



# Applications of nanotechnology in renewable energies—A comprehensive overview and understanding



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## ABSTRACT

One of the great technological challenges in 21st century is the development of renewable energy technologies due to serious problems related with the production and use of energy. A new promising area of research grows rapidly which is called Nanotechnologies are considered nowadays one of the most recommended choices to solve this problem. This review aims to introduce several significant applications of nanotechnology in renewable energy systems. Papers reviewed including theoretical and experimental works related with nanotechnology applications in solar, hydrogen, wind, biomass, geothermal and tidal energies. A lot of literature are reviewed and summarized carefully in a useful tables to give a panoramic overview about the role of nanotechnology in improving the various sources of renewable energies. We think that this paper can be considered as an important bridge between nanotechnology and all available kinds of renewable energies. From the other side, further researches are required to study the effect of nanotechnology to enhance the renewable energy industry especially in geothermal, wind and tidal energies, since the available papers in these fields are limited.

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## Contents

1. Introduction . . . . .	460
1.1. Manufacturing and advantages of nano-materials . . . . .	461
2. Nanotechnology applications in renewable energies . . . . .	463
2.1. Solar energy . . . . .	463
2.1.1. Solar cells types . . . . .	463
2.2. Hydrogen energy . . . . .	467
2.2.1. Fuel cells . . . . .	467
2.2.2. Fuel cells types . . . . .	467
2.2.3. Advantages of the fuel cell . . . . .	468
2.2.4. Diesel engine . . . . .	469
2.3. Biomass/bioenergy . . . . .	469
2.3.1. Biofuels . . . . .	469
2.3.2. Biogas . . . . .	470
2.3.3. Vegetable oil . . . . .	470
2.3.4. Bio-oil . . . . .	470
2.3.5. Biodiesel . . . . .	470
2.4. Wind energy/wind turbines . . . . .	471
2.5. Geothermal energy . . . . .	471
2.6. Tidal/water energy . . . . .	472
3. Conclusions . . . . .	472
Acknowledgements . . . . .	474
References . . . . .	474

## Nomenclature

Symbol	Description	Unit
$A$	area of the absorber plate [Eq. (3)]	(m <sup>2</sup> )
$A_c$	surface area of solar collector [Eq. (2)]	(m <sup>2</sup> )
$C_{\text{eff}}$	effective specific heat of the nanofluids [Eq. (3)]	(kJ/kg °C)
$F_R$	collector heat removal factor [Eq. (2)]	
$G_T$	global solar irradiation [Eq. (3)]	
$I$	current [Eq. (1)]	(A)
$I$	global solar radiation [Eq. (2)]	
$k$	thermal conductivity of the nanofluid [Eq. (1)]	(W/m K)
$l$	length [Eq. (1)]	(m)
$m$	mass flow rate of the working fluid [Eq. (3)]	(ml/h)
$T_1$	temperature of the wire at initial condition [Eq. (1)]	(°C)

$T_1$	inlet temperature of the working fluid [Eq. (3)]	(°C)
$T_2$	temperature of the wire at final condition [Eq. (1)]	(°C)
$T_2$	outlet temperature of the working fluid [Eq. (3)]	(°C)
$T_a$	ambient temperature [Eq. (2)]	(°C)
$T_{fi}$	inlet fluid temperature of solar collector [Eq. (2)]	(°C)
$t$	time [Eq. (1)]	(s)
$U_L$	Overall loss coefficient of solar collector [Eq. (2)]	
$V$	voltage [Eq. (1)]	(V)

### Greek symbols

$\alpha$	absorptivity [Eq. (2)]
$\tau$	transmissivity [Eq. (2)]
$\eta$	instantaneous collector efficiency [Eqs. (2) and (3)]

## 1. Introduction

Renewable energy can be defined as one type of energy sources which can be provide light, electricity and heat without polluting the environment. Energy generation from fossil fuels has been identified as the main reason of environmental pollution. The obvious advantage of renewable energy is that no fuel is required, which eliminates the emission of carbon dioxide. The current global energy problem can be returned to insufficient fossil fuel supplies and excessive gas emissions resulting from increasing fossil fuel consumption. It was reported that the present petroleum consumption was 10<sup>5</sup> times faster than the nature can create and at this huge rate of consumption, the world's fossil fuel reserves will be diminished by 2050 [1,2]. Also, it is interesting to mention that the global demand for energy is predicted to be approximately 30 and 46 TW by 2050 and 2100, respectively [3]. Fossil fuels are crude oil, coal and natural gas. They are not renewable, once burnt they are gone for ever. These sources supply more than 90% of our energy demand, but carry a steep environmental cost. For example, the concentration of CO<sub>2</sub> in the environment have increased from (280 to 370 ppm) over the past 150 years. It's expected to pass (550 ppm) in this century [4]. However, due to the huge demand of energy and lesser availability of fossil fuels there is a shift toward renewable energy sources. Examples of these sources of energy include solar, wind, biomass, hydrogen and geothermal energies. These clean sources can be used instead of conventional fossil fuels and nuclear energy. Nowadays, there is a huge interest in this subject since it is expected to provide 50% of the world's primary energy by 2040. Moreover, renewable energy can be play a crucial role to reduce gas emissions to the environment by about 70% during 2050. From the other side, a new science field grown quickly which is called Nanotechnology, has much and considerable attention in the recent years due to many engineering and technological applications. For example, the nano-materials (i.e., particles with diameters < 100 nm) can be used to reduce the size of information processing parts of most usable devices such as cell phones and lap computers. Scientists refer to this dimensional range of 1 to 100 nm as the nano-scale, and materials at this scale are called nanocrystals or nano-materials. Therefore, this reduction in size leads to reduce their required energy. Also, there are many benefits which can be observed from the design of nanotechnology based products for renewable energy which are [5]:

- (1) An increased efficiency of lighting and heating.
- (2) Increased electrical storage capacity.

- (3) A decrease in the amount of pollution from the energy using.
- (4) Nanotechnology will generate \$2.5 trillion in 2015.

Furthermore, nanotechnology can be used to improve renewable energy sources; for example wind energy efficiency can be improved by using light, more strength nano-materials for rotor blades. In biomass energy using nano-based precision farming to optimize crop used to produce biofuels. Nano-coatings can be used to prevent the corrosion in tidal energy equipments, while nanocomposites are utilized to make drilling machines in geothermal energy more fatigue-resistance. The present paper aims to introduce many significant applications of nanotechnology in renewable energy systems. Papers reviewed including theoretical and experimental works related with nanotechnology applications in solar, hydrogen, wind, biomass, geothermal and tidal energies. We think that this paper can be considered as an important bridge between nanotechnology and all available kinds of renewable energies.

### 1.1. Manufacturing and advantages of nano-materials

The term “nanomaterials” covers a wide range of materials including nanocrystalline materials, nanocomposites, carbon based nanomaterials (such as carbon nanotubes) and metal based nanomaterials (such as aluminium oxides). There are three general methods of manufacturing of nano-materials by suspending nanoparticles into base fluids. These methods can be classified as follows [6]:

- 1- Addition of acid or base to change the pH value of suspension.
- 2- Adding surface active agents and/or dispersants to disperse particles into fluid.
- 3- Using ultrasonic vibration.

In general, materials can have different properties at the nanoscale (nanometer is one billionth of a meter) than they do at larger size. Some materials become stronger, lighter increased stability or better at conducting electricity or heat or at reflecting light. Others display different magnetic properties or become chemically active in special ways [7]. The reason of this behavior, since when materials have one or more of their dimensions under (100 nm), the normal rules of physics and chemistry often no longer apply. As a result, many materials sometimes start to display surprising properties. The strength of nanomaterials, their ability to conduct electricity and rate of reactivity increase

dramatically. For example, silver shows increased anti-microbial properties, inert materials like platinum and gold become catalysts, while stable materials like aluminum become combustible. These new discovered properties of nanoscale materials have opened an exciting fields of study and applications in areas that can improve the quality of human life in both fields of energy and health [8]. For more detailed informations about nanomaterials, the reader can be go back to the review articles by Suh et al. [9] and Savolainen et al. [10]. Energy storage devices such as batteries and super-capacitors can be significantly modified by the application of nanotechnology. Materials can be engineered using nanotechnology to make the relevant components of lithium-ion batteries heat resistant, flexible and high-performance electrodes. Thermal energy storage could also be better enhanced using nanoporous materials like zeolites, which could be used as heat storages in both residential and industrial regions. Elcock [11] explained that the manufactured nano-materials can be classified according to their method of production. Some of them were produced “from the top down,” as when a bulk material (e.g., gold, silicate) was reduced to a mass of nanoscale particles. This method was used today in sunscreen products (titanium dioxide nanoparticles) and solar cells (aluminum oxide nanoparticles). The second type of manufactured nanoparticles were built “from the bottom up,” atom by atom or molecule by molecule. He refereed that nanoparticles of this type were still relatively difficult and expensive to manufacture, but they had the potential to impact energy development and use, transportation, electronics, manufacturing, and other disciplines. Mao and Chen [12] explained the role of nanotechnology in the development of selected renewable energy technologies. These technologies included (1) converting the energy of sunlight directly into electricity using solar cells; (2) converting solar energy into hydrogen fuel by splitting water into its constituents; (3) storing hydrogen in solid-state forms and (4) utilizing hydrogen to generate electricity through the use of fuel cells. It was clear that nanotechnology could dramatically enabled renewable energy to replace the traditional, environmentally unfriendly, fossil fuels in the future. Serrano et al. [13] reviewed some advances of nanotechnology to sustainable energy production, storage and use. In their review, they selected some significant contributions in the solar, hydrogen and new generation batteries and super-capacitors as an examples of the contributions of nanotechnology in the energy sector. They presented the following advantages of using nanotechnology in the sustainable energy:

- 1- The efficiency of the photovoltaic (PV) solar cells were increased, while their manufacturing and electricity production costs were reduced at an unprecedented rate.
- 2- Hydrogen production, storage and transformation into electricity in fuel cells were improved by using nanostructured materials. This was occurred by increasing hydrogen adsorption capacity which led to make the fuel cells more efficient and cheaper.

Brinker and Ginger [14] investigated the role of nanotechnology for sustainability, energy conversion, storage and conservation. They explained that energy use reduction was the main application for thermoelectricity (TE) waste heat recovery devices. These devices had a very low impact on the environment. Since, they were totally passive, clean and operated without any additional energy supply. Their use in cars and public transport systems would reduce the oil consumption. Subramani et al. [15] presented a comprehensive review of energy minimization strategies for membrane-based desalination processes and utilization of lower greenhouse gas emission renewable energy resources. The review covered the utilization of energy efficient design, high efficiency pumping, energy recovery devices, advanced membrane materials (nanocomposite, nanotube and biomimetic), innovative

technologies and renewable energy resources (solar, wind and geothermal). They referred that the use of carbon nanotubes could offered (30–50%) lower energy consumption than conventional seawater reverse osmosis desalination. They concluded that desalination energy could be reduced by the use of advanced membrane materials and application of innovative technologies. Guo [16] reviewed the relevant renewable energy technologies such as hydrogen fuel, solar cell, biotechnology based on nanotechnology, and the relevant patents for exploiting the future energy for the friendly environment. From his review, he concluded that if the nanotechnology field mixed with the renewable energy sources, the following points were satisfied:

- 1- Fuel cells became low cost and high efficient.
- 2- The production, distribution, and storage of hydrogen fuel became low cost.
- 3- Nanotechnology may help to increase the efficiency and decrease the cost of tapping solar energy.

