



A review of Safety, Health and Environmental (SHE) issues of solar energy system



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ARTICLE INFO

Article history:

Received 4 April 2014

Received in revised form

11 August 2014

Accepted 31 August 2014

Keywords:

Solar energy technology

Photo voltaic

Life Cycle Assessment

ABSTRACT

Solar energy is one of the cleanest forms of energy sources and considered as a green source of energy. Solar energy benefit ranges from low carbon emission, no fossil fuel requirement, long term solar resources, less payback time and other. However like other power generation sources, solar energy has also some Safety, Health and Environmental (SHE) concerns. This paper presents the overview of solar energy technologies and addresses the SHE impact of solar energy technologies to the sustainability of human activities. This paper will also recommend the possible ways to reduce the effect of potential hazards of widespread use of solar energy technologies.

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1. Introduction

Due to current economic reforms and enormous technological developments around the world, the energy consumption is increasing exponentially. In 2011–2012, the energy consumption was increased by 2.1% and in between 2000 and 2012, the energy consumption increase rate was 2.4% [1]. Total world energy use is also expected to rise by 56% in between 2010 and 2040 from 524 quadrillion British thermal units (Btu) in 2010 to 820 quadrillion Btu in 2040 [2]. Presently the maximum power consumption around the world at any given moment is 12.5 TW and it is expected by 2030, the world will require 16.9 TW [3]. According to the International Energy Agency (IEA) statistics, 32.8% of generation is based on oil, 27.2% based on coal, 20.9% is based on natural gas and the remaining 19.1% based on nuclear, hydro and others [4,5]. To fulfill the current projection of 16.9 TW by 2030, 13,000 large new coal power plants will be needed [2,6]. Heavily reliance on fossil fuel will also increase the CO₂ emission and the largest emission is coming from the electricity sector. In US, electricity generators consumed 36% of country energy from fossil fuels and emitted 41% of the CO₂ from fossil fuel combustion in 2011. Heavy rely on coal for electricity combustion is also among the reason for such high CO₂ emission. In 2011, 42% of electricity is produced from coal in US and accounted for 95% of coal consumed for energy [7].

The current need is to shift from conventional fossil fuel plants to mix clean source of energy. The promotion of alternative environmental friendly fuels can play a vital role to mitigate the CO₂ emission and favor economic growth. However to cut down the world CO₂ emissions from 42 Gt to 39 Gt, the worldwide investment in renewable energy sector assets need to be raised from \$100 billion to \$500 billion during 2010–2030 [8]. Thus, in addition to heavy investment in clean energy services, the power consumption should also be decreased by introducing energy efficient devices in the market to sustain the mixed clean energy source.

Renewable energy and nuclear power are the world's fastest-growing energy sources; each of them is increasing by 2.5% per year [4,5]. Study has shown that, the wind has a total potential of

around 1700 TW and solar has a potential of 6500 TW. However, currently 0.02 TW of wind and 0.008 TW of solar is being utilized [2]. Global environmental concerns and the escalating demand for energy have also accelerated worldwide attention on green energy. Solar energy potential is largest among the natural energy resources. Solar energy is obtained from the thermal radiation emitted by the sun. At ground level, solar irradiance is attenuated by the atmosphere to about 1000 W/m² in clear sky conditions within a few hours of noon – a condition called 'full sun'. Solar energy's potential estimates in the range from 1575 to 49,837 EJ/year, which is roughly 3–100 times the world's primary energy consumption in 2008 [9,10]. Nowadays, about 46 countries are actively promoting solar energy systems. The worldwide solar photovoltaic (PV) generation capacity continues to increase and has become a rapidly growing industry [11]. IEA has estimated the future growth of other renewable energy potential as shown in Fig. 1. By 2030 it is expected, that the renewable energy will contribute 450 billion kWh/year. However solar contribution will be less in comparison to wind and bio-mass due to low efficiency and other Safety, Health and Environmental issues. IEA has estimated that by 2050, electricity generation from PV will reach 4572 TWh (11% of global electricity production) and thus 2.3 Gt of CO₂ emissions per year will be achieved [12–14]. Here it is also a need to mention that the capacity factor of solar and wind based power plant is smallest among all renewable and non-renewable sources. Capacity factor is a measure of how often an electric generator runs for a specific period of time. The capacity factor of solar PV based plant is 0.16, CSP based plant is 0.43 and wind has only a capacity factor of 0.40 [15]. Thus the efficiency of such power plants needs to maximize to get the maximum output.

Solar energy benefit ranges from low carbon emission, no fossil fuel requirement, long term solar resources, less payback time and other. However like other power generation sources, solar energy has also some Safety, Health and Environmental (SHE) concerns, which needs to be addressed. For example in PV solar cells manufacturing, some highly toxic materials like cadmium, lead, nickel and other compounds are used, which have been restricted by the global environmental protection agencies [10,16–21]. Use of such materials on mass scale is highly unhealthy for the local

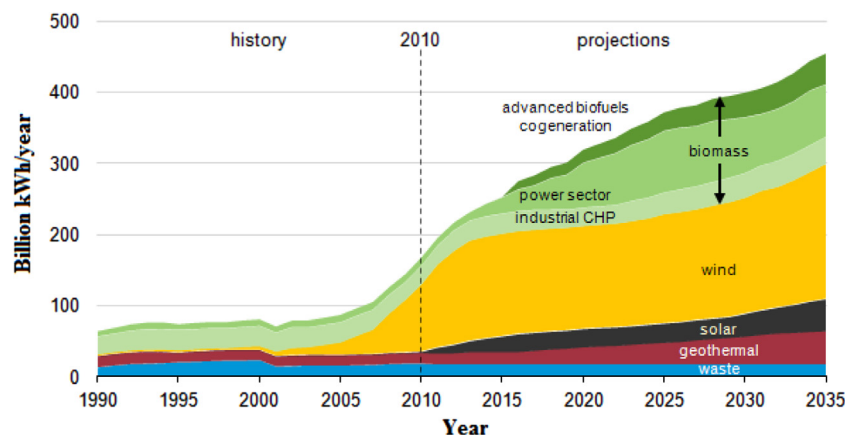


Fig. 1. Projected non-hydropower renewable electricity generation, 2010–2035 [12].

habitat. In addition, like other sources of power generation, PV modules also generate CO₂ and other GHG at some stages in their life. Pure silicon metal (Si_{met}) is used in PV panel manufacturing. Si_{met} is produced in electric arc furnaces from quartz reacting at very high temperatures with reduction elements like coal, coke, charcoal, wood chips and the furnace graphite electrodes. The basic carbo-thermic reduction reaction for production of Si_{met} is stated in Eq. (1).



The products of the process are silicon alloy, condensed silica fumes and recoverable heat energy. Until the last finish product in solar cell manufacturing, number of chemicals are used and different GHG emitted in different chemical processes are elaborated elsewhere [22–24]. Carbon emission is highest in solar PV cells in comparison to other solar energy approach. Solar plants scrap also needs careful handling in recycling process. Solar garbage comes under the electronic-waste (e-waste), thus careful handling is necessary in recycling process. This paper highlights the SHE issues related to the solar technology.

2. Solar technology

In general, solar technology has two major categories, i.e. solar photo-voltaic (PV) modules and concentrating solar power (CSP). PV cells convert sunlight energy into electrical energy by absorbing photons from the light and thus atoms move from the lower orbit to higher orbit and finally leave the parent atoms. CSP uses reflective surfaces to focus sunlight into a beam to heat a working fluid in a receiver. The steam produced from the heat is used to drive the turbine and subsequently the generator is run to produce power [5,25–28].

2.1. Photovoltaic (PV)

The basic building block of the PV devices is a semiconductor element known as PV cell. It converts solar energy into direct current electricity. When number of cells are interconnected, PV module is formed. The PV modules are integrated with a number of additional components, for example inverters, batteries, electrical components, and mounting systems to form a PV system. PV systems can be linked together to provide power ranging from a few Watts to 100 kW [11,29,30]. PV modules are classified on the basis of PV cells semiconductor materials. PV cell materials may differ based on their crystallinity, band gap, absorption, and manufacturing complexity. Each material has a unique strength and characteristic that influence its suitability for the specific applications [31,32].

