Chapter

Agrovoltaic and Smart Irrigation: Pakistan Perspective

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Abstract

The present study aims to investigate the prospects and challenges that need to be encountered for the adaptation of the novel agrovoltaic irrigation system (AVIS) in Pakistan. The agro-production scenario in Pakistan is periodically declining and leading toward the high delta crops, which develop severe pressure on the conventional energy and water resources. Groundwater might be a viable water source, but its pumping requires massive energy. In addition, excessive pumping declines the water table at a higher pace as compared to the recharge rate hence leading the country toward the exploitation of the valuable reservoir. The AVIS could be an energy-efficient and reliable irrigation solution in a manner of harvesting solar energy for driving smart irrigation systems capable to pumps the metered groundwater according to field requirements. Lack of local understanding, skilled/technical personnel, dependence on local technology, and major capital expenditures might impede technological adaption. The government should take necessary measures to replenish the groundwater reservoirs and also execute research projects that strengthen ground knowledge of AVIS.

Keywords: energy and water scarcity, groundwater exploitation, agrovoltaic, irrigation system

1. Introduction

Today's world faces several challenges, including population expansion, climate change, dwindling food supplies, energy crisis, and water shortages. The challenges are intertwined in a manner, and their cumulative impact is devastating, particularly for the agriculture sector [1]. According to the latest United Nations (UN) projection, the world's population will exceed 9.6 billion by 2050, implying significant food insecurity in near future [2]. In order to catch the pace of prevailing nutritional demands, agriculture communities ought to be enhanced by at least 1.5 times compared to

2012 [3]. However, recent statistics revealed that the production capacity needs to be increased by 70% for coping with the population hunger in 2050 [4]. On the other hand, the resources utilized for alleviating the production capacity are becoming increasingly scarce. For instance, the agriculture sector mainly relies on adequate supplies of water and energy. Agriculture consumes 70% of the global scale freshwater withdrawals for the growth of agriculture commodities [5, 6]. However, it has been identified that the freshwater reserves are shrinking due to climate change consequently impacting the agri-food supply chain thereby exploring alternative solutions such as desalination [7, 8]. On the other hand, according to Food and Agriculture Organization (FAO), agrarian activities mainly account for 30% of the global cumulative energy production [4, 9]. The Asian countries have a major footprint in the agriculture sector. In this spectrum, they consume 4,000,000 TJ of energy in 2018 to perform agriculture operations [4]. **Figure 1** presents the region-wise temporal variation of the energy utilized by the agriculture sector [4, 10, 11]. The origin of this energy is fossil fuels, which enable the modern farm mechanization, centering fertilizer application and enhancing the harvesting and post-harvesting efficiencies. However, the depletion of fossil fuel reserves limiting the farm efficiency [12, 13].

Pakistan stands in the lane of agricultural countries that produces its major food supplies from arable land. The agriculture sector employs 39–42.3% of the country's labor force and contributes 19.3% of gross domestic growth (GDP) [14, 15]. According to the Pakistan economic survey (PES), the agriculture growth in 2020–2021 was recorded at 2.67%, which is 1.33% less compared to 2018 (4.0%) [15]. Similarly, the share of the GDP obtained from the agriculture sector has gradually decreased due to minimization of surface water availability, high energy pricing, pest attacks, climate change, and other influencing factors that limit the agriculture productivity from its potential [15, 16]. Pakistan consumes 93.8% of its total freshwater withdrawals for agrarian activities. However, a dramatic shortfall in surface water supplies has been observed in the last few years. For instance, from 2018 to 2019, the freshwater shortfall was estimated at 18.5% [15]. According to Indus River System Authority (IRSA), an acute water shortage of 38% was recorded in 2022, which was aimed to irrigate the Kharif crops [17, 18]. Similarly, the pricing of on-farm energy sources is mounting.

