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Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic

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ABSTRACT

Renewable energy source (RES) based electrical power plants are widely considered green and clean due to their contribution to decarbonizing the energy sectors. It is apparent that RESs do not produce carbon dioxide, however their significant negative impacts on the environment are still found and cannot be ignored. In this paper, the environmental impacts of RES based power plants are analyzed through a comprehensive review considering solar thermal, solar photovoltaic, wind, biomass, geothermal, hydroelectric, tidal, ocean current, oceanic wave, ocean thermal, and osmotic effects. Solar thermal power is well known as concentrated solar power. A strength, weakness, opportunity, and threat (SWOT) analysis is carried out and discussed for all RES based power plants. Comparative SWOT analyses for solar photovoltaic and concentrated solar power plants are presented. The comparative environmental impact analyses for all existing RES based power plants are tabulated for various attributes. These attributes include but are not limited to human health, noise, pollution, greenhouse gas emission, ozone layer depletion, toxification, flooding, impact on inhabitants, eutrophication, dried up rivers, and deforestation. Based on the analysis, it is found that careful selection of RES for electrical power plants is necessary because improper utilization of RES could be very harmful for the environment.

1. Introduction

The conventional energy sources such as coal, oil, and natural gas, also known as fossil fuels, have been explored and exploited for power generation in power plants through the past few centuries. The most significant benefit of these energy sources is that they have high energy density. However, they emit carbon and other greenhouse gases when they are used. The global energy demand is rising each year and it is forecasted that the energy demand will have increased by 56% from 2010 levels by 2040 [1]. To reduce carbon emissions and fight global warming, it is essential to reduce the consumption of fossil fuels and increase the utilization of the more readily exploitable renewable energy sources (RESs) in the energy sector. RESs are often considered to be emission free and environmentally friendly energy sources. Although RESs are far better than fossil fuels, research shows that they can have adverse effects on the environment. If the whole idea of adopting RES is to save the environment, their improper handling may do the opposite. Many research articles have been published in the literature that have discussed the negative environmental impacts of a few specific RESs [2]. However, there is a lack of research that focuses on all the RESs and demonstrates their potential impacts on the environment. This paper illustrates the environmental impacts of all RESs with a SWOT analysis and provides some guidance on how to alleviate those adverse impacts.

With the arrival of the industrial revolution, the amount of greenhouse gases started to rise in the atmosphere. Over the last century, the global temperature has increased because of greenhouse gas emissions [3]. At present, the earth is getting progressively warmer over time. Extensive use of fossil fuels is one of the main reasons for global warming. Carbon dioxide (CO_2) and other greenhouse gases are released into the environment from fossil fuels-based power plants. Approximately 35% of greenhouse gases are emitted because of the existing power plants [4]. A study shows that, approximately 42% of NO_x and

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38% of SO_2 were emitted from coal-based power plants in China in 2015. Around 40% of the total greenhouse gases were produced due to coal-based power plants [5]. These gases are responsible for entrapping heat in the atmosphere which increases the global temperature. It is imperative to accept that our planet will become less livable if the temperature continues to rise at its current rate. The increased temperature melts glacier ice which increases the sea level height. Many islands as well as parts of many countries will drown, and catastrophic droughts and conflagrations will occur in many dry regions. To mitigate these problems, fast decarbonization of the power sector is required to achieve the 2 °C warming target discussed in the Paris Agreements [4,6]. Moreover, usage of alternative sources of energy are being adopted. An annual investment of US$3.5 trillion is required in the renewable and sustainable energy sector until 2050 [7]. Power plants that use natural gas emit 50% less CO_2 than that of other fossil fuel-based power plants. Hence, natural gas could be used as a transition fuel until RESs become more secure and sustainable [8]. The UN has proposed seventeen sustainable development goals for a green environment where affordable and clean energy is at seventh position. RESs are considered as emission free and are also readily accessible in nature. Fig. 1 illustrates the amount of electrical power generated by each type of RES based power plant [9]. It is evident that hydropower provides the highest proportion compared to any other RESs. Both solar PV and wind power each account for a quarter of the total share. Other RESs such as geothermal, concentrated solar thermal, ocean, and bio-power together constitute the remaining percentage which is just over 6%. The contribution of ocean power is only 0.02% although it has higher potential to increase this outcome compared to all other RESs. The utilization of RESs for electricity production throughout the world is presented in Fig. 2 [10]. Overall, many nations in Africa and the Middle East have shares less than 20% whereas many countries in Europe and South America along with Canada are above 60%. Some major countries such as the US, Mexico, China, Australia, Russia, etc., have proportions between 20 and 40%. Many countries are determined to reduce their dependence on fossil fuels and adopt RESs to protect the environment. The European Union has set a target to become the world leader in RESs by 2030 [11]. Approximately 28% of the total demand of the UK can be fulfilled by tidal energy alone [12]. The concept of an energy hub where energy can be generated, utilized, and stored is being explored in some of the published literatures [13–15].

While the use of RESs is essential for decarbonizing the power sector and to combat global warming, an obvious question arises as to whether this has any negative consequences on the environment. Research shows that many RESs have some adverse effects that are detrimental to the environment and nature. RESs are used to reduce harmful emissions for the betterment of the environment. However, the same environment can be harmed if the adverse effects of RESs are ignored. There is a dilemma where reliance on fossil fuels increases global warming and improperly regulated RESs can be detrimental for the environment.

Environmental impacts for few RESs are assessed in the literature. Impacts related to decommissioned wind turbines are demonstrated in Ref. [16]. Life cycle analysis confirms that approximately 70–80% of environmental impacts caused by wind turbines are due to the materials which are used for manufacturing purposes. A RES site selection process is discussed in Ref. [17], where economical, technical, and environmental criteria are defined. The study only focuses on photovoltaic (PV) modules and wind farms. Additionally, wave and tidal power plants are briefly discussed. In Ref. [18], various electrochemical effects on soil caused by wastewater from solar PV, wind, and biomass power plants are studied. The study presents current technologies to abate these concerns. However, it falls short in regard to focusing on other RES based power plants. Environmental impacts of biomass and wind power plants are analyzed in Ref. [19] using life cycle analysis, and the impacts are compared with each other. The study proposes that the most suitable location for a wind power plant is the desert. However, the study does not analyze other RESs.

It should be noted that many research articles in the literature which focus on the positive prospects of RESs tend to portray the negative impacts of fossils fuels on the environment. Thus, it often appears that the reduction of carbon emissions is the only solution to save the environment. Additionally, RESs are often assumed to have no demerits. The number of research papers that discuss the adverse effects of RESs is insignificant as compared to those where RESs are exalted. Hence, there should be a study where the negative impacts of all RESs are studied and discussed adequately. Therefore, this is considered as a most significant research gap that needs to be addressed to explore the full range of negative environmental impacts associated with all RESs. To the best knowledge of the authors, most studies cover the impacts of only a few RESs. In this paper, all available RESs are incorporated, and their negative impacts are discussed. The impacts of different RESs are summarized and presented in a tabular format for convenience. Finally, the proper implementation approaches of the RESs to alleviate the negative environmental impacts are discussed.

The rest of the paper is organized as follows. Harmful impacts of different RESs are described in the following sections. The terrestrial RESs are discussed from section 2 to 5 whereas sources that rely on water are investigated from section 6 to 9. Section 2 describes the impact from solar based power plants. Wind related issues are illustrated in Section 3. The subsequent section discusses biomass related concerns. Impacts caused by geothermal power plants are described in Section 5. Section 6 explains the impact caused by hydroelectric power plants. Section 7 provides insights regarding the effect of using tidal power plants. Impacts of ocean power plants are described in the next section. Effects of osmotic power plants are described in Section 9. A brief

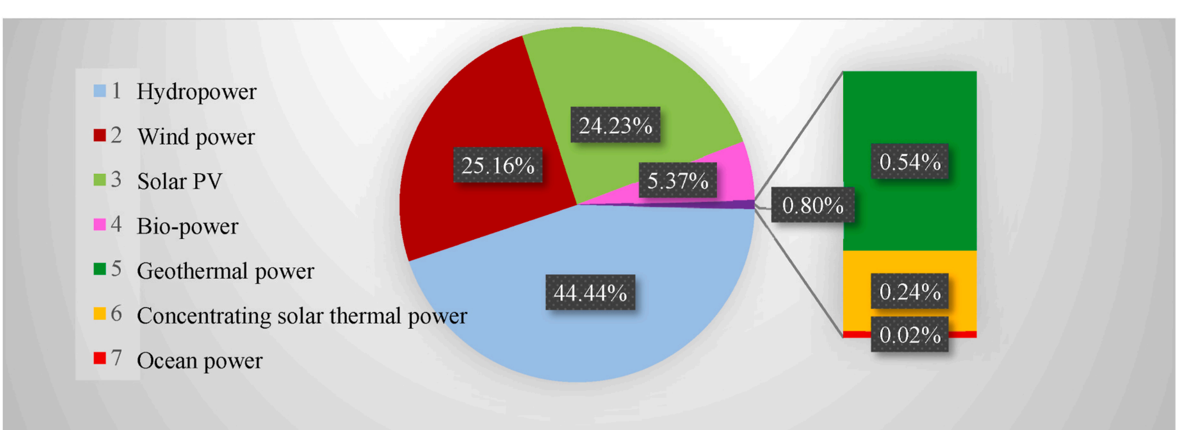


Fig. 1. Electrical power generation by RES based power plants [9].

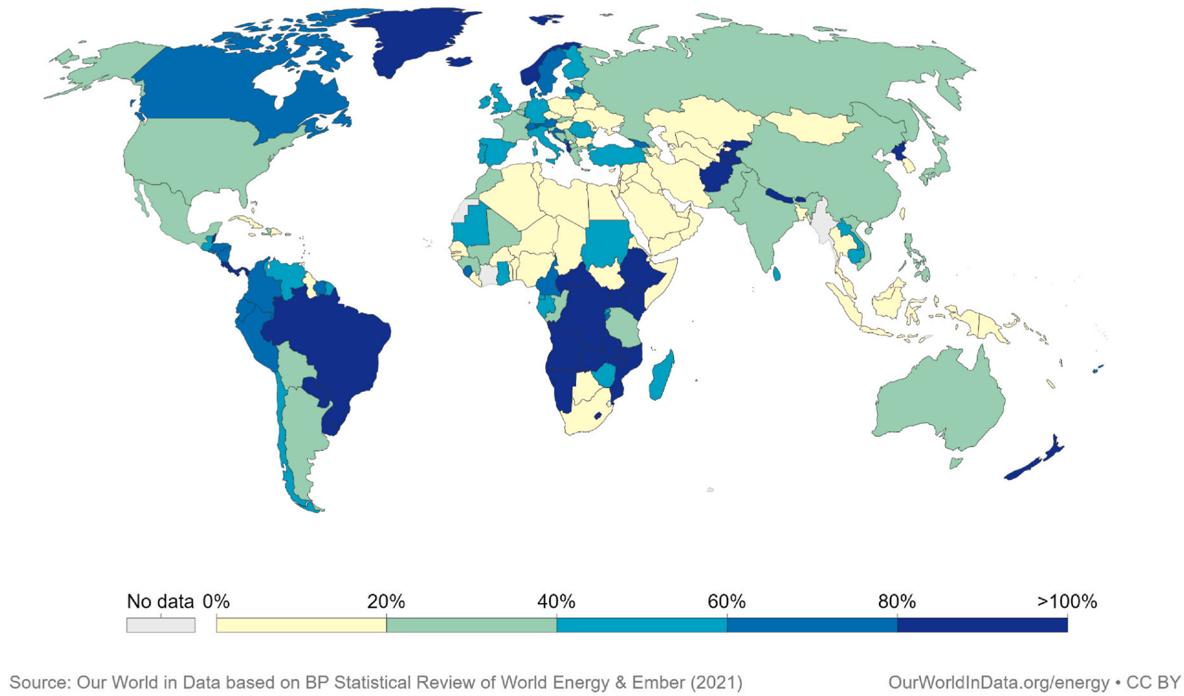


Fig. 2. Utilization of RESs throughout the world [10].

discussion of the overall situation is presented in Section 10. Section 11 concludes the paper.

2. Solar power plants

Solar energy has always been considered as clean energy, i.e., energy which is free from carbon emissions [20]. The surface of the earth receives nearly 140 PW power from the sun out of which only 36 PW can be utilized [21]. Photovoltaic (PV) and concentrated solar power (CSP) are the most remarkable techniques of harvesting energy from the sun; the latter are commonly referred to as "Concentrated solar thermal" systems. Nevertheless, literatures reveal that solar energy is not that clean [22]. The greatest disadvantage of solar energy is deemed to be its intermittent nature, i.e., not available during night or cloudy weather [23] and there are other disadvantages which affect the ecosystem [24]. The following subsections illustrate the environmental impacts of PV and CSP techniques.

2.1. Photovoltaic

A PV system converts sunlight into electricity without using any moving parts. Its maintenance cost is lower than many other RESs and it provides service for a long period. It has a simple design structure. It can generate microwatts in standalone systems and can go up to megawatts when connected at a large scale [21]. Currently the total installed capacity of solar PV systems is around 627 GW, making it the third highest power generating RES globally [9]. Solar PV cells have undergone extended research and development phases. First generation cells are made of crystalline silicon. Currently, monocrystalline silicon (mono c-Si) and polycrystalline silicon (poly c-Si) versions are prevalent. Thin film solar cells are considered as the second generation of solar PV cells. Copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (a-Si) are under the umbrella of thin film solar PV cells. Third generation cells are also made of thin films that often use inorganic material with an organometallic compound. Although there are many beneficial attributes of PV panels, research shows that there are some detrimental aspects which can harm the environment [25–28].

2.1.1. Effect on land and vegetation

To maintain the angle of the solar farm PV panels, a concrete structure is entrenched within the soil. Heat and water are not properly distributed in the soil. After the lifetime of the PV panels, the effectiveness of the soil gets diminished, and the vegetation restoration process gets hampered [29]. Furthermore, PV installations require a large land area. Approximately 3.5–10 acres of land are required for a utility level PV installation. Using those areas could potentially reduce cultivable lands. However, it would be an effective option to use neglected mining areas, contaminated brownfields, and transport corridors rather than cultivable lands [30]. Extracting energy from solar radiation can cause harm to small shrubs or vegetation. It is found that decreased vegetation increases dust. If dust accumulates in the near atmosphere, then it reduces the amount of solar radiation on panels or concentrator mirrors. The deposition of dust can significantly affect the performance of solar power generation systems. In a desert in Egypt, solar panels exposed to dust have had their power generation reduced by 35%. Moreover, increase in dust will also degrade air quality which will eventually create health issues [31].

2.1.2. Effect on wildlife

Solar PV affects the habitat of nearby species. In the Mojave Desert of California, tortoises dig burrows for their shelter which are also used by burrowing owls. When animals are removed from their habitat to build solar farms, they become unable to be facilitated in the surrounding ecosystem. Thus, the flora and fauna do not find their disturbed habitat livable. Moreover, many birds have died there because of the heat caused by solar modules or mirrors [25].

2.1.3. Toxic materials

Moreover, various flammable and toxic materials are produced during the construction of the PV panels which increases the risks associated with health and safety. In healthy operations, PVs do not emit radioactive materials and do not release liquid or gaseous pollutants. In individual CdTe or CIGS modules, small amounts of toxic materials are available which are not of much concern. However, in the large integration of PV modules, release of such toxic materials can cause havoc to occupational or public health [32]. If PV modules are not operated properly, then there is a small risk of catching fire due to the presence of some flammable gases. In the case of large plants where massive numbers of PV-arrays are placed, a slight maloperation may result in a serious fire. Moreover, the fluid which carries heat may pollute the nearby waterways if it leaks [32]. During the decommissioning stage of PV modules, certain toxic materials such as silica, arsenic, and cadmium dusts, if not handled properly, could affect public health. If silica dust gets inhaled for a long time, then it will create silicosis which produces scar tissues in the lungs [31].

In the most prominent technology for solar energy extraction, crystalline mineral quartz, also known as silicon dioxide, is used to create solar cells. Acquisition of the large quantities of quartz needed is difficult as the mineral is found mostly in mines and the miners have a high chance of getting silicosis. After a refining process, metallurgical grade silicon is created from quartz. This method requires large furnaces which need enormous amounts of energy to keep them heated. This heat is produced from non-renewable energy sources which emit CO_2. Afterwards, this form of silicon is further purified into what is known as polysilicon. In this process, a toxic material called silicon tetrachloride is formed as a byproduct. Rather than obtaining raw silica from the mines, silicon tetrachloride can easily be recycled to create more polysilicon. Although the latter method requires less energy than the former, the equipment for recycling is expensive. Hence, this toxic silicon tetrachloride is often dumped in the water or soil. As a result, hydrochloric acid is formed by the reaction $SiCl_4 + 2H_2O = 4HCl + SiO_2$. The increased toxicity of the soil makes its further use less effective [26]. In recent years, thin film solar cells are being used commonly. These cells have a number of toxic materials in them such as CdTe, CIGS, and gallium arsenide. Hence, proper care should be taken while disposing of these materials [30]. Solar panels can easily be damaged if they experience stormy weather. Hence, not only do the damaged solar panels need to be replaced, but careful measures must also be taken so that toxic materials do not get released into the open environment.

2.1.4. Effect on human health

Single walled carbon nanotube based solar cells offer high benefits. However, there are potential disadvantages which can become a cause of many human diseases. One major issue is that these solar cells create human respiratory disorders. During the manufacturing phase, particulates are created which are responsible for this disease. With the increased usage of these nanoparticles, the chances of getting exposed to them also becomes higher. If the particle size is decreased, then the surface area will increase for the same amount of mass [28]. Indium doped Tin Oxide (ITO) is used for coating of the solar panel glass and it also weighs around 87% of the total solar glass. The main element of ITO is indium which plays a vital role in human toxicity mainly because of the use of sulfuric acid leachate in its recovery stage [27]. It can also cause ozone layer depletion, acidification of the environment, eutrophication, etc. Moreover, the impact caused by ITO can significantly be reduced if it is supplanted by Florin doped Tin Oxide [27].

2.1.5. Greenhouse gas emissions

Research reveals that, during the whole lifecycle of PV cells, a large amount of carbon gets released. The carbon footprints are generated from the manufacturing process, transportation, and then during their installation. During the rest of their life, carbon emissions can be caused from maintenance and disassembling of the PV cells. Moreover, it is estimated that around 32–82g CO_2 per kWh gets emitted from the total lifespan of a PV system [30]. A contemporary solar PV panel usually lasts for approximately 25–30 years [33].

2.1.6. Dependency on batteries

In standalone PV systems, the whole demand is fulfilled by PVs rather than the utility grid. During daytime, PVs are used to supply power to the loads and at the same time they can charge the batteries. PVs are unable to produce power at night due to the unavailability of sunlight, hence the batteries are used to supply the loads. In these standalone PV systems, batteries incorporate heavy metals which adversely affect the environment [32]. The lifespan of these batteries is around 10 years after which their performance degrades significantly. Since most companies provide approximately 10 years of warranty for their batteries, they must be replaced 2 or 3 times during the lifespan of solar PVs [34].

Even though there are many environmental impacts caused by solar PV, literature show that there are many positive effects on the environment as well. During the operational period of PVs, various gases such as SO_2, NO_X, CO_2 are not emitted. For 1 kWh of electrical energy production through PVs, it is estimated that approximately 0.53 kg of CO_2 can be prevented from being emitted into the environment [35]. The decline of the generation of gases such as SO_2 and NO_X suppresses the incidence of various diseases. For instance, if the total PV generation becomes 70–100 GW, the number of death cases will be reduced by 300–440. Moreover, Chronic Bronchitis cases will be reduced by 205–301 and heart attacks will be reduced by 495–720. Other respiratory problems such as Asthma and Pneumonia cases will be reduced by 125–187. As for cardiovascular problems, the number of cases will be decreased by 116–160 [21]. In Ref. [32], it is mentioned that architects appreciate the placement of PV materials on rooftops which can improve the aesthetics of any building and the clients are pleased to have an alternative energy source.

In low solar irradiation regions, the environmental impacts of residential 3 kWp PV systems are assessed in Ref. [36] through life cycle analysis. Investigation is conducted on six different cells, viz. a-Si, mono c-Si, poly c-Si, ribbon silicon, CIGS, and CdTe. It is found that carbon emissions for PV systems are 10 times lower than for coal power plants, however, the carbon emissions for wind or nuclear power plants are 4 times higher compared to PV power plants [36]. From the results of the Eco-indicator 99 impact assessment tool, a comparison among six PV cells is made which shows that CIGS is better than the others in terms of environmental impact [36]. Carbon emissions of CIGS is slightly higher than CdTe and ribbon Si.

With the help of Eco-indicator 99, two perovskite solar systems are considered in Ref. [37] for life cycle assessment. Energy payback time and carbon emission levels were also calculated. One of the perovskites was made of ZnO thin film, a silver cathode, and ITO glass whereas the other one consisted of mesoporous TiO_2 scaffold, a gold cathode and FTO glass. Results from life cycle assessment of the proposed modules are compared with conventional PV modules and with an organic PV module. It is shown that overall, the ZnO module creates less impact on the environment as compared to all other modules. However, in some cases such as stratospheric ozone depletion, photochemical oxidation, and ionizing radiation, TiO_2 modules show remarkably fewer negative impacts than ZnO. For the proposed modules, the actual values of these categories are identified as harmless for the environment.

