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By : Chibani Nafa et Zemouli Abderrahmane

Topic

A smart self-controlled cleaning system for PV panels
« CleanRayX »

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Dedication Nafa

All praise is due to Allah, first and last, by whose grace all good things are accomplished.

I dedicate this humble work to :

My beloved family, and to my father who sacrificed so much for us—though circumstances prevent you from being here today, your love and prayers remain my guiding light.

To my devoted mother, who stood by us through thick and thin, supporting us both financially and emotionally without hesitation.

To my dear aunt, who raised me from childhood and became a second mother to me in every sense of the word.

All my relatives and friends who have steadfastly supported and encouraged me throughout this journey.

And to everyone who contributed to the realization of this work.

Dedication Abderrahmane

I dedicate this modest work to:

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Myself for standing tall whenever life digs ditches on my path to keep me down, for not giving up no matter how hard it is, my dear parents, for their endurance, encouragement, prayers, and above all, their immense sacrifices that have been behind the success of my studies, in recognition of their unwavering love.

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And to all those who helped us in the realization of this work, i really appreciate it.

Résumé

Ce mémoire traite de la perte d'efficacité des panneaux solaires photovoltaïques due à l'accumulation de poussière, notamment dans les régions arides comme l'Algérie. Il commence par une présentation des sources d'énergie renouvelable, en mettant l'accent sur l'énergie solaire et les défis environnementaux qui influencent sa performance. Une analyse détaillée de l'impact de la poussière sur le rendement des panneaux solaires est suivie d'un examen complet des méthodes de nettoyage existantes : manuelles, robotisées et électrostatiques.

La contribution principale de ce travail est le développement du CleanRayX, un système de nettoyage autonome et intelligent, conçu pour détecter l'accumulation de poussière et nettoyer les panneaux solaires sans intervention humaine. Le système utilise divers capteurs (LDR, capteurs ultrasoniques, détecteurs de pluie) et des microcontrôleurs (ESP32-WROVER et ESP32-CAM) pour effectuer un nettoyage conditionnel et efficace. Des tests pratiques et des mesures environnementales valident l'efficacité de la solution proposée. L'étude conclut que CleanRayX est un outil prometteur pour renforcer la durabilité de l'énergie solaire dans les environnements poussiéreux.

Abstract

This thesis addresses the efficiency loss in photovoltaic solar panels due to dust accumulation, particularly in arid regions like Algeria. It begins with an overview of renewable energy sources, focusing on solar energy and the environmental challenges that impact its performance. A detailed analysis of dust's effect on solar panel efficiency is provided, followed by a comprehensive review of existing cleaning methods, including manual, robotic, and electrostatic systems.

The core contribution of this work is the development of CleanRayX, an autonomous, intelligent cleaning system designed to detect dust accumulation and clean solar panels without human intervention. The system integrates various sensors—light-dependent resistors, ultrasonic sensors, and rain detectors—with microcontrollers (ESP32-WROVER and ESP32-CAM) to perform efficient, condition-based cleaning. Simulations and real-world testing demonstrate the effectiveness of the proposed solution in maintaining high energy output under varying environmental conditions. The study concludes that CleanRayX is a promising tool for enhancing solar energy sustainability in dusty climates.

Chapter I

Renewable energies

I. Introduction

With increasing awareness of environmental issues and the need for sustainable energy, renewable energy sources have become an important part of the global energy landscape. These sources, which include sunlight, wind, water, and heat from the Earth, provide clean and naturally replenished energy. Learning how each of these energy types works helps us understand their benefits and the role they play in meeting future energy needs.

This chapter gives an overview of the main renewable energy sources and explains their basic working principles. This background will help to better understand the developments and solutions discussed in the following chapters.

I.1. Definition of renewable energy

Renewable energy (also called green energy) is energy made from renewable natural resources that are replenished on a human timescale. The most commonly used renewable energy types are solar energy, wind power, and hydropower. Bioenergy and geothermal power are also notable in some countries. Some also consider nuclear power a renewable power source, although this is controversial, as nuclear energy requires mining uranium, a nonrenewable resource. Renewable energy installations can be large or small and are suited for both urban and provincial areas. Renewable energy is often deployed together with further electrification. This has several benefits : electricity can move heat and vehicles efficiently and is clean at the point of consumption. Variable renewable energy sources are those that have a fluctuating nature, such as wind power and solar power. In contrast, controllable renewable energy sources include dammed hydroelectricity, bioenergy, or geothermal power.

Renewable energy systems have rapidly become more efficient and less costly over the past 30 years [1]**.** A large majority of worldwide newly installed electricity capacity is now renewable [2]. Renewable energy sources, such as solar and wind power, have seen significant cost reductions over the past decade, making them more competitive with traditional fossil fuels [3]. In most countries, photovoltaic solar or onshore wind are the cheapest new-build electricity. [4] From 2011 to 2021, renewable energy grew from 20% to 28% of global electricity supply. Power from the sun and wind accounted for most of this increase, growing from a combined 2% to 10%. Use of fossil energy shrank from 68% to 62%. [5] In 2024, renewables accounted for over 30% of global electricity generation and are projected to reach over 45% by 2030 [6][7]. Many countries already have renewables contributing more than 20% of their total energy supply, with some generating over half or even all their electricity from renewable sources [8][9].

Renewable energy is usually understood as energy harnessed from continuously occurring natural phenomena. The International Energy Agency defines it as "energy derived from natural processes that are replenished at a faster rate than they are consumed". Solar power, wind power, hydroelectricity, geothermal energy, and biomass are widely agreed to be the main types of renewable energy [10]. Renewable energy often displaces conventional fuels in four areas : electricity generation, hot water/space heating, transportation, and rural (off-grid) energy services [11].

The renewable sources are cost effective, user-friendly, so that they can easily beat the fossil fuels. By promotingrenewable energy sources we can avoid, Air pollution, soilpollution and water pollution. Country's Economy willincrease. Throughout the year these sources are availablewithout affecting the Environment.

Figure I.1. Renewable energy sources for a sustainable future [12]

I.2.Types of renewable energy

There are many types of renewable energy, each one has its own technologies, advantages, and challenges.

I.2.1. Wind energy

Wind is the movement of air caused by pressure differences in the earth's atmosphere, which is caused by the uneven heating of the earth's surface from the sun. Because of earth's irregular surface, the slight tilt of the planet, and its rotation, different areas heat up at different rates. As warmer air expands and rises, it creates a pressure imbalance with the nearby cooler air, which then rushes in to fill that space. The greater the pressure difference, the stronger the wind. Generating wind energy is all about kinetic energy, also known as the energy of motion. A wind turbine takes the kinetic energy of wind and turns it into electrical energy.

Figure I.2. Wind mills [12]

I.2.1.1. Working principle of wind turbines

When the wind strikes the rotor blades, blades start rotating. The turbine rotor is connected to a high-speed gearbox. Gearbox transforms the rotor rotation from low speed to high speed. The high-speed shaft from the gearbox is coupled with the rotor of the generator and hence the electrical generator runs at a higher speed. An exciter is needed to give the required excitation to the magnetic coil of the generator field system so that it can generate the required electricity. The generated voltage at output terminals of the alternator is proportional to both the speed and field flux of the alternator. The speed is governed by wind power which is out of control. Hence to maintain uniformity of the output power from the alternator, excitation must be controlled according to the availability of natural wind power. The exciter current is controlled by a turbine controller which senses the wind speed. Then output voltage of electrical generator(alternator) is given to a rectifier where the alternator output gets rectified to DC. Then this rectified DC output is given to line converter unit to convert it into stabilized AC output which is ultimately fed to either electrical transmission network or transmission grid with the help of step up transformer. An extra units is used to give the power to internal auxiliaries of wind turbine (like motor, battery etc.), this is called Internal Supply Unit. The turbine blades are adjusted from their base hub using a system of gears and small motors or hydraulics. This system, called pitch control, can be electric or mechanical. It swivels the blades to align with wind speed, ensuring they capture the most wind energy efficiently. The nacelle, or the turbine's body, can rotate to face changing wind directions for maximum energy capture. An anemometer and wind vanes on the nacelle sense wind speed and direction. This data is sent to a control system that adjusts the nacelle's position using a yaw motor, aligning the turbine with the wind [14].

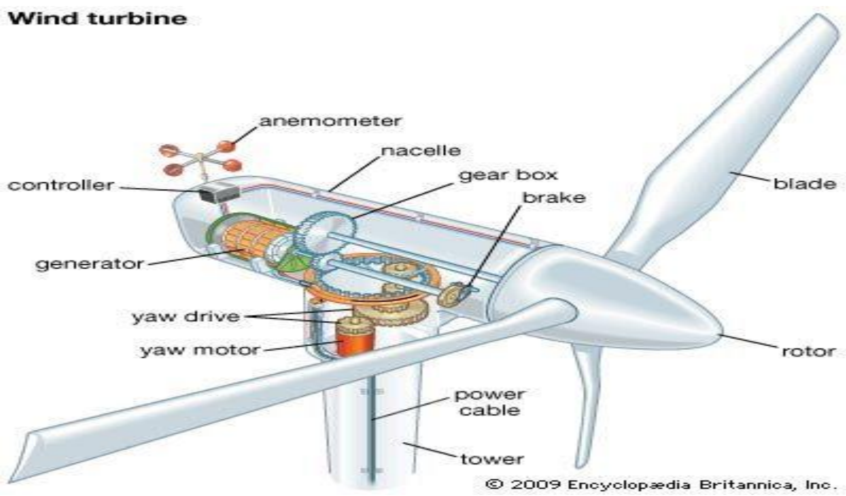


Figure I.3. Wind turbines main parts [15]

Although there are many different types of wind turbines, they can be summarized into two categories : Horizontal-axis wind turbines and Vertical-axis wind turbines.

I.2.1.1.a. Horizontal-axis wind turbines

Horizontal axis wind turbines can be classified into two main types : lift-type and drag-type. Lift-type turbines operate at high speeds, whereas drag-type turbines rotate more slowly. For electricity generation, lift-type horizontal axis turbines are predominantly used. Most of these turbines are equipped with mechanisms to adjust to changes in wind direction. In smaller turbines, this is typically achieved with a rudder, while larger turbines use wind sensors and a drive system powered by a servomotor. If the rotor is positioned in front of the tower, the turbine is known as an upwind turbine ; if it is behind, it is referred to as a downwind turbine. Horizontal axis wind turbines come in various designs : some feature reversed blades, others mount multiple turbines on a single tower to cut structural costs for a given power output, and some incorporate designs that generate vortices to concentrate and accelerate the airflow around the turbine.

Figure I.4. Horizontal-axis wind turbines [16]

I.2.1.1.b. Vertical-axis wind turbines

Vertical axis wind turbines (VAWTs) have the significant advantage of not requiring reorientation when wind direction changes. This simplifies their structural design compared to horizontal axis wind turbines and also reduces the gyroscopic forces acting on the system. Several VAWT designs rely on drag to generate rotation. These include wind wheels made of flat plates or fabric, which function purely on drag, and S-shaped wind turbines, which generate some lift but are still primarily drag-based. While these designs offer high starting torque, they typically have a low tip-speed ratio and produce relatively low power output for their size, weight, and cost.

Figure I.5. Vertical-axis wind turbines [17]

I.2.2. Hydropower energy

Hydropower, also referred to as water power or hydroelectric power, uses the energy of falling or fast-running water to power machines or produce electricity. It is a renewable energy source that uses the kinetic energy of flowing water, typically rivers, to spin turbines connected to generators, which then convert the mechanical energy into electricity. Hydropower is one of the oldest and most widely used forms of renewable energy. It currently accounts for a significant share of global and national electricity generation, providing clean, reliable, and flexible power that can help balance other variable renewable sources like wind and solar. Additionally, hydropower facilities can offer energy storage and grid stability services by adjusting water flow and electricity output in response to demand.

Figure I.6. Hydroelectric power plant [18]

I.2.2.1. Working principle of hydroelectric power plant

The water turbine changes the kinetic energy of the falling water into mechanical energy at the turbine shaft. The turbine drives the alternator coupled with it and converts mechanical energy into electrical energy, that's the basic working principle of hydroelectric power plants.

The main elements of a hydroelectric power plant are

Catchment area : the total area behind the dam in which water is collected and streamflow is obtained is known as the catchment area.

Reservoir : it is an integral part of the power plant, where water is stored and supplied to a water turbine continuously.

Dam : a dam is a barrier that stores water and creates a water head.

Slipway : due to heavy rainfall in the catchement area, the water level may exceed the storage capacity of the reservoir. It may affect the stability of the reservoir. A structure is formed around the reservoir to remove this excess water. This structure is known as slipway, it provides stability to the reservoir and reduces the level of water in the time of the flood.

Surge tank : it is a small tank (open at the top). It is provided to reduce the pressure surges in the conduit. It is located near the beginning of the conduit.

Penstocks : penstocks are open or closed conduits that carry water to the turbines. They can be designed according to water head or working pressure.

Water turbines : it works as an energy conversion device. It is a machine through which the potential energy of water is converted into the mechanical energy of shaft. The main types of water turbines are : impulse turbines and reaction turbines.

Impulse turbines : They are used for high water heads. It has a wheel fitted with elliptical buckets along its periphery. The whole water pressure is converted into kinetic energy, and it spins the wheel.

Reaction turbines : there are two main important types of reaction turbines : francis turbine and kaplan turbines. A francis turbine is used for low to medium heads. A kaplan turbine is used for low heads and large quantities of water.

Water turbine generators : they are low RPM synchronous generators with main exciters usually mounted at the top on the shaft end.

Power house auxiliaires : the hydroelectric power plant requires the same basic auxiliaries as any other power plant, such as the governor system, exciters, cranes, control panels, etc. Power supply for the auxiliaries, cranes, and lighting is usually arranged from a small independent hydraulic turbine and generators.

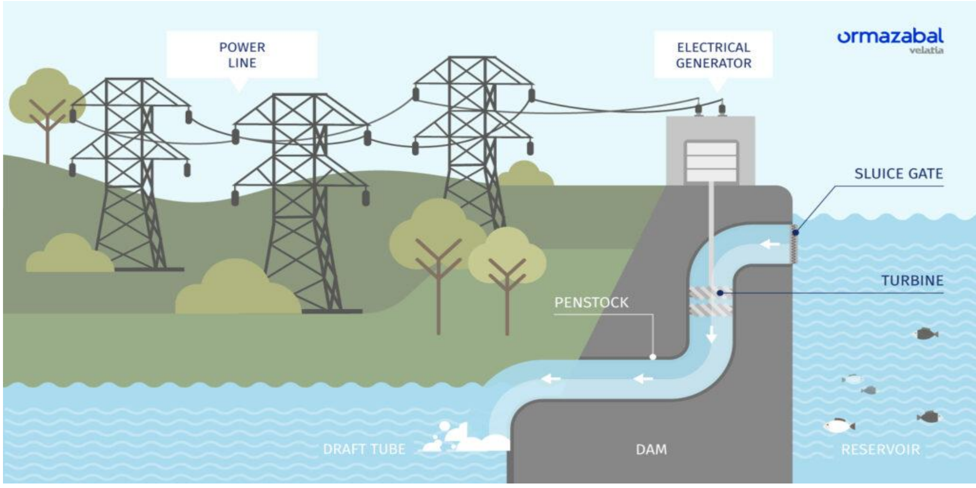


Figure I.7. Hydroelectric power plant main elements [19]

I.2.3. Geothermal energy

Geothermal energy is the heat from the Earth. It's clean and sustainable. Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma. Almost everywhere, the shallow ground or upper 10 feet of the Earth's surface maintains a nearly constant temperature between 50° and 60°F (10° and 16°C). Geothermal heat pumps can tap into this resource to heat and cool buildings. A geothermal heat pump system consists of a heat pump, an air delivery system (ductwork), and a heat exchanger-a system of pipes buried in the shallow ground near the building. In the winter, the heat pump removes heat from the heat exchanger and pumps it into the indoor air delivery system. In the summer, the process is reversed, and the heat pump moves heat from the indoor air into the heat exchanger. The heat removed from the indoor air during the summer can also be used to provide a free source of hot water [20].

Figure I.8. Geothermal energy power [21]

I.2.3.1. Principle working of geothermal power plant

Geothermal power plants use steam obtained from geothermal reservoirs to produce electricity. The steam comes from reservoirs of hot water found a few miles or more below the earth's surface. The steam rotates a turbine that activates a generator, which produces electricity.

To generate power from geothermal systems, three elements are needed :

Heat : Abundant heat is found in rocks deep underground, varying by depth, geology, and geographic location.

Fluid : Sufficient fluid to carry heat from the rocks to the earth’s surface.

Permeability Small pathways that facilitate fluid movement through the hot rocks.

The presence of hot rocks, fluid, and permeability underground creates natural geothermal systems. Small underground pathways, such as fractures, conduct fluids through the hot rocks. In geothermal electricity generation, this fluid can be drawn as energy in the form of heat through wells to the earth’s surface. Once it has reached the surface, this fluid is used to drive turbines that produce electricity.

There are three main types of geothermal power plant technologies : dry steam, flash steam, and binary cycle. The type of conversion is part of the power plant design and generally depends on the state of the subsurface fluid (steam or water) and its temperature.

Dry steam plants use hydrothermal fluids that are already mostly steam, which is a relatively rare natural occurrence. The steam is drawn directly to a turbine, which drives a generator that produces electricity. After the steam condenses, it is frequently reinjected into the reservoir.

Dry steam power plant systems are the oldest type of geothermal power plants, first used in Italy, in 1904. Steam technology is still relevant today and is currently in use in northern California at The Geysers, the world's largest single source of geothermal power [22].

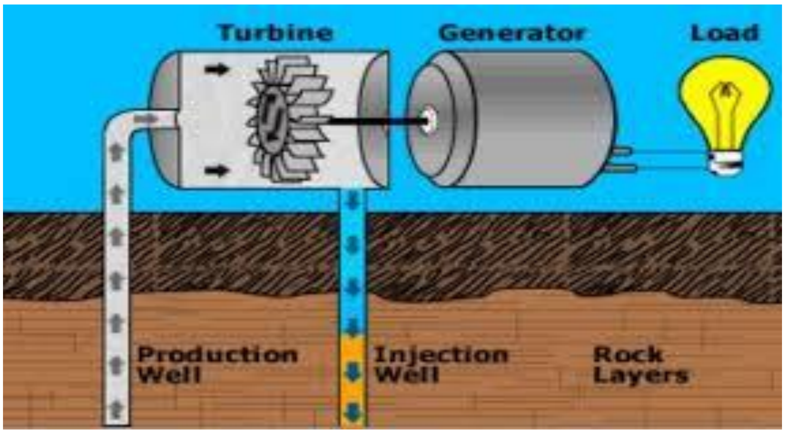


Figure I.9. Dry steam plants [23]

Flash steam plants flash steam plants are a common type of geothermal power plant in operation today. Fluids at temperatures greater than 182°C/360°F, pumped from deep underground, travel under high pressures to a low-pressure tank at the earth's surface.

The change in pressure causes some of the fluid to rapidly transform, or "flash," into vapor. The vapor then drives a turbine, which drives a generator. If any liquid remains in the low-pressure tank, it can be "flashed" again in a second tank to extract even more energy [22].

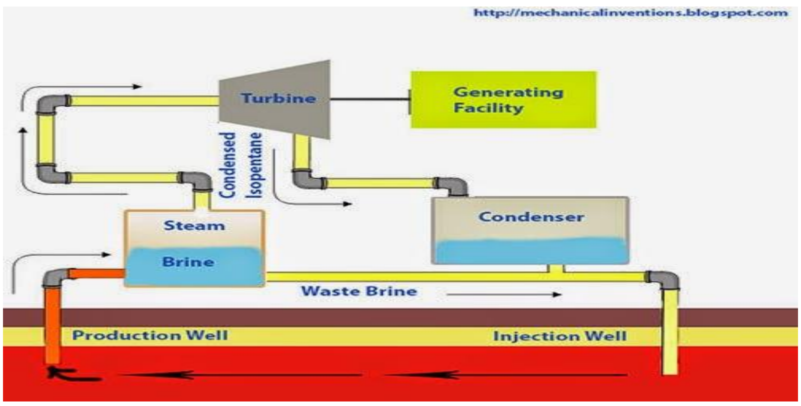


Figure I.10. Flash steam plants [24]

Binary-cycle geothermal power plants can use lower temperature geothermal resources, making them an important technology for deploying geothermal electricity production in more locations. Binary-cycle geothermal power plants differ from dry steam and flash steam systems in that the geothermal reservoir fluids never come into contact with the power plant's turbine units. Low-temperature (below 182°C/360°F) geothermal fluids pass through a heat exchanger with a secondary, or "binary," fluid. This binary fluid has a much lower boiling point than water, and the modest heat from the geothermal fluid causes it to flash to vapor, which then drives the turbines, spins the generators, and creates electricity.