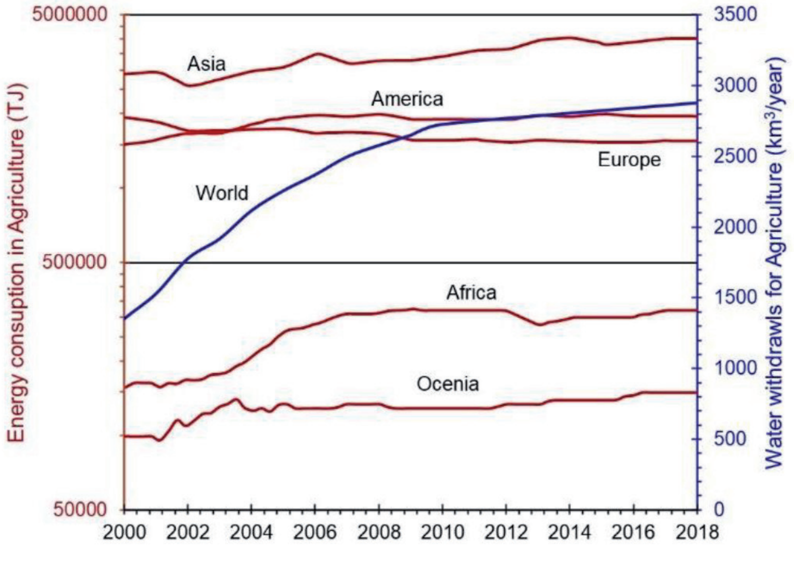


Figure 1.
Region-wise temporal variation of energy consumption and water withdrawal for agricultural activities reproduce here from [4, 10, 11].

The farmers are suffering from a shortage of fuel supplies. In this context, a sustainable alternative water and energy source are principally required in the country to improve crop productivity and for meeting the nutritional demands.

Groundwater is an alternative reliable resource of an adequate supply of freshwater. The dependency on the groundwater is increased in the last few years due to the depletion of surface water supplies [19]. Fortunately, Pakistan is blessed with the largest underground reservoir after China, India, and the USA, providing 60% and 90% of the irrigation and drinking water supplies, respectively [20]. Farmers are extensively pumping the groundwater in order to accomplish their water needs. For doing so, lifts pumps or tube wells are the ultimate sources to extract the underground water. In this context, a large number of tube wells are being installed across the country mainly driven with diesel as shown in **Figure 2**. Punjab mainly contains a high density of tube wells (995,456) followed by Sindh (71,454), Khyber Pakhtunkhwa (42,970), and Balochistan (39,567) with capacity varies between <10 and >25 horsepower (hp) [22]. Approximately 58% of tube wells in Pakistan have a capacity of 16–20 hp., necessitating massive fossil energy to operate [22]. The depletion and high pricing of the fossil fuels provoke food insecurity, which eventually destabilizes the country's economy furthermore, fossil fuel emissions are wreaking havoc on the ecosystem via global warming, shifting rainfall patterns, soil drying, and air pollution. The researchers concentrated their efforts in this area by constructing freestanding underground water pumping devices that could be fueled by renewable energy sources.

Solar photovoltaic (PV) technology has proven to be the most reliable on-farm energy source, capable to perform a variety of agro-operations [23]. Particularly for irrigation purposes a wide range of solar-driven pumps is being installed in order to accomplish the agricultural needs. However, due to the lack of groundwater governance in the country, massive groundwater extraction is committed by the farmers