Grebler and Nentwich [17] presented an article about the relationship between the nano-materials and the environment. They extracted the following notations:

- 1- Nanotechnology can be used to optimize materials, for example plastics or metals with carbon nanotubes (CNTs), will make airplanes and vehicles lighter and therefore make a reduction in the fuel consumption.
- 2- When nano-scale carbon black added to modern automobile tires leads to reinforce the material and reduce rolling resistance. This makes a fuel savings of up to 10%.
- 3- Nanomaterials can help for self-cleaning or “easy-to-clean” coatings. For example, if they added to glass, they save both energy and water in cleaning process, since such surfaces are easier to clean or not required to be clean continuously.
- 4- Nanotribological wear protection products such as fuel or motor oil additives can reduce fuel consumption of vehicles and extend engine life.
- 5- Nanoparticles such as flow agents allow plastics to be melted and cast at lower temperatures.
- 6- Nanoporous insulating materials in the construction industry can help to reduce the energy needed to heat and cool buildings.
- 7- Nanoceramic corrosion coatings for metals without toxic heavy metals (chromium, nickel), for example in automobiles, can replace environmentally harmful or hazardous chromium(VI) layers.
- 8- Nano-scale titanium dioxide and silica can replace the environmentally damaging bromine in flame retardants.

Yu and Xie [18] summarized the recent progress on the study of nanofluids, such as the preparation methods, the evaluation methods for the stability of nanofluids and the ways and mechanisms to enhance the stability of nanofluids. They presented the broad range of current and future applications of nanofluids in various fields such as energy, mechanical and biomedical fields. They refereed in their paper, that the nanofluids were prepared by the following most using methods:

- 1- Two-step method: It was considered the most widely used and economic method for preparing nanofluids. Nanoparticles, nanofibers, nanotubes, or other nanomaterials used in this method were first produced as dry powders by chemical or physical methods. Then, the nanosized powder will be dispersed into a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing and ball milling.
- 2- One-step method: It consisted of simultaneously making and dispersing the particles in the fluid. In this method, the

processes of drying, storage, transportation, and dispersion of nanoparticles were avoided. The one-step method can prepare uniformly dispersed nanoparticles, and the particles can be stably suspended in the base fluid.

Markovic et al. [19] presented an overview of the information and communication technology (ICT) benefiting from the development in nanotechnology with respect to sustainability and energy efficiency. They mentioned that the industry was benefiting from nanotechnology in many ways, including from its applications in smarter sensors, logic elements, computer chips, memory storage devices, optoelectronics and quantum computing. Also, nanomaterials could be used to improve the capacity of batteries and solar cells. Tan et al. [20] reviewed the applications and advantages of carbon nanotubes in energy conversion and storage such as in solar cells, fuel cells, hydrogen storage, lithium ion batteries, electrochemical supercapacitors and in green nano-composite design. They concluded that carbon nanotubes had the following advantages:

- 1- Integration of carbon nanotubes in solar and fuel cells had increased the energy conversion efficiency of these devices, which served as the future of renewable energy sources.
- 2- Carbon nanotubes doped with metal hydrides showed high hydrogen storage capacity of around 6 wt% as a potential hydrogen storage medium.
- 3- They showed high sensitivity toward the detection of environmental pollutants which were demonstrated by using carbon nanotubes based sensors.
- 4- Carbon nanotubes could be utilized as a reinforcement material in green nano-composites, which was advantageous in supplying the desired properties.

Daryoush and Darvish [21] investigated the application of nanomaterials to reduce the energy consumption. They mentioned in their article that nanocomposite materials with the basis of polymer (polymer matrix) were first presented during the 1970s and the technology of Sol–Gel had been used in order to disperse the mineral nanoparticles inside the polymer matrix. Moreover, nano-alumina was the best nano-structure which promised a new horizon in the ceramic industry. They illustrated also that, nano tubes were a new class of products and they had created a new revolution in the field of advanced materials. They suggested the following recommendations:

- 1- By using the nanotechnology in the manufacturing sector, the nonrenewable fuels can be saved for the electricity manufacturing. Therefore, it was recommended to use the nanomaterials in designing the power manufacturing centers.
- 2- By using the nanowires in the sectors of transmission and distribution of electric power, the electricity loss in the network and manufactured electricity can be reduced. Therefore, the reduction of manufactured electricity will lead to reduce the consumption of fossil and nonrenewable fuels.
- 3- The nanomaterials can be utilized in designing the buildings and industrial sites in order to reduce the thermal and cooling energy loss which was occurred as a result of the electricity consumption and direct consumption of nonrenewable energies.

## 2. Nanotechnology applications in renewable energies

### 2.1. Solar energy

Solar energy is one of best sources of renewable energy. It can be used efficiently in various practical applications like solar power plants, solar cell, seawater desalination, solar collectors

etc. In fact, sunlight falling on Earth offers a solution, since the hourly solar flux incident on Earth's surface is greater than the annual human consumption of energy in a year [22]. That is why the sun is so appearing as an ultimate energy source on the earth. The quantity of solar energy received by earth is a function of the season, with the highest quantity of incoming solar energy received during the summer months [23]. The big challenge in using these devices is that the clear weakness in the absorption properties of the conventional fluids which leads to reduce the efficiency of these devices. Nowadays, this problem can be solved easily and affectively by using the concept of nanotechnology. The increased surface area to volume ratio of nanoparticles should enhance solar energy collection and efficiency by exposing more conducting surfaces to the sunlight. Another area that nanotechnology will increase solar cell efficiency is by using materials like lead-selenide. These materials cause more electrons (and therefore more electricity) to be released when hit by a photon of light [24]. Furthermore, the cost is a major factor in the success of any solar technology. Because, converting solar energy into electricity occurs at a price comparable with fossil fuel. Semiconductor materials that exhibit a photovoltaic (PV) effect can be used to convert solar radiation into electricity through a photovoltaic process. Photovoltaics are surfaces typically consisting of a conducting oxide layer and a catalytic platinum layer that directly convert sunlight to an electrical energy. A device which converts photons from the solar light into electricity using electrons is called photovoltaic solar cell [22]. Solar energy is a very environment friendly. For example, if a distributed solar grid meets 1% of the world's electricity demands, approximately 40 million tons of carbon dioxide emissions can be saved per year [24].

#### 2.1.1. Solar cells types

There are various types of solar cells which can be described briefly as follows [25,26]:

*Dye-sensitized solar cell (DSSC):* This type of solar cells enables optical absorption and charge separation/injection by associating a dye sensitizer (a light-absorbing material) with a wide-bandgap semiconductor of nano-crystalline morphology as the photoanode. It is based on the combination of interpenetrating networks of mesoscopic semiconductor materials with electrolytes as alternatives to the p–n junctions of inorganic solid-state semiconductors in conventional solar cells.

*Organic-polymer-based PV solar cell (OPV):* In this type, excitons are separated into free electron–hole pairs by the effective field created across the heterojunction between two dissimilar organic materials, known as the donor and acceptor molecules. This type is produced as a result of the increasing requirements for inexpensive renewable energy sources, as a one option for the production of energy from light at very low cost.

*Hot carrier solar cells:* In this type, a freed electron is bumped high into the conduction band by a too-energetic photon. Therefore, its electronic temperature becomes quite hot (as high as 3000 K). The hot electron will relax to the bottom of the conduction band, typically within a few hundred femto-seconds, imparting heat to the lattice as it does so. This type of solar cells has the following advantages:

1. Using of a high-energy electron will increase the photovoltage of the device as well as its efficiency.
2. The excess energy will be prevented from heating the device and from lowering its efficiency.

Today's conventional photovoltaic solar cells are not much efficient and are very expensive to manufacture for large-scale electricity generation. They have many critical drawbacks such as,

they begin to lose their efficiency when they heat up and lose at least half of the solar energy striking them. Recently, nanoscience and nanotechnology technique can be used to produce a cheap and high efficient solar cells. Nanoparticles provide the following advantages in the solar power plants Taylor et al. [27]:

1. The extremely small size of the particles ideally allows them to pass through pumps and plumbing without adverse effects.
2. Nanofluids can absorb energy directly which exceeding intermediate heat transfer steps.
3. Nanofluids can be optically selective (i.e., high absorption in the solar range and low emittance in the infrared range).
4. A more uniform receiver temperature can be achieved inside the solar collector which reducing material constraints.
5. Enhanced heat transfer by higher convection and thermal conductivity may improve receiver performance.
6. Absorption efficiency may be enhanced by tuning the nanoparticle size and shape to the required application.

The next generation of solar cells is thin film solar cells (i.e., flexible sheets of solar panels) that are easier to produce and install, use less material and are cheaper to manufacture. For example, these sheets can be incorporated into a briefcase that charges laptop, cell phone or can covered buildings windows to collect solar energy from the entire building rather than just its roof. So, it can be used to supply power to high-rise buildings [28]. Experimental researches have already shown that quantum dots (tiny nanoparticles only a few nanometers in size) are three times more efficient for solar energy conversion than the best material currently used for solar cells [29]. Many studies are shown that when the classical fluids (such as water) mix with a small solid nanoparticles leads to a dramatic improvements in the thermo-physical properties of the working fluid (especially thermal conductivity and radiative properties of liquids). This of course leads to increase the efficiency of solar energy devices like solar cell, solar collectors. Some of these studies are summarized in the following section. Otanicar and Golden [30] performed a comparative environmental and economic analysis of conventional and nanofluid solar hot water systems. They concluded that the nanofluid based solar collector had a slightly longer payback period, but at the end of its useful life had the same economic savings as a conventional solar collector. Also, the results showed that the nanofluid based solar collector had a lower embodied energy (about 9%) and approximately (3%) higher levels of pollution offsets than a conventional collector. Natarajan and Sathish [31] investigated experimentally the role of nanofluids in solar water heater. Thermal conductivities had been measured by the transient hot-wire method. Conclusively, thermal conductivity enhancement depended on the volume fraction of the suspended particles and thermal conductivities of both particles and base fluids. The results proved that the nanofluids were effective than the conventional fluids and if were used as a heat transport medium, it increased the efficiency of the traditional solar water heater. The thermal conductivity of the nanofluid was calculated from the slope of the rise in the wire's temperature against logarithmic time interval given by the following equation:

$$k = \frac{IV}{4\pi(T_2 - T_1)l} \left[ \ln\left(\frac{t_2}{t_1}\right) \right] \quad (1)$$

Yu and Chen [32] reviewed the use of 1-D nanomaterials, including (nanotubes, nanowires and nanorods) for enhancing solar cell efficiencies. They mentioned that the nanotechnology offered significant opportunities to improve efficiencies of solar cells by facilitating photon absorption, electron transport and

electron collection. They summarized some benefits of 1-D nanomaterials as follows:

- 1- Direct path for charge transport.
- 2- Large surface areas for light harvest offered by the geometry of nanomaterials.
- 3- The mobility of electrons in 1-D nanomaterials is typically several orders of magnitude higher than that in semiconductor films.