Moreover, the ZnO module surpasses the TiO_2 module in three damage categories, namely resources, human health, and ecosystem quality. The most successful PV cell in this case is organic PV which shows the least impact in these categories. Finally, all PV modules are compared against their CO_2 emissions level. Surprisingly, perovskite modules demonstrate higher emissions, and CdTe shows the least emissions as compared to conventional modules [37]. The short lifespan of perovskite modules compared to others is the main reason for this result. Increase in lifespan will reduce the emissions however, it would be far less than that of conventional modules. Inclusion of CIGS modules would have completely fulfilled the knowledge gap.

Fig. 3 shows the classification of various types of solar cells with originating year and their efficiency [38]. The cells are classified in three groups according to their generations. The first and second generations originated from 1976 to 2001. The efficiency of these cells ranges from 21.2% to 27.6% for the first generation and 14%–23.4% for the second generation. The third generation originated since 1991 and the efficiency is between 12.3% and 29.1%. It is expected that the third

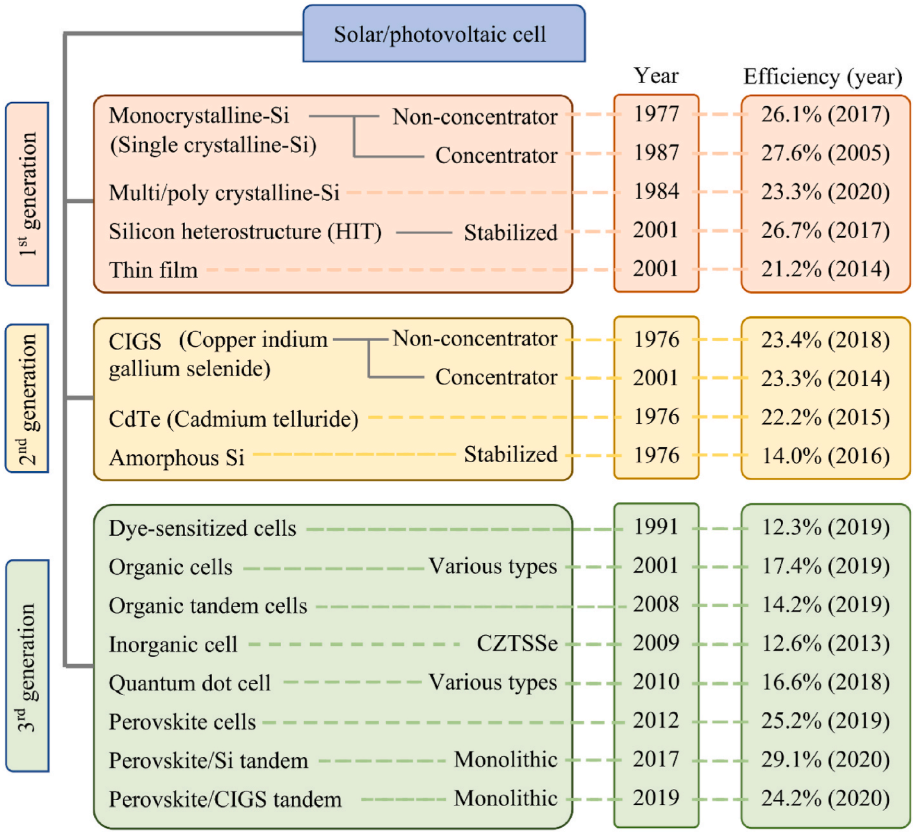


Fig. 3. Classification of solar cells [38].

generation will outperform others in terms of efficiency, stability, and cost. Table 1 illustrates the comprehensive SWOT analysis outcomes of PV power plants.

Solar PV technology is a mature RES that directly harness the energy from the sun. It can easily be installed in most of the areas. While installing PV panels, careful consideration must be given so that they does not affect the wildlife and vegetation process. Government should impose policies to monitor and capture the emissions that occur during the lifetime of PVs. Batteries should be replaced with more environment friendly energy storage technology. State of the art technologies should be incorporated in the mining process of raw materials so that effects on human health gets reduced.

2.2. Concentrated solar power

In concentrated solar thermal power plants, large numbers of reflecting devices such as mirrors are used to collect the sunlight by focusing them onto a heat accumulator. High level temperatures are developed which in turn can convert water into steam. The steam is used to propel steam turbines to produce electricity. Fundamentally, this is a RES which is free from carbon production during operation as it utilizes the sun. Mass level implementation can effectively reduce the use of fossil fuels and thus reduce overall carbon emissions. As of 2019, CSP has approximately 6.2 GW installed power capacity worldwide with around 21 GWh of thermal storage systems operated with it. Thermal storage ensures delivery of continuous power supply [9]. According to a report from the World Bank, the economic lifespan of CSP is approximately 25–30 years [39].

There are different types of CSP such as parabolic trough-, linear Fresnel-, and tower-based CSPs. In parabolic trough, a parabolic mirror or reflector is used to focus sunlight on tubes that carry fluid. The temperature reaches a peak of 390 °C. Molten salts, silicon-based fluids, and synthetic oils are used as the heat conducting fluid [39]. Leakage of this fluid will be detrimental to the nature. Tower based CSPs use a lot of reflectors, also known as facets, to concentrate the sunlight to a single tower where the temperature often reaches 565 °C [39]. Death of birds may occur if they come near the tower. Molten salts are used as thermal storage in emerging tower type CSPs. Molten salts work well under 600 °C. If the temperature rises beyond this threshold, they start to decompose. Moreover, these salts react when they are exposed to piping materials [40]. In Ref. [41], it is mentioned that concrete based thermal storage systems should help reduce the potential environmental impacts. Results of [42] reveal that molten salt-based energy storage systems reduce the overall environmental impact; however, salts that are synthesized have higher impacts than those that come from natural mines. Further research is required to identify the environmental impact from these salts. The third type of CSP is linear Fresnel which incorporates flat mirrors. It operates at 150–360 °C which is lower compared to other types. This reduces the bird fatality rate. To produce 1 MW of power, it needs less than 1 ha of land [39]. Even though linear Fresnel CSP is not as efficient as other CSPs, its impact on land and chances of accidents are quite less, making it suitable for the environment. Although the CSP system may seem basic, many studies show that there are harmful consequences on the environment.

2.2.1. Disturbance

A CSP hampers the visual aesthetics of an area. In addition to that, reflection of light could easily distract the passerby and/or the local drivers which can cause traffic disruption or even accidents. Construction of these plants should be handled carefully, and proper standards should be maintained so as to prevent accidents. Furthermore, a significant amount of investment and large space is required to facilitate construction of the plant. Nearly 4–16.5 acres of land are needed [30, 43].

Table 1
SWOT analysis of PV power plants.

Traits	PV
Strength	• Converts power from the sun without any intermediate stage. • Total emission is zero during operation. • Does not have any moving parts. • Power ranges from microwatt to megawatt. • Third largest RES with an installed capacity of 627 GW [9].
Weakness	• Installation cost is high. • Effective lifespan is around 25–30 years [33]. • Large land area is required [30]. • Needs high amount of water for cleaning and cooling [31]. • During the whole lifetime, around 32–82 g/kWh CO_2 gets released in the environment [30]. • Standalone or most PV systems require batteries that are harmful for the environment [32]. • The amount of output power fluctuates due to the intensity of solar irradiation. • Initial cost of implementing a PV system is high.
Opportunity	• Has a simple design. • Placing PV modules on rooftop increases household aesthetics [32]. • Many diseases such as asthma, pneumonia, and cardiovascular cases are alleviated [21]. • Mining areas, contaminated brownfields, and transport corridors are excellent locations for the placement of solar PVs [30]. • Silicon tetrachloride can be recycled to produce polysilicon [26].
Threat	• Natural state of soil is disturbed by the use of PV modules [29]. • Since sunlight is used for power production, soil effectiveness is reduced, and vegetation restoration processes are hindered [25,29, 32]. • Flammable toxic materials are produced in large integration of PV which can result in accidents [32]. • PVs are responsible for toxification which causes harm to public health [32]. • Water resources are contaminated by the toxic waste of solar PVs [26,32]. • The habitat of burrowing owls and other wild animals are affected adversely [25]. • Small particles from decommissioning of PVs degrades air quality [25,30]. • Land occupation by PV systems is harmful for revegetation process [25,29]. • Can get damaged by storms. • Adds to ozone layer depletion [27]. • Can cause eutrophication in nearby water sources [27]. • PVs rely on batteries which are costly and harmful for the environment [32].

2.2.2. *Bird fatality*

One of the most noteworthy issues regarding CSPs in dry regions is the death of birds [43]. Some species face difficulties in moving from one place to another due to the presence of a CSP. Even though a number of species can be moved to a new habitat, some species especially birds cannot be shifted. Over a period of 40 weeks, 70 birds have been found dead due to the 10 MW CSP in California. Among these deaths, around 81% occurred because of direct collision with the heliostat. The remaining 19% have been burnt because of the standby position of the heliostat [31].

2.2.3. *Water pollution*

CSPs need water for both cooling and dust cleaning purposes. Approximately 60–99% of the total water consumption is used for cleaning. As for cooling, they utilize either wet cooling or dry cooling [31]. For this purpose, CSPs require approximately 600–650 gallons of water per MWh of energy. However, these waters are not consumed, rather they are reused [30]. In arid places, dry cooling is more preferable than wet cooling due to paucity of water. However, for a time period of 20 years, the initial setup cost for a dry cooling system is 87–227% higher than the wet cooling system. Disposal of chemicals, dust particles, coolants, and herbicides can cause water pollution to deep water reservoirs [31]. CSP systems emit 36–91g CO_2/kWh which is slightly higher than PV systems but substantially lower than fossil fuel systems [30]. Different cooling techniques may become harmful from time to time. One of the most common cooling techniques is absorption cooling in which a vapor compression machine is used. Refrigerants such as ammonia and lithium bromide with water are expanded under low temperature and pressure. The thermal discharge of a CSP degrades the water resources. Release of these harmful chemicals could create water pollution [32]. Many CSPs accidently release various gases from different vaporized coolants and eventually could cause fire. These gases could affect public safety and health. Careful measures should be taken for chemical release.

Using a CSP with a seawater desalination plant can be beneficial for the environment as shown in Ref. [44] where a study was conducted on seven cities in which scarcity of fresh water was observed. Solar thermal power was used to treat seawater and brackish water. Results indicated that the average carbon emission of these plants was 4.32 kg CO_2 eq./m^3. The study showed that the proposed plant reduces CO_2 emissions to 47% of those from a traditional plant [23]. Table 2 illustrates the comprehensive SWOT analysis outcomes of CSP power plants.

CSP is a prominent RES technology that utilizes the energy from the sun to produce power. Its environmental impacts are less than that of solar PVs; hence, the power generation capacity should be increased. CSPs should be built in areas with less population so that disturbance, traffic issues, and accidents can be avoided. More research is required to eliminate the chances of bird fatality, and proper steps should be taken to capture the chemical disposal due to cooling so as to reduce water pollution.

3. Wind power plants

Wind energy is considered to be clean and eco-friendly. It is one of the oldest RESs, and much research has already been performed on it. It can easily be placed in both terrestrial and aquatic environments. It utilizes the speed of wind to generate electrical power with the help of a turbine. The blades of a wind turbine rotate if sufficient wind speed is available. The rotor of an electrical generator is coupled with a turbine and thus the rotary movement is utilized to generate electrical power. Based on the axis of their rotation, wind turbines are classified into two categories such as vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). HAWTs are mostly used to utilize wind energy due to their higher power capacity whereas VAWTs are receiving attention because of their ability to capture wind from any direction

Table 2
SWOT analysis of CSP power plants.

Traits	CSP
Strength	• Uses the sun to propel a steam turbine. • Currently, the installed power capacity is in the gigawatt range (6.2 GW) [9].
Weakness	• Economic lifespan is around 25–30 years [39]. • Requires many reflecting materials. • Requires large land area [30]. • Increases nearby bird fatality [31]. • CSP releases around 36–91 g/kWh CO_2 in the environment throughout its lifetime [30]. • Unable to produce power during night and cloudy days. • High amount of water is required for cleaning and cooling [31].
Opportunity	• Can be coupled with a seawater or brackish water treatment plant to get environmental benefits. • Can be used with thermal storage system for continuity of supply.
Threat	• Reflections can cause disturbance to nearby people [43]. • CSPs are susceptible to storms. • Wild animals and their habitat are disturbed by the installation of this plant [31]. • Noise from the operation of turbines creates disturbance to local residents. • Water for cleaning and cooling purposes can pollute nearby sources [32]. • Visual aesthetics are hampered by the presence of CSP [30].

[45]. Wind turbines produce around 651 GW of electrical power worldwide which gives it second position right after hydropower [9]. This large RES output significantly reduces carbon emissions, however, there are some studies which report several negative environmental impacts of wind turbines [46–48].

3.1. Noise and disturbance

One of the most reported issues regarding the wind turbine is noise. Two different types of noise are found, namely aerodynamic and mechanical noise. The mechanical noise can be alleviated by incorporating sound insulation. The aerodynamic noise can create headaches, hearing loss, and sleep disorders. It may even hamper the vestibular system. The intensity of this noise is higher near the base of the wind turbine. Another issue regarding wind turbines is that they create visual impacts. This distorts natural aesthetics and hinders local tourism [46]. Stormy weather makes wind farms vulnerable since wind turbines are placed at an extremely high altitude. Accidents associated with a large wind turbine can be catastrophic.

3.2. Bird fatality

Another problem is related to birds and their habitat. Birds can be injured or killed when they collide with the blades of a wind turbine. Moreover, lights near the wind farm attract nearby birds which increases the chance of collision. However, there is a debate on this issue because more birds are killed due to deforestation and urbanization. It is reported that, for an installed capacity of 1000 MW of wind turbines, only 20 birds die per year. In contrast, around 1500 birds per year die because of hunters. In addition to that, vehicle collision and electrification cause another 2000 deaths of birds per year. For every 250 deaths caused by humans, only one bird dies due to wind turbines [47].

The abatement of several environmental impacts caused by wind turbines are discussed in literature. In Ref. [48], one out of three blades of a turbine were colored black in a study to see if birds can detect the presence of this more visible obstacle. Fig. 4 illustrates the difference between conventional and the proposed wind turbines. The investigation was conducted at the Smøla wind power plant in Norway and the study took eleven years spanning from 2006 to 2016. From the beginning of 2006, highly trained search dogs were deployed who would lie down near a bird carcass. There are 68 turbines in the farm of which only 8 turbines, one pair at 4 different locations, were selected for investigation. After seven and a half years, in August 2013, one of the turbines from each pair had one of its three blades painted black. During these eleven years, 9557 turbine inspections were conducted and a total of 464 carcasses were found. Moreover, 1275 individual inspections took place for the 8 test turbines. The annual fatality report shows an average decrease of 71.9% for painted turbines with respect to the neighboring unpainted turbines [48]. Furthermore, bird fatality rates at different seasons were analyzed for the said eight turbines. For painted turbines, fatality rates were remarkably reduced during spring and autumn, whereas the opposite was observed during summer. It is mentioned that the seasonal fatality rates are reduced by 70.0%. The painted turbines significantly reduced the number of death of raptors.

3.3. Light-shadow effect

During operation of a wind turbine, sunlight may reflect off the blades. This flashing effect may create disturbance to nearby inhabitants. Using a non-reflective paint coating on the blades can abate this problem. A similar problem is caused by the shadows of the blades when they are cast on static objects. This is known as flicker/disco effect. More research is needed to fully understand the adverse effects of these flash and flicker effects on aquatic creatures [47].

3.4. Effect on aquatic habitat

The construction of wind turbines in offshore areas increases the turbidity of water which impedes the sunlight from reaching the seabed. This will have an effect on the benthic plants which will result in the alteration of benthic environments. The base of the offshore wind turbine acts as an artificial reef which affects biodiversity. Near the base area of offshore wind turbines, biodiversity of the protozoan community is found to not be as much as that of the benthic community. Furthermore, the communication of marine mammals such as dolphins can get obstructed due to the presence of electromagnetic fields of offshore wind

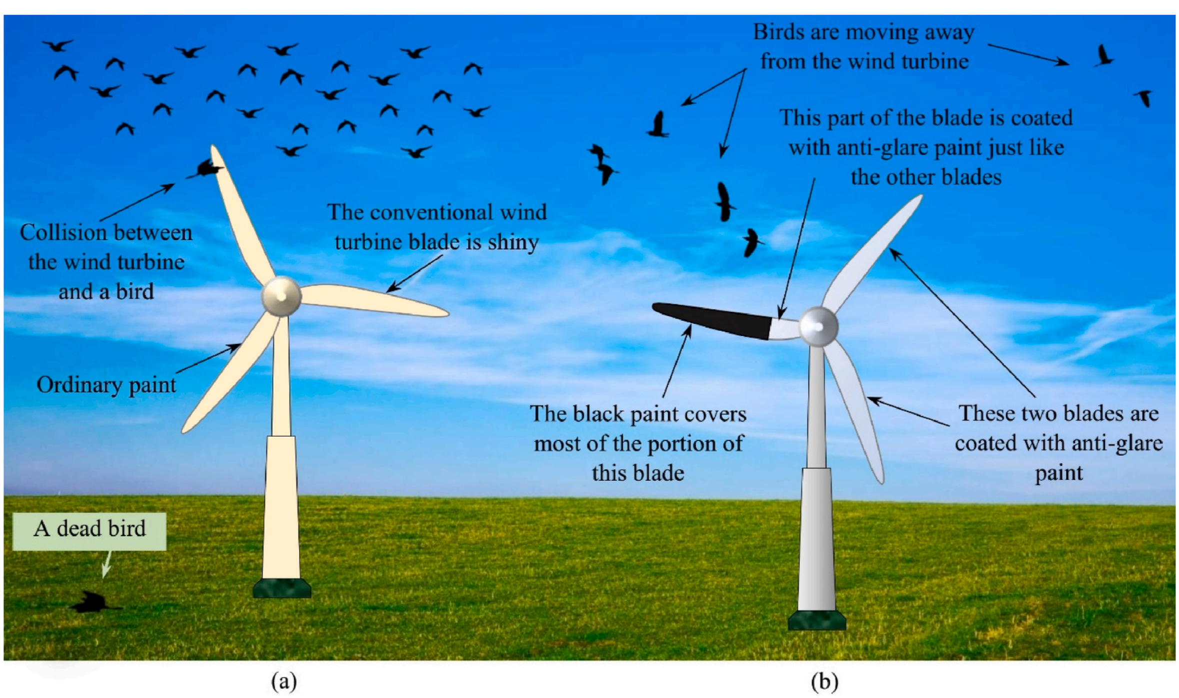


Fig. 4. Illustration of the interaction between birds and wind turbine generators: (a) conventional; and (b) proposed [48].

farms. Moreover, noise related to construction can also disturb nearby creatures. During the maintenance phase, lubricant oil and other debris can pollute the aquatic environment [47].

3.5. Wake effect

Another potential issue is the wake effect of wind turbines. After passing through a turbine, the wind loses its energy and its speed decreases. This turbulent downstream wind, also known as the wake of the wind turbine, increases the dynamic mechanical burden on other wind turbines [49]. This will decrease the overall lifespan of wind turbines while reducing the output power. For this reason, the overall emission per kWh energy will increase. Presently, different measures are being adopted to mitigate the impact of wake effect on power generation. Since VAWTs can produce power from turbulent winds, they should be placed behind HAWTs to mitigate the wake effect. It is believed that wake effect may influence the climate. Due to the lack of data, more research is needed to understand the potential impact of wake effect on the environment [47]. Devices that harness marine wind energy are an obstacle for aquatic creatures. Installation of offshore wind turbines will degrade the nearby habitat. For the installation of the turbines, pile drivers are required, which will mainly affect species that are acoustically sensitive.

A large onshore wind farm requires deforestation which leads to soil erosion. Oil and wastewater can seep deep underground and further pollute the soil. Moreover, large machinery required for installation can disrupt the ecological harmony. It is recommended to replant trees after establishing a wind farm [47]. Life cycle assessment of wind farms is performed in Ref. [16] where the decommissioning process and environmental impacts are analyzed. Recycling the materials will reduce the burden on natural resources which can be used in the future. Results show that recycling of a 60 MW wind farm can decrease around 7351 metric ton of CO_2. The material recycling can reduce around 70–80% of environmental impacts from a wind turbine. Table 3 demonstrates an overall SWOT analysis of wind turbines.

Having the second largest power generating capacity, wind turbines can easily be constructed, operated, and recycled, making them more environmentally friendly than most other RESs. The noise and flashing effects can easily be minimized by using rubber materials on the rotor and painting the blades with non-reflecting colors. Bird fatality can be reduced by painting one blade with black color. Turbulent wind created by the wake effect should be utilized through the use of VAWT.

Table 3
SWOT analysis of wind turbines.