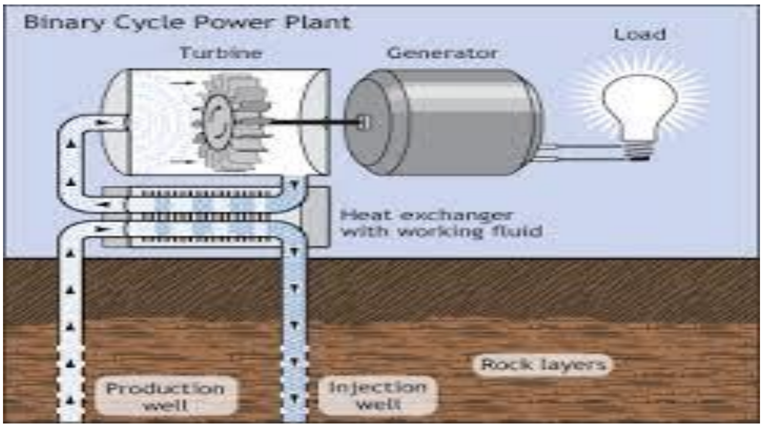


Figure I.11. Binary cycle plants [25]

I.2.4. Biomass energy

Biomass is the most important source for energy production supplied by agriculture. Effective harnessing of bio-energy can energize entire rural milieu in a country like India where nature offers various types of biomass. This energy is also available in the form of biodegradable waste, which is the rejected component of available biomass [26]. Biomass energy refers to fuels made from plants and animal wastes. The Biomass resource is organic matter in which the energy of sunlight is stored in chemical bonds. When the bonds between carbon, hydrogen and oxygen molecules are broken by digestion, combustion,or decomposition, these substances release stored energy. Biomass energy is generated when organic matter is converted to Energy. In alcohol fermentation, the starch in organic matter is converted to sugar by heating. This sugar is then fermented and finally ethanol is distiller and then blended with another fuel. An aerobic digestion converts biomass, especially waste product such as municipal solid waste and market waste. In this process, the facultative bacteria breakdown the organic material in the absence of oxygen and produce methane and carbon dioxide. Bioconversion is a nonpolluting, environmentally feasible and cost effective process [27]. The effluent and digester residues are rich in nitrogen and phosphorus, which can be recycled back to the soil as a fertilizer [28]. By using this method we can derive 70% of the energy. The biomass is mixed with water and stored in an airtight tank. The organic wastes (Municipal Solid Waste) are collected separately and dried natural method and shredded to the maximum particle size of 2 – 4 mm. This was stored in a plastic container at room temperature and was characterized and it was used during all anaerobic digestion treatment. Domestic sewage was collected from a college campus before disposal. It was used in all anaerobic digestion experiments for diluting the feedstock to achieve the required total solids concentration for the present investigation. Experiments were carried out in 5 lit. Capacity batch type reactor operating in semi continuous mode with daily feeding. The digester was operated at room temperature at a constant hydraulic retention time of 25 days with different organic loading rate. To start with, the digester was initiated by charging with 2.75 lit. of feed stocks (2% TS) along with 2 lit.of feed sludge. The digester was maintained anaerobically and stabilization was to take place for two weeks. During this stabilization period, pH was maintained in the range of 6.5 to 7.5 by adding sodium hydroxide. The pH and gas production were measured every day. It was found that the maximum biogas production is 0.36m3/kg of VS added/day at the optimum organic loading rate of 2.9 kg of VS / m3/d. In Chennai the government set up a power plant using vegetable waste as fuel. Daily 40 tones of market waste is going to be used for the power plant. The power plant will generate about 4800 units of electricity/day. The gas comprises 65% of methane and 35% of carbon di oxide, and is transferred into a gasholder and finally electrical energy is produced. The power generated from the plant will be sold at Rs.3.15/unit [29].

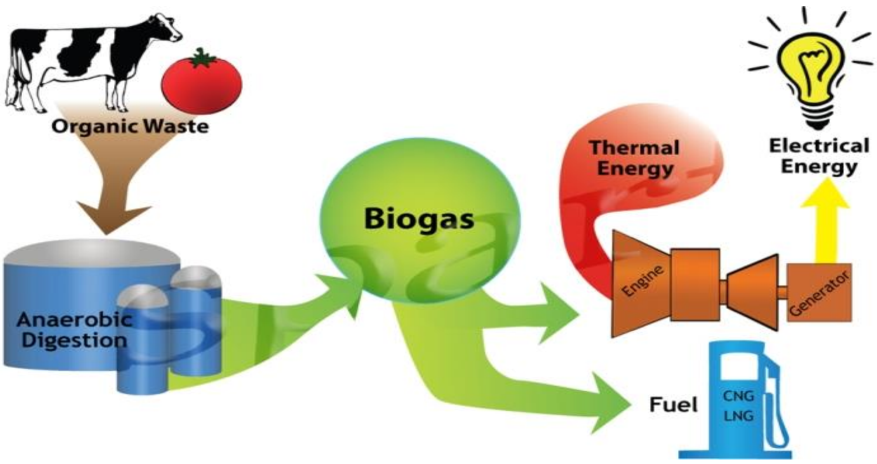


Figure I.12. Biomass energy and its promise [30]

I.2.4.1. Working principle of biomass unit

A biomass cogeneration unit is useful in all cases where simultaneous production of electricity and heat is necessary, such as district heating or certain industrial productions. Inside, the biomass can be used raw or treated.

In the first case, the raw biomass is conveyed to a burner which generates heat. The heat in turn heats a working fluid (usually water) that transforms into steam, acquiring mechanical energy through a pressure increase. The mechanical energy powers a turbine connected to a generator, which produces electricity. Part of the heat produced is conveyed to a hot water circuit which powers the thermal utilities.

In the case of biomass treatment, for example, through anaerobic digestion of organic materials in the absence of oxygen, the plant is powered by biogas, which has characteristics similar to methane gas. This biofuel powers an internal combustion engine connected to an electric generator and allows the simultaneous generation of electrical energy, hot water and steam.

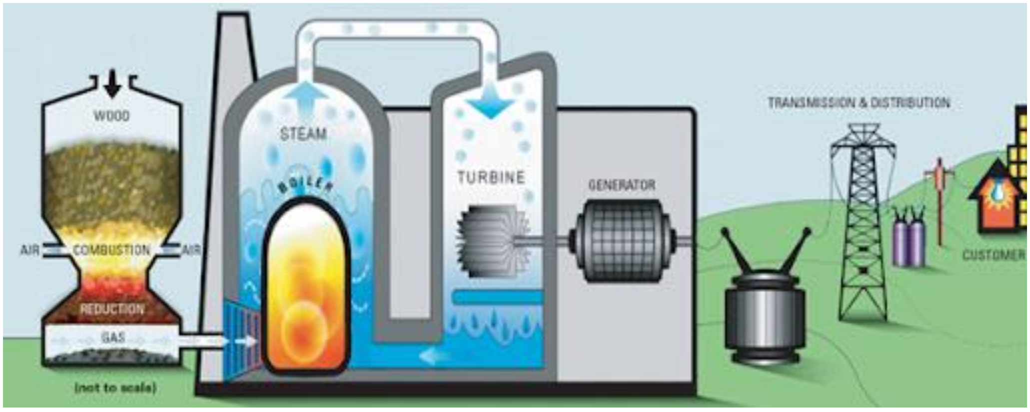


Figure I.13. Biomass gasification power generation technology [31]

I.2.5. Ocean energy

The oceans contain a huge amount of energy. Capturing this energy could have substantial benefits. The energy in the ocean waves is a form of concentrated solar energy that is transferred through complex wind-wave interactions. The effects of earth’s temperature variation due to solar heating, combined with a multitude of atmospheric phenomena, generate wind currents in global scale. Ocean wave generation, propagation and direction are directly related to these wind currents.

On the other hand, ocean tides are cyclic variations in seawater elevation and flow velocity as a direct result of the earth's motion with respect to the moon and the sun and the interaction of their gravitational forces. A number of phenomena relating to earth rotational tilt, rate of spinning, and interaction among gravitational and rotational forces cause the tide conditions to vary significantly over time. Tide conditions are more apparent in coastal areas where constrained channels augment the water flow and increase the energy density.

Ocean energy resources are contained in :

Tidal and currents : Potential energy associated with tides can be harnessed by building barrage or other forms of construction across an estuary, while kinetic energy associated with tidal (marine) currents can be harnessed using modular systems.

Waves : Kinetic and potential energy associated with ocean waves can be harnessed using modular technologies.

Temperature gradients Thermal energy due to the temperature gradient between the sea surface and deepwater can be harnessed using different Ocean Thermal Energy Conversion (OTEC) processes.

Salinity gradients : At the mouth of rivers where fresh water mixes with salt water, energy associated with the salinity gradient can be harnessed using pressure-retarded reverse osmosis process and associated conversion technologies.

I.2.5.1. Working principle of ocean power plants

The Tide is a regular rising and falling of the ocean's surface caused by changes in gravitational forces external to the Earth. A tidal power plant is a type of hydroelectric power generation facility that uses the tidal movements of ocean water to generate electricity. Tidal power plants work by constructing a dam-like structure across a tidal inlet or bay, which creates a tidal pool. As the tide flows in and out, it drives turbines, which in turn generate electricity.

There are two main types of tidal energy conversion systems

Tidal barrages

These are dams that are built across tidal estuaries. The gates of the barrage are opened when the tide is high, and the water flows through the barrage, turning turbines to generate electricity. Tidal energy can be used by putting turbines in the water and letting the waves turn them.

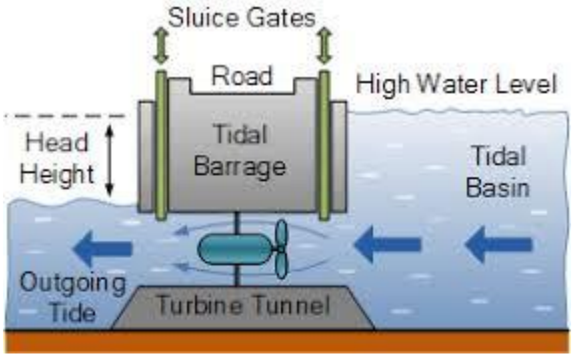


Figure I.13. Tidal barrage power generation [32]

Tidal turbines

These are turbines that are placed in the water and are turned by the flow of the tides. Tidal turbines can be either fixed to the seabed or floating

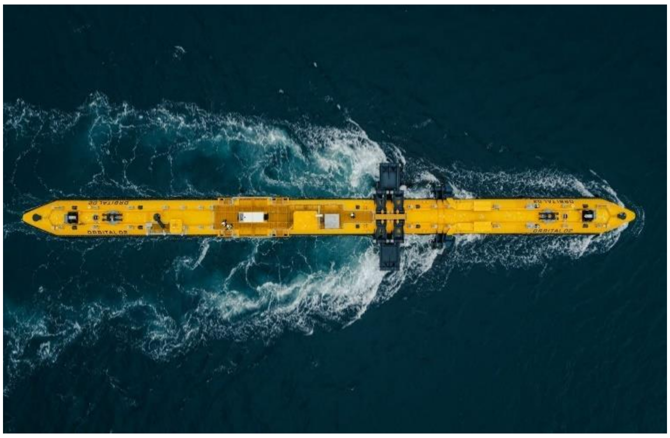


Figure I.14. Tidal turbines power generation [33]

Wave energy converters

Wave energy converters use the movement of waves to generate electricity. There are a number of different types of wave energy converters, but some of the most common include :

Point absorbers : buoys or other floating structures that move up and down with the waves. The movement of the buoy is converted into electricity using a linear generator.

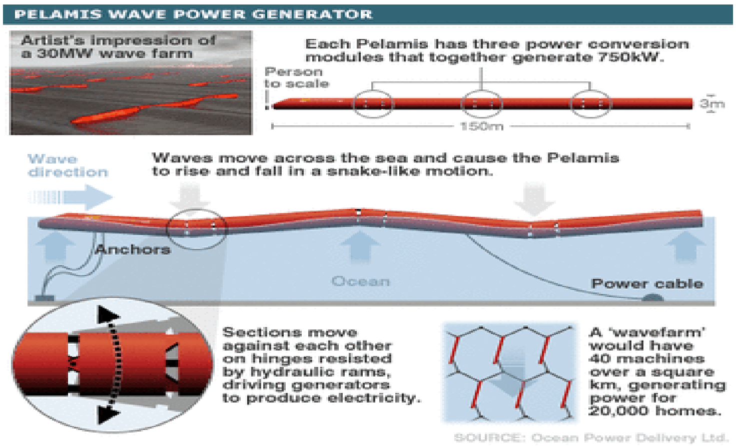


Figure I.15. Point absorbers wave power generation [34]

Attenuators : Attenuators are long, floating structures that are designed to absorb the energy of the waves. The energy of the waves is converted into electricity using a hydraulic system.

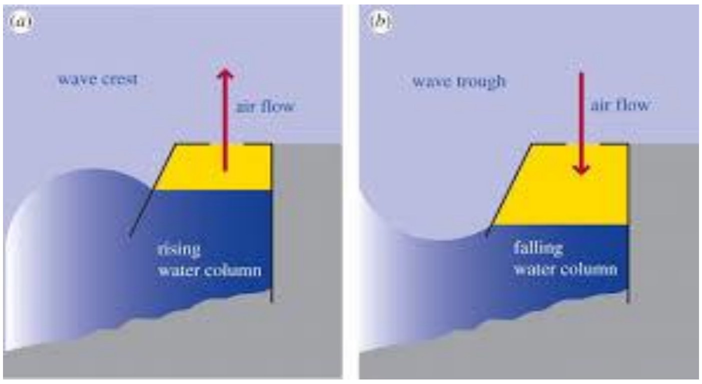


Figure I.16. Attenuators wave power generation [35]

Oscillating water columns (OWCs) : These are chambers that are partially submerged in the ocean. As the waves rise and fall, the air in the chamber is compressed and expanded. The compression and expansion of the air are used to turn a turbine, which generates electricity.

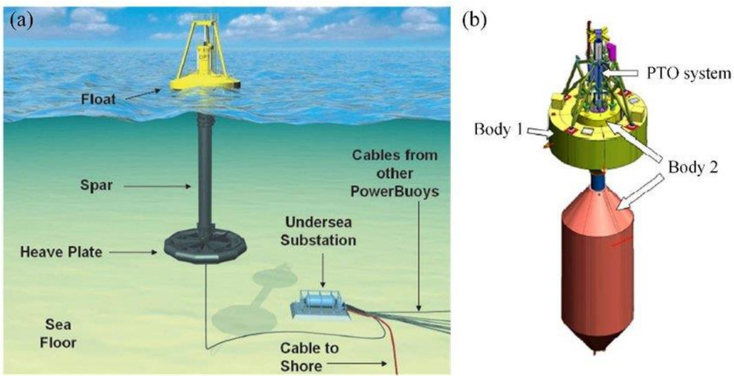


Figure I.17. Oscillating water columns (OWCs) [36]

Overtopping devices : These are structures that allows waves to flow over them, filling a reservoir. The water in the reservoir is then released through a turbine, which generates electricity.

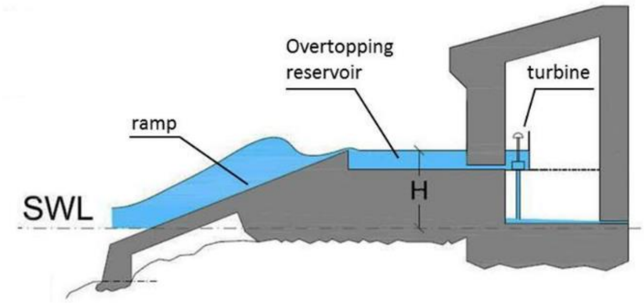


Figure I.18. OBREC illustration [37]

Inverted pendulum devices : This structure are anchored to the seabed. As the waves rise and fall, the pendulum moves up and down. The movement of the pendulum is converted into electricity using a hydraulic system

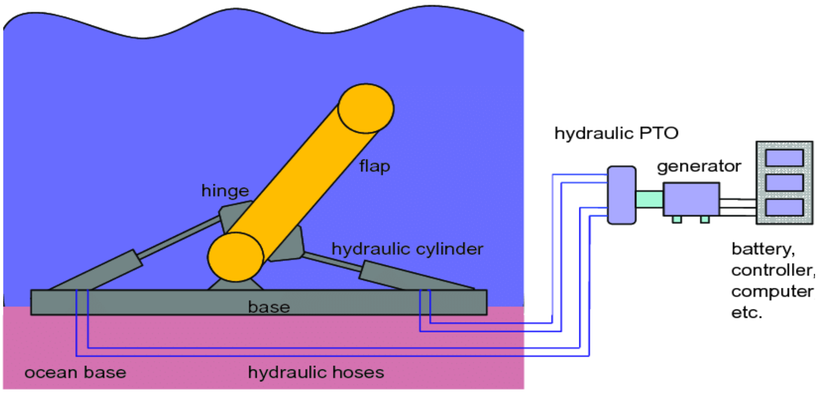


Figure I.19. A concept design of an 'Inverted Pendulum wave energy converter (WEC) [38]

OTEC systems

OTEC systems use the difference in temperature between the surface of the ocean and the deeper ocean to generate electricity. OTEC systems use a heat exchanger to transfer heat from the warm surface water to the cold deep water. The heat is then used to drive a turbine, which generates electricity.

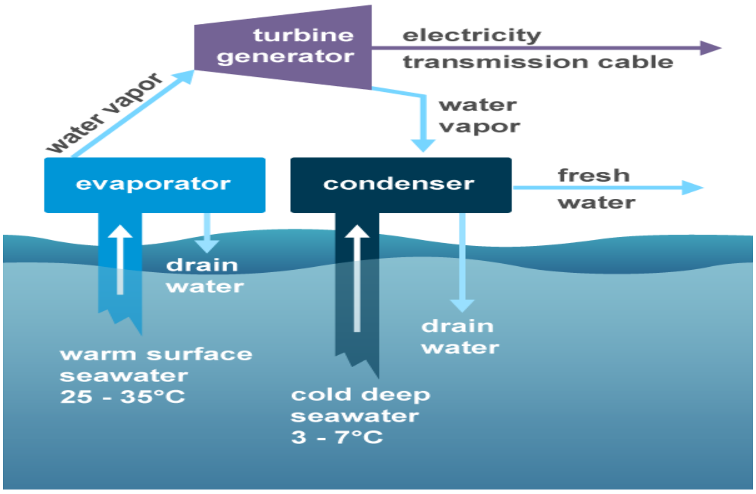


Figure I.19. OTEC systems power generation [39]

Salinity gradient Energy : Salinity gradient power technologies (also known as osmotic power or blue energy) use the difference in salinity between seawater and freshwater to generate electricity. Salinity gradient power technologies use a membrane to separate the seawater and freshwater. The difference in salinity creates a pressure difference, which is used to drive a turbine, which generates electricity.

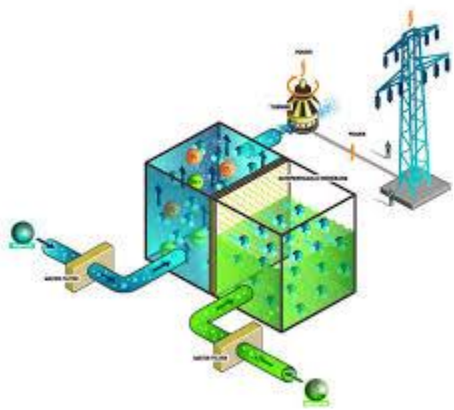


Figure I.20. Salinity gradient power technology

I.2.6. Solar energy

Among the various forms of renewable energy, solar power stands out due to its abundance, accessibility, and potential for sustainable development. As one of the fastest-growing energy sources worldwide. In the next chapter, we will take a closer look at solar energy, its principles, benefits, and the factors that can influence its performance.