Yuhas and Yang [33] presented a novel solar cell design that combined the ideal geometry of a nanowire-based solar cell with the concept of using environmentally friendly, inexpensive and durable semiconducting PV components. Their solar cell consisted of vertically oriented n-type zinc oxide nanowires, surrounded by a film constructed from p-type cuprous oxide nanoparticles. The results showed that the use of a vertically aligned nanowire array eliminated the problem of exciton diffusion versus light absorption by allowing the light to be absorbed in the vertical direction while allowing exciton extraction in the orthogonal direction. Otanicar et al. [34] reported an experimental results on solar collectors based on nanofluids made from a variety of nanoparticles such as carbon nanotubes, graphite and silver. They demonstrated an efficiency improvements of up to 5% in solar thermal collectors by utilizing nanofluids as an absorption mechanism. In addition, the experimental data were compared with a numerical model of a solar collector with direct absorption nanofluids. The experimental and numerical results demonstrated an initial rapid increase in the efficiency with volume fraction, followed by a leveling off in efficiency as volume fraction continues to increase. Fig. 1 explained that the addition of small amounts of nanoparticles caused a rapid enhancement in the solar collector efficiency from the pure fluid case until a volume fraction of approximately 0.5%. Liu et al. [35] highlighted some of the most exciting advances related with the preparation and characterization of nanomaterials for sustainable energy production. They mentioned that titanium dioxide (TiO<sub>2</sub>) was still the most investigated material for solar cell and solar fuel applications. But, currently TiO<sub>2</sub>-based cells were very inefficient with incident photon-to-current efficiencies of (10%) or less (at the band gap energy) and peak energy conversion efficiencies of (0.6%) or less over the whole solar spectrum. In their overview, they reported that the visible light photocurrent could be enhanced by coating TiO<sub>2</sub> nanowires with gold or silver nanoparticles. The enhancement was achieved due to optical scattering from the plasmonic nanoparticles, which increased the effective optical path of the thin film. Bazargan [36] employed dye sensitized solar cell (DSSC) (as explained in Fig. 2) fabrication procedure using natural pomegranate juice for sensitization of nanocrystalline TiO<sub>2</sub>. Platinum and graphite coated electrodes were prepared by

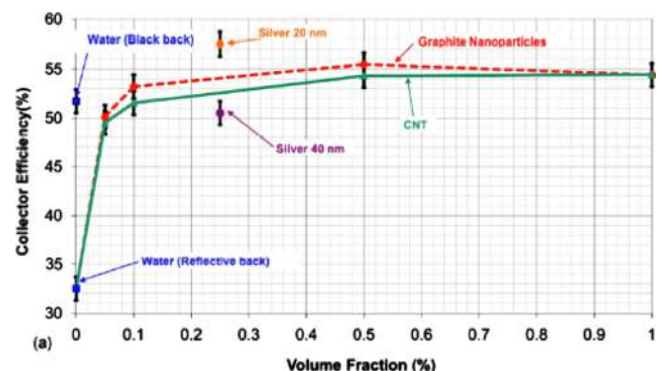


Fig. 1. Experimental microsolar thermal collector efficiency as function of nanoparticle volume fraction Otanicar et al. [34].

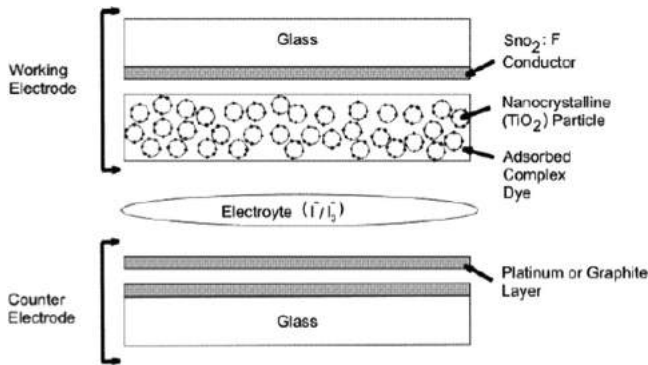


Fig. 2. Schematic of a dye solar cell used in Bazargan [36].

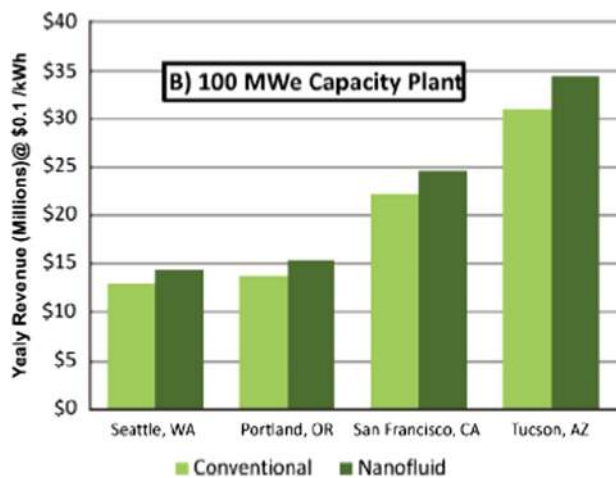


Fig. 3. Comparison of the estimated revenues for a (100 MWe) commercial scale plant by using a conventional and nanofluid receivers Taylor et al. [27].

pulse current electron deposition and soot staining method for use as counter electrodes. Photovoltaic parameters like short circuit current (ISC), open circuit voltage (VOC) and fill factor (FF) were evaluated for fabricated cells. The results illustrated that the fill factor for both cells was found to be (45%), while (ISC) and (VOC) for cells operating with carbon and platinum coated counter electrodes were increased from (360 to 400 mV) and from (175 to 200  $\mu$ A), respectively. The overall conversion efficiencies of fabricated (DSSC) were found to be (1.5%) for cell operated with platinum electrodeposited and (0.9%) for carbon coated counter electrodes. Taylor et al. [27] performed a simplified analysis to explain how a nanofluid-based concentrating solar thermal system would compare to a conventional one. They concluded that, nanofluids had excellent potential for power tower solar thermal power plants. Efficiency improvement on the order of 5–10% was possible with a nanofluid receiver. They explained that, these enhancements could be realized with a very little change in terms of materials, system design, and initial capital investment to the entire solar thermal system. Fig. 3 put a comparison (by using an optimized nanofluid receiver about 5% more efficient than a conventional one) in monetary terms assuming sale of electricity at 10 cents/kWh and scales it up to a 100 MWe, commercial-sized plant. The figure explained that this kind of enhancement adds nearly \$3.5 million to the yearly revenue of a large solar power plant. Sethi et al. [37] explained that using nano-structured layers in thin film solar cells offered three important advantages. First, due to multiple reflections, the effective optical path for absorption was much larger than the actual film thickness. Second, light generated electrons and holes need to travel over a much shorter

path and thus recombination losses were greatly reduced. As a result, the absorber layer thickness in nano-structured solar cells could be as thin as (150 nm) instead of several micrometers in the traditional thin film solar cells. Third, the energy band gap of various layers could be made to the desired design value by varying the size of nano particles. This allowed for more design flexibility in the absorber of solar cells. They concluded that solar cells efficiency could be improved by increasing the absorption efficiency of light as well as the overall radiation-to-electricity. Taylor et al. [38] examined the effectiveness of nanofluids in solar applications, to convert light energy to thermal energy by testing their absorption of the solar spectrum. They compared model predictions to spectroscopic measurements of extinction coefficients over wavelengths that were important for solar energy (0.25 to 2.5  $\mu$ m). A simple addition of the base fluid and nanoparticle extinction coefficients was applied as an approximation of the effective nanofluid extinction coefficient. Comparisons with measured extinction coefficients revealed that this approximation worked well with water-based nanofluids containing graphite nanoparticles but less well with metallic nanoparticles and/or oil-based fluids. They observed that for materials used in this study, over 95% of incoming sunlight could be absorbed (in a nanofluid thickness  $\geq 10$  cm) with extremely low nanoparticle volume fractions less than  $1 \times 10^{-5}$ , or 10 parts per million. They concluded, that nanofluids could be used to absorb sunlight with a negligible amount of viscosity and/or density increase. Baraton [39] presented an overview of nanosized titanium dioxide (nano-TiO<sub>2</sub>) for applications in photocatalytic water splitting and – more specifically – in dye-sensitized solar cells (DSSCs) which was explained in Fig. 4. It was shown that particle size and shape, crystallinity, surface morphology and chemistry of the TiO<sub>2</sub> material were considered as a key parameters to be controlled for enhancing the performance of the dye-sensitized solar cells. Mercatelli et al. [40] investigated the scattering and absorption properties of nanofluids consisting in aqueous suspensions of single wall carbon nanohorns. The characteristics of these nanofluids were evaluated in order to use them as direct sunlight absorber fluids in solar devices. The differences in optical properties induced by carbon nanoparticles compared to those of pure water led to a considerably higher sunlight absorption with respect to the pure base fluid. They concluded that the carbon nanohorns could be used efficiently for increasing the overall

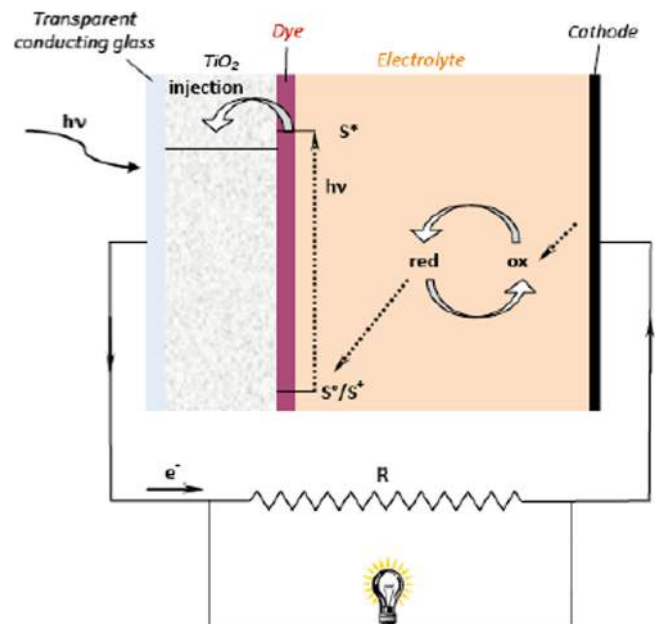


Fig. 4. Schematic principle of a dye-sensitized solar cell Baraton [39].