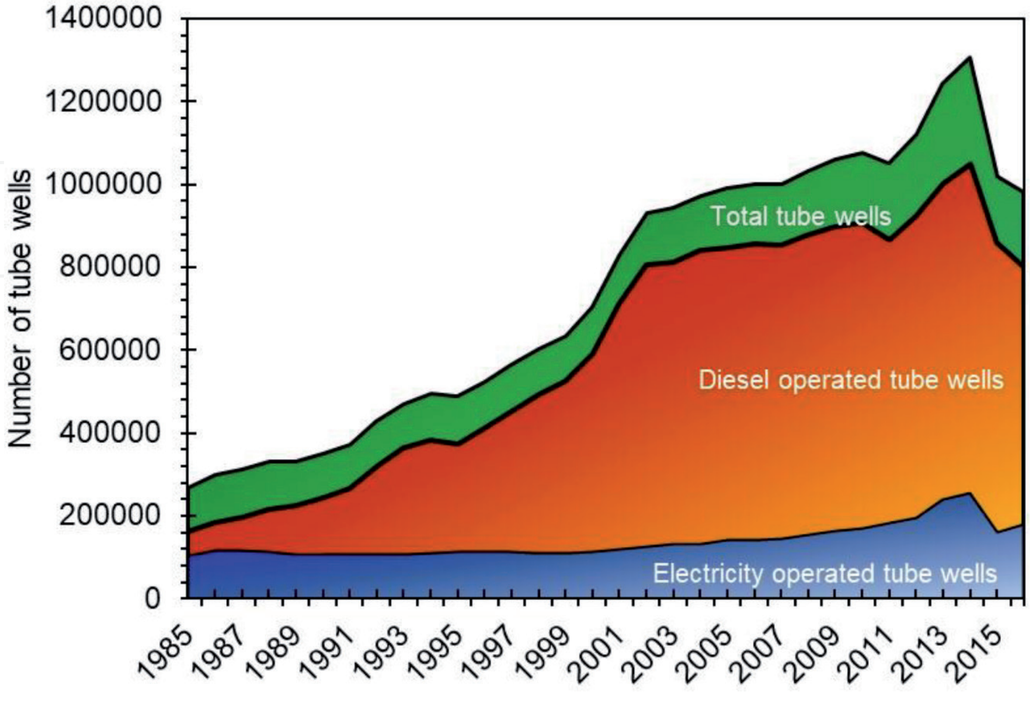
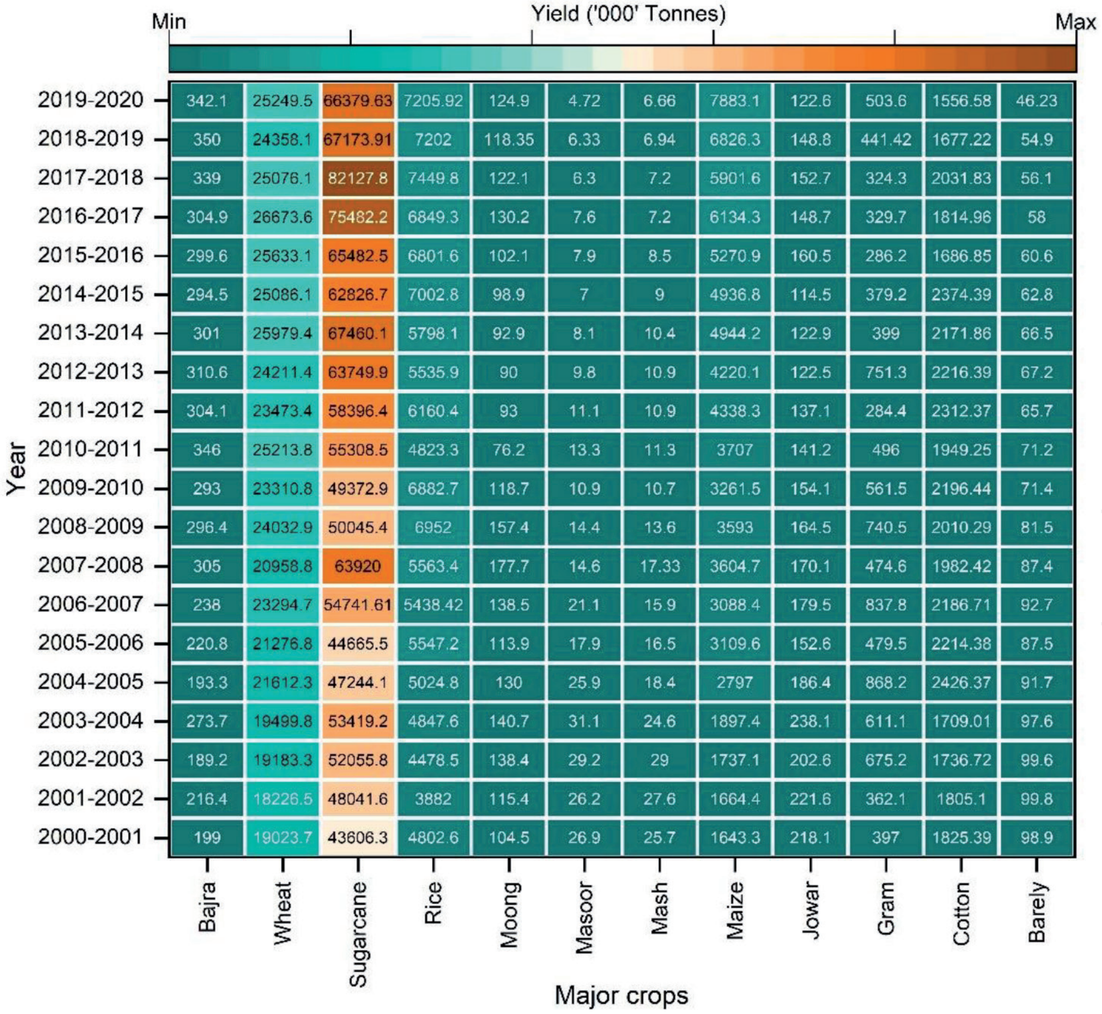


