Robotica: (2020) volume 38, pp. 1576–1604. © Cambridge University Press 2019
doi:10.1017/S0263574719001644

Renewable Energy for Robots and Robots for Renewable Energy – A Review

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(Accepted October 19, 2019. First published online: December 9, 2019)

SUMMARY
Fossil fuel sources are well suited to fulfill the energy needs of human beings. Unfortunately, there are some limitations and disadvantages pertaining to fossil fuels, some of which are drastic. The main issues are: firstly, there is a finite supply of these fuels, eventually this supply will be exhausted; secondly, burning fossil fuels contributes to global warming, leading to disastrous consequences for the environment and the health of humans. Switching to renewable energy sources is the viable solution to the aforementioned issues. Robots bring numerous benefits in a wide variety of applications. Introducing robots to production environments and other applications results in a remarkable improvement in terms of productivity and efficiency. In this paper, the integration between robots and renewable energy sources is discussed. In other words, two main points are investigated: (1) how can renewable energy be a viable source of energy for robots and (2) how can the renewable energy industry benefit from utilizing robots in the execution of renewable energy-related tasks. Some of the recent developments concerning the integration between robots and renewable energy are reviewed. In addition, more opportunities and expected advancements are also discussed.

KEYWORDS: Renewable energy; Robot; Drone; Solar energy; Hydrogen fuel cell.

1. Introduction
Fossil fuels (oil, natural gas, and coal) have several disadvantages:

(1) There is a limited supply of these fuels. Eventually, they will be exhausted.[1,2,25,57]
(2) The increasing scarcity of fossil fuels leads to higher costs.[23,59]
(3) Burning fossil fuels releases pollutants into the air, soil, and water causing dangerous diseases.[2,30]
(4) Burning fossil fuels sends greenhouse gases (GHGs) into the atmosphere, contributing to global warming and leading to severe climate changes in addition to other extreme conditions like floods and droughts.[2,30]

Nuclear power is risky, expensive, and produces dangerous wastes.[25,59] It is also based on a limited resource (uranium).[23] Germany will cease nuclear energy by 2022.[58]

Switching to renewable energy sources is the viable solution to the above threats[2,57] for the below reasons:

(1) Renewable energy resources will never be exhausted,[5] as they are naturally renewed[2–4,30] at a rate equal to or faster than the rate at which they are consumed.[4]

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(2) Most renewable energy investments are spent on building and maintaining the facilities, instead of importing fossil fuels.[5]
(3) Renewable energy sources are often called "clean" as they produce few or no pollutants.[2,57,59]
(4) Using renewable energy sources reduces GHG emissions, thus avoiding disastrous climate changes.[5,23,30,59,127]
(5) Other advantages of using renewable energy sources include job opportunities[24,30] and increased energy security.[30,59]

The recent years have witnessed an international interest for renewable energy resources. 2015 was a year of several agreements related to renewable energy, including commitments by the G7 and the G20 toward renewable energy.[115] In 2016, major companies like Google, Apple, and Microsoft have made large commitments to renewables. An alliance has also been established by the corporate community that focuses on finding ways for corporations to purchase renewable energy.[48] In 2017, the share of renewables in global power generation increased from 7.4% to 8.4%.[132] A known value of 157 GW of renewable power was produced in 2017, compared to 143 GW in 2016.[129] Germany is planning to rely completely on renewable sources for electricity supply by 2050.[58] Traditionally, the development of renewable energy technologies was mainly carried out by the United States and Europe. However, emerging countries are now actively taking place in activities related to renewable energy.[126] By achieving the transition to renewable energy, Iceland has made a remarkable success story in renewable energy development.[172] The aforementioned facts outline the wide adoption of renewable energy sources by the international community as an efficient alternative to fossil fuels.

The main disadvantages of renewables are: (1) cost,[59,131] and (2) fluctuating and intermittent generation.[25,32,59,60,131] These can be improved by: (1) resource diversity,[25,60] (2) using efficient control strategies, and (3) using smart grids for efficient storage and delivery of energy.[59,60,131] Other non-technical challenges include social, economic, and political issues.[59]

Employment effects of renewable energy

There are many benefits of promoting renewable energy. While all benefits are generally accepted, the impact of renewable energy on employment is still controversial.[181] Transitioning to renewable energy entails a contraction of the fossil fuel sector, along with a loss of jobs. An important question is whether renewable energy will create more jobs than will be lost in fossil fuels.

- *Types of employment effects*:[180]
  - ➢ *Direct employment effects:* include employment created by the core activities of a project excluding the intermediate inputs necessary for it, for example, the manufacturing of renewable energy equipment.
  - ➢ *Indirect employment effects:* cover traders as well as service and material providers.
  - ➢ *Induced employment effects:* can be associated with the downstream effects of the project and direct and indirect employment, including goods and services purchased by those employed directly and indirectly.

Renewable energy investments generate greater direct employment opportunities than those of conventional energy sources. Indirect and induced employment effects of renewable energy investments often only become visible over time. Their measurement is more complicated and controversial than that of direct employment effects, and there are important limitations to their assessment.[185]

- *Models to estimate the employment effects of renewable energy*:[180]
  - ➢ *Input–output methods:* can calculate direct, indirect, and induced effects.
  - ➢ *Analytical methods:* commonly used for regional or provincial studies where the input–output method cannot easily be applied. The method is usually reliant on extensive surveys. While the analytical method may not be able to determine indirect jobs, it can be a more transparent model.[181]

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

Table I. Increase in global renewable energy employment.

Year	Number of jobs (million)	Percentage increase (%)
2015	8.1	5
2016	8.3	2.8
2017	8.8	6.3

- *Factors affecting job estimates*
  - ➢ *Labor intensity of renewable energy:* renewable energy is more labor intensive during the construction and installation phases than conventional energy. Meaning that a given amount of workers in the renewable energy sector will produce less energy than the same amount of workers in the conventional energy sector.[181,187]
  - ➢ *Cost increases and availability of investment:* along with direct job losses in the conventional energy industry, promotion of renewable energy could also cause job losses through the drain on economic activity caused by higher electricity prices.[182]
  - ➢ *Counting job losses:* job losses in the conventional energy sector cannot be solely blamed on the uptake of renewable energy. The slowing down of employment in the conventional energy sector was due to factors such as the replacement of thermoelectric plants with less employment intensive alternatives.[183]
  - ➢ *Job quality and job skills:* while job ratios can be used to describe the amount of jobs that are created, describing the type of jobs created is much more difficult.[184]
  - ➢ *Influence of sources of information:* it is important to consider who performed the study, what sources of information were used to form the results, especially when using results from non-peer reviewed reports.[181]
- *Quantitative analysis*

In ref. [189], a study was conducted, focusing on employment impacts in the short-to-medium term, and leaving aside the long-term comparison of operations and maintenance employment. It was found that on average 2.65 full-time-equivalent (FTE) jobs are created from $1 million spending in fossil fuels, while that same amount of spending would create 7.49 FTE jobs in renewables. These job numbers include both direct and indirect (supply chain) jobs. Thus, each $1 million shifted from brown to green energy will create a net increase of 5 jobs.

Table I outlines the increase in global renewable energy employment (excluding large hydro):[175,178,179]

- ➢ IRENA suggests that jobs in the renewable energy sector could rise to 23.6 million in 2030.[179]
- ➢ In the United States, during 2015, renewable energy jobs increased by around 6%, while employment in oil and gas extraction and support activities contracted by 18%.[176]
- ➢ In China, during 2015, renewable energy employed around 3.5 million people, exceeding the 2.6 million employed in the country's oil and gas sector.[177]

- *Important facts*
  - ➢ For three consecutive years (2015, 2016, and 2017), countries with the highest number of renewable energy jobs are China, Brazil, the United States, India, Japan, and Germany.[175,178,179]
  - ➢ A factor that affects labor needs is increasing labor productivity, especially in bioenergy. Production of equipment such as solar photovoltaic (PV) panels and wind turbines is also subject to increased automation and results in the reduction in labor requirement in manufacturing. Finally, the automation of operation and maintenance of solar PV and wind plants may further reduce jobs.[178]
  - ➢ Clean energy spending creates more high-paying jobs than fossil fuels, while it is also better at creating jobs for low-skilled workers.[186]

- ➢ Some renewable energy jobs come at the expense of jobs in the conventional energy sector. However, job gains in renewables usually greatly outweigh the losses related to conventional energy.[188]
- ➢ Particular attention should be given to displaced workers from the conventional energy sector and work they can find in the renewable sector.[185]
- ➢ Meeting the increasing labor requirements of the renewable energy sector will require stable and predictable policy frameworks that encourage deployment, investments, and education.[175,178,179]
- ➢ There is no single clear result about whether renewable energy positively or negatively effects employment. It is important to note that even if a study demonstrates that renewable energy reduces net employment, there are other potential benefits for renewable energy.[184]

In 1961, the first industrial robot was installed.[70] Robots are getting more advanced in terms of efficiency, speed, accuracy, and flexibility.[75] Using robots in production processes and other applications introduces significant benefits in productivity.[6] Robots are used in numerous applications in diverse fields including manufacturing automation, maintenance, space and underwater exploration, hazardous waste disposal, monitoring and surveillance, surgery, rehabilitation, domestic services, and entertainment.[35,90] Important advantages of robots include:[6,72]

(1) Enhancing labor productivity, leading to increased production rates.
(2) Delivering relief from tiresome and hazardous work, thus improving safety.
(3) Improving product quality and reducing material waste.
(4) Robots can operate in harsh environments, under severe conditions (e.g., low or high temperatures).
(5) Robots do not need salaries or promotions, thus reducing operating costs.

