) on the day, by identifying and continually monitoring the optimal operating point on the power characteristic curve to ensure maximum power from the Solar PV module. The optimal operating point of an inverter is the Maximum Power Point (MPP). The device monitors and secures the Solar PV system to abserve the yield and in case of any problems detected, with the grid if connected, it disconnescts the PV system from the grid in the event of a safety problem or the need to support the grid. Since the Solar PV modules are alws live as long as the sun is shining, the inverter can cut or interrupt current from the Solar PV modules. The inverter therefore moderates and limits what would have been unrestricted flow of Direct Current (DC). It is therefore important to select a suitable inverter especially in terms of efficiency, performance and technology. Under sizing inverters should be avoided since it will not have the required capacity to process a large amount of module power transmitted during times of high soalr radiations To avoid damage, the permissible inverter input voltage should not be exceeded by the maximum Direct Current voltage.

Types of Invertors

There are three types of solar inveters, namely, The Grid Tie, Stand Alone and Battery Backup Inverters.

i.) The Grid Tie Inverter (GTI)

This is an electronic device that convets DC to AC and can operate in parallel with the utility grid. The DC voltage can be fed by a storage battery or it can be mounted on solar panels and faciliatate inter-connectivity of the electricity grid with the local power system. The Grid Tie Inverter (GTI) is able to provide electricity to a local load and electric simultaneously re-route the excess to the main grid thus lower the house electric bill. GTI circuits can be one, two or three stages, depending on the wattage and voltage levels.

ii.) The Stand-Alone Inverters

Standalone inverters are applied in isolated systems solar PV systems. They are structured such that they draw DC from PV charged batteries. The Stand-Alone Inverters are designed for operation in remote stand-alone applications or off grid power systems havimg battery backup. The design is such that the inverter draws DC power from charged batteries and convert it to AC power. The inverters are available in a variety of sizes and output.

iii.) Battery Backup Inverters

The battery backup inverters are designed to draw draw energy from a battery while at the same time manage the battery charge and move the excess energy to the grid. The battery backup inverter is equipped with anti-islanding protection and can supply AC energy to selected loads during an outage.

Solar batteries

A Solar Battery store energy received directly from the solar panel. And serve as ar 'arteries' of an efficient solar panel system. The batteries store energy originally transmitted by the sun through the solar panel, which enables the inverter to convert it to Alternating Current (AC) for consumption. Factors to consider in selection of a battery are the capacity, Power, Depth of Discharge (DoD), Round Trip Efficiency, Battery Life/Warranty and Manufacturer. The most popular types of storage batteries are lead acid, lithium ion and salt water. Lead acid batteries are mostly associated with off grid energy systems and havea relatively short life and low DoD but are cheaper. The Lithium ion is popular in applications with solar panel systems and is widely regarded as the best of the options. Lithium-ion batteries are lighter and more compact than the lead acid batteries and have a higher DoD and longer life span, but are more expensive. The Saltwater batteries are made of heavy metal compositions which make up the last two, and comprise of salt water electrolytes and are easy to recycle, but the bateries are relatively untested and unproven hence not commonly used in solar panel systems.

5. Discussion

Solar electricity, or Photovoltaic technology, is a process that involves direct conversion of sunlight to electricity for many applications including space programs. Advances in solar PV technology has led to the emergence of a stronger electricity market that provides a viable alternative in powering both grid and off grid homes. Even though we have many types of solar electric systems, three core components remain the module, inverter and battery. The modules convert sunlight into electricity, the inverters convert the direct current (DC) from the modules into Alternating Current (AC) which makes it safer for domestic applications, while the batteries store up excess electricity. Other important equipment for solar power systems includes circuit breakers and wirings. Advances in Solar PV technology have meant that we have , sunlight converting modules built into glass roofs, walls, car roof tops..

Through Net Metering additional electricity from PV system which is more than excess the facility consumption and storage can exported to the grid, allowing the customer to earn some revenue and pay for the net import alone. Solar PV systems, slightly differs with specific regards to the presence or not of battery storages. Grid connected (On grid) PV systems generally do not require batteries, except for some use as backup power in emergency situations. The Off grid and the Hybrid PV systems both have storage batteries due to their peculiar nature and the alternative power option they are conceptualized and built to provide. The Solar Energy Systems, can be used Off grid or On grid or hybrid mode.

i.) Ongrid

On-Grid Solar System or Grid Tied system, is always connected to the connected to the grid, and excess energy produced by the solar panels is supplied to the grid. When there is no sunlight, domestic load consumption goes up, it draws power from the grid's electricity. The system does not need a battery to store electrical energy which has both benefits and limitations. This system is relatively cheaper than the Off-grid or Hybrid systems, but the disadvantage is that that electricity cannot be stored within the system, so in case the grid is down, the system or users have no power .

ii.) Offgrid

Off-grid Solar Systems are standalone systems that are separate and independent of the power grid. The offgrid systems comprise the solar panel, a charge controller, inverter and then the electricity load or house that receives and uses the electricity supply. The solar panel receive solar radiatioasn and convey to the battery for storage, with no optional charge controller to srrve the purpose of limiting the rate at which electric current is added or drawn from the battery. Tan inveter is then used to convert the DC to AC current before supply to load centers or users.

iii.) Hybrid

The Hybrid Grid Solar System combines the core aspects of the On Grid and Off Grid Solar Systems. The system does not need a backup generator and are often referred to as the 'Off grid solar systems with a utility back up option'. The system has ability to switch between grid power and battery power at will and is less expensive than a complete stand-alone system and does not need a backup generator since the possibility or option for grid connection takes care of the backup power. The main limitation is inability to use in n remote areas having no no grid connection.

