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Review

Review of Photovoltaic Power and Aquaculture in Desert

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Abstract: PV (photovoltaic) capacity is steadily increasing every year, and the rate of increase is also increasing. A desert area with a large equipment installation area and abundant solar radiation is a good candidate. PV power plants installed in the desert have advantages in themselves, but when combined with desert aquacultures, additional benefits can be obtained while compensating for the shortcomings of the aquaculture industry. The importance of the aquaculture industry is increasing, with aquaculture products approaching half of the total supply of marine products due to sea environmental pollution and reduced resources. Moreover, in deserts, where marine products are difficult to obtain, aquaculture is a good way to save marine products. However, one of the many problems that complicate the introduction of aquaculture in the desert is that it is difficult to supply and demand electricity because the site is not near a viable electric grid. However, combination with PV can solve this problem. This paper investigates the solar power and aquaculture industry in the desert and explains the limitations and challenges of the solar power and aquaculture industry in the desert. Based on this, we hope to increase interest in the solar power and aquaculture industry in the desert and help with future research.

Keywords: solar power; aquaculture in desert; aquaculture; challenges; possibilities; desert

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1. Introduction

Solar energy consumption has been rapidly increasing all over the world. Solar PV (photovoltaic) capacity has increased approximately 20 times, from 39 GW (GigaWatt) in 2010 to 760 GW in 2020. This capacity growth is steadily increasing every year and, even compared to 2019, it increased by 139 GW [1].

The SGDs (Sustainable Development Goals) were established in 2015 to ensure that the world population can enjoy peace and prosperity by 2030. There are a total of 17 SGDs, and each goal must balance social, economic, and environmental sustainability. One of the SGDs is affordable and clean energy [2]. PV, one form of affordable and clean energy, is associated with environmentally friendly and socially beneficial economic activities [3]. For this reason, many countries are using large subsidies to promote the development of PV [4].

CSP (Concentrated Solar Power) and PV power is suitable for installation in the desert, with high thermal and solar irradiation and extensive land [5]. There are differences in technical features between CSP and PV. For instance, CSP presents a more mature, lower-cost technology and easy grid integration platform when compared to PV power [6].

On the other hand, PV is superior to CSP in terms of annual power production and land utilization, and the initial investment cost is also low [7]. Therefore, based on the meteorological and economic conditions, CSP or PV should be selected as suitable systems to be implemented in each desert to obtain the most efficient energy production.

The PV system has various problems, such as uncertain PV generation, supply–demand imbalance, voltage variation, and system frequency deviation, depending on the natural conditions. To eliminate these problems, a method of integrating PV and an ESS (Energy Storage System) has been proposed. A PV-integrated ESS is a suitable option for continuous and uninterrupted power supply [8]. Among the various EESs, the BESS (Battery Energy Storage System) is gaining popularity in the global energy market, with its characteristics such as usefulness in isolated microgrid systems, versatility, scalability, and modularity [9].

Aquaculture has been increasing for the past decade, with advanced technologies and high production. Aquaculture activities in the desert provide food sources for domestic citizens living in the desert quickly and conveniently, at a more reasonable price than importing them from other areas or other countries. In addition, deserts have favorable conditions for the development of aquaculture. For instance, the water resources in the desert are mostly groundwater resources, and they are often clean because they are not affected by other factors such as wastewater from humans, as well as from industry. Therefore, the water quality parameters are often suitable for fish culture as well as other species, rather than only cheap land.

However, aquaculture in the desert is not always advantageous. In desert conditions, there are limitations for developing technologies, as well as the diversification of cultured species. It is known that the environment in the desert is severe. For example, there is a large temperature difference between day and night and between seasons, and a lack of fresh water available for aquaculture, etc.

In addition, it is difficult to access electricity because of the vast distance from a viable grid for use in aquaculture. Therefore, to solve these problems, a method of performing solar energy generation and aquaculture together is preferred. Specifically, the development of aquaculture consolidation with solar energy in the desert is necessary. This is not only to supply food for people who live in the desert but also can be active in providing energy for aquaculture, as well as for people who live nearby. The generated electricity can be supplied not only to people in the desert and other close-by regions but also for aquaculture activities in the desert.

During the surveying of the related research, we reviewed many types of literature related to combining solar power and aquaculture [10,11]. However, the studies were conducted in an environment other than the desert. We believed that a system in the form of combining PV and aquaculture in the desert had advantages and novelty. Therefore, we reviewed the literature on solar power and aquaculture in the desert and suggested the possibility of combining the two methods.

The review indicates the status and the potential of the application of solar energy for the development of the aquaculture industry in desert regions recently, as well as worldwide in the future. Moreover, there are challenges for solar power systems in desert conditions. Using solar energy for aquacultures in the desert might be plausible based on the experience of applying solar power for aquaculture in inland areas. We hope to increase interest in solar energy and aquaculture in the desert and help with future research.

The structure of this paper is as follows. Section 2 describes the PV power plants and the aquaculture system in the desert. Section 3 describes the challenges of the PV power plants and the aquaculture system in the desert. Section 4 discusses aquaculture in the form of combining the two systems and presents directions for future research. Lastly, the conclusions of Section 5 summarize this paper and explain the expected impacts.

2. PV Power Plants and Aquaculture System in Desert

2.1. Solar Cells and PV System

A solar cell is a device that converts light energy directly into electricity by the photovoltaic effect that generates voltage and current in a material when exposed to light [12]. An individual solar cell device is a component of a PV module, which forms a PV system along with a PV module and various devices and systems. Figure 1 shows the components of a PV system.