Traits	Features
Strength	• Have the second largest power generating capacity in the world [9]. • Construction is simple. • Recycling process of wind turbine is easy [16].
Weakness	• Noise is generated from installation and maintenance of wind turbine [46]. • Visual disturbance is caused by wind turbine [46]. • Flashing and flickering effects cause disturbance [47]. • Large accidents can occur due to storms. • Output power fluctuates due to the variable speed of wind.
Opportunity	• Can be installed on both offshore and onshore area. • Painting one blade in black reduces bird fatality by over 70% [48]. • Environmental impacts are reduced through recycling [16]. • Nearly 7351 metric ton of CO_2 emission can be reduced through recycling [16].
Threat	• Can create headaches, hearing loss, and sleep disorders [47]. • Vestibular system can get damaged by continuous noise [47]. • Natural aesthetics are spoiled [46]. • Local tourism potential is affected by the installation of wind turbine [46]. • Small number of birds get killed by the blades [47]. • Offshore installation creates seabed disturbance which results in biodiversity and alteration of benthic habitats [47] • Electromagnetic fields can disrupt the communication between many marine mammals [47] • Debris and lubricating oil can pollute nearby environment [47] • Wind farm requires deforestation and causes soil erosion [47]

4. Biomass power plants

Biomass is one of the oldest sources of energy. For centuries, people have relied on wood to cook their meals and to heat their houses. Currently, biomass is processed from organic materials such as wood residue, ethanol, manure, switchgrass, wheat straw, human waste, etc., which are usually burned or dumped in landfills. Alternatively, biomass such as miscanthus, maize, millet, etc., can be grown for the sole purpose of energy production. The key chemical compound of biomass is hydrocarbon. The stored chemical energy is converted into electrical energy. Traditional coal power plants can be used to burn biomass for the production of electricity. Since its supply is not limited in nature, it is considered as a renewable energy source. However, research shows that biomass power plants are responsible for some environmental impacts. The following subsections illustrate these impacts.

4.1. Burning wood

The use of fossil fuels can be decreased by adopting charcoal, wood residues, and wood for cooking and heating purposes. Even though using wood will reduce the CO_2 emissions, the smoke from burning these will emit contaminants such as carbon monoxide. In many poor countries, people use charcoal and wood for cooking and heating. If trees are consumed at an excessively fast rate, it will cause deforestation. Hence, it is essential to use modern wood burning or pellet stoves to reduce toxic emissions and it is necessary to plant fast growing trees to preclude deforestation [50].

4.2. Burning waste

Urban solid wastes can be burned to produce energy which will reduce the amount of garbage inundating landfills. Nevertheless, burning these wastes will produce chemicals which are detrimental for nature. There are emissions controlling devices such as electrostatic precipitators, fabric filters, and scrubbers to trap pollutants of the air. In most waste to energy generating units, wastes are burned at approximately 1800 °F to 2000 °F (982 °C–1093 °C) which converts the wastes into less harmful chemicals. Moreover, acids that are present in the emissions are neutralized with the help of some liquid chemical sprays [50].

4.3. Biogas

Biogas primarily consists of methane and carbon dioxide which is found in livestock manure processing schemes, waste landfills, and sewage treatment plants. Although biogas itself includes methane, energy is extracted from it by burning it and then converting it into electricity. Hence, this will reduce the overall greenhouse gas emissions [50].

4.4. Liquid biofuels

Ethanol and biodiesel are considered as biofuels which can be used as an alternative to conventional transportation fuels. Usually, sugar canes and corns are used to produce biofuels. In 2007, the US government initiated a scheme to utilize 136 billion liters of biofuels by 2022. Hence, most of the petroleum sold in the US has a certain amount of ethanol. Even though biofuels are considered to be carbon neutral for consuming CO_2 during the growing stage and releasing it during the burning stage, a large amount of land is required to produce these energy crops which creates pressure on food crops. Moreover, a large space is also essential to store these crops before converting them into energy. Ethanol and petroleum ethanol blends create less emissions. The octane rating of these fuels is higher than conventional refined oils. However, ozone and smog which are harmful to nature are emitted due to evaporation from fuel tanks. Hence, petroleum needs to be processed properly before mixing ethanol to reduce these emissions. On the other hand, biodiesel emits less carbon monoxide, particulate matter, sulfur oxides, and other unburned hydrocarbons. Nevertheless, the level of nitrogen oxide emission is higher than petroleum diesel [50].

4.4.1. Deforestation and farming

The energy crops and food crops share similar environmental effects in terms of watering, erosion, and pest control. To grow energy crops at a mass level, many forest trees need to be cut down. Hence, deforestation will eventually increase greenhouse gases [51]. Moreover, these crops are transported to the energy plant using heavy vehicles which rely on fossil fuels.

4.4.2. Water use

Water resources are disrupted by coal and nuclear plants. As for biomass plants, water requirements are comparable to other electricity plants. Approximately 20 k–50 k gallons (75,708–189,271 L) are required to generate 1 MWh of energy. This heated water is discharged back into the source which will adversely affect the ecosystem. Moreover, the surplus of nutrients from the energy crops will flow into the water source. As a result, eutrophication may occur in those water sources. Furthermore, energy crops will require more water if they are grown in places having low rainfall [51].

4.4.3. Air emissions

Even though biomass is regarded as a clean renewable energy source, it releases harmful toxicants during combustion. Different feedstock or livestock have different levels of emissions. However, carbon monoxide, sulfur dioxide, and nitrogen oxide are common. Additionally, biomass wastes are malodorous. Electrostatic precipitators, gasification systems, and filters must be incorporated to mitigate this concern. On the other hand, cleaner biomass sources can also be used to reduce air emissions. Transportation of wastes from remote locations to the energy plant will leave a carbon footprint [51].

Life cycle analysis results of 14 biomass power plants are presented in Ref. [52] where two factors are identified that are responsible for emitting CO_2. First is the origin of the feedstock, and the other factor is the portion of sawmill wood chip used in the feedstock. These impacts are finally related to human health and ecological damage. Woodchip from sawmills and forests are used as feedstock. The power plants are categorized into two groups. Six small-sized power plants have a capacity of less than 1 MW whereas the medium-sized ones range from 1 MW to 3 MW. Small power plants have the highest impacts on nature. Most often these small power plants buy woodchips from different countries resulting in higher carbon emissions due to transportation. The medium sized power plants buy woodchip from local forests or sawmills. Hence, these show a lower impact on human health, ecosystem, and resources. A short wood supply chain is suggested by many researchers for mitigating this problem. The range of carbon emission is 14.93–90.70g CO_2 eq/MJ with an average emission of 45.84g CO_2 eq/MJ. A swot analysis of biomass power plants is shown in Table 4.

Being one of the most ancient RESs that are still in use, biomass technology can produce power from organic materials, abundantly available in nature. It can use the existing infrastructure of fossil fuel-based technology. Like PVs, biomass-based power plants require large portions of land to grow energy crops, creating pressure on food crops. Greenhouse gas emission along with toxic chemical discharge should be monitored carefully to protect the nature. Moreover, since biomass-based power plants causes deforestation, area of land, and ttrees should be planted as compensation.

Table 4
SWOT analysis of biomass power plants.

Traits	Features
Strength	• Produces electricity through greenhouse gases such as methane and carbon dioxide. • Biodiesel emits less greenhouse gases.
Weakness	• Burning wood residue, wood, and charcoal will emit carbon monoxide [50]. • Methane and carbon dioxide are present in biogas [50]. • Ozone and smog are emitted from machines that use biofuel [50]. • Level of nitrogen oxide emission is higher than from petroleum diesel [50]. • 20 k–50 k gallons (75,708–189,271 L) of water is required to harness 1 MWh of energy [51]. • Transportation of energy crops will leave carbon footprints behind [51]. • Unpleasant smell [51].
Opportunity	• Existing coal power plants can be utilized to generate electricity from biomass. • Biomass is abundant in nature. • Biomass energy can be used or stored as required.
Threat	• Urban solid wastes might have toxic chemicals that are harmful if burned as fuel [50]. • Average carbon emission is 45.84g CO_2 eq/MJ. • Large land area is required for planting feedstock [50]. • More consumption of trees causes deforestation which eventually speeds up global warming [50,51]. • More land is required to produce biofuel, hence pressure on food crops increases [50]. • When heated wastewater returns to its source, it disturbs the ecosystem [51]. • Wastewater will carry nutrients of energy crops which will cause eutrophication [51]. • Use of pest control for energy crops is harmful for the environment [51]. • Similar to food crops, feedstock of biomass can create erosion [51].

5. Geothermal power plants

Geothermal power plants (GPPs) utilize the thermal energy stored in the outer crust of the earth. At around 300–8000 m down in the earth, there are reservoirs where water or other geothermal fluids are used to capture the geothermal energy. This energy can be used directly for space heating. Emissions from this type of power plant are often extremely low [53]. As of 2019, approximately 95 TWh of electrical energy is harnessed through GPPs. The total installed capacity of GPPs is nearly 13.9 GW. In recent years, direct utilization of geothermal energy increased by 8% and most of this energy is used for space heating. Even though geothermal energy is available all the time, it can only be extracted from a few places on earth. Kenya, Indonesia, Turkey, and a few other countries have recently installed GPPs [9].

5.1. Greenhouse gas emission

Research outcomes show that GPP wastes contain several greenhouse gases such as CO_2, CH_4, H_2S, NH_3, etc. Approximately 380–1045 kg of CO_2 eq/MWh is produced through GPPs which contributes to global warming. Moreover, acidification of the environment occurs as GPPs produce around 0.1–44.8 kg of SO_2 eq/MWh. Furthermore, GPPs contribute to human toxicity by producing 1.1–31.6 kg of 1.4 DB eq/MWh. Additionally, it is reported that the GPP at Italy's Mount Amiata emits approximately 0.086–28.94kg/MWh of ammonia. Traces of chromium, selenium, antimony, arsenic, and mercury can also be found in some GPPs [53]. The range of global warming potential for the GPP at Amiata is around 380–1045 kg CO_2 eq/MWh with an average of 693 kg CO_2 eq/MWh. However, the average values in the case of gas based and coal-based power plants are 640 and 1068 kg CO_2 eq/MWh, respectively. Hence, the impacts of a GPP are comparable to other fossil fuel-based power plants [53].

A study in Ref. [54] shows that the amount of emissions from GPPs are very much case specific. One of the main reasons for this variance is because of varying diesel consumption for drilling. Environmental impacts are strongly related to the drilling technology and its duration of use. The subsurface properties of different locations are different; hence the drilling time, depth, and the number of boreholes vary from site to site. Moreover, risk associated to seismicity is another concern. It is reported that, after six days of the hydraulic stimulation in a planned GPP at Basel, seismic events were observed which reached the Richter magnitude of 3.4. It is advised to use electrical or thermal spallation drilling instead of diesel-based drilling to mitigate the environmental impacts. The number of additional boreholes should be determined prior to installation so that emissions are mitigated by sustainable power generation. Borehole length of 90 km will create less environmental impacts [54].

5.2. Acidification and toxicity

The acidification potential of the GPP at Amiata ranges from 0.1 to 44.8 kg SO_2 eq/MWh with the median at 12.5 kg SO_2 eq/MWh. In the case of gas and coal power energy sources, the average value is 0.6 kg and 5.1 kg SO_2 eq/MWh, respectively. Hence, the effects of acidification caused by GPPs are alarming [53]. As for human toxicity potential, the average value for a GPP is 5.9 kg of 1.4 DB eq/MWh. On the other hand, the average human toxicity potentials for gas and coal dependent power plants are 69.4 kg and 87.1 kg of 1.4 DB eq/MWh, respectively. Therefore, the GPP at Amiata is 15.2 times less harmful than fossil fuel power plants in terms of human toxicity potential.

Toxic substances such as arsenic and antimony which are detrimental to human health are present in geothermal water [53]. Kakkonda GPP in Japan is an example where the concentration of arsenic is approximately 3–4 mg/L whereas the environmental standard is 0.1 mg/L. To remove arsenic from geothermal water, the high gradient magnetic separation method is used in Ref. [55]. With a diameter of 50 μm, ferromagnetic wires are used to create a Bi-2223 pancake-based magnet which has outer and inner diameters of 306 mm and 240 mm, respectively. The coil is 352 mm in height with an inductance of 1.6H. The coil takes 1 min to reach 1.7T while operating at 180A. A cryocooler is used to set the temperature at 20K (−253.15 °C) by which the magnetic field of 1.82T is achieved. Three different pretreatment methods are adopted to separate arsenic. In the first method, ferrite formation is achieved by adding 400 mg/L of Fe^{2+}($FeSO_4$) into the water. Around 40% of arsenic is removed after magnetic separation. Suspended SiO_2 is not separated in this technique. Therefore, the first method has proven to be very inefficient. In the second method, oxidation of arsenic molecules is done by aeration. Afterwards, ferric hydroxide coprecipitate is formed by adding 200 mg/L of Fe^{3+}($Fe_2(SO_4)_3$). After successful magnetic separation, around 80% of arsenic is removed. The last technique is created by modifying the previous method in which fine particles of Fe_3O_4 having a diameter of 1 μm are added after the aeration process. Using this technique, approximately 90% of arsenic is removed. Furthermore, the effect of ferromagnetic particles and α-hematite particles in removing arsenic is analyzed. After taking five samples for each case, it is observed that 99.9% of particles are removed in both cases. Hence, this method could be utilized to rectify the geothermal water so that it does not pollute the environment. Furthermore, this water can easily be used in a variety of fields.

5.3. Effect on native inhabitants

A report on Olkaria power plant in Kenya reveals that the nearby Maasai community is adversely affected by the geothermal power plant. Due to the scarcity of skilled workers in some GPPs, many foreign workers are required to install, operate, and decommission these plants. The expansion of these plants will require more skilled workers which will hinder the indigenous cultures observed by the natives. Moreover, residential dwellers near the GPP may get affected by dust and or smell which will eventually create diseases such as cold, flu, vision problems, and even respiratory diseases. Furthermore, GPPs require excessive areas of land, and this might cause many native inhabitants to settle in other places [56]. For better understanding of the overall situation, a SWOT analysis of geothermal power plants is shown in Table 5.

Always available in some part of the world, geothermal energy is used by GPPs for space heating and to produce electrical energy. They demand large land areas for its operation that sometimes forces native residents to relocate. Toxic chemical discharge is found in wastewater that can pollute nearby water resources. Unpleasant odor, dust, and indirect emissions are observed from this RES. Emissions per kWh can be reduced by increasing number of the boreholes while making them as deep as 90 km. The most menacing threat from this RES based power plant is the seismic activities that can be catastrophic if it is near a densely populated area. This information should be kept in mind before installation of a GPP.

6. Hydro power plants

Hydroelectricity is produced by building a dam on a free running river. Water at higher altitude is released and falls on the blades of a hydro turbine which produces electrical power. Hydroelectricity is one of the oldest and most highly studied RESs. As of 2019, the total installed capacity of hydropower is approximately 1150 GW globally which is the highest among all RESs [9]. Apparently, hydro power plants do not emit any greenhouse gases during operation. However, certain environmental effects have been reported in some studies.

The barrier or dam which forms a reservoir for a hydro power plant hinders the migration process of fish. Moreover, dams are responsible for changing the temperature and flow of water. Furthermore, the chemical properties of the water and its surroundings change. These changes are detrimental for the physical and ecological features of the river. Most indigenous plants and animals will experience negative impacts. Besides, relocation of native inhabitants will create discomfort in their living. Additionally, many archeological sites, agricultural and natural areas will either be covered due to flooding or will dry up due to erosion and siltation. These reservoirs are created using steel and concrete and the equipment used in this process may create carbon emissions if fossil fuels are incorporated. However, the 50–100 years lifespan of these hydro power plants makes these emissions negligible. Mortality rate of fish due to hydro power turbines is approximately 5–10%. The US Department of Energy plans to decrease it to 2%. Shad, salmon, and many other fish usually swim upstream for reproduction. Hence, dams used in hydro power plants hinder their path which reduces their chance of mating [57].

Table 5
SWOT analysis of geothermal power plants.

Strength	• The source can be used for space heating without converting into electrical energy [9]. • Input of this power plant is always available. • The total installed capacity is 13.9 GW worldwide [9].
Weakness	• Wastewater of GPP contains CO_2, CH_4, H_2S, NH_3 [53]. • Presence of arsenic and antimony is found in the brine which can cause water pollution [53]. • Only a handful of locations in the world are suitable for this type of power plant [53]. • Large land area is required for operation [56]. • GPPs emits dust and unpleasant smell [56]. • Requires non-renewable energy for drilling boreholes [54].
Opportunity	• Using electrical or thermal spallation drilling can abate emissions [54]. • Additional boreholes will make the power plant more sustainable and will abate emissions [54]. • Borehole length of 90 km is beneficial for the environment [54].
Threat	• Native residents are relocated for the installation of GPP [56]. • Seismic activity is observed due to the installation of GPP [54].

6.1. Land requirements

Hydroelectric power plants in hilly areas require smaller amounts of land mainly because reservoirs can be made very deep to accommodate a large volume of water. In the case of hydroelectric power plants in flat areas, they take an enormous amount of land. For instance, the Balbina hydroelectric power plant floods 2360 km^2 of land to generate 250 MW of power whereas a small 10 MW hydroelectric power plant requires 0.253 km^2. Flooding a large-scale land mass will destroy cultivable lands, archeological sites, wildlife habitats, and forests. Moreover, relocation of native inhabitants also occurs to build reservoirs [58].

6.2. Wildlife impacts

As discussed earlier, floods caused by dams can destroy wildlife habitats. Moreover, these dams are also proven to be detrimental to the aquatic creatures. Even though there are technologies such as fish ladders that assist fish to go upstream for reproduction, many species are still being affected by the blades of turbines. Furthermore, excessive nutrients, sediments and weeds accumulate - due to the stagnant nature of reservoir water. Thus, eutrophication can occur near the surface of the dammed reservoir. Careful measures must be taken to eliminate these redundant weeds [59].

Water evaporation rates increase when the water is placed in a reservoir rather than in a flowing river. Moreover, withholding an excess amount of water can dry out some segments of the downstream river which affects plants and animals. Hence, a certain amount of water must be released to reduce this effect. Furthermore, the dissolved oxygen level of the reservoir water is low and the bottom most water which is passed downstream is cooler than river water. This deoxygenated cold water can impede the lifestyle of plants and animals. Therefore, aerating turbines are used to increase the amount of dissolved oxygen in the water. Moreover, it must be ensured that waters are taken from different levels to increase the overall temperature [59].

6.3. Emissions

It is assumed that greenhouse gases are emitted during the installation and decommissioning stage of hydro power plants. However, studies reveal that significant amounts of greenhouse gases are emitted indirectly during the operation of these plants. These emissions depend on the nature of the nearby land and also on the size of the plant. It is reported that approximately 4.5–13.61g of CO_2 eq./kWh gets released from small scale plants. For large plants installed in semi-arid areas, around 27.2g of CO_2 eq./kWh is emitted during their lifecycle. In tropical areas or in mild peatlands, the emissions are much greater. Floods decompose the nearby ground and plant life. As a result, methane and carbon dioxide gets released from decomposed vegetation and soil. It is estimated that emissions from the whole life cycle of a hydro power plant is around 226.8g of CO_2 eq./kWh [60]. Fig. 5 illustrates the emissions processes of an operating hydroelectric power plant [61]. The upstream part is a gathering point of organic matters coming from different natural sources. Some anthropogenic sources such as agricultural waste, industrial pollution, and domestic sewage also contribute to this flow of organic matters. Primary greenhouse gases in this flow are CO_2 and CH_4 which are released into the air by degassing or diffusive flux methods. Many aquatic plants take part in this process which further increases the emissions. A portion of organic matters are accumulated into the reservoir from which CH_4 is emitted through degassing. With the aid of methanogenesis, organic matters degrade and produce CO_2 and CH_4 most of which is emitted through diffusive flux and degassing. The remaining amounts of CH_4 are subjected to oxidation which results in additional CO_2 emission. Phytoplankton creates the oxygen that helps the oxidation process. Downstream of the hydroelectric dam, CH_4 is again released in air by the oxidation process.

6.4. Morphological impact

Hydroelectric power plants change the lifecycle of aquatic species, the hydrology of the rivers, and the concentration of nutrients dissolved in waters. Decreased water downstream can enhance the concentration of nutrients in the water which makes it unacceptable for irrigation and drinking. Decomposing of vegetation and plants drowned in the reservoir can emit CH_4 and CO_2. Toxic metals from the flooded lands can accumulate in the reservoir. Since sediments are trapped into the reservoir, the usual functionality of the river gets impeded which affects the coastal lagoons at the outflow to the sea. Thirty-three gigantic deltas are currently being receded due to the change in water flow of rivers caused by hydroelectric dams [62].

A brief comparison between effects caused by dams and free running rivers has been made in Ref. [62] where both long- and short-term geological changes have been analyzed. Moreover, effects on vegetation and fisheries have also been discussed for both cases. The Fuerte and Santiago Rivers in Mexico are dammed for hydropower generation.