efficiency of the sunlight exploiting device. Han et al. [41] investigated experimentally the thermal properties of carbon black aqueous nanofluids for solar absorption purpose. They prepared carbon black nanofluids by dispersing the pretreated carbon black powder into distilled water. The results showed that nanofluids of high-volume fraction had better photo-thermal properties. Both carbon black powder and nanofluids had a good absorption in the whole wavelength ranging from 200 to 2500 nm. They concluded that carbon black nanofluids had a good absorption ability of solar energy and could effectively enhanced the solar absorption efficiency. Arivalagan et al. [42] referred in their article that the best available solar cells had layers of several different semiconductors stacked together to absorb light at different energies but they still only managed to use (40%) of the Sun's energy. Commercially available solar cells had much lower efficiencies of about (15–20%). They concluded that nanotechnology could help to increase the efficiency of light conversion by using nanostructures. Jai Poinern et al. [43] explained that nanoparticles of functionalized carbon nanospheres (CNS) had the potential to improve the photo-thermal properties of the working fluid. (CNS) were produced by the pyrolysis of acetylene gas in a tube-based electric furnace/chemical vapor deposition apparatus. The reaction performed at 1000 °C in the presence of nitrogen gas without the use of a catalyst. The synthesized (CNS) were examined and characterized using field-emission scanning electron microscopy, transmission electron microscopy, X-ray diffraction spectroscopy, Raman spectroscopy, thermal gravimetric analysis and ultraviolet-visible analysis. The photo-thermal response of both nanofluids and films composed of (CNS) were investigated under 1000 W/m<sup>2</sup> solar irradiation. The results indicated that functionalized (CNS) nanofluids had the potential to effectively improve the solar absorption capabilities of direct-absorption solar collectors. Senthil Kumar et al. [44] performed an experimental analysis of nano fluid-charged wickless solar heat pipe collector (as shown in Fig. 5) by using the solar tracking system. The main object of their work, was to reduce the size of the solar flat plate collector. In their work, two identical experimental set up of flat plate collectors with same dimensions, using heat pipes were fabricated. In each set up, three identical wickless copper heat pipes were used having length of (620 mm) and outer diameter of (18 mm). The working fluid used in one set up was the pure water and in the

another was pure water with nano particles. The nano particles used were CNT having diameter of (10–12 nm) and length of (0.1–10 μ). They concluded that the nanofluid working fluid collector gave the better performance in all the operating conditions. For both fluids, it was observed that the solar tracking system was more effective and the trend of difference of their instantaneous efficiencies were found initially high. After that, it decreased and then their difference increased again. Mammadov [45] was developed a solar receiver having Cu+Ni+SiO<sub>2</sub> and Cu+Ni+ZnS nano-covered surface. The purpose of his work was to increase the absorption possibility and reducing heat loss of solar heating energy plants. He observed that the effectiveness of the solar receiver surface became high by painting the surface of it by these nano materials. Also, he mentioned that the nano-covered surface supplied to keep its optical properties stable until to the temperature of ( $T > 500$  °C). The results indicated that the developed solar receiver had a high absorption of solar thermal energy of about (94%) and low emittance of infra-red radiation of about (7%). Tiwari et al. [46] investigated theoretically the effect of using Al<sub>2</sub>O<sub>3</sub> / water nanofluid as an absorbing medium in a flat-plate solar collector. The effect of mass flow rate with different particle volume concentrations (0.5–2%) on the efficiency of the collector was studied also. The results showed that using 1.5% particle volume fraction of Al<sub>2</sub>O<sub>3</sub> nanofluid increased the thermal efficiency of solar collector in comparison with the conventional solar water heating system by about (31.64%). They defined the instantaneous collector efficiency which related the useful energy to the total radiation incident on the collector surface by the following equation:

$$\eta = \frac{A_c F_R [I(\tau\alpha) - U_L(T_{fi} - T_a)]}{A_c I} \quad (2)$$

Obaid et al. [47] performed an experimental investigation of the thermal energy storage by using nanofluid (adding magnesium oxide, MgO to distilled water). The size of the added particles was ranged from 20 to 30 nm for weight percent of 0.1, 0.2, 0.4 and 0.5 wt%. The system was designed to heat a building which was consisted of reflector which concentrated solar energy to heat the fluid passing through it, fluid storage tank to store the fluid which was circulated by using a pump and solar radiator which transfer the heat into the air in the room. They concluded that the effect of adding small quantities of nanoparticles (MgO) (i.e., 0.1 and 0.2 wt%) to pure water in the building heating system driven by solar energy minimized the heating loss time while the ability to heat gain was lower than pure water. A reverse behavior was obtained by adding large quantities of nanoparticles (MgO) (i.e., 0.4 and 0.5 wt%). Shankar and Manivannan [48] developed a numerical model of the solar water heating system by using water and nanofluid. They improved the efficiency of solar water heating system by using nanofluids as a working fluid. The theoretical results showed that about (10.88%) of an improved efficiency was observed at (0.025%) volume fractions of the nanofluids. While the experimental results by using water as a working fluid in the flat plate collector type solar water heater system was found to be maximum temperature of about (68.2 °C). They concluded that the heat energy of storage tank changed with corresponding time as shown in Fig. 6, where the comparison of heat energy storage of water and nanofluid had greatly achieved by the percentage improvement of (11.6%) for nanofluid usage in the system. Bedja [49] referred that DSSC (Dye Sensitized Solar Cells) and Quantum-Dots based solar cells became validated competitors to silicon conventional solar cells, having a power efficiency as high as (12.3%) for DSSC. Very recently, Verma and Kundan [50] investigated experimentally the effect of Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O based nanofluids on the direct absorption flat plate solar collector (DASC). The volume fractions of Al<sub>2</sub>O<sub>3</sub> nanoparticles used were (0.005%) and (0.05%). Efficiency of the collector was calculated

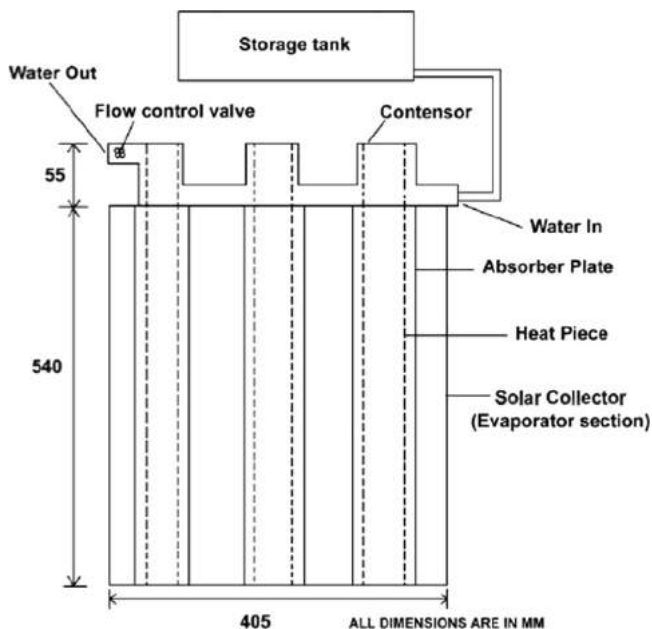


Fig. 5. Schematic of wickless solar heat pipe collector Senthil Kumar et al. [44].

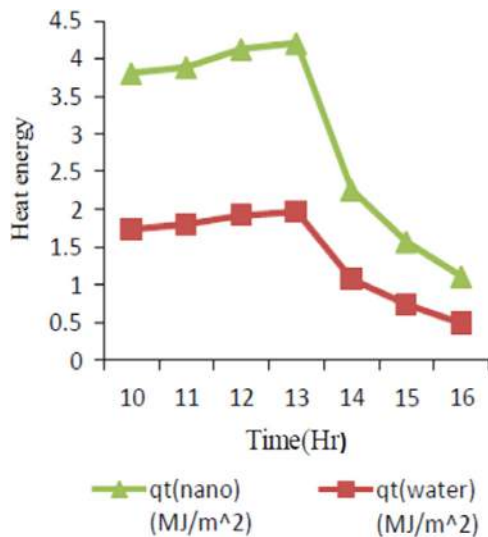


Fig. 6. comparison between heat energy of storage tank with time between water and nanofluid Shankar and Manivannan [48].

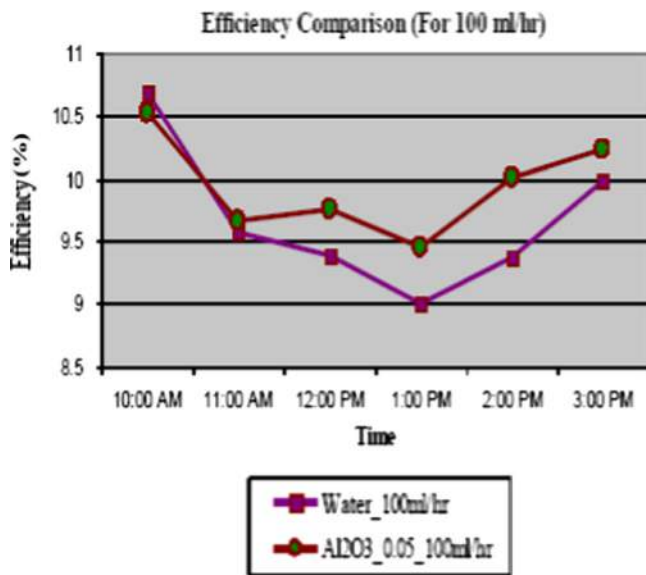


Fig. 7. Variation of the collector efficiency when  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids were used as compared to simple water for (100 ml/h) at different instants of time Verma and Kundan [50].

for different mass flow rates (60, 80 and 100 ml/h) of  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  based nanofluids. It was found that the collector efficiency increased about to (3–4%) when  $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$  nanofluids were used as compared to simple water as shown in Fig. 7. They calculated the collector efficiency by using the following equation:

$$\eta = \frac{mC_{\text{eff}}[T_2 - T_1]}{G_T A} \quad (3)$$

## 2.2. Hydrogen energy

### 2.2.1. Fuel cells

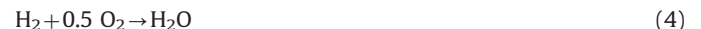
Hydrogen is not an energy source, but just an atomic energy carrier. Hydrogen and fuel cell technologies emerged as one of the most favorable solutions to diversity energy resources and to energy sustainability and environment [51]. Fuel cell is usually

considered in the framework of hydrogen, since it changes hydrogen and oxygen into water, producing electricity and heat in the process. This occurs in an environmentally friendly way, with no harmful carbon dioxide ( $\text{CO}_2$ ) emissions. However, methane and methanol can also be used for fuel cell. The fuel cell was designed by William Robert Grove in 1839 and can be defined as an electrochemical-energy scavenger that converts the chemical energy of a fuel, such as hydrogen or methanol, into electricity through a chemical reaction with an oxidizing agent, such as oxygen or air. Three factors affecting significantly the use of fuel cell for commercial purposes which are its efficiency and size (i.e., nano-fuel cells) together with safe storage of hydrogen. In spite of the huge advantages of the fuel cell, it still has many drawbacks such as high cost, durability issues and operability issues. Nanotechnology can be used to solve these drawbacks. In practice, the nano materials can be used in the membrane of the fuel cell (which is responsible for the separation of hydrogen into protons and electrons), catalysts and electrodes. This is due to the extremely large surface to volume ratio compared with bulk materials. One of the most significant applications of nanotechnology in hydrogen energy field is related with an efficient hydrogen storage. Storing large volumes of hydrogen fuel is either too bulky or expensive. This is a very severe limitation to use hydrogen as an alternative energy source. Scientists have found that nanoblades could hold large volumes of hydrogen [24]. Also, it can be saved inside a nano-materials such as carbon nanotubes (CNTs) and carbon nanofibers [52–57]. For example, carbon nanotube fuel cells are being used nowadays to store hydrogen which are considered the environmentally friendly form of energy. From the other hand, the hydrogen energy is still used extensively in the space vehicles, since it has the best energy-to-weight ratio of any fuel. Nanostructured materials are effectively utilized to improve the transformation of hydrogen energy into electricity by using the fuel cells.

