Chapter 1

Introduction

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1.1 Energy: importance and consumption

All of the achievements of mankind were sustained through the use of energy and it is vital to human being. At the root of modern society is the ability to harness energy. Energy is always conserved, but energy is constantly being converted from more useful to less useful forms. The rapidly increasing world energy consumption has raised concerns over difficulty in meeting the demands, depletion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). According to the data published by International Energy Agency, primary energy consumption has increased by 49% and CO_2 emissions by 43% during last two decades, with an average annual increase of 2% and 1.8% respectively (Pérez-Lombard et al., 2008). Energy Information Administration projects 48% increase in world energy consumption between 2012 and 2040. The outlook for energy use worldwide presented in the International Energy Outlook 2016 continues to show rising levels of demand over the next three decades. Asian countries including China and India, accounts for more than half of the world's total increase in energy consumption over the projection period. Concerns about energy security, effects of fossil fuel emissions on the environment, and sustained, long-term high world oil prices support expanded use of nonfossil renewable energy sources and nuclear power.

Renewables and nuclear power are the world's fastest-growing energy sources over the projection period. It has been expected that the renewable energy share will increase by an average 2.6% per year between 2012 and 2040. Even though nonfossil fuels are expected to grow faster than fossil fuels (petroleum and other liquid fuels, natural gas, and coal), fossil fuels still will account for more than three-quarters of world energy consumption till 2040. As oil prices rise in the long term, many energy users need to adopt more energy-efficient technologies and switch away from liquid fuels when feasible. Liquid fuels- mostly petroleum-based- remain the largest energy source. Coal is the world's slowest-growing energy source and top three coal-consuming countries are China, United States, and India. (Source: U.S. Energy Information Administration, International Energy Outlook 2016).

1.2 Need for sustainable energy

In broad terms, the concept of sustainable development is an attempt to combine growing concerns about a range of environmental issues with socio-economic issues (Hopwood et al., 2005). In simple words, it is a process of meeting human development goals while sustaining the ability of natural systems to continue to provide the natural resources and ecosystem services upon which the economy and society depends. Sustainable development is the organizing principle for sustaining finite resources necessary to provide for the needs of future generations of life on the planet. Sustainable development has the potential to address fundamental challenges for humanity, now and into the future. The concept of sustainable development can be interpreted in many different ways, but at its core is an approach to development that looks to balance different, and often competing, needs against an awareness of the environmental, social and economic limitations we face as a society.

At the moment, most of the energy the developed world consumes is produced from fossil fuels; that's not sustainable. The world needs another industrial revolution in which our sources of energy are affordable, accessible and sustainable. Energy efficiency and conservation, as well as decarbonizing our energy sources, are essential to this revolution. Reducing carbon emissions on the timescale needed to alleviate the worst risks of climate change will not be driven by our inability to find cost-effective sources of fossil fuels. Despite the significant growth in the use of renewable energy, the fractional sum of non-carbon- emitting sources of energy that remained constant during the past two decades is alarming (Chu and Majumdar, 2012). The choices that we make (or fail to make) in the coming years about sustainable energy will determine what world future generations will inherit. A secure long-term energy supply is one of the largest challenges for mankind in the 21st century. Energy is critical to global human development including the ecosystem, economic growth, employment and prosperity. In addition to the slowly diminishing availability, and intensive price rise, of fossil-based fuels, other factors such as efficiency of use, reliability, environmental and climate concerns, and the risk for social and political unrest, play increasingly important roles and call for committed and forceful efforts to change the present energy system to a sustainable one. An effective, clean, wise and reasonable uses of the existing conventional energy sources- oil, natural gas, coal and nuclear constitute a life-line to a truly sustainable energy system (Zach et al., 2006).

Following are the motivations for development of sustainable energy systems (MacKay, 2009)

a. First, fossil fuels are a finite resource. The abundant supplies of fossil fuels will end, bringing down the economic order with it. It has been estimated that at current rates of production, oil will run out in 53 years, natural gas in 54 years, and coal in 110 years. We have managed to deplete these fossil fuels- which have their origins somewhere between 541 and 66 million years ago- in less than 200 years since we started using them. Hence we seek alternative energy sources. Indeed given that fossil fuels are a valuable resource, useful for manufacture of plastics and all sorts of other creative material, perhaps we should save them for better uses than simply setting fire to them.

b. Second, secured long term energy supply is essential. Even if fossil fuels are still available somewhere in the world, but dependency is harmful to the nation's economy. A substantial number of old coal power stations and nuclear power stations will be closing down during the next decade. Hence there is a risk that energy demand will exceed supply of energy, if adequate plans are not implemented

c. Third, using fossil fuels changes the climate and the biggest contributor to climate change is the increase in greenhouse effect produced by carbon dioxide (CO_2). Most of the carbon dioxide emissions come from fossil-fuel burning. And the main reason we burn fossil fuels is for energy. So to fix climate change, we need to sort out a new way of getting energy. The climate problem is mostly an energy problem.

Sustainable energy development strategies normally involve three major technological changes: energy savings on the demand side, efficiency improvements in the energy production, and replacement of fossil fuels by various sources of renewable energy. Consequently, large-scale renewable energy implementation plans must include strategies for integrating renewable sources in coherent energy systems influenced by energy savings and efficiency measures (Lund, 1999; Lior, 2002; Afgan and Carvalho, 2002).

1.3 Renewable energy- towards sustainable solution

Since environmental protection concerns are increasing, both clean fuel technologies and new energies are being intensively pursued and investigated. It is clear that future growth in the energy sector is primarily in the new regime of renewable.

Therefore, shifting to renewable energy can help us meet the dual goals of reducing greenhouse gas emissions, thereby limiting future extreme weather and climate impacts, and ensuring reliable, timely, and cost-efficient delivery of energy. Investing in renewable energy can have significant dividends for our energy security. Renewable energies are energy sources that are continually replenished by nature and derived directly from the sun (such as thermal, photo-chemical, and photo-electric), indirectly from the sun (such as wind, hydropower, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). Renewable energy technologies turn these natural energy sources into usable forms of energy- electricity, heat and fuels. Fig. 1.1 illustrates the ability of renewable energy sources to provide over 3000 times the current global energy needs.

Renewable energy markets- electricity, heating and transportation- have been growing sharply over the last five years. The deployment of established technologies, such as hydro, as well as newer technologies such as wind and solar photovoltaic, has risen quickly, which has increased confidence in the technologies, reduced costs and opened up new opportunities.

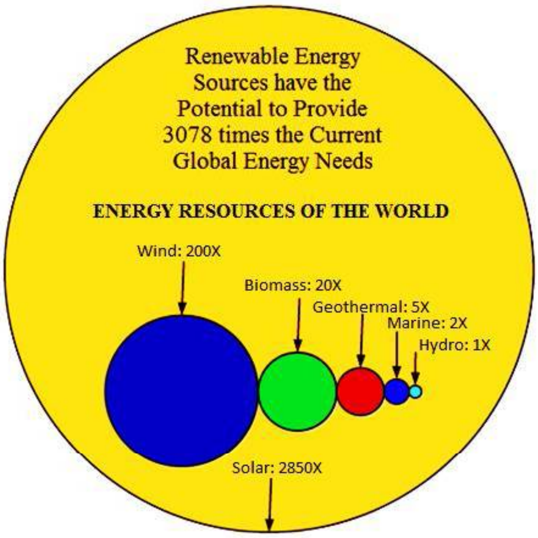

Fig. 1.1 Energy resources of the world

Global electricity generation from renewable energy sources is expected to grow 2.7 times between 2010 and 2035. The share of renewables in electricity generation is higher than in heat production or transport (Ellabban et al., 2014).