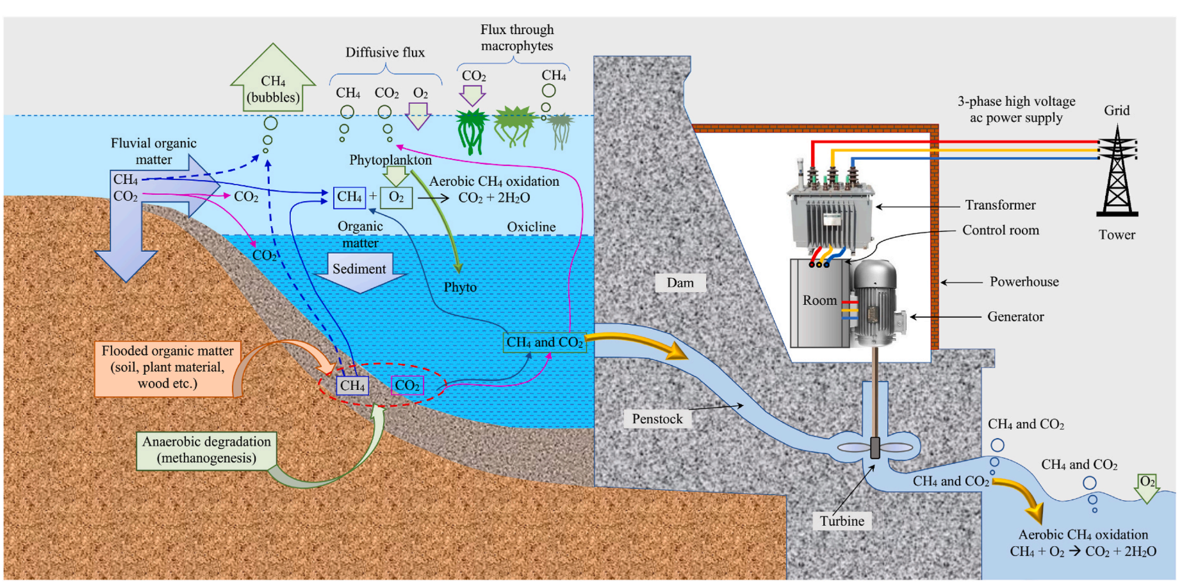


Fig. 5. The emission process of a hydroelectric power plant [61].

Only around 4% of the Fuerte River and approximately 2% of the Santiago River freely flow and stretch to their lower basins. In contrast, the San Pedro and Acaponeta Rivers are not dammed, hence they flow freely. Satellite images of all the four rivers during 1975 and 1990 have been collected from Landsat. Additionally, Google Earth is used to acquire the same satellite images for 2010. These images were compared to determine the amount of erosion or accretion that occurred from 1975 to 2010. During 1975–1990, the erosion rate of the Fuerte River was 7.9 ha/year and during 1990–2010 it escalated to 11.5 ha/year. In the case of the Santiago River, it expanded during 1975–1990 at a rate of 4.5 ha/year. But, after the installation of the dam during 1994, it started to erode quickly at 21.5 ha/year. On the other hand, a negligible amount of change is observed in the Acaponeta River. The expansion rate was 0.2 ha/year during 1975–1990 and the reduction rate was 0.4 ha/year during 1990–2010. In the case of the San Pedro River, it expanded by 7.4 ha/year and by 5.2 ha/year for the periods of 1975–1990 and 1990–2010 respectively [62].

The shoreline in the sandbar of these rivers is investigated. Results show that, the shoreline of the Santiago River decreased by 48.5 m/year. Moreover, the shoreline of the Fuerte River decreased by 14.3 m/year. On the other hand, the shoreline of the San Pedro River increased by 2.8 m/year. Insignificant changes were observed for the Acaponeta River. A vegetation survey demonstrated that dry and mangrove forests have grown significantly. Conversely, erosion in the dammed rivers have exposed the native plants to be washed away into the sea. Reports reveal that the shorelines of the Acaponeta and San Pedro Rivers have 26 and 33 types of plants, respectively. In contrast, the shoreline of the Santiago River has 4 and the Fuerte River has 8 types of plants. Fisheries are also affected due to hydroelectric dams. Before 2006, the estuary of the San Pedro River received 163 fishing boats whereas the Santiago River received 47 fishing boats. During 2006, the number of fishing boats in the estuary of the San Pedro River reached 1083 but no change was found for the Santiago River. In the Acaponeta River, 396 fishing boats were present in contrast to the Fuerte River which had only 19 fishing boats. During the fishing season of 2007–2006, 658 metric tons of seafood were collected from the San Pedro River. On the other hand, the Santiago River could provide only 35 metric tons. It is estimated that around US$1.3 M equivalent fisheries income were lost at the mouth of the Santiago River which could have been added to the natural capital of Mexico. Furthermore, loss of coastal and mangrove forests in the Santiago River reduced approximately US$ 3.9 M from the natural capital of the nation. Loss of mangrove forests imply that the trees are swept away into the ocean, and these will eventually be decomposed and will release CO_2 or CH_4 in the air. Finally, it can be said that the dams associated with hydroelectric power plants on the Fuerte and Santiago Rivers have reduced the regional income by 95% [62].

In Brazil's Amazonia, the effect of Jirau mega dam has been investigated in 26 1-ha areas of land filled with palm trees [63]. After the construction of the dam, the water level increased in Madire River, flooding 61.3% of palm species. Further, Várzea and terra-firme forests along with lands that are far away from the river were affected. The reservoir has completely drowned 6 types of palm species, and other 13 were partially drowned. Edaphic factors of soil such as P, N, pH, C, and texture were changed.

The country's thirty-year-old Balbina dam has also affected many areas, especially the igapó forests (blackwater forests) downstream of the Uatumã River [64]. These forests depend on periodic floods. After analyzing the vegetation seedlings, saplings, and strata-adults in this river, and comparing that with the Abacate River, which is unaffected by the dam, the study found that the dam has caused floral diversity in higher topographies of the igapó forests. The lower topographies are also affected since they experienced prolonged flooding periods.

6.5. Three Gorges project

With an installed capacity of approximately 22.5 GW, China's Three Gorges dam is the world's largest power station. Between 2003 and 2010, this power plant reduced carbon emissions by approximately 406.7 M metric tons [65]. However, studies reveal that it has some serious environmental repercussions. According to Ref. [65], approximately 142 M metric tons of sediments were found in the reservoir. Algal bloom along with eutrophication has been observed since 2003. From October 2002 to October 2010, the erosion rate per annum was 108.8 million m^3. Four domestic fish stock were reduced by around 78.2% in the period 2005–2010. Moreover, reservoir induced low degrees of seismic activity have been observed at regular intervals. Local air temperature rose by 0.2–1 °C and the precipitation level increased by 2–9% since the building of the dam. In contrast, the number of foggy days is decreased.

Being one of the oldest RESs, the environmental impacts of hydroelectric energy sources are studied the most. It can easily be concluded that no other RESs are as hazardous as hydroelectric power plants. Considering the said impacts, hydroelectric power plants are not as green as was initially deemed [59]. It is mentioned in Ref. [65] that four concerns must be met to mitigate the environmental impacts. They are strategic assessment, long-term monitoring, national policy, and future impact assessment. Table 6 demonstrates the overall SWOT analysis for better understanding of hydroelectric power plants.

Hydroelectric power plants are the most mature RES out of all. It provides power at a cheaper rate while having the highest power generating capacity. However, its impact on nature is far outweighs the advantages it offers. Impoundment and decommissioning stages require methods that emit carbon and other greenhouse gases in the atmosphere. The trapped sediments and other organic substances create eutrophication. Fish mortality increases, affecting aquatic ecosystem and nearby fisheries. Upstream area becomes flooded while downstream

Table 6
SWOT analysis of hydroelectric power plants.

Strength	• Have higher lifespans (50–100 years) than all other RESs [57]. • The potential is always available naturally. • One of the oldest RES based power plant types. • Highest power generating capacity (1150 GW) [9].
Weakness	• Installation and decommissioning stages emit greenhouse gas [60]. • Dam causes disruption in fish migration [59]. • Change in temperature of water adversely affects the nearby ecosystem [65]. • Relocation of local residents causes discomfort [65]. • Carbon emitting techniques are applied to form steel and concrete structure of the dam [57]. • Fish are vulnerable to turbine blades. Approximately 5–10% mortality rate of fish is observed [57]. • Reproduction of certain fish species gets hampered [57,59]. • The evaporation rate of still water is higher than flowing water. Hence precipitation increases [59,65]. • Increases air temperature of local environment [65].
Opportunity	• Hilly areas require less land to create a dam as compared to flat areas [58]. • Large scale power plants are economical. • Can produce power at a cheaper rate.
Threat	• Natural and agricultural areas will become ineffective due to either flooding or erosion. Archeological sites will also suffer [57,58]. • Accumulation of nutrients, weeds, and sediments will cause eutrophication [59,65]. • Downstream river may dry out due to reduced water flow [59]. • Cold and deoxygenated water adversely affects flora and fauna [59]. • Dried up water sources create desiccated soil and decomposed vegetation which emit greenhouse gas. Drowned plants also emit CO_2 [60]. • Irrigation process gets hampered [62]. • Change in water flow affects lagoons and deltas [62]. • Dams increase the erosion rate in rivers [65]. • Shoreline decreases due to lack of sediments which are trapped inside the reservoir [65]. • Dry and mangrove forests are washed away [62]. • The fisheries industry will face loss since fish reproduction is hindered [62].

area dries out. This results in diversity in flora and fauna. Moreover, lagoons and deltas are also affected due to erosion. Mangrove and blackwater forests are affected. Ambient temperature and humidity changes that indirectly alter the ecosystem. Hence, strict policies should be implemented to make new installation of dams difficult.

7. Tidal energy based power plant

Tidal energy is one of the most remarkable RESs. It uses the rise and fall of water during flood and ebb tide phases. Out of all devices that are used to capture tidal energy, the tidal barrage and tidal stream are the most noteworthy. Unlike solar and wind energy, tidal energy can easily be predicted. However, very few locations demonstrate promising potential for tidal energy which is a great disadvantage. Similar to other RESs, tidal energy is not free from environmental impacts. The following subsections describe the environmental impacts of tidal stream- and tidal barrage-based power plants.

7.1. Tidal stream generators

Using the kinetic energy of flowing water, tidal stream turbines generate power in a similar way as wind turbines which use kinetic energy of the wind. Unlike other renewables which occupy natural terrain, tidal stream generators are either incorporated into existing bridges or are fully submerged. High water velocity is often found at inlets and straits which are potential locations for the placement of tidal turbines. These turbines are placed either horizontally or vertically. Extracted energy from tidal streams is higher than wind since water is 784 times denser than air. Approximately 60kph of tidal current could provide equal or more energy than a wind speed of around 145kph, given that both use similar turbine systems [66,67]. A tidal stream turbine in the Strait of Larantuka, Indonesia generates nearly 10 kW-m^{-2} [68].

7.1.1. Effect on water flow

Extracting the energy from the tidal current will certainly reduce the speed of the current and, in some cases, may alter the direction of flow. Moreover, reducing the speed of water will hinder the deposition of particles which will affect the benthic area and will change the water level. To mitigate this issue, it is advised to extract around 10–20% of energy from the kinetic flux. However, energy from the kinetic flux is only a portion of the total available tidal energy. Hence, careful measures must be taken so that the flow of water does not decrease below the predefined speed [69].

In [70], a hydro-environmental model is simulated to determine the impacts of a tidal stream turbine array. The results show that turbines do not affect the water levels, but the upstream and downstream velocities were reduced significantly. The reduction factor is more than 25% in some areas within the turbine array. In contrast, the velocity increased near the sides of the turbine array. Moreover, a reduction of suspended sediment is observed within 15 km from the array and the opposite occurred near the side of the array.

A similar observation is found in Ref. [71] where the change in water level is around 0.025 m during the ebb. The upstream and downstream flow velocities decrease and the velocity at the side of the turbines increases. The maximum change in velocity is 0.25 ms^{-1} during flood. The disturbances can easily be observed at 1.7 km range from the turbine array. The energy density is reduced from 12 to 21% due to these changes.

Effects on suspended sediments are further studied in Ref. [72] where the results show that the transport of these sediments depends on the grain size. However, it is mentioned that further research is required to fully understand this impact. The effects on sea birds caused by tidal stream turbines are discussed in Ref. [73] which focuses on collision risks and displacement effects. Tidal stream energy is still at its early stage of development. Further research is required to fully understand its potential environmental impacts.

7.1.2. Fish behavior

The change in behavior of fish has been analyzed by Ref. [74] in the presence of a tidal stream turbine and a weather monitoring control unit. Approximately 396 and 523 schools of fish have been observed near the control unit and the device respectively. Due to the existence of energy extracting devices, the occurrence rate of these schools increases by 73.6%. Occurrences are mostly found during the night times and during the flood phases. These schools are found in the lower part of the water level during the flood phase. The mean distance of fish schools from the seabed is 18.56 m for the energy extracting device and 20.64 m for the control unit. Near the control unit, the mean distance increases during the night. Quite the opposite, the mean distance increases during daytime in the presence of the energy extracting device. Large amounts of fish schools are observed during the wake flow of the flood phase near the energy extracting device. However, subtle differences are found between flood and ebb phases near the control unit.

The size and concentration regarding fish schools reveal that the largest and highly concentrated fish schools near the control unit appear before sunset. The appearances of similar types of fish schools near the energy extracting device are found to be of a sporadic nature. Most of these schools are found in the mid-depth of the water column when the flow of water is high. During the whole tidal phase, a few large sized schools are found near the seabed at the location of the energy extracting device [74].

The behavior of fish schools is also discussed in Ref. [75], where three cases are analyzed. The first case has no turbines installed whereas the second case has stationary turbines, and lastly the third case consists of a rotating turbine. Data from fish tracking demonstrates that around 4049 and 11,641 fish tracks during flood and ebb phase, respectively, are observed for the absence of turbines. In the presence of the stationary turbine, the number of fish tracks increased to approximately 5076 for the flood phase and reduced to around 10,490 during the ebb phase. As for rotating turbines, the numbers reduce to 1734 and 1,715, respectively. Moreover, data regarding swimming patterns shows 12.5% of fish moving in the opposite direction of the current when the velocity of the current is at the operational stage. However, for a low-speed current, the number of fish moving against it increases to 26.9%. For currents having operational velocities, 13.6% of fish tracks move opposite to the current when there are no turbines whereas the number decreases to 11.4% when there are stationary turbines present. When there are rotating turbines, this number becomes 11.6%. In the absence of the turbines, around 29.2% of fish tracks are observed which were moving against the low-speed currents. The percentage reduces to 25.4% in the presence of turbines.

Furthermore, interactions between fish and turbines have been observed and three types of behavior are recorded. Firstly, some schools of fish neither feel attraction nor repulsion towards the turbine. Hence, they do not change their course of movement. Secondly, some schools avoid the turbines by changing their directions. Lastly, approximately 5% went straight into the turbines [75]. This may increase the mortality rate of fish. However, tidal turbines rotate at a speed of 8 rpm in the strongest currents [76]. Hence, the chance of blade strike is low.

7.1.3. Effect on aquatic habitats

Movements associated with rotors may create turbulence, vortices, sedimentation, and turbidity in the water. These problems will certainly affect the living organisms in that area as well as their habitat. Moreover, the shadow of the devices may be misinterpreted by nearby birds as fish shoals. Collision may occur with the rotating rotor and other living organisms which will increase the mortality rate. However, research reveals that nearby fish and other aquatic creatures can easily feel the pressure gradients caused by the devices. On the other hand, the structure that supports the rotor will disrupt the natural flow of water which eventually reduces the speed of water. It may also create wakes, vortices, turbulence, and accumulation of sediments. If these effects persist for a long time, then it will change the benthic habitat [69].

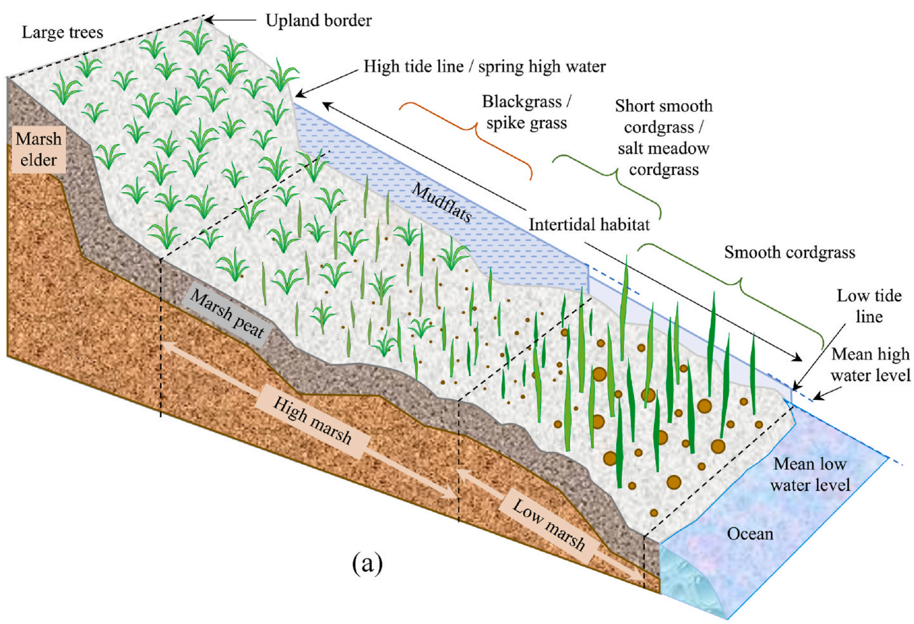
For the installation of tidal stream generators, pile drivers are required which will mainly affect species who are acoustically sensitive. In Ref. [77], the impact of tidal turbines on the seabed has been investigated using 3D computational simulation. It has been demonstrated that each blade of the turbine creates a sheet of vortex. The combined effect of these turbines in running condition creates a vortex filament at the back of the rotor. These vortices cause sediment entrainment into the flow, thus increasing bed shear stress. Furthermore, this increase in bed shear stress decays downstream of the turbine after approximately two diameters of rotor length. This effect becomes worse if the distance between the rotor and seabed decreases. Hence, it is advised to investigate the effects of placing the rotor near the seabed prior to installation.

7.2. Tidal barrage power plants

Near the estuaries and along the ocean, small dams are built to store water during flood phases. These waters are released through a turbine during ebb phases. This technology is widely known as a tidal barrage. A minimum of 5 m of water level difference or tidal range is required for viable operation, hence, only 40 locations worldwide are suitable for installation of tidal barrages [66]. The Sihwa and La Rance power plants are the largest tidal barrages, and they can generate 254 MW and 240 MW, respectively [9]. If the tidal range is 20 m, then the power density of a tidal barrage power plant is approximately 45W-m^{-2} [78]. In spite of having large potential, the development of tidal barrages is currently limited because of high initial investment, prolonged construction time, and some environmental impacts [79].

7.2.1. Effect on animal habitats

La Rance is one of the first ever built tidal barrages and is located in



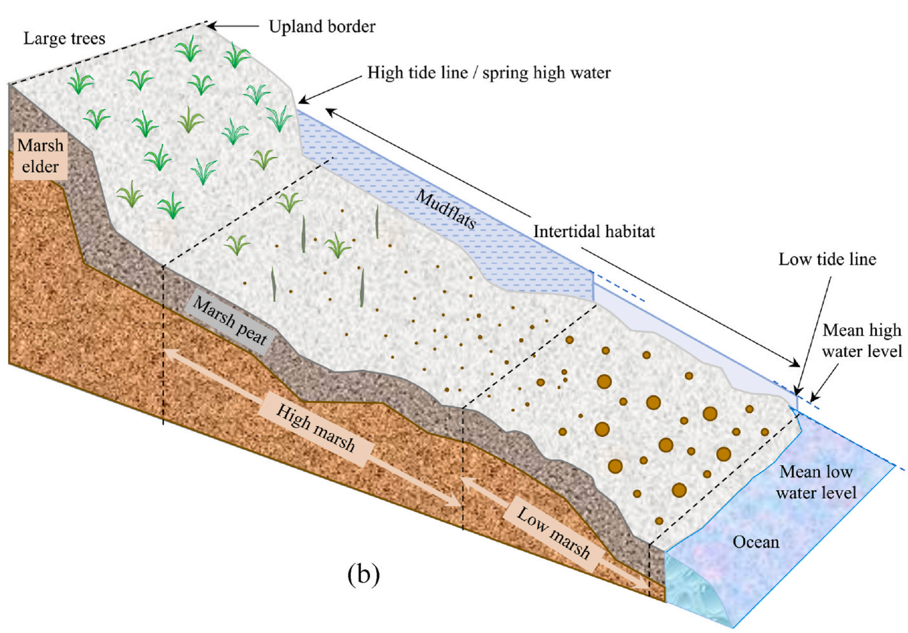


Fig. 6. Salt marsh near mudflats: (a) at natural condition, and (b) after installing the barrage [81].