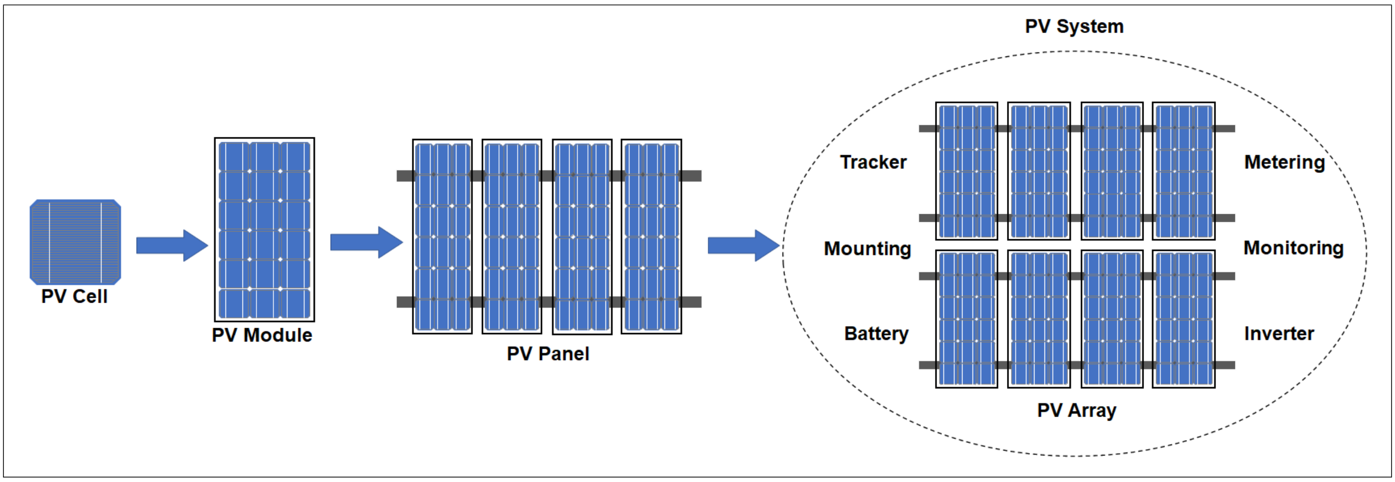

Figure 1. PV system.

PV modules form a PV array through the mounting system and are fixed to the ground or roof. The direction of the installed PV array may be adjusted through the tracker to receive more solar light. The DC (Direct Current) generated by the PV array is converted into AC (Alternating Current) through an inverter and stored through battery energy storage systems. The generated energy is measured and monitored by the metering and monitoring system before being transferred to the inverter.

PV affects various aspects, such as the economy, environment, society, and aesthetics. Renewable energy is more eco-friendly than conventional energy. A.K. Akella et al. discussed the impact of renewable energy systems on society, economy, and the environment [13]. Sánchez-Pantoja, N. et al. analyzed the aesthetic effects of solar energy systems on various factors, including land use and glare [14]. To alleviate disadvantages and gain advantages, the government is engaging in efforts to increase renewable energy use through subsidies to alleviate the initial investment burden and implement awareness improvement policies.

2.2. Possibility of Combining PV Power Plants and Aquaculture System in Desert

To combine solar power plants and aquaculture systems, it is important to select a location where the two systems can be installed and then select a location where they overlap, or to find an area that offsets the drawbacks of each one by installing both systems. In general, there are many approaches that have been considered before the installation of solar power plants. In particular, attention has been focused on the impact of PV and CSP power systems on the environment from the producing stages [15], installation, and operation stage [16]. For instance, before installing a PV power system, there are many studies that have to be conducted on natural environmental changes [17,18], impacts related to climate change [19], the ecosystem (wildlife) [20], water resources (underground water) [21], and the use of the land area for solar power plants rather than other energy projects [22], as well as the emission of hazardous materials from PV module manufacturing [23–26].

To solve the above issues and augment solar energy production, the desert area has been considered [27]. Solar energy from the desert has received much more attention in many countries around the world. There are several deserts where PV as well as CSP power plants have been installed. The desert areas in the world are presented in Table 1. Depending on the desert area, each region has a different level of solar irradiation. The highest solar irradiation is presented in the Sahara. In addition, Figure 2 shows a solar pyramid.

Table 1. The desert areas around the world.

Position	Name of Desert	Area (10^6 ha) [28]	Average Solar Irradiation ($MJ/m^2/d$) [29]
North America	Great basin	49	20.32
	Chihuahuan	45	19.68
	Sonoran	31	17.21
South Africa	Patagonian	67	12.81
	Atacama	36	22.08
Africa	Sahara	907	26.46
	Kalahari	57	22.54
Asia	Arabia	246	22.24
	Gobi	130	16.53
	Thar	60	21.44
	Takia Makan	52	16.19
	Kara kum	35	16.34
	Kyzyl kum	30	16.34
	Kavir	26	18.33
	Lut	5	5
Australia	Great Victoria	65	21.57
	Great Sandy	40	23.11
	Simpson	15	21.57
Total		1896	339.76

