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Robotic and Mechatronic Applications related to Renewable Energy – A Survey

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Abstract—It is convenient to use coal, oil, and natural gas for meeting mankind's energy needs, but there is a limited supply of these fuels on Earth. Renewable energy is becoming more and more important as the need for energy rises while fossil fuel depletes. Robots deliver a host of benefits in a wide variety of applications. Users introducing robots to their production processes and general applications have seen a significant transformation in their productivity and efficiency. In this paper, some of the recent developments concerning the integration between robots and renewable energy are investigated. In other words, how can renewable energy be a viable source of energy for robots and how can the renewable energy industry benefit from robots.

Keywords— renewable energy resources, solar energy, wind energy, wave energy, biomass energy, hydrogen cells, robots, motion mechanisms, solar and wind tracking

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I. INTRODUCTION

RENEWABLE energy comes from an energy resource that is replaced by a natural process at a rate that is equal to or faster than the rate at which that resource is being consumed [1], such as power generated from the sun or from the wind [2]. This energy cannot be exhausted and is constantly renewed [3]. It is convenient to use coal, oil, and natural gas for meeting energy needs, but there is a limited supply of these fuels on Earth. Eventually, they will run out. Renewable energy can help fill the gap [4]. Renewable energy sources have the following benefits [5]:

- ➢ Renewable energy sources have a much lower environmental impact than conventional energy sources.
- ➢ Renewable energy will never run out.
- ➢ Most renewable energy investments are spent on materials and workmanship to build and maintain the facilities, rather than on costly energy imports.

Robots deliver a host of benefits in a wide variety of applications. Users introducing robots and automated mechatronic systems to their production processes as well as their general applications have seen a significant transformation in their productivity and efficiency. Important robots' advantages are listed below [6]:

1. Reduced operating costs
2. Improved product quality and consistency
3. Improved quality of work for employees
4. Increased production output rates
5. Increased product manufacturing flexibility
6. Reduced material waste and increased yield
7. Improved workplace health and safety
8. Reduced labor turnover
9. Reduced capital costs
10. Save space in high value manufacturing areas.

In this paper, some of the recent developments concerning the integration between robots and renewable energy are investigated. The paper is organized as follows. In section II, the most important renewable energy sources are discussed. This is followed by section III, where the general classification of robots is discussed. Sections IV and V introduce some cases that demonstrate the great potential expected from the integration between robots and renewable energy. The paper is coronated by the conclusion in section VI.

II. RENEWABLE ENERGY

A. *Sources*

Solar energy can be used directly for heating and lighting buildings, for generating electricity, and for hot water heating, solar cooling, and a variety of commercial and industrial uses [5]. The sun's heat also drives the winds, whose energy, is captured with wind turbines [2]. Then, the winds and the sun's heat cause water to evaporate. When this water-vapor turns into rain or snow and flows downhill into rivers or streams, its energy can be captured using hydroelectric power [5]. Along with the rain and snow, sunlight causes plants to grow. The organic matter that makes up those plants is known as biomass [1]. Biomass can be used to produce electricity, transportation fuels, or chemicals. Hydrogen can be found in many organic compounds, as well as water. It is the most abundant element

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on Earth. But it does not occur naturally as a gas. It is always combined with other elements, such as with oxygen to make water. Once separated from another element, hydrogen can be burned as a fuel or converted into electricity [1,5]. Geothermal energy taps the Earth's internal heat for a variety of uses, including electric power production, and the heating and cooling of buildings. The energy of the ocean's tides come from the gravitational pull of the moon and the sun upon Earth [7]. In addition to tidal energy, there is the energy of the ocean's waves, which are driven by both the tides and the winds. The sun also warms the surface of the ocean more than the ocean depths, creating a temperature difference that can be used as an energy source. All these forms of ocean energy can be used to produce electricity [7].

In the following sections, a brief description for the most common renewable energy sources is presented (as shown in Figure 1).

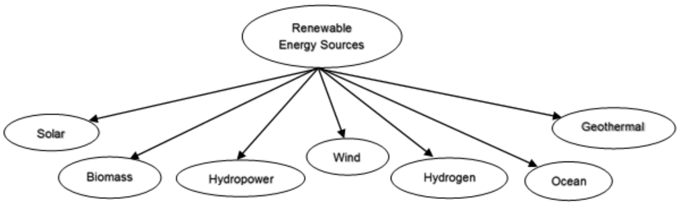

Figure 1 Renewable energy sources classification

1) Solar energy

The Earth's surface receives about 124 ExaWatts per year of solar power [8]. There are two methods for converting solar power into electricity, thermal which is based on concentrating solar power by mirrors or other type of reflectors to produce high temperature to generate water vapor with high pressure to rotate turbines to generate electricity or by making use of photovoltaic effect to convert solar power to electric power directly [9]. There are many types of technologies used to produce electricity based on photovoltaic principle. Crystalline silicon is the main technology, but there are other technologies under research [10]. Solar panels are shown in Figure 2.

Figure 2 Solar Panels [121]

Solar Energy can be classified as passive solar and active solar. Passive solar energy is making direct and indirect use of thermal energies from the sun [11]. Active Solar Energy is the use of the sun's electro-magnetic radiation in generating electrical energy [12]. A group of solar cells that are linked together are called a solar module. A group of solar modules that are linked together are called a solar array. A solar module or solar array is sometimes called a solar panel [13]. There are several methods for improving the efficiency of PV conversion, namely, solar tracking [14-16], optimization of solar cell configuration and geometry [17,18], new materials and technologies [19-21]. There are many reasons for deploying solar energy. Its ubiquity and sustainability mean that it is among the most secure sources of energy available to any country. It is also one of the least polluting energy resources. The annual amount of energy received from the sun far-surpasses the total estimated fossil resources (Figure 3). Solar energy is the largest energy resource on Earth [22].

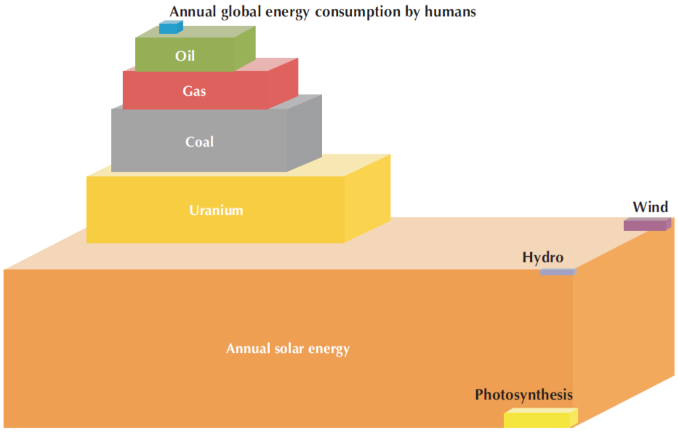

Figure 3 Total energy resources [125]

Solar energy varies throughout the day and year, and by location [7]. When the sun is lower in the sky, its energy is spread over a larger area, and is therefore weaker per surface area. This is called the "cosine effect". Supposing no atmosphere, in any place on a horizontal surface the direction of the sun at its zenith forms an angle with the vertical. The irradiance received on that surface is equal to the irradiance on a surface perpendicular to the direction of the sun, multiplied by the cosine of this angle (Figure 4).

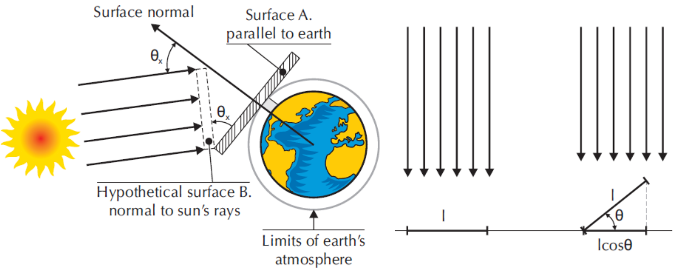

Figure 4 The cosine effect [126]

The amount of available irradiance declines especially in winter, as latitudes increase. The average extraterrestrial irradiance on a horizontal plane depends on the latitude (Figure 5). Positive energy buildings will have on their roofs and façades both solar thermal collectors and PV collectors (Figure

6). An integrated approach to the development of solar energy in buildings is shown in Figure 7.

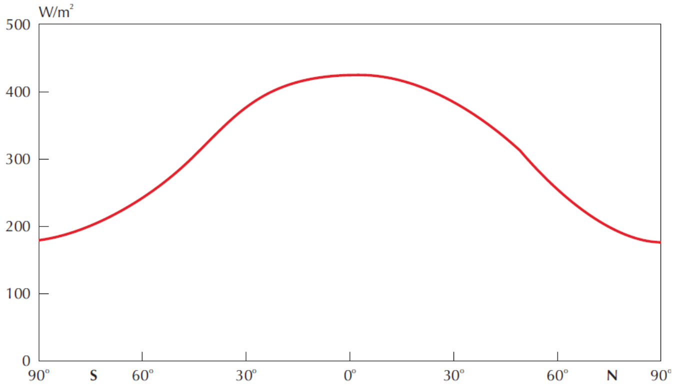

Figure 5 Average yearly irradiance [22]

Figure 6 Solar PV and thermal collectors on the same roof [127]

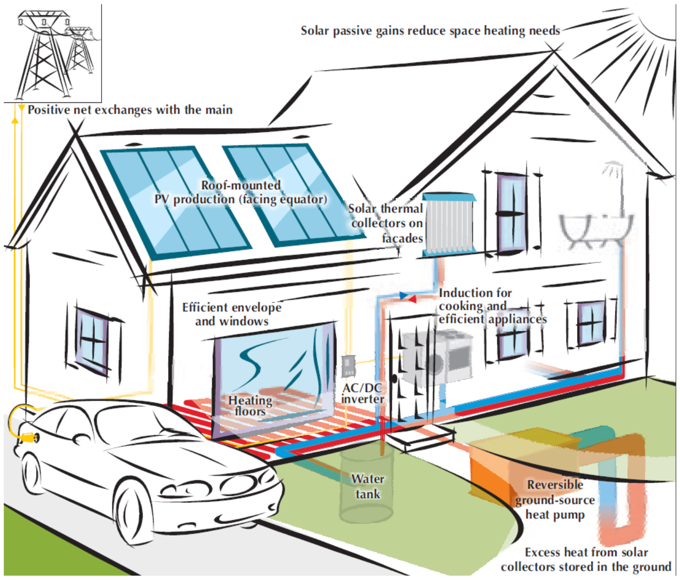

Figure 7 An integrated approach to the development of solar energy in buildings [22]

An integrated approach to the deployment of solar energy should aim to foster the deployment of the whole set of technologies that would facilitate the use of solar energy in buildings, and the use of buildings as decentralized generators of solar electricity. Photovoltaic (PV) cells are semiconductor devices that enable photons to "knock" electrons out of a molecular lattice, leaving a freed electron and "hole" pair which diffuse in an electric field to separate contacts, generating direct current electricity (Figure 8). Figure 9 illustrates various uses of solar heat and their respective levels of technology maturity. The idea of a rotating house has been proposed first as a solution to maximizing the view of a house. Rotating buildings offer invaluable benefits for energy efficient design. Rotating buildings could make the best use of wind and solar energy [23]. The Dynamic Architecture project is an 80 storey building that produces its own energy as well as for other nearby buildings, it achieves this with 79 wind turbines fitted between each rotating floor. Photovoltaic cells are placed on the roof of each rotating floor to produce solar energy [24]. The HELIOTROP is an energy-producing house, which in addition to its own electric power consumption, supplies the exceeding amount to the public power supply system. Under normal conditions the building rotates 15° per hour following the sun. 54m² of high-efficiency monocrystalline silicon solar cells are installed on the roof of the HELIOTROP [25].