1.4 Solar energy harvesting- need of the hour

The major resource of renewable energy comes from the Sun. The Sun delivers more energy to Earth in one hour than world consumes over the course of a year. Solar energy has been explored through solar thermal utilization, photovoltaic power generation, and so on (Duffie and Beckman, 2013; Tripanagnostopoulos, 2007; Charalambous et al., 2007). Solar thermal utilization is the most popular application among them. It is important to use solar energy to a wide range of applications and provide solutions through the modification of the energy proportion, improving energy stability, increasing energy sustainability, and enhancing system efficiency (Mekhilef et al., 2011). While large-scale solar thermal installations are being developed for electrical power generation, an alternative and currently unmet need is in compact solar energy sources that drive vital processes directly, in addition to the generation of electrical power. These types of small scale, stand-alone solar energy converters could directly enable a range of applications such as sterilization, distillation, desalination, etc. (Neumann et al., 2013).

Following are the two means of harvesting solar energy

1.4.1 Photovoltaic

Solar photovoltaic (PV) systems directly convert solar energy into electricity. The basic building block of a PV system is the PV cell, which is a semiconductor device that converts solar energy into direct-current electricity. PV cells are interconnected to form a PV module. The PV modules, combined with a set of additional application dependent system components form a PV system. PV systems are highly modular, i.e., modules can be linked together to provide power ranging from a few watts to tens of megawatts. The most established solar PV technologies are silicon based systems. More recently, so called thin film modules, which can also consist of non-silicon semiconductor material, have become increasingly important. Although thin films generally have a lower efficiency than silicon modules, their price per unit of capacity is low. Concentrating PV, where sunlight is focused onto a smaller area, is on the edge of entering full market deployment. Concentrating PV cells have very high efficiencies of up to 40%. Other technologies, such as organic solar cells, are still in the research phase. PV module manufacturing in large plants attracts better economies of the scale. PV technology has the advantage that it uses diffuse component of the sunlight along with direct component. This advantage produces higher efficiencies (Ellabban et al., 2014).

1.4.2 Concentrating solar power

Concentrating solar power (CSP) technologies produce electricity by concentrating direct- beam solar irradiance to heat a liquid, solid or gas that is then used in a downstream process for electricity generation. Large-scale CSP plants most commonly concentrate sunlight by reflection as opposed to refraction with lenses. Concentration is either to a line (linear focus) as in trough or linear fresnel systems or to a point (point focus) as in central- receiver or dish systems. CSP applications range from small distributed systems of tens of kW to large centralized power stations of hundreds of MW. The concentrating solar thermal power (CSP) market continued to advance in 2012, with total global capacity up more than 60% to about 2550 MW (Ellabban et al., 2014).

Fig. 1.2 shows the renewable energy share of global electricity production at the end of year 2015. Non-renewables have highest share of 76.3% and renewables contributing 23.7% out of which 16.6% is hydropower. Solar PV technology contributes only 1.2% and concentrating solar power contributes less than 0.4%.

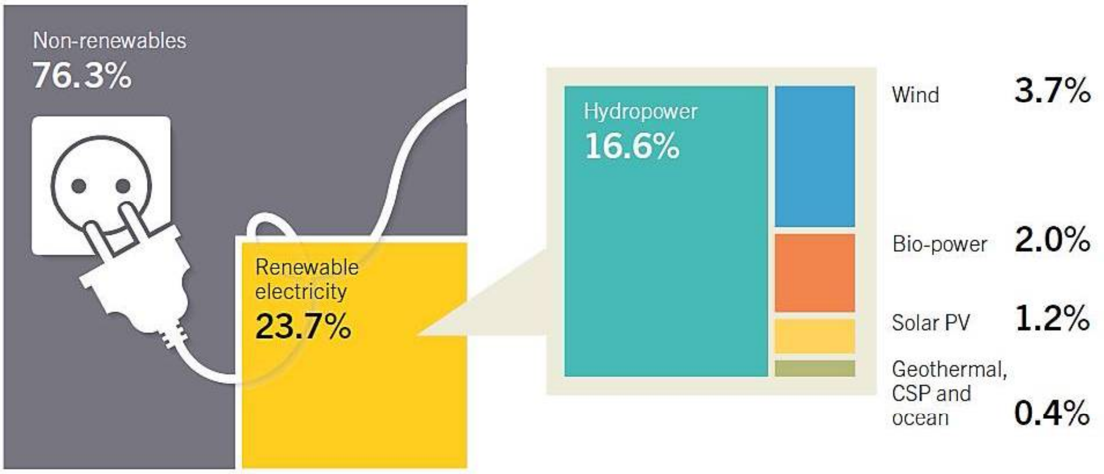

Fig. 1.2 Renewable energy share of global electricity production based on renewable generating capacity at the end of year 2015 (Renewables 2016: Global Status Report)

1.4.3 Solar thermal heating and cooling

Solar heating and cooling technologies collect thermal energy from the sun and use this heat to provide hot water, space heating, cooling, and pool heating for residential, commercial, and industrial applications (Ellabban et al., 2014). Energy use for heat accounted for about half of total world final energy consumption in 2015 (Fig.

1.3). Global consumption of heat energy growing at an average annual rate of less than 1% in recent years. Cooling demand also continued to increase in 2015 as a result of improved energy access and rising average global temperatures. In 2015, renewable energy's share of final energy use in the heat sector was 25%; of this share around one-third was from modern renewable energy (Fig. 1.3). In this bioenergy accounted for over 90%, solar thermal 8% and geothermal heat represented remaining 2% share of modern renewable heat generation. In the buildings sector, solar thermal energy account for the vast majority of modern renewable heat (with most recent estimates ranging from 7% to 10% of total heat demand combined). Recent years is witnessing increasing interest in and deployment of large-scale solar systems in district heating networks. Markets are also expanding for solar process heat in industry such as food and beverage as well as the copper industry, which has substantial demand for low-temperature heat (Renewables 2016- Global Status Report).