### 2.2.2. Fuel cells types

There are different kinds of fuel cells which can be explained briefly as follows [58]:

**Hydrogen fuel cell (HFC):** This type shown in Fig. 8 is utilized in automotive industry as a possible replacement for fossil fuels in passenger cars and public transportation. The net reaction of this type can be written as:



**Direct methanol fuel cell (DMFC):** This type shown in Fig. 9 is utilized in power portable small electronic devices such as laptop computers and cell phones. It has many characteristics such as low

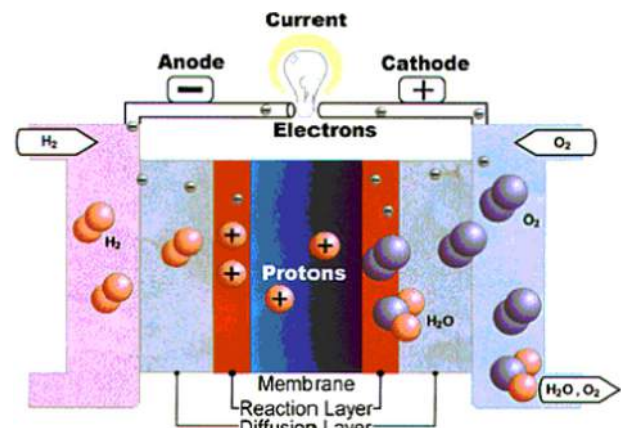


Fig. 8. Hydrogen fuel cell [58].



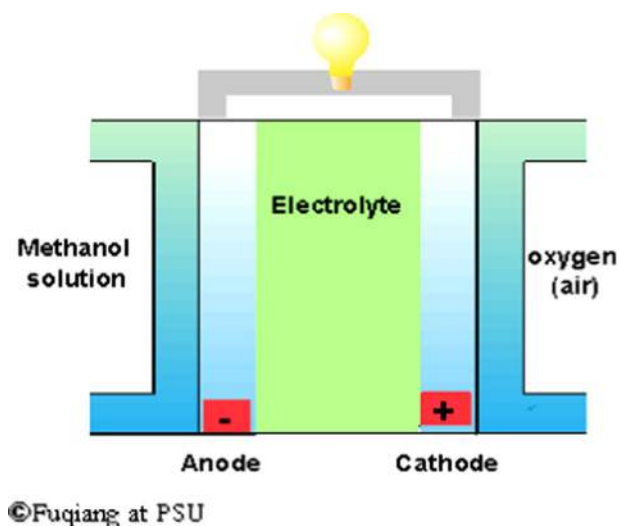
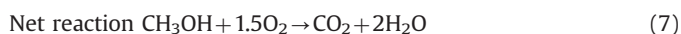
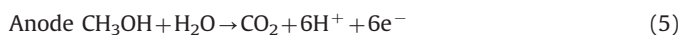


Fig. 9. Direct methanol fuel cell [58].

working temperature, high energy-conversion efficiency and low emission of pollutants. The chemical reactions of this type can be written as:



### 2.2.3. Advantages of the fuel cell

Fuel cell has many advantages such as [59]:

- 1- It gives clean energy with no  $\text{CO}_2$  emissions on  $\text{H}_2$  and less than 50%  $\text{CO}_2$  emissions on hydrocarbons. Also, it provides no  $\text{NO}_x$  or  $\text{SO}_2$  emissions.
- 2- Its efficiency is high (around 40–90%).
- 3- No noise energy source.

Abbaraju et al. [60] utilized composite Nafion membranes which containing  $\text{TiO}_2/\text{SnO}_2$  nanoparticles to enhance the proton exchange membrane fuel cells. They observed that the performance of the modified fuel cell was increased in comparison with the fuel cell with a conventional Nafion membrane especially at high temperatures. Jang et al. [61] mentioned that nanotechnology could be used as a powerful tool for economy production of hydrogen from solar energy in a clean, environmentally friendly and low-cost way by using water splitting by photocatalysis. Best and Dunstan [62] illustrated the effect of nanotechnology for photolytic hydrogen production from water. In their review, they overviewed many literature and methods used in attempting to overcome this problem. The background of photo-catalytic hydrogen production was also presented. Zhu and Zäch [63] reviewed the recent development of using nanostructured materials utilized for photocatalytic hydrogen production. They referred that nanotechnology was opening a new vista in the development of highly active, nanostructured photocatalysts with large surface areas for optimized light absorption, minimized distances (or times) for charge-carrier transport and further favorable properties. They concluded that photocatalytic hydrogen production offered unique opportunities to develop an alternative and sustainable energy system and to reduce emission of greenhouse gases. Alenzi et al. [64] demonstrated the possibility of hydrogen production photoelectrochemically from water/methanol decomposition using  $\text{Ag}/\text{TiO}_2$

nanocomposite thin films. They concluded that the  $\text{Ag}/\text{TiO}_2$  nanocomposite films showed high stability for hydrogen production for more than one month. Furthermore, films were more convenient to use than powders and could be easily recycled. Basri et al. [65] presented a review which was related with computational approaches for theoretical modeling of nanomaterials such as carbon nanotubes (CNT) through molecular dynamic techniques. They focused on nanocatalyst structure, catalyst support, and their applications in the direct methanol fuel cell (DMFC). They concluded that to replace carbon black with carbon nanostructures in catalyst supports, further experiments in fuel cells must be performed to evaluate electrochemical activity and long-term stability of catalysts supported on these new promising materials. Zhang and Silva [66] reviewed the most important researches related with the application of carbon nanotubes (CNTs) in polymer electrolyte based fuel cells (PEFCs). They considered the contribution of (CNTs) in terms of improving the mechanical strength and proton conductivity of polymer electrolyte membrane. They discussed also its role in electrocatalysis with respect to facilitating the utilization of noble metal catalysts (platinum) and exploring the platinum-free catalysts. Also, they investigated the consideration of (CNTs) as hydrogen storage materials. Based on the literatures reviewed, They extracted the following conclusions:

- 1- (CNTs) demonstrated a great potential as multifunctional materials in improving (PEFCs) performance.
- 2- (CNTs) can be inserted into the components of fuel cells to improve its performance and reduce its cost.
- 3- (CNTs) had a high strength and toughness to weight characteristics, which encouraged manufactures to use them as reinforcing fillers to improve the mechanical strength of (PEFCs).
- 4- (CNTs) can be used in electrocatalyst supports due to their high surface area and thermal conductivity. Also, they can be applied in gas diffusion layers due to their high electrical conductivity.
- 5- (CNTs) had a layered graphene tubular structure which enabled them very efficient for hydrogen storage. In fact, hydrogen can be adsorbed by (CNTs) in a physisorption manner by trapping it inside the cylindrical structure of the nanotubes or in the interstitial sites between nanotubes.

Elzatahry et al. [67] prepared by a simple chemical route the cobalt and nickel oxides-graphene nanocomposite for fuel cell applications. The structure, morphology and properties were characterized using X-ray diffraction (XRD) and Transmission Electron Microscope (TEM). The electrocatalytic activity for the methanol oxidation reaction in acidic medium of these nanocomposites compared to platinum had been confirmed using cyclic voltammetry technique. They concluded that the prepared cobalt oxide/graphene nanocomposite had been used successfully for methanol oxidation as a fuel cell application. Chung et al. [68] discussed the convergence of nanotechnology and modeling paradigm of sustainable energy system by using the polymer electrolyte membrane fuel cell as a benchmark example. They concluded that the development of a hierarchical multi-scale paradigm promoted the convergence of nanotechnology to sustainable energy technologies. Zhu et al. [69] gave a short review and advance knowledge on worldwide activities on the ceria-based multi-functional nano-composites, emphasizing on the latest semi-ion conductive nano-composites and their applications for new applied energy technologies. They presented an overview of nano-composites applications for advanced fuel cells (NANO-COFC). They concluded that a homogenous component/layer of the semi- and ion conducting materials could realize fuel cell all its required functions to avoid using three usual components (i.e., anode, electrolyte and cathode). Very recently, Lee and Kjeang [70] described for the first time a nanofluidic fuel cell (Fig. 10) which

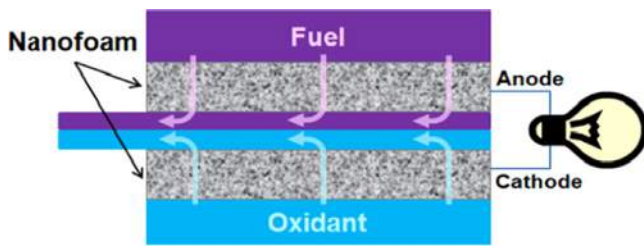


Fig. 10. Nanofluidic fuel cell Lee and Kjeang [70].

utilized fluid flow through nanoporous media. The concept of nanofluidics applied to membraneless, miniaturized fuel cells compatible with standard micromachining methods and on-chip integration. They concluded that their prototype demonstrated higher surface area, reduced activation over-potential, faster kinetic characteristics and moderately enhanced fuel cell performance in the high cell voltage regime with up to 14% higher power density. Therefore, their nanofluidic fuel cell had a high overall efficiency, low-cost and miniaturized power sources.