France. It experiences around 8 m average difference between flood and ebb which makes it suitable for placing a tidal barrage. The construction took almost five years with an initial investment of approximately US $100 M which makes other cheap alternatives such as wind, solar, and biogas preferable. The barrage hinders the migration of salmonids, shads, and eels [80]. It also causes some negative impacts in the benthic habitat. The structure of the barrage creates an artificial reef on which new species start to colonize. In contrast, those species that lived there before the establishment of the barrage struggle to survive due to the massive change in their habitat. However, a net increase in biodiversity is observed. If waste materials are not disposed of properly, then it will pollute the area and will increase the mortality rate of nearby creatures [81]. Fig. 6 illustrates the condition of a salt marsh near mudflats in its natural condition and a few years after installing the barrage.

Tidal barrages can reduce the tidal range by around 60%. If the tidal range is decreased, then the upper tidal zone will permanently be dried up whereas the lower tidal zone will always be submerged. This will change the intertidal habitat. Moreover, impeding the flow of tidal currents may change the turbidity and salinity of water which could be harmful for the local fish, birds, and other living organisms. Estuarine birds depend on salt marshes which grow near the mudflats of the intertidal habitats.

On natural conditions, tides bring nutrients to the land which supports the growth of these salt marshes. The intertidal habitat constitutes of two areas. First, the high marsh section where black grass (spike grass) is found. At the end of this section, towards the ocean, short smooth cordgrass (salt meadow cordgrass) is also observed. The second section is the low marsh area where smooth cordgrass is noticed. Interrupting the tides will reduce the supply of nutrients to these plants. As a result, the low marsh area loses most of its smooth cordgrasses whereas the high marsh area only has a few black grasses left near the high tideline.

Migratory birds may not find the place suitable and those who barely do will have to compete with the local birds to survive. Fish migration for breeding gets hindered due to the barrage. Hence, they may try to go through the turbines which increases fish mortality [81]. Even though barrages are often used as bridges which could enhance land accessibility, isolation of ships due to barrages may engender socio-economic concerns. Near the west coast of the UK, there are 5 foremost estuaries which have the potential of generating electricity through tidal barrages. 0-D and 2-D analyses by Ref. [82] show that these barrages can increase the tidal amplitude in the east coast of Ireland which will result in coastal flooding. Moreover, intertidal habitats will be lost in the basin which will eventually affect the birds near the estuaries. Furthermore, benthic habitats will be altered, and turbidity will be reduced in the Severn Estuary and the Bristol Channel which will increase biodiversity. However, it has been advised to implement a turbine having dual mode operation to mitigate these impacts [82].

7.2.2. Noise and vibration

During the installation phase of these devices, noise and vibration will be created by piling, drilling, vessel engines and propellers. These noises are high in magnitude but will last only during the construction period. In contrast, continuous noise will be generated by these devices during their operational phase. The loud noise will affect the living organisms. Larvae of many species will struggle to find a suitable settlement due to the presence of noise [81]. SWOT analyses of the overall situations for both tidal barrages and tidal stream power plants are shown in Table 7.

Both tidal stream and tidal barrage power plants have huge power producing potential, however, they can only be installed on certain locations throughout the world. While a tidal barrage requires a large amount of investment, people can be benefited for a long time by using it as a bridge. It disturbs the aquatic and inter tidal habitat which is essential for the survival of fish and birds. On the other hand, tidal stream generators can harness more power than wind turbines. It alters the flow of water that will alter the sedimentation pattern. As a result, aquatic habitat will experience biodiversity. Proper measures must be taken to protect the nearby species and their habitats when installing these two types of power plants.

Table 7
SWOT analysis of tidal barrages and tidal stream power plants.

Traits	Tidal Stream	Tidal Barrage
Strength	• Output power does not fluctuate. • Power potential 120 GW. • Power density is 10 kW-m^{-2} [68].	• Output power is highly predictable. • Power density is 45W-m^{-2} [78]. • Power potential 120–400 GW.
Weakness	• The turbines reduce upstream and downstream flow velocity [70,71]. • Water flow velocity at the side of the turbine farm increases [70,71]. • Very few locations are suitable for this type of RES.	• Initial investment is high for tidal barrage. • Construction of the power plant requires a lengthy timeframe. • Tidal range of 5 m is required for viable operation [66]. • Only 40 locations worldwide are suitable for this RES [66].
Opportunity	• Higher energy can be harnessed as compared to wind turbines using the same machines [67]. • Maximum turbine speed is 8 rpm which can reduce the chance of blade strike [76].	• Barrages can be used as bridges to increase land accessibility. • Increases visual aesthetics [82].
Threat	• Stationary turbine increases the occurrence rate of fish schools by 73.6%. Presence of rotating turbine decreases the presence of fish [75]. • 5% of fish schools go straight into the turbines which may increase fish mortality. • The shadows of associated devices may mistakenly be interpreted as fish by the predatory birds. Hence, they may collide with the turbine [69,73]. • Vortices, turbulence, sedimentation, and turbidity disturb local habitat and the surrounding creatures [69,77]. • Direction of water flow changes which also changes the deposition of sediments; hence water level and benthic habitats get affected [69,72].	• Inter tidal habitat cannot provide enough salt marsh due to lack of water, hence estuarine birds are deprived of their food [81]. • Breeding of migratory fish gets obstructed [81]. • Ship movements are restricted. • Loss of aquatic habitat. • Noise during construction.

8. Ocean power plants

While having the largest potential, ocean based RESs have the least installed capacity throughout the world. Ocean energy is always available and mostly predictable. As of 2019, the total operating capacity of ocean-based power plants is 535 MW [9]. Three most remarkable techniques of harnessing ocean energy are oceanic wave, ocean current, and ocean thermal. The following subsections discuss these techniques.

8.1. Oceanic wave energy

Approximately two-thirds of the world is covered by ocean. One of the key advantages of oceanic wave energy is its availability that is higher than any other RESs [83]. Oceanic wave energy is one of the most promising RESs which has a potential of generating 1TW–10TW of electrical power [84]. To harness the energy from oceanic waves, electrostatic, electromagnetic, and piezoelectric technologies are commonly used [85]. Oceanic wave energy (OWE) capturing devices remain either totally submerged, partially submerged, or floating. The presence of any foreign element in the ocean can be dangerous for the environment. Environmentalists are already worried about the impacts of the enormous amount of plastics in the ocean. Now, the presence of oceanic wave energy devices can make the situation worse.

In the case of OWE extraction, the presence of various devices in the ocean may result in underlying changes to the aquatic creatures both below and above the water level. Above the sea level, various migratory birds or different sea birds are affected due to the presence of these devices. Moreover, the devices at the ocean surface such as the Wave Dragon or the Pelamis take a considerable amount of space which creates a barrier in the path of many migratory species. Estuarine and shoreline devices are impassable and immovable which also hinders the migrating path. Under the sea level, many objects such as rotors, buoys, pressurized pipes, electrical cables, anchors, etc., are used. Many devices require large pipes that are entrenched deep down to a considerable depth. This will disturb the underwater inhabitants. The oscillating devices are installed on habitats which are covered up with sand. The rotors moving at a high speed on a horizontal axis can be hazardous to some fish, marine mammals, and diving birds [86]. Some wave energy extracting devices have a fishnet structure which may entangle nearby species. Maintenance and recycling processes of these devices are difficult [87]. If OWE extraction devices are installed in places where no creature lived before, then the presence of these device will become a support for some species and the place will transform into a livable habitat.

8.1.1. Chemical effects

During the installment, maintenance, and decommissioning procedures, there are always risks linked with aquatic vessel operations. In devices which incorporate hydraulic fluids, there is a possibility of undesirable spillage. These fluids are hazardous for aquatic creatures. Antifouling paints are used to reduce biological contamination which are detrimental to the aquatic lives. Toxic material such as ammonia can get leaked from the device which can further degrade the aquatic habitat. Increased quantities of discharged nutrients could cause eutrophication of certain areas. Furthermore, sea water interacting with concentrated metal may toxify surrounding areas [86].

8.1.2. Acoustic effects

The acoustic environment is essential for oceanic creatures, especially for communication with each other. Without a proper acoustic atmosphere, prey or predator sensing, orientation, and reproduction get impeded. During the installation phase of these devices, a high amount of acoustical noise is observed. The primary sources of noise are seismic analysis prior to installation, vessel activities, and construction related noise. Although the noise generated in these cases are high in intensity, they occur only for a short time. During the operational period, devices having surface moving parts such as hydro planes or water turbines create the most noise. Research shows that underwater noise affects fish and marine mammals. Marine mammals tend to move away from construction places because of noise. However, after the end of noises, they return back. This impact is negligible if the noise occurs for a short time. Nevertheless, it can turn out to be severe for large scale construction of turbines since these constructions last for a long time [86,88].

It is reported in Ref. [89] that green turtles behave abnormally because of noise caused by air guns for seismic surveys. The swimming movement increases when the noise is above 175 dB re 1 μPa rms. Caged squids are startled when exposed to a noise level of 156 dB re 1 μPa rms and rapid swimming activity is observed at 174 dB re 1 μPa rms. If noises generated by wave energy devices exceed these limits, then it can be harmful for these creatures.

In 2014, a project was developed by Ref. [90] to monitor the surrounding environments thorough acoustic noises. The Wave Energy Converter named Lifesaver was installed at the Falmouth Bay Test Site in the UK. At a distance of 200 m, an acoustic monitoring system is placed which consists of hydrophones, recorders, and a storage system. The device recorded at half an hour interval for two years. The data has been analyzed using short time Fourier transform. The results demonstrate that the number of acoustic signatures found from the hydrophones corresponds to the number of power-takeoffs.

8.1.3. Electromagnetic effects

Some species are able to sense electric fields and/or magnetic fields and they live near offshore and coastal environments. Oftentimes these species use the natural geomagnetic fields in order to properly orient themselves. The taxa of Chondrostei, Agnathans, and Chondrichthyes can respond to nearby electric fields through their electroreception sensors. These species usually locate prey or mates with the help of low frequency bio-electric fields. In large scale movements, these creatures orient themselves by electric fields. Energy from many devices is often transmitted to onshore substations through transmission lines where EMFs are formed. These devices that are placed offshore may affect the communication systems of these species [86].

8.1.4. Effects on pelagic and benthic habitats

Pelagic species and tunas will accumulate near anchored and floating devices which are similar to fish aggregating devices. This will eventually change the habitat of pelagic species. Moreover, many communities that grow on anchors, buoys and lines will sooner or later find themselves in the benthic zones. As a result, the habitat will change its nature and new species will occupy this new habitant. Pelagic and benthic habitats will experience increased biodiversity [86].

8.1.5. Marine species

The appearance of wave energy extracting devices will attract some predatory fish. This will increase the mortality rate of former inhabitants and also newer species that come along. These devices will affect the diving birds. Blade strike, collision, and entanglement are common phenomenons for these birds [86].

8.1.6. Nearshore activity

Nearshore oceanic energy extraction can become the cause of beach replenishment and destruction. It can also hinder the management and process of coastline defense. If the devices are installed near the shipping lanes, then the dredging ships will face difficulties to operate their routine function [86]. For the better understanding of the overall outcomes, Table 8 shows the SWOT analysis of ocean wave power plants.

8.2. Ocean currents

One of the largest untapped RESs is considered to be the ocean currents where approximately 450 GW of power can be produced. Ocean currents can represent a market worth around US$550 billion [91]. Ocean currents influence the global temperature distribution. Due to the Coriolis effect, warm waters from the equator are passed towards the polar region and cold waters follow the opposite path. This occurs in both hemispheres of the earth. Some aquatic species use this current for migration. The current also carries nutrients and planktons along its way which are the food for many microorganisms. If the current slows down or stops totally, intense weather conditions will be observed in many regions and the aquatic ecosystem will greatly suffer. According to Ref. [91], it will affect nearby benthic and pelagic environments. Offshore pot fisheries and trawling for shrimps and crabs will get impeded. Migratory routes which are used by many marine mammals and other aquatic species will experience difficulty. Additionally, sport fisheries and fish schooling will be affected. Along with these concerns, soft and hard coral reefs in the Florida Current can get damaged [91].

In [92], a global overview of ocean current potential is shown. It is mentioned that the theoretical available power in the Florida Current is 379 MW provided that no energy is being extracted. The study found 42 sites where the energy potential is high. However, turbines are

Table 8
SWOT analysis of ocean wave power plants.

Traits	Features
Strength	• Potential power generating capacity is 1TW–10TW [84]. • Input of this power plant is always available.
Weakness	• Initial setup cost of this power plant is high. • Maintenance cost is high. • Installation complexity is high for this type of power plant. • Device operates at low speed and low frequency due to the nature of waves.
Opportunity	• Some devices become habitat for nearby species [86]. • Pelagic and benthic habitats will experience biodiversity [86].
Threat	• Migratory birds experience obstructions in their path [86]. • Large pipes placement and solidification of the seabed disturbs nearby inhabitants [86]. • Moving rotor blades can cause injury to fish and/or birds [86,87]. • Chemical spillages from these devices are harmful for aquatic creatures [86]. • Toxification and eutrophication can occur in some areas [86]. • Construction noise affects acoustically sensitive creatures [86,88]. • Electric field or magnetic field disrupts mating in some species [86]. • Search for prey gets hindered due to EMF [86]. • Pelagic and benthic habitats will change [86]. • Predatory fish get attracted to certain devices; hence mortality rate of nearby animals increases [86]. • Some creatures may collide with or get entangled in these devices [87]. • Management and process of coastline defense get obstructed [86]. • Dredging ships are unable to follow their routine easily [86]. • Toxic ammonia can get leaked in closed systems which can degrade aquatic habitat [86]. • Maintenance of this power plant is difficult [87]. • Recycling the device components is challenging [87].

simulated in only 16 sites where the power potential is more than 120 MW. The simulation is performed using data that dates back to 2008. The results show that, after the placement of a virtual turbine in the current, the theoretical available power reduces by a factor ranging from 29% to 89%. The highest reduction factors are observed for Kyushu Island in Japan (89%), Luzon Island in the Philippines (87%), and east of Taiwan (75%). After implementing the virtual power plants, reduction in the speed of the currents is observed at different sites. In the case of the Florida Current, the drag of turbines reduces the average current velocity from 1.39m-s^{-1} to 1.08m-s^{-1}. Moreover, the current becomes weaker, and its direction becomes less stable. Despite a 22% reduction in average current velocity, it is a suitable place for harnessing energy. However, the scenario is not favorable on other sites. The Kuroshio Current where it passes Camiguin Island in the Philippines exhibits a velocity above 1.5m-s^{-1} which can provide power ranging from 855 MW to 1060 MW. The placement of two virtual turbines would shift the current towards the east by approximately 30 km. As a result, the velocity decreases to 0.89 ms^{-1} and the available power range becomes 110–465 MW.

8.3. Ocean thermals

Ocean thermal energy conversion (OTEC) utilizes the difference between warm surface water and deep cold water to create electricity. Any type of substrate that boils at the temperature of warm surface water is used in this process. Usually, ammonia is used for such an operation where it is boiled in the turbine evaporator chamber. The gas then rotates the turbine to produce electrical power. The gas is then passed to the condenser unit where it becomes liquid with the help of deep cold water. The liquid ammonia is passed back to the evaporator to complete the cycle. Global power potential of OTEC power plants is around 2 TW. In the northwestern slope of Kumejima Island, the power density at 1006 m depth is around 50W-m^{-2}. The promising location is less than 10 km distance from the shoreline. Fig. 7 presents the block diagram of an ocean thermal energy conversion system.

Since deep cold water has fewer biomass organisms, large volume intakes will create less impact. On the other hand, many aquatic creatures such as fish, planktonic or pelagic species, etc., rely on warm water. Hence, warm water intakes will adversely affect them. During the whole process, entrainment and impingement of nomadic creatures can take place which increases fish mortality. Oceanic thermal energy extraction requires large sized pipes which go very deep into the sands of the ocean. The resulting hardening of the bottom surface will change the aquatic lifestyle of the bottom communities. The hard surface will create an artificial reef and it will become a habitat for new creatures which will create biodiversity. In closed systems, oftentimes the working fluid is ammonia, a toxic chemical for fish. Any sort of leakage will create a hazard to its surrounding species [93].

Cold water is usually taken from 700 m to 1000 m depth whereas warm water is taken from 20 m depth. A commercial plant requires 500 m^3-s^{-1}. This will create an imbalance in nutrient concentration and plankton population density. Water quality will also degrade due to the corrosion of plant pipes. A biological concern that is caused by eutrophication is phytoplankton bloom which can occur due to the presence of rich deep-water nutrient in shallow water. However, this effect can be addressed by discharging at 70 m depth. Moreover, at a 1% light limited depth which is approximately 120 m, this bloom cannot occur. Additionally, the alkalinity and pH level may get altered and dissolved inorganic carbon and carbonated ion distribution will also change [93]. For a better insight, a SWOT analysis of ocean current and ocean thermal power plants are summarized in Table 9.

Since there are different types of power plants that depend on ocean currents, their environmental impacts are demonstrated in Table 10. Natural impacts are listed in the table for six different ocean power plants (onshore, floating, submerged, bottom, ocean current, ocean thermal), and the intensity of the impacts are indicated with bars where the number of bars indicate the level of impact.

Many of these RES based power plants are manufactured using the electricity that uses non-RES based power plants. Moreover, during the installation period, because of transportation, fossil fuels are mostly used. Therefore, RES based power plants are detrimental to the nature as their manufacturing and installation require the use of fossil fuels. Some of them are vulnerable to natural disasters and it is difficult for recycling the other power plants. Water toxification, algal and phytoplanktonic bloom, and eutrophication are among the most hazardous impacts on nature that are caused by these power plants. The impacts are not only harmful to aquatic environments, but also responsible for the death of fish.

The operating process of these power plants alter the flow of water which restricts the breeding process and affects the migration of aquatic species and nearby fisheries. Moreover, the existence of these power plants along with their installation and operational noise can adversely affect the natural beauty. It is found that the least damage is caused by the power plant that is installed onshore compared to others. Since onshore power plants are partially situated in the water, it has fewer effects than the others. Onshore power plants, however, are notorious for affecting the natural aesthetics. On the contrary, the highest impact is found for the power plants that are placed on the seabed. The remaining power plants have moderate impacts on the environments as per Table 10.

9. Osmotic power plants

Pressure retarded osmosis (PRO) is a technique by which clean energy is harnessed using two separate water columns having different salinity that are separated with a semipermeable membrane. Fig. 8 illustrates an osmotic power plant. It is a relatively new type of RES which has large potential.

It has an energy density of 0.75 kWh-m^{-3} with an efficiency of 91.1% [95]. The membrane is the heart of the whole process. PROs can be installed near the mouth of a river where fresh water from the mountains

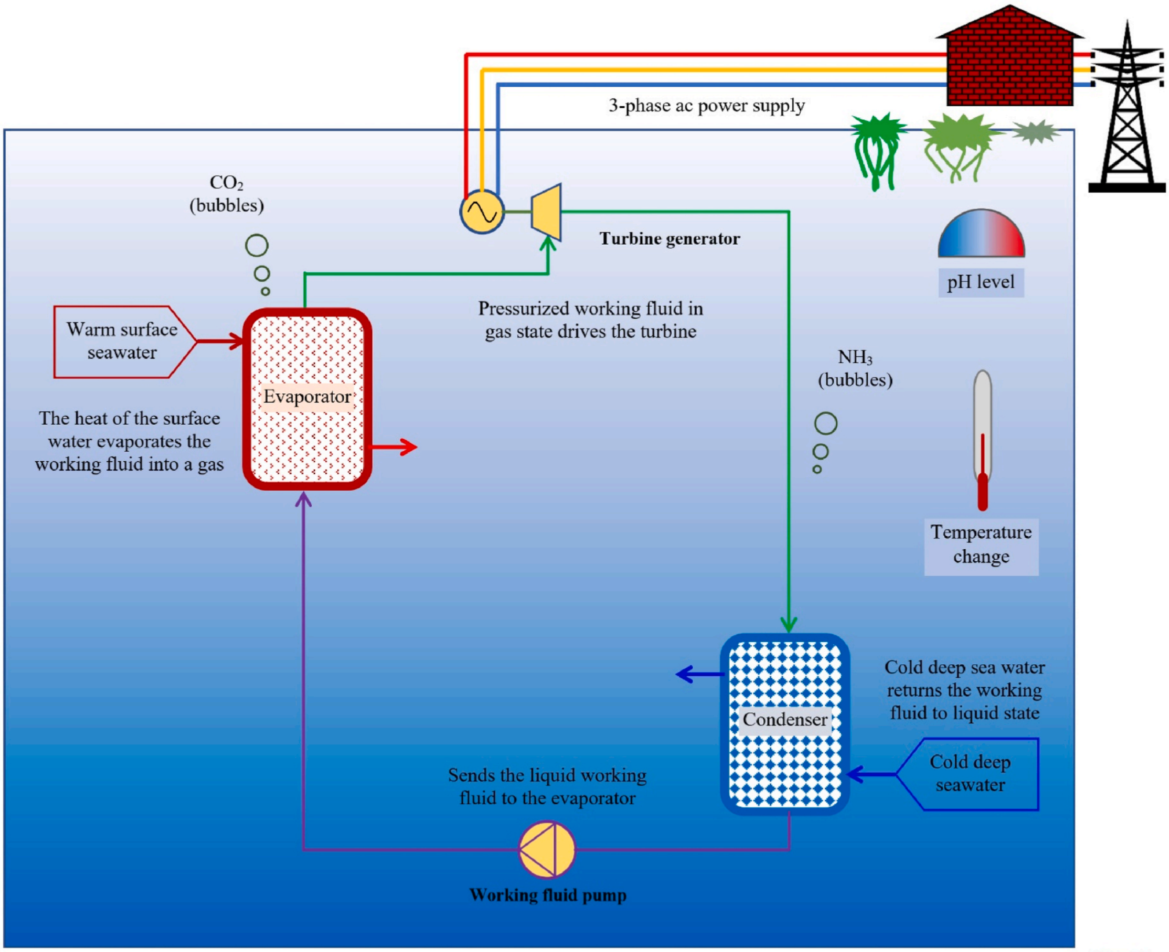


Fig. 7. Ocean thermal energy conversion system.

meets salty water of the sea (brine). When these waters are separated by a membrane, then fresh water passes towards the brine. Hence, a large volume of water gets accumulated in the brine column by the PRO and the pressure increases with volume. The pressurized water is used to move a hydro-turbine to produce electrical power. A 400 MW power plant in the Great Salt Lake in the USA can supply nearly 300 thousand households [96].