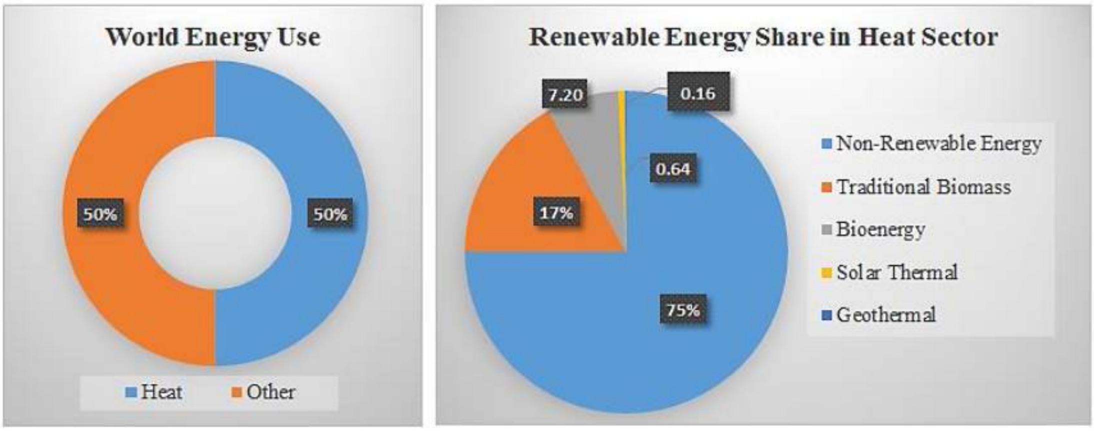

Fig. 1.3 World energy use and renewable energy share in heat sector in % (Renewables 2016: Global Status Report)

1.4.4 Solar energy harvesting using solar collectors

Solar collectors and thermal energy storage components are the two kernel subsystems in solar thermal applications. Solar collectors need to have good optical performance (absorbing as much heat as possible). A solar collector, the special energy exchanger, converts solar irradiation energy either to the thermal energy of the working fluid in solar thermal applications, or to the electric energy directly in PV (Photovoltaic) applications. For solar thermal applications, solar irradiation is absorbed by a solar collector as heat which is then transferred to its working fluid (air, water or oil). The heat carried by the working fluid can be used to either provide domestic hot water/heating, or to charge a thermal energy storage tank from which the heat can be drawn for use later (at night or cloudy days). Solar collectors are usually classified into two categories according to concentration ratios: non-concentrating collectors and concentrating collectors. A non-concentrating collector has the same intercepting area as its absorbing area, whilst a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the solar irradiation to a much smaller receiving area, resulting in an increased heat flux so that the thermodynamic cycle can achieve higher Carnot efficiency when working under higher temperatures (Tian and Zhao, 2013).

Flat plate collectors and hybrid Hybrid photovoltaic/thermal (PVT) collectors are the popular systems in non-concentrating collectors. Flat-plate solar collectors are usually permanently fixed in position, and therefore need to be oriented appropriately. A typical flat-plate solar collector usually consists of glazing covers, absorber plates, insulation layers, recuperating tubes (filled with heat transfer fluids) and other auxiliaries. Researchers have worked on various glazing materials to increase transmittance, providing anti-reflection coatings on glazing cover to reduce reflection losses, providing best absorbing coatings on the absorber plate to increase absorption of sun light. The heat absorbed by the absorber plate needs to be transferred to working fluids rapidly to prevent system overheating. Researchers also have worked on enhancement of solar receivers with porous insertions. It has been also found that oscillating flow can significantly improve heat transfer by increasing thermal diffusivities of the working fluids in solar collectors. Employing double-pass structure for solar receiver is another idea to achieve a better heat transfer rate. Internal fins fixed on solar collector panels also found to improve the heat transfer performance. Hybrid PVT Collectors simultaneously convert solar energy into electricity and heat. A typical PVT collector consists of a PV module and an absorber plate (acting as a heat removal device) attached on the back of the PV module. The heat removal plate cools the PV module down to a suitable temperature for better electrical performance, and at the same time, it collects the waste heat, which can then be utilised for low temperature applications (Tian and Zhao, 2013).

Most of the significant amount of recent research on PVT collectors has been related to flat-plate collectors, with their investigation focusing on absorber plate and tube dimensions (Bergene and Lovvik, 1995), fluid flow rates (Prakash, 1994), tank size (Agarwal and Garg, 1994), PV cell packing factor (Fujisawa and Tani, 2001), use of amorphous silicon (Platz et al., 1997), use of metal fins (Tonui and Tripanagnostopoulos, 2007), and multiple-passage configurations (Hegazy, 2000).

In concentrating collectors, heliostat field collectors, parabolic dish collectors, parabolic trough collectors are among the few popular ones. Concentrating collectors (usually equipped with sun-tracking techniques) have much higher concentration ratio than non-concentrating collectors. They can achieve higher temperatures of working fluids, meaning that it is possible to achieve a higher thermodynamic efficiency. The Heliostat field collector, also called the central receiver collector, consists of a number of flat mirrors/heliostats. An optimised field layout of heliostats can efficiently reflect solar light to the central tower, where a steam generator is located to absorb thermal energy and heat up water into the high-temperature and high-pressure steam (to drive turbine generators). Parabolic dish collectors use an array of parabolic dish-shaped mirrors (similar in shape to a satellite dish) to focus solar energy onto a receiver located at the common focal point of the dish mirrors. Heat transfer fluid contained in the receiver is then heated up to desirable working temperatures and pressures in order to generate electricity in a small engine attached to the receiver. Parabolic dish technologies have following advantages: high optical efficiency, low start-up losses and good modularity which can be easily scaled up to meet the power needs in remote area, where centralised power supply is too expensive. Parabolic trough collectors can concentrate sunlight with a concentration rate of around 40, depending on the trough size. The focal line temperature can be as high as 350°C to 400°C. The key component of such collectors is a set of parabolic mirrors, each of which has the capability to reflect the sunlight that is parallel to its symmetrical axis to its common focal line. At the focal line, a black metal receiver (covered by a glass tube to reduce heat loss) is placed to absorb collected heat. Parabolic trough collectors have multiple distinctive features and advantages over other types of solar systems. Firstly, they are scalable, in that their trough mirror elements can be installed along the common focal line. Secondly, they only need two-dimensional tracking (dish-engine collectors need three-dimensional tracking, making systems more complicated), so they can achieve higher tracking accuracy than dish-engine collectors (Tian and Zhao, 2013).

1.4.5 Limitations of solar collectors

The primary disadvantages of the conventional solar thermal collectors that limit the enhancement of the solar energy collection efficiencies beyond certain value are losses associated at various stages in the system. In flat plate collectors, there are reflection losses from glazing glass, convection losses from absorber plate and overall radiation losses from the collector. Absorber plate has its own limitations to absorb the incident solar light and convert it into heat energy. Transfer of heat from absorber plate to working fluid is required to take place rapidly to prevent system overheating which reduces system life considerably. Further the use of porous insertions, oscillating flow, double pass structure and internal fins could not improve efficiency considerably rather high manufacturing costs limit the use of such collectors in general (Tian and Zhao, 2013). Large floor space requirement is another disadvantage of these systems apart from several others listed above. The less efficiency lead to longer payback periods of such systems (Ibrahim et al., 2011).

In case of concentrating solar collectors, primary limitation on receiver design is the heat flux that can be absorbed through the receiver surface and transferred into the heat transfer fluid, without overheating the receiver walls and the heat transfer fluid within them (Tian and Zhao, 2013). Solar tracking systems introduced in concentrating solar collectors enhance the efficiencies multifold. However, they also have several important disadvantages in their greater mechanical complexity (and, therefore, higher maintenance costs), less rigidity (entailing more failures and less operating time with high wind loads) and more auxiliary piping (involving higher solar field thermal losses). The need to clean their components also increases maintenance costs. As Parabolic trough concentrators (PTCs) can only use beam solar radiation, their installation is geographically limited, and at very high wind speeds operation must be interrupted and the collectors sent into off-focus position (Fernandez-Garcia et al., 2010). It has been observed that concentrator systems collect little diffuse radiation depending on the concentration ratio and solar reflecting surfaces tend to lose their reflectance with time and require periodic cleaning and refurbishing (Kalogirou, 2004). Hence improvement in efficiency of solar energy absorption beyond certain limit is not possible by changing only collector configuration.