There are three general families of photovoltaic (PV) modules in the market today. They are mono-crystalline silicon, polycrystalline silicon, and thin film [33]. The cells in a mono-crystalline module are made from a single silicon crystal. This crystal is cut

into wafers roughly 0.2 mm thick before the wafers are chemically treated and electrical contacts are made. They are cut from single crystals to become highly efficient. These modules convert up to 15% of the energy from the sun into electricity, and test models over 20% [34]. Polycrystalline (also known as multi-crystalline) modules are made from cells containing lots of small silicon crystals [35]. This makes them the production cost cheaper but also slightly less efficient than mono-crystalline modules. Many small crystals provide polycrystalline modules a frosted look. While the 0.2 mm wafers in crystalline cells are already incredibly thin, the layers making the thin-film modules are of just 2 μm which is about 40 times thinner than a strand human hair (a micron is one-millionth of a meter). The layers can be deposited on glass forming a panel similar to the crystalline modules, but many other materials can also be used and even flexible panels can be made. Although the efficiency of thin-film panels is only about 10%, they use less material and are cheaper than crystalline modules [33,36–38].

The efficiency and share of the basic PV technologies is given in Table 1 [11]. Solar cells based on silicon (Si) semiconductors account for nearly 90% of 2011 sales of photovoltaic (PV) products. In 2011, annual production of Si-based PV has reached more than 15 GW [39]. There are also other emerging technologies, including concentrating photo-voltaic (CPV) and organic solar cells [11,40]. Generally stated, PV module has an overall efficiency of 10% with the manufacturing cost of \$1 per electrical Watt [19,28]. However there has been a wide variation in cost, based on the type of materials.

Electricity production from solar photovoltaic (PV) has continued its remarkable growth trend in 2011, even in the midst of a financial and economic crisis [41]. In the past decade 2000–2011, the enormous growth of PV markets was observed around the world and particularly in Europe. The average global PV module price has also been dropped from about 22 USD/W in 1980 to less than 4 USD/W in 2009, while for the larger grid connected applications the prices have dropped down to roughly 2 USD/W in 2009 [42]. R&D work is also being carried for further improvement in efficiency and reduction in manufacturing cost of PV modules. IEA has also made '2050 roadmap' for improvement in solar technology efficiency and reduction in cost. It is targeted to achieve up to 25% and 15% efficiency in crystalline and thin film technology respectively [12]. However on the other hand, production of these panels consumes substantial amounts of energy and produces waste water and hazardous by-products which are released to the air during the manufacturing process [43,44]. Recycling technologies for reusing silicon from the solar cells are still not commercially in place but it has been proven that making a solar panel from recycled components require 1/3 of the energy than that of producing panels from the scratch. The total composition of various solar module is represented in Table 2 [45], however by considering weight, the solar cell materials are only 4% of the total weight [46]. The point of concern in the manufacture of solar panels is that the silver used in the module is

Table 1
The efficiency and share of the basic PV technologies [12].

PV technologies	PV cell materials	Efficiencies (%)	Share in global market (%)
Crystalline silicon technology	Mono-crystalline silicon (sc-Si)	14–20	85–90
	Poly or multi-crystalline silicon (mc-Si).	13–15	
	Thin films	Amorphous silicon (a-Si)	6–9
MicromorphSilicon (μc-Si)			
Cadmium telluride (CdTe)		9–11	
Copper-indium-diselenide (CIS)		10–12	
Copper-indium-gallium-diselenide (CIGS).			

leftover and is considered a dangerous waste. Production of these panels in high quantities could also lead to the depletion of silver resources. Research and development initiatives are taking place to recover key materials such as silicon glass, ethylene vinyl acetate (EVA) foil and aluminum from existing panels which can be recycled and used to make new panels [43,47]. Research and development initiatives are taking place to recover key materials such as silicon glass, EVA foil and aluminum from existing panels which can then be recycled and used to make new panels.

2.2. Concentrating solar power (CSP)

CSP technologies produce electricity by concentrating the sun's rays to heat a medium that is used either directly or indirectly to heat a fluid in engine process (e.g., a steam turbine) which is used to drive an electrical generator. In current commercial designs of heat-collection element in CSP, a heat transfer oil is circulated through the steel pipe where it is heated (to nearly 400 °C), but systems using other heat transfer materials such as circulating molten salt or direct steam are currently being used [10]. Molten salt retains heat efficiently, so it can be stored for days before being converted into electricity. That means electricity can be produced during the periods of peak in the cloudy days or even several hours after sunset [48,49].

In general, CSP technology utilizes three alternative technological approaches to heat the medium: trough systems; power tower systems; and dish/engine systems as shown in Fig. 2 and described below [50,51].

Table 2
Composition of c-Si and thin film modules from PV cycle study-2007 [45].

Proportion in %	c-Si (crystalline silicon cells)	a-Si (amorphous silicon cells)	CIS (copper indium diselenide cells)	CdTe (cadmium telluride cells)
Glass	74	90	85	95
Aluminium	10	10	12	< 0.01
Silicon	Approx. 3	0.1	–	–
Polymers	Approx.6.5	10	6	3.5
Zinc	0.12	< 0.1	0.12	0.01
Lead	< 0.1	< 0.1	< 0.1	< 0.01
Copper (cables)	0.6	–	0.85	1.0
Indium	–	–	0.02	–
Selenium	–	–	0.03	–
Tellurium	–	–	–	0.07
Cadmium	–	–	–	0.07
Silver	–	–	–	< 0.01

- (1) **Trough systems** use large, U-shaped (parabolic) reflectors (focusing mirrors) which have oil-filled pipes running along their center, or focal point, as shown in Fig. 2(a). The mirrored reflectors are tilted toward the sun, and focused the sunlight on the pipes to heat the oil inside as much as 750 °F. The hot oil is then used to boil water, which makes steam to run conventional steam turbines and generators [50,52,53].
- (2) **Power tower systems** also called central receivers, used in many large, flat heliostats (mirrors) to track the sun and focus its rays onto a receiver. As shown in Fig. 2(b), the receiver sits on top of a tall tower in which concentrated sunlight heats a fluid, such as molten salt which can be as hot as 1050 °F. The hot fluid can be used immediately to make steam for electricity generation or stored for later use [48,49].
- (3) **Dish/engine systems** use mirrored dishes (about 10 times larger than a backyard satellite dish) to focus and concentrate sunlight onto a receiver as shown in Fig. 2(c). In dish/engine system, the receiver is mounted at the focal point of the dish. To capture the maximum amount of solar energy, the dish assembly tracks the sun across the sky. The receiver is integrated into a high-efficiency 'external' combustion engine. The receiver, engine, and generator composed a single, integrated assembly mounted at the focus of the mirrored dish [48,54,55].

CSP has reached a cumulative installed capacity of about 0.7 GW, with another 1.5 GW under construction. The capacity factors for a number of these CSP plants are expected to range from 25% to 75% and it can be higher than PV because CSP plants contain the opportunity to add thermal storage where there is a commensurate need to overbuild the collector field to charge the thermal storage [10]. Projects are now under development or under construction in many countries including China, India, Morocco, Spain and the United States and are expected to produce electricity a total of 15 GW [56]. US DoE has focused on developing the CSP technologies to achieve the technical and economic targets. The SunShot Initiative program of US DoE goal is to reduce the levelized cost of electricity generated by CSP to \$0.06/kWh or less, without any subsidy, by the year 2020. The DOE SunShot Initiative is a national collaborative effort to make solar energy cost-competitive with other forms of electricity by the end of the decade [52,57]. CSP has several advantages over other technologies, like one advantage of CSP plants is that they are often located in areas with limited amenity or esthetic value. Desert land for solar plants could be in many ways better than agricultural land for biomass energy [58]. Greenhouse gas emissions for CSP plants are estimated to be in the range of 15–20 g of CO₂-equivalent/kWh, which is much lower than CO₂ emissions from fossil-fired plants which are 400–1000 g CO₂-eq/kWh [58].