PROs are not free from environmental impacts. The mixture of fresh water and brine, also known as brackish water, is released into the shallow region of the sea. This will increase the concentration of nutrients in the shallow area which causes eutrophication. A study on a prototype of an osmotic power plant that spanned for three years discovered that the amount of phosphorous at 35 m depth is higher than the euphotic level [96]. However, the effect of large-scale implementation needs further research.

If the temperature of the brackish water is different from the ambient water of the sea, then the local environment may become affected. Chemicals that are used to clean the membrane are not harmful since they do not accumulate in the environment. However, if the amount of these chemicals exceeds their predefined limit, then that may lead to toxicity of the water. Moreover, the power generation needs to be halted for cleaning purposes. Frequent cleaning will hinder the continuity of power supply. Even though multiple cells can mitigate this problem, it would increase the cost of the infrastructure.

Another problem which may arise is the change in salinity of the surface sea water. Deep sea water is more saline than shallow sea water. If brackish water is released into the shallow layer, then the salinity will increase beyond that of the deep layer which may change the local ecosystem. Nearby species will be affected due to the change in salinity of their habitat. If the outlet pipe of the brackish water is placed well below the euphotic layer, then these issues may decrease. In addition to these issues, another concern arises due to the vast requirement of fresh water. A 20 MW osmotic power plant requires fresh water at a rate of 26.7 m^3-s^{-1}. For comparison, the average discharge of the Thames River in London is around 65 m^3-s^{-1}. If the flow of the river is greatly reduced, then the estuarine environment will get affected.

A 25 MW osmotic power plant will require a land area that equals the size of a football ground which implies that it does not require a large amount of land. If this plant is built below sea level, then the freshwater can easily be pressurized with the aid of gravity. Pairing an osmotic power plant with a desalination plant will reduce some environmental issues. The outlet of a desalination plant usually disposes of the brine into the sea which has some negative impacts on the environment. If the brine from the desalination plant can be used in the power plant, then it will reduce some impacts. A brief SWOT analysis of osmotic power plants is illustrated in Table 11.

10. Life cycle analysis

Life cycle analysis (LCA) is used to determine the adverse effects on the environment caused by an activity, process, or product. It measures the total amount of material and energy required. For complete assessment, disposal of wastes and emissions are quantified as well. LCA spans over the whole life cycle of the activity, process, or product starting from acquisition of raw materials, their transportation and preprocessing, manufacture, use, maintenance, reconditioning, reuse, recycling of

Table 9
SWOT analysis of ocean current and ocean thermal power plants.

Traits	Ocean Current	Ocean Thermal
Strength	• Power potential of ocean current is approximately 450 GW [91].	• Utilizes the thermal difference of shallow and deep layers of sea. • Power density 50W-m^{-2}. • Power potential is approximately 2 TW.
Weakness	• Placement of a turbine reduces its velocity and changes its direction [92]. • Available power reduces with the placement of turbines [92].	• Poor efficiency. • Far away from shoreline.
Opportunity	• Market worth is around US $550 billion. • Responsible for thermal distribution of the earth [91]. • Carries nutrients and microorganism to facilitate the ecosystem [91]. • Helps fish migration [91].	• Biodiversity increase [93].
Threat	• Thermal distribution of the earth will be hindered. • Extreme weather condition might be observed in different places of the earth. • Benthic and pelagic habitats will be affected [91]. • Fisheries will be disturbed [91]. • Migration of aquatic animals will become difficult [91]. • Fish schools, sport fisheries and coral reefs will be affected [91].	• Toxification and water pollution are caused if ammonia is leaked [93]. • Change in aquatic habitat is observed [93]. • Entrainment and impingement of nomadic creatures can occur [93]. • If fish are exposed to toxic chemicals, then mortality increases [93]. • Eutrophication and algal bloom can occur from chemical leakage [93]. • pH and alkaline level are imbalanced near the power plant [93]. • Carbonated ion distribution will alter [93].

materials, and final disposal. LCA provides many environmental indicators along with some impact categories so that the burdens on three environmental areas (soil, atmosphere, and water) are determined. The four phases of LCA, shown in Fig. 9, are governed by the guidelines of ISO 14040 [97]. The outcome of LCA can be used for strategic planning, policy making, marketing, and improving the product.

Goal and scope definition: The goal of the study should be clearly stated in a few sentences. It must provide the intended application, explanations for conducting the study, select the audience, and state whether public comparative assertions will be made with the results. The scope of the study explains the details and extent of the analysis. It also shows that the goals are achievable within the given constraints.

Life cycle inventory analysis (LCI): In this step, raw materials are quantified, and energy requirements are determined. Emissions with regards to land, air, and water are calculated. It accounts for all the elementary flows connecting each unit during the lifetime of the product or process.

Life cycle impact assessment (LCIA): With the aid of the data found through LCI, the potential human health hazards and adverse environmental impacts are determined. The following steps are required to successfully complete an LCIA.

Selection of Impact Categories and Method: To start this assessment, relevant impact categories and a proper method for evaluating them must be chosen based on the geographic area of the study. There are many well-known standard LCIA methods such as Available Water Remaining (AWARE), ReCiPe, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), etc.

Using an LCA Software: Afterwards, with the help of an LCA software (GABI, SimaPro, OpenLCA, etc.), the inventory results are classified and assigned to relevant impact categories.

Characterization: Then the impact categories are quantified by characterization factors by which every stream of an impact are converted to a common unit. The end results are called impact category indicators.

Optional steps are often used by many LCA practitioners in which LCIA results are grouped, normalized, and weighted. Thus, the number of impact categories at the endpoints are reduced, namely as, for example, human health, resource availability, and ecosystem quality. While the endpoint categories may not give a detailed explanation of the whole process, it is easier to present the results to any non-technical individual. Since different practitioners assign different impact category groups, weighting factors, and normalization factors, it is recommended to apply the same approach while comparing various technologies that share similar product or process.

Life cycle interpretation: To conclude the analysis, a summary is required which portrays important concerns based on LCI and LCIA results. A discussion and recommendation based on the goal and scope should be given.

The LCA calculation is utilized in assessing energy conversion, exploitation, and sustainability. A comparative analysis using LCA between fossil fuel-based energy sources and RESs can be incisive. It is imperative to say that RESs will definitely outperform fossil fuel-based energy sources. However, performing LCA on different types of RESs is also essential for achieving a sustainable environment. Table 12 shows the studies that perform LCA on different RES based power plants. Different researchers use different methods of LCA to evaluate the impacts of RES based power plants.

The results obtained with LCA are not exhaustive. Rather these depend on the method of LCA being used. For instance, comparison between ReCiPe 2016 versus CML-IA baseline is made. The number of impact categories vary depending upon the context of the study. Climate change is used as the most common impact category. Different impact categories require different sophisticated scientific characterization models. The number of substances for different studies are not the same [105]. Comparisons between EDIP97 and CML 2001 are made. Except for chemical impacts on human health, other impact categories show minor differences in the applied methods. Comparison between EDIP97 and Eco -indicator 99 are made and the results are different, but the conclusions are the same [106]. Comparisons among ReCiPe 2008, Eco-indicator 99, and IMPACT 2002+ are made [107]. It is recommended to avoid any straightforward comparison between scores obtained from different methods for a given indicator. No matter which method is chosen, the most harmful product will be the same in most cases. In a few instances where the end results vary, the reason behind this is often due to the variations of weighting coefficients for an impact category. Location and resource availability are also responsible for generating different results [107].

In [101], international life cycle data (ILCD) 2011 and ReCiPe 2016, two different methods for LCA, are applied to different power plants. The results are presented in Fig. 10 where the numbers, referring to different power plants, are arranged from left to right in descending order based on their impact category. Fig. 10 proves that the outcomes or results of LCA for any system are not the same.

Fig. 10 illustrates LCA results of 6 different power plants by contrasting two different LCA methods, namely ReCiPe 2016 and ILCD 2011. The first column gives detail of the particular's attributes found through LCA. From the second to penultimate column, these refer to the magnitude of each attribute and are organized in descending order. These columns are colored based on the descending order of magnitude. For example, the column associated with the highest magnitude is given the color violet. The next columns are colored with blue, light blue, dark ash, ash, and light ash, respectively. The last column shows whether ReCiPe 2016 or ILCD 2011 is used to quantify the magnitude of that attribute for each power plant.

Each power plant is signified with a number, and for better

Table 10
Environmental impacts of different oceanic power plants.

Environmental Impacts	Ocean wave-based power plants				Ocean Current	Ocean Thermal	References
	Onshore	Floating	Submerged	Bottom			
Availability based on time	II	II	II	II	II	II	[94]
Availability based on area	II	II	II	II	III	III	[94]
Power reduction after installation	II	II	III	II	IIII	I	[92]
Human health	II	II	II	II	II	II	[94]
Natural aesthetic affected	IIIII	IIII	III	II	II	II	[94]
Tourism potential affected	III	II	II	II	II	II	[94]
Effect on weather	I	I	I	I	III	I	[94]
Dependency on non-RES	III	III	III	IIII	I	I	[94]
Installation noise	III	III	III	III	III	III	[86,88]
Operation noise	III	III	III	III	III	III	[94]
Recycling complexity	II	III	III	IIII	IIII	IIII	[87]
Chance of accident	II	III	II	I	I	I	[94]
Susceptible to storms	III	IIIII	IIII	II	I	I	[94]
Predator inefficacy	I	I	I	I	I	I	[86]
Collision or entanglement	I	I	III	III	III	III	[87,93]
Impingement	I	I	I	I	III	III	[93]
Biodiversity	I	I	I	III	III	III	[86,93]
Bird loss	I	III	III	I	I	I	[86,87]
Affecting bird migration	I	III	III	I	I	I	[86]
Ship movement	I	III	III	I	I	I	[86]
Water pollution	II	II	III	III	III	III	[94]
Water toxification	II	II	III	IIII	III	IIIII	[86,93]
Mating process of fish	I	II	II	III	III	III	[86]
Migration of fish and other aquatic animals	I	II	III	III	III	III	[91]
Affecting the flow of water	I	II	III	III	III	III	[91]
Eutrophication	II	II	III	IIII	III	IIIII	[86,93]
Affecting aquatic habitat	I	III	IIII	IIII	III	III	[86,91,93]
Fish mortality	III	III	III	III	III	III	[86,87,93]
Algal bloom	II	II	III	IIII	III	IIIII	[93]
Phytoplankton bloom	II	II	III	IIII	III	IIIII	[93]
pH level	I	I	I	I	I	III	[93]
Alkaline level	I	I	I	I	I	III	[93]
Distribution of carbonated ion	I	I	I	I	I	III	[93]
Altering current speed	I	I	I	III	III	I	[92]
Altering current direction	I	I	I	III	III	I	[92]
Fisheries are affected	II	II	II	III	III	I	[91]
Coastline defense	I	III	III	I	I	I	[86]
Fish school	I	I	I	I	III	I	[91]
Coral reef	I	I	I	III	III	I	[91]

visualization, these numbers are further given a certain color as indicated in the figure caption. For instance, number 4 refers to solar PV and is labeled with orange color. For the first and last columns, two different colors are used that indicate whether the outcome of the two LCA methods are the same for that attribute or not. If the outcomes match, then the color of that attribute and corresponding methods are green, otherwise, it is colored as beige. If there are any attributes that have a few power plants having the same position according to the two methods, those power plants are colored according to their positional color. If the opposite happens, then the color of the power plant takes place. This is exemplified by the attribute named "ozone depletion". The first three cells have the color according to their magnitude because the position of each power plant matches exactly. However, the remaining three cells do not match which is why they are colored according to their identity. It can be said that results found from different LCA methods are not comparable since different LCA methods have different midpoint categories. Therefore, a standard and globally accepted LCA method is required for RES based power plants that will incorporate precise midpoints and will provide accurate results.

11. Discussion

It took many years for researchers to discover the adverse effects of fossil fuels on the environment. To reduce the emissions caused by fossil fuels, many RESs have been deployed without thinking about their effect on the ecosystems. The same mistake should not continue to be repeated; hence this paper portrays the negative impacts of all types of RESs on the environment.

Use of solar energy through PV will continue to grow with the emerging improvements of PV cells. The latest cells, i.e., perovskite solar cells, are better for the environment. Due to their high price and stability problems, these cells are not commercialized yet. To mitigate the impacts on the environment, more focus should be given to enhancing the efficiency and stability of these cells. Mass production will reduce the cost. For existing cells, manufacturing and decommissioning processes must be handled properly so as to reduce the impacts. Acquiring certain required materials for PV panels results in mineral, fossil, and renewable source depletion whereas CSPs only require steel pipes, reflectors made from silicon, and conventional boilers which are available in the market. CSPs are harmful for some flora and fauna. CSPs need a large area to place the reflectors and concentrator whereas PVs can be installed even on the roof of a building. Emerging CSPs have a thermal storage system where molten salts are used. Regular maintenance must be done to prevent chemical reactions between the salt and the pipe. Thermal storage systems based on concrete show less environmental impacts. For cleaning and cooling the reflectors, CSPs require a lot of water. The water becomes contaminated by the presence of UV rays present in direct sunlight. Various micro-organisms mix with the water and pollute nearby water sources. If there is a leak in the pipes or if steam gets released into the environment, then surrounding freshwater and marine water will be polluted and algal bloom along with eutrophication will be observed. This will also contribute to terrestrial acidification. Contaminated steam or water increases both cancer and non-cancer toxicity in human. In the case of PVs, similar impacts could occur, but on a low

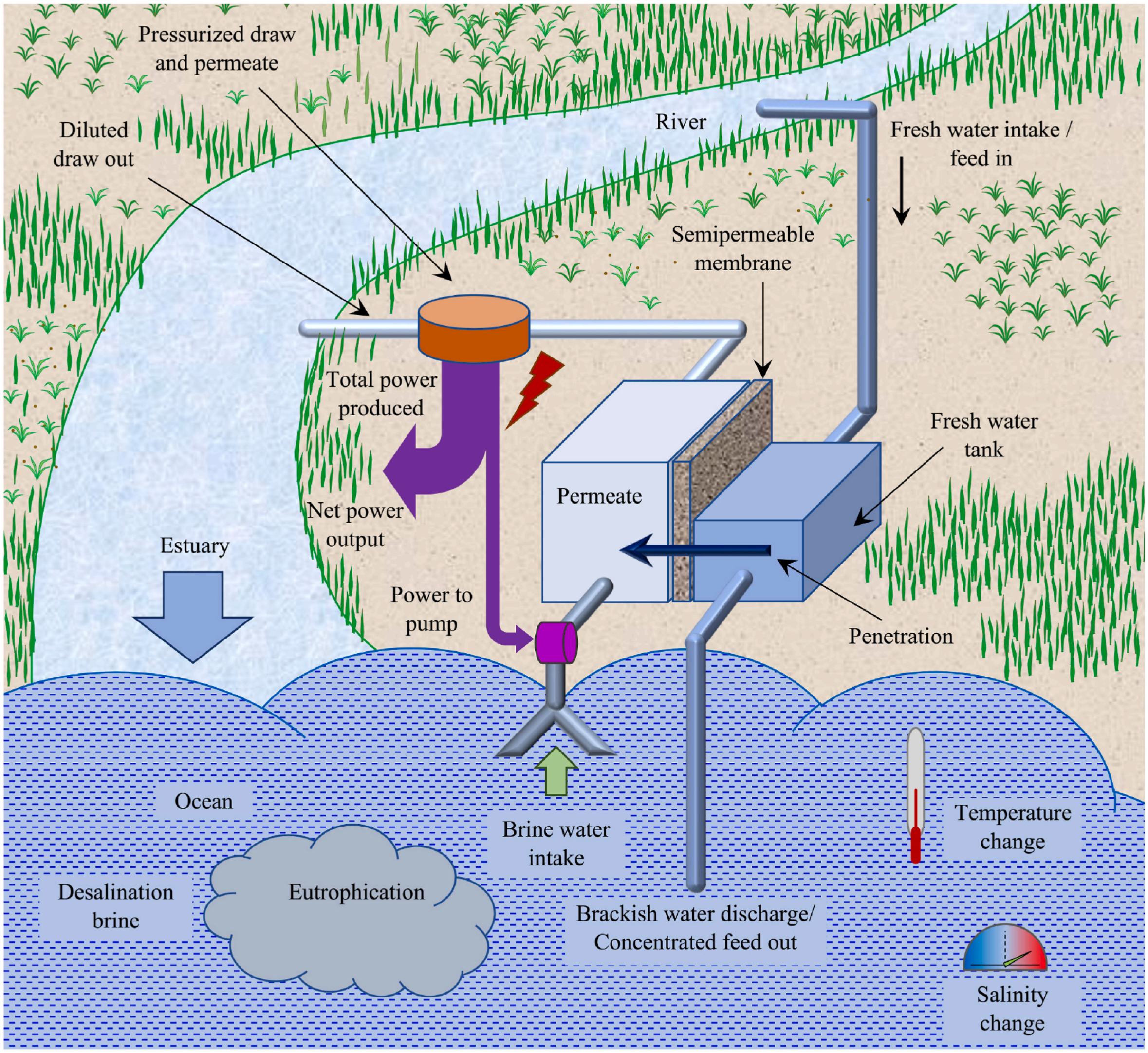


Fig. 8. An osmotic power plant with potential natural impacts.

Table 11
SWOT analysis of osmotic power plants.

Traits	Features
Strength	• Less land is required for proper operation [96]. • Energy density is around 0.75 kWh-m^{-3} [95]. • Efficiency is 91.1% [95].
Weakness	• Cleaning and maintenance require power shutdown. Discontinuation of power can be resolved by incorporating multiple cells. • Multiple cells require high investment.
Opportunity	• Input of this power plant is always available. • Pairing with desalination plant will reduce some environmental impacts [96].
Threat	• Increases the toxicity of water through cleaning chemicals [96]. • The salinity of shallow sea water changes [96]. • Velocity of river flow reduces [96]. • Eutrophication can occur from excessive nutrient discharge [96]. • Temperature of shallow level sea water changes [96].

scale. Proper policies and necessary measures should be taken into consideration to mitigate the problems. If this type of power plant is coupled with a desalination plant, some environmental impacts can be reduced.

Considering the power generating capacity and environmental impacts, wind turbines outperform all other RESs. They have the second largest power generating capacity and their impacts are much lower than many other third generation RESs. Their turbine blades should be colored with a non-reflecting coating, and one blade should be colored black to reduce the flickering effect and the death of birds. Sound insulation should be used to reduce the effect of noise.

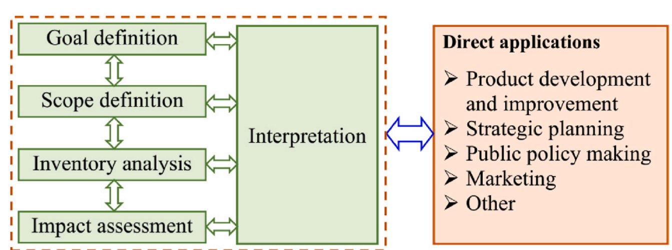


Fig. 9. The phases of LCA with its applications [97].

Biomass power plants can use existing coal power plants for proper operation which is considered to be a great advantage over other RESs. However, the amount of emissions should be minimized so as to reduce the impacts on nature. Advanced carbon capture, utilization and storage (CCUS) technologies should be used to capture the CO_2 from biomass power plants. The captured CO_2 can be compressed and utilized for other applications including in the food and oil industries [110]. Short

Table 12
Previous studies on LCA of different RES based power plants.