1.5 Nanoscience and nanotechnology - potential to harvest solar energy

Nanoscience and nanotechnology refer to the control and manipulation of matter at nanometer dimensions. This control has made it possible to have life, which is a collection of most efficient nanoscale processes (Pradeep, 2007). It is the emerging science of objects that are intermediate in size between the largest molecules and the smallest structures that can be fabricated by current photolithography; that is, the science of objects with smallest dimensions ranging from a few nanometers to less than 100 nanometers (Poole and Owens, 2003). These very small structures are intensely interesting for many reasons.

Nanostructures are in a range of sizes in which quantum phenomena- especially quantum entanglement and other reflections of the wave character of matter- would be expected to be important. Quantum phenomena are, of course, the ultimate basis of the properties of atoms and molecules, but are largely hidden behind classical behaviour in macroscopic matter and structures (Hey and Walters, 2003). Quantum dots and nanowires have already been prepared and demonstrated to show remarkable electronic properties. Many properties of material change with change in size, especially when size is reduced to nanoscale range. As a matter of fact, nanomaterials have unique properties relative to bulk counterpart which impart them beneficial characteristics. Particle size and surface area play a major role in establishing properties of nanomaterials. Seemingly, decreasing the size of the materials leads to an exponential increase in surface area relative to volume, thereby making the nanomaterial surface more reactive on itself. The large surface area to volume ratio results in a substantial proportion of atoms having different magnetic coupling with neighbouring atoms leading to differing magnetic properties. Giant magnetoresistance (GMR) is a phenomenon observed in nanoscale multilayers consisting of strong ferromagnet (Fe, Co, Ni) and a weaker magnetic or non-magnetic buffer (Cr, Cu). It is usually employed in data storage and sensing. In small nanoclusters the effect of reduced dimensionality on electronic structure has the most profound effect on the energies of highest occupied molecular orbital (HOMO) which is valence band and the lowest unoccupied molecular orbital (LUMO), essentially the conduction band. Due to larger proportion of surface atoms, the atoms present in nanomaterials possess a higher energy as compare to atoms present in bulk structure.

The optical emission and adsorption occurs when the transition of the electrons take place between these two states. Semiconductors and many metals show large changes in optical properties such as color, as a function of particle size. Other properties which may be affected by reduced dimensionality include photocatalysis, photoconductivity, photoemission and electroluminescence. Shape of nanomaterials also have influence on its properties. For example, one-dimensional nanowires may offer ultralow thermal conductivities, quite different from that of carbon nanotubes. The changes which occur in electronic properties as the system length scale is reduced are related mainly to the increasing influence of the wave-like property of the electrons (quantum mechanical effects) and the scarcity of scattering centres. As the size of the system becomes comparable with the de Broglie wavelength of the electrons, the discrete nature of the energy states becomes apparent once again, although a fully discrete energy spectrum is only observed in systems that are confined in all three dimensions. In certain cases, conducting materials become insulators below a critical length scale, as the energy bands cease to overlap. Owing to their intrinsic wave-like nature, electrons can tunnel quantum mechanically between two closely adjacent nanostructures, and if a voltage is applied between two nanostructures which aligns the discrete energy levels in the density of states (DOS), resonant tunnelling occurs, which abruptly increases the tunnelling current. All these phenomena can be utilised to produce radically different types of components for electronic, optoelectronic and information processing applications, such as resonant tunnelling transistors and single-electron transistors.

The melting point drastically falls when the particle size of the material approaches to the nanoscale ranges. This phenomenon related to melting point depression is very prominent in nanoscale materials which melt at temperatures hundreds of degrees lower than bulk materials. All the nanomaterials possess high mechanical strength as compared to their conventional counterparts. The mechanical strength of nanomaterials may be one or two times higher in magnitude than that of single crystals in the bulk form.

Optical properties exhibited by nanomaterials are quite different from their bulk counterpart. The reason behind this change in property is mainly due to the effect of the surface plasmon resonance. In addition, the increased energy level spacing is also an important criterion for this changing behaviour. Due to increased band gap for semiconductor nanoparticles absorption edge is shifted toward shorter wavelengths. Surface Plasmon resonance effect changes due to change in particle size which in turn changes the colour of metallic nanoparticles. The coherent excitation of entire free electrons in the conduction band may produce an in-phase oscillation, called surface plasmon resonance. When the size of a metal nanocrystal is smaller than the wavelength of incident radiation, a surface plasmon resonance is generated. On resonance, light is tightly confined to the surface of the nanostructure, until it gets eventually absorbed inside the metal, or scattered back into photons (Poole and Owens, 2003; Murty et al. 2013).

Therefore, nanoscience and nanotechnology have large potential to contribute to a sustainable energy system both through more efficient use of current energy sources and by enabling breakthrough solutions towards novel energy sources and systems. On the short term nanotechnology solutions have started impacting current energy system, based mainly on fossil fuels, by contributing to more efficient conversion and use of energy. On a longer term (decades) the contributions to a truly sustainable energy system will grow in importance. Table 1.1 gives an areas in which nanoscience and nanotechnology may contribute to a sustainable energy system (Zach et al., 2006).

Table 1.1

Various areas where nanoscience and nanotechnology is expected to have a significant impact on energy systems

Area	**Nanotechnology Aspect**
Energy Sources	
Renewables Solar Thermal, PV, solar hydrogen, satellite power, wind, hydro, biomass, Nuclear fusion and fission, geothermal	Light harvesting materials, materials, sensors, catalysis, nanofluids, etc.
Non-Renewables Oil, gas, coal, etc.	Catalysis, materials, sensors, etc.
Energy Storage	
Water dams, hydrogen storage, batteries, supercapacitors, etc.	Materials, catalysis, kinetics, electrolytes, etc.
Energy Conversion	
Combustion engines, turbines, fuel cells, thermo/piezoelectric material, etc.	Materials, diagnostics, electrolytes, etc.
Energy Use	
Industrial/mining, residential, transportation, etc.	Sensors, materials, etc.

One of the great promises of nanoscience and nanotechnology is that we are able to do more with less. By using less material overall, the load on our natural resources are lowered. By using less energy to operate smaller, more efficient devices, we require less fuel and pollute less (Hutchison et al., 2008; Alvarez at al., 2009; Meng at al., 2009).

1.5.1 Nanomaterials- synthesis routes

The most popular way of classifying the synthesis routes is based on how the nanostructures are built, and such an approach leads to two routes, namely, the 'bottom up' and the 'top-down' approaches. In the bottom-up approach, individual atoms and molecules are brought together or self-assembled to form nanostructured materials in at least one dimension.

a. Bottom-up approaches

Various techniques such as physical vapour deposition, chemical vapour deposition, spray conversion processing, sol-gel process, wet chemical synthesis, self-assembly are among the popular ones. All the techniques that start with liquid and gas as the starting material fall into this category.

b. Top-down approaches

In this approach, a microcrystalline material is fragmented to yield a nanocrystalline material. Here, mechanical alloying, equal channel angular pressing, high-pressure torsion, nanolithography, high energy ball milling are few of the established and commercialized routes. All the solid state routes fall into this category.