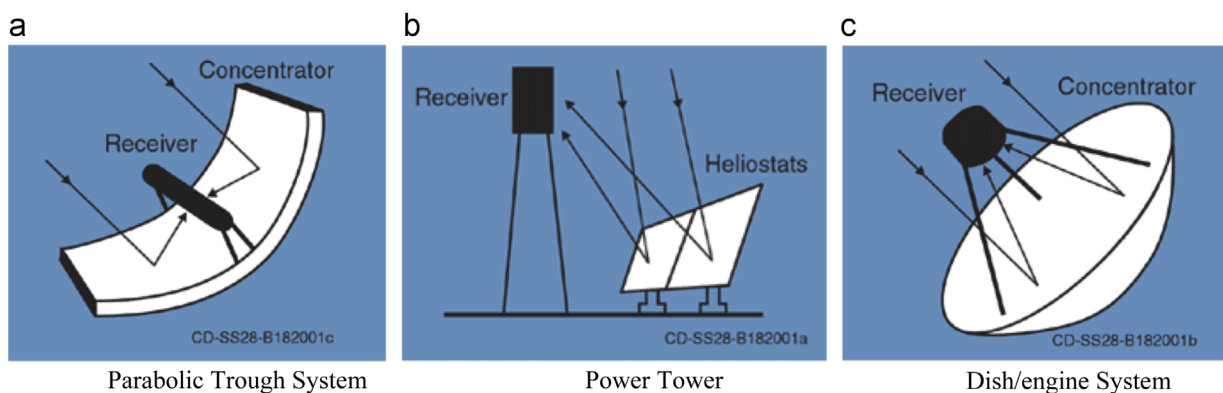


Fig. 2. Schematic diagram of different arrangement of CPS panels [52].

3. Life Cycle Assessment for harmonization in technology comparison

Life Cycle Assessment (LCA) is a tool for sustainability analysis of renewable and conventional energy technologies [21]. LCA aims at evaluating all environmental impacts associated with a given product or service at all stages of its lifetime from 'cradle to grave' such as from resource extraction and processing, through construction, manufacturing and retail, distribution and use, repair and maintenance, disposal/decommissioning and reuse/recycling [59,60]. The goal of the LCA is to bring harmonization in technology to reduce the uncertainty for environmental impacts of renewable and make the information useful to decision-makers in the near term [61]. The Intergovernmental Panel on Climate Change (IPCC) special report on renewable energy sources and climate change mitigation provides a comprehensive review concerning these sources and technologies, the relevant costs and benefits, and their potential role in a portfolio of mitigation options [5,62]. Four terminologies are commonly used in comparing different technologies (for example, among solar technologies) and power generation sources (conventional and renewable).

- (1) Carbon footprints
- (2) Energy pay back ratio (EPR)
- (3) Energy pay back time (EPT)
- (4) Life cycle land use (LCLU)
- (5) Levelized cost of electricity (LCOE)

3.1. Carbon footprints

Carbon footprint is used to find the amount of CO₂ that enters to the atmosphere over the full life cycle (from cradle to grave) of a process or product. It is expressed as grams of CO₂ equivalent per kilowatt hour of generation (gCO₂eq/kWh) [63]. Carbon footprints are sensitive to various factors including operating conditions and country of its manufacture. Renewable energy sources also have a carbon footprint value because they also emit greenhouse gases particularly during construction phase. Fig. 3 shows comparison of the carbon foot prints values for conventional and renewable energy based power plants. The carbon emission from fossil fuel based conventional power plants is significantly high as comparison with and renewable energy based power plants. In case of fossil fuels, carbon capture and storage (CCS) technologies have the potential to reduce emissions from fuel combustion considerably, but are yet to be proven feasible at full scale. Modeling shows coal-fired generators

with CCS which will have carbon foot prints ranging from 160 to 280 gCO₂eq/kWh [31,64]. In case of renewable energy sources, such plants do not generate GHG during operation, most of the emissions come during the construction phase and the production of fuels (where applicable). For generators based on ambient energy flows, such as solar energy, the local energy resource also has an important influence on the carbon footprint values. This is because higher electricity outputs cause lower footprints, as total emissions are spread over a greater amount of electricity [31,64]. Similarly location has also an important effect on the carbon footprint. For example in case of wind generation, figures from one UK study indicate that a micro-wind turbine would have a carbon footprint of around 38 gCO₂eq/kWh for locations with an average annual wind speed of 4.5 m/s. This is the minimum wind speed recommended for small wind systems by the industry trade body. The same study indicates that locations with an average wind speeds of 6 m/s would give footprints of 20 gCO₂eq/kWh, while locations having 3 m/s wind speed would give 96 gCO₂eq/kWh [31,64]. In general fossil fueled electricity generation has the largest carbon footprint (above 1000 gCO₂eq/kWh) and renewable technologies have low carbon footprints (< 100 gCO₂eq/kWh). Future carbon footprints can be reduced for all electricity generation technologies if the high CO₂ emission phases are fueled by low carbon energy sources [64].

3.2. Energy payback ratio (EPR)

Energy payback ratio (EPR) is the ratio of total energy produced during a system's normal lifespan, divided by the energy required to build, maintain and fuel it. If a system has a low payback ratio, it means that much energy is required to maintain it and this energy is likely to produce many environmental impacts. A high ratio indicates good environmental performance. If a system has a payback ratio between 1 and 1.5, it consumes nearly as much energy as it generates, so it should never be developed. For fossil fuels, it means environmental impacts at extraction, transportation and processing of fuels. For renewable sources, it means environmental impacts at building the facility [66]. If the ratio is close to unity, it means it consumes as much energy as it produces, so it should never be developed. Thus the value of EPR should be as large as possible to generate favorable economics. However the amount of pollutants emitted per kWh of electricity generation should be as low as possible [67–69]. The EPR for conventional and renewable energy resources is shown in Fig. 4.

Fig. 4 shows that renewable energies have large variations, due to variable site-specific conditions. Hydropower clearly has the

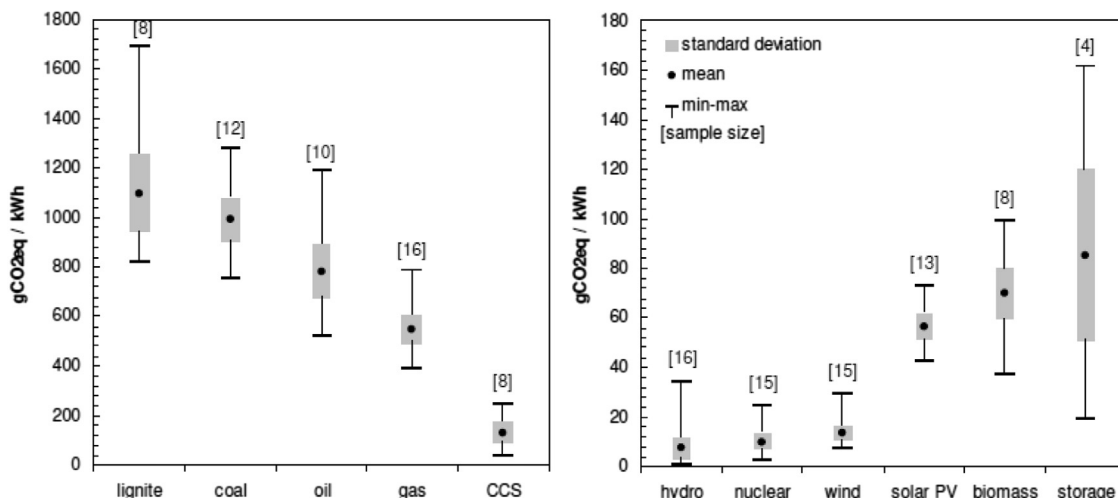


Fig. 3. Summary of life-cycle GHG emissions for selected power plants [65].