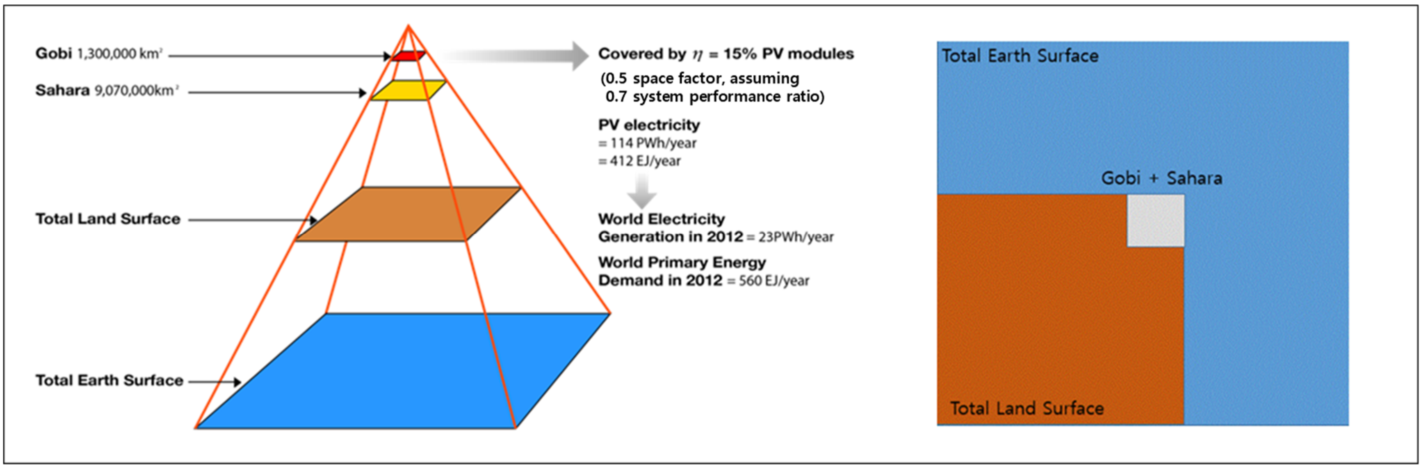

Figure 2. Solar pyramid.

Table 1 shows the desert area and the corresponding amount of solar irradiation across the world. However, not all deserts present a feasible location for the installation of PV power plants.

Through researching several factors, such as environmental factors, policies, sites, and human factors, there are some desert areas that have been recently chosen or are expected to be chosen for the installation of PV power—for example, Negev, Thar, Gobi, Sonora, Sahara, and Great Sandy [27]. Figure 3 shows some potential installations of PV power plants in deserts around the world [6].

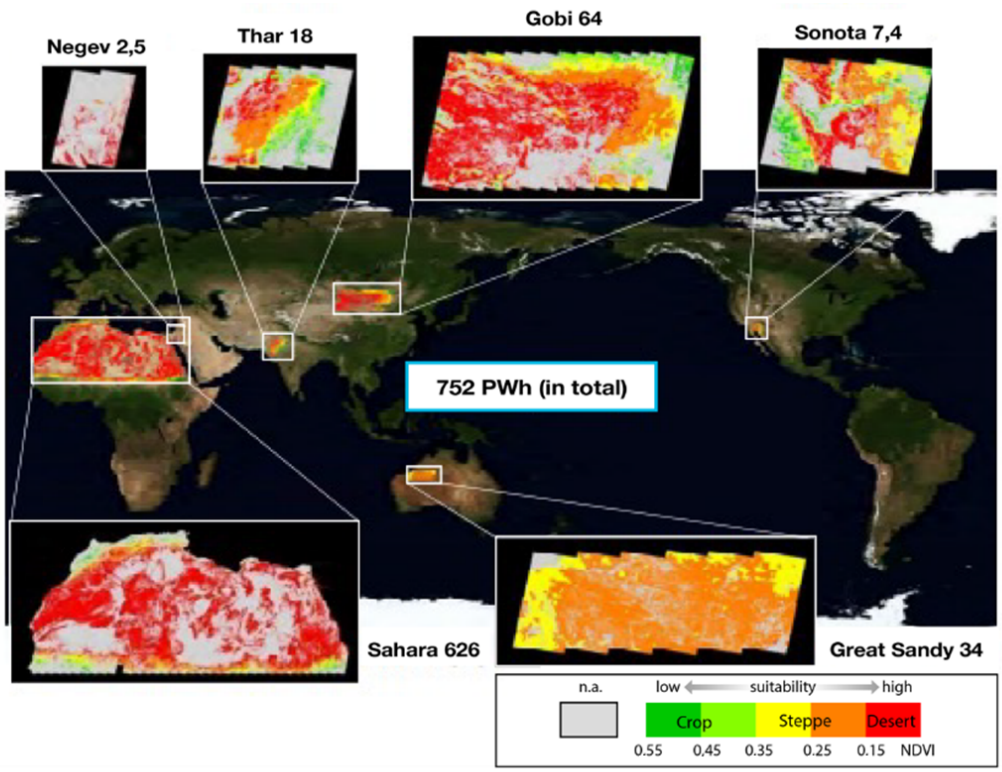

Figure 3. Some potential installations of PV power plants in deserts around the world.

Cases such as Israel, one of the earliest countries to develop aquaculture in the desert condition, also face the same challenges in operating fish farms, which require a great deal of time to set up and complete. Moreover, there are three culture technologies, namely RAS (Recirculation Aquaculture Systems), cages, and opened tanks [30,31], with different popular cultured species, including fresh species with underground water, such as silver perch [32,33], black bream [34], tilapia, carp, and catfish [31]; and marine species with saline underground water, such as rainbow trout [33,35] and artemia [30]. There is less diversity of cultured species in the desert than in aquaculture on land because the environmental conditions are only suitable for some species in the desert. The production of aquacultures in the desert has shown some positive results. Figure 4 shows a graphical abstract of solar power and aquaculture in the desert.

2.3. PV Power Plants in Desert

With the advantages of a wide area of land and solar irradiation, PV power plants have recently been gradually increasing in desert areas all over the world.