I. Conclusion

This chapter provided an overview of the main renewable energy sources and their fundamental working principles. Understanding these different forms of clean energy highlights the potential they hold for a sustainable future, while also laying the groundwork for addressing practical challenges in their implementation. This foundation prepares us to focus more specifically on solar energy and the factors affecting its efficiency in the following chapters.

Chapter II

Solar energy and dust impact

II.1. Solar energy

II.1.1. Introduction

Solar energy is one of the most abundant and sustainable sources of energy available on Earth. Derived from the sun's radiation, it can be harnessed using various technologies such as solar panels and solar thermal systems to produce electricity or heat. As concerns about climate change, environmental degradation, and fossil fuel depletion continue to grow, solar energy has emerged as a key solution for meeting the world's increasing energy demands in a clean and renewable way. With rapid advancements in solar technology and decreasing costs, solar energy is playing an increasingly vital role in the transition toward a more sustainable and energy-efficient future.

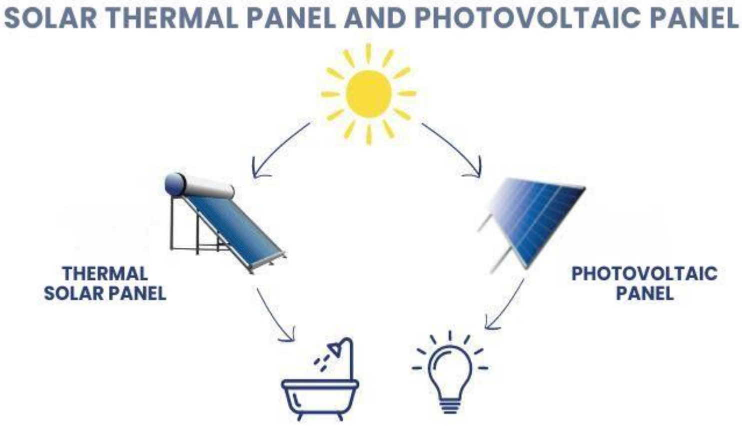


Figure II.1. Solar thermal panel and photovoltaic panel [40]

II.1.2. History of solar energy

In theory, solar energy was used by humans as early as the 7th century B.C. when history tells us that humans used sunlight to light fires with magnifying glass materials. Later, in the 3rd century B.C., the Greeks and Romans were known to harness solar power with mirrors to light torches for religious ceremonies. These mirrors became a normalized tool referred to as "burning mirrors." Chinese civilization documented the use of mirrors for the same purpose later in 20 A.D.

Another early use of solar energy that is still popular today was the concept of "sunrooms" in buildings. These sunrooms used massive windows to direct sunlight into one concentrated area. Some of the iconic Roman bathhouses, typically those situated on the south-facing side of buildings, were sunrooms. Later in the 1200s A.D, ancestors to the Pueblo Native Americans known as the Anasazi situated themselves in south-facing abodes on cliffs to capture the sun's warmth during cold winter months.

In the late 1700s and 1800s, researchers and scientists had success using sunlight to power ovens for long voyages. They also harnessed the power of the sun to produce solar-powered steamboats. Ultimately, it's clear that even thousands of years before the era of solar panels, the concept of manipulating the power of the sun was a common practice.

The development of solar panel technology was an iterative one that took a number of contributions from various scientists. Naturally, there is some debate about when exactly they were created and who should be credited for the invention. Some people credit the invention of the solar cell to French scientist **Edmond Becquerel**, who determined light could increase electricity generation when two metal electrodes were placed into a conducting solution. This breakthrough, defined as the "photovoltaic effect," was influential in later PV developments with the element selenium.

In 1873, Willoughby Smith discovered that selenium had photoconductive potential, leading to William Grylls Adams' and Richard Evans Day's 1876 discovery that selenium creates electricity when exposed to sunlight. A few years later, in 1883, **Charles Fritts** actually produced the first solar cells made from selenium wafers – the reason some historians credit Fritts with the actual invention of solar cells.

However, solar cells as we know them today are made with silicon, not selenium. Therefore, some consider the true invention of solar panels to be tied to Daryl Chapin, Calvin Fuller, and Gerald Pearson's creation of the silicon photovoltaic (PV) cell at Bell Labs in **1954**. Many argue that this event marks the true invention of PV technology because it was the first instance of solar technology that could actually power an electric device for several hours of a day. The first ever silicon solar cell could convert sunlight at four percent efficiency, less than a quarter of what modern cells are capable of.

Some of the earliest uses of solar technology were actually in outer space, where solar was used to power satellites. In 1958, the Vanguard I satellite used a tiny one-watt panel to power its radios. Later that year, the Vanguard II, Explorer III, and Sputnik-3 were all launched with PV technology on board. In 1964, NASA was responsible for launching the first Nimbus spacecraft, a satellite able to run entirely on a 470-watt solar array. In 1966, NASA launched the world's first Orbiting Astronomical Observatory, powered by a one-kilowatt array.

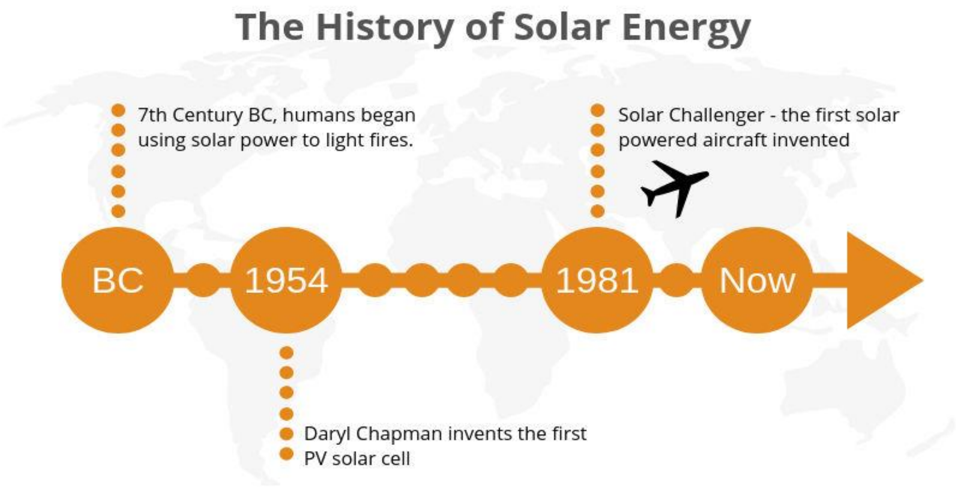


Figure II.2. The history of solar energy [41]

II.1.3.Definition of Solar energy

Basically, Solar energy is any type of energy generated by the sun.

Solar energy is created by nuclear fusion that takes place in the sun. Fusion occurs when protons of hydrogen atoms violently collide in the sun's core and fuse to create a helium atom. This process, known as a PP (proton-proton) chain reaction, emits an enormous amount of energy. In its core, the sun fuses about 620 million metric tons of hydrogen every second. The PP chain reaction occurs in other stars that are about the size of our sun, and provides them with continuous energy and heat. The temperature for these stars is around 4 million degrees on the Kelvin scale (about 4 million degrees Celsius, 7 million degrees Fahrenheit).

In stars that are about 1.3 times bigger than the sun, the CNO cycle drives the creation of energy. The CNO cycle also converts hydrogen to helium, but relies on carbon, nitrogen, and oxygen (C, N, and O) to do so. Currently, less than two percent of the sun's energy is created by the CNO cycle.

Nuclear fusion by the PP chain reaction or CNO cycle releases tremendous amounts of energy in the form of waves and particles. Solar energy is constantly flowing away from the sun and throughout the solar system. Solar energy warms Earth, causes wind and weather. The energy, heat, and light from the sun flow away in the form of electromagnetic radiation (EMR).

Solar energy is a renewable resource, and many technologies can harvest it directly for use in homes, businesses, schools, and hospitals. Some solar energy technologies include photovoltaic cells and panels, concentrated solar energy, and solar architecture.

There are different ways of capturing solar radiation and converting it into usable energy. The methods use either active solar energy or passive solar energy.

Active solar technologies use electrical or mechanical devices to actively convert solar energy into another form of energy, most often heat or electricity. Passive solar technologies do not use any external devices. Instead, they take advantage of the local climate to heat structures during the winter, and reflect heat during the summer.

Solar energy can split into two main types (thermal and photovoltaic), an each one has its own panel that is built with certain technology to convert that energy.

II.1.3.1. Thermal solar panel

Solar thermal panels are devices designed to capture and convert sunlight into heat energy, which is typically used for heating water, air, or other fluids for residential, commercial, or industrial applications. Solar thermal panels use collectors often flat-plate or evacuated tube designs to absorb solar radiation and transfer the heat to a working fluid, which then delivers the energy to a storage system or directly to its point of use.

Figure II.3. Solar thermal panel [42]

II.1.3.1.a. Working principle

The panels absorb energy from the sun and transfer this energy to heat water. The hot water generated is stored in the special, highly insulated cylinder. This cylinder is designed for use with solar panels and will replace the existing hot water cylinder in retro-fit situations.

The panels can supply up to 60 per cent of a household's domestic hot water needs over a year and can work even in cloudy or overcast conditions. Peak output is during summer months when there is more daylight and solar energy available.

For maximum efficiency all solar panels should be mounted on south facing roofs (between south-east and south-west) at an angle of about 30 to 50 degrees. They should also be clear of shade from trees, chimneys or surrounding buildings.

There are two types of solar thermal panels :

- Flat plate
- Evacuated tube

The evacuated tube panels can be a bit more efficient, especially in the winter months. They can also be used on shallower sloped roofs by rotating the tubes so that the collectors inside the tubes face the sun.

Flat plate panels however can be sized to produce the same output and can be integrated into the roof while the evacuated tube systems are fixed above the roof surface

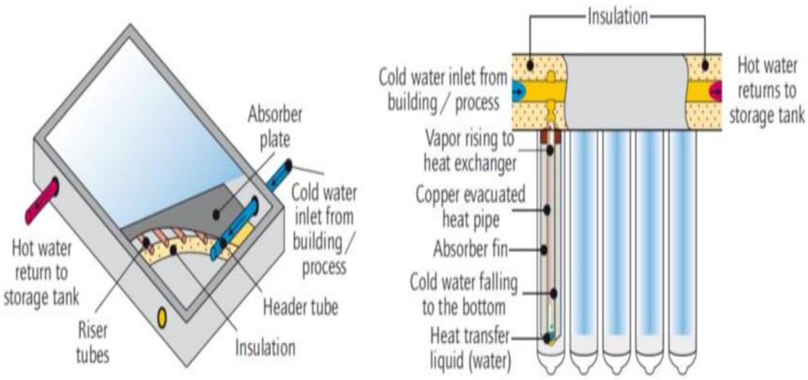


Figure II.4. Flat plate collector and evacuated tube collector [43]

II.1.3.2. Photovoltaic solar panel

A photovoltaic solar panel is a device that converts sunlight directly into electricity using the photovoltaic effect. It consists of multiple solar cells, typically made from semiconductor materials such as silicon, which absorb photons from sunlight and release electrons, generating an electric current. These panels are designed to harness renewable energy from the sun in a clean and sustainable way. Photovoltaic panels can be used in a variety of applications, from small-scale residential systems to large solar farms, and their efficiency and affordability have improved significantly over recent years due to advances in technology and manufacturing processes.

Figure II.5. Photovoltaic solar panels [44]

II.1.3.2.a. Working principle

The working principle of photovoltaic (PV) solar panels is based on the photovoltaic effect, a process by which certain semiconductor materials generate an electric current when exposed to sunlight. When sunlight hits the surface of a solar panel, photons from the sunlight are absorbed by the semiconductor material, typically silicon, within the solar cells. This energy excites the electrons in the material, causing them to break free from their atomic bonds. The structure of the solar cell includes an internal electric field that directs these free electrons toward metal contacts, creating a flow of electric current. This direct current (DC) can then be used immediately, stored in batteries, or converted into alternating current (AC) using an inverter for use in homes, businesses, or the power grid. The entire process operates silently and without moving parts.

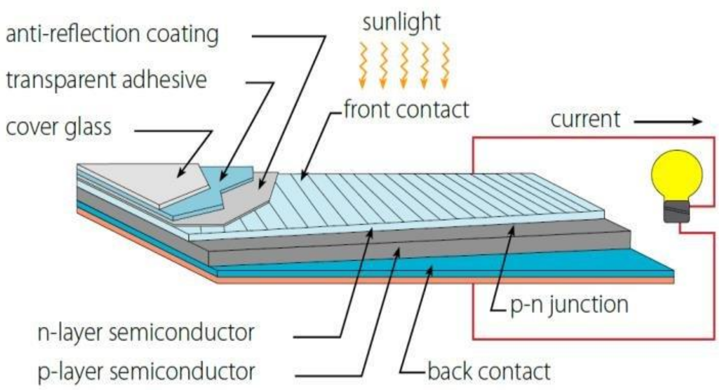


Figure II.6. Components of a solar cell [45]

II.1.3.2.b. Solar Panel Components

Solar panel components include photovoltaic cells, glass covering, encapsulants, back sheets, an aluminum frame, and a junction box. Each of these components serves a specific purpose so that the solar panels can create solar energy effectively and efficiently.

a. Photovoltaic Cells

The key component of a solar panel is the photovoltaic (PV) cell, also referred to as solar cells. These cells are made up of semiconductor materials, such as silicon, which can convert sunlight into electricity. When sunlight hits the PV cell, it knocks electrons loose from the atoms in the semiconductor material, causing them to flow through the cell and create an electrical current. The more light that hits the cell, the more electricity is produced.

PV cells come in different shapes and sizes, depending on their intended use. Some are rectangular, while others are square or circular. The most common type of PV cell is made from silicon, but there are also other materials used for specialized applications.

b. Glass Cover

The next component of a solar panel is the glass cover. This layer serves multiple purposes. Firstly, it protects the PV cells from external elements such as rain, snow, and hail. Additionally, the glass cover allows sunlight to pass through, maximizing the amount of light that reaches the PV cells. The type of glass used for solar panels is specially designed to be durable and transparent. Solar glass is typically 3mm to 4mm thick.

c. Encapsulant

Located between the PV cells and the back sheet is a layer called the encapsulant. This component serves as an adhesive, holding together all of the components of a solar panel. It also protects the PV cells from moisture and other external factors that may cause damage. EVA film (ethylene vinyl acetate) is typically used for encapsulating solar cells.

d. Back sheet

The back sheet is a thin layer of material that covers the back of the solar panel. Its primary function is to protect the inner components from moisture and other environmental factors. The most common materials used for backsheets are Tedlar or TPT, which are both durable and weather-resistant.

e. Aluminum Frame

To provide structural support and protect the inner components, solar panels are housed within a frame. The frame is typically made from aluminum or steel and provides rigidity to the panel. It also serves as a mounting point for installation on rooftops or other structures.

f. Junction Box

The last component of a solar panel is the junction box, which is located at the back of the panel. It serves as a connection point for all of the wiring and cables inside the solar panel, allowing for easy access to connect multiple panels in a solar array. The junction box also contains diodes, which prevent reverse current flow and protect against potential electrical hazards.

Each component of a solar panel plays an essential role in its functionality. Understanding these components can help you make informed decisions when installing solar panels for your home or business. With the continued advancements in technology, solar panels are becoming more efficient and affordable, making them a viable option for generating clean energy and reducing reliance on traditional sources of electricity.

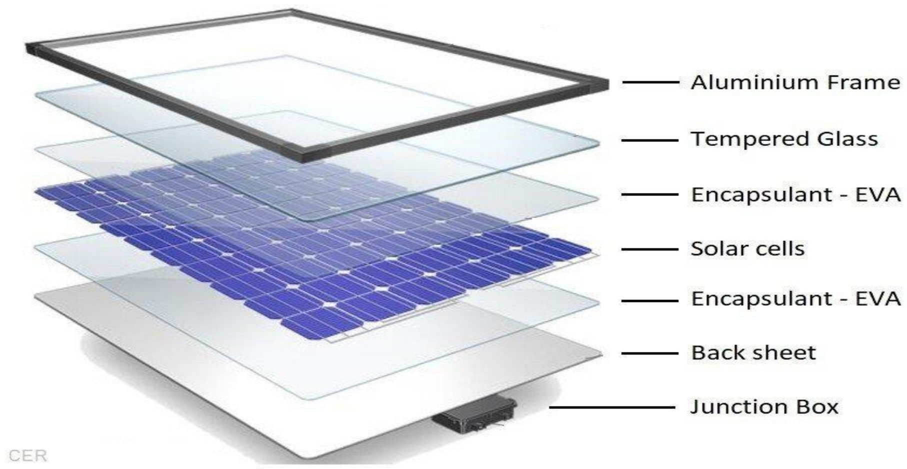


Figure II.7. Solar Panel Construction [46]

II.2. Dust impact on PV panels performance

The performance of the photovoltaic panel is measured in Wp (watt peak, or power). A 200 Wp solar panel produces between 24 and 40 kWh per month (or 800 to 1300 Wh per day) and around 100 W (or 0.1 kW) to 165 W (or 0.16 kW) per hour with a consumption of 8 h per day [47]. The standard warranty for the efficiency (performance) of a solar panel is 25 years, at 80% of the initial performance [48].

The efficiency of photovoltaic modules is influenced by the following factors : their location, longitude, latitude, angle of inclination, the material from which they are made, orientation, temperature of the solar cell, pollution, humidity, solar radiation, dust coverage [49].

The dust deposited on the panel acts as a barrier between the solar radiation and the panel. It does affects photovoltaic panel performance, yield, and profitability. The maximum power of the photovoltaic panel covered with dust was reduced by 8.41% compared to that of the clean solar panel [50]. Covering the panel with dust reduces its power and efficiency.

This reduction in irradiance results in lower energy output and diminished overall performance. In regions with frequent dust storms or arid climates, the impact can be especially severe, leading to efficiency losses ranging from a few percent to over 30%, depending on the type and thickness of the dust layer. Additionally, long-term exposure to abrasive particles can cause physical degradation of the panel surface, further affecting performance and durability. Regular cleaning and maintenance are therefore essential to ensure optimal energy production and prolong the lifespan of solar panels in dusty environments.

Figure II.8. Clean solar panels vs dirty solar panels [51]

Regular cleaning of photovoltaic (PV) panels is essential to maintain their energy efficiency. For this reason, scientists and engineers have paid increasing attention to the development of efficient, automated, and cost-effective cleaning methods. Regular maintenance ensures optimal performance and extends the lifespan of solar installations, especially in dusty or arid regions.

II. Conclusion

This chapter focused on solar energy as a key renewable resource, tracing its historical development and examining the two main types of solar panels : thermal and photovoltaic. Understanding how these technologies work is essential to appreciating their role in modern energy systems. A critical issue affecting their performance ‘‘dust accumulation’’ was also explored, revealing how even small amounts of surface soiling can lead to significant efficiency losses. These insights underscore the importance of maintenance solutions, setting the stage for the next phase of this study: the development of an automatic cleaning system to preserve and enhance solar panel performance.

Chapter III

Solar Photovoltaic Panels Cleaning Methods

III.Introduction

Maintaining the efficiency of solar panels is essential for maximizing their energy output and ensuring long-term performance. One of the key factors affecting solar panel efficiency is the accumulation of dust, dirt, and other particles on their surfaces, which can significantly reduce the amount of sunlight reaching the cells. To address this challenge, various cleaning methods and technologies have been developed to keep solar panels clean and operating at optimal levels.

This chapter explores the different approaches used for cleaning solar panels, ranging from manual techniques to advanced automated systems. Understanding these methods provides a foundation for evaluating their effectiveness, advantages, and limitations, which is crucial for designing efficient maintenance solutions

III.1. PV panels cleaning methodes and systems

Solar panel cleaning systems are designed to remove dirt, dust, and other debris that can accumulate on the surface of solar panels and reduce their efficiency. There are several methods and technologies for cleaning solar panels as discussed in the following sections.