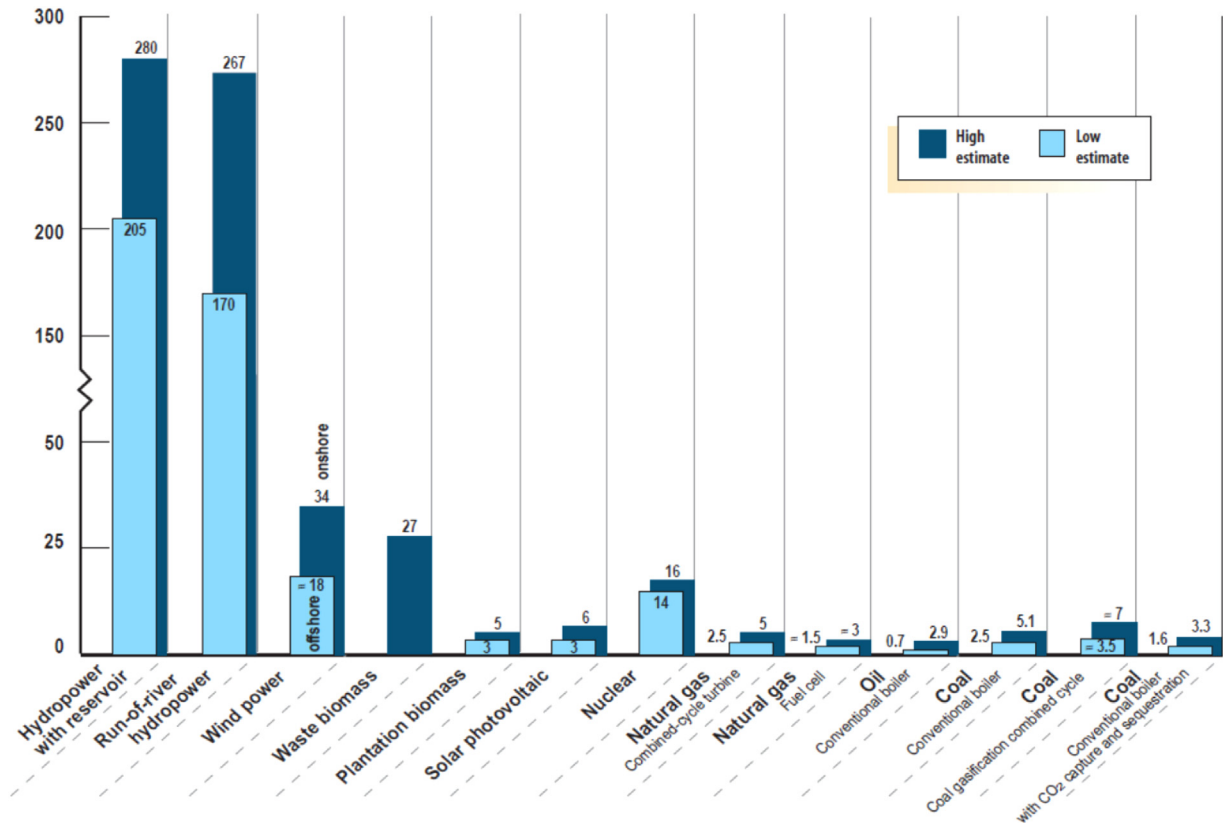


Fig. 4. Energy payback ratio (EPR) for conventional and renewable energy resources [10].

highest performance, with EPR of 205 and 267 compared to fossil fuel systems with typical ratios of 5–7. Wind power also has a very good performance (ratio of 80). However, this ratio is overestimated because the calculations did not consider the need for backup capacity to compensate for wind fluctuations [66].

3.3. Energy payback time (EPT)

Energy payback time (EPT) is the time required for a generation technology to generate the amount of energy that was required to build, fuel, maintain and decommission it. The EPT is closely linked to the energy payback ratio and depends on assumptions made on the lifetime of a technology [59,70–73]. EPT also exists as a criterion for LCA analysis of different technologies. Table 3 lists the EPT of different power system technologies [10].

The main reasons for variation in EPT values in Table 3 are fuel characteristics (e.g. moisture content), cooling method, ambient and cooling water; temperatures and load fluctuations (coal and gas), uranium ore grades and enrichment technology (nuclear), crystalline or amorphous silicon materials (PV solar cells), economies of scale in terms of power rating (wind) and storage capacity and design (concentrating solar). For some renewable energy sources, for example wind and PV, energy payback times have decreased because of economies of scale and technological progress [59]. However, the location-specific capacity factor has a major influence on the energy payback time in particular for intermittent renewable energy sources. In the case of fossil fuel and nuclear power technologies, the impact of fuel extraction and procession may increase in parallel with the decline in conventional fuel and rise in unconventional fuel. Fig. 5 shows the EPT for silicon and CdTe PV modules [74]. The payback period for thin films based solar cell is less than the wafer based Si. For example, EPBT for CdTe material plants is 1.1 years compared to 1.7, 2.2, and 2.7 years for ribbon, multi-, and mono-Si technology respectively [75].

Table 3

Energy payback time of electricity generating technologies [10].

Technology	Energy payback time (EPT)		Most commonly stated life (years)
	Low value	High value	
Brown coal new subcritical	1.9	3.7	30
Black coal new subcritical	0.5	3.6	30
Black coal new subcritical	1.0	2.6	30
Natural gas (open cycle)	1.9	3.9	30
Natural gas (combined cycle)	1.2	3.6	30
Heavy water reactors	2.4	2.6	40
Light water reactors	0.8	3.0	40
Photo-voltaic	0.2	8.0	25
Concentrating solar	0.7	7.5	25
Geo thermal	0.6	3.6	30
Wind turbines	0.1	1.5	25
Hydro electricity	0.1	3.5	70

3.4. Life-cycle and land-use (LCU)

Different critics consider different criteria for finding out the land usage in Life Cycle Assessment. Many critics consider that renewable energy resources occupy more land as compared to conventional resources [76–78]. However, some authors did not include the land transformation (land use change) and land occupation (land use for a certain period) while comparing technologies [79]. The land transformation indicates the area of land altered from a reference state (unit: m^2), while the land transformation occupation denotes the area of land occupied and the duration of the occupation (unit: $\text{m}^2 \times \text{year}$). Fig. 6 represents the total land-area transformation for different electricity generation sources [80–83]. Table 4 shows the overall land use for renewable energy plant to supply electricity.

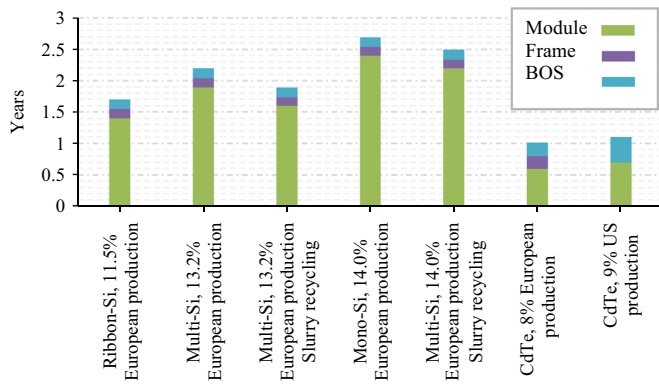


Fig. 5. Energy payback time for silicon and CdTe PV modules [74].

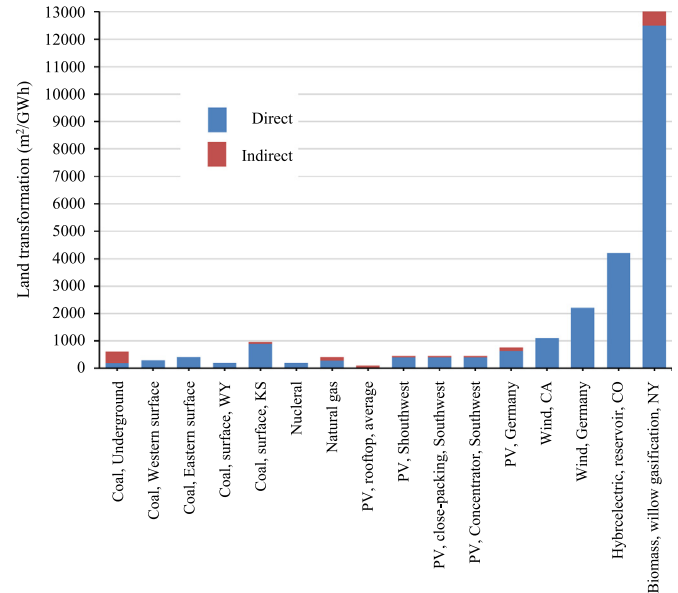


Fig. 6. Life-cycle land transformation for fuel cycles based on 30-years' timeframe [80].

Table 4

Estimation of the land for renewable energy plant to supply electricity [84].