Parker et al. [36] evaluated that the Mojave Desert has the potential to develop renewable energy, particularly solar power plants. Lately, the Mojave PV power plant has become known as the largest desert plant in the world, with 250 MW (MegaWatt) of solar electricity generated in the designed production system [37]. Considering the case of the Sahara Desert, it is said that the Sahara Desert has significant potential to build a PV power plant as it is near to and can supply electricity for people in North Africa, as well as for sale in Europe, especially in Southern Europe [38]. CPV (Concentrated PV) and VLS-PV (Very Large Scale PV) are the most prevalent technologies in this area because of the cost-effective installation, with three types, named type 1, type 2, and type 3, with three different lifetimes of around 30 years, 20 years, and 34 years, respectively. In the beginning, the target energy production was approximately 1 GW; then, over time, this can be scaled up to 10 GW [6]. Based on the vast energy of the sun, Amin Al-Habaibeh and other scientists showed that it is possible to generate a huge amount of energy from the sun of over 22 billion GWh per year [39]. On the edge of the Sahara Desert, which belongs to Southern Morocco, the Noor Power Plant, a CSP plant, is installed, with an energy capacity of 510 MW [40,41]. However, it has been shown that although a large-scale PV power plant is installed and can cover the energy demands for the whole world, this type of installation can also affect the global climate and the desert's vegetation. On the other edge of the Sahara Desert, Tunisia built a CSP plant with 2.250 MW of energy capacity [42].

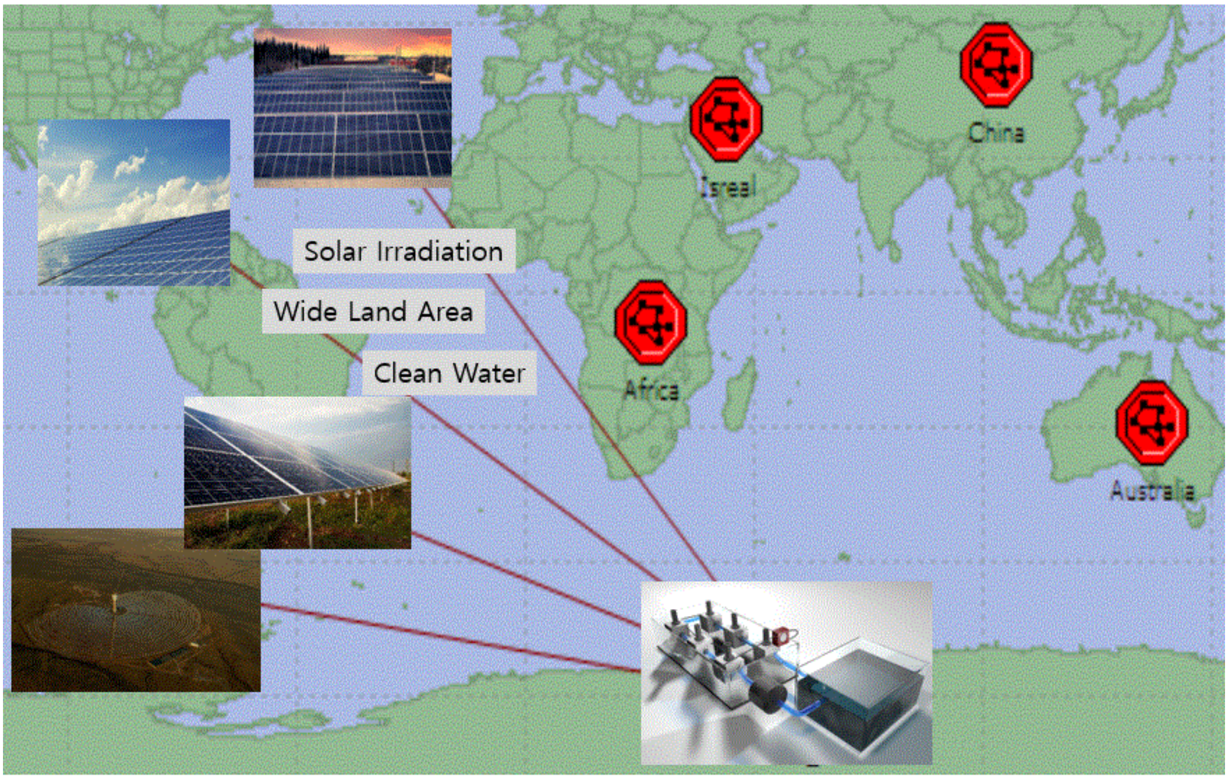

Figure 4. Graphical abstract of solar power and aquaculture in the desert.

In case of the Gobi Desert, which is near to Mongolia and China, a 1 GW VLS-PV power plant was installed. The desert is vast and therefore presents difficulty in identifying suitable locations for PV power plants while efficiently maintaining low costs. In Naran Soum (Mongolia) and Tibet (China), the capacities of two PV systems are 5 kW and 100 kW, respectively, covering a combination of three countries: Mongolia, China, and Korea [6].

In addition, one of the highest solar radiation levels is observed in the Atacama Desert. The Cerro Dominador solar thermal plant is the first CSP plant in Latin America (Chile) and was built with a capacity of 110 MW [43].

In Dubai, the Mohammed bin Rashid Al Maktoum Solar Park is the largest solar power plant in the world. The project was finished in five phases, the first, second, third, fourth, and fifth phases, with 13 MW, 200 MW, 800 MW, 950 MW, and 900 MW of production capacity, respectively. PV technologies were used for the first, second, third, and fifth phases, but CSP and PV were used for the fourth phase [43].

Dubai's future plan is to achieve 5000 MW of production capacity by 2030. The largest photovoltaic power plant is situated in the Kupuqi Desert in Dalate Banner, Ordos, Inner Mongolia, with 1000 MW of production capacity [44]. Figure 5 shows photographs of solar power plants in the desert [45–49].