Usually, the bottom-up techniques can give very fine nanostructures of individual nanoparticles, nanoshells, etc., with narrow size distributions, if the process parameters are effectively controlled. The top-down techniques do not usually lead to individual nanoparticles; however, they can produce bulk nanostructured materials. Many of the bottom-up approaches have difficulties in scale up, while the top-down approaches can be easily scaled up. Thus, one can see that both these approaches are complementary to each other, depending on the requirement of a particular application. (Murty et al., 2013).

1.5.2 Characterization of nanomaterials

The characterization of small structures or small-sized materials in the nanometric-scale usually calls for sophisticated characterization tools. Characterization of nanomaterials and nanostructures has been largely based on certain critical advancement of conventional characterization methods developed for bulk materials. For example, X ray diffraction (XRD) has been widely used for the determination of crystalline character, crystallite size, crystal structures and lattice constants of nanoparticles, nanowires and thin films. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM), together with electron diffraction, have been commonly used in the characterization of nanoparticles to get an idea of the size, shape and defects present in these materials. Optical spectroscopy is used to determine the size of semiconductor quantum dots. Scanning probe microscopy (SPM) is a relatively new characterization technique and has found widespread application in nanotechnology. The two branches of SPM are scanning tunnelling microscopy (STM) and atomic force microscopy (AFM). Although both STM and AFM are true surface imaging techniques that can produce topographic images of a surface with atomic resolution in all three dimensions, in combination with appropriately designed attachments, STM and AFM have found a much broader range of applications, such as nanoindentation, nano-lithography and patterned self-assembly. Almost all solid surfaces, whether hard or soft, electrically conductive or not, can be studied with STM/AFM. Surfaces can be studied in a gaseous medium such as air or vacuum, or in liquid (Murty et al., 2013).

1.5.3 Use of nanomaterials for solar energy absorption

a. Solar selective coatings on solar collectors

The key component of a flat plate solar thermal collector is the solar absorber surface, the properties of which strongly affect the efficiency of the solar thermal conversion system. Ideally such surfaces absorb most of the incoming solar radiations (high absorptance) without losing much of the thermal energy through re-radiation from heated surface (low emittance). However, no single material in nature can meet these criteria.

As such, there is a need to optimize the optical and structural properties of a surface through the use of a combination of materials, the modification of the surface, or the synthesis of multilayer solar absorber materials to achieve the desired wavelength selectivity. Such surfaces are called solar selective absorber (SSA) surfaces. Other factors for consideration in the production of photothermal absorbers are long thermal durability, simplicity, cost-effectiveness in fabrication as well as minimal environmental impact in the production process. The most widely used industrial solar selective absorbers nowadays are metal particles in ceramic (cermet) structures which are produced by electrochemical or vacuum deposition methods. Some well-known examples include electroplated black chrome ($Cr–Cr_2O_3$) and nickel-pigmented anodic Al_2O_3 (synthesized via the electroplating/electrochemical method) as well as evaporated titanium nitride film ($TiNO_x$) and nickel–nickel oxide ($Ni–NiO_x$) synthesized via a vacuum deposition/sputtering method (Amri at al., 2014).

A large number of solar selective coatings such as Ni- Al_2O_3, Ni-SiO_2, Fe-Al_2O_3, Cr-SiO, Mo-Al_2O_3, Mo-SiO_2, W-Al_2O_3, etc have been developed for high temperature solar thermal applications. But only few of them such as Mo-SiO_2, W-Al_2O_3, Mo-Al_2O_3 and M-AIN cermets have been successful. These coatings have excellent thermal stability in vacuum. Despite the fact that this absorber coating is highly stable in vacuum, it has limited thermal stability in air (Barshilia, 2014).

b. Nanoparticle suspensions (nanofluids) for solar energy absorption

Direct absorption solar collectors have been proposed for a variety of applications such as water heating; however the efficiency of these collectors is limited by the absorption properties of the working fluid, which is very poor for typical fluids used in solar collectors. It has been shown that mixing nanoparticles in a liquid (nanofluid) has a dramatic effect on the liquid thermophysical properties such as thermal conductivity. Nanoparticles also offer the potential of improving the radiative properties of liquids, leading to an increase in the efficiency of direct absorption solar collectors. Nanofluid plays a key role to enhance the efficiency in solar systems (Otanicar et al., 2010).

1.5.4 Limitations of solar selective absorber (SSA) coatings

One of the essential requirements of solar selective absorbers is their stable structural composition when they operate at high temperatures along with the high selectivity to sun light. The high temperature stability of most of the solar selective coatings is not good. Few of them though are stable in vacuum, but they have limited stability in presence of air. Further, optical properties of these coatings degrade with rise in temperature or over a period of use and they do not give consistent performance or efficiency over the service life. That's why only few of them are useful, despite the fact that there are many coatings materials reported in the literature.

Also coating deposition methods are difficult to carry out and are expensive. Although a substantial proportion of flat plate solar hot water collectors have been synthesized using these methods, they still have disadvantages. The electrochemical treatment methods are relatively simple and have a low operating temperature, yet these methods utilize large amounts of material and are not environmentally friendly. Vacuum and sputtering deposition methods are low in material consumption, have good reproducibility and low levels of environmental pollution but they are, nonetheless, less cost-effective because they require a large investment in rather complicated production equipment with high operational cost and high energy intensity in production. Other methods of SSA production such as chemical vapour deposition (CVD) and mechanical grinding also have their own drawbacks. In general, the CVD method has good potential in industrial-scale production but there are difficulties in ensuring the stoichiometry of the metal oxides produced. Mechanical grinding is a simple and cost-effective method of SSA production but the selectivity of the absorber material is low (Barshilia, 2014; Amri et al., 2014).

Thus very few solar selective absorber materials have been commercial success because of high cost material, expensive processing while making coatings, specificity to high selectivity, materials stability problems at high temperature and problems in durability and performance degradation over the period. On the other hand area of nanofluid is expanding at an exponential rate with novel materials and fluids being reported every day. Nanofluids based solutions have potential for commercialization in solar energy absorption systems because of simple methods, low cost materials, high efficiencies, low processing cost, etc (Kasaeian et al., 2015)

1.6 Nanofluids- origin of the concept

Over the last few years, energy consumption has increased drastically. Therefore, new energy saving strategies are continuously being developed to overcome the threat of energy shortage. Heat exchangers are widely used in industrial systems in the field of energy conservation, conversion and recovery. Thus, it is obvious that providing more efficient heat exchanging systems can mitigate the energy concerns considerably. With progresses of thermoscience and thermal engineering, many efforts have been devoted to heat transfer enhancement.