Type of powerplant	LCA method	Outcome	Reference
Solar PV	Eco-indicator 99	Perovskite solar cells show less stable CO_2 emissions. Sensitive analysis on these solar cells indicates that, if the performance and lifespan increase over time, these cells will become the most environmentally friendly among other solar cells.	[98]
CSP	ReCiPe 2016 and IPCC2013	Environmental impacts of CSPs with and without thermal storage units are measured. Results show that molten salt based thermal storage units are more natural ecosystem friendly than its counterparts. The study also finds that molten salts from the mines are better than synthesized salts in terms of impacts on nature.	[42]
Wind power plant	CML 2001	Impacts of wind-, nuclear-, and hydro-power-plants were compared. The study finds that wind power plants have the most impacts on nature. Moreover, the manufacturing phase of wind and hydro-power-plants were significant whereas the decommissioning phase of nuclear power plant was of greatest impact.	[99]
Biomass power plant	TRACI, ReCiPe 2008, and IMPACT 2000+	Feedstock production creates significant impact. Apart from the smog and ozone layer depletion, other categories were less impactful. Transportation distances also play a role in the greenhouse gas emissions.	[100]
Geothermal power plant	ILCD 2011 and ReCiPe 2016	Geothermal power plants showed better results than the existing national energy mix. However, when compared with solar PV and wind power plants, geothermal power plants cause greater environmental impacts.	[101]
Hydro power plant	Impact 2002+, IPCC, and ReCiPe 2016	The research focused on alpine and non-alpine region-based hydro power plants. Alpine regions are better than non-alpine regions in terms of CO_2 emissions and global warming potential. Comparison with other sources such as fossil fuel, wind, biomass, and photovoltaic based power plants show that hydro power plants are more suited for the environment.	[102]
Tidal power plant	CED and IPCC 2007	LCA on Severn Barrage shows that it has large environmental implications. The highest contribution came from its operational stage. The performance can be improved by excluding the flood pump which, in turn, will reduce the output power slightly.	[103]
Ocean power plant	ReCiPe 2016 and CED	LCA was conducted on first generation Pelamis wave energy converter. Results show that it has lower impact on the environment compared to conventional power plants. However, other RES based power plants demonstrate better performance than this	[104]

distance wood supply chains must be adopted to lessen the emissions associated with transportation, and the mix of sawmill woodchip should be less than 70%. It should be ensured that the growing of energy crops should not become a burden on food crops.

Geothermal power plants produce few impacts on the environment, most of which can be reduced by creating additional deep boreholes with electrical or thermal spallation drilling. However, if seismic activities become more frequent, then tapping energy by this method should be ceased to avoid catastrophic havoc.

Hydroelectric power plants are one of the oldest and most hazardous RESs. The hazards caused by this RES must be reduced through monitoring the impacts, setting appropriate policies, and forecasting future possible effects. Establishment of new hydroelectric dams should be halted for a sustainable environment. In future, when the dependence on fossil fuel is eliminated, policies should be made to remove these plants and restore the rivers which will be beneficial for nature.

Tidal stream generators change the behavior of nearby fish, alter the water velocity, and change the natural habitat. However, as the turbines rotate very slowly, the chance of fish fatality is low. Until future effects that are not perceived today are revealed, this RES can be used with proper measures. Costly tidal barrages can be installed in only 40 places worldwide. By using small turbines at a lower height, the effects on salt marshes and migratory birds can be reduced. However, this would significantly lower the power generation output, and the per unit energy cost will increase as a result. Feasibility studies should be made so as to assess the impacts on the environment and determine the per unit cost of energy.

Oceanic wave energy-based power plants have a variety of energy capturing devices. Onshore devices are comparatively less hazardous to nature. Submerged, bottom placed, and floating type devices are almost equally harmful for the environment. Hence, onshore devices should be used more, and extensive research should focus on ways to reduce the impacts of other devices. Energy from ocean currents is difficult to capture since they are far from the shoreline, and placement of turbines reduces the speed of current. If the current is stopped, then extreme climate conditions will be observed in many parts of the world. Ocean thermal power plants use ammonia which is a toxic chemical. Any form of leakage can be hazardous for nearby aquatic creatures. Hence, appropriate sites should be properly selected before installation. Osmotic power plants should be coupled with a desalination plant. The brine water output of osmotic power plants can be fed to the desalination plant. This method reduces the impacts caused by brine water discharge.

Table 13 accumulates all the impacts on nature due to each type of RES. Four colors are used to indicate the gravity of an impact. Orange and yellow colors indicate the high and moderate impacts, respectively, whereas green refers to beneficial impacts on the environment. The gray color denotes the power plants where no significant impacts have been found so far. The impacts can be categorized into five groups, namely air, water, soil, human related concerns, and miscellaneous. In the case of air, change in temperature, precipitation, and severe greenhouse gas emission are observed which is caused by hydroelectric power plants. Solar PV and CSP are also liable for greenhouse gas emission along with ozone layer depletion. Birds' ecosystem is hindered by many RESs. Significant numbers of birds die each year because of collision with wind turbines. On the other hand, reduction of salt marshes due to the use of tidal barrages affects the bird habitat and fewer birds migrate to that area. Apart from osmotic power plants, all RESs somehow affect the

Attribute	Order of the magnitude						Method
Acidification	3	1	6	2	5	4	ILCD 2011
	3	1	6	2	5	4	ReCiPe 2016
Freshwater eutrophication	6	5	2	1	4	3	ILCD 2011
	6	5	2	1	4	3	ReCiPe 2016
Freshwater ecotoxicity	5	6	2	1	3	4	ILCD 2011
	5	6	2	1	3	4	ReCiPe 2016
Land use	5	6	4	2	3	1	ILCD 2011
	6	5	2	1	4	3	ReCiPe 2016
Particulate matter	3	1	6	2	5	4	ILCD 2011
	3	1	6	2	5	4	ReCiPe 2016
Human toxicity (cancer effect)	5	6	2	1	3	4	ILCD 2011
	5	6	2	1	3	4	ReCiPe 2016
Human toxicity (non-cancer effect)	3	6	2	5	1	4	ILCD 2011
	6	5	2	1	3	4	ReCiPe 2016
Marine eutrophication	6	2	3	1	5	4	ILCD 2011
	6	5	2	1	4	3	ReCiPe 2016
Ozone depletion	6	2	1	5	4	3	ILCD 2011
	6	2	1	3	5	4	ReCiPe 2016
Water resource depletion	6	2	1	5	4	3	ILCD 2011
	6	5	2	1	3	4	ReCiPe 2016

Identification of power plants

Number	Color
6	
5	
4	
3	
2	
1	

Identification of the order of magnitude

Magnitude	Color
The highest	
Higher	
High	
Low	
Lower	
The lowest	

Identification of changes

Meaning	Color
The same	
Different	

Fig. 10. Comparison of LCA results with ILCD 2011 and ReCiPe 2016 based on 6 power plants where 1 indicates GPP operating with emission treatment plant, 2 refers to GPP without emission treatment plant, 3 represents GPP where 40% emission is released in nature, 4 refers to solar PV, 5 indicates wind power plant, 6 represents national energy mix [101]. The power plants are assigned certain colors for better visualization. If the successive orders from the results of the two methods do not match, then the colors of the power plants help identify the difference in their positions. ILCD 2011: [108], ReCiPe 2016 [109].

atmospheric environment.

In aquatic ecosystems, all RESs affect the nature except biomass. The most highly reported crisis, eutrophication, is caused by hydroelectric, ocean wave based, and osmotic power plants. This effect of osmotic power plants can be minimized by placing the discharge pipe in deep water. As for the other two power plants, reducing eutrophication is challenging. Suspended sediments are displaced by hydroelectric and tidal barrage systems. It changes the flow of water as observed in osmotic power plants. The change in water flow further affects the habitats of nearby aquatic creatures. As a result, the migration and mating processes of fish are hampered. The situation is exacerbated when the water becomes contaminated which causes the death of fish. Hydroelectric power plants harm the environment by drying up rivers, causing floods, changing the shape of deltas and lagoons, and changing the temperature and oxygen level of water, etc. The submerged power plants often hinder the movement of water vehicles and disrupt the coastline defense. Hydroelectric and tidal barrage systems have the highest impact whereas biomass and geothermal plants have minimal effects on the aquatic environment.

Observation from terrestrial impacts show that a hydroelectric power plant is hazardous, especially in terms of desiccation and erosion of soil. The drying up of rivers downstream of a hydroelectric dam result in detrimental effects on the soil. The soil cannot produce vegetation easily which further affects local communities. Earthquakes are observed because of the hydroelectric and geothermal power plants. Moreover, these power plants, along with biomass ones, require large land areas which could otherwise be used for food crops. Large land areas are also required for solar PV, CSP, and wind farms. These power plants change the terrestrial habitats of many wild animals including resettlement. Prolonged usage of these lands reduces the effectiveness of land fertility. Moreover, many power plants demand deforestation for their installation. During the lifetime of each power plant, installation, maintenance, and decommissioning processes causes both air and soil pollution. Maximum impact on land is caused by hydroelectric power plants whereas little to no impact is observed for aquatic power plants.

Many RES based power plants disturb humans and animals both visually and acoustically. All the power plants generate noise during their installation, operation, and maintenance phases. One exception to this is solar PV which is silent during its operational phase. Visual impact is created by wind turbines, CSPs, and floating type oceanic wave-based power plants that may hinder the movement of aircraft and water vehicles. Another problem related to humans is the resettlement of residential inhabitants. The most problematic power plants are hydroelectric and geothermal ones since they are able to be installed only in specific sites. Lastly, the complexity due to recycling is difficult within most of the power plants. Decommissioning of hydroelectric power plants is not only costly but also a challenging task since the original installation has already altered the geographic nature of the environment.

RES based power plants must be placed such that they do not cause much harm to the environment. Hydroelectric power plants, one of the most archaic RESs, are much more harmful than the others. Similarly, tidal barrages are also detrimental for the natural environment. Therefore, the attention of policy makers must be sought to restrict any upcoming hydroelectric and tidal barrage projects. Although solar PV generates large amounts of power, it should be carefully installed so that the impacts on nature can be minimized. By way of contrast, in terrestrial areas biomass power plants and wind turbine generators have the least impact on nature. Hence, they should be possible to implement on a large scale. In aquatic region, onshore power plant is preferred since it has lower impact on oceanic environment. RESs, installed on riverbanks, should be carefully monitored as rivers are directly affected by different types of RES based power plants.

LCA is a useful tool to identify the environmental impacts associated with any proposed system. However, in a study where six different power plants went through two different LCA methods (ILCD 2011 and ReCiPe 2016), the results showed that LCA methods are not exhaustive. The order of the power plants, based on the magnitude of certain impacts, differed from one LCA method to the other. This is due to the definition of midpoint criteria being different for the two methods.

Table 13
Environmental impacts of different RES based power plants.

	Environmental Impacts	RES based power plants											
		Solar PV	Solar thermal	Wind turbine	Biomass	Geothermal	Hydro-electric	Tidal barrage	Tidal stream	Ocean wave	Ocean Current	Ocean Thermal	Osmotic
Impacts related to air	Greenhouse gas emission	[30]	[30]			[53]	[60]						
	Ozone layer depletion	[27]											
	Air pollution	[30], [25]				[56]							
	Air toxification												
	Change in air temperature						[65]						
	Change in air precipitation						[59] [65]						
	Bird loss		[31]	[47]				[81]	[73]	[86] [87]			
	Affecting bird habitat	[25]						[81]	[73]				
	Affecting bird migration									[86]			
Impacts related to water	Ship movement									[86]			
	Water pollution	[32], [26]	[32]	[47]		[53]	[59]	[69], [77].			[91]	[93]	
	Water toxification					[53]				[86]	[91]	[93]	[96]
	Mating process of fish						[57] [59] [62]	[81]		[86]	[91]		
	Migration of fish and other aquatic animals						[57] [59]	[81]			[91]	[93]	
	Change in water temperature						[65]						[96]
	Affecting the flow of water						[62]	[69]	[70] [71]		[91]		[96]
	Change in water salinity												[96]
	Effect on suspended sediment						[59], [65]	[69], [77].	[72]				
	Eutrophication	[27]					[59], [65]			[86]	[91]	[93]	[96]
	Affecting aquatic habitat			[47]			[59]	[69], [75], [77].		[86]	[91]	[93]	
	Fish decline						[57]	[75]		[86] [87]			
	Flooding						[57] [58]						
	Dried up rivers						[59]						
	Oxygen level of water						[59]						
	Affecting deltas and lagoons						[62] [65]						
	Fisheries are affected						[62]				[91]		
	Coastline defense									[86]			
Impacts related to soil	Land requirement	[30]	[30]		[50]	[56]	[58]						[96]
	Soil pollution/disturbance	[29]		[47]									
	Soil toxification	[32]											
	Desiccated Soil						[60]						
	Erosion of soil			[47]			[57] [58] [65]						
	Effect on irrigation						[62]						
	Mangrove forests						[62]						
	Affects soil efficacy												
	Deforestation			[47]									
	Effect on vegetation	[29], [25]					[60]	[81]					
	Seismic activity					[54]							
	Relocation of wild animals	[25]											
	Affecting terrestrial habitat	[25]	[31]										

Impacts related to human	Human health	[32]		[47]									
	Disturbance to humans		[43]	[47]									
	Relocation of native residents					[56]	[65]						
	Visual disturbance		[30]	[46]									
	Unpleasant smell					[56]							
	Natural aesthetic affected			[46]									
	Tourism potential affected			[46]									
	Archeological places affected						[57] [58]						
Miscellaneous impacts	Availability based on time												
	Availability based on area					[53]							
	Power reduction after installation												
	Dependency on non-RES					[54]	[57]						
	Battery dependency	[32]											
	Installation noise			[46]		[54]				[86] [88]			
	Operation noise			[46]									
	Recycling complexity									[87]			
	Chance of accident	[32]	[43]										
	Water for cooling	[31]	[31]										
	Susceptible to storms												
	Communication of species affected			[47]							[91]		
	Predator inefficacy							[69]		[86]	[91]	[93]	
	Collision or entanglement								[73]	[87]	[91]	[93]	
	Impingement							[69]			[91]	[93]	
	Biodiversity			[47]						[86]	[91]	[93]	

Moreover, LCA data that are freely available are not comprehensive whereas useful LCA data are not readily available for all. Hence, there should be a unique and accurate LCA method that will only be used for RES based power plants so as to eliminate the potential for ambiguity in differing results. Furthermore, the outcomes of these analyses should be readily accessible in the public arena so that future researchers can work without any difficulty.

12. Conclusions

Anthropogenic interference is often detrimental for the environment. The desire for energy should not be so intense that the environmental impacts are overlooked. The adverse effects on the environment are not only caused by fossil fuels but RESs are also responsible as well. Comparatively, RESs are more viable since the impacts instigated are insignificant as compared to those of long-term traditional methods. Alternative energy sources should be sought so that the reliance on fossil fuel gets diminished while the energy demand is still met. Significant research must be conducted to fully understand the impacts and to find sustainable solutions so that human existence in this world can be prolonged.

In this paper, a comprehensive review has been carried out on the environmental impacts caused by RES based electrical power plants. In this review, all the possible RES based power plants including solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic are considered. It is found that each of the RESs has environmental impacts, however, these can be minimized by careful selection and the method of their utilization. The negative environmental impacts depend on the type of fuel/RES, size/scale, method of use, location and several factors as pointed out in this paper. For example, despite solar photovoltaics having many detrimental environment effects, the large amount of existing solar power plants makes it difficult to abate its use. However, by utilizing the rooftop area of buildings, the effect on land can be mitigated significantly. On the other hand, since only a few solar thermal power plants exist, their environmental impacts are not comprehensively investigated. Geothermal power plants, found in some specific places, can be deleterious for nature. Earthquakes caused by them could bring destruction of nearby wildlife. Hence, further installation of this type of plant should be carefully monitored.

Considering the severity of negative environmental impacts, hydroelectric power plants are found to be the most hazardous amongst all RESs. All leading national stakeholders should hold a summit, similar to the Paris Climate Change conference, where they pledge not to install any hydro plants in the future. When the use of fossil fuel comes to an end, measures should be taken to restore the rivers to the way they were.

Water based RESs have promising potential, but they can produce only a fraction of total generated power. Their effects on the environment can be reduced if the site selection is done properly. Moreover, behavior of fish and other sea creatures in the vicinity should be monitored regularly. Osmotic power plants are installed in only a few places throughout the world. The effect on nature caused by these plants is found to be lower compared to other RESs. If these are coupled with other solar thermal and salt-water refinement plants, then environmental benefits can be maximized.

Wind turbine generators demonstrate the least adverse environmental effects compared to others which make them the most sustainable renewable energy source. To maximize their utilization, more suitable sites should be explored where wind turbines can be installed. Precautionary steps should be taken to decrease their effects on the environment.

Accumulation of the substantial environmental impacts of multiple RES based power plants has previously been done in a few research articles and a detailed SWOT analysis is occasionally found. This review has extensively identified and tabulated the greater environmental impacts associated with all types of RES based power plants and provided the SWOT analysis for them so that policy makers, stakeholders, and decision makers in the energy sectors are well informed and can be benefited from it. The review found that the environment would become more sustainable if the RES based power plants are installed and operated properly. The detailed environmental impacts of the RES based power plants considering research gaps are presented in Table 13. This explores the full range of environmental impacts of different RES based power plants that will provide the future direction and strong point of reference for the researchers working further in this field. In future, further research is required to build a more exhaustive LCA method that will enable researchers to compare the impacts from different RES based power plants. The data and software associated with LCA must also be publicly available so that investigators can easily and accurately assess the impacts and take proper decisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Nomenclature

Short form	Full meaning
a-Si	Amorphous silicon
brine	Salty water of the sea
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CSP	Concentrated solar thermal
GPP	Geothermal power plants
HIT	Silicon heterostructure (heterojunction with intrinsic thin layer)
ITO	Indium doped Tin Oxide
LCA	Life cycle analysis
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
mono c-Si	Mono-crystalline silicon
OTEC	Ocean thermal energy conversion
OWE	Oceanic wave energy
poly c-Si	Poly-crystalline silicon
PRO	Pressure retarded osmosis
PV	Photovoltaic
RES	Renewable energy source

Terminologies

Term	Definition
Midpoint impact indicators	Impact categories that are analyzed in LCIA are called midpoint impact indicators.
Endpoint impact indicators	Every midpoint impact indicator has a final impact on any of the three following impact categories. 1. Human Health 2. Ecosystem quality 3. Natural resource scarcity These three are the main concern of protection. These are called endpoint impact indicators.
Acidification	It measures the acidic levels of terrestrial area. The unit used for this is kg SO_2 eq./kg emission
Climate change	It refers to the increase in greenhouse gas in air. It is expressed as kg CO_2 eq./kg emission
Freshwater eutrophication	It indicates the rise of algal bloom and other aquatic plants in water resources due to the increased intensity of nutrients in air, soil, and water. The unit used for this indicator is kg phosphorus eq./kg emission.
Freshwater ecotoxicity	It refers to the toxic level in freshwater sources caused by emission of toxic substance in air, water, and soil. The unit for this indicator is 1,4-dichlorobenzene eq./kg emission.
Particulate matter (PM)	It indicates a mixture of small particles such as droplets dust, metal, organic chemical substrates, and acids. This indicator is measured in kg PM 2.5-μm eq./kg emission.
Human toxicity (cancer effect)	In human environments, the level of toxic substance that causes carcinogenic effect is indicated by human toxicity. The unit for this indicator is 1,4-dichlorobenzene eq./kg emission.
Human toxicity (non-cancer effect)	In human environments, the level of toxic substance that does not produce carcinogenic effect is indicated by human toxicity (non-cancer effect). The unit for this indicator is 1,4-dichlorobenzene eq./kg emission.
Marine eutrophication	In euphotic zone of marine water, if the amount of nutrients increases, then eutrophication is observed. This is measured with the help of this indicator. The unit for this indicator is kg nitrogen eq./kg emission.
Ozone depletion	In stratospheric region, the level of ozone depletion is indicated by it. To measure this impact, the unit used here is kg CFC-11 eq./kg emission.
Water resource depletion	It refers to the volume (in m3) of water used per volume (in m^3) of water extracted from the reserved water source.
Algal bloom	Rapid rise of algae in marine water and freshwater ecosystems
Carcinogenic effect	An effect that will most likely cause cancer.
Euphotic zone	It is the layer of water that is exposed to sunlight by which phytoplankton can use photosynthesis.

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(*continued*)

Term	Definition
Eutrophication	It is the process where nutrients such as phosphate, nitrate etc. are increased in a water source. It results in increased aquatic plants which reduces the dissolved oxygen in water.
Toxic substance	A poisonous element that prompts health hazards.
Droplet	An extremely small drop of liquid.
Organic chemical substrate	A substrate that is made of carbon-hydrogen bonds. Most living creatures consist of organic chemicals.