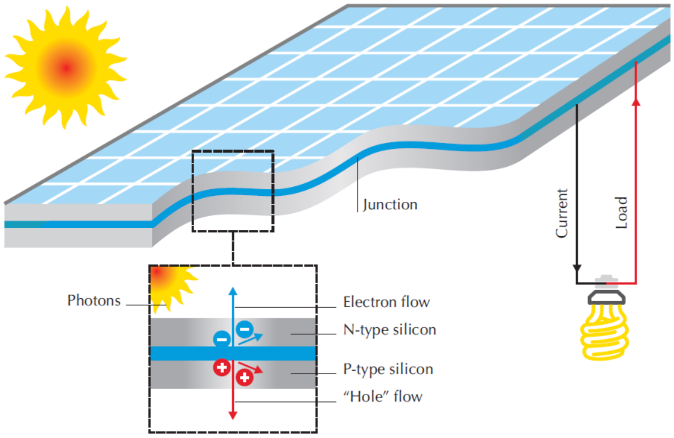

Figure 8 The photovoltaic effect [128]

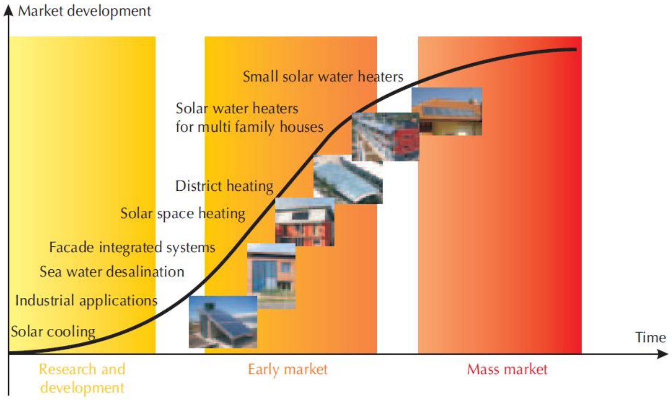

Figure 9 Various uses of solar heat [132]

2) *Wind energy*

The extraction of power from wind began very early in centuries, with wind powered ships, grain mills and threshing machines. The term Wind Turbine is used nowadays for a machine with rotating blades that converts the kinetic energy of wind into useful power [26]. Turbines catch the wind's energy with their propeller-like blades. Usually, two or three blades are mounted on a shaft to form a rotor. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity [27]. Wind energy relies, indirectly, on the energy of the sun. A small proportion of the solar radiation received by the Earth is converted into kinetic energy [28]. The Earth's rotation, geographic features and temperature gradients affect the location and nature of the resulting winds [29]. Though wind turbines from hundreds of Watts to tens of kilo-Watts in size do not benefit from the economies of scale that have helped reduce the cost of larger wind turbines, they can be economically competitive with other supply alternatives in areas that do not have access to centrally provided electricity supply [30]. Among the first technologies to harness the energy from the wind were those that used the kinetic energy of the wind as a means of marine propulsion, grinding of grain and water pumping [31]. The mechanical or electrical use of wind energy can also be applied for, among other things, water desalination and purification [32]. New concepts to harness the energy of the wind for propulsion are also under development, such as using large kites to complement diesel engines for marine transport [33,34]. Most turbines stop producing energy at wind speeds of approximately 20 to 25 m/s (cut-out speed) to limit loads on the rotor and prevent damage to the turbine's components. Wind turbines in the 1970s and 1980s were designed using simplified design models, which in some cases led to machine failures. The need to address these issues, combined with advances in computer processing power, motivated designers to improve their calculations during the 1990s [35,36]. The deployment of wind energy must overcome a number of challenges that vary in type and magnitude depending on the wind energy application and region [77]. An onshore wind farm is shown in Figure 10. In the 1970s and 1980s, a variety of onshore wind turbine configurations were investigated, including both horizontal and vertical axis designs (Figure 11) [78].


Figure 10 Onshore Wind Farm [121]

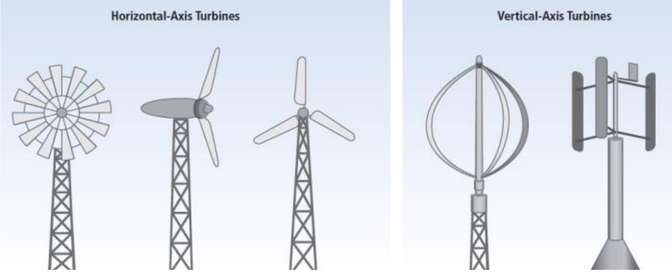

Figure 11 Early wind turbine designs [131]

After a period of further consolidation, turbine designs largely centered around the three-blade, upwind rotor; locating the turbine blades upwind of the tower prevents the tower from blocking wind flow onto the blades and producing extra aerodynamic noise and loading. The three blades are attached to a hub and main shaft, from which power is transferred to a generator. The main shaft and main bearings, gearbox, generator and control system are contained within a housing called the nacelle. Figure 12 shows the components in a modern wind turbine. Onshore wind turbines are typically grouped together into wind power plants, sometimes also called wind farms. These wind power plants are often 5 to 300 MW in size (taller towers provide access to a higher-quality wind resource, and larger rotors allow a greater exploitation of those winds as well as more cost-effective exploitation of lower-quality wind resource sites) [120].

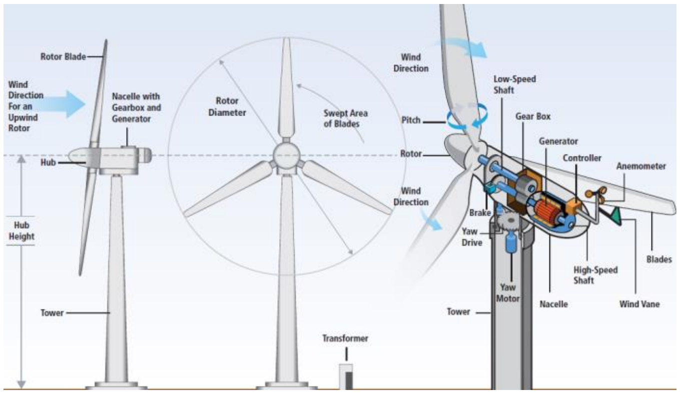

Figure 12 Basic components of a modern, horizontal-axis wind turbine with a gearbox (Design by NREL) [120]

An offshore wind farm is shown in Figure 13. The primary motivation to develop offshore wind energy is to provide access to additional wind resources in areas where onshore wind energy development is constrained by limited technical potential and/or by planning and siting conflicts with other land uses [79-81].


Figure 13 Offshore Wind Farm [121]

Several characteristics of wind energy are different from those of other generation sources. These characteristics must be considered in electric system planning and operation to ensure reliable and economical operation of the electric power system. First, the quality of the wind resource and therefore the cost of wind energy is location dependent [82,83]. Second, wind energy is weather dependent and therefore variable [84-88]. Third, wind power output has lower levels of predictability [82]. Estimating the environmental benefits of wind energy is complicated by the operational characteristics of the electric system and the decisions that are made about investments in new power plants to economically meet electricity demand [89-91]. The precise balance of positive and negative environmental and health effects of wind energy is system specific. Monetized figures for climate change damages, human health impacts, material damages and agricultural losses show significant benefits from wind energy [92]. The environmental damages associated with other forms of electricity generation and benefits associated with wind energy have been summarized many times in the literature [93-95]. The possible impact of wind power plants on the local climate has also been the focus of some research. Wind power plants extract momentum from the air flow and thus reduce the wind speed behind the turbines, and also increase vertical mixing by introducing turbulence across a range of length scales [96,97]. These two processes are described by the term "wind turbine wake" [98]. In addition, wind energy development impacts human activities and well-being in various ways. The possible impacts of wind power plants on aviation, shipping, fishing, communications and radar must also be considered, and depend on the placement of wind turbines and power plants [99]. Electromagnetic interference (EMI) associated with wind turbines can take various forms [100]. Wind turbines can interfere with detection of signals through reflection and blockage of electromagnetic waves and creation of large reflected radar returns, including Doppler produced by rotation of turbine blades. Many EMI effects can be avoided by appropriate siting [101]. Visual impacts, and specifically how wind turbines and related infrastructures fit into the surrounding landscape, are often among the top concerns of communities considering wind power plants [102-106], of those living near existing wind power plants [107-109] and of institutions responsible for overseeing wind energy development [110]. Concerns have been expressed for on- and off-shore wind energy [111,112]. Noise from wind turbines can be a problem. There are claims that sub-audible sound, that is, below the nominal audible frequency range, may cause health effects [113], but a variety of studies [114,115] have not found sufficient evidence to support those claims. Regarding audible noise from turbines, environmental noise guidelines are generally believed to be sufficient to ensure that direct physiological health effects are avoided [116]. Some nearby residents, however, do experience annoyance from wind turbine sound [117-119], which can impact sleep patterns and well-being. Significant efforts have been made to reduce the sound levels emitted by wind turbines [120].