In this paper, the integration between two major disciplines, namely robotics and renewable energy sources is investigated. The paper tries to answer the following questions: (1) what are the benefits of using renewable energy as a power source for different types of robots? and (2) what are the benefits of using robots to accomplish renewable energy-related tasks? Some of the recent developments concerning the integration between robots and renewable energy are reviewed. In addition, more opportunities and expected advancements are also discussed. The paper is organized as follows: in Section 2, the most important renewable energy sources are discussed. In Section 3, general criteria used for classification of robots are discussed, with emphasis on classification from the *mobility* point of view. Section 4 discusses the benefits that can be gained by employing robots in different tasks related to renewable energy sources including manufacturing of renewable energy equipment, different processes related to renewable energy projects, troubleshooting, and maintenance with emphasis on solar energy. Section 5 discusses the advantages of using different types of renewable energy as power sources to operate robots depending on robot type and application. Section 6 discusses some cases where both robots and renewable energy can be simultaneously employed for the other. Section 7 discusses the main points related to this research including further opportunities and developments. Section 8 concludes the paper.

2. Renewable Energy Sources

2.1. Solar energy

About 124 EW of solar power hits the Earth's surface per year.[8] Solar energy can be classified as: (1) *passive solar energy* is the direct or indirect use of the sun's thermal energy,[11] (2) *active solar energy* using the sun's radiation to generate electricity.[12] Two methods are available for converting solar power into electricity: (1) *indirectly* (*thermal)* by collecting and concentrating solar power to produce steam which is then used to drive a turbine, (2) *directly* using PV effect.[9,131] Several technologies are available for producing electricity based on the PV effect, for example, crystalline silicon.[10] The output power of PV cells is largely influenced by the weather, date, and time.[56] A group of solar cells are called a *solar module*. A group of solar modules are called a *solar array*. A solar module or array is sometimes called a *solar panel*.[13] Several methods exist for improving

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

the efficiency of PV conversion: (1) solar tracking,[14–16] (2) optimization of solar cell characteristics,[17,18] and (3) developing new materials and technologies.[19–21] Because of its ubiquity, solar energy is one of the most secure sources of energy for any country. It is also one of the least polluting energy resources.[22] The intermittent and fluctuating generation are major disadvantages of solar energy.[7]

There are some situations where a solar energy system is hard to be implemented, such as densely populated countries, bumpy terrains, and high-latitude regions. Suggested methods to mitigate these issues are discussed below:

- *Densely populated countries*
  - ➢ *Agrivoltaic systems*

Using large areas of land for solar farms will increase competition for land resources between food production demand and energy demand.[157] This competition becomes more acute in densely populated regions and mountainous areas. This issue can be mitigated using the concept of agrivoltaics or co-developing the same area of land for both a solar PV power station and conventional agriculture.[156] The idea of combining agriculture and solar energy development into an agrivoltaic system was first proposed in ref. [154]. Depending on the level of shade allowed by the pattern of installation, crops grown under the PV modules can be as productive as full-sun plots.[153] Utilizing shade tolerant crops enables crop yield losses to be minimized.[156] Agrivoltaic systems maximize the efficiency of water use as water used for cleaning the overhead PV panels can also be used to water the crops below it.[155] The solar PV modules can be mounted either on the ground or on stilts with the area underneath the stilts used for agriculture to ensure better land use.[153,156] However, the increased land use efficiency comes with a higher cost in racking. The crop selection, mounting height, optimal tilt angle, solar irradiation, and local climate play a role in the optimal selection of PV system geometry for an agrivoltaic system. The configuration for the PV is determined by formulating an optimization problem with the objective of maximizing the solar irradiation incident on the PV which in turn is proportional to the power output of the PV module, taking into account the additional land cost from minimizing inter-row shading,[156] ensuring that the crops get the required amount of sunlight under the PV panels and minimizing the cost of installation of the panels.[155]

In ref. [152], conventional options (separation of agriculture and energy harvesting) were compared with two agrivoltaic systems with different densities of PV panels. The results indicate that agrivoltaic systems may be very efficient: a 35–73% increase of global land productivity was predicted for the two densities of PV panels. In ref. [153], the effect of the placement of half density and quarter density PV panels on shading patterns over an agricultural land at different months of the year was studied. The analysis was conducted with panels placed at a height of 4 m above the ground to provide access to the crops for farm workers and machinery. With half density and quarter density panel distribution, the agricultural land received about 60% and 80% of the direct sunlight compared to a land without panels.

➢ *Transmission of solar power between countries*

Although this solution may face some technical difficulties, but it is still possible[160]

➢ *Rooftop solar panels*

California became the first state in the United States to make solar mandatory for new houses. Beginning in 2020, newly constructed homes must have solar panels[161]

➢ *Transparent solar cells*

MIT researchers are making transparent solar cells. The new solar cells absorb only infrared and ultraviolet light. Visible light passes through the cells unimpeded. They estimate that using coated windows in a skyscraper could provide more than a quarter of the building's energy needs without changing its look[158]

➢ *Offshore solar plants*

For example, the 70 MW Kagoshima Nanatsujima mega solar power plant[159]

- *Bumpy terrains*

The workaround to undulating topography is non-intrusive mounting options made for slopes, grades, and hills. The common solution is extended post length, but installers can make custom brackets or install panels in smaller rows or single-bay tables[162]

- *High-latitude regions*

Installations at high elevations experience more frequent snowfall and hence might suffer a certain production loss. However, an analysis of solar energy installations in mountainous countries is presented in ref. [163] taking Switzerland as an example has concluded that irradiance in the absence of clouds is larger at high elevations. Also, the presence of snow with its high surface reflectance will increase the yield of PV panels when optimal tilt angles are used. Steeper installation angles are also preferable for self-removal of snow through sliding. Also, steeper panels will suffer less from soiling due to dust, dirt, and other particles. The study also concluded that weighing the effect of lower production values against having a cleaner panel at 90° tilt would need to be done on a case-by-case basis because it requires site-specific information regarding snow, dust, and wind.

2.2. *Wind energy*

A wind turbine is a machine with rotating blades that converts the kinetic energy of wind into electric power.[26,27,92] Wind energy is influenced by solar energy. A small amount of the solar radiation is converted to kinetic energy.[28] The location and characteristics of the resulting winds are affected by many factors, for example, geography and temperature gradients.[29] The primary classification of a wind turbine is based on shaft orientation and rotational axis. A turbine with its shaft mounted parallel to the ground is called a horizontal axis wind turbine. A turbine with its shaft normal to the ground is called a vertical axis wind turbine.[148] Wind energy can also be classified as onshore and offshore. The primary reason for developing offshore wind energy is to provide access to wind resources in areas where onshore wind energy is unavailable and/or siting conflicts exist with other purposes.[79–81] In refs. [93–95], the advantages of wind energy as well as the environmental damages related to other methods of electricity generation have been discussed. However, the deployment of wind energy must overcome a number of issues:[77] (1) The cost of wind energy depends on the location,[82,83] (2) wind energy is intermittent and fluctuating,[84–88,131] and (3) the output power is hard to predict.[82,131] Human welfare is also affected by wind energy development in different ways:[99] (1) electromagnetic interference related to wind turbines,[100,101] (2) visual impacts,[102–106] and (3) noise generated by wind turbines may be annoying and causes health problems.[113,117–119]

2.3. *Biomass energy*

Biomass energy was used long ago by burning wood for cooking and to keep warm.[71] Biomass is a general term for all organic material that originates from plants.[134] Through the process of photosynthesis, chlorophyll in plants captures the sun's energy by converting carbon dioxide from the atmosphere and water from the soil to carbohydrates. When these carbohydrates are burned, they return back to carbon dioxide and water, thereby the energy they contain is released.[122,133,134] Biomass can be converted to thermal energy, fuel, and other chemical products through various processes.[133]