Technology	Land per year (km²/GW)
Flat-plate PV	10–50
Solar thermal or PV concentrator	20–50
Wind	100
Biomass	1000

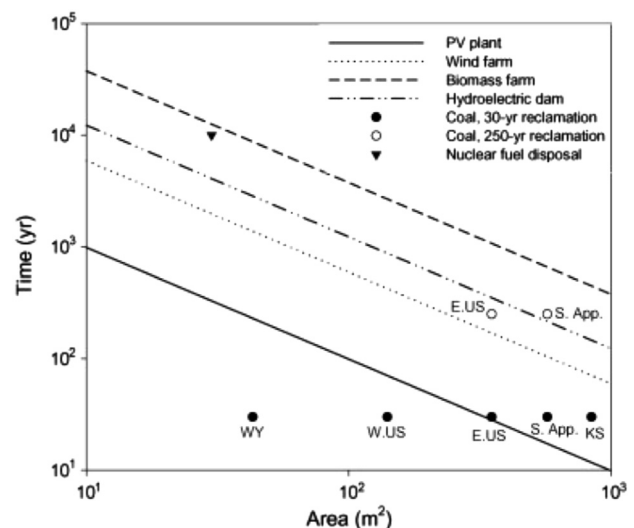


Fig. 7. Land occupation for 1 GWh of electricity from conventional and renewable energy [80].

shortened PV system energy pay-back times. The latter is expected to be reduced from maximum two years in 2010 to 0.75 year in 2030 and below 0.5 year in the future. Finally, the operational lifetime is expected to increase from 25 to 40 years.

4. Solar energy impacts on Safety, Health and Environment (SHE)

Solar energy is considered as one of the cleanest forms of power generation. However as compared to other energy resources, solar energy has also some disadvantages. Solar energy benefits could be

From Fig. 6, it could be observed that the PV transforms the least amount of land in comparison with other renewable technologies. Also LCA is highly sensitive to the location and environmental condition of the exposed side [80,85]. The land occupation per unit of electricity generation from conventional power sources like coal and nuclear sources is very sensitive to the length of recovery for allocated area. Fig. 7 represents the land occupation patterns for conventional and renewable energy systems for 1 GWh of electricity [23,72,78–80]. Fig. 7 shows that the biomass farming entails the greatest land occupation (380,000 m² year/GWh) followed by nuclear-fuel disposal (300,000 m² year/GWh). However the PV power plant with 13% efficiency requires 9900 m² year/GWh of land occupation [80].

3.5. Levelized cost of electricity (LCOE)

LCOE represents the per-kilo-watt-hour cost (in real dollars) of building and operating a generating plant over an assumed financial life and duty cycle. Capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed capacity factor for each plant type are included in calculating LCOE [86]. It is calculated using Eq. (2) [87].

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total lifetime energy production}} \quad (2)$$

It is often stated as a convenient measure of the overall competitiveness of different generating technologies. Fig. 8 represents the LCOE for conventional and renewable energy sources.

In Fig. 8, the LCOE for each technology is evaluated based on the capacity factor indicated in Table 5 [88], which generally corresponds to the high end of its likely utilization range. The duty cycle for intermittent renewable resources, wind and solar, is not operator controlled, but dependent on the weather. The capacity factor ranges for these technologies are as follows: wind – 31–45%, wind offshore – 33–42%, solar PV – 22–32%, solar thermal – 11–26%, and hydroelectric – 30–65%. The levelized costs are also affected by regional variations in construction labor rates and capital costs as well as resource availability [86].

In summary, PV technologies are proved to be sustainable and environmental-friendly regarding the GHG emission rate, EPBR, EPBT and land usage in comparison to conventional energy sources. The levelized cost of solar power generation is found higher than the existing possible methods. Table 6 summarizes a set of general technology targets for PV systems up to 2050, expressed in terms of (maximum) conversion efficiency, energy-payback time, and operational lifetime [89]. Typical commercial flat-plate module efficiencies are expected to increase from 16% in 2010 to 25% in 2030 with the potential of enhancement up to 40% in 2050. Concurrently, the use of energy and materials in the manufacturing process will become significantly more efficient; leading to the considerably

enlisted as, low carbon emission, no fossil fuel requirement, long term solar resources, less payback time and others. However it has been seen that every form of generation source has carbon emission at some stages. In the manufacturing of PV solar cells, some highly toxic materials like cadmium, lead, arsenic, nickel and others are used, those have been restricted by global environmental policies [10,17]. For example in thin-film cadmium-telluride (CdTe) PV modules, restricted e-product cadmium is used which is also known as human carcinogen [12,90]. Such material use on mass scale is highly harmful from the SHE point of view. Solar plants scrap also needs careful handling in recycling process. Solar garbage comes under the e-waste. Consistent annual growth and high production in

solar market, needs proper planning to handle the future solar garbage. Otherwise it will become difficult to handle tons of wastes. For example, a 10 MW electricity generation plant consumes 2000 tons of thin-film solar panels needed [91]. These issues are discussed in detail in subsequent sections.

4.1. Positive impacts of solar energy

Solar energy is one of the cleanest forms of energy, with remarkable solar potential available all over the world. Benefits of solar energy lies with the minimization of utilization of natural resources particularly those diminishing very fast (like oil, coal and others), reduction in emission of CO₂ and consumption of water and the availability of huge amount of Si semiconductor materials availability for solar panel constructions. These advantages are discussed in detail in this paper.

4.1.1. Saving in natural energy resources

The fossil fuel resources are depleting very fast, depending on the increase of energy consumption. The energy consumption and production rate is increasing and it is expected by 2025, energy consumption will supersede the energy production rate, thus the world has to face the energy shortage problem. The yearly statistics of energy production and consumption is given in Table 7 [92].

According to [92] statistics report, the daily world energy fuel consumption has increased, up to 3.1% in oil, 7.4% in gas and 7.6% in coal consumption per day basis from 2009 to 2010. The world proven energy reserves are expected to be expired in 100 years. The expected end of energy reservoirs is given by reserves to production ratio (R/P ratio), which is measured in years. R/P ratio depends on current energy reservoirs and the production/consumption during that year. The proved reserves of fossil fuel is given in detail in Table 8. If the reserves remaining at the end of the year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate. Renewable energy is although vast in quantity but still the need for fossil fuels could not be diminished. Fossil fuels are considered reliable source of energy, however tidal, wind and solar are intermittent sources of energy and depend on environmental conditions. Geologists also advise us that, it is necessary to leave enormous amount of fossil fuels in the ground to reduce the risk of climatic change [93].

4.1.2. Water consumption reduction

Earth is considered as a blue planet, 70% water and rest of the 30% is land. Although out of 70%, fresh water available is only 3% [94]. According to the World Health Organization report, one-third of the Earth's population is leaking the necessary quantities of water from their requirement. On the other hand United nation estimates that by 2050, half of the world's population will live in those countries which will have shortage of water, largely in Asia, Africa, and Latin America [95–97]. The expected water requirement till 2050 is given in Table 9.

One of the largest consumption is due to conventional power plants for the condensing portion of the thermodynamic cycle. Average water consumption (gal/MWh) for conventional and renewable power plants is shown in Fig. 9 [98]. Water consumption is

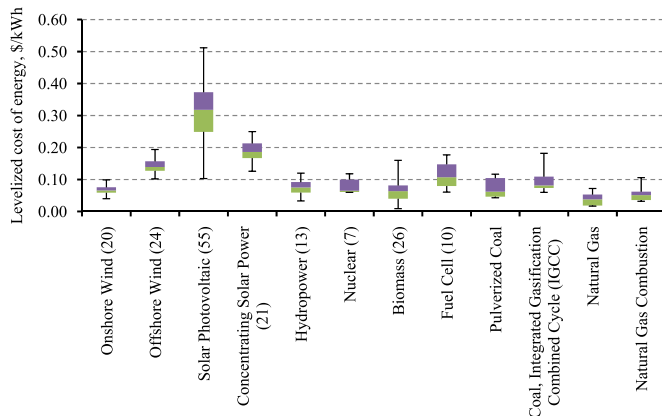


Fig. 8. Levelized cost of energy (LCOE) for conventional and renewable energy sources [88].

Table 5
Capacity factors of conventional and renewable energy sources [88].