3) Biomass energy

People have used biomass energy for thousands of years, ever since people started burning wood to cook food or to keep warm. Today, wood is still the largest biomass energy resource [71]. 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 [122]. By using various transformation processes such as combustion, gasification and pyrolysis, biomass can be transformed into "bio-fuels" for transport, "bio-heat" or "bio-electricity" [26]. Figure 14 shows the most common biomass categories derived from agriculture, forests and wastes, and the conversion routes that are expected to become economic by 2020 [136].

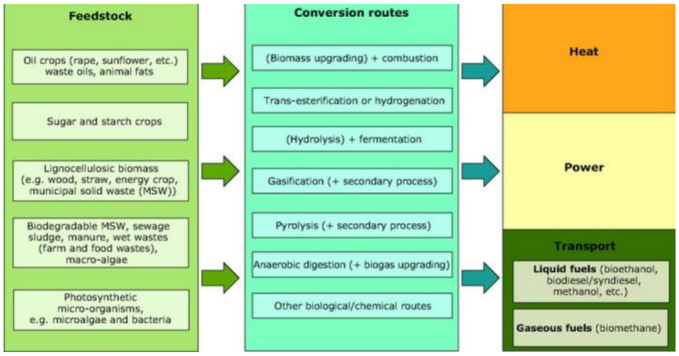

Figure 14 Routes for converting biomass to energy [136]

4) Ocean energy

The ocean can produce two types of energy: thermal energy from the sun's heat, and mechanical energy from the tides and waves. Oceans cover more than 70% of Earth's surface, making them the world's largest solar collectors. The sun's heat warms the surface water a lot more than the deep ocean water, and this temperature difference creates thermal energy.

Ocean thermal energy is used for many applications, including electricity generation. Ocean mechanical energy is quite different from ocean thermal energy. Even though the sun affects all ocean activity, tides are driven primarily by the gravitational pull of the moon, and waves are driven primarily by the winds. As a result, tides and waves are intermittent sources of energy, while ocean thermal energy is fairly constant [69].

5) Hydro energy

Hydroelectric power comes from water at work, water in motion. In the hydrologic cycle (Figure 15), atmospheric water reaches the earth's surface as precipitation. Some of this water evaporates, but much of it either percolates into the soil or becomes surface runoff. Water from rain and melting snow eventually reaches ponds, lakes, reservoirs, or oceans where evaporation is constantly occurring [26].

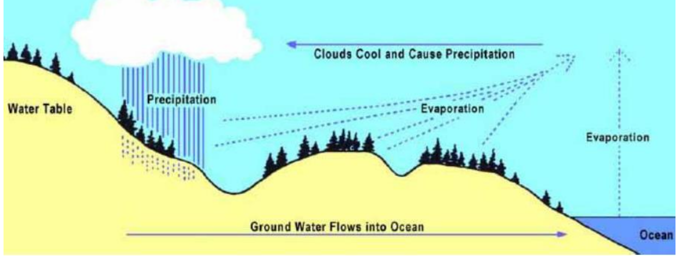

Figure 15 Hydrologic cycle [26]

The most common type of hydroelectric power plant uses a dam on a river to store water in a reservoir. Water released from the reservoir flows through a turbine, spinning it, which in turn activates a generator to produce electricity [47].

6) *Geothermal energy*

Geothermal energy is defined as natural heat from within the Earth, captured for production of electric power, space heating or industrial steam. It is present everywhere beneath the Earth's surface, although the highest temperature, and thus the most desirable, resources are concentrated in regions of active or geologically young volcanoes. Figure 16 is a simplified representation of an ideal geothermal system [26]. The heat continuously flowing from the Earth's interior is estimated to be equivalent to 42 Tera-Watts of power [130]. Direct-use applications include heating buildings, growing plants in greenhouses, drying crops, heating water at fish farms, and several industrial processes such as pasteurizing milk [68].

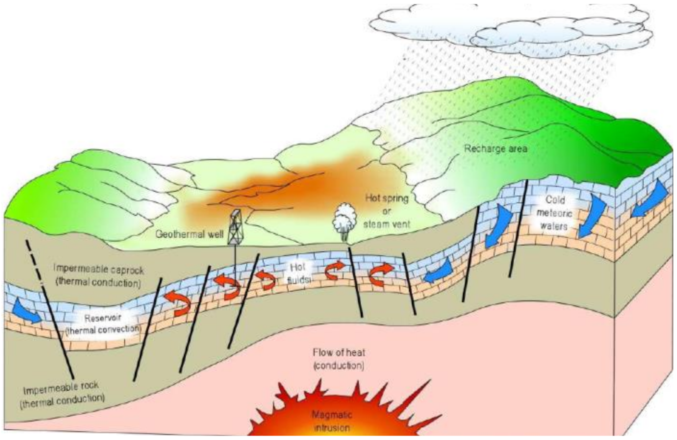

Figure 16 Schematic Representation of an Ideal Geothermal System [26]

7) *Hydrogen energy*

Hydrogen is the simplest element. It is also the most plentiful element in the universe. Hydrogen does not occur naturally as a gas on the Earth – it is always combined with other elements. A fuel cell combines hydrogen and oxygen to produce electricity, heat, and water. Fuel cells are often compared to batteries. Both convert the energy produced by a chemical reaction into usable electric power. However, the fuel cell will produce electricity as long as fuel (hydrogen) is supplied, never losing its charge. Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric motors propelling vehicles. Fuel cells operate best on pure hydrogen. But fuels like natural gas, methanol, or even gasoline can be reformed to produce the hydrogen required for fuel cells [46].

B. *New trends*

1) *Hybrid projects*

One of the up-and-coming innovations in renewable power is the siting of two different technologies in the same location. [121]. Figure 17 depicts the renewable energy hybrid projects over 10 MW by country.

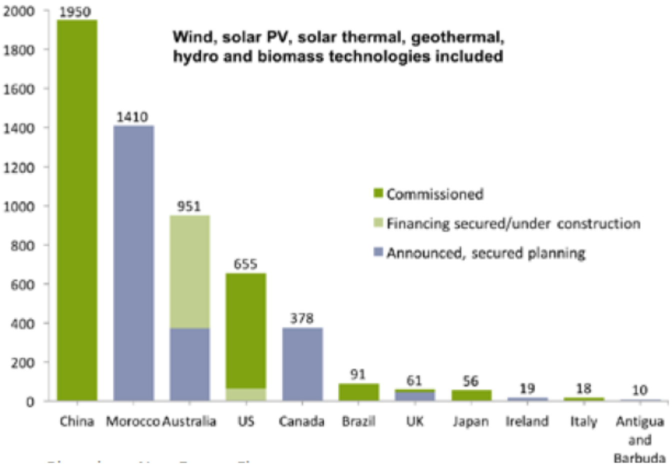

Figure 17 Renewable Energy Hybrid Projects over 10MW [129]

2) *Data analytics*

Better analysis and a true understanding of implications is needed. Taking "Siting" as an example, the following questions can be identified [123]:

1. Does the site have strong resource availability?
2. How will the generated energy flow to demand points?
3. How will a resource connect to these lines and with how much competition?
4. Can the appropriate permits and clearance be approved?

3) *Corporate renewables*

Not only did Google, Apple, Microsoft and other major companies make huge commitments to renewables in 2016, but the corporate community also came together formally under an alliance designed to find more ways for corporations to buy renewable energy [48].

III. ROBOTS

A. *Overview*

The first industrial robot shown in Figure 18 was installed in 1961 [70]. Robots are becoming more effective, faster, accurate and flexible [75]. Robots enhance labor productivity in industry and deliver relief from tiresome, monotonous, or hazardous works. Moreover, robots perform many operations better than people do, and they provide higher accuracy and repeatability. Robots are used in extreme environments. They can work at low and high temperatures; they do not even need lights, rest, fresh air, a salary, or promotions [72]. Millions of arm-type robots, as the one shown in Figure 19, have been built and put to work at tasks such as welding, painting and packaging [70]. Other subclasses include service robots which supply services such as cleaning or personal assistance [76]; field robots which work outdoors such as those shown in Figure 20 and humanoid robots (Figure 21) [70].

Figure 18 The first Unimation robot [70]

Figure 19 A modern six-axis robot from ABB [70]

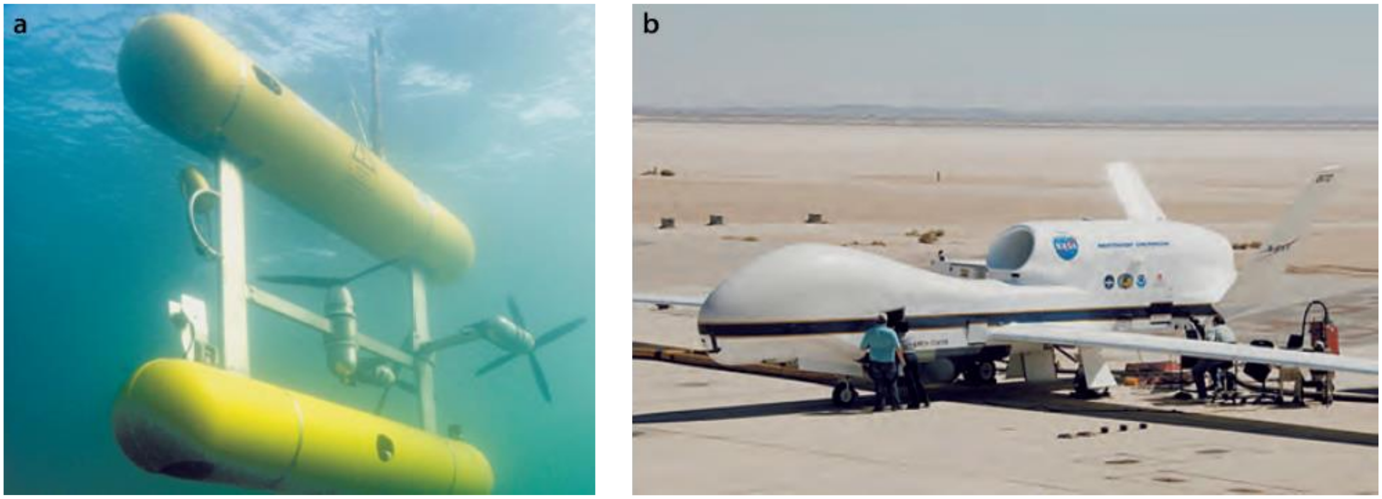

Figure 20 Non land-based robots: a. SeaBed type AUV operated by the Australian Centre for Field Robotics; b. Global Hawk UAV [70]

Figure 21 Honda's Asimo humanoid robot [70]

B. *Classification*

Robots can be classified as shown in Figure 22. These classifications are discussed below [72]:

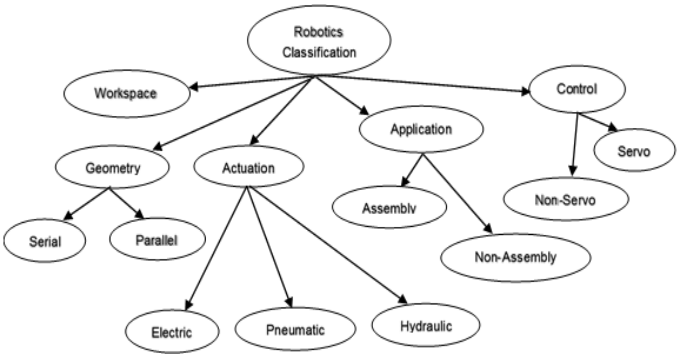

Figure 22 Robots Classification

Geometry: A robot is called a serial manipulator if its kinematic structure does not make a loop chain. It is called a parallel manipulator if its structure makes a loop chain.