Figure 2.
Number of tube wells installed in Pakistan is segregated based on primary energy resources reproduce here from [21].

irrespective of their agriculture requirements. Consequently, stressing and exhausts the reservoir at a higher pace. In this context, alternative, viable policies, and smart irrigation technologies are principally required in order to mitigate the food insecurity arising from the water shortfall. Agrovoltaic irrigation system (AVIS) conception could be a remarkable and promising solution that not even metered the groundwater pumping but also utilized the culturable land for twin benefits (i.e., solar energy harvesting and agriculture production). The study presents the novel conception of AVIS and explores the prospects and challenges that need to be encountered for the potential adaptation of the technology at the farm level. In addition, the study highlights the consequences and possible remedies for the commercialization of the AVIS.

2. Agro-production scenario in Pakistan

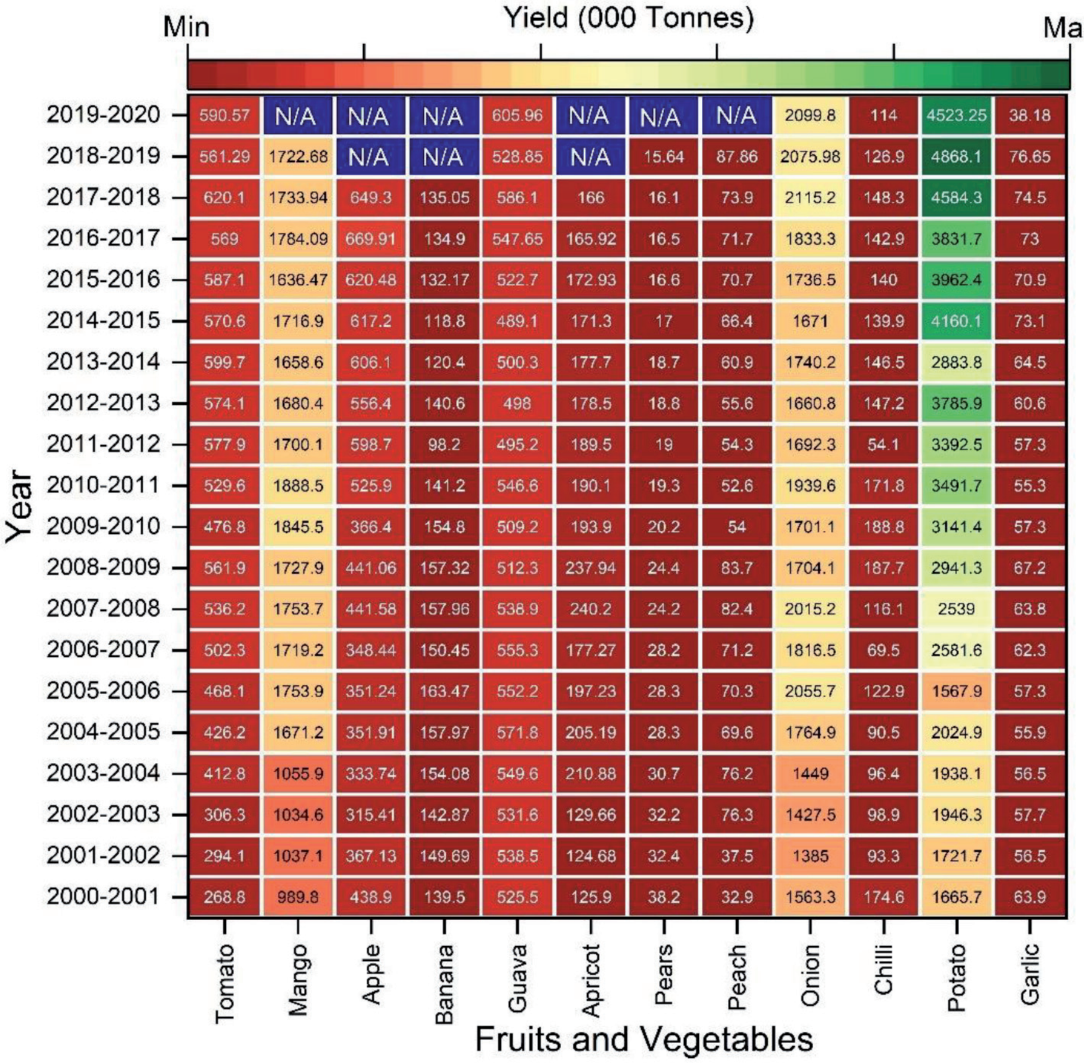
Pakistan has two cropping seasons i.e., Kharif and Rabi for the production of crops. Major crops produced in the Kharif season are bajra, sugarcane, rice, moong, mash, maize, jowar, and cotton while wheat, masoor, and barley crops are produced in the Rabi season to accomplish the nutritional demands [24]. **Figure 3** shows temporal



Year	Bajra	Wheat	Sugarcane	Rice	Moong	Masoor	Mash	Maize	Jowar	Gram	Cotton	Barely
2019-2020	342.1	25249.5	66379.63	7205.92	124.9	4.72	6.66	7883.1	122.6	503.6	1556.58	46.23