The Hybrid Grid Solar System consists of solar panels, charge controller, battery bank, inverter and a meter and is connected to both the house and the grid. The hybrid grid solar system is relatively expensive but the photocells are easy to maintaine, are environmentally friendly and produce no greenhouse gas emissions and the have no noise pollution compared to hydropower stations and wind turbines.

The minimum life of a Solar PV system is 20-year lifeline, with little operation and maintenance cost. The main limitation for PV is there is direct dependence on availability of solar radiations to produce power hence the need for storage facilities. The production of Solar PV can lead to toxic generation and release to the environment of chemicals like Arsenic and Cadmium which have some environmental impact. Solar Energy is also relatively more expensive to produce due to low conversion efficiency and low caoacity factor. The main attraction to solar energy as a fure energy option is the dropping costs globally and complementary increase of conversion efficiencies and capacity factor.

6. Solar thermal Power Systems

For solar thermal power plants, solar radiation is used for power generation in what is otherwise a conventional power plant process. Sunlight is concentraed by mirrors on a radiation collector to up a heat-bearing medium, like thermal oil. A turbine is then used to transforms the thermal energy into electricity (US Energy Information Administration 2023).

The Solar thermal power/electric generation systems collect and concentrate sunlight to generate high temperature heat for power generation. The systems are equipped with solar energy collectors which have two main compnents i.e. reflectors and to capture and focus sunlight onto a receiver. A heat-transfer fluid is heated and circulated in the receiver to generate steam in most systems. The steam generated runs a turbine, coupled to a generator for electricity generation. Tracking systems are used in solar thermal power systems to keep sunlight focused onto the receiver always even as the sun changes positions in the skys. Solar thermal power plants consist of a large array of solar ollectors that supply thermal energy to the turbine-generator.

Solar thermal power systems can also be equipped with thermal energy storage system component to allow solar collector system to heat an energy storage system during the day, for power generation in the the evening or during cloudy weather. Solar thermal power can also be hybrid systems that use other fuels like natural gas or even geothermal to supplement solar energy during periods of low solar energy.

Types of concentrating solar thermal power plants

Three main types of solar concentrating power are.

i.) Linear concentrating systems, like the parabolic troughs and linear Fresnel reflectors
ii.) Solar power towers
iii.) Solar dish/engine systems

a.) Linear concentrating systems

These systems collect the solar energy using long, rectangular, curved (U-shaped) mirrors which focus sunlight onto receivers (tubes) that run the length of the mirrors. The concentrated sunlight heating a fluid flowing through the tubes and send heat to the heat exchanger to boil to produce steam to run a conventional steam-turbine generator for power generation. The two major types of linear concentrator systems, are; the parabolic trough systems which has a receiver tubes positioned along the focal line of each parabolic mirror, and linear Fresnel reflector systems, which has a receiver tube positioned above several mirrors to facilitate the mirrors greater mobility in tracking the sun.

A linear concentrating collector power plant has many of collectors in parallel rows that are typically aligned in a north-south orientation so as to maximize radiations collection. The design enables the mirrors to track the sun from east to west during the day and concentrate sunlight continuously onto the receiver tubes.

b.) Parabolic troughs

A parabolic trough collector is equipped with g parabolic-shaped reflector which focuses the suns radiations on a receiver pipe located at the focus of the parabola. It is designed such that the collector tilts with the sun to keep the radiations focused on the receiver as the sun changes position and angle. As a parabolic shape, a trough focuses the sunlight from 30 times to 100 times its normal intensity (concentration ratio) on the receiver pipe, which is located along the focal line of the trough, to achieve operating temperatures as higfh as 750°F (Figure 2)
.

Figure 2. Parabolic trough power plant

The Solar Energy Generating System (SEGS) located in the Mojave Desert in California is one of the largest. parabolic trough linear concentrating system. This facility has had nine separate plants over time, with SEGS I, being the firt to operate between 1984 and 2015, and the second, SEGS II, operated between 1985 to 2015. The SEGS III–VII (having net summer electric generation capacities of 36 megawatts (MW), were commissioned in 1986, 1987, and 1988. While SEGS VIII (8) and IX (9), with net simmer electric generation capacity of 88 MW, started operations in 1989 and 1990, respectively. SEGS 3, 4, 5, 6, 7, and 8 stoped operations in 2021, but SEGS 9 came in operations in December 31, 2021. F.