2.4. *Ocean energy*

The basic ways to harness the ocean's energy are: (1) *tidal energy:* the tides are cyclic variations in the level of seas and oceans resulting from the combined effects of the gravitational forces exerted by the Moon and the Sun, and the rotation of Earth, (2) *wave energy:* it is continuous but highly variable, (3) *ocean thermal energy conversion*: by exploiting the temperature difference between shallow and deep waters, energy can be extracted using a heat engine.[69,96,97]

2.5. *Hydroelectric energy*

Hydroelectric power is generated from water in motion.[26] The potential energy of water is converted to kinetic energy that rotates a turbine to generate electricity.[47,107] Hydropower advantages

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

include high efficiency, low operating costs, and minimal maintenance requirements. Hydro reservoirs also provide inherent energy storage that allows fast response to electricity demand variations across the grid, and compensation for intermittent generation from other sources. Major hydropower issues include public acceptance, high initial costs, long payback periods, and long construction cycles. Also, there are concerns about GHG emissions from reservoirs caused by organic material.[107] Hydroelectric power plants can be categorized according to size: (1) *micro plant* generates <100 kW, (2) *mini plant* generates 100 kW–1 MW, (3) *small plant* generates 1 MW–30 MW, and (4) *large plant* generates >30 MW.[108]

2.6. *Geothermal energy*

Geothermal energy is defined as natural heat from within the Earth.[26] The total geothermal energy available is approximately 42 TW.[130] A geothermal reservoir is formed when hot water or steam is trapped in cracks under a layer of impermeable rocks.[110,114] Applications of geothermal energy include heating, growing plants in greenhouses, and several industrial processes.[68] Geothermal energy is plentiful in the regions of active volcanoes.[26] The unique geographical characteristics have bestowed Iceland with a rich supply of geothermal energy.[111,112] Geothermal resources can be classified as: (1) *convective* include liquid- and vapor-dominated types, (2) *conductive* include hot rock and magma over a wide range of temperatures,[31] and (3) *deep aquifers* contain circulating fluids in pores and cracks at depths >3 km.[110] Some issues need to be considered before developing a geothermal energy project, for example, land licenses, environmental and societal impacts.[109]

Geologic perspective on geothermal play systems. Throughout the past decades, many resource-type schemes and definitions were published, based on temperature and thermodynamic properties. Temperature has been the essential measure of the quality of the resource. Relying on temperature alone is inconsistent and insufficient.[192] Also, temperature and thermodynamic properties are not known before drilling is undertaken.[190] Supplementary to the surface thermal information, geophysical data, geologic data, fault mapping, and other tools are used to characterize subsurface geologic structures and support drilling decisions.[194,197] An alternative possibility to cataloging geothermal energy systems is by their geologic characteristics, referred to as geothermal plays. A geological-based geothermal play-type catalog helps in understanding the nature of a resource and defining appropriate exploration strategies, reservoir evaluation and quantification of the geothermal potential.[192] As geothermal resources are components of geological systems, it is expected that some form of geological system analysis would be a fundamental step in geothermal resource assessments and that geological features would be used to distinguish between different types of geothermal systems. The play type is a common concept in the exploration for subsurface natural commodities. A play type describes the generic geological environment that might host an economic accumulation of the commodity. The identification of a certain play type has implications for exploration and extraction strategies.[190] In geological survey, features like faults, rock units, alteration zones, geothermal springs, travertine outcrops, mud volcanoes, fumaroles, steam-heated lakes, geysers, and mud pots are the main studied phenomena.[191]

In ref. [197], the results of 3D geologic analyses of two geothermal systems in the Basin and Range, USA were presented. The methodology is a quantitative and geologically focused technique that can be used to characterize geothermal areas. Surficial and subsurface geologic and geophysical data are synthesized in the construction of detailed 3D geologic maps of geothermal areas. Based on these 3D geologic maps, several geologic attributes that control permeability development and geothermal fluid flow along faults were examined.

Geothermal play systems

- *Convection dominated play systems*

Include the majority of operating geothermal power plants worldwide.[192] These play systems occur in areas of active tectonism,[195] active volcanism,[196] young plutonism, and elevated heat flow caused by extensional tectonics.[193]

- ➢ *Magmatic plays* relatively shallow, liquid magma activity is the dominant feature in all Magmatic Geothermal Plays. Extrusive magmatic plays can be found in regions with active basaltic volcanism at divergent plate margins (e.g., Iceland), basaltic to andesitic volcanism along island arcs (e.g., Java, Indonesia, and some New Zealand systems), or recent andesitic to dacitic volcanism (e.g., South American Andes or Taiwan). Intrusive magmatic plays may have no recent associated extrusive volcanism, but be evident as intrusive bodies within volcanic piles or beneath flat terrain along pathways of active faulting.
- ➢ *Plutonic plays* incorporate a heat source in the form of a young, crystallized but still cooling, intrusive igneous body. This play type is typically located along continent–continent convergent margins with recent plutonism. *Plutonic plays without recent volcanism* are related to the emplacement of felsic plutons, and are characteristic of mature subduction zones and decaying volcanism in continental crust. This play type can be found in regions with declining volcanism and fore- or back-arc regions of fold-thrust belts along subduction zones (e.g., The Geysers, California). *Plutonic plays with recent volcanism* are illustrated by the example of the Larderello geothermal system (Italy), which is controlled by the interaction between igneous rocks and faults.
- ➢ *Fault-controlled plays* In an Extensional Domain Geothermal Play the mantle is elevated due to crustal extension and thinning. The elevated mantle provides the principal source of heat for geothermal systems associated with this play type. Examples of geological settings hosting Extensional Domain Geothermal Plays include the Great Basin (Western USA) and Western Turkey.
- ➢ *Hybrids* some convective geothermal systems incorporate geological elements of more than one play type. For example, the Taupo Volcanic Zone in New Zealand hosts over 20 identified convective geothermal systems within an extensional zone containing both magmatic and plutonic bodies.[190]

- *Conduction-dominated play systems*

Include hydrothermal and petrothermal systems in sedimentary basins or crystalline rock. Applying advanced reservoir technology and engineering to developing man-made geothermal technology reservoirs and improving their efficiency is more important in conduction dominated play systems than in convection-dominated play systems.[192]

- ➢ *Intracratonic basin plays* incorporate a reservoir within a sedimentary sequence laid down in an extensional or thermal sag basin. Examples include the North German Basin (Germany) and the Paris Basin (France).
- ➢ *Orogenic belt/foreland basin plays* incorporate a sedimentary reservoir within a foreland basin adjacent to an orogenic mountain belt. Examples include the Molasse basin extending through France, Switzerland, Germany and Austria, and the Alberta Deep basin in Canada.
- ➢ *Basement (crystalline rock) plays* are a faulted or fractured crystalline (usually granitic) rock with very low natural porosity and permeability but storing vast amounts of thermal energy. An example is the Cooper Basin in Australia.[190]

The countries currently producing the most electricity from geothermal reservoirs are the United States, New Zealand, Italy, Iceland, Mexico, the Philippines, Indonesia, and Japan.[198]

2.7. *Hydrogen energy*

2.7.1. Overview. Hydrogen is the most abundant element in the universe. It is always combined with other elements.[46] Hydrogen can be acquired from various resources, both renewable and non-renewable.[98] It can be stored as a fuel using fuel cells to be utilized in many applications such as transportation and distributed generation systems. Hydrogen can also be used as a storage medium for electricity generated from intermittent renewable resources like solar and wind, thus providing a solution to one of the major issues of renewable energy.[98] A fuel cell uses hydrogen and oxygen to produce electricity, heat, and water. Both fuel cells and batteries convert chemical energy to electrical energy. However, the fuel cell will produce electricity as long as hydrogen is provided.[46] Hydrogen fuel cells play a vital role in accelerating the transition to a sustainable energy system.[98]

2.7.2. Hydrogen safety. All fuels have some degree of danger associated with them. The safe use of any fuel focuses on preventing situations where the three combustion factors [ignition source (spark or heat), oxidant (air), and fuel] are present. With a thorough understanding of fuel properties, appropriate engineering controls and guidelines can be established to ensure safe handling and use of a fuel.[215] A number of hydrogen's properties make it safer to handle and use than other fuels. For example, hydrogen is non-toxic.[215] In addition, because hydrogen is much lighter than air, it dissipates rapidly in case of a leak.[199,215] Some of hydrogen's properties require additional controls to ensure its safe use. Specifically, hydrogen has a wide range of flammable concentrations in air and lower ignition energy than gasoline or natural gas, which means it can ignite more easily.[199,215] Because hydrogen burns with a nearly invisible flame, special flame detectors are required. Some metals can become brittle when exposed to hydrogen, so selecting appropriate materials is important to the design of safe hydrogen systems. Training in safe hydrogen handling practices is a key element for ensuring the safe use of hydrogen. In addition, testing of hydrogen systems (tank leak tests, hydrogen tank drop tests, etc.) shows that hydrogen can be produced, stored, and dispensed safely.[215] Safe practices in the production, storage, distribution, and use of hydrogen are essential for deployment of hydrogen and fuel cell technologies.[200,201,214] Safety is not only a technological issue but also the major psychological and sociological issue facing the adoption of the hydrogen economy.[200] Hydrogen faces increased public concern about hydrogen-related hazards.[202] An important factor in promoting public confidence will be the development and adoption of internationally accepted codes and standards.[200]