III.1.1. Manual Cleaning with Water and Soft Brushes or Sponges

Manual cleaning is the most traditional and widely used method for maintaining solar panels. It involves rinsing the panels with clean water to remove loose dust and debris, followed by gently scrubbing the surface with a soft brush or sponge. Often, a mild soapy solution or diluted vinegar and hydrogen peroxide blends are used to break down stubborn dirt such as bird droppings or pollen. After scrubbing, the panels are thoroughly rinsed with water to remove any soap residue, which could otherwise attract more dirt or cause shading. The key to this method is using non-abrasive tools and gentle pressure to avoid scratching the delicate glass surface or damaging the protective coatings.

The main advantage of manual cleaning is its low cost and accessibility, making it suitable for small residential systems or occasional maintenance. It allows for targeted cleaning of heavily soiled spots and uses simple materials like garden hoses and soft sponges. However, it is labor-intensive and time-consuming, especially for large installations. Safety is a significant concern when panels are on rooftops, requiring proper equipment and precautions. Additionally, cleaning under direct sunlight or when panels are hot can cause water spots or thermal stress, potentially damaging the panels or leaving streaks that reduce efficiency.

Figure III.1. Manual cleaning with water, brush and soap [52]

III.1.2. Soap-less Cleaning with Deionized Water and Brushes

This method builds on manual cleaning but replaces regular water and soap with deionized (DI) water and specialized rolling or vehicle-mounted brushes. Deionized water is purified to remove minerals and impurities, preventing the formation of mineral deposits or soap films on the panel surface. The brushes gently scrub the panels while DI water lifts grime without leaving residues that could attract further dirt accumulation.

The advantage of this technique is its environmentally friendly nature and its ability to clean without chemical residues, which helps maintain panel transparency and efficiency over time. It is particularly effective for commercial or large-scale solar farms where consistent cleaning is required. However, it demands specialized equipment and access to DI water, which can increase operational costs. This method is less practical for small-scale or residential users due to these requirements.

Figure III.2. Soap-cleaning with deionized water and brushes [53]

III.1.3 Electrostatic Cleaning

Electrostatic cleaning is an innovative and emerging technology that uses electrostatic forces to remove dust from solar panel surfaces without physical contact or water. This method involves applying an electrostatic charge to a transparent sheet or coating on the panel. When a high alternating current (AC) voltage is applied, the electrostatic forces act on dust particles, shaking or repelling them off the surface. This process can be done on dry panels and does not require water or brushes, minimizing wear on the panels.

The main advantage of electrostatic cleaning is its waterless and chemical-free operation, making it ideal for water-scarce regions and reducing maintenance needs. It also avoids mechanical abrasion, preserving the panel’s protective coatings. However, electrostatic cleaning is still largely experimental and not widely commercialized. It requires a power source and technical installation, and its effectiveness can vary depending on the type of dust and environmental conditions.

Figure III.3. Electrostatic Cleaning [54]

III.1.4 Automated Smart Cleaning Solutions

Startups like Dustoss are developing innovative automated cleaning systems that combine sensors, robotics, and smart algorithms to optimize cleaning schedules and methods. These solutions may integrate multiple cleaning techniques, such as brushes, air blowers, or electrostatic systems, and adapt to real-time soiling conditions to maximize efficiency and minimize resource use. While details vary, these smart systems aim to reduce operational costs and improve cleaning effectiveness for large solar installations.

III.1.5 Robotic Cleaning Systems

Robotic solar panel cleaners represent a cutting-edge approach to maintenance. These devices are designed to autonomously or semi-autonomously traverse solar panel arrays, cleaning surfaces with soft microfiber brushes, airflow, or fine water mist. Some robots, such as those deployed in the Middle East by companies like Ecoppia, are solar-powered and operate nightly, cleaning panels without using high-pressure water that could damage the panels. The robots also maintain their own solar panels and recharge between cleaning cycles.

The primary benefit of robotic cleaning is its ability to save labor and time, especially for large-scale solar farms where manual cleaning would be impractical. Robots provide consistent, frequent cleaning that helps maintain peak energy production. They also reduce safety risks by minimizing human access to rooftops or difficult terrain. On the downside, robotic systems require a significant upfront investment and ongoing maintenance. They also need technical expertise for operation and troubleshooting, and their cost-effectiveness diminishes for smaller installations.

Figure III.4. Photovoltaic cleaning robot [55]

III.1.6 Natural Rainwater Cleaning

Rainwater can naturally wash away some of the loose dust and dirt that accumulates on solar panels. When rain falls, it can rinse off particles and reduce the need for manual cleaning. However, rainwater is often insufficient to remove heavier grime, sticky residues, or bird droppings. Moreover, rain can sometimes worsen soiling by causing dirt to accumulate at the bottom edges of panels or by leaving mineral deposits and streaks, especially in areas with hard or polluted rainwater. The cleaning effect of rain also depends heavily on the frequency and intensity of rainfall, making it unreliable in arid or dusty environments.

The advantage of rainwater cleaning is that it requires no additional cost, labor, or equipment, making it an environmentally friendly option. However, its inconsistency and limited effectiveness mean that relying solely on rainwater often results in reduced panel efficiency over time.

III.1.7 Waterless Vibration Cleaning

This technique uses mechanical vibrations to dislodge dust and dirt from the surface of solar panels without the use of water or physical scrubbing. Vibrators or piezoelectric actuators are attached to the panel frames and produce high-frequency vibrations that shake off dust particles. This method minimizes the risk of scratching or damaging the panel surface since it avoids direct contact with brushes or sponges. It is particularly useful in arid regions where water is scarce. However, it requires installation of vibration devices and may consume additional energy. The effectiveness can vary depending on how strongly dust adheres to the surface and the vibration frequency applied.

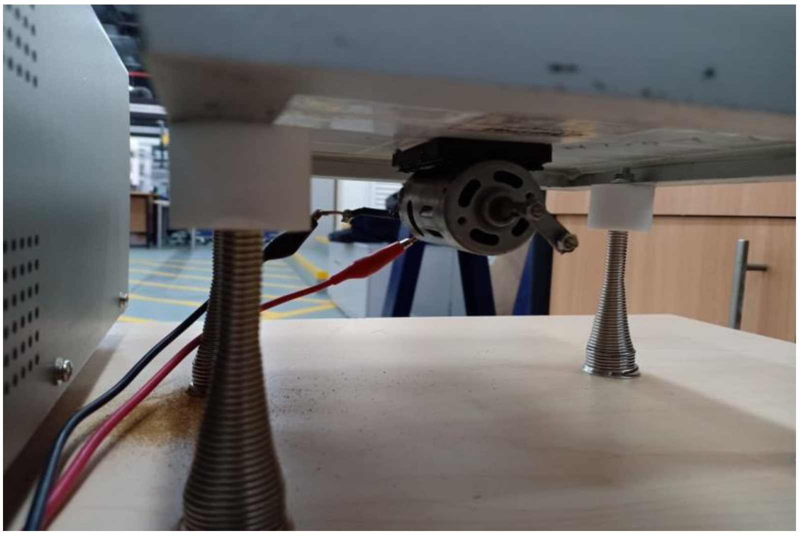


Figure III.5. Vibration tech for self-cleaning solar panels [56]

III.1.8 Nanoparticle Coatings

Special hydrophobic or self-cleaning nanoparticle coatings can be applied to solar panels to reduce dust adhesion and facilitate easier cleaning. These coatings create a surface that repels water and dirt, causing particles to slide off naturally with minimal rain or light cleaning. Some coatings also have photocatalytic properties that break down organic grime under sunlight. The advantage is reduced cleaning frequency and water usage. However, such coatings may degrade over time, require reapplication, and add upfront cost. Their long-term durability and impact on panel efficiency are still under study [57].

III.Conclusion

Each solar panel cleaning method operates on distinct principles, from manual scrubbing and water rinsing to advanced robotic and electrostatic technologies. Manual cleaning remains the most accessible but requires care and safety precautions. Soap-less DI water cleaning offers residue-free results for larger installations. Robotic cleaners automate maintenance but at a higher cost. Natural rainwater provides a free but unreliable cleaning effect, while electrostatic cleaning promises a waterless, low-wear solution still in development. Selecting the appropriate cleaning method depends on factors such as installation size, environmental conditions, budget, and safety considerations. Regular and proper cleaning ensures solar panels perform efficiently and extend their operational lifespan.

Chapter IV

The proposed solution ‘‘CleanRayX’’

IV.1. What is Clean RayX ?

‘‘CleanRayX’’ is an autonomous intelligent cleaning system specifically designed for solar panels exposed to dusty environments, such as those found in Algeria.

IV.2. The goal of the system

The main goal (purpose) is to carry out an automatic cleaning system (device) for solar panels to remove dust to maintain the highest electricity efficiency and effectiveness (high yield). The mechanism moves from the starting point until the end of the cycle then goes back to the initial position while removing dust to make sure the whole surface is clean.

IV.3. Function principle

The system starts cleaning when it detects (spots) enough dust that blocks light from the solar panel cells. A photoresistor is implanted in the solar panel to spot the dust, another one is implanted beside the solar panel to consistantly check on the weather.

The external photoresistor is set as a reference. The internal photoresistor that is implanted inside the solar panel spots the dust whether the top surface is clean or dirty.

A comparison that happens between the two photoresistors will decide when it should start and when to stop (we set a ratio of 10% as a reference that it can be adjusted according to the installation needs, when the difference is greater or equals to 10%, the robot starts cleaning), preserving energy and cost as much as possible while keeping a high yield.

An ultrasonic sensor is implanted on the edge of the solar panel as a limit switch sensor (some sensors can be replaced with another different ones that does the same work as for example the limit switch sensor).

Also a rain sensor so the system doesn’t function in the rain.

IV.4. Components of our system

1. Mechanical Structure
   a) Lightweight chassis (plastic)
   b) Drive wheels with anti-slip coating gears, belts, motor mounts
   c) Locomotion system DC motors
   d) Movement motor drivers (L298N)
2. Cleaning mechanism rotating brushes

3. Sensors
    a) LDR (Light Dependent Resistor), also known as a" photoresistor ", is an electronic component whose electrical resistance changes based on the intensity of light it is exposed to. When the light level is high, its resistance decreases, allowing more current to pass through. Conversely, in darkness or low light, its resistance increases significantly, restricting the flow of current.
    b) Conductive (electrical) rain sensor detects rainfall by measuring changes in electrical conductivity on its surface. It typically consists of a grid or pattern of exposed conductive traces mounted on a non-conductive base. When the surface is dry, there is little or no electrical connection between the traces. However, when raindrops fall on the sensor, the water—being slightly conductive—bridges the gaps between the conductive paths, allowing current to flow. This change in conductivity signals the presence of rain. The sensor then sends this information to a connected system, which can trigger automated responses.
    c) Ultrasonic sensor is a device that measures the distance to an object by using ultrasonic sound waves. It works by emitting a high-frequency sound wave (typically around 40 kHz) from a transmitter. When this wave hits an object, it reflects back to the sensor, and the receiver detects the echo. By calculating the time it takes for the echo to return, the sensor determines the distance to the object using the speed of sound.

4. Control System
    a) ESP32-WROVER (hosts the web interface, controls the robot)
    b) ESP32-CAM (streams live video)
    c) Power supply modules 7.4V systems
    d) Sensors Ultrasonic sensors (detect edges or obstacles)

5. Communication and Interface

Web Interface hosted on ESP32-WROVER Live video streaming via ESP32-CAM Wi-Fi connection (controlled via phone or PC). Software System HTTP server (for the control page) Code to control motors and sensors (Arduino or ESP-IDF) Video stream handler.

IV.5. Assembly diagrams

The figures below shows how the components are related, allowing the system to function according to the desired purpose.

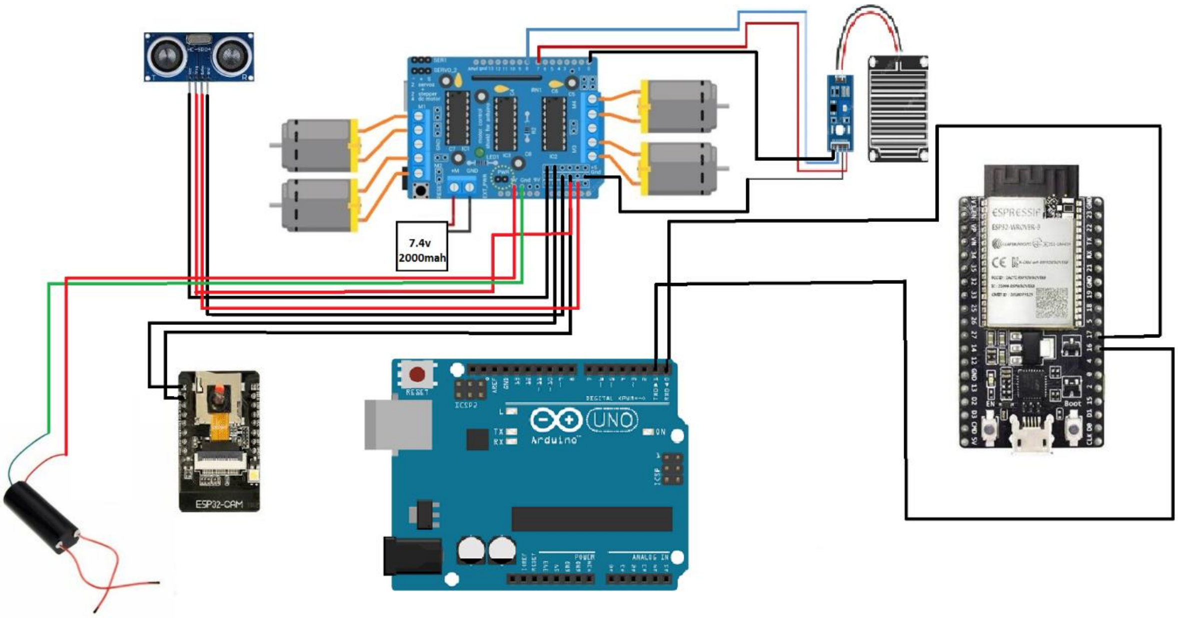


Figure IV.1. assembly diagram for action part

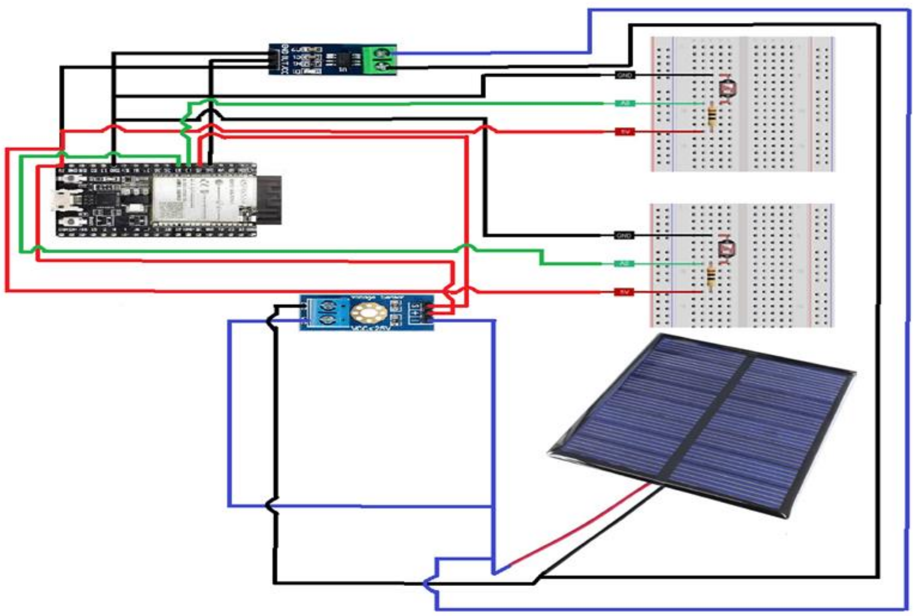


Figure IV.2. assembly diagram for detection part

IV.6. Measurements and Interpretation

To better understand the environmental and functional factors affecting solar energy production, a series of targeted measurements were conducted. These include: (1) the intensity of natural light over several days under varying weather conditions to observe fluctuations in solar exposure; (2) the electrical output (puissance) of a solar panel under those same conditions to assess performance; and (3) specific measurements using a photoresistor integrated into the solar panel setup to monitor light intensity while incrementally applying dust. This last test aims to simulate the impact of environmental dust accumulation on light absorption and energy generation. Together, these measurements provide a comprehensive view of the solar panel’s responsiveness to real-world conditions and external factors that influence its efficiency.

Here’s the mesurements of the intensity of natural light over three days under varying weather conditions

Table IV.1. Light measurements

Time / Day	7 .30 AM	1.30 P.M	4.30 P.M	7.30 P.M	3.30 A.M
Day one(sunny day)	5197.0 lx	100415.0 lx	10130.0 lx	331.0 lx	0.0 lx
Day two(Rainy day)	250.0 lx	9418.0 lx	2318.0 lx	4.0 lx	0.0 lx
Day three(meduim)	2723.0 lx	54916.0 lx	6224.0 lx	167.0 lx	0.0 lx

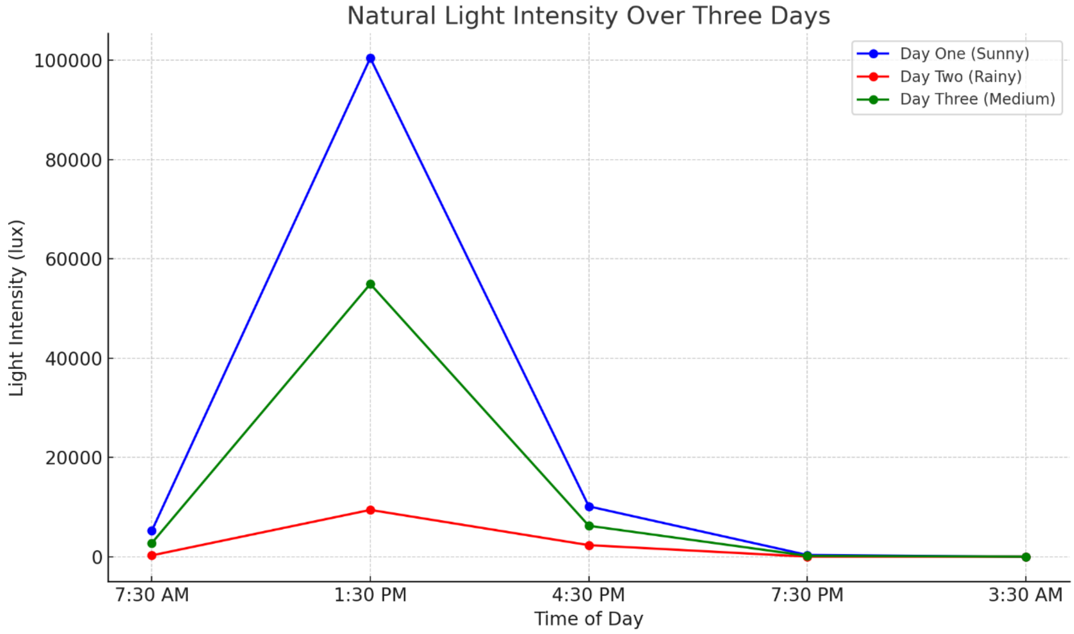


Figure IV.3. Natural Light Intensity Over Three Days

…Interpretation

Day One (Sunny Day)

- **Interpretation:**
  The data shows a typical pattern for a sunny day.
  - At **7:30 AM**, light intensity starts relatively high (5197 lx), indicating early sunlight.
  - By **1:30 PM**, it peaks dramatically at **100,415 lx**, consistent with full midday sun.
  - At **4:30 PM**, it decreases to **10,130 lx**, showing the sun beginning to descend.
  - By **7:30 PM**, the intensity drops significantly to **331 lx**, close to sunset.
  - At **3:30 AM**, there's no sunlight, so the intensity is **0 lx**.

This pattern reflects strong and direct sunlight during most of the day, with a rapid decrease toward the evening.

Day Two (Rainy Day)

- **Interpretation:**
  This day shows the effects of thick cloud cover and rain.
  - Light intensity is very low at **7:30 AM** (**250 lx**) and remains subdued throughout the day.
  - Even at **1:30 PM**, the peak is only **9418 lx**, much lower than the sunny day.
  - The rest of the day follows a similar low-light trend with **2318 lx** at 4:30 PM and only **4 lx** by 7:30 PM.
  - Again, **0 lx** is recorded at night (3:30 AM).