Workspace: The workspace of a manipulator is the total volume of space the end-effector can reach. The workspace is broken into reachable workspace and dexterous workspace.

Actuation: robots are actuated electrically, hydraulically, or pneumatically. Other types of actuation include piezoelectric, shape memory alloy, and polymeric.

Control: Robots can be classified by control method into servo (closed loop control) and non-servo (open loop control) robots.

Application: robots can be classified into assembly and non-assembly robots. However, in the industry they are classified by the category of application such as welding, painting, assembling, inspecting, sampling and manufacturing.

C. *Types*

Two of the most important robot types related to renewable energy are defined below:

Industrial Manipulators: Re-programmable multi-functional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks, which also acquire information from the environment and move intelligently in response [73].

Drones: Drones (as shown in Figure 23) are unmanned aircrafts. They may be remotely controlled or can fly autonomously through software-controlled flight plans [74].

Figure 23 A remotely controlled Drone [133]

IV. APPLICATION OF ROBOTICS TO HARNESS RENEWABLE ENERGY

Figure 24 shows some of the general areas where robots can be used to harness renewable energy. Examples in each of these areas will be discussed in the following sections.

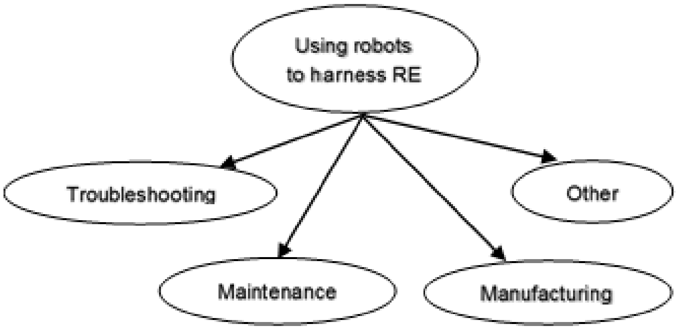

Figure 24 Possible areas of applying robotics to harness renewable energy resources

A. *Troubleshooting in dangerous environments*

It is estimated that more than 20,000 MW of generation capacity is offline globally at all times due in part to outage-related inspections, reducing the ability of electric grids to absorb variable renewable sources like wind and solar. Electricity generation can require extreme heat conditions. When a system failure occurs that halts electricity generation and it is needed to inspect and repair equipment, one must wait until temperatures reach a sufficiently low level for someone with personal protective equipment to enter the confined space safely to inspect and repair the equipment. AES [60] is looking for innovative unmanned technologies to conduct inspection work that can resist extreme heat and keep people safe while improving energy availability by getting plants back online more quickly [60].

B. *Troubleshooting in hard-to-reach places*

DTU [61] inaugurates a laboratory where researchers will complete a modular robot for use in e.g. offshore wind turbine platforms. The robot will be used for inspection, and the long-term vision is that it will be able to carry out underwater repairs on foundations and rigs [61].

In [154,144], a wire-driven parallel robotic system for the maintenance of offshore wind turbines is described (Figure 25 and Figure 26).

In [143], the robot system for maintenance and inspection of blade on offshore wind turbine power system is described. The robot can move by itself on the blade surface by inchworm mechanism, which is constructed by two active wheels and two passive wheels that can fix the robot body on the blade, one extendable and contractible actuator (as shown in Figure 27 and Figure 28).

In [146], the mechanism and system design of MAV (Micro Aerial Vehicle)-type wall-climbing robot for inspection of wind blades and non-flat surfaces is presented (as shown in Figure 29).

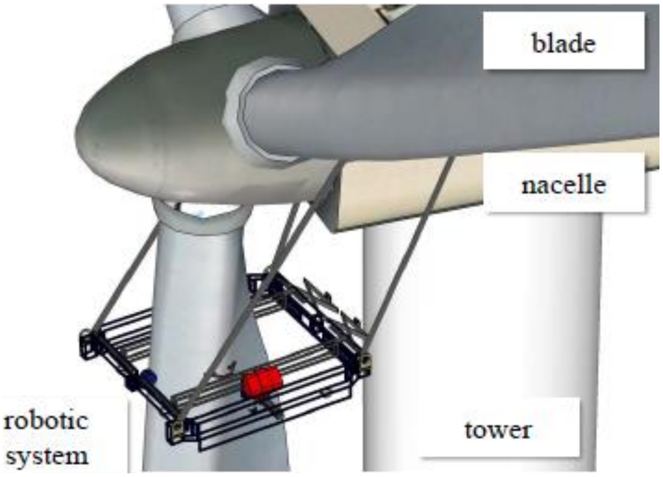

Figure 25 Maintenance robot for offshore wind turbine [154]

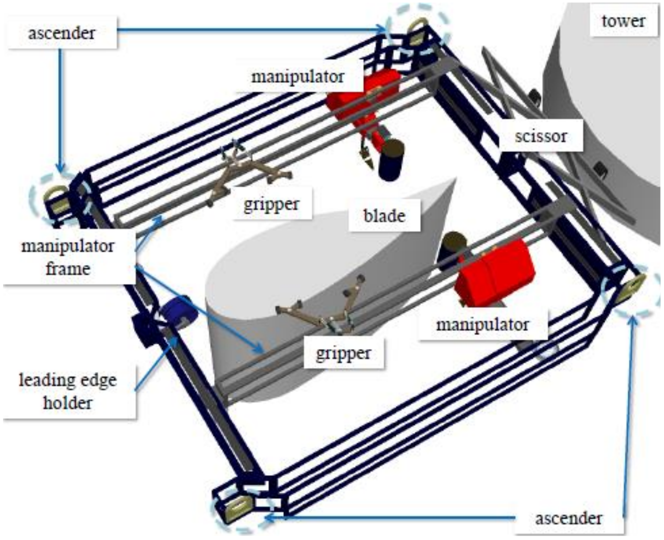

Figure 26 Robotic system for O&M of offshore wind turbine [154]

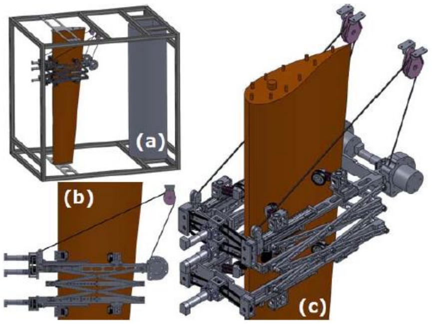

Figure 27 Inchworm type robot, a. system overview with test-bed, b. side view, c. diagonal view [143]

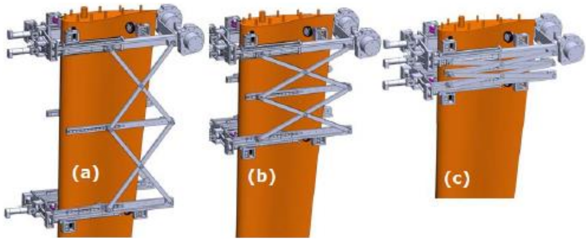

Figure 28 Telescopic motion for inspection and Maintenance [143]

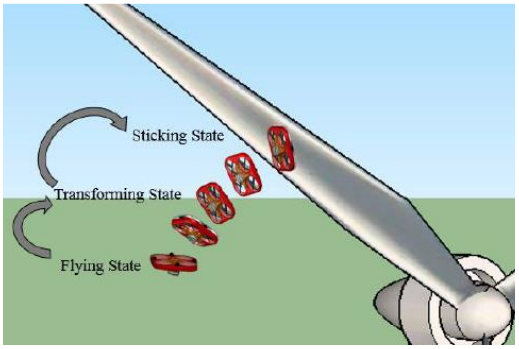

Figure 29 Possible states: flying, transforming and sticking [146]

GE Global Research is advancing technology that will make the inspection of wind turbines faster and more reliable for customers [62]. Currently, an inspector examines the massive turbine blades from the ground, about 100 meters away, by using a high-power telescope. Now, partnering with Ithaca, N.Y.-based International Climbing Machines, GE engineers have explored a way to do the work using a remote-controlled, robotic device that can scale the wind tower with a wireless, high-definition video camera strapped to its back. The motivation for the closer inspection is to obtain a more accurate picture of the overall health of the wind turbine blades. From the safety of the ground, an inspector would have a real-time, view of the blades from less than 10 meters away, allowing for a more thorough examination and evaluation of their condition. This new technology was tested at a wind farm in Texas with positive results. Other advantages to using the climber over conventional methods include better weather tolerance. No longer would inspections have to be delayed due to poor lighting conditions, rain, or snow. GE scientists are also in the process of developing a microwave scanner that could be fitted onto the robotic vehicle, enabling an even better view of the wind blades. The use of microwaves would do more than provide a surface view; it would allow inspectors to see through the blade material giving an even earlier indication of any breakdown in the structure [62].

C. High precision manufacturing

The race to build a better solar cell is looping through the National Renewable Energy Laboratory (NREL), where new robots are fabricating thin-film cells and analyzing glitches faster and with more precision than ever before. The robot working with silicon can build a semi-conductor on a six-inch-square plate of glass, plastic or flexible metal in about 35 minutes. It pivots and dishes like a point guard, sifts like a master chef, analyzes like a forensics expert and does it all while maintaining a vacuum seal on the entire process [63]. Simultaneously, it can analyze glitches and measure light absorption, while preparing the next half-dozen plates. Solar companies know how to make solar cells in a dozen different ways (as shingles, as windows, as fanny packs, as attachments to space vehicles) but they constantly are searching for ways to lower costs and gain efficiency [63].