Hydrogen storage technologies

- *Physical-based storage* (compressed gas, liquid, and cryo-compressed). Cryogenic vessels have an additional protection layer (vacuum jacket) in case of accidents,[203,205] making cryo-compressed storage highly safe.[205] Also hydrogen has low adiabatic expansion energy at cryogenic temperatures.[203] Therefore, in case of leakage or tanker rupture a severe explosion would not happen unless something cause ignition of the gas. Low temperature of the leaked hydrogen gas can lead to damage and malfunctioning of the adjacent valves or pressure relief devices which are not strictly rated.[204]
- *Material-based storage* (chemical sorption and physical sorption). As of today, physical sorption technologies are far from being widely used since all experiments have been conducted on small scales and the performance criteria are not satisfactory.[201]

Hydrogen delivery technologies

- *Gaseous hydrogen delivery (pipelines and tube trailers).* To make sure the tube trailer is safe to use, several tests such as hydrostatic burst, penetration test, and pressure and temperature cycle tests are performed.
- *Liquid hydrogen delivery*
- *Material-based hydrogen carriers* can offer higher safety levels, due to low storage pressure, manageable properties at ambient conditions, and good gravimetric density compared to gaseous storage.[201]

Problems to address

- *Material properties-related issues*

  ➢ *Hydrogen impact on materials*: hydrogen embrittlement is an important concern for steel pipelines. To tackle the problem, fiber reinforced polymer can be used rather than using other types of steel.

  ➢ *Liner blistering in pressure vessels* in a composite overwrapped pressure vessel, a polymer liner is assembled with a metallic boss and wrapped with carbon fiber composites. Liner is used to ensure that the vessel is sealed. Under high pressures, plastic liner absorbs hydrogen gas and if depressurization occur too fast, then the accumulated gas cannot escape by

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

diffusion and blistering happens. The question of how exactly blistering can affect leakage in pressure vessels needs to be addressed

- ➢ *Damage mechanisms of carbon fibers:* the properties of composite pressure vessels depend on a large number of parameters. Understanding the physics behind fiber breaks is vital to design a reliable storage vessel.[201] Exact properties are very hard to achieve and as proposed in ref. [206], using probabilistic approaches for predicting fiber failures is a reasonable option.
- ➢ *Resistance to fire and high temperature in storage vessels:* Whenever resins and polymers are used, the maximum operational temperature would be a concern. Accordingly, fire protection and understanding the composite materials behavior in fire is of very important. A common protection method to protect storage vessels from burst is thermally activated pressure relief device), this device empties the vessels in case of elevated temperatures.[201] Another method to protect storage vessels from fire is to apply intumescent paint on their outer surface.[201] In ref. [207], the impact of using container walls around above-ground hydrogen storage vessels in a fueling station is investigated. This study proves that container walls are able to greatly reduce the radiative heat flux from a fire located near the storage tanks.

- *Hydrogen handling-related issues*

  - ➢ *Temperature variation:* inside tanks during filling and emptying can result in a shorter lifetime of storage vessels in the long run unless design improvements be applied. Determining the best location of installing measurement devices is of interest. One approach that can be more convenient (to install and maintain) is estimating the temperature inside the tank by monitoring external temperatures (bosses and outer surface) but it would require more experimental data to calibrate sensors accurately.
  - ➢ *Hydrogen leakage* hydrogen molecules are light and small. Therefore, they can permeate through materials and/or penetrate through seals relatively easily.[201] In enclosed areas, the leakage is more dangerous. Since hydrogen is odorless and colorless, people would not realize if there is a leak. Thus, detection is necessary using accurate and reliable sensors. Advances in this regard have been explained in ref. [208].
  - ➢ *Pressure fluctuations in pipelines:* Pressure fluctuation would exist in the system due to variability in production rate of renewable sources and variations in the demand for hydrogen gas. These fluctuations may severely damage the distribution network. Studies are required to estimate the amplitude of the expected fluctuations, characterize the impacts, and design the control scenarios.[201]

Tools and Methods

- *Quantitative risk assessment* (QRA) the purpose of QRA is to provide information for decision making about a system. A common way that QRA can help making decisions is to determine whether or not the risk of failure in a system is as low as reasonably practicable.[201] The use of a standard platform for conducting hydrogen QRA enables various industry stakeholders to produce defensible, traceable, repeatable, and verifiable calculations of risk and consequences. A quality QRA incorporates a large amount of information spanning multiple disciplines.[213] The amount of available data for hydrogen-related failures and accidents is limited and this is mainly why performing a credible QRA for hydrogen is still challenging. QRA for hydrogen infrastructures has been discussed in ref. [210]. The HyRAM toolkit establishes a standard methodology for conducting QRA and consequence analysis relevant to assessing the safety of hydrogen infrastructure. The HyRAM integrates deterministic and probabilistic models for quantifying risk of accident scenarios and characterizing the impact of hydrogen hazards.[213] HyRAM is able to calculate three risk metrics:[212]

1. Fatal accident rate: Expected number of fatalities per 100 million exposed hours.
2. Average individual risk: Expected number of fatalities per exposed individual.
3. Potential loss of life: Expected number of fatalities per dispenser-year.

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- *Remaining useful life estimation* Estimating RUL is pivotal in condition-based maintenance and prognostics. Therefore, it would affect safety evaluation.[209]
- *Data collection* in addition to data concerning accidents and root cause, it is important to know the hydrogen physical behavior in different conditions, its interaction with other materials and all other influencing parameters to be able to accurately figure out the consequences and risks.[201] Valuable efforts have been made to mitigate the issue of lacking data. For instance, Hydrogen Incident and Accident Database[211] is an online database that is continually collecting and categorizing data.
- *The Hydrogen Tools Portal*[216] aims to support implementation of the practices and procedures that will ensure safety in the handling and use of hydrogen in a variety of fuel cell applications. The portal brings together and enhances the utility of a variety of tools and web-based content on the safety aspects of hydrogen and fuel cell technologies to help inform those tasked with designing, approving, or using systems and facilities, as well as those responding to incidents

3. Classification of Robots

Robots can be classified according to several criteria:[72]

- *Geometry:* serial and parallel manipulators.
- *Workspace:* reachable and dexterous workspace.
- *Actuation:* electrical, hydraulic, pneumatic, etc.
- *Control:* servo (closed loop control) and non-servo (open loop control) robots.
- *Application:* assembly and non-assembly robots.

For the purposes of this paper, a classification of robots according to "*mobility*" is discussed below:

i. *Fixed (Industrial Manipulators):*

Follow programmed steps to execute variety of tasks such as moving materials, painting, and welding.[73] Most of the industrial robots are either parallel or serial arms. There are many types of serial manipulators, the most prevalent ones are: the Cartesian, cylindrical, Selective Compliance Articulated Robot Arm (SCARA), and anthropomorphic.[36] There are two basic types of parallel manipulators: classical and cable based. Cable-based parallel manipulators consist of a fixed base and a mobile platform, which are connected by several cables. They are structurally similar to the classical parallel ones, but the legs are replaced with cables. A modular re-configurable parallel robot consists of a number of discrete modules that can be mechanically and electrically connected with each other. They can be referred either to classical or to cable-based parallel manipulators.[55]

ii. *Mobile:*

Mobile robots can be autonomous, semi-autonomous, or non-autonomous.[78] Fully autonomous robots can operate without a continuous external control, semi-autonomous robots require the guidance of an operator but with the capability of executing certain tasks on their own such as obstacle avoidance. There are several types of mobile robots:[36, 78]

(1) *Flying (drones), also unmanned aerial vehicles (UAVs):*

Unmanned aircrafts that may be remotely controlled or can fly autonomously.[74]

(2) *Marine:*

- *Water surface robots:* unmanned surface vehicles (USVs) and autonomous surface vehicles (ASVs).
- *Underwater robots:* unmanned underwater vehicles and autonomous underwater vehicles (AUVs).

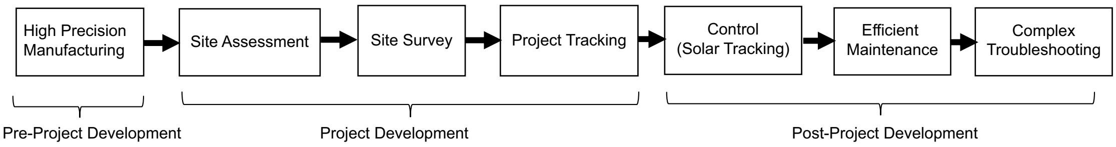

Fig. 1. Tasks related to pre-, post-, and active solar power plant project development.