2018-2019	350	24358.1	67173.91	7202	118.35	6.33	6.94	6826.3	148.8	441.42	1677.22	54.9
2017-2018	339	25076.1	82127.8	7449.8	122.1	6.3	7.2	5901.6	152.7	324.3	2031.83	56.1
2016-2017	304.9	26673.6	75482.2	6849.3	130.2	7.6	7.2	6134.3	148.7	329.7	1814.96	58
2015-2016	299.6	25633.1	65482.5	6801.6	102.1	7.9	8.5	5270.9	160.5	286.2	1686.85	60.6
2014-2015	294.5	25086.1	62826.7	7002.8	98.9	7	9	4936.8	114.5	379.2	2374.39	62.8
2013-2014	301	25979.4	67460.1	5798.1	92.9	8.1	10.4	4944.2	122.9	399	2171.86	66.5
2012-2013	310.6	24211.4	63749.9	5535.9	90	9.8	10.9	4220.1	122.5	751.3	2216.39	67.2
2011-2012	304.1	23473.4	58396.4	6160.4	93	11.1	10.9	4338.3	137.1	284.4	2312.37	65.7
2010-2011	346	25213.8	55308.5	4823.3	76.2	13.3	11.3	3707	141.2	496	1949.25	71.2
2009-2010	293	23310.8	49372.9	6882.7	118.7	10.9	10.7	3261.5	154.1	561.5	2196.44	71.4
2008-2009	296.4	24032.9	50045.4	6952	157.4	14.4	13.6	3593	164.5	740.5	2010.29	81.5
2007-2008	305	20958.8	63920	5563.4	177.7	14.6	17.33	3604.7	170.1	474.6	1982.42	87.4
2006-2007	238	23294.7	54741.61	5438.42	138.5	21.1	15.9	3088.4	179.5	837.8	2186.71	92.7
2005-2006	220.8	21276.8	44665.5	5547.2	113.9	17.9	16.5	3109.6	152.6	479.5	2214.38	87.5
2004-2005	193.3	21612.3	47244.1	5024.8	130	25.9	18.4	2797	186.4	868.2	2426.37	91.7
2003-2004	273.7	19499.8	53419.2	4847.6	140.7	31.1	24.6	1897.4	238.1	611.1	1709.01	97.6
2002-2003	189.2	19183.3	52055.8	4478.5	138.4	29.2	29	1737.1	202.6	675.2	1736.72	99.6
2001-2002	216.4	18226.5	48041.6	3882	115.4	26.2	27.6	1664.4	221.6	362.1	1805.1	99.8
2000-2001	199	19023.7	43606.3	4802.6	104.5	26.9	25.7	1643.3	218.1	397	1825.39	98.9