  Overall, the rainy conditions significantly reduce the amount of natural light.

Day Three (Medium Day)

- **Interpretation:**
  This day represents an intermediate scenario, likely partly cloudy.
  - The morning starts with **2723.5 lx**, higher than the rainy day but much lower than the sunny day.
  - The midday value at **1:30 PM** is **54,916.5 lx**, a moderate intensity indicating partial sun coverage.
  - The intensity gradually decreases in the afternoon (**6224 lx at 4:30 PM**) and falls to **167.5 lx** by 7:30 PM.
  - Nighttime measurement is again **0 lx**.

  This day shows fluctuating or diffused sunlight, typical of mixed weather (partially cloudy or hazy skies).

To evaluate the performance of a 5V, 3A solar panel under varying weather conditions, the table below presents the estimated power output at different times of the day across three scenarios : sunny, rainy, and partly cloudy. The calculations assume that maximum power (15W) is reached under full sunlight (100,000 lux), with output scaling linearly according to light intensity. This comparison highlights how environmental factors significantly influence the panel’s energy production throughout the day.

Table IV.2. Power Output a (5V ,3A) Solar panel Over Three Days

Day \ Time	7 .30 AM	1.30 P.M	4.30 P.M	7.30 P.M	3.30 A.M
Day one(sunny day)	0.78 W	15.00 W	1.52 W	0.05W	0.00 W
Day two(Rainy day)	0.04 W	1.41 W	0.35 W	0.00 W	0.0 W
Day three(meduim)	0.41 W	8.24 W	0.93 W	0.03 W	0.0 W

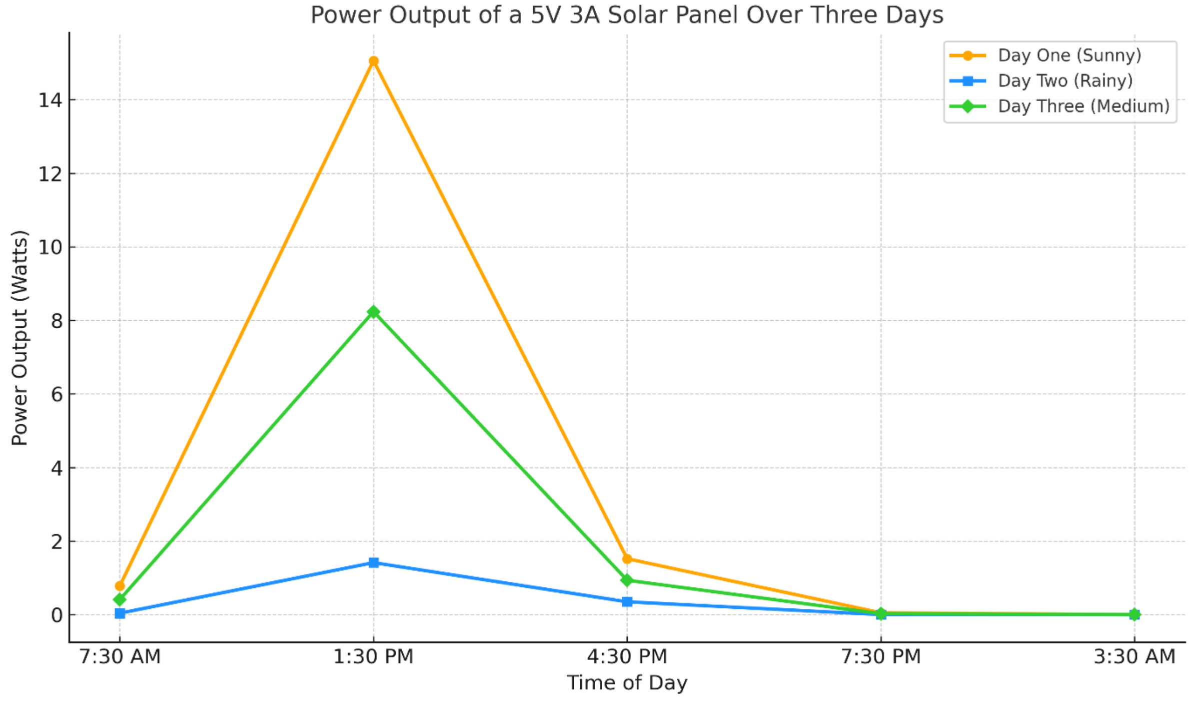


Figure IV.4. Power Output a (5V ,3A) Solar panel Over Three Days

🌞 Day One (Sunny Day) :

- The curve rises steeply and reaches its **maximum output (15W)** around **1:30 PM**, which corresponds to peak sunlight.
- Power output is **moderate at 7:30 AM (0.78W)** and still **significant at 4:30 PM (1.52W)**.
- It drops sharply in the evening (**0.05W at 7:30 PM**) and is **zero at night**.

- **Interpretation :** The panel works at full efficiency under direct sunlight. This day represents **ideal solar conditions** for energy harvesting.

 Day Two (Rainy Day) :

- The entire curve stays **very low**, peaking at just **1.41W at 1:30 PM**.
- In the morning and evening, power drops to **almost zero (0.04W or less)**.
- **Interpretation :** The solar panel performs **poorly under cloudy or rainy conditions**, making it unreliable for power-demanding applications during such weather.

⛅ **Day Three (Medium/Partly Cloudy) :**

- This curve lies **between the sunny and rainy day** curves.
- It reaches a moderate peak of **8.24W at 1:30 PM** and produces **some usable power** in the morning (**0.41W**) and afternoon (**0.93W**).
- Power also drops in the evening (**0.03W at 7:30 PM**) and is **zero at night**.
- **Interpretation :** This represents a **partially effective day** for solar energy. It could support small loads or charge batteries over time but not at full capacity.

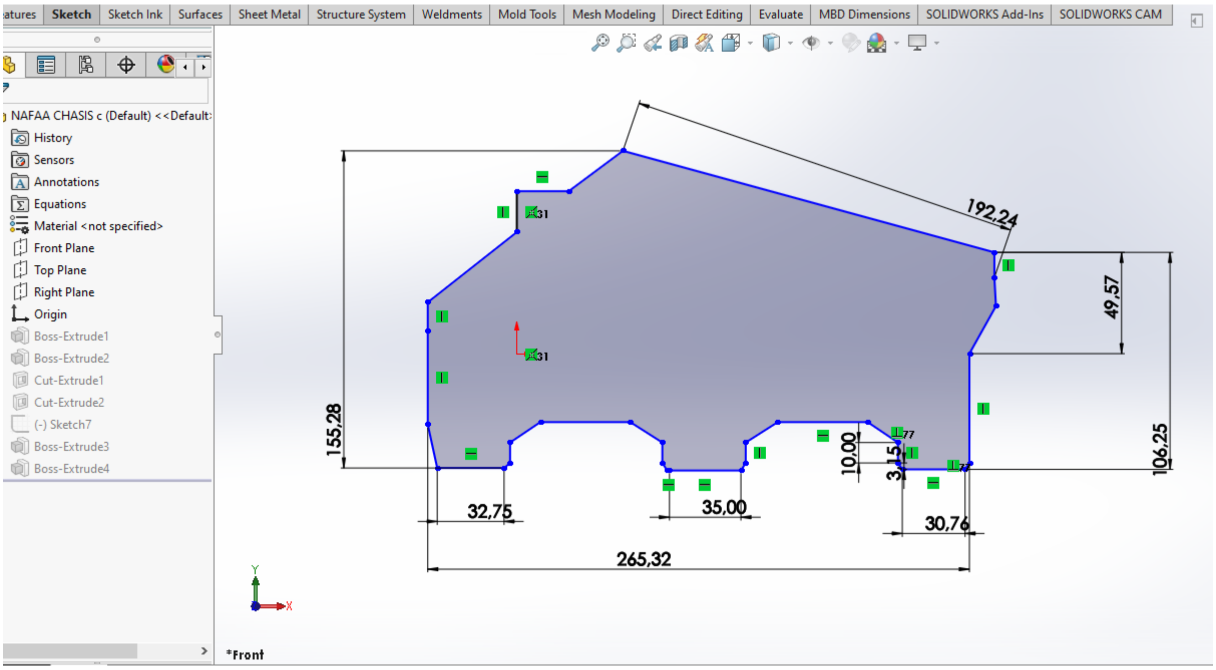
Overall Insight :

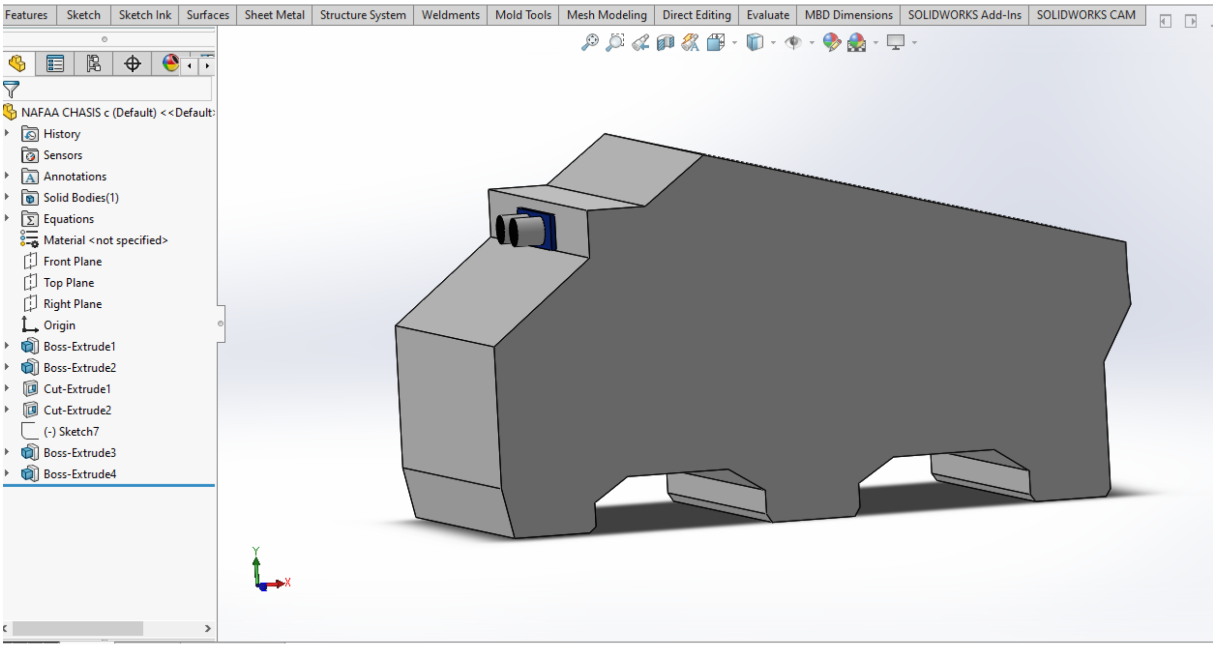
- **Maximum efficiency** is highly dependent on **sunlight intensity**, which follows a clear daily pattern.
- To ensure **reliable power**, a system should include **energy storage** (like batteries) or a **hybrid power source**, especially for use on cloudy or rainy days.

IV.7. Conception and design

SOLIDWORKS CONCEPTION

The following figures illustrate the mechanical components of the robot, designed using solidworks. These parts represent the structural foundation and the elements of the system.





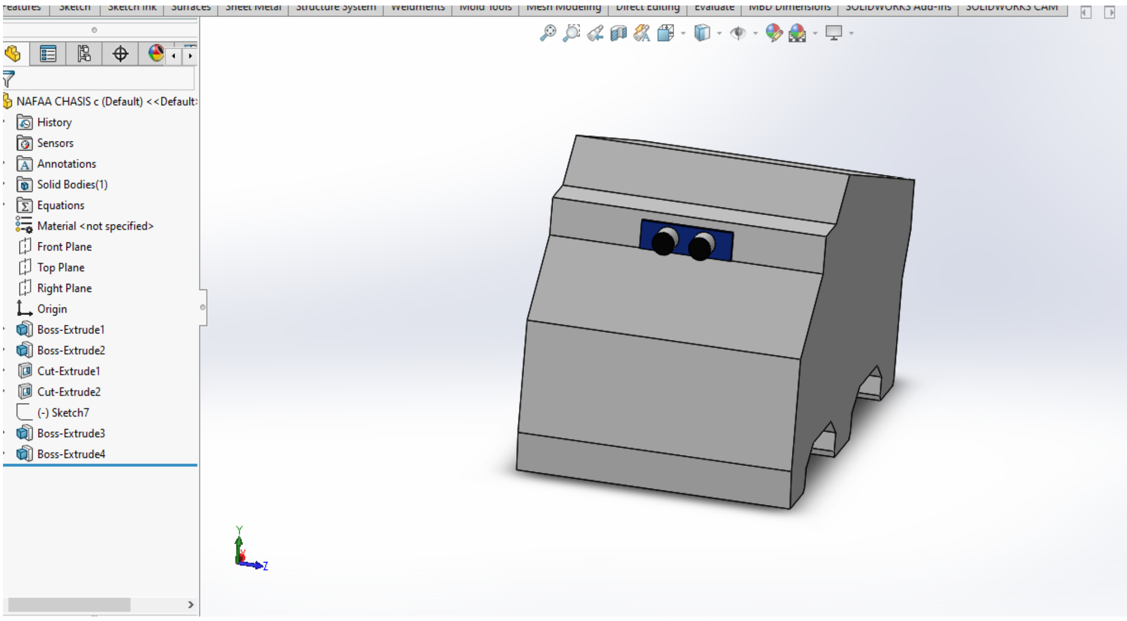


Figure IV.5. CleanRayX body « printed by 3D printer PLA »

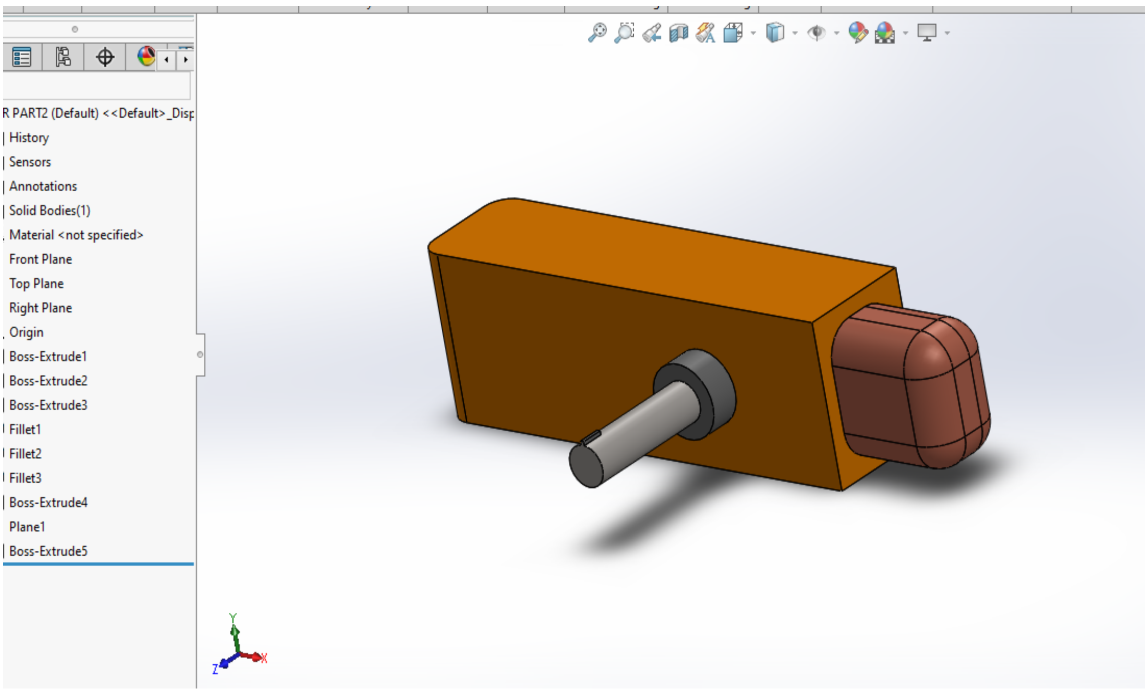
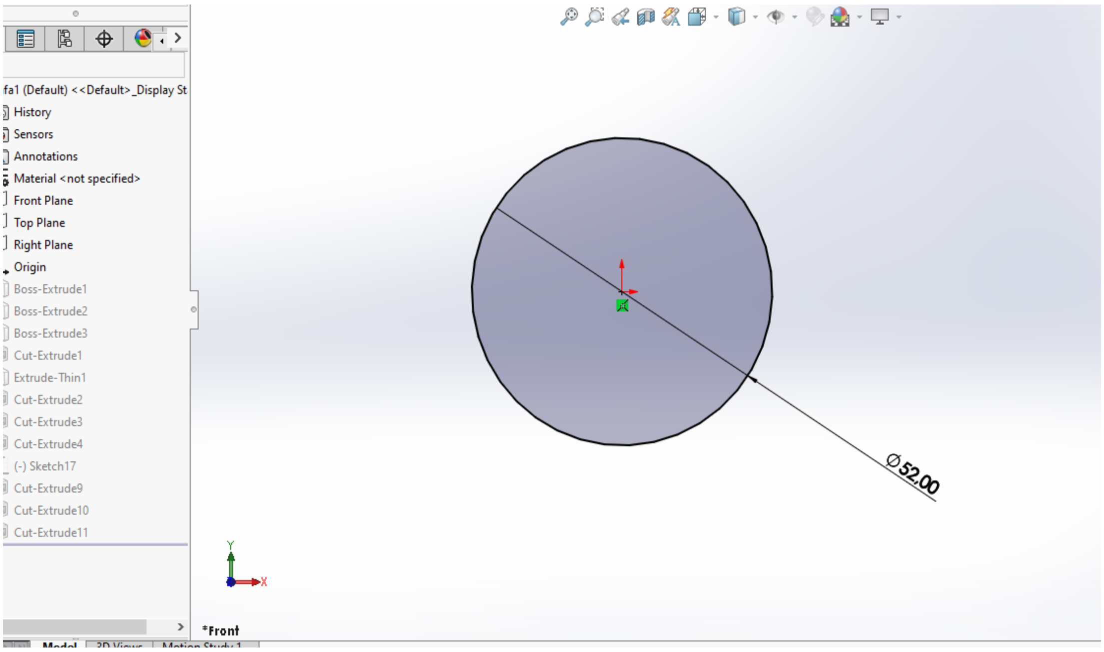
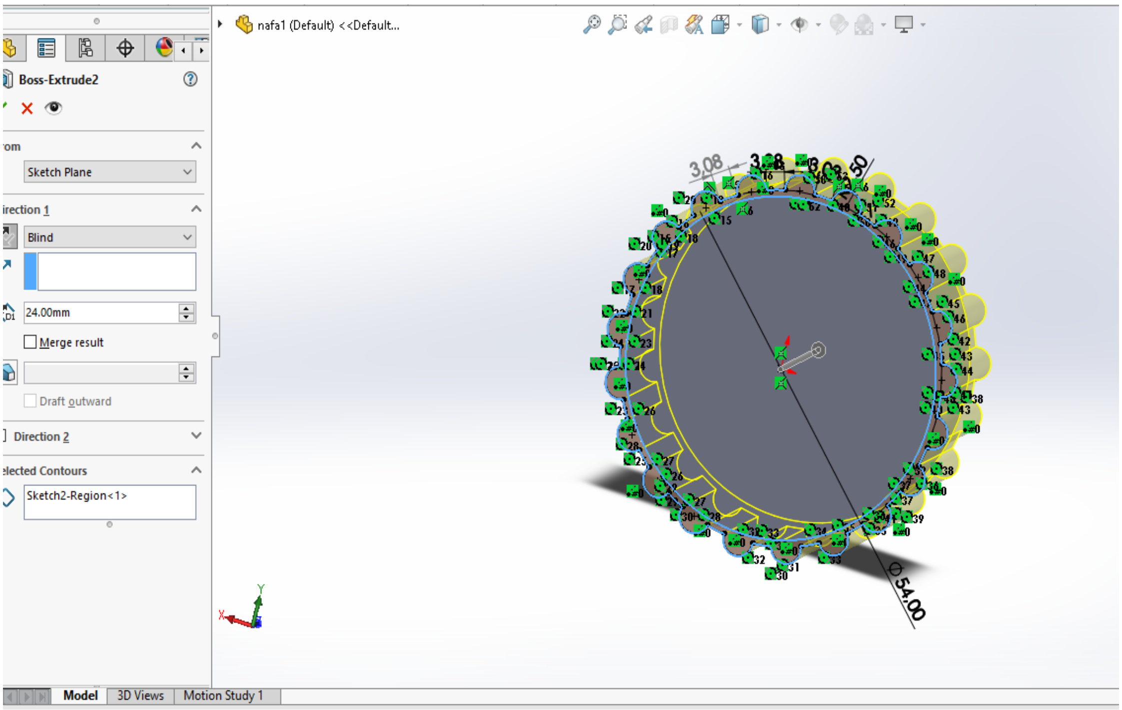