(3) *Terrestrial*

- *Wheeled Robots:* characterized with simple control, high load capacity, efficiency, and reduced cost.
- *Tracked Robots:* best suited for rough terrain. The main disadvantage is the lower speed compared to wheeled robots.
- *Legged Robots:* legs improve the mobility of robots. They are able to move in soft and rough terrains.
- *Hybrid Robots:* merge the capabilities of both wheeled and legged robots by incorporating both wheels and articulated legs in the same system.[36]

4. Robots for Renewable Energy

Considering the numerous advantages of robots that proved to be very helpful in several diverse applications, renewable energy is not an exception. It is obvious that using robots in every possible aspect related to renewable energy is expected to add huge benefits that could have been missed otherwise. Renewable energy is not just another application for robots. Switching to renewable energy is a strategic decision for the well-being of humanity. As such, using an effective tool like robots to harness renewable energy is not an option, it is a must. In this section, some of the renewable energy-related tasks where robots can be used are discussed. These include manufacturing, renewable energy project development, troubleshooting, maintenance, and control.

4.1. A case study – The solar power plant

Considering the development of a solar power plant project, key areas for which robots can be applied are identified in three phases, namely pre-project development phase, active project development phase, and post-project development phase (as depicted in Fig. 1). In the following sub-sections, each task depicted in Fig. 1 is described with examples given from the literature.

4.1.1. High precision manufacturing. Solar cell fabrication is now a mature industry. However, manufacturing companies are always trying to attain lower costs and higher efficiency by exploring new technologies and techniques. In an effort to build a better solar cell, the National Renewable Energy Laboratory (NREL) has been developing new robots for the fabrication of thin-film solar cells, analyzing glitches with higher speed and accuracy.[63] An agreement that aims at developing a fully automated PV production lines with high production rates has been conducted between Spire Corp. and KUKA GmbH. This is achieved by integrating KUKA's expertise in industrial robots and automation solutions with Spire's PV module production equipment.[66]

4.1.2. Site assessment. Site assessment is an early step in project development and one of the major factors affecting project success.[123] It is defined as the evaluation of a site's feasibility for project development.[64] Identification of resource potential is an important factor for deciding on the best site. It is a process that depends on an intensive analysis of localized weather patterns.[123] A power plant can cost lots of money. A clock starts ticking at the very moment when an investor sets that money aside for the project. Every day in which that money is not earning revenues translates into loss. Consequently, building a good project is important but how fast this project is built is crucial so that the project starts generating revenues as soon as possible. For a solar power plant, the clock starts ticking with the *site assessment* step. Traditionally, a service like Google Earth was used for this purpose. However, the expected accuracy in this case could be very low. Consequently, more time was spent assessing the site. Using high resolution drone imagery, every detail of the site is visible very quickly. It is estimated that by using drones, the time it takes to build a proposal-ready site assessment is reduced by 90%.[64]

4.1.3. Site survey. After a site is considered suitable for a project, the next step is to conduct a site survey. Drones can also play an important role at this stage. Even if survey-grade GPS is used, the process takes a long time and much effort for a survey to be completed. On the other hand, drones can quickly build precise topology maps by flying over a site. In addition to accelerating the early stages of the project, the responsible teams can benefit from the available precise information to accurately estimate resource utilization at the project site, further reducing project costs.[64]

4.1.4. Project tracking. Project tracking across large sites is not an easy task. Tracking different crews across large areas is a tedious task. For the project manager, this can create an unpleasant situation of disjointed information; consequently, it can be difficult to fully understand the information for quick decision making. This can hinder their ability to manage the site effectively. Drones can provide images of the whole site in real time, enabling the project manager to view the general status of the project at a glance. Furthermore, it allows them to deal with other issues like manpower, materials, safety, etc. Because the information is digitized and can be stored in the cloud, this also allows project managers to easily analyze the results of the current project as well as projects conducted in the past. Lessons learned can then be applied for better results in future projects. The ultimate outcome is an immediate and continuous improvement in project velocity. During the early stages of drone technology development, the concern was about making drones functional and reliable. Now, in the era of data collection and analytics, drones are expected to play a much more important role.[64]

4.1.5. Control (solar tracking). The incident solar radiation on a fixed PV panel is continuously changing due to the on-going change in relative positions of the Sun and the Earth. To achieve maximum efficiency of a PV panel, it is necessary to provision the panel with a solar tracking system.[49] Solar tracking systems can be classified according to several criteria:[7,49]

- Number of rotation axes
- Orientation method of solar panels:
  - ➢ Orientation based on a previously computed sun trajectory
  - ➢ Online orientation (instantaneous response to actual solar radiation)
- Activity type (active or passive solar trackers).[49]

The design of a single axis solar tracker system was proposed in ref. [49]. The system determines the optimum panel position with respect to the Sun using a light intensity sensor. An intelligent drive unit that receives its input signals from the light sensor is used to drive a DC motor to control the position of the panel. The design of an automatic solar tracker robot was discussed in ref. [139]. The robot is programmed to detect sunlight by using two light dependent resistors. A servo motor aligns the solar panel to receive maximum light. A digital compass is used to detect the robot's position. SoRo-Track is presented in ref. [142], a two-axis soft robotic actuator for solar tracking and building integrated PV applications.

4.1.6. Efficient maintenance. The efficiency of solar cells may deteriorate remarkably as a result of the deposition of dust, bird droppings, tree leaves, and similar substances.[51–53] The amount of dirt deposited on solar panels depends on many factors, for example, location and weather. An appropriate strategy should be implemented for cleaning the solar panels, otherwise severe losses may result. Power loss may reach about 25% annually. The profit of the solar power plant owner may drop by 15–17%. Higher losses are also expected in extreme cases.[52] Dirt may also lead to permanent damage of the panel. Solar panels cleaning is not always an easy task as the solar panels are usually installed in dangerous and/or hard to reach locations. Manual cleaning is not practical as it takes much effort and time. Automatic cleaning is thus the obvious solution.[51] Many types of "cleaning robots" have been developed for automatic cleaning of solar panels. A solar panel equipped with auto-cleaning robot is described in ref. [54]. A self-cleaning solar panel employing a robot designed

Table II. Capital, operational, and maintenance expenses of different cleaning methods.

	Expenses			
Cleaning method	**Capital**	**Operational**	**Maintenance**	**Suitable for**
Vehicle-mounted	High	High	High	Low and medium soiling levels
Semi-automated	Low	Low	Low	Low and medium soiling levels
Portable	Medium	Low	Low	Rooftop installations
Fully automated	Very high	Very low	Low	High soiling levels Large PV systems
Manual	NA	High	NA	Rooftop installations Small solar systems
Self-cleaning	NA	NA	NA	Very low soiling levels Panels with high tilt angles

to meet the specification of the flat plate panel was proposed in ref. [50]. The robot utilizes brushes that are driven by DC motors. The Solarbrush proposed in ref. [51] is an autonomous robot that can be used for dry cleaning of solar panels. The robot utilizes tracks made of suction cups to move over the panels. The robot is able to cross gaps up to 30 mm and can work on surfaces tilted up to 35°. Wash panel produces robots that can clean arrays of solar panels by moving a vertical brush horizontally over a row of panels. A water hose is used for wetting the panels during the cleaning process.[51] A portable cleaning robot that can traverse the entire length of a panel has been proposed in ref. [141].

Cost analysis of solar panel cleaning methods
Cleaning methods

- *Vehicle-mounted systems:* consist of a brush attached to a vehicle which drives between the PV module rows.
- *Semi-automated:* placed at the beginning of each PV module-mounting table. The device then moves automatically over the surface of the PV modules. After completing one PV module table, the device has to be placed onto the next PV module table manually.
- *Fully automated:* installed on each row of a PV system. Devices are programmed to move along a single module row without requiring any manual intervention.
- *Portable robots:* when operating autonomously, they have sensors and a control system for detecting the end of the PV module. Other devices are driven by remote control, in this case manual inputs are required.[169]
- *Manual cleaning using a* soft brush and deionized water.
- *Self-cleaning* PV modules are installed at different tilt angles in various climate zones resulting in different soiling patterns, affecting the self-cleaning ability of the PV modules.[169] In arid and semi-arid regions, less precipitation results in a lower self-cleaning ability.[171]

Cleaning costs
Table II compares the capital, operational, and maintenance expenses of different cleaning methods in addition to the situations in which each method is preferred.

Notes concerning costs

- An advantage of semi-automated method is that the device can be stored in protected environment when it is not needed, increasing its lifetime and decreasing maintenance cost.[169]
- Operational costs of manual cleaning include labor cost plus the cost of materials used for cleaning.[165]
- The operational costs are heavily dependent on the required cleaning frequencies.[169] In ref. [168], a method was devised to determine the optimal number of days between cleaning cycles depending on a number of factors, for example, cost of cleaning, average daily losses in solar conversion efficiency due to dust.