Better heat removal can be achieved by decreasing the area to volume ratio of thermal devices which is one of the most important factors in thermal design. This idea motivated researchers (Tuckerman and Pease, 1981) to propose microchannel heat sink (MCHS) about two decades ago. After that, many researches proved the effectiveness of using micro-channel heat exchangers for thermal enhancement purposes. Lately, due to the advancement of micro fabrication technology, microchannels and microtubes are manufactured and utilized in industries such as microelectronics, aerospace, biomedical, robotics, telecommunications and automotive (Mohammed et al., 2011) The main reasons for development of miniaturized and light weight heat exchangers are space and size limitations, energy and material savings, ease of unit handling, growing need for heat transfer augmentation with increasing energy demands and cooling requirement of microscale and microelectronic devices.

Several studies have proposed methods to improve the thermal-hydraulic performance and reduce unit sizes of conventional heat exchangers. However, in order to have more efficient and cost effective heat exchangers, several approaches have been investigated over the years. Passive technique, employing ribs or grooves on the inner surface of heat exchangers, has been one of the frequent approaches to break the laminar sub-layer and create local wall turbulence due to flow separation and re-attachment between successive corrugations, which reduces the thermal resistance and significantly enhances heat transfer. Although many studies available in the open literature have proven the significant effect of geometry modification on heat transfer enhancement in recent years, this technique has already reached its limit. Presently, available heat transfer working fluids such as water, engine oil and ethylene glycol are widely used in many industrial applications like heating or cooling processes, chemical production, microelectronics, power generation, air-conditioning, and transportation. These conventional heat transfer fluids have inherently low thermophysical properties as compared with solids. Hence, there is a pronounced need to develop alternative heat transfer fluids with higher cooling capability which can improve the compactness and effectiveness of heat exchangers (Vanaki at al., 2016).

The issue of heat removal from small scale devices which can generate a high amount of heat flux has attracted substantial attention from researchers. To ensure that heat exchangers deliver their best performance, working fluids with greater thermal conductivity are required. Since solid particles have larger thermal conductivity than conventional fluids, dispersing these particles in to the base fluid is anticipated to increase the thermal conductivity of the whole mixture (Sundar and Singh, 2013). Therefore, in order to overcome the limited heat transfer capabilities of common fluids, Maxwell first proposed a theoretical work which showed the possibility of enhancing the thermal conductivity of liquids by mixing micron-sized solid particles (Maxwell, 1881). Later, few researchers experimentally analysed the suspensions containing micron size particles and found the considerable enhancement in the thermal conductivity of base fluid. However, problems such as rapid sedimentation caused by these particles have kept this concept far from practical use (Ahuja, 1975). Recent advances in nanotechnology resulted in appearance of a new generation of fluid called nanofluid- a colloidal mixture of nanoparticles smaller than 100 nm (Choi, 1995). Many research groups experimentally reported a substantial increase in the thermal conductivity (Fan and Wang, 2011) and the convective heat transfer coefficient of such fluids (Daungthongsuk and Wongwises, 2007). Nanofluids have unique thermal transport properties and superior performance that are unavailable in traditional heat transfer fluids. Compared to conventional solid–liquid suspensions for enhancing heat transfer, nanofluids show higher potential for increasing the heat transfer rates in heat exchangers for the following reasons (Wen et al., 2009):

- High heat transfer surface between particles and fluids and therefore high effective thermal conductivity.
- High dispersion stability with predominant Brownian motion of particles.
- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Less particle clogging as compared to convention slurries, thus suitable for use in microsystems.
- Adjustable properties, including thermal conductivity and surface wettability by varying particle concentrations to suit different applications.

1.6.1 Preparation methods for nanofluids

a. *Two-Step Method*

Two-step method is the most widely used method for preparing nanofluids. Nanoparticles, nanofibers, nanotubes, or other nanomaterials used in this method are 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. Two-step method is the most economic method to produce nanofluids in large scale, because nanopowder synthesis techniques have already been scaled up to industrial production levels.

b. *One-Step Method:*

To reduce the agglomeration of nanoparticles, a one-step physical vapour condensation method has become more popular. The one-step process consists of simultaneously making and dispersing the particles in the fluid. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles are avoided, so the agglomeration of nanoparticles is minimized, and the stability of fluids is increased. The one-step processes can prepare uniformly dispersed nanoparticles, and the particles can be stably suspended in the base fluid.

One-step physical method cannot synthesize nanofluids in large scale, and the cost is also high. The most important disadvantage is that the residual reactants are left in the nanofluids due to incomplete reaction or stabilization. It is difficult to elucidate the nanoparticle effect without eliminating this impurity effect (Yu and Xie, 2012).

1.6.2 Stability of nanofluid

The agglomeration of nanoparticles results in not only the settlement and clogging of microchannels but also decreasing thermal conductivity of nanofluids. So, the investigation on stability is the key issue that influences the nanofluids application. Many methods have been developed to evaluate the stability of nanofluids. The simplest method is sedimentation method. The variation of concentration or particle size of supernatant particle with sediment time can be obtained by special apparatus such as high resolution camera. For the sedimentation method, long period for observation is the defect. Therefore, centrifugation method is developed to evaluate the stability of nanofluids. The zeta potential is useful in that its value can be related to the stability of colloidal dispersions. Therefore, colloids with high zeta potential (negative or positive) are electrically stabilized, while colloids with low zeta potentials tend to coagulate or flocculate. Spectral absorbency analysis is another efficient way to evaluate the stability of nanofluids. In general, there is a linear relationship between the absorbence intensity and the concentration of nanoparticles in fluid (Yu and Xie, 2012).

1.6.3 Nanofluid property analysis

Measurement of effective thermal conductivity of nanofluid mixture and study of degree of its enhancement over the value for base fluid is main purpose of the nanofluid research. Viscosity, density and specific heat are the other important nanofluid properties that affect the heat transfer through nanofluid. Transient hot wire method is popularly employed to measure the thermal conductivity of nanofluid mixture. Viscosity measurements are carried out using Brookfield viscometer. However, density and specific heats are measure using regular specific gravity bottle and differential scanning colorimeter (DSC) respectively (Wang and Mujumdar, 2007).

1.7 Nanofluids for efficient solar energy absorption

Heat transfer enhancement in solar based systems is one of the critical issues in energy saving and compact designs. In the fields of the research and technology involving the exploitation of renewable energies, solar thermal collectors have gained an increasing role in the last few years. These devices are heat exchangers that transform the energy of solar radiation to internal energy of some exchange medium. Typically, solar energy is absorbed by black-surface tubes (classically, a black-painted or oxidized surface in tight thermal contact with the tubes), but this configuration entails various limitations such as radiation losses, large floor space requirements, etc. (Mercatelli et al., 2011). A major shortcoming of the solar collectors, however, is their low thermal conversion efficiency. Conventional heat transporting fluids are water or oil-based such as ethylene glycol, engine oil, etc and have low heat absorption and heat transfer capacity (Verma and Tiwari, 2015). Due to its renewable and non-polluting nature, solar energy is often used in applications such as electricity generation, thermal heating, and chemical processing. The most cost-effective solar heaters are of the 'flat-plate' type, but these suffer from relatively low efficiency and outlet temperatures.