Other than SEGS 9, other parabolic-trough solar thermal electric facilities operating in the United States as of December 2021, are:

i.) Solana Generating Station: a 296 MW, two-plant facility with an energy storage component in Gila Bend, Arizona, that started operating in 2013

ii.) Mojave Solar Project: a 275 MW, two-plant facility in Barstow, California, that started operating in 2014

iii.) Genesis Solar Energy Project: a 250 MW, two-plant facility in Blythe, California, that started operating in 2013 and 2014

iv.) Nevada Solar One: a 69 MW plant near Boulder City, Nevada, that started operating in 2007

c.) Linear Fresnel reflectors

The Linear Fresnel reflector (LFR) systems is similar to a parabolic trough system. The mirrors or reflectors concentrate sunlight onto a receiver located above the mirrors. The reflectors use the Fresnel lens effect, which allows for a concentrating mirror with a large aperture and short focal length. The Linear Fresnel reflector (LFR) systems can concentrate the sun's energy to about 30 times its normal intensity. Compact linear Fresnel reflectors (CLFR) also referred to as concentrating linear Fresnel reflectorsare a type of LFR technology equipped with multiple absorbers within the vicinity of the mirrors. The many receivers allow the mirrors to change their inclination to minimize blockage of adjacent reflectors' access to sunlight. This improves the system efficiency and reduces material requirements and costs. A demonstration compact linear Fresnel reflectors (CLFR) solar power plant that was built at Bakersfield, California, in 2008 is no longer operational.

d.) Solar power towers

A solar power tower system uses a large field of flat, sun-tracking mirrors called heliostats which concentrate solar radians to a receiver on the top of a tower. The system can concentrate the sun radiationa as much as 1,500 times. Water is used as a heat transfer fluid in some power towers while more advanced designs are using molten nitrate salt which has superior r heat transfer and energy storage capabilities. With thermal energy-storage capability the system can generate power during cloudy weather. The first demonstration solar power tower was built and operated near Barstow, California, between 1980s and 1990s.There were two solar power tower facilities operating in the US in 2021, namely.

i.) Ivanpah Solar Power Facilitywhich has got three separate collector fields and towers with a combined net summer electricity capacity of 393 MW in Ivanpah Dry Lake, California. The facility started operation in the year 2013

ii.) Crescent Dunes Solar Energy Project which is a 110 MW one-tower facility equipped with energy storage at Tonapah. The facility was commissioned in 2015 (Figure 3)

Figure 3. Solar power tower

e.) Solar dish/engines

The Solar dish/engine systems use a mirrored dish that is like a very large satellite dish usually composed of many smaller flat mirrors formed into a dish shape. This dish-shaped surface directs and concentrates solar radians onto a thermal receiver, that absorbs and collects the heat and transfers it to an engine generator. The Stirling engine is the most commonly heat engine used. A fluid heated by the receiver to move pistons and create mechanical power which rotates a generator or alternator to generate electricity.

The solar dish/engine systems always point straight at the sun and concentrates the solar energy at the focal point of the dish. The concentration ratio of the solar dish is higher than that of the linear concentrating systems, and can attain a working temperature greater than 1,380°F. The power system with a solar dish can be mounted at the focal point of the dish, which makes it suitable for remote locations. The e energy may also be collected from several installations and centrally converted to electricity. However, there is no e no utility-scale solar dish/engine projects in commercial operation (Figure 4).

Figure 4. Solar dish/engines, Source: Stock photography

7. Sustainability of Solar

Solar energy, much like wind, is one of the most sustainable energy sources currently available. In fact, given its modular and scalable nature — where it can be utilized as part of massive solar fields or mounted on individual homes — it may be the most practical form of sustainable energy in use today.

Solar power uses photovoltaic solar panels that convert energy from photons (light from the sun) into usable energy for us here on earth. Though this form of energy is not the most efficient, it has improved dramatically over the past 50 years — especially in the past decade. Solar energy efficiency improved from less than 5% efficiency up to 22% today. And with this efficiency improvement, cost improvements followed. The price of solar power has decreased 60% since 2008; it is even considered to be the cheapest form of energy in history.
Some of the best attributes that make solar energy one of the best and most sustainable forms of energy include:

- No fuel input
- Unlimited energy from the sun, the most abundant energy of all by far
- Long-term use potential
- No CO2 or other GHGs
- Ability to be used anywhere in the world, and even outside the world (in outer space)
- Ability to be implemented anywhere, from garage roofs, to roadways, to Mars rovers

Much like with wind energy, producing solar energy can also be used as a form of carbon offset to lower overall emissions from other energy sources.
8. Environmental Impact of Solar