- Factors specific to residential installations may influence the cost of manual cleaning: Rooftop installations incur higher costs than ground installations. Also, steeper roofs may incur additional cost.[174]
- A disadvantage of manual cleaning is that the operational cost varies greatly by region. For example, compared to the national average in the United States, labor cost varies by −35% and +63% for McAllen and Katy, respectively, although both cities are in the same state.[174] Cleaning costs will also vary depending on the soiling type. For example, in the Middle-East, where the predominant soiling type is sand – which does not require much material or labor to be cleaned – the cleaning cost is relatively small compared to other countries.[166] A similar concern pertains to vehicle-mounted cleaning as the price of the fuel necessary to operate the vehicle may vary between different countries. On the contrary, the operational costs of robotic-based methods are more consistent among different regions and countries.
- Long module rows are beneficial to reduce the costs. A gap between modules may cause an interruption in the cleaning process. This means that either the cleaning device needs to be manually transferred or, if it is permanently installed, another device must be installed.

Real-world cases

Tests conducted on a plant in the Middle East indicated costs of $18,000/year to clean 4.5 MW of panels using a pair of Exosun machines, compared with $30,000/year for using cleaning vehicles. Both methods would use two workers. The savings mainly come from cutting vehicle fuel and depreciation costs. The price of an Exosun machine is around 15% of the price of a panel-washing vehicle. Maintenance cost is around $2,500/year for two robots, according to company estimates.[173] In ref. [164], a comparison between the performances of panels that were cleaned daily by automated robotic system that uses silicone rubber foam brush with no water versus manually cleaned panels using deionized water on a weekly basis was conducted. It was concluded that the performance difference after 1 week of not being cleaned reaches approximately 1.5%.

Factors affecting the choice of the cleaning method

- Cleaning requirements (frequency and cleaning method) are very much location-dependent and need individual decisions for each PV system.
- *Soiling level* based on the expected climate conditions at the site, including rain, humidity, dew, wind, and ambient temperatures over the course of a year.
- *Soiling Type*
  - ➢ Sand type affects their ability to be easily removed.[169] Fine sand particles are more challenging than coarse particles: (1) Fine sand has a higher shading impact on the PV modules,[172] causing higher power losses. (2) Coarse sand particles can be more easily blown off by the wind, allowing self-cleaning.[170]
  - ➢ *Anthropogenic pollution* (busy roads, industrial sites, agricultural activities, etc.) increase the level of soiling.
  - ➢ *Seasonal effects* (pollination or seeding) can have a strong effect on soiling.
- The further away a PV system is from a low cost labor settlements, the higher the potential labor costs and the more advantageous a fully automated system may be.[169]
- In moderate temperature zones, module cleaning plays a less important role (except in the case of anthropogenic soiling).[169] In Germany, for example, soiling-related performance losses are around 1% without cleaning.[170]
- Depending on the cost of cleaning and the level of dust accumulation, the cleaning operation may be justified or not.[168] In ref. [167], it was concluded that cleaning is justified in Murcia, to some degree in Munich, but not justified for Stockholm.
- In dry regions, using water for cleaning is not the optimal solution. Access to water is usually limited and can only be available at high cost. Local authorities may also prohibit the use of water for cleaning. Robotic-based cleaning improves cleaning efficiency, eliminating the need for water, offering major potential savings on vehicle and labor costs. Robotic cleaning technology can save several billions liters of water over the lifetime of a plant.[169]

General guidelines

- Robotic cleaning is generally more efficient and of higher quality than manual methods.[173]
- Every PV system requires an individual analysis to determine the cleaning costs based on the type of cleaning system selected.[169]
- If cleaning costs are taken into account at the PV system planning stage, and efforts made to minimize these costs, it is expected that the system will incur lower costs and deliver higher performance compared to systems where cleaning is not planned in advance.[169]
- The selected system should have no sensitive parts exposed to desert conditions so that minimal maintenance of the cleaning device would be required. Maintenance should be easy, fast, and require few tools so that it can be performed by unskilled, low-cost labor.[169]
- Merely considering the capital and operational costs to choose between different cleaning methods is not accurate. There are other advantages to robotic systems that should be assessed and taken into consideration. These features are unique to robotic cleaning systems which enhance their performance and increase their efficiency, resulting in indirect cost savings compared to manual cleaning. For example, Ecoppia's autonomous cleaning devices are controlled from the cloud and can be pre-set to clean on a predetermined cycle, or they can be activated to clean the plant on an ad-hoc basis. Fast response times are particularly beneficial following dust storms which can cut plant output by up to 40% within minutes.[173]

It can be concluded that no single cleaning method is suitable for all scenarios. Different factors should be evaluated to decide on the suitable cleaning method for every solar PV system.

4.1.7. Complex troubleshooting. A relatively small solar power plant contains thousands of panels. Trying to find a bad panel in this plant is a very difficult task. The heat generated by solar panels can be exploited using a drone equipped with a thermal sensor to quickly and easily spot the bad panels in the whole site. In ref. [64], this concept was applied to spot the bad panels in a 4.5 MW solar power plant containing 18,000 panels. The drone was able to fly the entire site in less than 40 min. It would have taken weeks to accomplish the same task using the traditional method.

4.2. More on using robots for renewable energy

Similar to the tasks described in the previous section related to solar energy, additional examples are given below for two tasks applied to different renewable energy sources, namely, the *"High Precision Manufacturing"* task applied to hydrogen energy and the *"Complex Troubleshooting*" task applied to wind energy.

4.2.1. Manufacturing (hydrogen fuel cell). Manufacturing of hydrogen fuel cell stacks involves dealing with highly sensitive, thin materials soaked in corrosive acids which makes material handling very difficult. Robots can provide high precision and efficiency when used in the assembly of hydrogen fuel cell stacks.[65]

4.2.2. Troubleshooting (wind turbine). Conventionally, wind turbine inspection is conducted by an inspector examining the turbine from the ground using a high-power telescope.[62] GE Global Research has partnered with, International Climbing Machines, Ithaca to develop a fast and reliable technology for the inspection of wind turbines. Using a remote-controlled robot that can inspect the wind turbine using a wireless camera. The close inspection has the following advantages: (1) acquiring a precise overview of the wind turbine health status, (2) inspections do not have to be postponed because of bad lighting and/or weather conditions. A microwave scanner has been also developed to allow inspections through the blade material providing an early evidence of any failure in the structure.[62] In refs. [120,144], a wire-driven parallel robot has been developed for the maintenance of offshore wind turbines. A robotic system for the maintenance of offshore wind turbines has been described in ref. [143]. A mechanism consisting of two active wheels and two passive wheels that can fix the robot on the blade allows the robot to move on the blade surface. The system design of micro aerial vehicle), wall-climbing robot for the inspection of wind turbine blades has been presented in ref. [146].

Table III. Feature comparison between AR 2, Phantom 4, and Mavic 2 Pro.

Drone	Specs							
	Year	**Flight time (min)**	**Camera**	**Max speed (km/h)**	**Obstacle sensing**	**Subject tracking**	**Internal storage**	**Trajectory prediction**
Parrot AR 2	2012	12	720p	40	No	No	No	No
DJI Phantom 4	2016	28	4K	72	Yes	Based on 2D images	No	No
DJI Mavic 2 Pro	2018	31	4K	72	Omnidirectional	Based on 3D view	8GB	Yes

Table IV. Average efficiency and capital costs over time for three different types of PV cells.

PV type	Year	Efficiency (%)	Cost ($/W)
Crystalline silicon	1995	12	6
	2005	15	3.5
	2015	16	2
Thin film	1995	6	6
	2005	10	2
	2015	12	1
Concentrator	1995	15	6
	2005	19	2
	2015	24	1

4.3. Efficiency of robots versus efficiency of renewable energy sources

In this section, the efficiency of robots (considering drones as an example) compared to the efficiency of renewable energy (considering solar PV as an example) is discussed, showing that the efficiency of drones and solar PV is increasing over time. The aim is to demonstrate the viability of sustainable interaction between these two technologies.

4.3.1. Drones' efficiency. Data analytics, artificial intelligence, machine learning, and the cloud are adding more capabilities to drones – and robots in general – enhancing efficiency, agility, performance, and completely reshaping the way robots are being utilized. Table III shows the features of three drone models developed by Parrot and DJI.[227–230] New features are being developed while existing features are also enhanced in newer models.