#### 2.2.4. Diesel engine

Recently, much attention are done by researchers for using hydrogen in internal combustion engine. When hydrogen burns in an internal combustion engine the exhaust is clean water vapor. Therefore, it is better than CO<sub>2</sub> emissions related with fossil fuels [71]. As mentioned earlier, nanofluids have many important properties, one of them related with their strong ability to absorb the radiation. Therefore, they can be utilized efficiently in the combustion process to reduce it. Heywood [72] explained that the radiation heat transfer in diesel engines contributed (20–35%) of the total heat transfer, and it mostly came from soot particles formed during combustion processes. Recently, the efficiency of the internal combustion engine is about (30–40%). Nanotechnology could improve the combustion process by designing specific catalysts with maximized surface area [73]. Kao et al. [74] added nanofluid in the form of aluminum nanoparticles coated by alumina submerged in water to diesel fuel to explore the effect of high temperature reaction responding to diesel engine performance, fuel consumption and exhaust emission. They concluded that aluminum nanoparticles promoted the diesel fuel combustion. Kao et al. [75] presented a significant chemical reaction of hydrogen combustion during aqueous aluminum nanofluid combustion in diesel fuel. The results showed that hydrogen burns in a single-cylinder diesel engine in the presence of an active aqueous aluminum nanofluid. The nanoparticles were made by applying a plasma arc to aluminum nanopowder submerged in water. The average diameter of the aluminum nanoparticles was about (40–60 nm) and they were covered with thin layers of aluminum oxide due to the high oxidation activity of pure aluminum. During combustion, the alumina served as a catalyst and the coated aluminum nanoparticles were denuded and decomposed the water to yield the hydrogen. Fig. 11 showed the smoke percent against the brake mean effective pressure (BMEP) for both diesel (D) and aqueous aluminum nanofluid mixed diesel fuels (AN+D) at three engine speeds. It can be observed that, the reduced smoke concentrations at (1200 and 1800 r/min) indicated clearly that the combustion with (AN+D) fuel was more complete at these speeds than with (D) fuel. They concluded also that the total combustion heat increased while the concentration of smoke and nitrous oxide in the exhaust emission from diesel engine were decreased when the diesel fuel mixed with aqueous aluminum nanofluid. Nagar et al. [76] reviewed some important applications of nanofluids. They mentioned that if the aluminum nanoparticles were covered with thin layers of aluminum

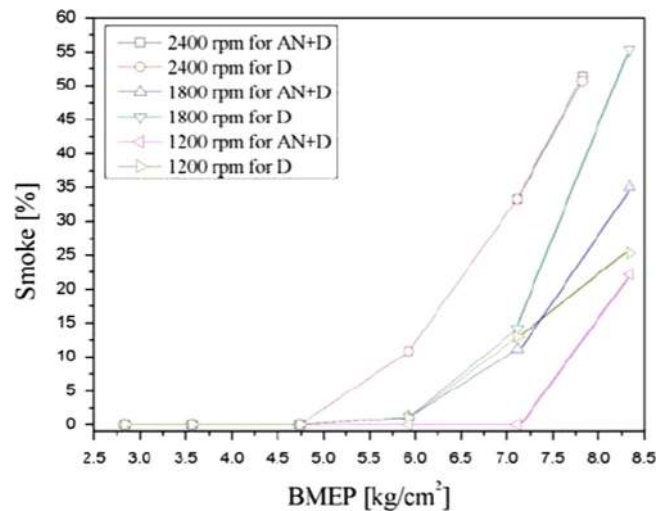


Fig. 11. Smoke concentrations for (AN+D) fuel and (D) fuel under varied loads Kao et al. [75].

oxide a larger contact surface area with water was created and this will increase decomposition of hydrogen from water during the combustion process. During this combustion process, the alumina acted as a catalyst and the aluminum nanoparticles served to decompose the water to yield more hydrogen.

### 2.3. Biomass/bioenergy

Biomass is a term called to all organic materials that stem from plants (including algae, trees and crops). Biomass is produced by green plants converting sunlight into plant material through photosynthesis and includes all land and water-based vegetation, together with organic wastes. The biomass resource can be considered as an organic matter, in which the energy of sunlight is stored in chemical bonds. When the bonds between adjacent carbon, hydrogen and oxygen molecules are broken by digestion or combustion, these substances release their stored chemical energy. Biomass is presently estimated to contribute of about 10–14% of the world's energy supply [77,78]. In fact, Bioenergy is the only alternative and cheap source of energy which can be made easily available to the world. Bioenergy is defined as the energy stored in materials made with the help of living things. There are many types of bioenergy sources which can be summarized as follows [79,80]:

#### 2.3.1. Biofuels

Biofuels were considered as a potential automotive fuel with a bright future. They are fast advancing as a new research area to provide alternative sources of renewable energy. Ethanol and methanol (for examples) which are considered as an excellent biofuels and are highly flammable and made by certain yeasts. They can be made from plant sugars or plant fibers. Currently, Brazil and USA account for nearly 80% of global biofuels production. Both countries produce mainly bioethanol (USA from maize and Brazil from sugar cane). Bioethanol is the most commonly used biofuel for spark ignition (gasoline) engine applications due to similar auto-ignitability properties to those of gasoline fuel. In the next few decades, global demand for transport fuel is expected to grow significantly by up to 55% by 2030 compared to 2004. This will accelerate the growth in demand for biofuels, as they are expected to make an increasing contribution to meet future energy needs of the mankind [81]. Biofuels have many advantages such as they burn very cleanly and deliver more power than gasoline. Biofuels are considered renewable, because plants can be

grown every year. From the other hand, they are friendly environment. Since, the raw materials of biofuels are basically plant sugars dissolved in water. While, fossil fuels are hydrocarbons composed almost from carbon and hydrogen. The main challenge for the future is to develop biofuels which do not interface with the food chain and high efficient in terms of both costs and energy. For further informations about biofuels, one can be go back to Brennan and Owende [82] and Pittman et al. [83].

### 2.3.2. Biogas

It is a flammable gas similar to the natural gas consists mostly of a mixture of gases, usually carbon dioxide and methane. It makes by bacteria when air or oxygen is absent. Biogas can be used instead of natural gas for heating and cooking and is considered to be a source of renewable energy. This is because the production of biogas depends on the supply of grass, which usually grows back each year. Biogas is used also in the transportation field. For example, in Sweden during 2008 approximately 15,000 cars and hundreds of buses and trucks were running by biogas. Biogas is produced from four main sources [81]:

- 1- Sewage treatment plants.
- 2- Landfills.
- 3- Cleaning of organic industrial waste streams.
- 4- Mesophilic and thermophilic digestion of organic waste.

### 2.3.3. Vegetable oil

They have comparable energy density, heat of vaporization and stoichiometric air/fuel ratio with mineral diesel. Vegetable oils in diesel engines lead to a significant reductions in emissions of sulfur oxides, carbon monoxide, smoke and noise [84].

### 2.3.4. Bio-oil

Is a dark brown viscous, corrosive and acidic with distinctive smoky odor used as fuel for furnaces, gas turbine, diesel engines, boiler and stationary engines. They obtained from air dried wood by high pressure liquefaction (HPL) result in a complex mixture of volatile organic acids, alcohols, aldehydes, ethers, esters, ketones and non volatile components. These oils could be upgraded catalytically to give an organic distillate product which is rich in hydrocarbons and useful chemicals. Bio-oil has a complex chemical composition contained chemical products of lignocelluloses biomass like aliphatic alcohols/aldehydes, furanoids, pyranoids, benzenoids, fatty acids and high molecular mass hydrocarbons [85]. Maa and Hanna [86] presented a comprehensive review about biodiesel production. They referred that the used cooking oils were utilized as a raw material to produce it. There are four primary ways to make biodiesel, direct use and blending, micro-emulsions, thermal cracking (pyrolysis) and transesterification (Alcoholysis). The most commonly used method was transesterification of vegetable oils and animal fats. They concluded that, the transesterification reaction was affected by molar ratio of glycerides to alcohol, catalysts, reaction temperature, reaction time and free fatty acids and water content of oils or fats. Also, they stated that the adoption of continuous transesterification process and recovery of high quality glycerol from biodiesel by-product (glycerol) were considered as a primary options to reduce the cost of biodiesel production. Sajith et al. [87] illustrated experimentally that using nanosized cerium oxide particles as additives on biodiesel fuel were found to appreciably reduced the emission levels of hydrocarbons and  $\text{NO}_x$  components. This was occurred by enhancing hydrocarbon oxidation and promoting complete combustion. Mahmood and Hussain [88] were used nanobiotechnology to convert experimentally the spent tea into hydrocarbon fuels

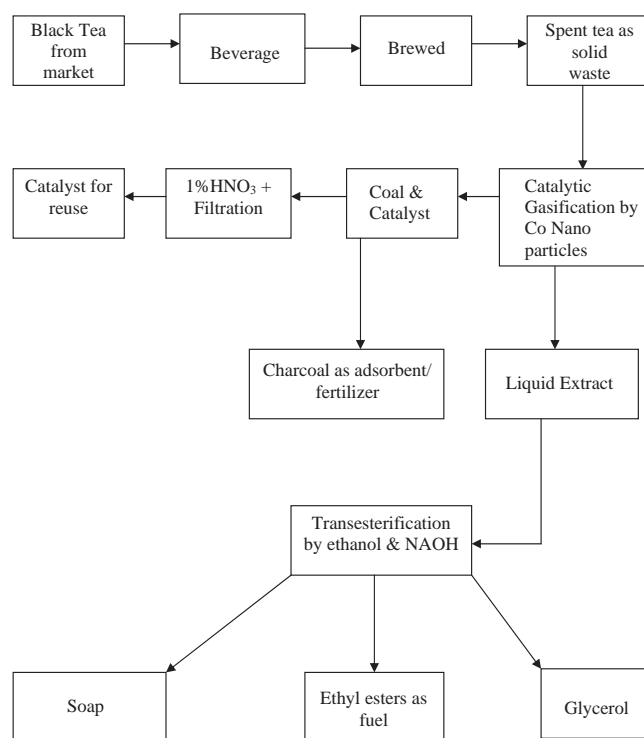


Fig. 12. Schematic representation of the biofuel production from spent tea Mahmood and Hussain [88].

(i.e., bioethanol, biodiesel and charcoal) as shown in Fig. 12. The experimental work included three steps for the conversion of spent tea into biofuels. In the first step, spent tea was gasified using Co-nano catalyst at (300 °C) and atmospheric pressure. Catalytic gasification of spent tea yielded (60%) liquid extract, (28%) fuel gases and (12%) charcoal. Gaseous products contained (53.03%) ethane, (37.18%) methanol and (4.59%) methane. In the second step of the experiment, liquid extract of spent tea obtained from gasification, on transesterification gave (40.79%) ethyl ester (biodiesel). In the third step, “*Aspergillus niger*’s” growth on spent tea produced (57.49%) bioethanol. They concluded that spent tea (solid waste) was not only used for the production of biodiesel and bioethanol but also hydrocarbon fuel gases. Goh et al. [89] incorporated iron oxide nanoparticles into single-walled carbon nanotubes (SWCNTs) to produce magnetic single-walled carbon nanotubes (mSWCNTs). They recycled the immobilized enzyme, toward useful applications in biofuel production processes. Their results, combined with the intrinsic properties of the nanotubes, paved the way for greater efficiency in carbon nanotube-enzyme bioreactors, reduced capital costs in industrial enzyme systems and improved the efficiency of biofuel production.