A research project at Rensselaer Polytechnic Institute (RPI) is under way to address the expense of mass producing hydrogen fuel cells by using robots to assemble fuel cell stacks [65]. Rensselaer uses three new industrial robot systems to help develop a flexible robotic process to produce the fuel cell stacks. The U.S. Department of Energy has suggested that the cost of manufacturing fuel cells is the single biggest obstacle on the road to the hydrogen economy. A component that represents a major portion of the total system cost is the stack assembly in a Proton Exchange Membrane (PEM) fuel cell. In a PEM fuel cell, hydrogen is split into protons and electrons on one side of a thin polymer membrane. The membrane allows protons to pass through, but electrons are forced to go around, creating a flow of electrical current. On the other side of the membrane, the electrons recombine with the protons and with oxygen from the air, creating water and heat as the only byproducts. To produce enough energy for most applications, multiple fuel cells are combined in a fuel cell stack. To begin addressing the PEM stack assembly process, the researchers plan to create a flexible robotic "work cell" which will include various pieces of robotic equipment designed to handle materials with great precision. Many of the materials in PEM stacks are thin, flexible, soaked in corrosive acids, or highly sensitive to changes in humidity and temperature. This makes material handling orders of magnitude more difficult than methods used for simple flexible materials. The researchers will use existing automated methods to gain a deeper understanding of how PEM stack materials respond to various handling techniques, while also researching new ways to sense material properties throughout the process [65].

Spire Corp. [66] entered into an agreement with KUKA GmbH to combine its machine technology and address the growing demand for fully automated large-scale photovoltaic (PV) manufacturing lines. This will accelerate the integration of KUKA's automation expertise with Spire's module manufacturing equipment to produce fully automated, high-throughput facilities [66].

D. *Complex troubleshooting*

In the modern age of solar energy, 4.5 MW is not a big power plant, generally occupying less than 50 acres of land. But from the perspective of a field technician, size is all relative. A plant that size has about 18,000 panels. Trying to find a bad panel out there can be like "looking for a needle in a haystack". ArrayCon [64], one of the largest builders of utility-scale solar power plants was recently hired by a plant owner to find and replace a run of bad solar panels on a 4.5 MW power plant. It would have taken weeks to do this task the traditional way. Instead, they were able to take a different path, they used a drone service provider to spot the bad panels for them before they serviced the plant. Using a thermal sensor and a sophisticated flying robot, PrecisionXYZ [64] was able to fly the entire site in under 40 minutes and provide ArrayCon the results the next day. Not only did they spot the bad panels, they identified a number of strings that were offline and an entire subarray that was tracking incorrectly. Thermal imagery combined with drones are a real game changer for maintaining these assets. Because energized assets like solar panels generate heat, a drone equipped with a thermal camera allows to quickly assess the site and easily spot the problem areas. It is almost like that "needle in haystack" has a blinking light attached to it. It really accelerates the entire troubleshooting process [64].

E. *Site assessment*

Drones can have an impact on solar economics long before the power plants are even built; by accelerating build times they are driving costs out of the entire structure for the solar industry. Drones could reduce power plant construction costs by up to 30 percent. Consider a 100-MW power plant that can cost up to $200 million. A bank or other investor sets that money aside in order to create that cash-producing asset called a solar power plant. Furthermore, the moment the bank sets that money aside the clock starts ticking. Every day in which that money is not earning returns for an investor translates into opportunity costs. It is about how quickly one can build a quality project so the bank can start making money off that asset. So project velocity is not just important, it is everything. For solar power plants, that clock starts ticking with something called a site assessment. It would be convenient to think of this as pre-screening of a site's viability for project development. Historically these were done with Google Earth or an equivalent service. Unfortunately, the imagery and accuracy of these services can be very course, requiring project developers to spend more time assessing the site. With high resolution drone imagery, every detail of the site is visible within days. SunPower estimates that by using drones they can cut 90% off the time it normally takes to build a proposal-ready site assessment [64].

F. *Site survey*

Of course, once a site is deemed favorable for a project, one still needs to actually build it. Similarly in this case, drones play a big role in accelerating the entire process. Traditionally, land surveys for projects are conducted once a project is approved. Even with modern survey-grade GPS technology, the process is labor-intensive, and it can take more than a month before a survey is completed. In contrast, drones flying over a site use a process called photogrammetry to build highly accurate maps very quickly [64]. In general, the higher and faster the drone flies, the lower the details and accuracy. Conversely, flying "low and slow" gives greater accuracy and details. This is why drones are the ideal solution for building extremely accurate topology maps across large areas. Drones are an ideal use case for large, utility-scale solar power plants. Not only does this accelerate the front end of the project, it also provides design and engineering-teams centimeter-level fidelity. This allows them to more accurately estimate resource utilization at the project site, further reducing project costs [64].

G. *Project tracking*

Since the information is provided in the form of a digital model, construction organizations can now integrate that information into their project tracking, which leads us to yet another area where drones help drive out costs. Tracking project velocity across a 100 to 200-MW site is not easy. The tracking process of work crews across hundreds of acres and each crew has their own set of challenges is a tedious job. For the overall project manager, this can create a situation where information is disjointed, and without the context of the overall job site, it can be difficult to assimilate for quick decision making. This can end up hindering their ability to manage the site effectively. Drones re-establish site context, delivering images of the entire project site in real time, allowing a manager to see at a glance the status of the overall project. More importantly it enables them to address a host of issues that might not otherwise be obvious, manpower, material or safety, all of which can impact project velocity and ultimately delivery. Because all the information is now digitized and stored in the cloud online, this also allows project management teams to more easily analyze the results of not only the current project, but of projects conducted in the past. Lessons learned can then be applied for better results in future projects. The net result is an immediate improvement in project velocity, and continuous improvement in project velocity over time. In an industry that is constantly trying to find another $0.01/Watt of savings, the potential savings drones represent are huge. At the end of the day, drones are a robotic tool designed to extend the capabilities of people, teams, and managers. Moreover, while the first era of drone technology was simply about making drones reliable, consistent and functional, the second era (the era of data collection) is having a much more profound impact. In the age of automation, drones are the front-line forces driving value creation in construction economics [64].

H. Efficient maintenance

1) The need for cleaning the solar modules

The output power of photovoltaic cells is closely related with the weather, date and time [56] (Figure 30). Deposition of dust, bird droppings, sand, tree leaves and salted water-stains can significantly degrade the efficiency of solar installations [51-53]. Soiling accounts for dirt, snow, and other foreign matter on the surface of the PV module that prevents solar radiation from reaching the solar cells. Dirt accumulation is location and weather dependent. The solar module surface contamination is multi-factorial process. The local environment comprises site-specific factors influenced by the nature of prevailing human, industrial, agricultural activities, road transportation, built environment characteristics, natural vegetation types and weather conditions. The annual electrical power loss due to the soiling of modules can be substantial, the values range from 5.2 to 17%. In extreme cases, higher values may occur (25%). Without proper surface cleaning, solar farm's performance and the owner's profit can drop up to 15-17% in the long term. Regular cleaning of solar modules is therefore essential. In extreme and very dry sandy climates where rain cleans are not or only minimally enforced, failure of panel cleaning can cause even greater losses. The solar power generating facility owner or operator can no longer be able to change any construction features, such as wire resistance, or the inverter efficiency. It is very important to choose the cleaning time period properly, because the intensity of soiling process in the summer is stronger. However, about two-thirds of the energy production is in this period, so the negative impact of PV modules pollution is at its peak [52]. The rate at which the power reduces over time is unpredictable as it depends on various environmental factors. Precipitation plays a considerable role in the cleaning capability it must be said that rainfall often does not suffice because some types of soil cement and stick.

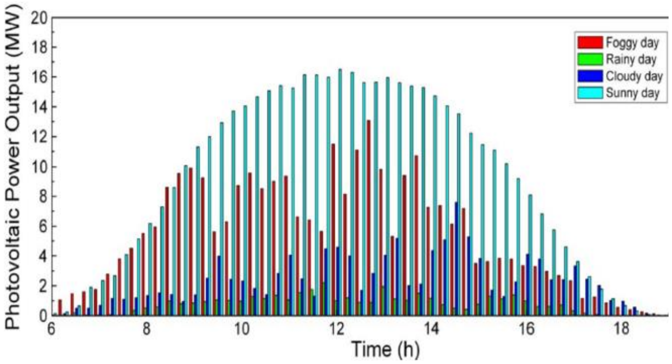

Figure 30 PV system power output under different weather conditions [51]

The same counts for bird droppings which do not flush away either. However cleaning solar panels is not always as straightforward. There is the issue of accessibility as the PV panels often are situated in dangerous and difficult to reach places. It might be hard to clean them manually and it takes time to do it safely. Secondly, cleaning a panel only once a year might not have a significant impact on the yearly energy yield for the simple reason that dirt stacks up again in a short period of time making the difference negligible. Especially if it is needed to contract someone to clean the panels, it might just not be economical. However, leaving panels uncleaned can lead to permanent damage of the glass limiting the lifespan of the installation. The logical solution is to clean them automatically and autonomously. Unfortunately, there is no abundance of such products available and therefore often built to purpose robots do the job. As a result cleaning robots are only cost-effective on vast plants. Cleaning robots are commonly installed on rails along the panels. These make the installation relatively expensive for two reasons. The first reason is that more material costs more money. All parts are machined and often are built to purpose, in order to fit a specific plant. The second reason is the labor costs for installing the track system. There are other solutions for cleaning panels like sprinkler systems or robots driving on caterpillar tracks made from suction cups [51].

2) Losses in PV systems

➢ Soiling

When time passes, PV panels get covered with a layer of dirt, hence decreasing the amount of light hitting the cells. The amount of power lost due to soiling is dependent on several factors. First of all it depends on the type of dirt deposited on the panel [51]. Possible polluters [57] are sea salt, pollen or matter from air pollution, agricultural activity, construction and other natural sources. Secondly there is the influence of precipitation. Both the amount of rainfall and the time between rain events change the layer pile up. A large amount of the accumulated pollution is washed away by rainfall while in periods of drought losses increase rapidly. All these factors can be brought back to the geographical location and the climate the system operates in. A last important factor is the angle at which the panel is tilted. The lower the angle, the faster dirt accumulates having a maximal effect when panels are installed horizontally. Soiling is a very complex process due to the large variety of parameters.