8.1. Environmental Impacts

The harmful impacts of solar power are linked to land use, habitat loss, water use, soil and water pollution, human health, and toxic chemicals/hazardous compounds (e.g., sulfuric acid, hydrochloric acid, nitric acid, and hydrogen fluoride) during solar panel manufacture. The review done by Kourkoumpas et al. (2018) for different PV cell types indicated that the average predicted GHG emission rates for the tested systems were 36.75 g CO_2eq/kWh during PV cells production. On the other hand, the authors in Pacca et al. (2007) find that thin-film cadmium telluride PV releases the lowest air pollution and consumes the lowest power during module manufacturing. The emissions of GHG coming from solar PV power generation are assessed using the well-known life cycle assessment technique in Mahmud et al. (2018) and Sheng-Qiang et al. (2012). It is worth noting that the maximum amount of dangerous nitrous oxide and carbon dioxide emission were the responsibility of the cable and inverter, respectively. However, the converter, battery and power meter are mostly responsible for land transformation (Mahmud et al., 2018). A utility-scale solar power plant requires a lot of land. This may be in contradiction to the current land use. The utilization of many hectares of land could lead to land clearing grading, tree cutting and using agricultural lands, which may also cause soil erosion, soil compaction, and channel changes. Additionally, solar power plants might affect soil during the extraction, exploration, manufacture, and disposal of minerals (Hernandez et al., 2014). It is important to mention that the battery energy system used widely in solar power has many adverse impacts on the environment and other sectors of life, as reviewed in detail in Hannan et al. (2021b) (Figure 5).

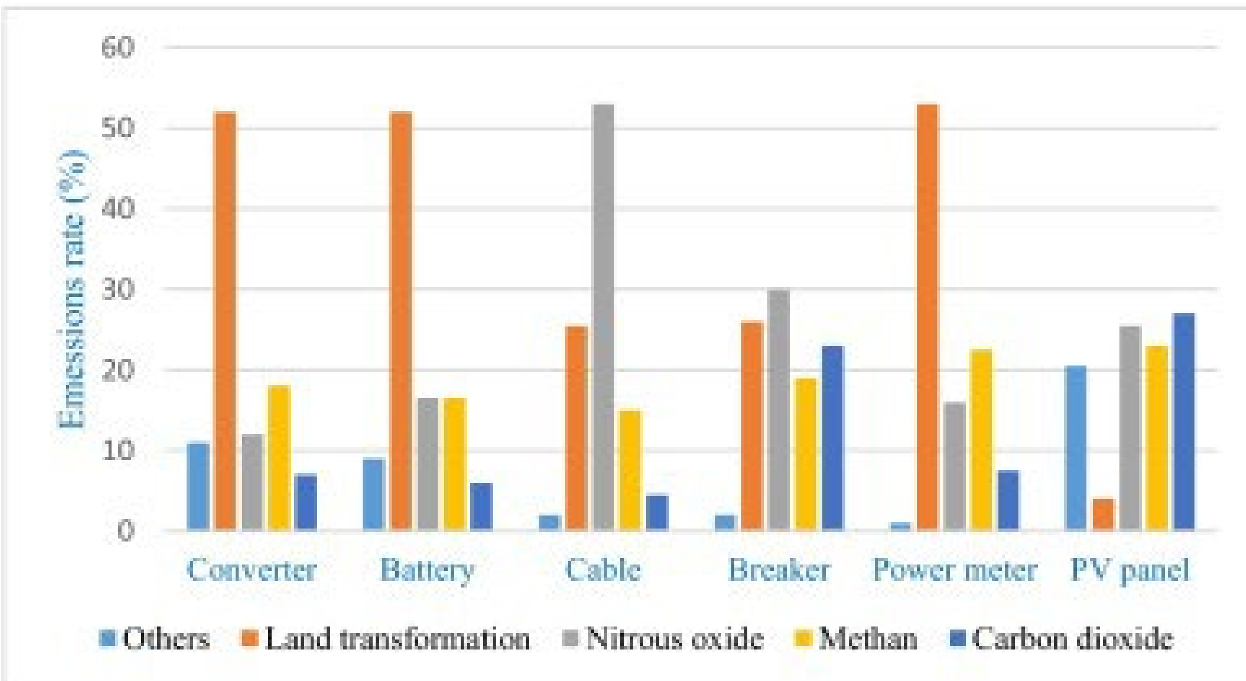
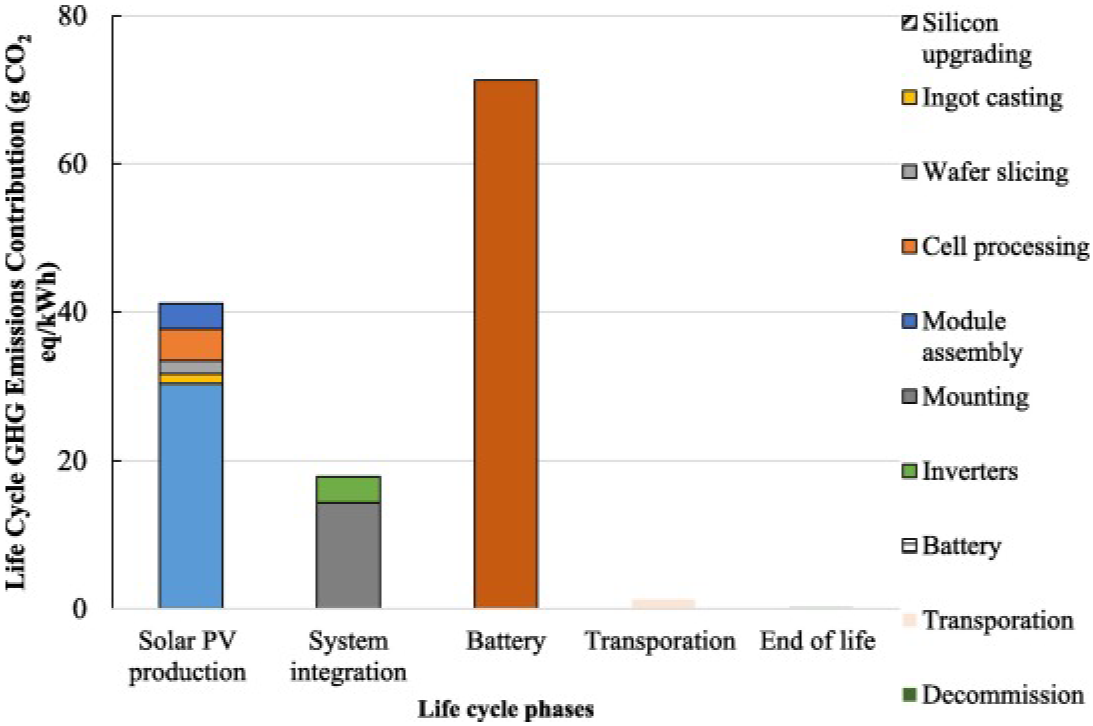