Figure 5. Solar power plants in the desert. (**A**) China; (**B**) the Kubuqi Desert in China; (**C**) the Mohammed bin Rashid Al Maktoum Solar Park in Dubai; (**D**) the Cerro Dominador solar thermal plant in Chile; (**E**) the Mojave Desert.

2.4. Aquaculture in Desert

2.4.1. Aquaculture System

Although conducting aquaculture in the desert is not simple, several countries have been increasing their aquaculture activities in the desert. Israel is one of the typical examples of a place located in severe environmental conditions. It is still difficult to develop aquaculture as in the inland; however, achieving the objective of culturing fish in the Negev Desert is possible [50]. Aquaculture in the desert has been ongoing since the 1980s. There are 15 farms that are currently in operation to supply domestic and ornamental fish for exportation.

Figure 6 shows some typical farms in the Negev Desert. These are evidence that it is possible to develop aquaculture in the desert. Appelbaum [50] gave conclusions after an extensive period of research on aquaculture in desert conditions that the brackish desert water is suitable for the development of aquaculture due to the following: due to the good water quality in the desert, high-quality and economical fish can be cultured, with no parasites that cause diseases in fish; there is a diversity of cultured species that are suitable for survival and growth in the desert; modern technologies can be applied for aquaculture.

Figure 6. A typical fish farm named Re'em in the desert in Israel. (**A**) Fish farm; (**B**) raceway system; (**C**) high density of red tilapia in raceway system.

Meanwhile, Table 2 shows the current aquaculture systems in the deserts around the world, including Australia [30], South Africa [31], Israel [50], and some countries in Asia [51].

Table 2. Aquaculture systems in the desert.

Area	Aquaculture Systems	References	Remark
Australia	Pond-based Enclosed tanks Shallow lakes	Kolkovski [30]	Can cover FPV [33] For culture of artemia Microalgae
Asia	Pond	Karimov [51]	
Israel	Pond	Appelbaum [50] Hulata and Simon [52]	
South Africa	Recirculation aquaculture system (RAS) Cage culture Earth pond culture Open tank	Mapfumo [30]	

The 'Biofloc' technology, developed in 2008 by the National Institute of Fisheries Science in Korea, was applied to a farm in the Sahara Desert in Algeria, enabling it to produce around 5000 kg of shrimp per year. Biofloc is an eco-friendly technology that purifies and reuses wastes emitted by organisms as they grow with microorganisms, as shown in Figure 7 [51,53].

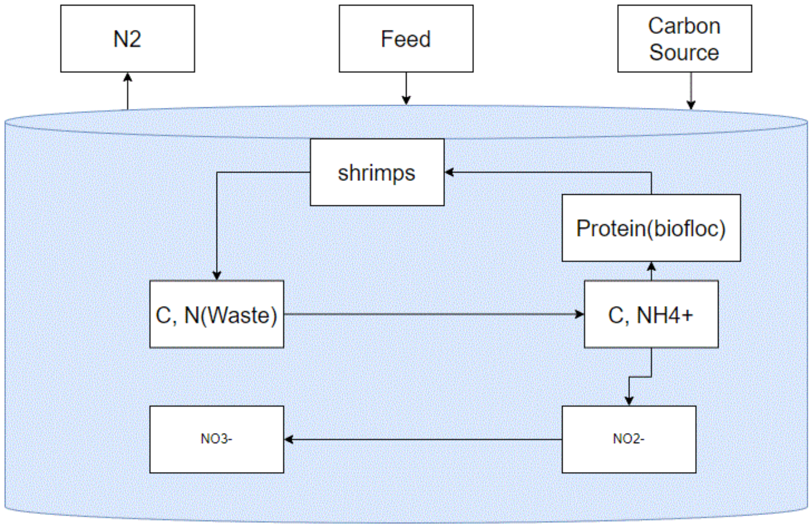

Figure 7. Shrimp farm in Sahara Desert with Biofloc technology.

2.4.2. Cultured Species

Tilapia is the most popular fish species cultured in the desert. Depending on the environmental conditions, there are a number of species that have been cultured, such as catfish, seabass, carp, red drum, barramundi, and ornamental fish (guppy, platy fish, green swordtail, angelfish freshwater, and armored catfish) [50]. In the case of seawater, desalination is needed. A desalination plant can convert brackish water into freshwater to serve the needs of aquaculture and agriculture. On the other hand, instead of desalination, they can culture some fish that are suitable for water with low salinity, such as marine species (yellowtail, snapper), barramundi [35,54,55], rainbow trout [35], and artemia [56]. Carp is the most popular in Asia—for example, silver carp (*Hypophthalmichtys molitrix*); common carp (*Cyprinus carpio*); bighead carp (*Hypophthalmichtys nobilis*); grass carp (*Ctenopharyngodon idellus*); and crucian carp (*Carassius auratus*) [53].

2.4.3. Water Utilization

The combination of aquaculture and agriculture is an efficient way to use water in the desert. They use water for culturing fish; then, this wasted water subsequently becomes a source for agriculture irrigation. This technique not only improves water utilization, but also preserves the scarce water resources. In fact, wastewater generated from aquaculture in Egypt was used for agriculture to reduce the consumption of fertilizers [50]. In addition, water used in aquaculture can be reused using Biofloc technology. Figure 8 shows a desalination plant that has the capability of producing 4 million tons of freshwater per year in the Ramat district in the Negev Desert [50].

Figure 8. Desalination plant in the Negev Desert.

3. Challenges

3.1. Challenges of PV Power Plants in Desert Area

Dust/soiling, hail, temperature, etc., are the environmental factors in the desert that can affect PV systems. These factors decrease the energy production and increase the maintenance costs, as well as shortening the life span, of the PV cells.