Technology	Capacity factor	Technology	Capacity factor
Wind, onshore	0.38	Hydropower	0.50
Wind, offshore	0.39	Bio-power	0.83
Solar, photovoltaic	0.16	Fuel cell	0.95
Solar, concentrating solar power (CSP)	0.43	Natural gas combined cycle	0.87
Coal, integrated gasification combined cycle	0.85	Natural gas combustion turbine	0.30
Enhanced geothermal system (EGS)	0.95	Pulverized coal	0.85
Nuclear	0.90	Geothermal, hydrothermal	0.95

Table 6
PV technology target [89].

Target year	2008	2020	2030	2050
Typical flat-plate module efficiencies	Up to 16%	Up to 23%	Up to 25%	Up to 40%
Typical maximum system energy pay-back time (in years) in 1500 kWh/kWp regime	2 years	1 year	0.75 year	0.5 year
Operational lifetime	25 years	30 years	35 years	40 years

Table 7
Energy production and consumption (in million tonnes oil equivalent) [92].

Years	2000	2005	2010	2015	2020	2025	2030
Total energy production	9387.00	10,867.20	12,145.60	13,565.80	14,685.11	15,619.62	16,604.65
Total energy consumption	9382.42	10,800.94	12,002.35	13,360.41	14,627.05	15,634.60	16,631.56

Table 8
Proved reserves of fossil fuels (BP statistical review-2011) [60].

Region	Oil		Natural gas		Coal	
	Thousand million barrels	Share of total (%)	Trillion cubic metres	Share of total (%)	Total million tonnes	Share of total (%)
North America	74.3	5.4	9.9	5.3	245,088	28.5
South and Central America	239.4	17.3	7.4	4.0	12,508	1.5
Europe and Eurasia	139.7	10.1	63.1	33.7	304,604	35.4
Middle East	752.5	54.4	75.8	40.5	32,895	3.8
Africa	132.1	9.5	14.7	7.9	265,843	30.9
Asia Pacific	45.2	3.3	16.2	8.7	860,938	100.0
World	1383.2	100.0	187.1	100.0	118.37	
R/P*	46.16		58.60			

* Reserves-to-production (R/P) ratio.

Table 9
Water requirements for energy production in the world [94,95].

Year	2005	2015	2035	2050
Total world water for energy (billions m ³)	1815.6	1986.4	2087.8	2020.1

vital and is a great concern especially for countries like Singapore and Saudi Arabia, where clean water is highly valuable. Dubai, high-tech city, has been built in a desert and has the world's highest per capita rate of water consumption [99]. From Fig. 9, it can be seen that using renewable energy sources, water can be preserved and could be effectively utilized for other purposes. In case of PV, water use for operations is minimal. Experimental evidence demonstrates that although frequent washing increases output, it likely leads to economic losses [100]. Concentrating solar thermal plants (CSP), like all thermal electric plants, require water for cooling. Water use depends on the plant design, plant location, and the type of cooling system. The water usage for CSP could be significantly reduced by using dry cooling approaches. However, the tradeoffs to these water savings are higher costs and lower efficiencies. In addition, dry-cooling technology is significantly less effective at temperatures above 100 °F [10,101].

4.1.3. Land transformation/land use

Solar like other renewable energy resources has some distinct features as compared to conventional source of energy. Like conventional power plants, solar energy sources do not need further extraction of resources once the infrastructure has been developed. Moreover the land could be used for other purposes, like plantation and shading [102]. Direct land-use requirements for small and large PV installations range from 2.2 to 12.2 acres/MW, with a capacity-weighted average of 6.9 acres/MW. Direct land-use intensity for CSP installations ranges from 2.0 to 13.9 acres/MW, with a capacity-weighted average of 7.7 acres/MW [103]. On the other hand fossil fuel based plants need lands for their power plant as well as for the extraction of resources. Land transformation (primarily for residential or industrial areas) period for fossil fuel based plants is based on the amount of extraction per day. Also in case of fossil or nuclear plants land is marked and left, in search of fuels for future use. On the other hand, Si material exists in the nature in abundant quantity,

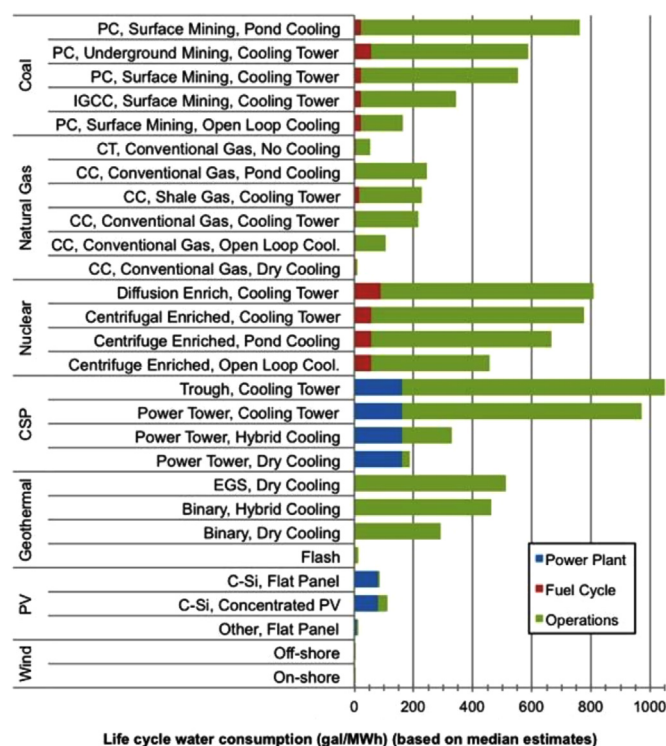


Fig. 9. Estimated life cycle water consumption factors for conventional and renewable generation technologies [98]. Note: EGS=enhanced geothermal system; CT=combustion turbine; CC=combined cycle; IGCC=integrated gasification combined cycle; and PC=pulverized coal, sub-critical.

Table 10
Land-use requirements for PV and CSP projects in the United States [103].

Technology	Direct area (acres/MWac)	Total land use (acres/MWac)
Small PV (> 1 MW, < 20 MW)	5.9	8.3
Large PV (> 20 MW)	7.2	7.9
CSP	7.7	10

no specific land is required for extraction [93,104]. Table 10 shows the summary of land-use requirements for PV and CSP projects in the United States [103]. Direct land use represents the disturbed land due to physical infrastructure or development due to solar and total area use represents all land enclosed by the site boundary.

4.1.4. Reduction of carbon dioxide emission

One of the main advantages of solar energy is zero air pollution during power generation. This makes the solar energy among the cleanest form of energy on earth. Solar energy does not burn oil, thus it does not produce any toxic gases. However some toxic materials are widely used in solar cells manufacturing. These environmental tolls are negligible when compared with the damage inflicted by conventional energy sources. The burning of fossil fuels releases roughly 21.3 billion metric tons of carbon dioxide into the atmosphere annually [105,106] stated that a 50 MW parabolic trough power plant can eliminate 80,000 tons of CO₂ emissions annually. Fig. 10 shows the carbon foot prints values for renewable energy based power plants.

Solar energy although has the largest carbon foot prints value in renewable technologies. However future improvements in

cumulative GHG emissions from PV are likely to arise from improvements in module efficiency, increased lifetime, less silicon mass per module and lower use of electricity for the production process [65]. It is also important to note that solar PV technology is a fast-improving technology and frequent LCA studies are being published in order to keep the pace with the advancements.

4.1.5. Noise and visual impacts

Solar modules do not suffer with the noise problem. Solar energy is a static source of power generation with no rotating parts. Also, there will be some employment benefits during the

construction phase and especially for large schemes during the operational phase. Solar panels contain no moving parts and thus produce no noise. Wind turbines, by contrast, require noisy gearboxes and blades. However fossil fuel based plants and renewable source of energy (including wind and hydro) have noise problems [21,60,107,108]. The noise problem from power plants makes it unsuitable for placement nearer to the population. Proper sites are marked for their placements. Solar technology is changing is very fast. Options for reduction of energy demand must always be considered along with the assessment of PV application. Instead of roof-topped panels, special bricks with integrated special PV modules are also made. Fig. 11 shows such type of construction giving esthetic look [60,109].