Figure 5. Emissions of greenhouse gases from solar PV power over a 100-year period.

8.2. Life cycle GHG emissions

The total life cycle GHG emissions were 131.86 g CO_2 eq /kWh of generated electricity. Figure. 6 shows the breakdown of system GHG emissions by life cycle stage. The largest GHG emissions contribution is due to battery manufacturing, which accounts for 54% of the total. Anode and cathode production processes are the components most responsible for high GHG emissions. The GHG emissions are driven by the large mass share of these components, which together accounts for around 67% of the total mass, and the corresponding energy-intensive processes to produce key materials, for example, cobalt sulfate, nickel sulfate, manganese sulfate for the cathode, and copper for the anode. The high GHG emissions are also associated with the use of polytetrafluoroethylene materials as a binder in the anode manufacturing process. Polytetrafluoroethylenes are characterized by the release of high global warming potential GHG gases such as chlorofluorocarbon and hydrofluorocarbon. Electrolytes and case manufacturing (aluminum and steel) account for 15% and 19% of battery-related GHG emissions (Mehedi, 2022, Al Shetwi, 2022, Wu et al. 2022, Okoye et al. 2019, US Energy Information Administration 2023)



1. Download : Download high-res image (234KB)
2. Download : Download full-size image

Figure 6. Life cycle GHG emissions by phase.

The second largest GHG emissions are from the production phase of the solar PV panels (Figure 6). The most GHG-intensive processes in the production phase are associated with upgrading the quartz sand to a usable form, namely industrial grade (14.40 g CO_2 eq /kWh) and solar grade silicon (15.99 g CO_2 eq /kWh). During the assembly processing stage, the aluminum frames are another major source of GHG emissions, 10.90 g CO_2 eq /kWh. The GHG emissions from direct land use are marginal. The values range from 0.80 to 2.76 g CO_{2eq}/kWh for arid grasslands and mixed areas, which is low compared to overall life cycle GHG emissions. Direct land-use change GHG emissions were calculated by discarding the transmission and distribution line area requirements as they do not directly affect the life cycle emissions.

To provide a contextual understanding of the results of this study, Table 1 lists some established electricity-generating technologies and impact assessment indicator figures extracted from studies that used a similar system boundary. The table makes clear that coal-based power plants have the biggest impact on the environment based on GHG emissions, but they also have a very high NER. The ranges shown for domestic natural gas-based power plants are averaged values for simple and combined cycles; they have significantly fewer GHG emissions than coal. They also provide high energy yield during their life cycle. These two fossil fuels are currently the major electricity sources in Alberta. However, renewable energy such as wind and hydroelectricity are relevant as they account for more than 61% of the renewable energy-based electricity produced in Alberta Meaningful LCA results based on regional characteristics for these two technologies were not found in the literature. According to the results obtained in this study, the energy and environmental performance of utility-scale solar farms would be most comparable with wind energy. Economic lifetime assumptions for hydropower reservoirs are 70 to100 years, which remains one of the main reasons for their low emissions and high life cycle energy yield predictions (Table 1).

Table 1. GHG emission and energy performances of conventional and renewable energy sources.