The consistent development of drones' features and capabilities has opened the door for a long list of applications in which the drones can be effectively deployed, for example, search and rescue operations, aerial photography, agriculture, shipping and delivery, and engineering applications.[236]

4.3.2. Solar PV's efficiency. Early silicon solar PV cells were characterized with high cost and low efficiency. However, as time passes, efficiency increased while the cost decreased. In 1955, Hoffman Electronics introduced PV products with a 2% efficiency. The efficiency increased to 14% in 1960. In 1985, researchers at the University of New South Wales have developed a solar cell with over 20% efficiency. In the 21st century, the efficiency continues to rise and the future forecast shows that there are no signs that the efficiency would stop increasing. In 2018, the global-weighted average cost of electricity from solar PV declined by 13%. Cost reductions for solar power are expected to continue into the next decade. By 2020, solar PV will be a less expensive source of electricity than the cheapest fossil fuel alternative.[232] The average efficiency and capital costs over time for three different types of PV cells are shown in Table IV.[235]

The efficiencies of all three types have been increasing while the cost is decreasing. Efficiency values as high as 44.4% have been obtained by Sharp and NREL. However, this has only been possible in laboratory setups.[235] Recently, extensive research has been conducted with the aim of developing new methods to enhance the efficiency of solar PV. Some of the latest innovations are listed below.

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

In ref. [231], a new plant-inspired solar cell based on photosynthesis is developed. The new solar cell is a nano-hybrid structure containing both biologically derived (biotic) and inorganic (abiotic) materials. A light-harvesting protein from a cyanobacteria, semiconducting nanocrystals (quantum dots), and a two-dimensional semiconducting transition metal are combined. According to the researchers, the efficiency of the new solar cell is boosted by 30% compared to single-layer molybdenum diselenide. Thin-film solar cells made from cadmium telluride need far less raw material (up to 100 times less) compared to conventional solar cells made from crystalline silicon, making them cheaper to manufacture. They also absorb sunlight at nearly the ideal wavelength. As a result, electricity generated by thin-film solar cells is the least expensive available today. However, thin-film cells are less efficient at converting sunlight into electricity than silicon wafers. Researchers at Colorado State University and Loughborough University discovered that adding selenium to the mix can boost the efficiency to around 22%.[233] Sandwiching an oxygen-rich layer of silicon between a solar cell and its metal contact allowed researchers to reach an efficiency of 26.1%.[234]

5. Renewable Energy for Robots

Examples of different types of robots powered by renewable energy sources are discussed below. Classification of robots from the *mobility* point of view was discussed in Section 3 as it is most relevant to the purposes of this paper. Renewable energy sources are most appropriate for powering mobile robots. Moreover, the type of mobile robot dictates the appropriate renewable energy source to be used to power the robot. Solar energy is an appealing option for all robot types. The high efficiency of hydrogen fuel cells makes them attractive for flying robots, while wave energy is an obvious option for marine robots.

5.1. Renewable energy-powered flying robots

5.1.1. Solar-powered UAVs. A flapping wing robot incorporating a flexible UHF antenna and an epitaxial lift-off thin-film III–V solar cell array for wireless communication and power generation has been described in ref. [145]. The design of a re-configurable solar UAV capable of transforming between fixed-wing and quad-rotor states has been presented in ref. [116]. In the quad-rotor state, the aircraft relies on stored energy. When stored energy is about to drain, the aircraft transitions to the fixed-wing state where the on-board batteries will be able to recharge. This process is repeated.

5.1.2. Fuel cell-powered UAVs. The high efficiency of fuel cells compared to batteries makes fuel cell-powered UAVs most suitable for applications requiring long range flights. Fuel cell-powered UAVs are appropriate for commercial applications of up to 10 kW.[67]

5.2. Renewable energy-powered marine robots

The necessity of collecting massive amounts of data for different purposes has encouraged the development of different types of autonomous vehicles used for collecting such data. These vehicles have different capabilities in terms of durability, autonomy, etc. Among these platforms are the AUVs and ASVs.[37–45] There are three main challenges pertaining to AUVs and ASVs: (1) energy, (2) communications, and (3) navigation over a long period of time and long distances. The use of renewable energy helps to mitigate these issues, allowing marine robots to accomplish missions that last for months.[37]

5.2.1. Solar-powered ASVs and AUVs. The SAUV-II, described in refs. [39–42], is a solar-powered AUV designed for prolonged monitoring and surveillance missions, incorporating bi−directional communication and underwater instrumentation. The SAUV-II can operate continuously for several months using solar energy to recharge its batteries during daylight. Some of the problems and limitations pertaining to the design and utilization of a solar-powered AUV have been considered in ref. [38]. The paper discussed the power management problem in different situations and the optimum combination of the size needed for energy storage, the travel distance and/or tasks to be executed by the vehicle considering the available solar energy. In ref. [124], an intelligent navigation system for a renewable energy-powered unmanned AUV used for observation and monitoring is proposed. The vehicle incorporates PV panels and a methanol fuel cell, allowing the vehicle to operate for long periods. A neuro-biologically inspired control system is used for intelligent navigation. The vehicle is equipped with sensors to monitor the underwater environment. The Ocean

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

Atmosphere Sensor Integration System (OASIS) was introduced in refs. [43, 44]. The OASIS is a long duration solar-powered ASV developed for open ocean observation. The AAS Endurance, presented in ref. [45] is an ASV supplied with special equipment for the study of marine mammals. The vehicle is powered using solar panels and a methanol fuel cell.

5.2.2. Wave energy-powered ASVs and AUVs. A reversible energy conversion mechanism is proposed in ref. [151], based on the structure of the multi-joints robotic fish. The mechanism can operate as a drive unit and as a power take-off (PTO) unit that is able to capture wave power for the robotic fish. The results revealed that the developed PTO unit is able to convert wave energy to electrical energy with high efficiency, providing a solution for the energy problem of the AUVs. Motion simulation of wave energy-powered USV under certain sea conditions is performed in ref. [128]. In ref. [140], Gaussian process models were used to predict the speed of the Wave Glider ASV by observation of environmental parameters. In ref. [125], the dynamic model of wave-driven USV is described. The wave and driving force are calculated. Empirical data and experimental platform of the vehicle are used to determine the hydrodynamic coefficients.

5.3. Solar-powered terrestrial robots

The Solar-powered Exploration Rover (SOLERO) was described in ref. [33,34]. A Mars environment model has been used as a reference to assess SOLERO's performance.[33] Similar solar-powered vehicles operate on Earth. However, the challenge for SOLERO is that Mars is farther from the sun than Earth; consequently, the available solar power is much lower and thus designing a reliable system is more difficult.[89] In ref. [91], indoor tests were conducted for a solar-powered robot using high-power light sources. In ref. [135], the path planning and power management for a solar-powered unmanned ground vehicle (UGV) were examined. In ref. [136], a hybrid-powered robot incorporating solar panels and batteries has been presented. A charging system allows the batteries to be charged from the solar panels. In ref. [137], motion simulation and vibration analysis of the Cassette Handling Robot were performed. In ref. [138], a solar-powered industrial mobile robot has been discussed. In ref. [147], an automatic solar charging system which can track the sun used for transmission lines robot has been discussed. Manipulation control of a space robot with flexible solar panels has been discussed in refs. [149, 150].

In general, the ability to reduce the dependence on fossil fuels by any degree is advantageous to a certain extent. However, according to the United Nations' Intergovernmental Panel on Climate Change, renewables are to supply 70–85% of electricity by 2050 to avoid worst impacts of climate change.[238] As such, it is expected that every equipment that is currently relying on fossil fuels would attain this percentage relative to its overall energy requirements by employing a hybrid-powered system. However, in certain situations, the transition from using fossil fuels to using renewable energy sources is confronted by technological limitations that need to be adequately addressed. As an example, the case of agricultural robots is discussed below.

Agricultural machines require large amounts of energy, usually fossil fuels, emitting large amounts of pollution to the atmosphere. Due to the issues related to fossil fuels, it is desired to progressively reduce the use of fossil fuels and shift this usage to renewable energy sources to reach the percentage of renewable energy sources relative to the fossil fuels so that the combination would be beneficial to the environment.

In ref. [237], a hybrid energy system used in robotic tractors for precision agriculture is evaluated. The experiments were conducted using a UGV which is based on the CNHi Boomer 3050 CVT compact tractor. The objectives were to design and assess a hybrid energy system including the removal of the alternators from the tractor and the modification of the agricultural implements to replace the PTO system power with electric power, using small pumps and small fans. These changes improved energy use and reduced the atmospheric pollution emission from the internal combustion engine. The hybrid energy system used the original combustion engine of the tractor in combination with a new electrical energy system, which consisted of batteries, a hydrogen fuel cell, and solar PV cells to achieve a substantial decrease in fossil fuel use and a consequent reduction in the emission of pollutants. An analysis of the exhaust gases using the internal combustion engine as the single power source and using the hybrid energy system was carried out to compare the results obtained. The results showed a reduction in emissions of almost 50% for the best case. This work demonstrates that it is possible to combine current agricultural machines, which use ICEs for power, with clean energy sources to obtain significant reductions in the emission of GHGs. Offloading the ICE to a greater or lesser extent can be regarded as an intermediate step toward the use of completely clean energy systems.