There are so many methods introduced to increase the efficiency of the solar water heater. Focus of such studies are normally on improvement of collector configuration. But the novel approach is to introduce the nanofluids in solar water heater instead of conventional heat transfer fluids. The poor heat transfer properties of these conventional fluids compared to most solids are the primary obstacle to the high compactness and effectiveness of the solar system. The essential initiative is to seek the solid particles having thermal conductivity of several hundred times higher than those of conventional fluids (Saidur et al., 2011).

Recently researchers have become interested in the use of nanofluids in collectors, water heaters, solar cooling systems, solar cells, solar stills, solar absorption refrigeration systems, and a combination of different solar devices due to higher thermal conductivity of nanofluids and the promising properties of nanoparticle. How to select suitable nanofluids in solar applications is a key issue. The effectiveness of nanofluid as absorber fluid in a solar device strongly depends on the type of nanoparticles and base fluid, volume fraction of nanoparticles, properties of nanoparticles, temperature of the liquid, size and shape of the nanoparticles, pH values, and stability of the nanofluids (Bozorgan and Shafahi, 2015). In solar collectors, the absorbed incident solar radiation is converted to heat. The working fluid conveys the generated heat for different applications. Solar collectors are categorized in two types, non-concentrating (flat) and concentrating collectors. Non concentrating solar collectors are usually used for low and medium temperature applications such as space heating and cooling, water heating, and desalination. While concentrating solar collectors are exploited in high temperature applications such as electricity generation. Nanofluid has shown a good ability in enhancing the efficiency of solar systems (Kalogirou, 2004). Due to its attractive economics and the possibility of storage, solar thermal energy is garnering significant interest and investment in recent years. In order to deliver enough heat to make electricity, solar energy must be efficiently concentrated, absorbed (i.e. converted to heat), and delivered to a thermal plant. Once the heat is delivered there is little departure from a conventional coal or gas-fired thermal power plant.

These enhancements translate to the following possible advantages of nanofluids in solar power plants: 1) nanofluids can absorb energy directly skipping intermediate heat transfer steps as shown in Fig. 1.4. 2) The nanofluids themselves and the glazing they are contained by can be optically selective (high absorption in the solar range, low emitance in the infrared), 3) a more uniform temperature can be achieved inside the collector (reducing material constraints), 4) heat transfer via increased particle motion and thermal conductivity may be improved in the receiver (Kim et al., 2006; Bang and Chang, 2005; Heris et al., 2006), and 5) absorption efficiency is enhanced because nanoparticles have a broader absorption peak than bulk metals (Otanicar et al., 2009). Some of the researchers have also shown (theoretically and experimentally) that in low temperature solar collectors ($<100^0$C) efficiency can be improved by using nanofluids (Otanicar et al., 2009; Tyagi et al., 2009, Kasaeian et al., 2015).

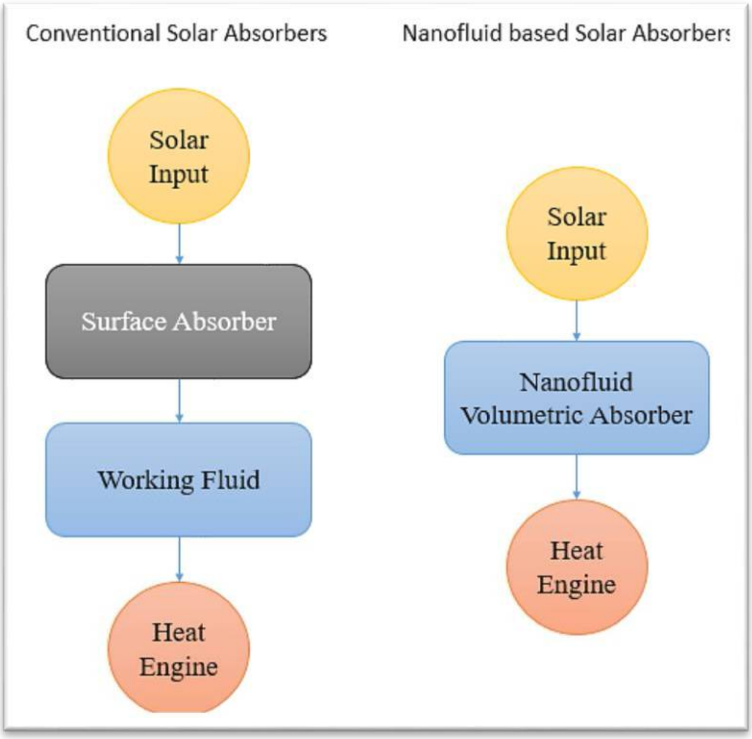

Fig. 1.4 Comparison of conventional solar thermal energy absorbers with nanofluid based absorbers

Considering the low absorption efficiencies of the conventional solar collectors, it is wise choice to adopt the nanofluids as a working fluid for efficient direct absorption of the solar energy. Solar energy absorption using nanofluids will prove to be appreciable solution towards sustainable energy systems in long term.

1.7.1 Need of nanofluids for efficient solar energy absorption

As discussed in previous sections, conventional solar thermal collectors have very poor efficiency and therefore these collectors are unable to harvest the solar radiation to the fullest extent. The focus solar energy utilization and improvement in efficiency of absorption had been around the solar thermal collector modifications only. Variety of new configuration and modifications in solar collectors have enable increase in solar conversion efficiencies to some extent. Concentrating solar collectors such as parabolic dish concentrators, parabolic trough collectors have improved the efficiencies several times over the flat plate collector configurations. Few research groups also have worked on kind of absorber coating applied on the collector surface for improving the collector efficiencies. But these materials have their own limitations such as high temperature stability problems, long term performance and durability, high cost materials, expensive processing methods, etc These attempts could not yield significant improvement in solar conversion efficiencies. This type of collector exhibits several defects, such as limitations on incident flux density and relatively high heat losses (Tyagi et al., 2009). Therefore, more research is required to improve the efficiencies further.

The continuous development of nanotechnology would provide powerful support to the research of solar working fluid. Compared with bulk materials, nanoscaled materials have many unique properties, such as small size effect, surface and boundary effect, quantum size effect and so on. The optical property of nanoparticle changed widely, which leads to have a special photoabsorption property (Iida and Ishihara, 2004). So, the novel approach is to introduce the nanofluids in solar water heater instead of conventional heat transfer fluids (water, ethylene glycol, heat transfer oils, etc). The poor heat transfer properties of these conventional fluids compared to most solids are the primary obstacle to the high compactness and effectiveness of the system. The essential initiative is to seek the solid particles having thermal conductivity of several hundred times higher than those of conventional fluids. An innovative idea is to suspend ultrafine solid particles in the fluid for improving the thermal conductivity of the fluid. The early studies, however, used suspensions of millimetre- or micrometre-sized particles, which, although showed some enhancement, experienced problems such as poor suspension stability and hence channel clogging, which are particularly serious for such systems. The fluids with nanosized nanoparticles suspended in them are called "nanofluids." The suspended metallic or nonmetallic nanoparticles change the transport properties and heat transfer characteristics of the base fluid (Choi, 1995; Natarajan and Sathish, 2009). In consideration of the excellent photoabsorption property of nanoparticle and the favourable heat transfer properties of nanofluid (a suspension of metal, metal–oxide, etc nanoparticles in base liquid through a certain method), researchers have put forward to use the nanofluid as the working fluid for direct absorption solar collector. Utilizing nanofluid to absorb solar radiative energy directly, can enhance the efficiency of solar collector multifold (He at al., 2013). Because of the extremely small size, nanoparticles particles can pass through pumps and plumbing with modest adverse effects. Moreover, there are plenty of different nanoparticles that can be chosen based on their optical characteristics and application under consideration. Besides, by employing nanofluids in solar receivers, more uniform receiver temperatures can be achieved inside the collector. This will reduce material constraints (Ladjevardi et al., 2013).