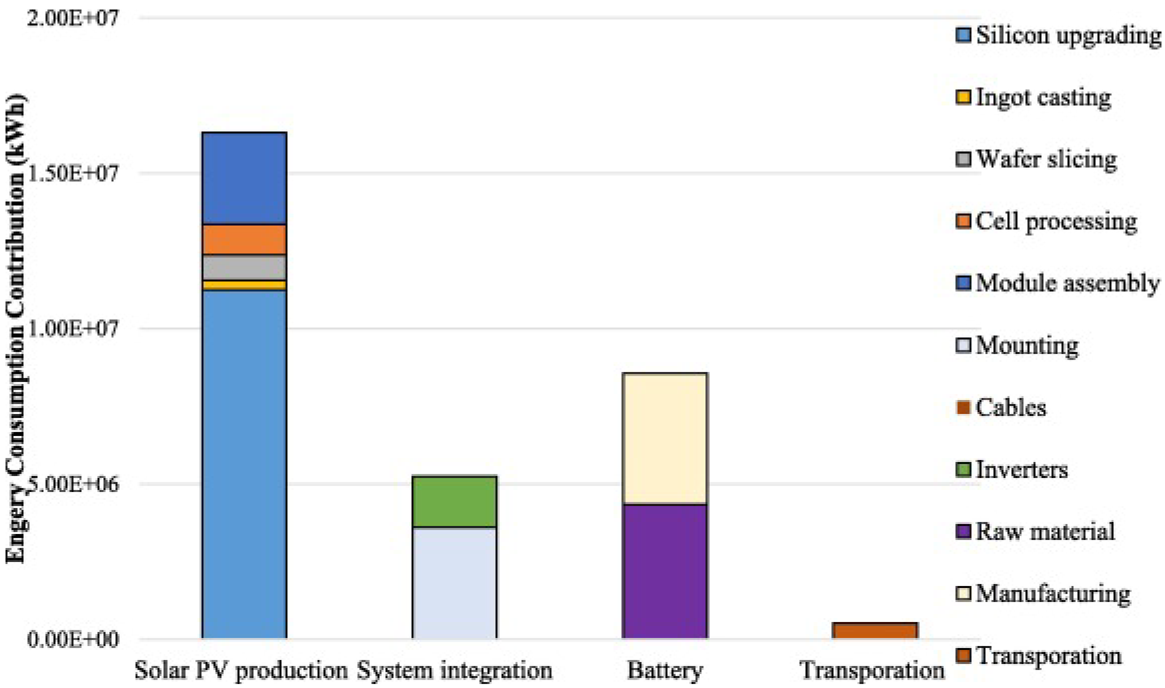
System Type	GHG (gCO_2/kWh)	EPBT (years)	NER (kWh/kWh)
Coal-fired	780–1029.65	1.73	29–31
Natural gas	400–725.75	9–12	28
Nuclear	22.2–24.2	0.8	74.92
Hydropower (run of river/non-tropical)	0.5–152	0.37–8.92	3.27–112.7
Wind (onshore)	3–45	0.58–1.4	3.9–16

Bearing in mind Alberta's long-term plan to phase out coal power plants, the feasibility of using renewable energy sources as the baseload must be considered, as earlier discussed. That said, life cycle GHG emissions from such electricity sources would still be significantly lower than coal power as shown in Table 1. The harmonized LCA results from National Renewable Energy Laboratory also suggest that coal power energy has twenty times more life cycle GHG emissions per kWh than solar, wind, and nuclear-based electricity. The largest contribution of the emissions is from fuel combustion for the fossil-based sources, and, for renewable technologies, upstream emissions are the key drivers.

The land-use footprint from utility-scale solar farms largely depends on the transmission and distribution line length, which is defined as the distance from the power plant to the end user. In this study, a range of values from 0.25-1.23 m^2/kWh was found for twin axis systems for transmission and distribution line lengths of 100–500 km and from 0.23-1.15 m^2/kWh for fixed-width systems. The land footprint attributed only to the PV and balance of system installation is insignificant.