Figure IV.6. DC motors


History
Sensors
Annotations
Material <not specified>
Front Plane
Top Plane
Right Plane
Origin
Boss-Extrude1
Boss-Extrude2
Boss-Extrude3
Cut-Extrude1
Extrude-Thin1
Cut-Extrude2
Cut-Extrude3
Cut-Extrude4
(-) Sketch17
Cut-Extrude9
Cut-Extrude10
Cut-Extrude11
Ø52.00
*Front


nafa1 (Default) <<Default...
Boss-Extrude2
Sketch Plane
Blind
24.00mm
Merge result
Draft outward
Direction 2
Sketch2-Region<1>
Ø54.00
Model
3D Views
Motion Study 1

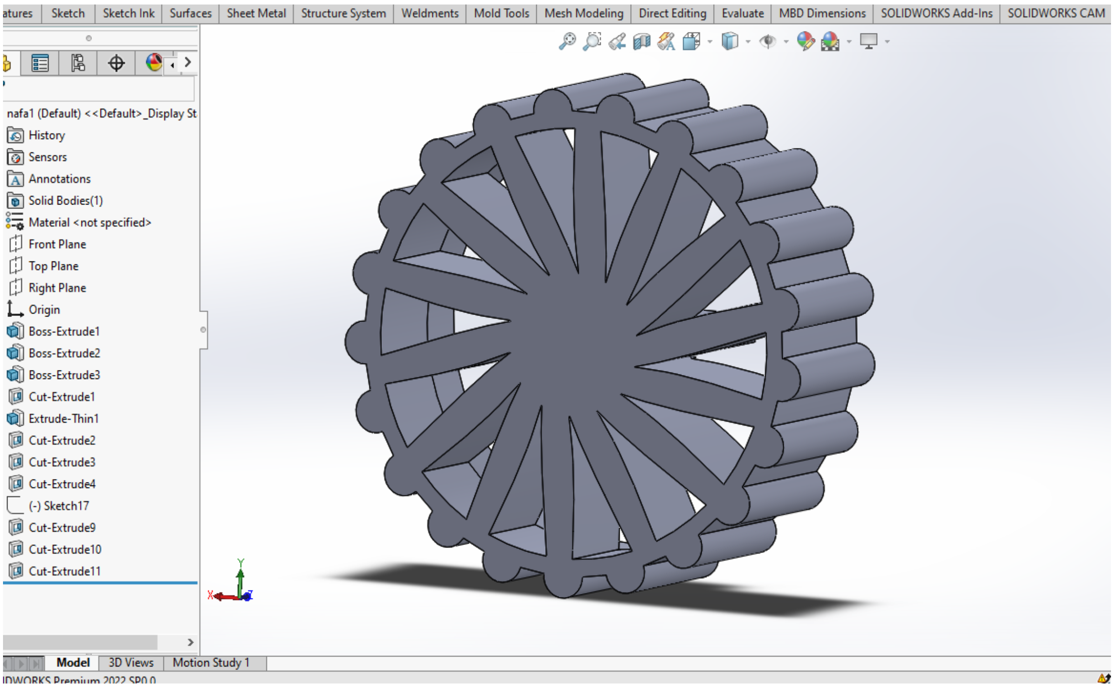


Figure IV.7. wheel of CleanRayX ‘printed with 3D printer resin’

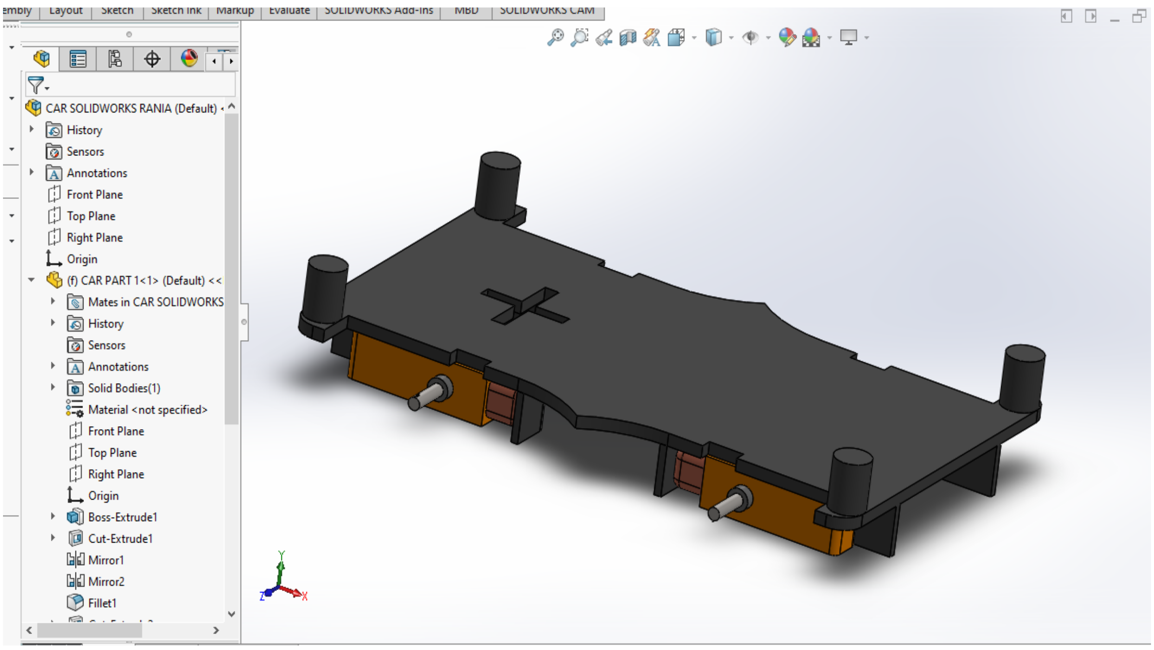


Figure IV.8. Assembly of Chassis and DC motors of CleanRayX

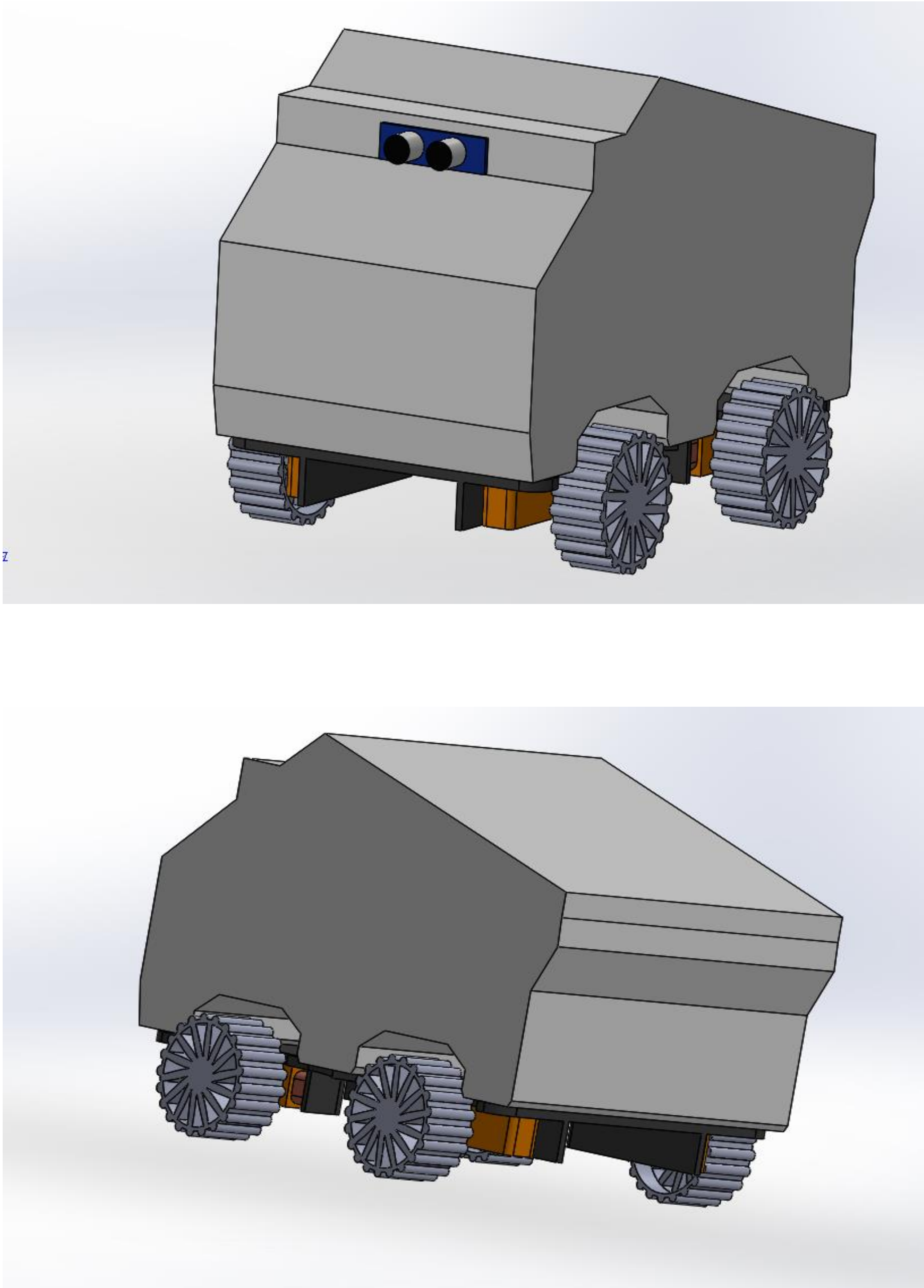


Figure IV.9. Assembled view of the robot’s mechanical compnents

The following figures show the final prototype produced, it also shows the streaming option for surveillance.

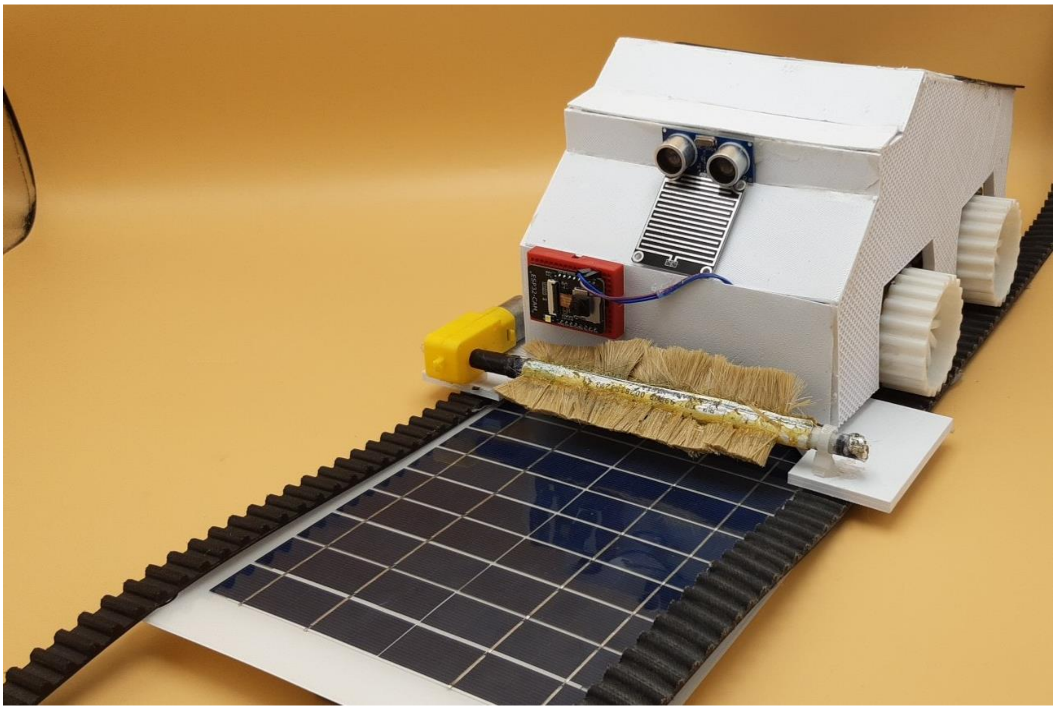


Figure IV.10. Prototype Clean Ray X

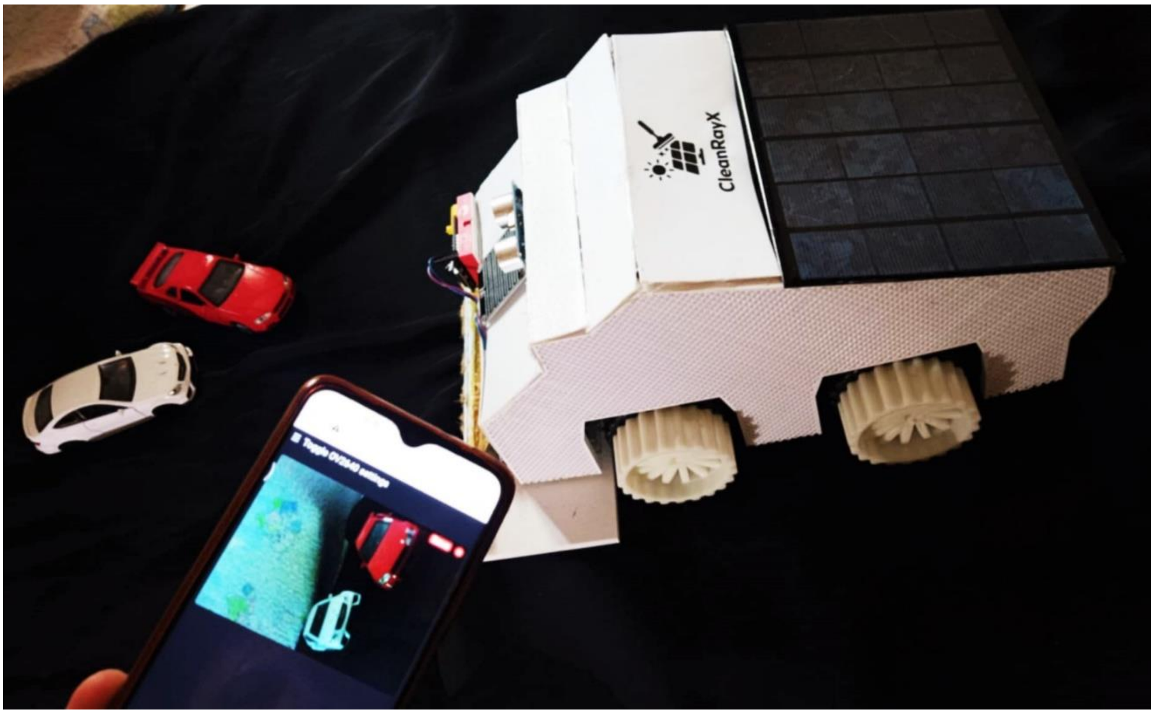


Figure IV.11. Prototype "Clean Ray X" streaming

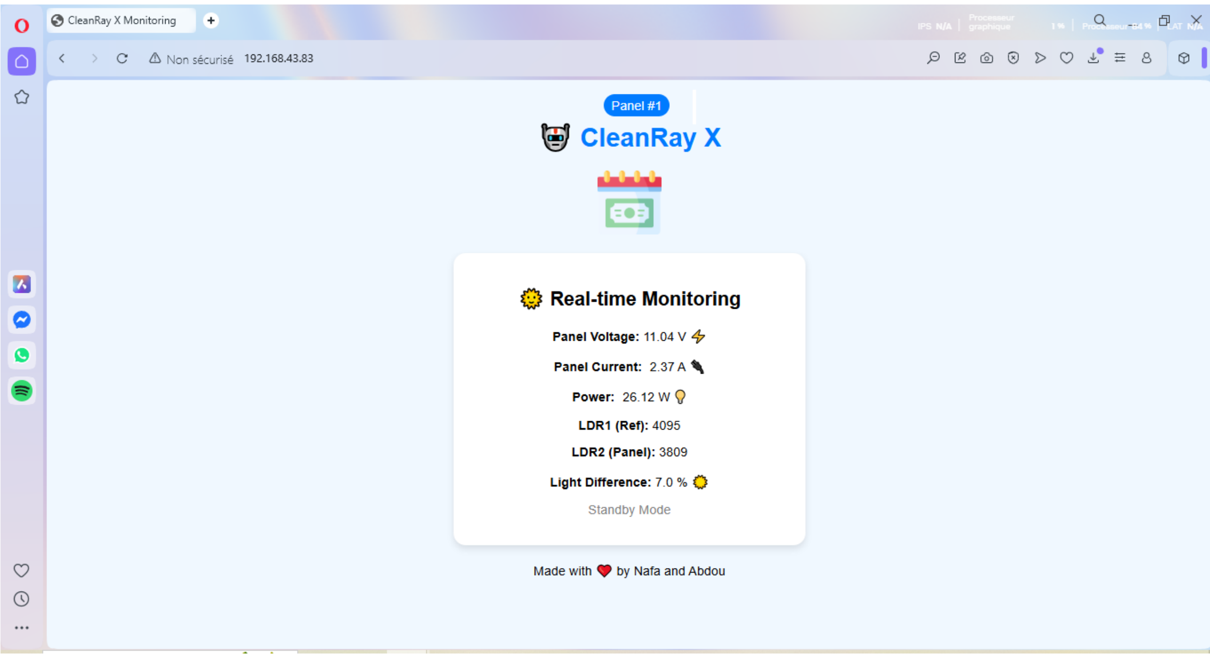


Figure IV.12. Cleaning system’s web interface « standby mode »

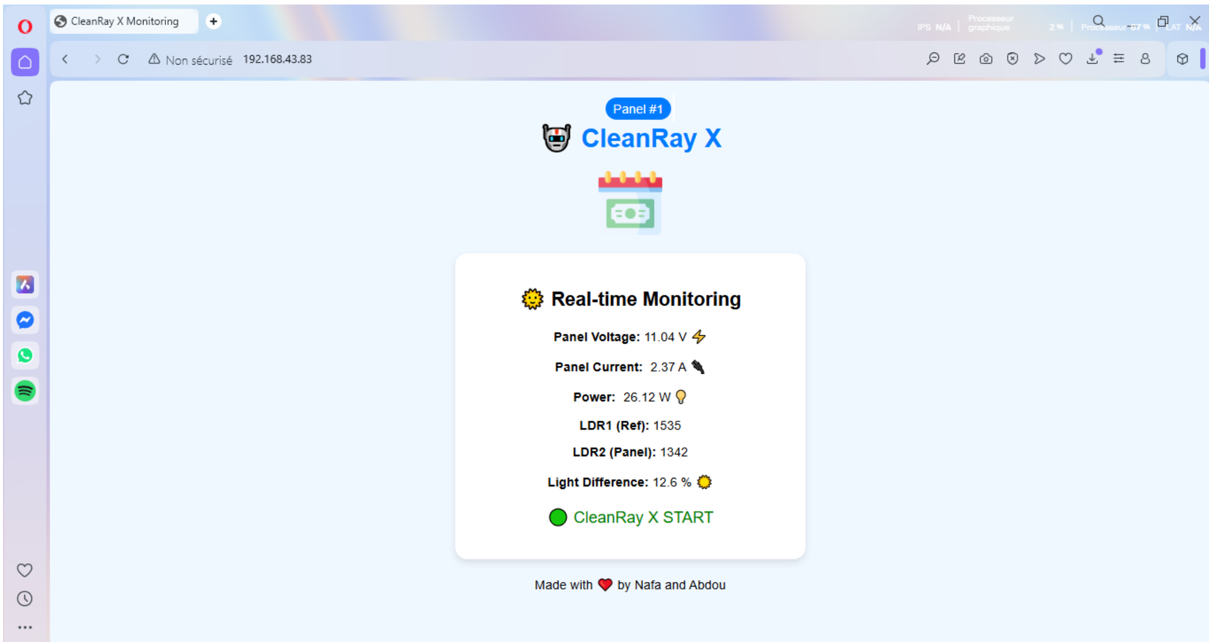


Figure IV.13. Cleaning system’s web interface « operational mode »

Conclusion

In this chapter, we presented the design, structure, and operation of CleanRayX, an autonomous intelligent system aimed at addressing the efficiency losses of solar panels caused by dust accumulation. By integrating sensors (LDR, ultrasonic, rain sensor), ESP32 microcontrollers, and a mechanical cleaning system, CleanRayX can automatically detect when cleaning is needed and respond accordingly without human intervention.