- Major Sources of Soiling [52]:
  A systematic review of possible sources and types of pollutants helps to choose the most suitable cleaning strategy and technology for a given place.
- Natural sources of pollution and types of soiling:
  - Moving sand and soil particles caused by wind
  - Bird droppings
  - Pollen
  - The leaves adhering on PV module surface moved by the wind
  - Contaminated rain.
- Varieties of contamination coming from human activity:
  - Air pollutants coming from industrial plants
  - Dust and other air pollutants caused by agricultural activities
  - Dust generated by dirt road traffic
  - Pollution from road transport
  - Combustion products from conventional residential heating systems [52]

- Degeneration
  Over time, PV cells lose some of their efficiency due to a various amount of non-reversible damage. A couple of reasons for this phenomenon are oxidation, delamination, cell cracks, irreversible soiling and hotspots [58]. This last one is a phenomenon caused by shadows or localized dirt. Because the cells do not supply energy they will start to act like a dissipater and heat up, leaving burned areas and damaging the panels notably. Irreversible soiling typically takes place at the lower edge of the panel. The polluted environment in combination with water and the alkalis in the glass result in a loss of optical transmittance along the lower edge of the PV module (Figure 31).

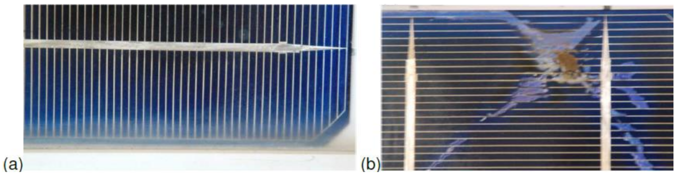

Figure 31 Examples of panel degradation due to (a) haze and (b) hotspots without bypass protection [51]

Both phenomena cause a reduced short-circuit current and result in a reversed polarity, consuming energy and increasing temperatures leading to failure of the strings. To minimize the impact on the performance, modern solar panels have a system with bypass diodes, shutting of cells in order to protect the cells and the entire panel. As a consequence the bypassed zone will not be providing energy. Both phenomena cannot be totally ruled out but keeping the panels clean can certainly help slowing down the degeneration of the modules [51].

- Snow
  Snow can be seen as an extreme form of soiling. Snow limits the amount of radiation penetrating through to the cells, reducing the final yield. On tilted panels the snow starts slipping and gradually the output power increases again, but on flat panels the snow will cover the panel until it melts again (Figure 32) [51].

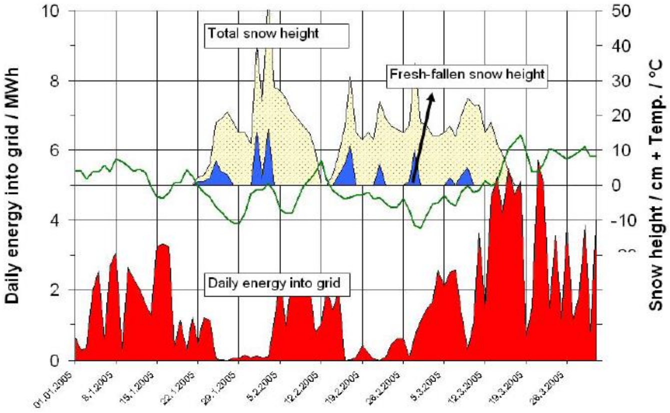

Figure 32 Influence of fresh fallen snow and total snow height on the energy yield [51]

3) *Cleaning robots*

A solar panel supported with auto-cleaning robot is described in [54]. Similarly, in [55], an automated cleaning robot was designed to clean the flat windows of the buildings.

This robot automatically cleans the outside of windows on a facade with vertical jambs and horizontal bars. In [50], self-cleaning solar panels utilizing a robot designed to meet the specification of the flat plate panel were proposed. The robot consists of brushes driven by DC-motors. A design for an autonomous cost-effective cleaning robot was proposed in [51]. The Solarbrush [51] (Figure 33) is a light-weight, autonomous robot for dry cleaning solar panels in dry environments. Using tracks made of suction cups, it moves over the panels making it possible to cross gaps up to 30 mm and working on surfaces tilted up to 35°.

Figure 33 The Solarbrush robot [51]

Different kinds of brushes can be attached to the robot. Power comes from a rechargeable battery [51]. The Ecoppia E4 (Figure 34) is a fully autonomous robot that uses microfiber brushes to sweep the dust off of panels. It is designed for large rows of panels situated in dry and sandy environments. By making use of gravity the brushes move downwards spinning, creating an airflow that helps blowing off the dust. The robot makes use of an on-board solar panel and battery to store energy that allows the robot for cleaning at night. Wash Panel produces robots that clean arrays of PV panels by moving a vertical brush horizontally over a row of panels a water hose is attached for wetting the panels while cleaning (Figure 35). Sprinkler systems are often used in dry areas to keep panels clean. It has the same cleaning effect as rainfall and will clean panels at a relative low cost. Like most systems, the one produced by Heliotex, consists of a water filtration system and soap dispensing system. Although this is a relatively good working system, there are a couple of drawbacks to it. First off, the large amount of water it uses as it cleans the panels multiple times a day. This is needed because as the panels get dirtier it becomes trickier for the sprinklers to remove all the soiling. Secondly both filters and soap level have to be monitored and taken care of both taking time and money.

Figure 34 Ecoppia E4 cleaning robot [51]

Figure 35 An example of a “Wash Panel” system [51]

Lastly, there is the fact that wet panels make dirt stick to the panels [59] causing the panels to get dirtier in the long run. This system is suitable for very dry sandy areas where sand stacks up very fast but will not clean as thorough as a brush system [51].

In [141], a portable robotic cleaning device is developed featuring a versatile platform which travels the entire length of a panel. An Arduino microcontroller is used to implement the robot's control system (Figure 36). Manual cleaning of PV panels is shown in Figure 37.

I. Solar tracking

Due to the continuous change in the relative positions of the sun and the earth, the incident radiation on a fixed PV panel is continuously changing, reaching a maximum point when the direction of solar radiation is perpendicular to the panel surface. In this context, for maximal energy efficiency of a PV panel, it is necessary to have it equipped with a solar tracking system. Automatic solar tracking systems (using light intensity sensing) may boost the conversion efficiency of a PV panel, thus deriving more energy from the sun [49].

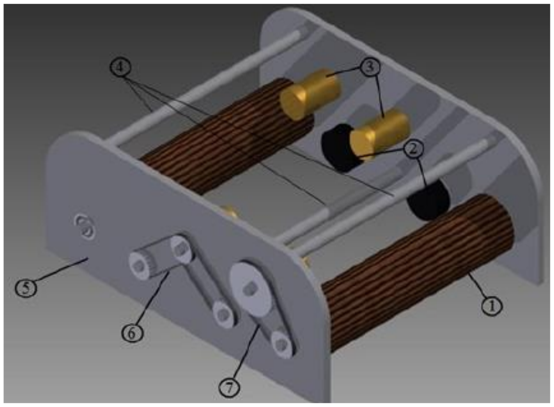

Figure 36 The cleaning robot system: [141]
(1) brush, (2) wheels, (3) motors, (4) connecting rods, (5) side panels, (6) Wheel driving system, (7) brush driving system

Figure 37 Manual cleaning of PV panels with water-fed pole [51]

Solar tracking systems can be classified according to several criteria [7,49]:

- Number of rotation axes.
- Orientation type
  - Solar tracking systems that orient the PV panels based on a previously computed sun trajectory
  - On-line Solar tracking systems that reacts to the instantaneous solar light radiation.
- Activity type (active or passive solar trackers) [49].

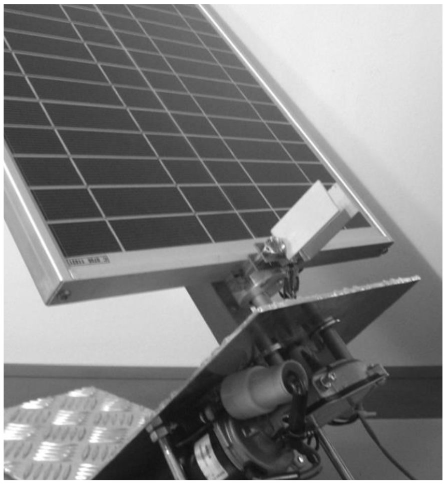

Figure 38 Single-axis solar tracking system [49]

In [49], the design of a single axis solar tracker system was proposed. The system automatically searches the optimum PV panel position with respect to the sun by means of a DC motor controlled by an intelligent drive unit that receives input signals from a light intensity sensor (Figure 38).

In [139], the design of an automatic Solar Tracker Robot (STR) was discussed (Figure 39). The robot is capable of tracking maximum light intensity. The main components of the robot consist of microcontroller namely PIC16F877A, sensors, servo motors and digital compass. This robot is programmed to detect sunlight by using two Light Dependent Resistors (LDR). Servo motor aligns the solar panel to receive maximum light. Digital compass is used to detect the position of the robot. Two modified DC servo motors will move the robot back to the original position once the robot is out of position.

Figure 39 The solar tracker robot and solar panel

Figure 40 Adaptive Solar Façade [137]

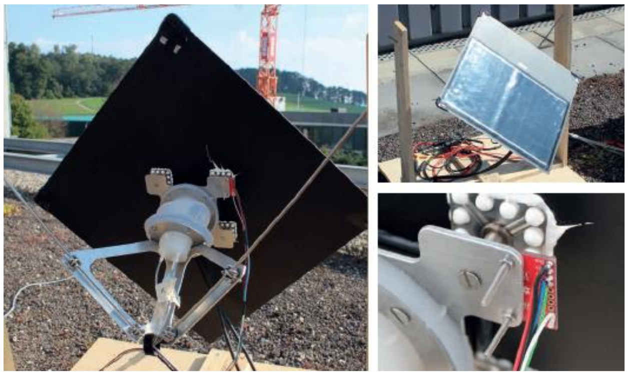

Figure 41 SoRo-Track, Left: Back view, Top right: Front view, Bottom right: Sparkfun breadboard with IMU 9150 sensor [142]

In [142], SoRo-Track is presented, a two-axis soft robotic actuator (SRA) for solar tracking and building-integrated photovoltaic applications (Figure 40 and Figure 41).