Visual intrusion is highly dependent on the type of the scheme and the surroundings of the PV systems. It is obvious that, if a PV system is applied near an area of natural beauty, the visual impact would be significantly high. In case of modules integrated into the facade of buildings, there may be positive esthetic impact on modern buildings in comparison to historic buildings or buildings with cultural value.

4.2. Negative impacts of solar energy

Solar energy is considered as a 'Green Source' of energy. However there are some Safety, Health and Environmental issues, which should be addressed before the wide spread application of solar technology. Solar panels are based on nanotechnology, which is considered as a 'clean tech' technology [114]. To see the impact of solar panel, its life could be split into three stages, manufacturing, operation (generation), decommissioning. It is true that photovoltaic solar panels do not pollute the air during power generation however

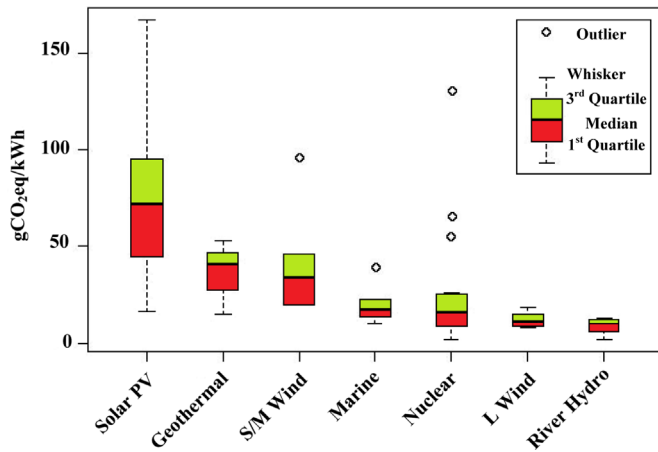


Fig. 10. Carbon Footprints for renewable electricity [64].

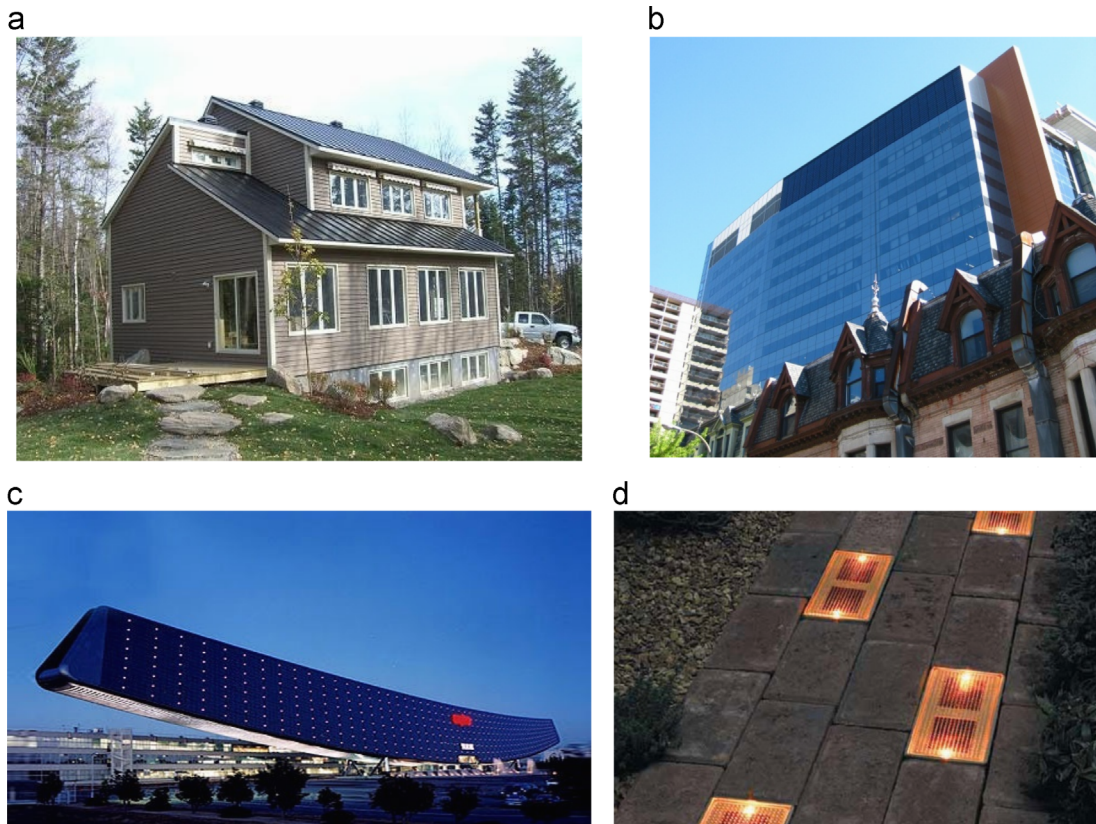


Fig. 11. Solar energy constructed outlook; (a) residential house based on building integrated photovoltaic/thermal technology [110]; (b) Integrated combined solar thermal and electric generation building [111] at John Molson School of Business, Concordia University. (c) The Solar Ark [112, 113], a sign board in Japan under Sanyo Electric Co., Ltd. (d) Solar Brick LED Lights.

manufacturing process of them involves many toxic materials, which is highly harmful from SHE perspective. There are some concerns after the completion of expected life of panel and in their recycling process. These issues will be discussed in this section [115].

4.2.1. Cost of land

Large-scale solar farms need a big space for their installation. Approximately 1 m² of land produces 200 W of electricity, depending on the location, efficiency and other environmental conditions [6,116,117]. This problem becomes prominent for those countries which have already high population density like Singapore, having an area of 697 sq.km [66], with population density above 7680/sq.km. Finding cheap land in such countries is quite difficult. Also high cost of land will also affect the per unit electricity cost. Land use could be minimized by increasing the solar panels efficiency or to mount the cells on a rooftop [6]. With current efficiency of solar panel, the top roof area of houses in USA will only fulfill the 1/10th of total US energy requirement [6].

4.2.2. Toxic chemical content in solar panel manufacturing

Different chemicals are used in manufacturing of solar panels, particularly during extraction of solar cell. For example, cadmium (Cd) is used in cadmium telluride based thin film solar cells as a semiconductor material to convert solar energy into electrical energy which is highly toxic element. National Institute of Occupational Safety & Health (NIOSH) considers cadmium dust and vapors as carcinogens (causing cancer). Similarly many hazardous chemicals are used as solvents to clean dust and dirt from the solar panels. European Union has initially banned Cd, Pb, Hg and other toxic compounds as per the regulations of the Restriction of Hazardous Substances Direc-

tive (RoHS) [118–122]. However the European Union decision highly affected the production of solar panel based on cadmium telluride (CdTe). In November 2010, EU law exempted the solar panel from a ban in order to facilitate the solar manufacturing industry and also to attain the set targets for renewable energy generation [123]. These toxic materials have special concerns, particularly for local habitats. In recent years, September 2011, accidents due to dumping of hazardous chemicals into the water supply has led to local protest and finally resulted the shutdown of the company [124]. PV panels are threat to the environmental contamination if improperly disposed of upon decommissioning due to the use of toxic materials in their composition [76]. On the other hand, the accidental release of heat transfer fluids (water and oil) from parabolic trough and central receiver systems could form a health hazard. The hazard could be substantial in some central tower systems, which use liquid sodium or molten salts as a heat-transfer medium. Indeed a fatal accident has occurred in a system using liquid sodium. These dangers could be avoided by moving to volumetric systems that use air as a heat-transfer medium. Central tower systems have the potential to concentrate light to intensities that could damage eyesight. Under normal operating conditions this should not pose any danger to operators, but failure of the tracking systems could result in straying beams that might pose an occupational safety risk at site [60]. The partial list of toxic materials used in solar industry, their use and impact on human health, safety and environments are presented in Table 11.

4.2.3. Ecological impacts

Solar energy facilities have direct impacts on local habitats and nearby surroundings. The construction of solar farms on large scale needs clearing of land which adversely affects the native

Table 11
Safety, Health and Environmental (SHE) impact from the toxic compounds [78,80,125–127].