7.3 Energy use profile and net energy ratio (NER)

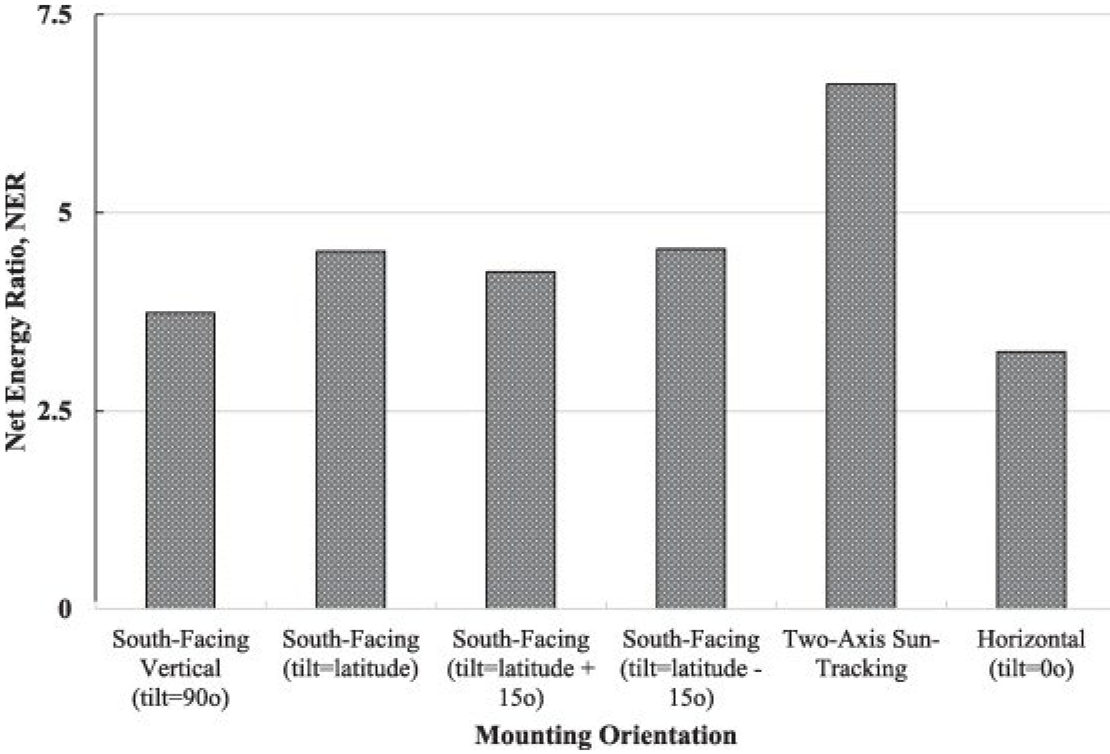
Figure 3 shows the energy consumption in various stages of the life cycle of a utility-scale solar power plant with a rated capacity of 5 MW_p with a two-axis mounting structure. The energy consumed during the life cycle is estimated to be 3.1×10^7 kWh_e. Upstream processes related to raw material extraction and production of solar PV panel assembly are the largest contributor, 53% of the total consumption. Upgrading silicon ore into a usable form for solar cells alone consumes 37% of this energy. Process energy in the form of heat and electricity was found to be responsible for most of this energy use. This value is considerably lower than those reported in the literature mainly due to the large share of renewables in Canada's energy mix. The module assembly also has a significant contribution to the energy consumption of the solar PV production stage. Upstream energy consumed in aluminum production is responsible for a large share. According to the life cycle inventory analysis, each panel requires around 67.4 kWh_e to produce the aluminum frames needed. Energy used in material extraction and battery manufacturing accounts for 28% of the total consumption. The electrodes (cathode and anode), the main parts of the battery system, are responsible for the largest share of energy consumption. The high energy-intensive processes of cathode and anode production are the key drivers of high energy use. Energy uses for system integration are due to mounting structures (12%) and inverters (5%). The contributions from transportation and end-of-life are marginal (Figure 7).



1. Download : Download high-res image (222KB)
2. Download : Download full-size image

Figure 7. Energy consumption profile of a 5MWp utility-scale solar farm.

Figure 7 presents the NER results for a utility-scale solar power plant with several orientations. The values range from 3.2 to 6.6, which indicates that the systems are net energy producers. The net energy ratio is highly dependent on the efficiency and lifetime of the solar PV panels, as they are the only energy-generating equipment in the assumed system boundary and these two parameters dictate how much energy will be generated throughout the entire life cycle. Continuous improvement in the solar PV industry to increase efficiency and lifetime for solar PV panels should increase NERs in the future (Figure 8).

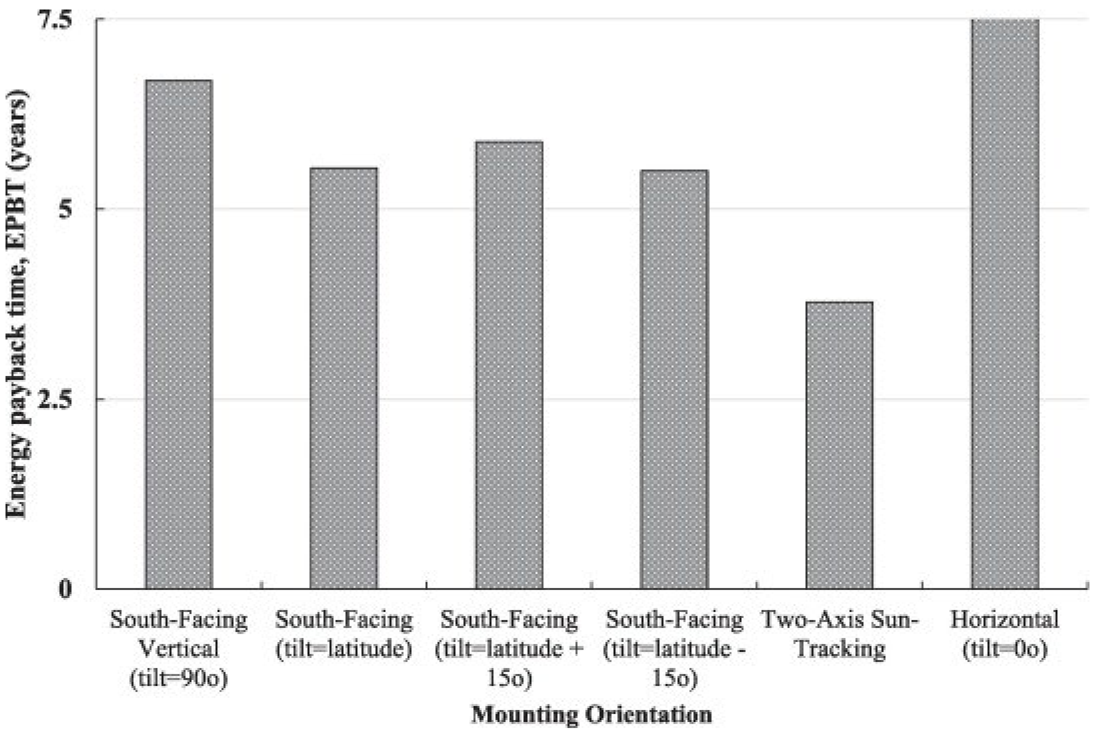


1. Download : Download high-res image (435KB)
2. Download : Download full-size image

Figure 8. Net energy ratio for different orientations.