J. Wind turbine's nacelle and blades position control

The orientation of the shaft and rotational axis determines the first classification of the wind turbine. A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal axis wind turbine or (HAWT). A vertical axis wind turbine (VAWT) has its shaft normal to the ground [148]. Choosing a proper site for the towers is certainly the starting point for maximizing the output of a large wind farm. But for the most efficient conversion of the kinetic energy of wind into mechanical energy, or "wind power". Additional control over the position of each turbine's nacelle and blades is essential. This is the task of the yaw and pitch drives, which adjust the physical orientation of those components in response to fluctuations in the velocity and direction of prevailing breezes [147] (see Figure 42).

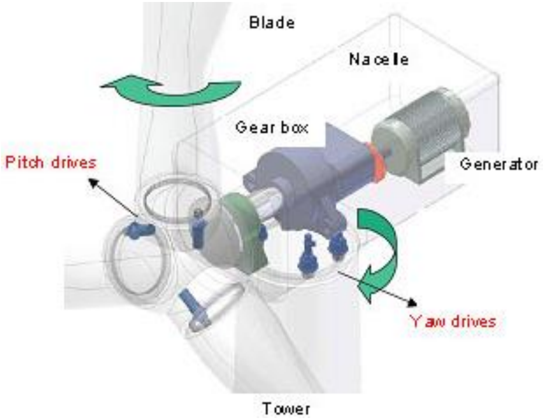

Figure 42 Yaw and pitch drives on wind turbine [147]

Control methods [149]:

- Drivetrain Speed
  - Fixed (direct grid connection)
  - Variable (indirect grid connection)
- Blade Regulation
  - Stall - blade position fixed
  - Pitch - blade position changes with wind speed

A wind turbine is shown in Figure 43.

Figure 43 Wind turbine [150]

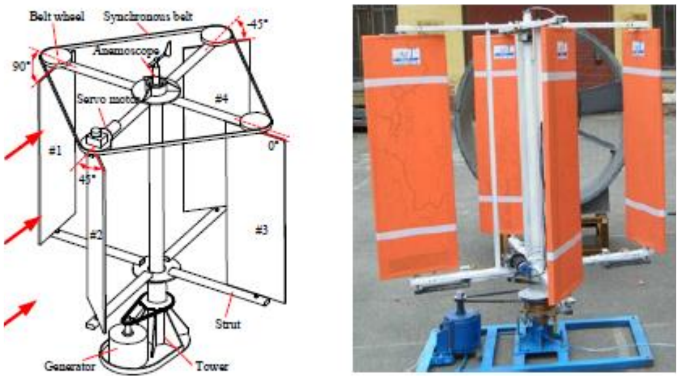

Figure 44 Structural concept and experimental prototype of SB-VAWT with collective pitch control [153]

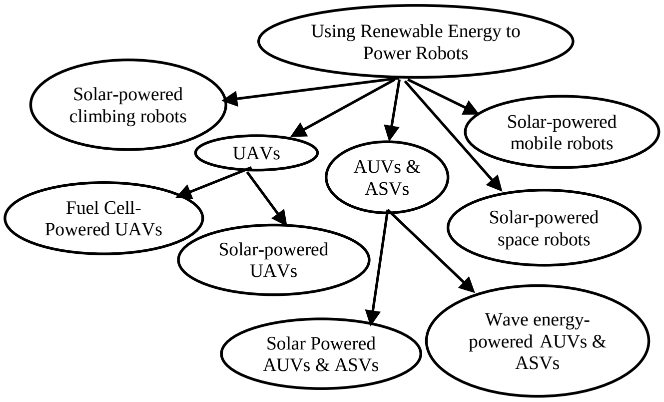

Figure 45 Using renewable energy for robotic applications

Figure 46 A Hydrogen Fuel Cell [134]

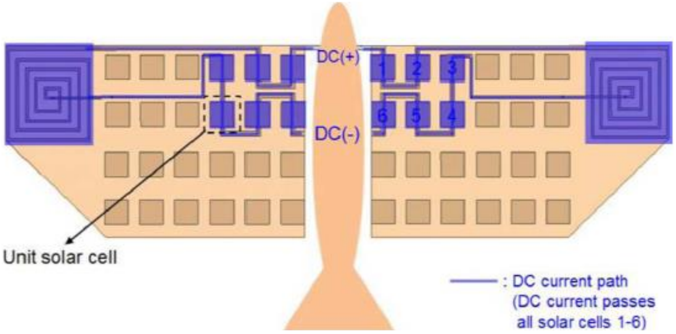

Figure 47 Flapping-wing robot [145]

In order to improve the self-starting capacity of straight-bladed vertical axis wind turbine (SB-VAWT), a prototype with collective pitch control (CPC) was developed in [153]. The pitch angle of each blade was adjusted by a blade pitch control mechanism, consisting of four driving wheels attached to the blades and one servo motor, and motion of each blade was half of the rotor (Figure 44).

V. USING RENEWABLE ENERGY IN ROBOTIC APPLICATIONS

Some of the possible renewable energy types used to power different types of robots are shown in Figure 45.

A. Renewable energy-powered UAVs

1) Fuel cell-powered UAVs

Unmanned aerial vehicles (UAVs or drones) with fuel cell propulsion systems are most applicable for commercial applications at scales of up to 10 kW. Although fuel cell systems are currently significantly more expensive than the battery systems typically used at this size, the higher system energy density allows them to provide much longer fight durations and/or more energy for auxiliary systems than battery systems. They also have a lower heat signature and less vibration than engine-based systems. Several commercial prototypes have been developed, as well as systems built for the military sector. Fuel cell UAVs will be most suitable for applications requiring long range flights, but UK legislation currently restricts UAV flight beyond visual line of sight. This could inhibit deployment of UAVs in the most appropriate mode for fuel cells [67]. A hydrogen fuel cell is shown in Figure 46.

2) Solar-powered drones

The integration of a flexible UHF antenna with an epitaxial lift-off thin-film III-V solar cell array used for power generation and wireless communication in a flapping-wing robotic platform is described in [145] (Figure 47).

In [140], the concept of a small-scale hybrid unmanned aerial vehicle capable of augmenting the maneuverability of a quad-rotor with the energy collection and supply of a solar-powered fixed-wing aircraft is presented (Figure 48).

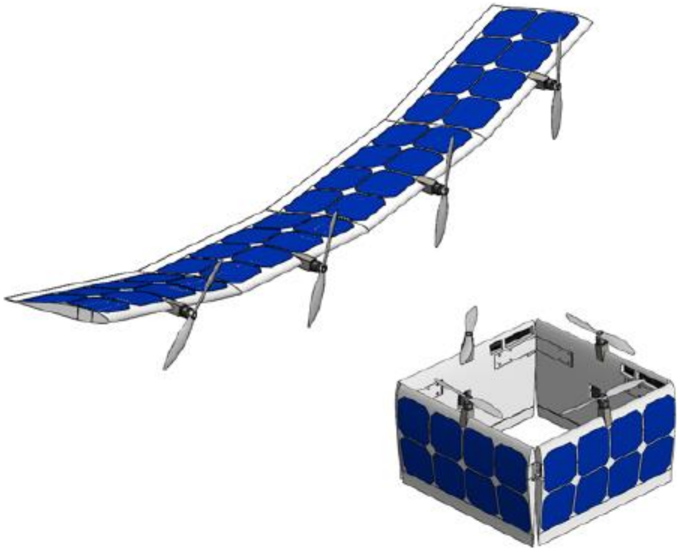

Figure 48 Fixed-wing and quad-rotor states of SUAV [140]

B. *Renewable energy-powered AUVs & ASVs*

1) *Background*

The need for data collection on different scales in time and space, has promoted an effort to develop different types of autonomous vehicles that enable the collection of such data. These platforms have varying capabilities of communication, durability, mobility, capacity and autonomy. Within these different platforms, are in addition to others, Autonomous Underwater Vehicles (AUVs) and Autonomous Surface Vehicles (ASVs) [37-45].

2) *Motives*

According to [37], there are three main limitations in autonomous underwater vehicles: energy, navigation over a long period of time and long distances and user communication with the platform. The use of solar energy begins to overcome these limitations by adding to the submarine's ability to regenerate energy when needed, giving the ability to last for weeks and months on mission, instead of hours. Blidberg et al. [38] discuss power management in different situations and find an optimum combination of the size needed to store energy and the travel distance measurement and/or works to be undertaken by the vehicle depending on the solar energy available in the area. Special effort is made in the balance between displacement (speed and distance) and tasks (duration and frequency of measurements, number of sensors on board). Their study raises a number of scenarios, where the energy is distributed in different ways, according to the needs of the mission in question, but it is possible to select different settings for each scenario.

3) *Solar-powered AUVs*

The SAUV-II vehicle (Figure 49), described in [39-42], is a solar powered AUV designed for long endurance missions such as monitoring, surveillance, or station keeping, with bi-directional communication in real time and underwater instrumentation. The SAUV-II operates continuously for several months using solar energy to recharge its lithium ion batteries during daylight hours.

Figure 49 The SAUV II vehicle [135]

In [124], an intelligent navigation system for an unmanned autonomous underwater vehicle powered by renewable energy and designed for shadow water inspection in missions of a long duration is proposed. The vehicle capable of operating during long periods of time for observation and monitoring. The vehicle integrates photovoltaic panels and a methanol fuel cell, together with neuro-biologically inspired control architecture for intelligent navigation. The system is composed of an underwater vehicle, which tows a surface vehicle. The surface vehicle is a small boat with photovoltaic panels, a methanol fuel cell and communication equipment, which provides energy and communication to the underwater vehicle. The underwater vehicle has sensors to monitor the underwater environment such as side-scan sonar and a video camera in a flexible configuration and sensors to measure the physical and chemical parameters of water quality on predefined paths for long distances. The underwater vehicle implements a biologically inspired neural architecture for autonomous intelligent navigation. Navigation is carried out by integrating a kinematic adaptive neuro-controller for trajectory tracking and an obstacle avoidance adaptive neuro-controller. The autonomous underwater vehicle is capable of operating during long periods of observation and monitoring. This autonomous vehicle is a good tool for observing large areas of sea, since it operates for long periods of time due to the contribution of renewable energy. It correlates all sensor data for time and geodetic position. This vehicle has been used for monitoring the Mar Menor lagoon.

4) *Wave energy-powered AUVs*

Based on the structure of the multi-joints robotic fish, a reversible energy conversion mechanism is proposed in [151]. The mechanism not only can work as drive unit but also can work as power take-off (PTO) unit which is able to capture wave power for the robotic fish (Figure 50).