3.1.1. Dust/Soiling

Dust/soiling is the most severe problem in the installation of PV power systems in desert areas. It affects not only energy production, but also the lifetime of PV cells. Through research in Abu Dubai, Kassim [57] found that the energy production suffered a loss of 13% after a month of observation of the PV modules in a PV power plant because of dust. In some places, through a combination of other environmental factors, the loss of energy production can sometimes reach approximately 50% at PV power plants in the desert [58]. Therefore, a lot of research has been conducted about dust, as well as to determine a suitable method for cleaning the PV modules. The final goal of these studies is to improve the energy production, decrease the cost of electricity, decrease the cleaning costs, and increase the lifetime of the PV modules.

Another study was conducted by Touati et al. [59], who investigated the effects of weather and environmental factors on the performance of solar PV systems by using a variety of PV technologies. They used different PV technologies, such as mono-crystalline PVs and semi-flexible PVs. The results of the study supply useful information to utilize and maintain solar PVs in the desert in Qatar. This was based on the sensitivity of three kinds of PVs to several environmental factors that were considered, such as temperature, humidity, and dust. Regarding the effects of temperature and humidity, mono-crystalline PVs are less affected than semi-flexible PVs.

However, semi-flexible PVs decrease the panels' susceptibility to dust and protect them more effectively than mono-crystalline PVs. The obtained results indicate that amorphous PVs are the most suitable for the installation of solar power systems in the desert because of their efficiencies with environmental factors. In the same field, many researchers have also presented the results in many regional deserts around the world, as described briefly in the following.

Al Siyabi et al. [60] showed that, in the desert, dust is one of the most severe issues that needs to be considered, largely in part due to cleaning costs (maintenance/preservation), which decreases the efficiency of the PV system. In this study, a solar power system was installed for a car park. The experiment was conducted with different tilt angles: 0, 5, 10, 15, and 23 degrees. The hypothesis was that choosing a suitable tilt angle could potentially reduce the attachment of dust onto the panels and thereby increase the surface area exposure to maximize the receipt of solar irradiation. The results showed that increasing the tilt angles of the PV modules could reduce dust and increase the electricity generation. Fountoukis et al. [61] conducted an experiment in a solar power plant for fields, modeled in Qatar for 12 months. The goal of the experiment was to test how dust accumulation affects the solar energy capacity through factors such as meteorological conditions, electricity production, solar irradiation rates, and the concentration of particulate components on PV modules in desert conditions. The results showed that dust particle sizes of under 10 μm had little impact on daily energy production due to gravitational settling. The research suggested that floating PV modules should be used in solar power plants because their susceptibility to dust accumulation is limited.

Additionally, based on the factors that cause dust attachment on PV modules, there are many factors that have an effect on dust settlement, such as wind speed, dust characteristics (type, size, shape, and weight), temperature and humidity, the characteristics of desert locations, and the direction/tilt angle of the PV system [62]. Based on these factors, several studies have been conducted to obtain an overview and trends to build PV power plants in the desert to generate high electricity production.

It is well known that dust is one of the main issues that causes problems for PV panels in desert regions. On the other hand, some areas with high humidity in combination with the presence of dust present an environment where particulates are generated such that they accumulate on the surface of the microstructure of the PV panel. This occurrence further complicates the ability to clean the panels with normal cleaning methods, especially without the use of water, according to Ghazi et al. [63]. Jiang, Yu et al. conducted a study to estimate the cleaning frequency. Various parameters, such as the installation tilt angle, air dust concentration, and wind speed, were used to estimate the cleaning frequency, and the effect of each parameter on the cleaning frequency was analyzed [64].

There are many methods that have been deployed for cleaning the PV modules in the desert, such as wash and wipe, spray and wipe, wash robots, machines, and entirely by human force [65]. Among these, although wash and wipe, spray and wipe, wash robots, and machines incur a high cost, they are fast and efficient. Figure 9 shows different PV panel cleaning methods in the desert [27].

Figure 9. Popular PV panel cleaning methods in the desert. (**A**) Spraying water; (**B**) special cleaning vehicle; (**C**) water pipes; (**D**) human method; (**E**) special pressured water brush.

Improving the PV material is also a good way to alleviate the limitations in the cleaning process, as well as the limitations in solar irradiation absorption—for example, coating the PV surface with materials that can be free of dust [66–71]. Isaifan et al. [68] investigated a useful material for coating PV modules that can be self-cleaned without water in the desert's environmental conditions. TiO_2 nanocolloids, known as a thin coating film, were used as a material to cover the surfaces of PV modules. The results showed that the dust accumulation rate was 56% of the coating film, compared to bare glass substrates, after a week of the experimental period. In fact, the cleaning process was achieved without water.

In addition, Arabatzis et al. [68] tested liquid SSG to coat the surfaces of PV modules for self-cleaning. The experiment was conducted for many months in a desert environment by comparing two types (coated and uncoated PV panels), based on the efficiency of energy production. The results indicated that the coated panel had less dust attachment than the uncoated PV panel because of its super hydrophobicity trait. The electricity generation rate increased by 5–6%.

Meanwhile, Zhong et al. [69] suggested a self-cleaning system by using a novel super-hydrophilic coating material called 3-triethoxysilylpropylamine (KH550) and TiO_2, which was applied to PV panels in the desert. The obtained results proved that this material was excellent in its self-cleaning performance. More research was also conducted by Luque et al. [71], who performed an experiment for two months to examine soiling removal from a bifacial PV module, compared to a monofacial module. Results showed that the soiling rate was 0.236% per day and 0.301% per day for the bifacial and monofacial PV module, respectively.