6. Robots and Renewable Energy – Two Way Interaction

In some scenarios, both robots and renewable energy can be simultaneously employed for each other. In other words, a robot can be powered from a renewable energy source while conducting a renewable energy-related task. A couple of examples are given below.

The Ecoppia E4[51] is a fully autonomous robot that uses microfiber brushes to clean the dust accumulated on solar panels. It is designed for large rows of panels located in dry environments. The robot uses an on-board solar panel and a battery to store energy that allows cleaning at night. In ref. [76], an autonomous vacuum cleaner for solar panels was developed. The system contains two subsystems (a robotic vacuum cleaner and a docking station). The robotic vacuum cleaner uses a two stage cleaning process to remove the dust from the solar panel. The robot charges its battery from the docking station using power drawn from the solar panels.

The abovementioned examples are for solar-powered robots conducting a maintenance task for solar panels. Other similar scenarios exist for mutual interaction between robots and renewable energy.

7. Discussion

7.1. Data Analytics

Successful project development requires extensive analysis of the available information in fundamental areas like site assessment, inter-connection impact, etc.[123] Using simulation tools for data analytics and forecasting speeds up the decision-making process, saving time and money for everyone involved in the renewable energy industry (project managers, engineers, financial analysts, and researchers). Examples of such tools are given below:

- *Velocity Suite* by ABB is a data and analytics solution that allows the identification of irradiance, cloud cover, etc. to assess potential solar sites. This is also true for wind facilities, but with more variables involved.[123]
- *PROMOD* by ABB is a simulation tool used to conduct production cost modeling. PROMOD can be used to forecast the market price of power, future revenues and costs. It can also simulate the effects of intermittent energy from wind, solar, and other renewable energy projects on transmission congestion.[123]
- *System advisor model (SAM)* by NREL is able to calculate the performance and financial metrics of renewable energy projects. SAM can be used to simulate the performance of solar, wind, geothermal, and biomass energy sources, and it includes a model that can be used for comparisons with conventional systems.[61]

7.2. Hybridization opportunities

7.2.1. Hybrid Renewable Energy Projects. One of the promising innovations in renewable energy development is the co-existence of two different technologies in the same site. Many hybrid renewable energy projects have been built or are under development worldwide, including hydro-solar, wind-solar, biomass-geothermal, etc. It has become apparent in recent years that many opportunities exist for hybrid projects. Advantages of hybrid projects include: (1) shared land and grid connections leading to reduced CAPEX, (2) higher power generation, (3) reduction of intermittent generation, and (4) shared workforce for cleaning, security, etc. leading to reduced OPEX. For a hybrid project, the total savings on CAPEX are estimated at 3–13% and for OPEX 3–16%. The challenges include (1) simultaneous generation from both sources may lead to curtailment, (2) lack of familiarity with hybrid projects among investors. Curtailment can be reduced if the hybrid renewable project is accompanied by energy storage.[121]

By the end of 2016, four of the world's top turbine companies – GE, Gamesa, Goldwind, and Mingyang – had entered the solar industry. Some companies were developing locally integrated solar PV-wind hybrid projects during the year, and Suzlon (India) and Gamesa both announced plans

https://doi.org/10.1017/S0263574719001644 Published online by Cambridge University Press

to increase their focus on wind-solar hybrids, which can strengthen a plant's generation profile and enable sharing of resources for construction and maintenance. Hybrid projects that include storage technologies also are being developed.[217] In 2017, Siemens Gamesa announced its first hybrid contract for a solar PV-wind power facility in India, and Vestas began constructing the first phase of the Kennedy Energy Park, Australia's first utility-scale wind, solar PV, and energy storage hybrid project.[218]

Attempts to provide solar power to rural communities in developing countries have been thwarted by the inherent intermittency of solar energy. These systems would cease providing power once the sun went down, during overcast skies, or the rainy season. The Tulip tackles this problem by taking a concentrated solar system and backing it up with biogas to continue providing power when the sun is unavailable. An AORA Tulip is a hybrid solar power system that combines the technologies of concentrated solar and biogas into a modular package that can provide energy to off-grid rural locations. It is an efficient energy system with a relatively high kWh per land. A single Tulip can power 30–40 homes.[219]

7.2.2. Hybrid-task robotics. Hybrid renewable energy projects open the door for new opportunities and possibilities. Considering the integration between robots and renewable energy, a new class of *hybrid* robots can be devised. In this regard, a *hybrid* robot refers to a robot that is capable of performing one or more tasks (maintenance, troubleshooting, etc.) pertaining to both renewable energy sources that are co-located inside the hybrid renewable energy plant. For example, a robot that is capable of conducting troubleshooting tasks for both solar and wind energy sources, a hybrid robot for a hybrid renewable energy plant, for further cost reduction.

7.2.3. Hybrid-powered robotics. The most important disadvantage of electrical UAVs is the limitation of flight range. The power system of UAV is expected to have both high energy density and power density. Neither solar cells nor fuel cells can supply total power demanding of UAV alone with satisfactory performance.[225] The solution is to combine different power sources that can be connected either in serial, parallel, or serial–parallel in a hybrid configuration.[220] The main benefits of hybrid power systems with fuel cells compared with pure battery power systems are achieving a higher specific energy and energy density, providing redundancy in power supply, reducing the possibility of failure, improving energy efficiency,[226] and achieving higher endurance.[221]

Hybrid power systems are classified as: (1) active, with control elements and (2) passive, with a direct coupling among the system components. The active configuration allows a decoupling of sizing and operating conditions on batteries and fuel cell using DC/DC converters, allowing a more precise control of the power system. Their main disadvantages are system complexity, reduced efficiency due to voltage loss, system cost, and higher weight and volume. Passive configurations with direct connections to the DC bus offer the advantages of lower losses, reduced cost and simpler architecture, lower weight, and volume.[222]

Detailed investigations of the static and dynamic performance of hybrid systems are required to address integration challenges.[221] The difference in characteristics between the fuel cell and the battery makes the hybrid power system highly coupled and complicated. Therefore, effective energy management strategies are very important and necessary in design of hybrid fuel cell/battery power systems.[223]

Types of energy management systems for hybrid power systems

- Rule-based (state machine control, power following control)
- Intelligent-based (neural networks, fuzzy logic)
- Optimization-based (dynamic programming, equivalent consumption minimization strategy, model predict control)
- Others (e.g., frequency decoupling).[225]

In ref. [223], an energy management system is designed to control the hybrid fuel cell and battery power system for electric UAVs. An executable process of online fuzzy energy management strategy is proposed and established. The proposed system exhibits good effectiveness and flexibility for long endurance missions

In ref. [220], the performance of a passive hybrid power plant control system to be implemented in a lightweight UAV was investigated. The power plant is based on a high-temperature proton-exchange membrane (PEM) fuel cell connected in parallel to a set of lithium-polymer batteries. Test performed in steady state demonstrates that the use of the hybrid system increases the efficiency of the stack by more than 7%. The hybridization of the stack with the batteries eliminates sudden peaks in the current generated by the stack, which are responsible for prompt degradation phenomena that drastically reduce its useful lifetime. In the steady-state test, it is verified that the efficiency of the stack is 44.3% compared to a maximum efficiency of only 36.4% for the PEM fuel cell. A test performed to study the dynamic behavior of the p-HPP demonstrated that the presence of LiPo batteries in this configuration smooths out the sharp peaks of the current curve of the HT-PEMFC, reducing the degradation phenomena that they can induce.[220] In ref. [221], a series of tests were performed on the AeroStack hybrid, fuel-cell-based power train. The results confirm that the AeroStack's lithium-polymer battery plays a crucial role in its response to dynamic load changes and protects the fuel cell from membrane dehydration and fuel starvation. In ref. [224], the results of tests for the hybrid AeroStack fuel-cell/battery power system were presented. The results demonstrate that the performance of the fuel cell can deviate significantly from its steady-state polarization curve for short periods of time and that careful selection of the mission profile (or inversely, selection of a specific fuel-cell/battery combination for a given mission) can increase overall performance and reduce fuel consumption by up to 3% by exploiting the high efficiency of the fuel cell at part load.

8. Conclusions

Renewable energy and robots, two disciplines that once seemed unrelated to each other are now converging into an ecosystem whereby they are related and beneficial to each other. This paper presented an overview of the integration between robots and various renewable energy sources. Robots can be used in a variety of applications and tasks related to renewable energy sources, for example, they can be used to automate and accelerate the manufacturing process of solar panels, maintenance and troubleshooting of solar energy and wind energy plants. Robots can also be useful in all phases of a renewable energy project (site assessment, site survey, etc.) and can achieve faster and more efficient results saving effort and money. On the other side, renewable energy can be useful as a power source for robots, especially those involved in long-term autonomous missions. A wide range of opportunities are yet to be explored in this regard.

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