We detailed the system's components, explained its control logic, and validated its performance through real-world measurements of light intensity and power output under varying weather conditions. These tests confirmed the significant impact of dust on solar panel efficiency and the relevance of automated maintenance solutions.

Ultimately, CleanRayX demonstrates a practical and scalable approach to enhancing the sustainability of solar energy, especially in dust-prone environments. This solution lays the groundwork for further innovation and offers a meaningful step toward more efficient and autonomous renewable energy systems.

Appendix A

CODING

```
#include <AFMotor.h>
#include <NewPing.h>

// Définition des broches
#define TRIG_PIN A3       // Ultrason Trig
#define ECHO_PIN A4       // Ultrason Echo
#define RAIN_SENSOR 8     // Capteur de pluie digital (D0 connecté à
D8)
#define MAX_DISTANCE 15   // Distance d'arrêt en cm
#define MOTOR_SPEED 150   // Vitesse des moteurs (0-255)

NewPing sonar(TRIG_PIN, ECHO_PIN, MAX_DISTANCE);

AF_DCMotor motor1(1, MOTOR12_1KHZ);
AF_DCMotor motor2(2, MOTOR12_1KHZ);
AF_DCMotor motor3(3, MOTOR34_1KHZ);
AF_DCMotor motor4(4, MOTOR34_1KHZ);

void setup() {
  pinMode(RAIN_SENSOR, INPUT);
  // Initialiser tous les moteurs
  motor1.setSpeed(MOTOR_SPEED);
  motor2.setSpeed(MOTOR_SPEED);
  motor3.setSpeed(MOTOR_SPEED);
  motor4.setSpeed(MOTOR_SPEED);
}

void loop() {
  // Vérifier s'il pleut (LOW = pluie détectée)
  if (digitalRead(RAIN_SENSOR) == HIGH) { // Pas de pluie
    // Mesurer la distance
    unsigned int distance = sonar.ping_cm();

    if (distance == 0) {
      // Si aucune mesure valide (distance trop grande), avancer
      moveForward();
    } else if (distance <= MAX_DISTANCE) {
      // Obstacle détecté à <= 15 cm
      moveStop();
      delay(1000); // Attendre 1 seconde
    } else {
      // Pas d'obstacle proche, avancer
      moveForward();
    }
  } else {
    // Il pleut - arrêter le robot
```

```
    moveStop();
  }
  delay(50); // Petit délai entre les mesures
}

void moveForward() {
  motor1.run(FORWARD);
  motor2.run(FORWARD);
  motor3.run(FORWARD);
  motor4.run(FORWARD);
}

void moveStop() {
  motor1.run(RELEASE);
  motor2.run(RELEASE);
  motor3.run(RELEASE);
  motor4.run(RELEASE);
}
```

Sensors ………..

```
#include <WiFi.h>
#include <WebServer.h>

// WiFi credentials
const char* ssid = "D-Link244";
const char* password = "28101975";

// Analog input pins
const int pinCurrent = 34;    // ACS712
const int pinVoltage = 35;    // Voltage sensor
const int pinLDR1 = 32;       // Reference LDR
const int pinLDR2 = 33;       // Panel LDR

// Constants
const float referenceVoltage = 3.3;
const int analogMax = 4095;
const float VrefACS = 2.5;    // ACS712 rest voltage
const float Sensitivity = 0.185; // Sensitivity for ACS712 5A

WebServer server(80);

// Function to generate HTML content
String pageHTML() {
  int rawCurrent = analogRead(pinCurrent);
  int rawVoltage = analogRead(pinVoltage);
  int rawLDR1 = analogRead(pinLDR1);
  int rawLDR2 = analogRead(pinLDR2);

  float voltageSensor = (rawVoltage * referenceVoltage) / analogMax;
```

```
  float panelVoltage = voltageSensor * (25.0 /
referenceVoltage);  // Adjust based on divider

  float sensorVoltage = (rawCurrent * referenceVoltage) / analogMax;
  float current = (sensorVoltage - VrefACS) / Sensitivity;

  float ldrPercent = ((float)(rawLDR1 - rawLDR2) / rawLDR1) * 100.0;

  float powerVA = panelVoltage * current;

  String statusMsg = (ldrPercent >= 10.0) ? "<p style='color:green;
font-size:20px;'>▯ CleanRay X START</p>" : "<p
style='color:gray;'>Standby Mode</p>";

  String html = "<!DOCTYPE html><html><head><meta charset='UTF-8'>";
  html += "<meta name='viewport' content='width=device-width,
initial-scale=1.0'>";
  html += "<meta http-equiv='refresh' content='3'>";
  html += "<title>CleanRay X Monitoring</title>";
  html += "<style>";
  html += "body { font-family: Arial; background-color: #f0f8ff;
text-align: center; padding: 20px; }";
  html += "h1 { color: #007BFF; }";
  html += ".card { background: white; border-radius: 15px; padding:
20px; margin: 10px auto; width: 90%; max-width: 400px; box-shadow: 0
4px 8px rgba(0,0,0,0.1); }";
  html += "img { width: 80px; margin-bottom: 10px; }";
  html += "</style></head><body>";

  html += "<h1>▯ CleanRay X</h1>";
  html += "<img src='https://cdn-icons-
png.flaticon.com/512/4285/4285640.png' alt='robot sticker'>";

  html += "<div class='card'><h2>🌣 Real-time Monitoring</h2>";
  html += "<p><strong>Panel Voltage:</strong> " +
String(panelVoltage, 2) + " V ⚡</p>";
  html += "<p><strong>Panel Current:</strong> " + String(current, 2)
+ " A 🔌</p>";
  html += "<p><strong>Power:</strong> " + String(powerVA, 2) + " VA
💡</p>";
  html += "<p><strong>LDR1 (Ref):</strong> " + String(rawLDR1) +
"</p>";
  html += "<p><strong>LDR2 (Panel):</strong> " + String(rawLDR2) +
"</p>";
  html += "<p><strong>Light Difference:</strong> " +
String(ldrPercent, 1) + " % ☀</p>";
  html += statusMsg;
  html += "</div>";
```

```
  html += "<footer style='margin-top:20px;'>Made with ☒ by Nafa and
Abdou</footer>";
  html += "</body></html>";

  return html;
}

void setup() {
  Serial.begin(115200);
  WiFi.begin(ssid, password);
  Serial.print("Connecting to WiFi");
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("\nConnected!");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());

  server.on("/", []() {
    server.send(200, "text/html", pageHTML());
  });

  server.begin();
}

void loop() {
  server.handleClient();
}



#include <WiFi.h>
#include <WebServer.h>

const char* ssid = "D-Link244";
const char* password = "28101975";

WebServer server(80);

void handleRoot() {
  String html = "<html><body>"
                "<h1>Contrôle Moteur</h1>"
                "<a href=\"/start\"><button>Démarrer</button></a>"
                "<a href=\"/stop\"><button>Arrêter</button></a>"
                "</body></html>";
  server.send(200, "text/html", html);
}
```

```
void handleStart() {
  Serial2.println("start"); // Envoi via UART2
  Serial.println("Commande START envoyée");
  server.send(200, "text/plain", "START envoyé");
}

void handleStop() {
  Serial2.println("stop"); // Envoi via UART2
  Serial.println("Commande STOP envoyée");
  server.send(200, "text/plain", "STOP envoyé");
}

void setup() {
  Serial.begin(115200);
  Serial2.begin(9600, SERIAL_8N1, 16, 17); // UART2 (RX=16, TX=17)

  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  Serial.println("\nWiFi connecté");
  Serial.print("IP: ");
  Serial.println(WiFi.localIP());

  server.on("/", handleRoot);
  server.on("/start", handleStart);
  server.on("/stop", handleStop);
  server.begin();
}

void loop() {
  server.handleClient();

  // Vérification périodique de la connexion
  static unsigned long lastCheck = 0;
  if (millis() - lastCheck > 10000) {
    if (WiFi.status() != WL_CONNECTED) {
      WiFi.reconnect();
    }
    lastCheck = millis();
  }
}
```

```
#include <AFMotor.h>
#include <NewPing.h>

// Définition des broches
#define TRIG_PIN A3       // Ultrason Trig
#define ECHO_PIN A4       // Ultrason Echo
#define RAIN_SENSOR 8     // Capteur de pluie digital (D0 connecté à
D8)
#define MAX_DISTANCE 15   // Distance d'arrêt en cm
#define MOTOR_SPEED 150   // Vitesse des moteurs (0-255)

NewPing sonar(TRIG_PIN, ECHO_PIN, MAX_DISTANCE);

AF_DCMotor motor1(1, MOTOR12_1KHZ);
AF_DCMotor motor2(2, MOTOR12_1KHZ);
AF_DCMotor motor3(3, MOTOR34_1KHZ);
AF_DCMotor motor4(4, MOTOR34_1KHZ);

void setup() {
  pinMode(RAIN_SENSOR, INPUT);
  // Initialiser tous les moteurs
  motor1.setSpeed(MOTOR_SPEED);
  motor2.setSpeed(MOTOR_SPEED);
  motor3.setSpeed(MOTOR_SPEED);
  motor4.setSpeed(MOTOR_SPEED);
}

void loop() {
  // Vérifier s'il pleut (LOW = pluie détectée)
  if (digitalRead(RAIN_SENSOR) == HIGH) { // Pas de pluie
    // Mesurer la distance
    unsigned int distance = sonar.ping_cm();

    if (distance == 0) {
      // Si aucune mesure valide (distance trop grande), avancer
      moveForward();
    } else if (distance <= MAX_DISTANCE) {
      // Obstacle détecté à <= 15 cm
      moveStop();
      delay(1000); // Attendre 1 seconde
    } else {
      // Pas d'obstacle proche, avancer
      moveForward();
    }
  } else {
    // Il pleut - arrêter le robot
    moveStop();
  }
  delay(50); // Petit délai entre les mesures
```

```
}

void moveForward() {
  motor1.run(FORWARD);
  motor2.run(FORWARD);
  motor3.run(FORWARD);
  motor4.run(FORWARD);
}

void moveStop() {
  motor1.run(RELEASE);
  motor2.run(RELEASE);
  motor3.run(RELEASE);
  motor4.run(RELEASE);
}
```

Sensors ....

```
#include <WiFi.h>
#include <WebServer.h>

// WiFi credentials
const char* ssid = "D-Link244";
const char* password = "28101975";

// Analog input pins
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const int pinVoltage = 35;    // Voltage sensor
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const int pinLDR2 = 33;       // Panel LDR

// Constants
const float referenceVoltage = 3.3;
const int analogMax = 4095;
const float VrefACS = 2.5;    // ACS712 rest voltage
const float Sensitivity = 0.185; // Sensitivity for ACS712 5A

WebServer server(80);

// Function to generate HTML content
String pageHTML() {
  int rawCurrent = analogRead(pinCurrent);
  int rawVoltage = analogRead(pinVoltage);
  int rawLDR1 = analogRead(pinLDR1);
  int rawLDR2 = analogRead(pinLDR2);

  float voltageSensor = (rawVoltage * referenceVoltage) / analogMax;
  float panelVoltage = voltageSensor * (25.0 / referenceVoltage);
 // Adjust based on divider
```

```
  float sensorVoltage = (rawCurrent * referenceVoltage) / analogMax;
  float current = (sensorVoltage - VrefACS) / Sensitivity;

  float ldrPercent = ((float)(rawLDR1 - rawLDR2) / rawLDR1) * 100.0;

  float powerVA = panelVoltage * current;

  String statusMsg = (ldrPercent >= 10.0) ? "<p style='color:green;
font-size:20px;'>□ CleanRay X START</p>" : "<p
style='color:gray;'>Standby Mode</p>";

  String html = "<!DOCTYPE html><html><head><meta charset='UTF-8'>";
  html += "<meta name='viewport' content='width=device-width,
initial-scale=1.0'>";
  html += "<meta http-equiv='refresh' content='3'>";
  html += "<title>CleanRay X Monitoring</title>";
  html += "<style>";
  html += "body { font-family: Arial; background-color: #f0f8ff;
text-align: center; padding: 20px; }";
  html += "h1 { color: #007BFF; }";
  html += ".card { background: white; border-radius: 15px; padding:
20px; margin: 10px auto; width: 90%; max-width: 400px; box-shadow: 0
4px 8px rgba(0,0,0,0.1); }";
  html += "img { width: 80px; margin-bottom: 10px; }";
  html += "</style></head><body>";

  html += "<h1>□ CleanRay X</h1>";
  html += "<img src='https://cdn-icons-
png.flaticon.com/512/4285/4285640.png' alt='robot sticker'>";

  html += "<div class='card'><h2>□ Real-time Monitoring</h2>";
  html += "<p><strong>Panel Voltage:</strong> " +
String(panelVoltage, 2) + " V ⚡</p>";
  html += "<p><strong>Panel Current:</strong> " + String(current, 2)
+ " A □</p>";
  html += "<p><strong>Power:</strong> " + String(powerVA, 2) + " VA
□</p>";
  html += "<p><strong>LDR1 (Ref):</strong> " + String(rawLDR1) +
"</p>";
  html += "<p><strong>LDR2 (Panel):</strong> " + String(rawLDR2) +
"</p>";
  html += "<p><strong>Light Difference:</strong> " +
String(ldrPercent, 1) + " % ☀</p>";
  html += statusMsg;
  html += "</div>";

  html += "<footer style='margin-top:20px;'>Made with ☒</footer>";
  html += "</body></html>";
```

```
  return html;
}

void setup() {
  Serial.begin(115200);
  WiFi.begin(ssid, password);
  Serial.print("Connecting to WiFi");
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("\nConnected!");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());

  server.on("/", []() {
    server.send(200, "text/html", pageHTML());
  });

  server.begin();
}

void loop() {
  server.handleClient();
}
```

```
#include <WiFi.h>
#include <WebServer.h>

const char* ssid = "D-Link244";
const char* password = "28101975";

WebServer server(80);

void handleRoot() {
  String html = "<html><body>"
                "<h1>Contrôle Moteur</h1>"
                "<a href=\"/start\"><button>Démarrer</button></a>"
                "<a href=\"/stop\"><button>Arrêter</button></a>"
                "</body></html>";
  server.send(200, "text/html", html);
}

void handleStart() {
  Serial2.println("start"); // Envoi via UART2
  Serial.println("Commande START envoyée");
```

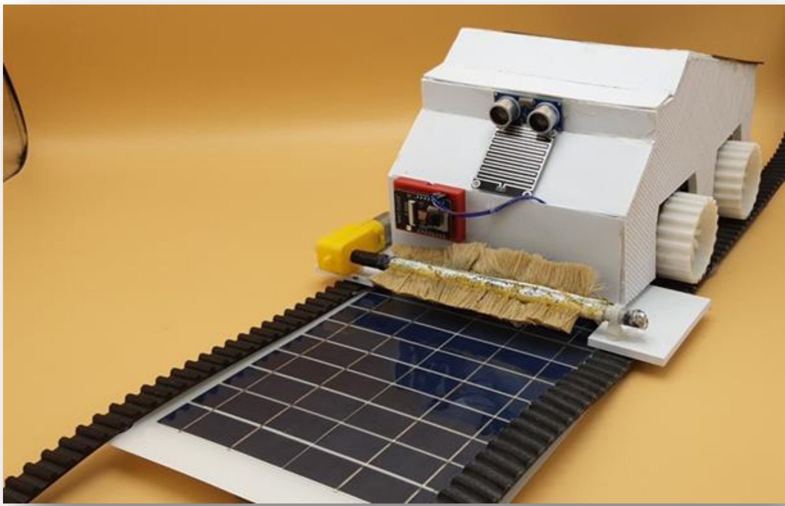
```
  server.send(200, "text/plain", "START envoyé");
}

void handleStop() {
  Serial2.println("stop"); // Envoi via UART2
  Serial.println("Commande STOP envoyée");
  server.send(200, "text/plain", "STOP envoyé");
}

void setup() {
  Serial.begin(115200);
  Serial2.begin(9600, SERIAL_8N1, 16, 17); // UART2 (RX=16, TX=17)

  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  Serial.println("\nWiFi connecté");
  Serial.print("IP: ");
  Serial.println(WiFi.localIP());

  server.on("/", handleRoot);
  server.on("/start", handleStart);
  server.on("/stop", handleStop);
  server.begin();
}

void loop() {
  server.handleClient();

  // Vérification périodique de la connexion
  static unsigned long lastCheck = 0;
  if (millis() - lastCheck > 10000) {
    if (WiFi.status() != WL_CONNECTED) {
      WiFi.reconnect();
    }
    lastCheck = millis();
  }
}
```

Appendix B

CleanRayX – Appendix

1. Project Idea (Solution)

In the heart of Algeria, there was a solar energy managers, who faced daily challenges in maintaining the efficiency of his photovoltaic panels. Due to the harsh desert climate, dust and dirt accumulate rapidly on the panels, significantly reducing their energy output. They spent long hours cleaning the panels manually, which not only affected his productivity but also increased operational costs.



This is where the role of the "CleanRayX" project comes ina revolutionary and automated system designed to clean photovoltaic panels efficiently. CleanRayX is an integrated solution aimed at solving the challenges of panel maintenance in regions with high dust accumulation, like Algeria.

The idea has evolved into an intelligent cleaning system equipped with sensors and a mobile structure that automatically detects and cleans the panels. The system uses a combination of brushes and a motor-driven mechanism to ensure that dust and dirt are effectively removed without damaging the panels. Moreover, CleanRayX is designed to be self controlled, also the important informations are displayed via a smartphone or computer, offering flexibility and convenience for users.

Thanks to this project, the efficiency of solar panels will be restored, leading to higher energy production and, consequently, lower maintenance costs. This solution will contribute to the growth of the renewable energy sector in Algeria and improve the overall sustainability of solar energy operations.

2. Value Propositions – CleanRayX

1. Modernity

CleanRayX represents the integration of modern technology into the renewable energy sector. Designed to meet the challenges of solar installations in arid regions, this intelligent system leverages automation and connectivity to deliver efficient, hands-free panel cleaning.

2. Addressing New Needs

In regions where dust accumulation is frequent and intense, CleanRayX meets a growing need : maintaining high photovoltaic efficiency without manual labor. It offers a simple, innovative, and automated solution to keep solar panels performing at their best.

3. Performance

Equipped with smart sensors, precision motors, and specially designed cleaning brushes, CleanRayX ensures the rough and safe cleaning. It helps maintain the maximum energy output of solar installations over time.

4. Adaptability

CleanRayX is built to adapt to various types of solar panels, whether ground-mounted or rooftop. Its modular structure allows it to operate in different settings and configurations, based on the user's specific needs.

5. Precision and Speed

Thanks to its motorized mechanism and control algorithms, CleanRay X performs fast, accurate, and consistent cleaning. It significantly reduces maintenance time while ensuring high efficiency.

6. Design

The system features a compact and functional design that integrates seamlessly into existing solar installations. It is robust, visually appealing, and easy to install.

7. Cost Reduction

The system helps save significantly on labor and maintenance expenses. It minimizes water usage (if humidification is used) and extends panel lifespan through gentle, regular cleaning.

8. Compatibility with Various Environments

CleanRayX can operate in diverse environmental and climate conditions. It is suitable for agricultural, industrial, or residential solar installations, regardless of size.

9. Ease of Use

With an intuitive user interface accessible via smartphone or computer, CleanRayX is easy to operate even for non-technical users. Its plug-and-play nature ensures simple and quick deployment.

3. Business Objectives

1. Increased Energy Productivity

Maximize the energy output of solar panels by ensuring regular, efficient, and automated cleaning, maintaining optimal performance levels over time.