Another study by Abushgair et al. [72] proposed different cleaning materials, such as crystal glass (AJJL-CSS), GIE (Galsilk 7, isopropanol, ethanol, water), TGIE (TiO_2, Galsilk 7, isopropanol, ethanol, water), sodium hexametaphosphate, and NanoUltra, which were applied on PV panels in a hot and arid area. The results indicated that all coating materials were useful for decreasing the temperature of PV panels and reducing the dust deposition on PV panels.

The rainy season is also considered a factor to support the cleaning of PV panels. However, this is challenging in desert areas. On the other hand, some research has shown that using water to clean panels may affect the efficiency of PV panels that are installed in the desert [50].

Meanwhile, Moharram et al. [73] investigated how to clean PV panels using non-pressurized water. They found that the efficiency rate of the PV panels was significantly reduced after 45 days of the experiment when using non-pressurized water for cleaning. However, in severe conditions, they chose to use recycled water to clean the PV panels as an efficient method. Bin Ahmed et al. [74] proposed a cleaning system in the Quaid-e-Azam solar power plant, depending on the natural existing conditions. They used recycled water to clean the PV panels. This worked to preserve the scarce water resources and to decrease the cost of cleaning through the reduction of the volume of clean water needed to clean the PV system. It is efficient for the Bahawalpur Desert, which has a lot of dust and needs a large amount of water to clean the PV panels. It is also a good solution for widespread application in other deserts.

Drones, a novel means of cleaning PV panels, have been applied recently because of their advantages of cleaning without water, using automatic cleaning protocols, and being a highly mobile system. However, there are some disadvantages, such as their high price, the need for electricity/fuel, as well as the need for more research [75].

Recently, Al-Housani et al. [76] proposed a cleaning system by implementing unmanned drones for cleaning PV panels in the larger-scale PV power plants in the desert, after evaluating the results of different cleaning methods/techniques. The goal of this study was to enhance efficiency, and reduce operational costs, time, and effects on the environment. They collected some parameters, such as cost, time/frequency, efficiency rate, and energy consumption. The results showed that using unmanned cleaning drones is an efficient method that can solve the problems for others in a larger-scale PV power plant in the desert.

3.1.2. Other Factors

Besides soiling/dust, hail storms also affect solar power plants. Sharma et al. [77] found that ice stones can crack PV panels. Therefore, they suggested that the climate of the solar power plant sites should be known before installation. In addition, the speed and direction of the wind, and the desert atmosphere, particularly the wind speed, the force of gravity, and the size and mass of particles, have the most significant effects on the solar power systems [78,79]. Sabziparvar, Ali A. used data from Iran's semi-arid desert to predict solar radiation, which has a significant impact on solar power generation, and modified and compared the existing models of Sabbagh, Paltridge, and Daneshyar. In particular, the modified Sabbagh model can perform more accurate predictions of global solar radiation in arid and semi-arid deserts than previous studies, with an average error of less than 2% [80]. The distance for transferring electricity from the desert to the user is also a challenge when choosing a site for the installation of a solar power plant. Moreover, energy loss may occur due to problematic parts of the system. Henrik Zsiborács et al. were able to detect energy loss due to the distance of PV power plants or faulty operation based on monitoring data associated with PV systems, and the solution is simple enough to easily adapt to real-time supervision and management platforms [81].

3.2. Challenges of Aquaculture Operation in Desert Areas

The main challenges for operating aquaculture in the desert are associated with particular characteristics, such as meteorology, human resources, aquaculture technologies, government policies, etc., in each specific desert area.

In the case of Namibia, South Africa, according to Mapfumo [31], the main challenges are presented as follows. The investors/farmers are not very interested in participating in aquaculture in the desert because these activities entail much greater financial costs than in the inland area. On the other hand, with the high risks of significant costs in facility construction, operation, and management activities for aquaculture systems in the desert, financial institutes are hesitant to supply money for farmers. Water resources are very scarce. Specifically, there is no water on the surface in the months of drought. In addition, some water quality parameters in groundwater are not suitable for cultured species. Aquaculture technology is also limited in this country because of a lack of experience. Moreover, farmers must still import feed and other materials that are used for culturing fish. This is one of the factors that contributes to the increasing operational costs.

For Australia, Kolkovski [30] found that there are several challenges that have been discussed after the deployment of some projects to develop aquaculture in the desert throughout Australia, such as water resources, species for culturing, environmental problems (water quality, disease from the environment), policy from locals and the government, finances, and the market. The specific challenges will be briefly described below. In the case of New South Wales, water used for aquaculture obtains saline from underground water. However, the long drought season is a factor that causes a severe decrease in the level of underground water; therefore, it is necessary to consider the biological characteristics of each fish species when choosing the suitable species to be cultured in the desert. In addition, the conditions of weather, temperature, and water quality are so severe in the desert that they can cause a high mortality rate for cultured species. For instance, the range of water temperature is large between day and night. As with other desert areas, the high costs of labor, feed, techniques, facilities, etc., are also major challenges to the development of aquaculture.

For desert areas in Central Asia, the development of aquaculture is not well supported by the government, along with a lack of laborers, lack of diversity of cultured species and cultured systems, lack of high-quality food, poor facilities, lack of finances from the government, low level of technologies applied in aquaculture, low human resources, and lack of training [52,53].

In addition, for a case in Israel, Hulata and Simo [79] indicated some difficult conditions hindering aquaculture activities in the desert. The main limitations of aquaculture are as follows: the water quality is mostly brackish water, which means a lack of fresh water. Therefore, in order to have fresh water for aquaculture operation, it is necessary to desalinate the water. This may increase the cost of operations. On the other hand, the cost of feed also increases because most materials are imported. Most farms are not large enough; therefore, it is necessary for farmers to join a trading system to sell their products on the market. The wasted water needs to be treated before being released into the natural water. All the factors mentioned above increase the production costs and therefore decrease profits.