Figure 3.
Temporal variation of major crop yields for both Kharif and Rabi seasons in Pakistan from 2000 to 2020 reproduce here from Agriculture Marketing Information Service (AIMS) http://www.amis.pk/agristatistics/production.aspx.

variation in production capacity of major crops for both Kharif and Rabi seasons in Pakistan from 2000 to 2020. It has been realized that, in the Kharif season sugarcane, rice and maize have a major footprint thereby cultivating more than 70% of the agricultural land [25]. According to recent statistics revealed by the crop reporting service, in 2020, 1143.62 km^2, 2746.11 km^2, and 826.13 km^2 areas in Punjab have been utilized to grow sugarcane, rice, and maize, respectively [26]. On the other hand, in the Rabi season wheat has been extensively grown covering more than 70–75% of arable land. Similarly, in fruits and vegetable production, Pakistan has a major global market footprint, particularly in mango and potato production. **Figure 4** shows the temporal variation of the fruit and vegetable yields from 2000 to 2020. The matrix-shaped filled color gradient indicates that onion, potato, and mango production has periodically increased. If compared with 2000, the production of potato mango, and onion increases by 63.17%, 42.50%, and 25.55%, respectively in 2020. However, in 2022 it has been expected that mango production will fall by approximately 50% due to severe water shortages and heatwaves [27]. In addition, from **Figures 3** and **4** it has been realized that cropping pattern is more likely to lead toward the cultivation of high delta crops, which needs massive water supplies. However, the available water supplies are not likely to fulfill the potential needs of the crops.



Year	Tomato	Mango	Apple	Banana	Guava	Apricot	Pears	Peach	Onion	Chilli	Potato	Garlic
2019-2020	590.57	N/A	N/A	N/A	605.96	N/A	N/A	N/A	2099.8	114	4523.25	38.18
2018-2019	561.29	1722.68	N/A	N/A	528.85	N/A	15.64	87.86	2075.98	126.9	4868.1	76.65
2017-2018	620.1	1733.94	649.3	135.05	586.1	166	16.1	73.9	2115.2	148.3	4584.3	74.5
2016-2017	569	1784.09	669.91	134.9	547.65	165.92	16.5	71.7	1833.3	142.9	3831.7	73
2015-2016	587.1	1636.47	620.48	132.17	522.7	172.93	16.6	70.7	1736.5	140	3962.4	70.9
2014-2015	570.6	1716.9	617.2	118.8	489.1	171.3	17	66.4	1671	139.9	4160.1	73.1
2013-2014	599.7	1658.6	606.1	120.4	500.3	177.7	18.7	60.9	1740.2	146.5	2883.8	64.5
2012-2013	574.1	1680.4	556.4	140.6	498	178.5	18.8	55.6	1660.8	147.2	3785.9	60.6
2011-2012	577.9	1700.1	598.7	98.2	495.2	189.5	19	54.3	1692.3	54.1	3392.5	57.3
2010-2011	529.6	1888.5	525.9	141.2	546.6	190.1	19.3	52.6	1939.6	171.8	3491.7	55.3
2009-2010	476.8	1845.5	366.4	154.8	509.2	193.9	20.2	54	1701.1	188.8	3141.4	57.3
2008-2009	561.9	1727.9	441.06	157.32	512.3	237.94	24.4	83.7	1704.1	187.7	2941.3	67.2
2007-2008	536.2	1753.7	441.58	157.96	538.9	240.2	24.2	82.4	2015.2	116.1	2539	63.8
2006-2007	502.3	1719.2	348.44	150.45	555.3	177.27	28.2	71.2	1816.5	69.5	2581.6	62.3
2005-2006	468.1	1753.9	351.24	163.47	552.2	197.23	28.3	70.3	2055.7	122.9	1567.9	57.3
2004-2005	426.2	1671.2	351.91	157.97	571.8	205.19	28.3	69.6	1764.9	90.5	2024.9	55.9
2003-2004	412.8	1055.9	333.74	154.08	549.6	210.88	30.7	76.2	1449	96.4	1938.1	56.5
2002-2003	306.3	1034.6	315.41	142.87	531.6	129.66	32.2	76.3	1427.5	98.9	1946.3	57.7
2001-2002	294.1	1037.1	367.13	149.69	538.5	124.68	32.4	37.5	1385	93.3	1721.7	56.5
2000-2001	268.8	989.8	438.9	139.5	525.5	125.9	38.2	32.9	1563.3	174.6	1665.7	63.9