References

[1] Rahman A, Aziz T, Nahid-Al-Masood, Deeba SR. A time of use tariff scheme for demand side management of residential A time of use tariff scheme for demand side management of residential. Energy Rep 2021;7:3189–98.
[2] Rodrigues E, Gomes Á, Gaspar AR, Antunes CH. Estimation of renewable energy and built environment-related variables using neural networks – a review. Renew Sustain Energy Rev 2018;94:959–88.
[3] Ma S, Chen G, Guo M, Zhao L, Han T, Zhu S. Path analysis on CO2 resource utilization based on carbon capture using ammonia method in coal-fired power Plants. Renew Sustain Energy Rev 2014;37:687–97.
[4] Maamoun N, Kennedy R, Jin X, Urpelainen J. Identifying coal-fired power plants for early retirement. Renew Sustain Energy Rev 2020;126:109833.
[5] Yang Y, Campana PE, Yan J. Potential of unsubsidized distributed solar PV to replace coal-fired power plants, and profits classification in Chinese cities. Renew Sustain Energy Rev 2020;131:109967.
[6] Clark R, Zucker N, Urpelainen J. The future of coal-fired power generation in Southeast Asia. Renew Sustain Energy Rev 2020;121:109650.
[7] Curtin J, McInerney C, Gallachóir BÓ, Hickey C, Deane P, Deeney P. Quantifying stranding risk for fossil fuel assets and implications for renewable energy investment: a review of the literature. Renew Sustain Energy Rev 2019;116:109402.
[8] Gürsan C, Gooyert V de. The systemic impact of a transition fuel: does natural gas help or hinder the energy transition? Renew Sustain Energy Rev 2021;138:110552.
[9] Renewables 2020. Global status report. REN21, [Online]. Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf. [Accessed 20 August 2020].
[10] Ritchie H, Roser M. Renewable energy," our world in data [Online]. Available: https://ourworldindata.org/renewable-energy. [Accessed 20 October 2021].
[11] Balaban G, Lazaroiu G, Dumbrava V, Sima C. Analysing renewable energy source impacts on power system national network code. Inventions 2017;2(3):23.
[12] Todeschini G. Review of tidal lagoon technology and opportunities for integration within the UK energy system. Inventions 2017;2(3):14.
[13] Maroufmashat A, Taqvi S, Miragha A, Fowler M, Elkamel A. Modeling and optimization of energy hubs: a comprehensive review. Inventions 2019;4(3):50.
[14] Hu J, Liu X, Shahidehpour M, Xia S. Optimal operation of energy hubs with large-scale distributed energy resources for distribution network congestion management. IEEE Trans Sustain Energy 2021;12(3):1755–65. Jul.
[15] Son Y-G, Oh B-C, Acquah MA, Fan R, Kim D-M, Kim S-Y. Multi energy system with an associated energy hub: a review. IEEE Access 2021;9:127753–66.
[16] Jensen J. Evaluating the environmental impacts of recycling wind turbines. Wind Energy 2019;22:316–26.
[17] Shao M, Han Z, Sun J, Xiao C, Zhang S, Zhao Y. A review of multi-criteria decision making applications for renewable energy site selection. Renew Energy 2020;157:377–403.
[18] Ganiyu SO, Martínez-Huitle CA, Rodrigo MA. Renewable energies driven electrochemical wastewater/soil decontamination technologies: a critical review of fundamental concepts and applications. Appl Catal B Environ 2020;270. Art no. 118857.
[19] Gao C-k, Na H-m, Song K-h, Dyer N, Tian F, Xu Q-j, Xing Y-h. Environmental impact analysis of power generation from biomass and wind farms in different locations. Renew Sustain Energy Rev 2019;102:307–17.
[20] Liu Y, Zhang Mengya. Unpacking stereotypes about sustainable energy: knowledge, policy, and public misperceptions of solar energy and coal in China. Energy Res Social Sci 2021;71. Art. no. 101832.
[21] Hosenuzzaman M, Rahim N, Selvaraj J, Hasanuzzaman M. Global prospects, progress, policies, and environmental impact of solar. Renew Sustain Energy Rev 2015;41:284–97.
[22] Muhammad Tawalbeh AA-O, Kafiah F, Abdelsalam E, Almomani F, Alkasrawi M. Environmental impacts of solar photovoltaic systems: a critical review of recent progress and future outlook. Sci Total Environ 2021;759. Art. no. 143528.
[23] McCormick P, Suehrcke H. The effect of intermittent solar radiation on the performance of PV systems. Sol Energy 2018;171:667–74.
[24] Schileo G, Grancini G. Lead or no lead? Availability, toxicity, sustainability and environmental impact of lead-free perovskite solar cells. J Mater Chem C 2021;9(1):67–76.
[25] Laine DC. Effects of solar power farms on the environment. 24 4 Sciencing 2017 [Online]. Available: https://sciencing.com/effects-solar-power-farms-environment-13547.html. [Accessed 31 January 2020].
[26] D. Mulvaney, "Solar energy isn't always as green as you think," IEEE Spectrum, 13 Nov. 2014. [Online]. Available: https://spectrum.ieee.org/greentech/solar/solar-energy-isnt-always-as-green-as-you-think. [Accessed 31 01 2020].
[27] Celik I, Mason BE, Phillips AB, Heben MJ, Apul D. Environmental impacts from photovoltaic solar cells made with single walled carbon nanotubes. Environ Sci Technol 2017;51(8):4722–32. FEb.
[28] Healy ML, Dahlben LJ, Isaacs JA. Environmental assessment of single-walled carbon nanotube processes. J Ind Ecol 2008;12(3):376–93.
[29] Balali MH, Nouri N, Omrani E, Nasiri A, Otieno W. An overview of the environmental, economic, and material developments of the solar and wind sources coupled with the energy storage systems. Int J Energy Res 2017;41:1948–62. May.
[30] Environmental impacts of solar power," Union of Concerned Scientists, 05 03 2013. [Online]. Available: https://www.ucsusa.org/resources/environmental-impacts-solar-power#references. [Accessed 01 02 2020].
[31] Hernandez R, Easter S, Murphy-Mariscal M, Maestre F, Tavassoli M, Allen E, Barrows C, Belnap J, Ochoa-Hueso R, Ravi S, Allen M. Environmental impacts of utility-scale solar energy. Renew Sustain Energy Rev 2014;29:766–79.
[32] Tsoutsos T, Frantzeskaki N, Gekas V. Environmental impacts from the solar energy technologies. Energy Pol 2005;33:289–96.
[33] Harrisons Energy. How long does a solar panel last?. 25 Jun Harrisons Energy 2021 [Online]. Available: https://www.harrisonsenergy.co.nz/article/how-long-does-a-solar-panel-last. [Accessed 2 October 2021].
[34] Sendy A. How long do solar panels actually last?. 5 May Solar Reviews 2021 [Online]. Available: https://www.solarreviews.com/blog/how-long-do-solar-panels-last. [Accessed 2 October 2021].
[35] Cheng J, Yeh C, Tu C. Trust and knowledge sharing in green supply chains. Supply Chain Manag Jun. 2008;13(4):283–95.
[36] Laleman R, Albrecht J, Dewulf J. Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renew Sustain Energy Rev 2011;15(1):267–81.
[37] Gong J, Darling SB, You F. Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts. Energy Environ Sci 2015;8:1953–68.
[38] Kopidakis N. Best research-cell efficiency chart. NREL, 4 Jan. 2021. [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html. [Accessed 25 September 2021]. Accessed.
[39] M. M. Njore and J. E. Sinton, "WorldBank CSP report - concentrating solar power - clean power on demand 24/7 - FINAL," World Bank, 27 Jan. 2021. [Online]. Available: https://pubdocs.worldbank.org/en/849341611761898393/WorldBank-CSP-Report-Concentrating-Solar-Power-Clean-Power-on-Demand-24-7-FINAL. [Accessed 3 Oct. 2021].
[40] Ho CK. Safety of thermal energy storage systems for concentrating solar power plants. 2017 [Online]. Available: https://www.osti.gov/servlets/purl/1431547. [Accessed 2 February 2022].
[41] Laing D, Steinmann WD, Viebahn P, Gräter F, Bahl C. Economic analysis and life cycle assessment of concrete thermal energy storage for parabolic trough power plants. ASME. J. Sol. Energy Eng. 2010;132(4). Art no. 041013, Nov.
[42] Gasa G, Lopez-Roman A, Prieto C, Cabeza LF. Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with and without thermal energy storage (TES). Sustainability 2021;13(7). Art. no. 3672, Mar.
[43] Breeze P. Chapter 11 - solar integration and the environmental impact of solar power. In: Solar power generation. Academic Press; 2016. p. 81–7.
[44] Alhaj M, Al-Ghamdi SG. Integrating concentrated solar power with seawater desalination technologies: a multi-regional environmental assessment. Environ Res Lett 2019;14(7):074014. Art. no.
[45] Kouloumpis V, Sobolewski RA, Yan X. Performance and life cycle assessment of a small scale vertical axis wind turbine. J Clean Prod 2020;247. Art. no. 119520.
[46] Nazir MS, Mahdi AJ, Bilal M, Sohail HM, Ali N, Iqbal HM. Environmental impact and pollution-related challenges of renewable wind energy paradigm – a review. Sci Total Environ 2019;683:436–44.
[47] Nazir MS, Ali N, Bilal M, Iqbal HM. Potential environmental impacts of wind energy development: a global perspective. Curr Opin Environ Sci health 2020;13:85–90.
[48] May R, Nygård T, Falkdalen U, Åström J, Hamre Ø, Stokke BG. Paint it black: efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. Ecol Evol 2020;10:8927–35.
[49] González-Longatt F, Wall P, Terzija V. Wake effect in wind farm performance: steady-state and dynamic behavior. Renew Energy 2012;39(1):329–38.
[50] Biomass and the environment. 25 October [Online]. Available: https://www.eia.gov/energyexplained/biomass/biomass-and-the-environment.php. [Accessed 29 February 2020].

[51] Dilthey MR. Negative effects of biomass. Sciencing, 25 April 2018. [Online]. Available: https://sciencing.com/negative-effects-biomass-19624.html. [Accessed 4 March 2020].
[52] Paletto A, Bernardi S, Pieratti E, Teston F, Romagnoli M. Assessment of environmental impact of biomass power plants to increase the social acceptance of renewable energy technologies. Heliyon 2019;5(7). Art. no. e02070.
[53] Bravi M, Basosi R. Environmental impact of electricity from selected geothermal power plants in Italy. J Clean Prod 2014;66:301–8.
[54] Menberg Kathrin, Pfister S, Blum P, Bayer P. A matter of meters: state of the art in the life cycle assessment of enhanced geothermal systems. Energy Environ Sci 2016;9(9):2720–43.
[55] Chiba A, et al. Removal of arsenic from geothermal water by high gradient magnetic separation. IEEE Trans Appl Supercond March 2002;12(1):952–4.
[56] Mariita NO. The impact of large-scale renewable energy development on the poor: environmental and socio-economic impact of a geothermal power plant on a poor rural community in Kenya. Energy Pol 2002;30(11–12):1119–28.
[57] 13 Nov Hydropower explained: hydropower and the environment. US Energy Information Administration; 2019 [Online]. Available: https://www.eia.gov/energyexplained/hydropower/hydropower-and-the-environment.php. [Accessed 10 February 2020].
[58] Fearnside PM. Brazil's Balbina dam: environment versus the legacy of the pharaohs in Amazonia. Environ Manag Aug. 1989;13(4):401–23.
[59] Fearnside PM. Environmental and social impacts of hydroelectric dams in Brazilian Amazonia: implications for the aluminum industry, vol. 77. World Development; 2016. p. 48–65.
[60] Electricity from renewable resources: status, prospects, and impediments. Washington, D.C: THE NATIONAL ACADEMIES PRESS; 2010.
[61] Edenhofer O, Madruga RP, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, Stechow C von. Renewable energy sources and climate change mitigation: special report of the intergovernmental panel on climate change. New York, NY, USA: Cambridge University Press; 2012.
[62] Ezcurra E, Barrios E, Ezcurra P, Ezcurra A, Vanderplank S, Vidal O, Villanueva-Almanza L, Aburto-Oropeza O. A natural experiment reveals the impact of hydroelectric dams on the estuaries of tropical rivers. Sci Adv 2019;5(3). eaau9875, Mar.
[63] Santos E A dos, Medeiros MB, Ferreira EJ, Simon MF, Oliveira WL, Costa FR. Palm distribution patterns in the southwestern Brazilian Amazon: impact of a large hydroelectric dam. For Ecol Manag 2020;463. Art. no 118032.
[64] da Rocha M, de Assis R, Piedade M, et al. Thirty years after Balbina Dam: diversity and floristic composition of the downstream floodplain forest, Central Amazon, Brazil. Ecohydrology Aug. 2019;12(8):2144.
[65] Xu X, Tan Y, Yang G. Environmental impact assessments of the three Gorges project in China: issues and interventions. Earth Sci Rev 2013;124:115–25.
[66] 09 May Tidal energy. OpenEI; 2019 [Online]. Available: https://openei.org/wiki/PRIMRE/MRE_Basics/Tidal_Energy#:~:text=Energy%20is%20collected%20when%20the,have%20been%20identified%20as%20feasible. [Accessed 19 September 2020].
[67] Using the power of the tidal streams to generate electricity [Online]. Available: http://www.alternative-energy-tutorials.com/tidal-energy/tidal-stream.html. [Accessed 18 February 2020].
[68] Orhan K, Mayerle R. Assessment of the tidal stream power potential and impacts of tidal current turbines in the Strait of Larantuka, Indonesia. Energy Proc 2017; 125:230–9.
[69] El-Geziry TM, Bryden IG, Couch SJ. Environmental impact assessment for tidal energy schemes: an exemplar case study of the Strait of Messina. J Marine Eng Technol 2009;8(1):39–48.
[70] Ahmadian R, Falconer R, Bockelmann-Evans B. Far-field modelling of the hydro-environmental impact of tidal stream turbines. Renew Energy 2012;38(1): 107–16.
[71] Ramos V, Carballo R, Álvarez M, Sánchez M, Iglesias G. Assessment of the impacts of tidal stream energy through high-resolution numerical modeling. Energy 2013; 61:541–54.
[72] Li X, Li M, Amoudry LO, Ramirez-Mendoza R, Thorne PD, Song Q, Zheng P, Simmons SM, Jordan L-B, McLelland SJ. Three-dimensional modelling of suspended sediment transport in the far wake of tidal stream turbines. Renew Energy 2020;151:956–65.
[73] Isaksson N, Masden EA, Williamson BJ, Costagliola-Ray MM, Slingsby J, Houghton JD, Wilson J. Assessing the effects of tidal stream marine renewable energy on seabirds: a conceptual framework. Mar Pollut Bull 2020;157. Art. no. 111314.
[74] Fraser S, Williamson BJ, Nikora V, Scott BE. Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation. Energy Rep 2018;4:65–9.
[75] Bevelhimer M, Scherelis C, Colby J, Adonizio MA. Hydroacoustic assessment of behavioral responses by fish passing near an operating tidal turbine in the east river, New York. Trans Am Fish Soc 2017;146(5):1028–42.
[76] Environmental monitoring for marine energy," Pacific Northwest National Laboratory, [Online]. Available: https://www.pnnl.gov/environmental-monitoring-marine-energy#:~:text=Tidal%20currents%20create%20tidal%20energy,energy%20into%20power%20using%20tides.&text=Even%20in%20the%20fastest%20currents,about%208%20rotations%20per%20minute.. [Accessed 20 Sep. 2020].
[77] Vybulkova L, Vezza M, Brown R. Simulating the environmental impact of tidal turbines on the seabed. In: 2013 oceans; 2013. San Diego.
[78] Roberts A, Thomas B, Sewell P, Khan Z, Balmain S, Gillman J. Current tidal power technologies and their suitability for applications in coastal and marine areas. J Ocean Eng Marine Energy 2016;2:227–45.
[79] Parker DM. Environmental implications of tidal power generation. IEE Proc Sci Meas Technol 1993;140(1):71–5.
[80] Frid C, Andonegi E, Depestele J, Judd A, Rihan D, Rogers SI, Kenchington E. The environmental interactions of tidal and wave energy generation devices. Environ Impact Assess Rev 2012;32(1):133–9.
[81] Hooper T, Austen M. Tidal barrages in the UK: ecological and social impacts, potential mitigation, and tools to support barrage planning. Renew Sustain Energy Rev 2013;23:289–98.
[82] Wolf J, Walkington IA, Holt J, Burrows R. Environmental impacts of tidal power schemes. Proc Institution Civil Eng Maritime Eng 2009;162(4):165–77.
[83] Molla S, Farrok O, Rahman A, Bashir MS, Islam MR, Kouzani AZ, Mahmud MAP. Increase in volumetric electrical power density of a linear generator by winding optimization for wave energy extraction. IEEE Access 2020;8:181605–18.
[84] Farrok O, Ahmed K, Tahlil A, Farah M, Kiran M, Islam M. Electrical power generation from the oceanic wave for sustainable advancement in renewable energy technologies. Sustainability 2020;12. Art. no. 2178.
[85] Kiran MR, Farrok O, Abdullah-Al-Mamun M, Islam MR, Xu W. Progress in piezoelectric material based oceanic wave energy conversion technology. IEEE Access 2020;8:146428–49.
[86] Boehlert GW, Gill AB. Environmental and ecological effects of ocean renewable energy developmen: a current synthesis. Oceanography 2010;23(2):68–81.
[87] Rahman A, Farrok O, Islam MR, Xu W. Recent progress in electrical generators for oceanic wave energy conversion. IEEE Access Jul. 2020;8:138595–615.
[88] Copping A, Battey H, Brown-Saracino J, Massaua M, Smith C. An international assessment of the environmental effects of marine energy development. Ocean Coast Manag 2014;99:3–13.
[89] McCauley RD, et al. Marine seismic surveys—a study of environmental implications. APPEA J 2000;40(1):692–708.
[90] Walsh J, Bashir I, Thies PR, Johanning L, Blondel P. Acoustic emission health monitoring of marine renewables: Illustration with a wave energy converter in Falmouth Bay (UK). In: Oceans 2015 - Genova. Genoa; 2015.
[91] Finkl CW, Charlier R. Electrical power generation from ocean currents in the Straits of Florida: some environmental considerations. Renew Sustain Energy Rev 2009;13(9):2597–604.
[92] B. Barnier, A. Domina, S. Gulev, J.-M. Molines, T. Maitre, T. Penduff, J. L. Sommer, P. Brasseur, L. Brodeau and P. Colombo, "Modelling the impact of flow-driven turbine power plants on great wind-driven ocean currents and the assessment of their energy potential," Nat Energy, vol. 5, p. 240–249, Mar. 2020.
[93] Devis-Morales A, Montoya-Sánchez RA, Osorio AF, Otero-Díaz LJ. Ocean thermal energy resources in Colombia. Renew Energy 2014;66:759–69.
[94] Mendoza E, Lithgow D, Flores P, Felix A, Simas T, Silva R. A framework to evaluate the environmental impact of OCEAN energy devices. Renew Sustain Energy Rev 2019;112:440–9.
[95] Yip NY, Elimelech M. Thermodynamic and energy efficiency analysis of power generation from natural salinity gradients by pressure retarded osmosis. Environ Sci Technol 2012;46(9):5230–9.
[96] Helfer F, Lemckert C, Anissimov YG. Osmotic power with pressure retarded osmosis: theory, performance and trends – a review. J Membr Sci 2014;453: 337–58.
[97] International Organization for Standardization. Geneva, Switzerland: ISO; 2006. *ISO 14040:2006—Environmental Management—Life Cycle*.
[98] Gong J, Darling SB, You F. Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts. Energy Environ Sci 2015;8:1953–68.
[99] Wang L, Wang Y, Du H, Zuo J, Li RYM, Zhou Z, Bi F, Garvlehn MP. A comparative life-cycle assessment of hydro-, nuclear and wind power: a China study. Appl Energy Sep. 2019;249:37–45.
[100] Weldu YW. Life cycle human health and ecosystem quality implication of biomass-based strategies to climate change mitigation. Renew Energy Aug. 2017; 108:11–8.
[101] Basosi R, Bonciani R, Frosali D, Manfrida G, Parisi ML, Sansone F. Life cycle analysis of a geothermal power plant: comparison of the environmental performance with other renewable energy systems. Sustainability 2020;12(7). Art. no. 2786.
[102] Mahmud MAP, Huda N, Farjana SH, Lang C. A strategic impact assessment of hydropower plants in alpine and non-alpine areas of Europe. Appl Energy 2019; 250:198–214.
[103] Kelly K, McManus M, Hammond G. An energy and carbon life cycle assessment of tidal power case study: the proposed Cardiff–Weston Severn barrage scheme. Energy 2012;44(1):692–701.
[104] Thomson R, Chick J, Harrison G. An LCA of the Pelamis wave energy converter. Int J Life Cycle Assess 2019;24:51–63.
[105] Maranghi S, Brondi C. Life cycle assessment in the chemical product chain. Springer International Publishing; 2020.
[106] Dreyer L, Niemann A, Hauschild M. Comparison of three different LCIA methods: EDIP97, CML2001 and eco-indicator 99. Int J Life Cycle Assess 2003;8(4): 191–200.
[107] Stavropoulos P, Giannoulis C, Papacharalampopoulos A, Foteinopoulos P, Chryssolouris G. Life cycle analysis: comparison between different methods and optimization challenges. Procedia CIRP 2016;41:626–31.

[108] Chomkhamsri K, Wolf M-A, Pennington D, Pant R, Sala S. The international reference life cycle data system (ILCD) handbook. EU publications; 2012.
[109] Huigbregts M, et al. ReCiPe 2016, A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization. Bilthoven, The Netherlands: National Institute for Public Health and the Environment; 2016.
[110] Internation Energy Agency. About CCUS. Technology Report — April. 2021. [Online]. Available: https://www.iea.org/reports/about-ccus. [Accessed 3 October 2021]. Accessed.