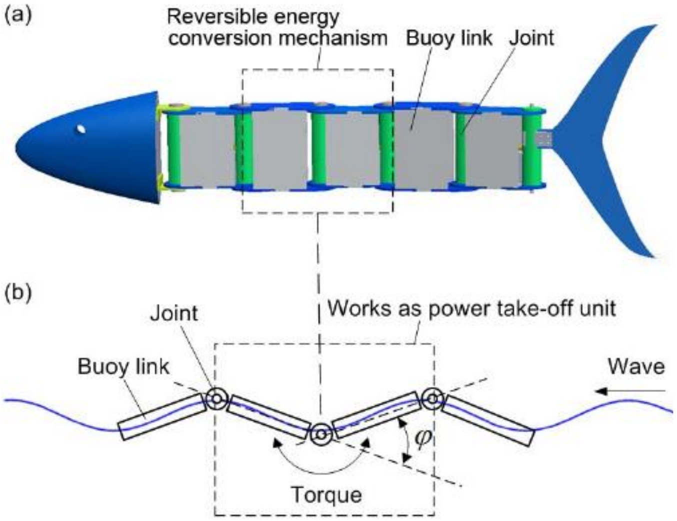

Figure 50 Robotic fish:
(a) Working mode (b) Energy harvesting mode

5) *Solar-powered ASVs*

A new long duration solar powered ASV for oceanographic and atmospheric scientific research missions is presented in [43,44]. A fleet of three Ocean Atmosphere Sensor Integration System (OASIS) ASV platforms has been developed to provide a low-cost, reusable, re-configurable, long-duration, ocean observing capability to support ongoing research in key areas, such as carbon dioxide air sea flux and phytoplankton productivity. The OASIS ASV platform is comprised of five major subsystems. The structural subsystem includes the deck/hull components, mast and internal mounts. The power subsystem contains six 170W solar panels, an automated charge controller, twelve 12V deep-cycle gel-cell marine batteries, DC-DC converters, isolators, a power bus and a fuse bank. The propulsion subsystem includes the rudder and propeller control surfaces, as well as the motors, drivers and controllers to operate them. The vehicle computer, communications hardware, navigation sensors, adapters and relay bank are among the components contained in the onboard control subsystem. The payload subsystem includes a suite of standard water and atmospheric sensors.

The AAS Endurance [45] is an autonomous surface vehicle described as a project to be developed in three years, driven by the Austrian Society for Innovation in Computer Science, State University of Austria and the Oregon State University. It is an autonomous sailing boat, which uses sensors, actuators and an intelligent control system to manage without being driven. This autonomous marine vehicle has special equipment for the study of marine mammals, it has solar panels that generate up to 285W and a methanol fuel cell that supplies auxiliary 65W.

In [138], a hybrid autonomous vehicle, Aqua-Quad, is presented, which combines a multi-rotor vertical take-off and landing aircraft with environmentally hardened electronics, exchangeable sensor suite and a solar recharge system in order to provide long endurance sensing in aquatic environments in support of a variety of missions (Figure 51).

6) *Wave energy-powered ASVs*

Motion simulation of Wave-driven unmanned surface vehicle under certain sea conditions is performed in [152]. In [155], Gaussian process models to predict the speed of the Wave Glider autonomous surface vehicle from observable environmental parameters is examined (Figure 52). The nonlinear dynamic model of Wave-driven unmanned surface vehicle is described in [156]. The wave and driving force are calculated, and hydrodynamic coefficients are determined according to the empirical data and experimental platform of WUSV (Figure 53).

C. *Solar-powered space robots*

Manipulation Control of a Space Robot with Flexible Solar Panels are discussed in [157,158].

D. *Solar-powered climbing robots*

An automatic solar charging system which can track the sun used for transmission lines robot is described in [159]. The system includes solar charging system, automatic tracking solar system and quick connect-separate mechanism. The system is designed to reduce the number of workers climbing the tower to replace the battery (Figure 54).

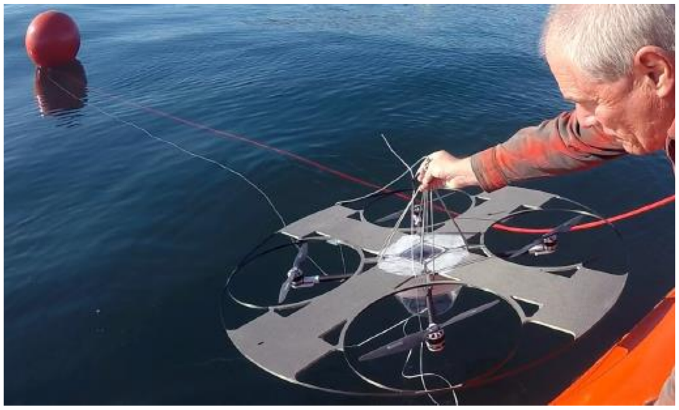

Figure 51 Deploying the Aqua-Quad

Figure 52 The Wave Glider platform [155]

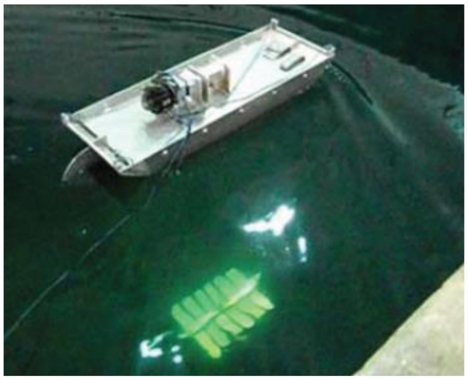

Figure 53 Experiment platform of WUSV in water-tank [156]

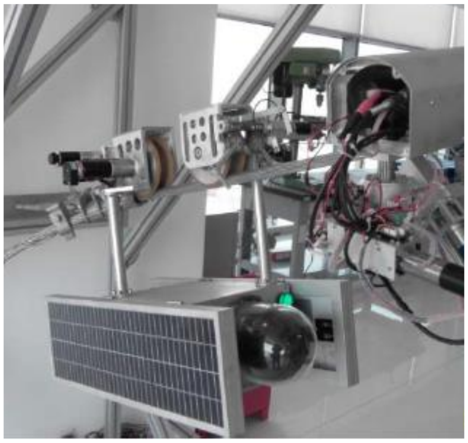

Figure 54 Transmission Line Robot [159]

E. *Solar-powered mobile robots*

In [160], an Industrial Mobile Robot Platform was designed that would run on solar power making use of an array of photovoltaic panels (Figure 55). Motion Simulation of the Cassette Handling Robot (Figure 56) and analysis of its vibration were performed in [161]. A hybrid system implementing the use of solar panels and batteries to power a robot is presented in [162]. The main aim is to integrate a charging system which allows the batteries to be charged from solar panels, wall outlet, as well as a deployable solar charging station. In [163], an integrated path planning and power management problem for a solar-powered unmanned ground vehicle (Figure 57) is examined.

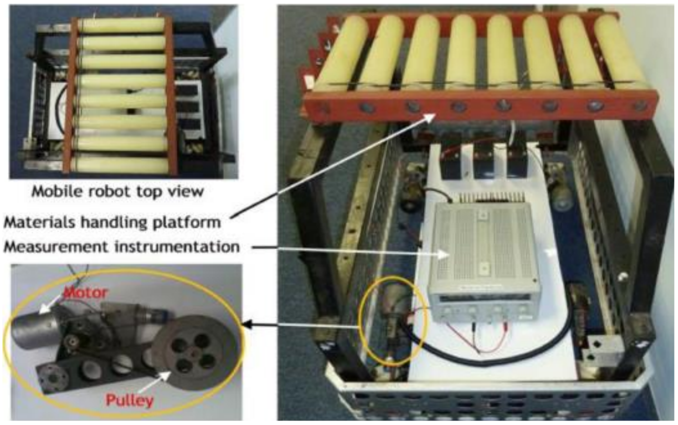

Figure 55 Mobile robot system front and top view [160]

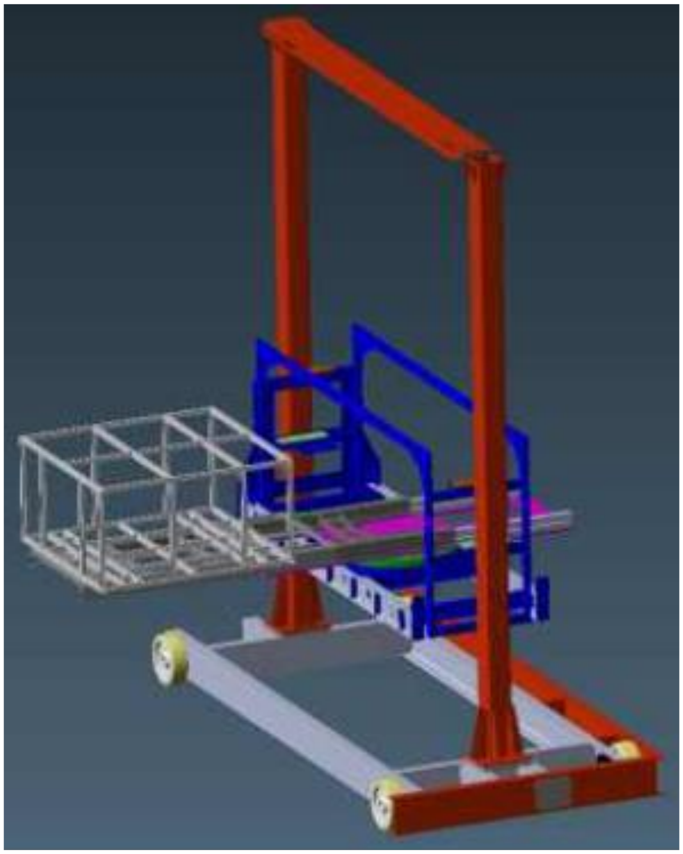

Figure 56 Cassette Handling Robot [161]

Figure 57 Demonstration vehicle with 18 W solar panel [163]

VI. CONCLUSION

Industrial robots can be used to automate and accelerate the manufacturing process of solar panels. They can also be used in a variety of applications in cleaning, troubleshooting, site surveys and site planning of solar and wind energy applications. Robots and Drones can be useful in all phases of a renewable energy project (siting, site survey, etc.) and can achieve faster and more efficient results saving effort and money. Drones can also be used in troubleshooting and maintenance operations. Moreover, renewable energy can be useful as a power source for robots, especially those involved in long-term autonomous missions. This paper presented a survey of the interactions between Robots and Mechatronic Systems with various Renewable Energy Resources.

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