Toxic Compounds	Purpose	Safety, health and environmental impact
Ammonia (NH₃)	To produce anti-reflective coatings for solar PV modules.	Skin irritation, eyes irritation, throat problem, lungs problems, mouth and stomach burns.
Arsenic (As)	Used in GaAs solar PV cells, resulted from the decomposition of GaAs	Heart beat problems, throat infection, lung cancer, nausea, vomiting, reduced blood cells, skin darkening, red spot on skin, liver problem, etching in hands and feet.
Silicon (Si)	Used as a PV semiconductor material	Crystalline Si causes respiratory problems, irritating skin and eyes, lung and mucus problems
Lead (Pb)	To wire, solder photovoltaic electrical components.	Damages nervous system, weakness in bones, can also cause anaemia, high level exposure resulting in miscarriage for pregnant woman, damages the brain and kidneys, highly carcinogenic element.
Nitric acid (HNO₃)	To clean wafers and reactors, remove dopants.	Potential cause for chemical burns.
Sulfur hexafluoride (SF₆)	Used to etch semiconductors and clean reactors in PV manufacturing.	The most powerful greenhouse gas known.
Cadmium (Cd)	Cd is used in cadmium telluride based solar cells as a semiconductor to convert solar energy into electricity.	Cd dust and vapours are highly toxic and considered as carcinogens. Also effect the respiratory system, kidneys and blood cells and can cause prostate, diarrhoea, chest tighten and lung cancer.
Hydrogen (H₂)	Used in manufacturing amorphous-Si solar cells.	Highly explosive.
Hexavalent Chromium (Cr-VI)	Used in screw, solar chassis board and as a coating material in solar panel to absorb solar radiation.	Cr is a carcinogenic element, means causes cancer.
Polybrominated biphenyls (PBBs) and brominated diphenylethers (PBDEs)	Used in circuit boards and solar panel inverters	Recognized as toxic and carcinogenic and are described as endocrine disrupters.
Acetone	These solvents are used to clean microscopic dirt and dust off of chips.	Eyes and nose irritation, throat infection, kidney and liver problem, nerve damage, birth defects, sexual problems including lowered ability to reproduce males.
Iso-propanol	To clean microscopic dust and dirt from solar chips.	Vomiting, Eyes irritation, depression, dermatitis, nausea, unconsciousness, respiratory failure, death or coma.
Toulene		Headaches, hearing loss, confusion, memory loss, pregnancy problems, retarded growth.
Xylene		Skin irritation, eye irritation, nose infection, throat and breathing problems, pregnancy problems, liver and kidneys infection.
1,1,1-Trichloroethane		Dizziness and loss of mind, reduced blood pressure, unconsciousness, stop heart beating.
Hydrochloric acid (HCl)	To produce electrical grade silicon, clean and etch semiconductors	Skin problem, eyes and nose infection, respiratory problem, food digestion, mouth and throat infection, respiratory depression.

vegetation, wildlife and loss of habitat. If at the optimum solar site, trees and bushes exists and blocking the sunrays, it needs to be removed [6]. The native drainage and irrigation system also disturbed due to solar sites. The presence of cattle animals can reduce the efficiency of PV modules due to the increased rate of dust and dirt in the surroundings. Special chemicals are used for dust suppressants and herbicides cleaning at solar facilities, which results in contamination of the surrounding and groundwater [57,128]. Engineering methods can be used to mitigate these impacts. On the other hand, CSP generates electricity by driving the heat engines located on the ground. The high temperature of fluids or materials is achieved by receiving the energy from optical concentrated solar receiver, as shown in Fig. 12. The height of CSP and the reflected light beams cause interference with aircraft operations [83,129].

4.2.4. Decommissioning and recycling of solar panels

Solar modules present some SHE concerns after the completion of their expected life (20–30 years). Disposing them on landfills is a big challenge for local municipal committees due to the use of small amounts of hazardous materials. Authors in [91] have discussed centralized and decentralized recycling strategies. The current growth of solar market is quite large and the time is to do proper planning to handle the future solar garbage, otherwise it will become difficult to handle tons of wastes. For example, to produce 10 MW electricity there is a need of 2000 t of thin-film solar panels [91,130]. The proper collection of scrap panels, safe recycling and reduced emission procedure should be adopted. The proper guidelines for their handling have been discussed elsewhere [23,91,131–134].

Non-profit organization has come up in the market for the safe disposal and recycling of PV modules. PV Cycle, along with the non-profit association is working throughout Europe by targeting the recycling rates of 80% and 85% by 2015 and 2020 respectively [135]. First solar and the leading solar panel manufacturer has started the recycling of solar panels and continuously looking the ways of optimizing its recycling program. Approximately 90% of the module weight is recovered. Estimated recovery of semiconductor materials (Te and Cd) is 95%, which is quite good sign from SHE point of view, otherwise additional disposal cost will be required for proper disposal of generated hard used wastes [17,133,136,137]. The potential non-air impact of conventional and renewable energy power sources have been summarized in Table A1.

5. Recommendations for a clean solar industry

Solar energy provides tremendous environmental benefits when compared to the conventional energy sources. In addition to preserve

natural resources, their main advantage is total absence of almost any air emissions or waste products during operation. The current growth of solar industry is remarkable however the above SHE issues should not be neglected. Solution of one problem of lack of energy resources for power generation should not result in generation of other problems. People are very much concerned about the disposal and hazardous wastes due to solar power plants waste [77]. Following recommendations could be adopted to make the solar industry a clean or nearer to clean industry:

- Reduction and step-by-step elimination of hazardous materials used in chemical processing of semiconductor materials.
- Life time for solar equipment should be improved, in order to increase the energy pay back ratio and thus minimizing GHG and CO₂ emission.
- Efficiency of solar panels should be improved in order to minimize the land use and thus generating minimum ecological impacts.
- Need to carry out a thorough survey to understand the environmental impact of setting solar panels on local habitants.
- Need to carry out research to find out eco-friendly semiconductor materials and other chemicals used for their treatment.
- Strict guidelines should be followed during manufacturing of solar panels, for human safety.
- Strict guidelines should be followed during disposal of hazardous wastes, generated in solar panel manufacturing.
- Generated wastes should be chemically treated before dumping into the sea, in order to protect the aquatic lives in the sea.
- On-call systems should be developed for collection of dead-solar-panels from houses for their safe disposal.
- To minimize the cost of recycling, such modules should be developed, which are easy to disassemble and detach the materials from the glass.
- Water based eco-friendly solvent should be developed for cleaning dust and dirt from the solar panels.

6. Conclusion

This paper has summarized the Safety, Health and Environmental (SHE) impact of solar energy system on local inhabitants. The production of solar energy systems in the world has increased majorly due to enormous amount of untapped solar potential, eco-friendly characteristics and to overcome possible energy fuel shortage in near future. Solar energy provides tremendous environmental benefits when compared to the conventional energy sources. However solar systems also generate GHG emission particularly in production stages and the waste of solar industry comes under e-garbage and must be handled carefully. Innovative production technologies in improving the PV modules module efficiency, increased lifetime, less silicon mass per module, lower use of electricity for the production process and proper recycling would help to lower the environmental impacts.

Acknowledgment

Authors would like to acknowledge the University of Malaya for funding the project under the project no. UM.K/636/1/HIR (MOHE)/ENG46.

Appendix A

See Table A1.



Fig. 12. Existing concentrated solar power plants (CSP) [90].

Table A1

Potential non-air environmental impacts of several conventional power sources [138].

Power source	Land use	Water consumption	Water quality/discharge	Solid waste and ground contamination	Bio-diversity
Coal	High	High	Moderate to high	High to low	High
Natural gas	Moderate	Low	Zero to high (depends on the extraction method)	Low	Low
Nuclear	Moderate	High	High	High	Moderate to high
Hydro with storage	High	Moderate	Moderate	Moderate	Moderate
Run of river hydro	Low	Low	Zero	Zero	Low
Solar PV and thermal electric	High to low (depend on location where PV modules are mounted)	Zero to low	High to low	Zero	Zero
Wind	Moderate	Zero	Zero	Low	Low
Geothermal	Low	Zero	Low	Zero	Low
Marine wave and tidal	Low	Zero	Zero	Zero	Low
Biomass	High to low	Moderate	Moderate	Low	High

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