### 2.3.5. Biodiesel

Is methyl or ethyl ester of fatty acid made from virgin or used vegetable oils and animal fats or recycled cooking grease. The use of biodiesel in conventional diesel engines leads to a substantial reduction in emission of unburned hydrocarbons and carbon monoxide (CO). Pure biodiesel (B100) is the lowest-emission diesel fuel. Biodiesel is also considered an oxygenated fuel, which meaning it contains a reduced amount of carbon and higher hydrogen and oxygen content than fossil diesel. This improves absolutely the combustion of biodiesel and reduces the particulate emissions from unburnt carbon. Furthermore, the high lubricity of biodiesel extends the lifetime of fuel injection systems as well as metallic

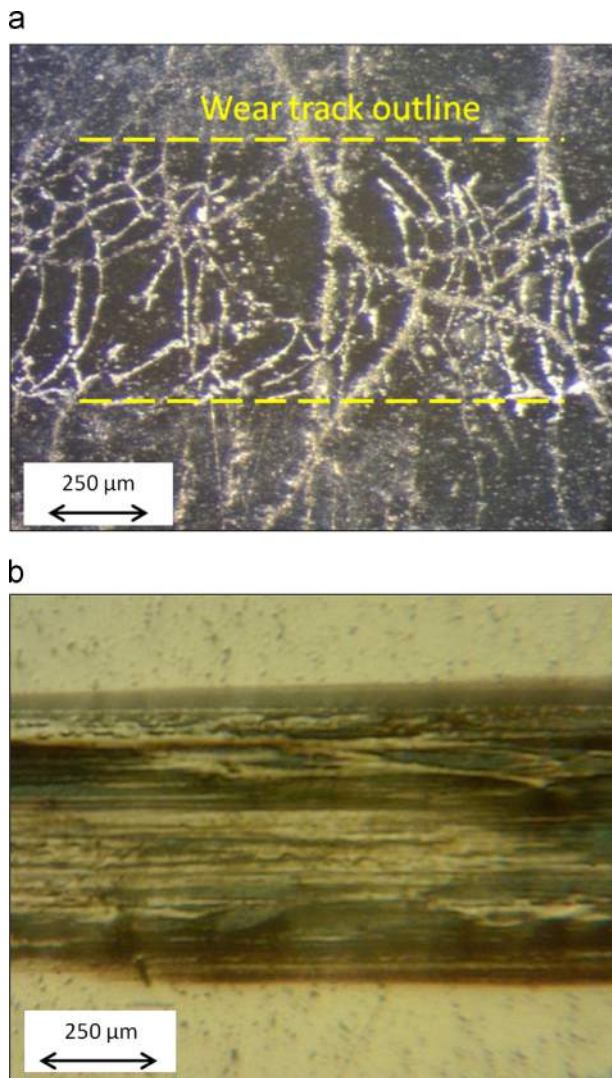
components that have sliding contacts with each other. Wen et al. [90] performed an experimental study about the preparation of KF/CaO nanocatalyst and its application in biodiesel production from Chinese tallow seed oil. The effects of different preparation conditions on biodiesel yield were investigated and the structure of the catalyst was characterized. They concluded that the biodiesel yield was reached up to 96.8% in the presence of KF/CaO nanocatalyst and could be used efficiently to convert the oil with higher acid value into biodiesel. Hu et al. [91] used a nano-magnetic solid base catalyst (KF/CaO-Fe<sub>3</sub>O<sub>4</sub>) for biodiesel production. The results indicated that, when the reaction was carried out at (65 °C) with a methanol/oil molar ratio of 12:1 and a catalyst concentration of (4 wt%), the biodiesel yield exceeded 95% at 3 h of reaction time. They concluded that the nano-magnetic solid base catalyst used in the preparation of biodiesel gave a good prospect of its development and application. Qiu et al. [92] performed an experimental study to prepare a heterogeneous solid base nanocatalyst for transesterification of soybean oil with methanol to biodiesel. The experimental results showed that a 16:1 molar ratio of methanol to oil, 6.0% catalyst, 60 °C reaction temperature and 2 h reaction time gave the best results and the biodiesel yield of about (98.03%) was achieved. Kaur and Ali [93] prepared lithium impregnated calcium oxide and used it as a solid catalyst for the biodiesel production from the transesterification of karanja and jatropha oils. The complete transesterification of karanja and jatropha oils was achieved in 1 and 2 h, respectively, 65 °C, utilizing 12:1 molar ratio of methanol to oil. They concluded that the biodiesel was produced efficiently by their method. Yan et al. [94] developed a novel concept and practical method for high-yielding production of biodiesel with 95% yield from grease for one-pot esterification and transesterification by using tandem lipases. The results showed that the developed tandem-lipases system gave a great potential for biodiesel production from waste grease. Chen et al. [95] investigated experimentally the possibility of using well-dispersed sulfated zirconia nanoparticles as a high-efficiency catalysts for the production of bis(indolyl) methanes and biodiesel. The mechanism of the formation of the synthesized zirconia nanoparticles was also proposed. Satisfactory yields and esterification ratio were obtained under optimal reaction conditions. Ngo et al. [96] performed an efficient and green transformation of waste grease containing high amount of free fatty acid to a biodiesel fuel using highly active and easily recyclable magnetic nanobiocatalyst aggregates. They concluded that this method gave high yielding (98%) one-pot production of biodiesel from grease with excellent recyclability. Zhang et al. [97] utilized experimentally the carbon-based nanostructured catalyst with medium acid density for biodiesel production by catalytic distillation. They concluded that the produced biodiesel synthesis was promising and easy to amplify, by avoiding some drawbacks of previous available methods. Hipólito et al. [98] produced experimentally the biodiesel fuel by using sodium titanate nanotubes (STNT) as a catalyst. It was found that the (STNT) catalyst did not require a high temperature thermal pre-treatment (activation) before the transesterification reaction. They obtained a high biodiesel yields (97–100%) with using (STNT) after a chemical reaction of 8 h. They concluded that the increase in the reaction temperature to (100–120 °C) had a positive effect on the biodiesel yield. Konwar et al. [99] presented a review on latest developments in biodiesel production using carbon-based catalysts. They indicated that the two key reactions in biodiesel production were the esterification and transesterification. It was mentioned that use of carbon-based (AC) catalysts in these reactions opened doors for cost minimization and environmentally biodiesel production by eliminating problems associated with the conventionally used reaction schemes. They concluded that catalyst played an important role in biodiesel production and using it made the biodiesel production more “greener” one.

#### 2.4. Wind energy/wind turbines

Wind energy is another type of renewable energies which can be defined as the use of the wind as an energy source. A wind energy system (i.e., wind turbine) converts the kinetic (moving) energy of the wind into mechanical or electrical energy that can be utilized for practical use. In fact, wind turbines don't need to burn the fuel. Therefore, they considered friendly to the environment. From the other side, the wind is connected to the sun, so as the sun shines the wind exists on the earth. The effects of wind energy on the environment are generally less problematic than those result from other power sources. Recently, more than 23 billion kWh of clean and cheap electricity are being produced annually around the world. For example, India power production utilizing wind energy is estimated around 1000 MW, while Germany produced about 4400 MW of electricity from wind energy [100]. As of 2011, Denmark is generating more than a quarter of its electricity from wind and 83 another countries around the world are using wind power on a commercial basis. In 2010, wind energy production was over (2.5%) of total worldwide electricity usage and growing rapidly at more than (25%) per annum [101]. Wind power plants are dependent on wind. The wind speed needs to be at least (13–15 m/s) to fully utilize a wind power plant to its perfect effect. For smaller types, wind speed of (10 m/s) may be sufficient. Because it is not always windy, the efficiency of wind power plants is about (30–60%) on average. The energy provided by a wind turbine is proportional to the square of its blade length. For more informations about the wind energy, the reader can be go back to Sherif et al. [102] and Dalili et al. [103]. Nano-composite materials have an excellent strength to weight and stiffness to weight ratios. Therefore, they enable the construction of longer, more strong blades. Nanotechnology can be used also to increase the wind turbine efficiency by reducing energy losses caused by some tribological issues like micro-pitting, wear, scuffing and spalling in gear boxes. This can be satisfied via nano-lubricants and low-friction coatings [104]. Greco et al. [105] evaluated experimentally using a sliding contact linear reciprocating rig, the friction and wear behaviors of a boron nitride based surface treatment and nano-particle lubricant additives for wind turbine gearbox applications to accommodate severe operating conditions and mitigate surface originated failure. Nano-colloidal boron-nitride based lubricant additives were considered as a complementary technology to react with the borided surface to form a wear protective tribofilm. Fig. 13 showed an optical micrographs of wear track on borocarbured flat surface (Fig. 13(a)) and carburized flat surface (Fig. 13(b)). The results indicated that the wear track on the carburized surface was clearly identifiable and showed an evidence of significant abrasive wear. The wear track on the borocarbured surface was much less noticeable and the surface within the wear track was smoother than the surrounding surface. They concluded that a nano-colloidal boron nitride additive in a commercial gear oil chemically reacted with the borided surface to form a wear protective tribofilm. Moreover, the borided surfaces enhanced the mechanical properties of the surface layer, leading to improve wear resistance.

#### 2.5. Geothermal energy

Geothermal energy can be defined as the thermal energy extracting from the earth's crust that varies in length between 5 and 10 km. At these high depths, the temperature is very high. Therefore, nanofluids can be used as a cooling fluids to cool the pipes which exposed to this high temperatures. Also, it can be used to cool the required parts like sensors and electronics in drilling machines which working under high friction and high temperature environment. Geothermal energy sources are



**Fig. 13.** Optical micrographs of wear track on: (a) borocarbided flat surface and (b) carbided flat surface Greco et al. [105].

classified in terms of the measured temperature as low ( $< 100\text{ }^{\circ}\text{C}$ ), medium ( $100\text{--}150\text{ }^{\circ}\text{C}$ ) and high temperature ( $> 150\text{ }^{\circ}\text{C}$ ) while they extracted by using a ground heat exchangers [106]. The geothermal gradient, which is the difference in temperature between the core of the earth and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. From the other side, nanofluids can be used as a working fluid to extract energy from the earth core and processed it into a power plant system to produce large amounts of work energy [76]. Geothermal energy has various applications. For example, district heating applications use networks of piped hot water to heat many buildings across entire communities. More than 72 countries have reported direct use of geothermal energy. Iceland being the world leader where about (93%) of its homes are heated with geothermal energy. For this reason, Iceland saving over (100\$ million) annually in avoided oil imports. Also, it is now considered one of the cleanest countries around the world due to geothermal energy applications [107]. In fact, geothermal power plants can operate 24 h per day, providing base-load capacity, and the world potential capacity for geothermal power generation is estimated to be (85 GW) over the next 30 years. But, geothermal power is accessible only in limited areas of the world, including the United States, Central America, East Africa, Iceland, Indonesia, and

Philippines [108]. However, the major challenge encountered in the geothermal energy utilization is the requirement of deep borings which often causing tremors or earthquakes. Nanofluids can encapsulate or absorb substantially higher orders of energy as compared to the normal thermal fluids. This observation opens up a range of future research prospects of using less deep borings to utilize geothermal energy as mentioned by Ganguly [109].

### 2.6. Tidal/water energy

As the Earth spins on its axis, it rotates through the oceanic tidal bulge raised by the Moon. This leads to the well-known rise and fall of the tides, roughly at 12.5 h intervals along the seacoast. This process is repeated every day, so the tidal energy represents another source of renewable energy [110]. In general, the water energy can be considered as a huge source of renewable energy for two reasonable reasons. The first is about 70 percent of the earth's surface is covered by water. The second one that the world's potential for wave energy is about (10,000–15,000 TW h) per year. The power obtained from the sea waves can be used in water desalination, hydrogen production, ocean mining, liquid and solid sated synthesized fuels and ice production [111]. Very recently, Qu et al. [112] explained in their review that nanotechnology offered opportunities to develop next-generation water supply systems. They explained that nano-materials had many extraordinary properties such as high surface area, photosensitivity, catalytic and antimicrobial activity, electrochemical, optical, and magnetic properties which provided useful features for many applications such as sensors for water quality monitoring, specialty adsorbents, solar disinfection/decontamination, and high performance membranes. They concluded that the development of nanotechnology must go in parallel with environmental health and safety research to develop sustainable water management.