4. Discussion

Aquaculture can reduce poverty and ensure food security. The proportion of the aquaculture industry is increasing, with almost half of all fish products produced through aquaculture. In particular, it has been proven through various cases that it is possible to use the aquaculture industry to secure fish in desert inland areas, where it is difficult to secure fish.

Although the desert may have the ideal conditions to develop solar power, there are not many reports or articles that have centered around using solar power in aquaculture in the desert until now. Aquaculture requires an abundant amount of surface water; therefore, developing an aquaculture industry in a location that has limited surface water re-sources is a challenge. The most significant reason that people doubt the possibility of such an endeavor is the low efficiency of aquaculture and high investment, such as high costs and high risks compared to other regions [31]. However, Israel is one of the most promising examples of developing aquaculture in the desert. Through their review, Hulata and Simon [79] showed that it is possible to culture many species in different technologies and cultured systems in the desert with high production.

Moreover, it is known that one of the most difficult conditions in which to develop aquaculture is freshwater. However, there are several solutions that have been applied, such as choosing suitable cultured species that can live in brackish water, or building a desalination station to produce freshwater for aquaculture, based on the experiences of aquaculture operations in many countries, such as Israel, Australia, South Africa, or some countries in Asia. In addition, there are examples of using solar power in aquaculture for cultured freshwater fish, as well as marine fish [82–95] and shrimp [87–88], in ponds, cages, and RAS, in many countries around the world. Solar power systems generate electricity to supply energy for several devices in aquaculture facilities.

Examples are aeration systems in ponds [89]; water quality control machines [85,90]; pumps, aerators, UV (ultraviolet) filters, and LED (Light-Emitting Diode) lights [91]; and the aquaculture field [82]. Therefore, based on the advantages of land and solar irradiation in the desert, the existing experience in the implementation of solar power inland [93,94], and the application of solar power for aquaculture in inland, as well as the experience of developing aquaculture in the desert, it is possible to apply solar power to aquaculture in the desert.

There are studies explaining the advantages of aquaculture in Africa, including Egypt. Ms, Farrage explained that aquaculture in Egypt produces wastewater, but it can be used for agriculture to reduce the use of fertilizers [95]. In recent years, the proportion of aquaculture has increased in Africa due to major factors such as the increased demand for fish, improved investment environment, and reduced production risk. In addition, in recent years, the GDP (Gross Domestic Product) growth rate of the top countries where aquaculture production has been increasing rapidly has been on the rise. Due to this trend, investment in aquaculture and production increases are positive [96]. This suggests that aquaculture in the desert area of Africa could be expanded. In line with this trend, Laith A. Jawad and Saad Mohammed Saleh Abdulsamad evaluate the introduction of the aquaculture industry in Iraq, which has not yet been implemented in the desert. In Iraq, the environment for aquaculture is well established due to its large available desert area and abundance of mostly groundwater, and researchers have made recommendations for desert aquaculture [97]. In addition, Hülya, S. and T. Sana Yagoub Abdallah studied the future direction of aquaculture in North African countries using time series analysis, principal component analysis, and hierarchical cluster analysis with data from the United Nations' Food and Agricultural Organization. As a result, it is predicted that aquaculture production will increase by up to 37.7% by 2030 when positive conditions are satisfied [98].

5. Conclusions

The desert is considered a suitable location to develop the solar power industry, with its many advantages, particularly good solar irradiation and large land area. There are several solar power plants, including both CSP plants and PV power plants, that have been installed in many deserts around the world. However, some disadvantages also exist that affect the energy production and lifetime of solar modules, such as dust/soiling, temperatures, hail storms, electricity transferring systems, etc.

In general, it is thought that the aquaculture industry in the desert area will be difficult to develop. In fact, there are disadvantages to the aquaculture industry in desert areas, but this does not mean that there are no advantages. Since groundwater is mainly used in the desert, the water quality is better than inland, and the production volume is also guaranteed to some extent if an aquaculture species suitable for the brackish water environment is selected. In fact, aquaculture is operated in desert areas in some countries, including Egypt and Israel, and it is performing well. The development of aquaculture in the desert has been improved with the high production and diversity of cultured species.

To date, the application of solar power for aquaculture in desert areas has not been reported. However, based on the achievements and experiences of solar power plants, desert aquaculture, as well as the application of solar power for aquaculture inland, it is possible to use solar power in the desert as a major form of energy consumption in aquaculture. Furthermore, more research is needed in order to investigate problems with solar power and to improve energy production with low investment costs. More research is also needed about how to apply solar power for aquaculture in the desert at a low cost. Using floating PV to generate electricity for aquaculture is also an upcoming future trend. In addition, using solar power as an energy resource to produce freshwater, which is highly necessary for aquaculture and people in the desert, is considered an excellent solution that should be widely explored.

In this paper, we discussed how to apply solar power to the aquaculture industry in the desert. Previously, the aquaculture industry and solar power were recognized as separate areas of study. With our work, we hope that the research in the two fields, which were considered different fields, can be combined to compensate for their shortcomings.

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Abbreviations

PV	Photovoltaic
GW	Gigawatt
SGD	Sustainable Development Goal
CSP	Concentrated Solar Power
ESS	Energy Storage System

BESS	Battery Energy Storage System
DC	Direct Current
AC	Alternating Current
RAS	Recirculation Aquaculture Systems
MW	Megawatt
CPV	Concentrated PV
VLS-PV	Very Large-Scale PV
UV	Ultraviolet
LED	Light-Emitting Diode
GDP	Gross Domestic Product

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