There are two competing forces in a small particle suspension; namely Brownian motion (ensuring incessant motion of the particles) and the gravitational force. As the particle size becomes smaller (approaching the nanometer scale), Brownian motion becomes predominant and makes the suspension stable Furthermore, the chemical nature of the nanoparticles, pH, and viscosity of the dispersed phase has a profound effect on the stability of these nanoparticle dispersions (Taylor et al., 2013) Indeed, the use of nanofluids as both a volumetric solar collector and heat transfer fluid is now seen as a method of improving efficiencies and reducing costs in solar thermal devices (Mahian et al., 2013). Furthermore, the concentration of nanoparticles can easily be controlled such that the incident radiation is absorbed over the entire volume of nanofluid, instead of over a thin surface layer, thus limiting heat losses to the surroundings (Otanicar et al., 2011). Several different types of nanoparticles in various base fluids have been modelled and tested experimentally for this purpose. These include metallic nanoparticles, carbon nanotubes (CNT), graphite, carbon black, carbon nanohorns, etc. All of these materials have been shown to be effective solar absorbers (Hordy et al., 2014).

Variety of promising light absorbing, conducting nanomaterials such as copper, copper oxide, iron oxide, silica, titanium dioxide, zinc oxide and carbon nanoparticles either have not been studied to fullest extent and sufficient data is lacking for few base fluids such as ethylene glycol, silicone oil apart from water. Additionally, limited data is available for the use of nanoparticle suspensions in the applications such as desalination, azeotropic separation, etc

Focus of present work is identification and synthesis of various light absorbing nanomaterials from different material groups, preparation of stable nanofluids, analysis of nanofluid properties for efficient heat transfer and to study various nanofluids for solar energy absorption, desalination of hard water and separation of azeotropic mixtures such as ethanol-water, etc

1.8 Aim and objectives

***Aim*:** To conduct the significant research in the field of solar energy absorption using nanofluids for developing innovative nanomaterial-base fluid combination that promotes the effective and efficient absorption of solar thermal energy for heating, desalination and separation processes.

***Objectives*:**

- To identify and synthesize various light absorbing and conducting nanomaterials having special photoabsorption properties
- To characterize synthesized nanomaterials with modern tools such as X-ray diffraction (XRD), scanning electron microscopy (SEM), dynamic light scattering (DLS) and Energy Dispersive X-ray Spectroscopy (EDS or EDX) to find the morphology
- To identify suitable heat transfer fluids as base fluids to be used with above synthesized nanomaterials and thereby synthesis of stable suspensions of nanoparticles i.e. nanofluids
- To analyze the thermo-physical properties of nanofluids such as heat transfer coefficient, viscosity and density both experimentally and theoretically
- To study the solar energy absorption for various nanofluids focused in parabolic dish concentrator
- To study the efficiency of solar water desalination with above synthesized nanomaterials suspended in hard water/sea water.
- To conduct the experiments for solar energy enabled separation of azeotropic mixtures such as ethanol-water by suspending light absorbing, conducting nanomaterials.

1.9 Scope of the thesis

This thesis is organized in such a way that each chapter has its own introduction, conclusion and list of references.

The ***first chapter*** provides an introductory background on energy and its importance and world energy consumption. It throws a light on how conventional energy sources – fossil fuels are depleting at faster rate and why sustainable energy systems are desired and how renewable energy sources will help to meet sustainable energy demands in long term. In this solar energy is the free and abundant source of energy. Various solar energy devices are also discussed in this chapter. Further potential of nanoscience and nanotechlogy for solar energy absorption has been discussed.

Limitations of various existing systems and need of nanofluids for efficient solar energy absorption has been are discussed in brief.

The comprehensive literature review on the application nanofluids for solar energy absorption for conventional heating applications, solar water desalination and separation of complex mixtures such as azeotropes is reported in the ***second chapter***. The extensive literature survey carried out mainly focuses on the earlier reports on selection and synthesis of nanomaterials, use of various nanomaterials and their suspensions in different base fluids, thermo-physical property analysis, solar enabled heating, desalination and separation applications. In addition to this possible effect of various parameters on synthesis of nanomaterials, nanofluids, effect of various nanomaterials on solar energy absorption is also discussed. The reports of the earlier work done on this topic have also been examined to set the objectives of the present research.

Third chapter presents the study of metal nanomaterials mainly copper and aluminium. Copper nanoparticle are synthesized using reported method in addition to the few parametric variations during the synthesis. Aluminium nanoparticles were commercially purchased. Preparation of copper and aluminium nanofluids and their thermophysical property evaluation is presented in this chapter. Solar energy absorption in water, ethylene glycol and silicone oil is extensively studied along with solar water desalination using copper and aluminium nanoparticles is also reported in this chapter. Possibility of azeotrope separation using nanofluid based approach is also presented in this chapter.

Forth chapter reports the metal oxide nanomaterials giving synthesis of copper oxide nanoparticles and effect of various parameters on the morphology during the synthesis. Iron oxide nanoparticles were commercially purchased. Further copper oxide and iron oxide nanofluids preparation and property evaluation is presented in this chapter. Studies on solar energy absorption in water, ethylene glycol and silicone oil using these nanomaterials is also reported along with studies on solar water desalination. Possibility of azeotrope separation using nanofluid based approach is also presented in this chapter.

Fifth chapter exhibits the study of semiconductor nanomaterials viz. silica, zinc oxide and titanium dioxide. Studies on novel synthesis routes for different size silica nanoparticles, zinc oxide nanodots and nanowires, titanium dioxide nanowire and nanotube is presented. Titanium dioxide nanoparticles were commercially obtained.

Nanofluid preparation and thermo-physical property evaluation is also reported in addition to solar heating of water, ethylene glycol and silicone oil and solar water desalination in presence of above nanomaterials. Possibility of azeotrope separation using nanofluid based approach is also presented in this chapter.

Sixth chapter deals with synthesis of carbon nanomaterials to obtain different sizes of carbon nanospheres. Carbon nanofluid preparation and heat transfer property evaluation is presented in this chapter. Solar heating of various heat transfer fluids water, ethylene glycol, silicone oil and solar water desalination in presence of carbon nanoparticles is also reported in this chapter. Possibility of azeotrope separation using nanofluid based approach is also presented in this chapter.

Seventh chapter summarizes the overall conclusions of the present work. Promising materials out of all the four material groups are proposed here and materials are recommended for solar energy absorption in water, ethylene glycol and silicone oil and solar water desalination applications.

Eighth chapter recommends future perspectives of the current study. Though the comprehensive work has been done in the present work, there are few important things which need significant attention for commercial success of nanofluid based solar systems.

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