2. Environmental Sustainability

Reduce the use of natural resources, especially water, and improve energy efficiency through an eco-friendly cleaning system designed for long-term sustainability.

3. Improved Profitability

Deliver a clear return on investment by increasing solar energy production and significantly lowering long-term maintenance costs.

4. Enhanced Competitiveness

Provide a cutting-edge solution that boosts energy performance and positions users at the forefront of the clean energy transition.

4. Market Share Strategy

1. Short-Term Goal

Target key market segments with immediate needs for automated panel cleaning :Public institutions, Large private photovoltaic installations, Individual homeowners with rooftop solar panels.

Objective : capture approximately 20% of this segment in Algeria.

2. Medium-Term Goal

Expand geographic coverage and strengthen distribution networks to increase the market share to 40% within the next five years.

3. Long-Term Goal

Establish CleanRay X as the national leader in smart solar panel cleaning solutions, aiming to reach over 60% market share through continuous innovation and strong customer satisfaction

Project Schedule – CleanRayX

Month	Task	Details	Main Outcome
1-2	Site Preparation and Legal Procedures	• Selection of testing location • Installation of basic infrastructure • Legal and administrative preparations	Site ready and compliant with technical and legal requirements
3	Component Acquisition	• Supplier research • Purchase of components	All materials available for system assembly
4	Prototype Assembly	• Mechanical and electronic integration • Assembly of the mobile structure and cleaning mechanism	Functional and assembled prototype
5	Programming and Initial Testing	• Development of control code • Movement and cleaning system testing	System tested under controlled conditions
6	Improvement and Validation	• Adjustments based on test results • Optimization of power use and detection system	Validated, reliable and optimized version
7	Commercial Launch	• Launch strategy creation	Official launch of the project to pilot market

		• Production of initial models for client testing	
8	Training and Customer Support	• Creation of installation and user guides • Setup of technical support system	Users trained and supported for optimal system adoption

5– Innovative Aspects

1- Nature of Innovations

Considering the specifics of the CleanRayX project, the innovation lies at the intersection of several types, but it can primarily be categorized as a technological innovation and a market innovation.

2-Technological Innovations

CleanRayX focuses on using advanced technology to address the problem of solar panel efficiency loss due to dust accumulation. It incorporates:

Sensors to detect the level of dust and environmental conditions.

Automated motorized cleaning mechanism that operate without manual intervention.

Remote control systems accessible via smartphones or computers for real-time management.

3-Market Innovations

The system targets a new and growing need in the solar energy sector automated maintenance solutions by providing : Improved energy yield through efficient and regular cleaning of solar panels.

A cost-effective and accessible product for various customers such as public institutions, large-scale solar farms, and individual users.

A competitive edge for users through better performance and reduced operational downtime.

Additionally, CleanRayX can also be seen as an incremental innovation:

It improves upon traditional manual cleaning methods by integrating automation and smart control.

It enhances efficiency and sustainability without completely changing the existing infrastructure of solar panel installations.

6– Conclusion

1-CleanRayX is primarily classified as:

- Technological Innovation
- Market Innovation
- Incremental Innovation

This combination highlights the multifaceted nature of the project and its impact on both technology and the renewable energy market.

7-Areas of Innovation

In the context of the **CleanRayX** project, the areas of innovation can be clearly defined as new services and solutions introduced into the solar energy maintenance sector. These innovations are aimed at improving efficiency, reducing operational costs, and supporting the transition to smarter, cleaner energy systems:

Smart Solar Maintenance Services

CleanRayX provides automated and personalized maintenance through real-time environmental data analysis. This allows for timely cleaning operations based on actual dust levels, improving overall solar panel performance and lifespan.

Precision Monitoring Systems

The solution includes advanced sensors and control units that accurately detect dust accumulation and panel conditions. These tools ensure efficient cleaning schedules and minimal energy loss, maximizing the effectiveness of photovoltaic installations.

Remote Management Platforms

Through a dedicated mobile or web interface, users can monitor system status, initiate cleaning cycles, and access performance reports from anywhere. This innovation enhances convenience, reduces manual effort, and ensures real-time responsiveness.

Automated Robotic Cleaning Solutions

The CleanRayX device automates the physical cleaning process using motorized mechanisms and soft brushes. It minimizes human intervention, ensures consistent cleaning quality, and is safe for all types of photovoltaic surfaces.

Data Collection and Analytics Tools

The system stores and processes data related to dust levels, panel efficiency, and operational cycles. This data supports preventive maintenance strategies, performance optimization, and decision-making for both private and institutional users.

Sustainable Operation Design

CleanRayX promotes sustainability by reducing water and energy consumption compared to traditional manual cleaning methods. Its environmentally responsible approach aligns with the goals of green energy development.

8- Strategic Analysis

A. Potential Market

1. Public Institutions and Governmental Entities

Scope: Public institutions managing large-scale solar farms, including universities, ministries, and regional development agencies.

Needs: Efficient, automated maintenance systems that can reduce operational costs and maintain optimal energy production in public photovoltaic infrastructure.

Potential: With Algeria's increasing investment in renewable energy, CleanRayX can support public institutions in maintaining high performance and long-term sustainability of solar installations.

2. Large Private Solar Installations

Scope: Industrial and commercial facilities with large photovoltaic fields (e.g. farms, factories, solar energy companies).

Needs: Reliable, autonomous systems for regular cleaning to ensure consistent energy generation and avoid production losses due to dust accumulation.

Potential: As industrial actors move towards greener operations, CleanRayX offers a cost-effective, low-maintenance solution to optimize solar efficiency and profitability.

3. Individual Homeowners with Rooftop Solar Panels

Scope: Residential users who have installed rooftop solar panels for personal energy consumption or partial grid contribution.

Needs: A compact, affordable, and user-friendly cleaning system that ensures their panels operate at peak efficiency with minimal manual effort.

Potential: The growing adoption of solar energy in residential areas opens a market for a lightweight version of CleanRayX that suits individual households, enhancing energy independence and reducing bills.

4. Additional Market Segments

Solar Cooperatives: These organizations can help promote and distribute CleanRayX among their members, especially in rural or suburban solar communities.

Research and Training Institutions: These can participate in testing and validating the technology while also training future technicians and engineers on solar maintenance innovation.

Government Support: The Algerian government may provide financial incentives, grants, or favorable policies to encourage the adoption of automated solar maintenance systems, aligning with national renewable energy goals.

B. Competition Intensity

Direct Competitors

Manual Cleaning Services

Represent a significant portion of the market, especially for small and medium installations. Their limitations include labor cost, time consumption, and inefficiency.

Basic Robotic Cleaners

Some startups offer simple robotic systems, but they often lack adaptability, smart control features, or remote operation.

Traditional Maintenance Operators

These include technicians who clean solar panels as part of general maintenance ; however, they are not optimized for regular, efficient panel upkeep.

Estimated Market Share

Manual and traditional solutions : ~50%

Entry-level automation solutions : ~20%

High-end and smart systems (like CleanRayX): growing niche, estimated at ~10% and rapidly increasing.

C. Strategic Analysis of the CleanRayX Project

1. Potential Market

1.1 Small and Medium Solar Energy Producers (individuals, farmers, SMEs)

Number : With the widespread adoption of solar energy in rural and semi-urban areas, several thousand small individual or agricultural photovoltaic installations are estimated in Algeria.

Needs : Automated and low-cost solutions to maintain the performance of solar panels, especially in desert regions prone to frequent soiling.

Potential : A robot like CleanRayX can extend the lifespan of panels, optimize energy production, and reduce manual maintenance costs.

1.2 Large Public and Private Institutions

Number : Approximately 200 to 500 large industrial or institutional solar installations.

Needs : Regular, uninterrupted cleaning of large photovoltaic surfaces to ensure maximum efficiency.

Potential : CleanRayX provides a reliable, programmable, and low-operating-cost solution, suitable for consistent maintenance.

1.3 Other segments

Photovoltaic Installers : Integrate CleanRayX as a service or complementary product to their offerings.

Training and Research Institutions: For validation and development of advanced versions.

Government: Aware of the energy transition, it can promote the use of local technologies through subsidies and equipment programs.

2. Intensity of Competition

Importers of solar cleaning robots: High cost, after-sales service located abroad, and poorly adapted to the local climate.

Local manual cleaning companies: Low-cost labor but low efficiency, with a risk of panel damage or premature wear.

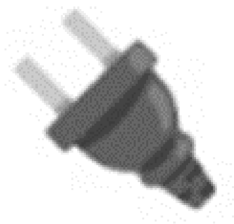
DIY (do-it-yourself) technologies : Low reliability and not automated.

Strategic_Positioning: CleanRayX aims to strike a balance between performance, cost, and adaptability to Algerian needs (dry climate, sand, limited budget).

3. Marketing Strategy

3.1 Target Audience Identification

Primary Target: Large institutions and agricultural operations using solar panels.



Secondary Target: Individual farmers, small-scale solar energy producers, and local communities.

3.2 Marketing Message

Increase the efficiency of solar installations through regular and automated cleaning.

Reduce costs and risks associated with manual cleaning.

Promote clean and sustainable energy production using local technology.

3.3 Marketing Channels

Renewable energy trade shows: Prototype presentations.

Digital marketing: Social media, video demonstrations, interactive website.

Partnerships: Collaboration with solar installers and photovoltaic equipment distributors.

Direct marketing: On-site demonstrations for large farms or local communities.

9. Marketing Mix

Product :

An autonomous cleaning robot, solar-rechargeable, adaptable to different installation sizes.

Price :

Competitive pricing compared to imported alternatives.

Special launch offer or lease-to-own option.

Government subsidies and flexible payment plans.

Promotion :

Customer testimonials, before/after cleaning videos.

On-site demonstrations with performance studies.

"Made in Algeria" label highlighted in communications.

Distribution :

Network of solar equipment resellers.

Direct online sales.

Presence in sun-rich wilayas (regions).

5. Measuring Marketing Effectiveness

Indicators : Number of robots sold, customer feedback, market share in solar installations, savings achieved by clients.

Tools : Satisfaction surveys, field tests, monthly performance dashboards.

Quarterly Review : Marketing strategy adjusted every quarter based on results and field feedback.

10-CleanRayX Project Production and Organization Plan

1. Production Process

A. Design and Engineering

Planning Phase :

Identify user needs (solar farms, farmers, institutions).

Define the technical specifications of the robot (compatible panel types, autonomy, charging method, movement system, sensors).

Design Phase :

Create 3D models of the robot and its subsystems (chassis, cleaning arm, water tank if applicable, electronic modules).

Prototype the arrangement of components : ESP32-CAM, motors, batteries, spraying/cleaning system.

Engineering Phase :

Select technical components (motors, microcontrollers, sensors).

Develop control interfaces (web interface, streaming system, WiFi connectivity).

Software integration between the control unit and the video module.

B. Manufacturing and Assembly

Procurement Phase :

Selection of local/international suppliers for electronics (AliExpress, Digikey) and mechanical parts (hardware stores, local sheet metal fabrication, 3D printing).

Purchase of ESP32 modules, Li-Ion batteries, motors, belts, wheels, plastic or aluminum materials.

Manufacturing Phase :

Machining or 3D printing of mechanical parts (chassis, motor mounts).

Cutting and preparing mounting elements (test solar panels, templates).

Assembly Phase :

Assembly of mechanical parts and integration of electronic components.

Installation of the cleaning system (brushes, spraying, suction depending on the model).

C. Testing and Validation

Testing Phase :

Mobility tests, adhesion on panels, and WiFi range tests.

Verification of live video functions and remote control via the web interface.

Data Validation Phase :

Evaluation of energy output after cleaning.

Sensor calibration (tilt, obstacle detection, battery level).

Real-world condition tests (dust, heat, slope).

2. Quality Management

Quality Management System :

Inspired by ISO 9001 standards, with documentation established for each stage (specifications, testing, maintenance).

Inspection and Control :

Inspection of electronic and mechanical sub-assemblies after each assembly step.

Systematic testing of each robot before delivery.

Continuous Improvement :

Collection of user feedback for rapid iteration.

Remote firmware updates (OTA) when applicable.

3. Supply Chain Management

Supplier Selection :

Electronics : Reliable suppliers with CE/RoHS certification.

Mechanical: Local suppliers to reduce lead times and costs.

Inventory Management :

Maintain a stock of critical components (motors, ESP32 boards, batteries).

Forecast demand peaks (summer, high sunlight periods).

Monitoring and Control :

Use of a tracking dashboard for deliveries and inventory movements.

Integration of a traceability system for each robot produced.

4. Operations Management

Production Planning:

Initially produce on demand (small batches).

Transition to semi-industrial production after product validation and initial sales.

Production Scheduling:

Production schedule based on team capacity and demand.

Use of management software (such as Trello or a simplified ERP system).

Monitoring and Control:

Track deadlines, quality, and performance using weekly indicators.

Coordination meetings to address delays or defects.

5. Human Resources Management

Recruitment and Training:

Core team composed of an electronics engineer, a mechatronics technician, and a developer.

Ongoing training in microcontrollers, electrical safety, and product design.

Motivation and Compensation:

Competitive salary based on the Algerian market.

Performance bonuses and recognition of innovative ideas.

Professional Development:

Internal workshops (training on IoT, CAD, project management).

Participation in conferences and technology fairs.

6. Technical Offering CleanRayX **Structure:**

Chassis made of lightweight aluminum« Alloy6061 » or heat-resistant ABS plastic.

Modular system adaptable to different panel formats.

Components:

Control Module: Microprocessor with integrated web server.

Streaming Module: CAM with WiFi connectivity.

Drive System:4 DC motors.

Power: Rechargeable battery + integrated solar panel (optional).

Potential Suppliers:

Electronics: Local suppliers.

Mechanical Parts: Local Fab Lab, 3D printing, or CNC cutting services.

11-Offering – CleanRayX

A. Components of the CleanRayX Robot

Robot Structure:

Lightweight aluminum chassis (via 3D printing or CNC cutting) to ensure both durability and lightness.

Modular system designed to fit various solar panel sizes.

Cleaning System:

Soft rotating brushes or motorized microfiber pads.

Optional high-pressure water spray system.

Suction or scraping module to remove debris.

Electronic Control:

Microprocessor for hosting the web control server.

CAM for real-time video streaming.

Rechargeable lithium battery, with optional integrated solar panel for extended autonomy.

Mobility:

Geared DC motors with wheels or tracks for stable movement on inclined surfaces.

Tilt and position sensors to prevent falls and detect obstacles.

B. Recommended suppliers

Item	Proposed Supplier	Location	Remarks
Electronic components	TechnoHub Algeria or ElectroDZ	Algiers, Algeria	Reliable suppliers and robotics equipment.
Chassis and mechanical supports	Fablab Biskra or local CNC workshops	Biskra, Algeria	Laser cutting, aluminum, 3D printing.
Brushes and cleaning systems	Hydro Clean Algeria	Algiers, Algeria	Specialized in industrial cleaning systems.
Batteries and power supply	Soleco Energy Algeria	Oran, Algeria	Specialist in solar batteries.
Software	In-house development	—	Adapted to the system.

Local Approach: All suppliers are primarily selected within Algeria to support the national economy, reduce supply lead times, and minimize logistics costs.

12-Workforce – CleanRayX

A. Technical Roles

Electromechanical Engineers

Design of the robotic system, component selection, integration of electronic and mechanical modules. Assembly and testing technicians

Physical assembly of robots, verification of wiring, functional testing (motors, sensors, cameras).

Power Electronics / Charging Specialist

Battery sizing, design of solar or wired charging circuits.

Sensor and Navigation Specialist

Integration of obstacle and tilt sensors, ensuring safe movement on solar panels.

B. Commercial and Marketing Roles

Identifies clients (solar farms, local authorities), conducts on-site demonstrations, and negotiates sales.

CleanRayX Product Manager

Oversees the technical evolution of the product, gathers customer feedback, and monitors the competition.

Digital Communications Manager

Promotes the product via social media, creates video and demo content of the robot, and manages the CleanRayX website.

C. Support and Administrative Roles

Logistics Manager

Monitors component stock levels, manages procurement, and prepares shipments to clients.

After-Sales Service Technician

Provides technical assistance remotely or on-site, handles preventive and corrective maintenance.

Administrative Assistant

Manages invoices and handles communication with suppliers and clients.

D. Additional Resources

Student Internships

Welcomes interns in engineering, embedded systems, or digital communication to strengthen the team.

Specialized Freelancers

Experts in industrial design, web development, or digital marketing

Hired for specific short-term missions.

Financial strategy – CleanRay X

1. Costs and burdens

Category	Item	Quantity	Unit Price (DZD)	Subtotal (DZD)
✓Hardware	15W Solar Panel	1	10000	10,000
	ESP32-Wrover Module	2	3000	6,000
	High tension generator	1	2,500	2,500
	Motor Driver L298N (HW130)	1	500	500
	12V DC Motor	4	1000	4,000
	Battery 12V	1	10,000	10,000
	Battery Holder + BMS	1	600	600
	Chassis and 4 wheels	1	35000	35,000
	Insulation liquid	1	1000	1,000
	Rain sensor	1	500	500
	Voltage sensor	1	500	500
	current sensor	1	500	500
	Photoresistor	5	200	1, 000
	DC DC Booster	1	2,000	2,000
	Rotating brush	1	1,900	1,900
	Cables	Pack	1,000	1,000
	Hardware Subtotal			**75,000**
✓Overhead Costs	Tools	Pack	1,500	1,500
	Maintenance	3 years	20,000	20,000
	Rent	Per month	1,500	1,500
	Overhead Subtotal			**25,000**
✓Total Unit Cost				**100,000DZD**

2-Annual Cleaning Solutions Cost Comparison

Item	Traditional Manual Cleaning	Serbot AG (Switzerland)	SolarCleano (Luxembourg)	CleanRay X (Local)
Number of workers / units	50 workers	50 units	50 units	50 units
Cost per worker / unit	(30,000 DZD/month × 12 = 360,000 DZD) × 50 = 18,000,000 DZD	350,000 DZD	320,000 DZD	150,000 DZD
Tools cost	16,000 DZD × 50 = 800,000 DZD	Integrated	Integrated	Integrated
Water consumption	480,000 × 2 DZD = 960,000 DZD	Not used	Not used	Not used
Glass cleaning liquid	7,500 L × 100 = 750,000 DZD	Not used	Not used	Not used
Brushes (two types)	160 × 1,000 = 160,000 DZD	Not used	Integrated	Integrated
Annual maintenance	Simple and manual	Complex and costly	Moderate	Easy and low-cost
Estimated annual cost	20,670,000 DZD	17,500,000 DZD	16,000,000 DZD	7,500,000 DZD

3-Profits over 5 years

Year	Quantity	Profits
2026	20	1,000, 000
2027	50	2,500,000
2028	80	4,000,000
2029	120	6,000,000
2030	160	8,000,000

4-Business Model Canvas version zero – CleanRayX

<table>
<tr><th colspan="5">The Business Model Canvas</th></tr>
<tr><th>Key Partners</th><th>Key Activities</th><th>Value Propositions</th><th>Customer Relationships</th><th>Customer Segments</th></tr>
<tr><td rowspan="3">- Component suppliers (motors, ESP32, etc.)

- Mechanical subcontractors (parts, structure)</td><td>- Product design and technical improvement

- Manufacturing / assembly

- Marketing and customer outreach</td><td rowspan="3">- Automated, cost-effective, and efficient system for cleaning solar panels

- Reduction in energy losses by up to 30%

- Flexible offering : sale, rental, or subscription-based cleaning service</td><td>- Personalized technical support

- Responsive after-sales service (remote or on-site)</td><td rowspan="3">- Public institutions.

- Large private photovoltaic installations

- Individual homeowners with rooftop solar panels.</td></tr>
<tr><th>Key Resources</th><th>Channels</th></tr>
<tr><td>Team composed of mechanical and electrical engineer workers and energy engineers</td><td>- Direct sales (website, social media)

- showroom</td></tr>
<tr><td colspan="3">Cost Structure</td><td colspan="2">Revenue Streams</td></tr>
<tr><td colspan="3">-Cost of development and manufacturing

-Marketing cost</td><td colspan="2">- location and sales.

- Customer training - paid technician training modules</td></tr>
</table>

Summary

Summary

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