### 3. Conclusions

The present work gives a comprehensive overview and understanding of nanotechnology applications in renewable energy field (Tables 1–5). For example, nanotechnology makes a huge revolution in the size and design of renewable energy devices utilized for energy conversion and storage, environmental monitoring, as well as green engineering of environmental friendly materials. It is shown that, nanomaterials play a significant role on the human life, by providing a cheap and clean energy which is now become a global industry. Some important conclusions are summarized below:

- 1- The use of nano-materials in the renewable energy field can play a crucial role in increasing the efficiency of solar cell, fuel cell and wind turbine.
- 2- Nanotechnology can improve the developed countries ability to reduce the environmental impact of burning fossil fuels to produce energy.
- 3- Nanotechnology makes a significant reductions in the cost of expensive components, such as solar cells as well as in the areas of hydrogen production and storage.
- 4- Nanotechnology can be considered as a key enabler of the increasing hydrogen energy utilization.
- 5- Bio fuels industry greatly improved by utilizing nano-practices.
- 6- Further researches are needed to study the effect of nanotechnology in geothermal, wind and tidal energies, since the number of published papers in these fields are very limited compared with the corresponding papers related with the other types of the renewable energies.

**Table 1**  
Summary of investigations of nanotechnology applications in solar energy.

Method	Reference	Year	Application	Results and remarks
Experimental	Otanicar and Golden [30]	2009	Solar collector	The nanofluid based solar collector had a lower embodied energy (about 9%) and approximately (3%) higher levels of pollution offsets than a conventional collector
Experimental	Natarajan and Sathish [31]	2009	Solar water heater	The nanofluids were effective than the conventional fluids and if were used as a heat transport medium, it increased the efficiency of the traditional solar water heater
Theoretical (review)	Yu and Chen [32]	2009	Solar cell	The nanotechnology offered significant opportunities to improve efficiencies of solar cells by facilitating photon absorption, electron transport and electron collection
Experimental	Yuhas and Yang [33]	2009	Solar cell	The use of a vertically aligned nanowire array eliminated the problem of exciton diffusion versus light absorption
Experimental and numerical	Otanicar et al. [34]	2010	Solar collector	Efficiency improvements of up to 5% in solar thermal collectors by utilizing nanofluids as an absorption mechanism
Theoretical	Liu et al. [35]	2010	General	The visible light photocurrent could be enhanced by coating TiO <sub>2</sub> nanowires with gold or silver nanoparticles
Experimental	Bazargan [36]	2010	Dye sensitized solar cell (DSSC)	The (ISC) and (VOC) for cells operating with carbon and platinum coated counter electrodes were increased from (360 to 400 mV) and from (175 to 200 μA), respectively
Experimental	Taylor et al. [27]	2011	Power tower solar collectors	Efficiency improvement on the order of 5–10% was possible with a nanofluid receiver
Theoretical	Sethi et al. [37]	2011	Solar PV cell	Solar cells efficiency could be improved by increasing the absorption efficiency of light as well as the overall radiation-to-electricity
Experimental	Taylor et al. [38]	2011	Determining the optical properties of nanofluids	They observed that for materials used in this study, over 95% of incoming sunlight could be absorbed
Theoretical	Baraton [39]	2011	Dye-sensitized solar cells	The particle size and shape, crystallinity, surface morphology and chemistry of TiO <sub>2</sub> were considered as a key parameters for enhancing the performance of the dye-sensitized solar cells
Experimental	Mercatelli et al. [40]	2011	Solar devices	Carbon nanohorns could be used efficiently for increasing the overall efficiency of the sunlight exploiting device
Experimental	Han et al. [41]	2011	Solar absorption	Carbon black nanofluids had a good absorption ability of solar energy and could effectively enhance the solar absorption efficiency
Theoretical (review)	Arivalagan et al. [42]	2011	General	Nanotechnology could help to increase the efficiency of light conversion by using nanostructures
Experimental	Jai Poinern et al. [43]	2012	Direct-absorption solar collectors	The functionalized (CNS) nanofluids had the potential to effectively improve the solar absorption capabilities of direct-absorption solar collectors
Experimental	Senthil Kumar et al. [44]	2012	Wickless solar heat pipe collector	The nanofluid working fluid collector gave the better performance in all the operating conditions
Experimental	Mammadov [45]	2012	Solar receiver	The developed solar receiver had a high absorption of solar thermal energy of about (94%) and low emittance of infra-red radiation of about (7%)
Theoretical	Tiwari et al. [46]	2013	Flat-plate solar collector	Thermal efficiency of solar collector was increased by about (31.64%) in comparison with the conventional solar water heating system
Experimental	Obaid et al. [47]	2013	Building solar heating system	The effect of adding small quantities of nanoparticles (MgO) to pure water minimized the heating loss time while the heat gain was lower than pure water. A reverse behavior was obtained by adding large quantities of nanoparticles
Numerical	Shankar and Manivannan [48]	2013	Solar water heater	About (10.88%) of an improved efficiency was observed at (0.025%) volume fractions
Experimental	Verma and Kundan [50]	2013	Direct absorption solar collector	The collector efficiency increased about to (3–4%) when Al <sub>2</sub> O <sub>3</sub> –H <sub>2</sub> O nanofluids were used as compared to simple water

**Table 2**  
Summary of investigations of nanotechnology applications in hydrogen energy.

Method	Reference	Year	Application	Results and remarks
Experimental	Kao et al. [74]	2005	Diesel engine	The aluminum nanoparticles promoted the diesel fuel combustion
Experimental	Kao et al. [75]	2008	Single-cylinder diesel engine	The total combustion heat increased while the concentration of smoke and nitrous oxide in the exhaust emission from diesel engine were decreased when the diesel fuel mixed with aqueous aluminum nanofluid
Experimental	Abbaraju et al. [60]	2008	Fuel cell	The performance of the modified fuel cells were increased by using TiO <sub>2</sub> /SnO <sub>2</sub> nanoparticles especially at high temperatures
Theoretical [review]	Zhu and Zäch [63]	2009	Photocatalytic hydrogen production	The photocatalytic hydrogen production offered unique opportunities to develop an alternative and sustainable energy system and to reduce emission of greenhouse gases
Experimental	Alenzi et al. [64]	2010	Hydrogen production	The Ag/TiO <sub>2</sub> nanocomposite films showed high stability for hydrogen production for more than one month
Theoretical [review]	Basri et al. [65]	2010	Direct methanol fuel cell (DMFC)	Further experiments in fuel cells must be performed to evaluate electrochemical activity and long-term stability of catalysts
Theoretical	Zhang and Silva [66]	2011	Polymer electrolyte based fuel cells (PEFCs)	(CNTs) can be inserted into the components of fuel cells to improve its performance and reduce its cost
Experimental	Elzatahry et al. [67]	2012	Fuel cell	The prepared cobalt oxide/graphene nanocomposite had been used successfully for methanol oxidation as a fuel cell application
Theoretical	Chung et al. [68]	2012	Polymer electrolyte membrane fuel cell	The development of a hierarchical multi-scale paradigm promoted the convergence of nanotechnology to sustainable energy technologies
Theoretical [review]	Zhu et al. [69]	2013	Fuel cell	Homogenous component/layer of the semi- and ion conducting materials could realize fuel cell all its required functions to avoid using three usual components (i.e., anode, electrolyte and cathode)
Experimental	Lee and Kjeang [70]	2013	Nanofluidic fuel cell	Their nanofluidic fuel cell had a high overall efficiency, low-cost and miniaturized power sources

**Table 3**  
Summary of investigations of nanotechnology applications in biofuels.

Method	Reference	Year	Application	Results and remarks
Experimental	Sajith et al. [87]	2010	Biodiesel fuel	The addition of nanosized cerium oxide particles on biodiesel fuel were found to appreciably reduced the emission levels of hydrocarbons and NO <sub>x</sub> components
Experimental	Mahmood and Hussain [88]	2010	Biofuels	Nanobiotechnology could be used successfully for the production of biofuels from spent tea (solid waste)
Experimental	Goh et al. [89]	2012	Biofuels	They reduced capital costs in industrial enzyme systems and improved the efficiency of biofuel production
Experimental	Wen et al. [90]	2010	Biodiesel fuel	The biodiesel yield was reached up to 96.8% in the presence of KF/CaO nanocatalyst and could be used efficiently to convert the oil with higher acid value into biodiesel
Experimental	Hu et al. [91]	2011	Biodiesel fuel	The nano-magnetic solid base catalyst used in the preparation of biodiesel gave a good prospect of its development and application
Experimental	Qiu et al. [92]	2011	Biodiesel fuel	The results showed that a 16:1 molar ratio of methanol to oil, 6.0% catalyst, 60 °C reaction temperature and 2 h reaction time gave the best results and the biodiesel yield of about (98.03%) was achieved
Experimental	Kaur and Ali [93]	2011	Biodiesel fuel	The complete transesterification of karanja and jatropha oils was achieved in 1 and 2 h, respectively, 65 °C, utilizing 12:1 molar ratio of methanol to oil
Experimental	Yan et al. [94]	2012	Biodiesel fuel	The developed tandem-lipases system gave great potential for biodiesel production from waste grease
Experimental	Chen et al. [95]	2013	Biodiesel fuel	They obtained satisfactory yields and esterification ratio under optimal reaction conditions
Experimental	Ngo et al. [96]	2013	Biodiesel fuel	They concluded that the transformation of waste grease to a biodiesel fuel gave high yielding (98%) one-pot production of biodiesel from grease with excellent recyclability
Experimental	Zhang et al. [97]	2014	Biodiesel fuel	The produced biodiesel synthesis was promising and easy to amplify, by avoiding some drawbacks of previous available methods
Experimental	Hipólito et al. [98]	2014	Biodiesel fuel	They obtained a high biodiesel yields (97–100%) with using (STNT) after a chemical reaction of 8 h
Theoretical [review]	Konwar et al. [99]	2014	Biodiesel fuel	The catalyst played an important role in biodiesel production and using it made the biodiesel production more “greener” one

**Table 4**  
Summary of investigations of nanotechnology applications in wind energy.

Method	Reference	Year	Application	Results and remarks
Experimental	Greco et al. [105]	2011	Wind turbine gear box	Nano-colloidal boron nitride additive in a commercial gear oil chemically reacted with the borided surface to form a wear protective tribofilm

**Table 5**  
Summary of investigations of nanotechnology applications in geothermal energy.

Method	Reference	Year	Application	Results and remarks
Review	Ganguly [109]	2012	General	Nanofluids can encapsulate or absorb substantially higher orders of energy as compared to the normal thermal fluids

7- Wind turbine performance can be significantly enhanced by using nano-particles. Furthermore, they increase the life of wind turbines by increasing their resistance to wear, fatigue failure and severe operating conditions.

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