7.4 Energy payback time (EPBT)

Figure 5 shows the EPBTs of utility-scale solar PV plants at different mounting orientations. Mounting orientations have a significant effect on the overall energy yield of large-scale solar farms. The orientation determines how much solar energy will fall on the panels and thus how much energy can be converted to usable electricity. As EPBT is a measure of how long a system takes to return the amount of energy that has been invested during its material formation, production, transportation, installation, and estimated energy use at the end of life, a lower EPBT is always desired. The lowest EPBT of 3.9 years is estimated when dual-axis trackers are considered as mounting structures. On average, using a dual-axis tracking system would reduce the EPBT of large-scale solar farms by 1.7. Solar panels having the same or a ± 15º tilt angle as the latitude of the location are the next best options with an EPBT of around 4.3 years (Figure 9).



1. Download : Download high-res image (463KB)
2. Download : Download full-size image

Figure 9. Energy payback time for different orientations.

9. Conclusion

Globally, the electricity sector is among the major greenhouse gas (GHG) emitters, mainly because of the use of fossil fuels. A radical transformation of the sector through a steady and evolutionary process towards a high share of renewable energy sources is vital to achieving the 1.5 °C climate change target. This is more relevant for fossil fuel-dominated energy mix jurisdictions. Grid-connected utility-scale solar PV has emerged as a potential pathway to ensure deep decarbonization of electricity in many regions. Research on utility-scale solar PV projects mainly focuses either on technical or economic feasibility, and literature assessing on environmental performance is scarce. Evaluating the life cycle environmental benefits is essential to provide scientific insight to policymakers to support decisions in the wide deployment of solar to ensure the transition to a low-carbon economy. Utility-scale solar PV is still in the early stages in Canada, hence the environmental consequences need to be investigated and compared to conventional sources of electricity. This research aimed to develop a bottom-up process-based LCA to evaluate the energy and environmental performance of large-scale solar PV farms in Alberta, Canada. The study provides robust life cycle inventory data based on the most recent commercially available technologies and maps the entire value chain. Models were used to simulate a utility-scale solar power plant and determine the required equipment sizes, thereby improving the reliability of the results. The electricity generation models developed used location-specific solar insolation data and considered changes in performance from snowy conditions. The life cycle energy profile for a utility-scale solar power plant shows that most of the energy is consumed during raw material extraction, production, and assembly of solar panels, which together account for 53% of the total consumption. Energy associated with battery manufacturing also has an important contribution, around 28% of the total consumption.

The two-axis sun tracking system offers the highest mean NER value (6.6), which indicates that the system is a net energy producer. Continuous improvements in efficiency and lifetime solar PV technology would further increase the NER. The life cycle GHG emissions range from 98.3 to 149.3 g $CO_{2\ eq}$ /kWh with a mean value of 123.8 g $CO_{2\ eq}$ /kWh. Battery manufacturing has the largest emissions contribution (54%) which results from anode and cathode production processes. The trade-off between energy efficiency and GHG reduction can also be understood through sensitivity and uncertainty analyses. The study provides key insights to policymakers to support decisions on the wide deployment of solar to ensure the transition to a low-carbon economy.

References

Al-Shetwi, A. Q. "Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges," *Science of The Total Environment,* vol. 822, p. 153645, 2022/05/20/ 2022, doi: https://doi.org/10.1016/j.scitotenv.2022.153645.

Mehedi, T. H., E. Gemechu, and A. Kumar, "Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems," *Applied Energy,* vol. 314, p. 118918, 2022/05/15/ 2022, doi: https://doi.org/10.1016/j.apenergy.2022.118918.

Okoye C. and U. I. Igariwey, "Solar pv power generation: Key insights and imperatives," *International Journal of Energy and Environmental Research,* vol. 7, no. 3, pp. 31-41, 2019. [Online]. Available: https://www.eajournals.org/wp-content/uploads/Solar-Pv-Power-Generation.pdf.

US Energy Information Administration. "Solar thermal power plants." US Energy Information Administration. https://www.eia.gov/energyexplained/solar/solar-thermal-power-plants.php (accessed 28 February, 2023).

Wu, C., X.-P. Zhang, and M. Sterling, "Solar power generation intermittency and aggregation," *Scientific Reports,* vol. 12, no. 1, p. 1363, 2022/01/25 2022, doi: https://doi.org/10.1038/s41598-022-05247-2.

Biographies

Moses Jeremiah Barasa Kabeyi is currently a doctoral researcher in the department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Mechanical and Production Engineering and MSc. in Mechanical and Production Engineering from Moi University, in Kenya, and an MA in Project planning and Management from University of Nairobi, Kenya. He also has a Diplomas in Project management, Diploma in Business management and a Diploma in Management of non-governmental organizations (NGOs) from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers and conference papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.