Figure 4.
Temporal variation of fruit and vegetable yields in Pakistan from 2000 to 2020 reproduce here from Agriculture Marketing Information Service (AIMS) http://www.amis.pk/agristatistics/production.aspx.

3. Sources of irrigation in Pakistan

Irrigation is the practice of watering crops or plants by digging pipes and ditches in the ground. The primary goal of irrigation is to supply water to crop fields making the land fertile. In Pakistan, irrigation water is obtained from three primary sources, including surface water, rainwater, and groundwater. Following is a brief description of these irrigation sources.

3.1 Surface water

Rainfall and melting snow form streams and storage reservoirs such as tanks, ponds, and damns, that are the primary source for the generation of surface water. Dams are erected along the river and water is channeled to agricultural areas through canals and irrigated the farmer's fields by means of gravity flow. However, the distribution of surface water from the canal head to the farmer's field triggers huge conveyance losses. In Pakistan, Indus Basin Irrigation System (IBIS) is the largest irrigation network that contributes to the conveyance of the surface water [28]. However, exponential growth in industrialization, urbanization, and population causes depletion of the surface water supplies in the IBIS [29, 30]. Additionally, the IBIS is highly vulnerable to adverse impacts of climate change owing to its geo-climatic situation. **Figure 5** represents the temporal variation of the surface water generated at the canal head and delivered at the farm end for both Kharif and Rabi crops. It can be seen that total surface water (both for Kharif and Rabi crops) generated at the canal head was 121.59 billion cubic meters (Bm^3) during 2019–2020 while 98.93 Bm^3 of the water delivered at the farm end resulted in huge conveyance losses. This amount of surface water could not fulfill the water requirements of both Kharif and Rabi crops. On the other hand, surface water irrigation is generally regarded to be free of energy cost because of gravity flow. However, an effective canal network requires operational energy for preservation e.g., removal of sediment, as well as vegetation and strengthening of canal banks [31].

3.2 Rainwater

Rainwater is another source of water that comes from rainfall to meet the irrigation requirements of crops. However, rainfall patterns and intensity are continuously decreasing because of the vulnerability of climate change. Climate change is impacting not just rainfall intensity but also the amount of annual rainfall [32]. The country's territory falls into arid to semi-arid regions where three-fourths of the country receives an annual rainfall of less than 250 mm, therefore rainfall alone is generally insufficient for growing crops, particularly in Baluchistan province having less water availability [33, 34]. During monsoon periods greater than 75% of the rainfall falls, which provides about 30 Bm^3 for irrigation but this is only enough to meet 15% of water requirements by the crops [35].

Figure 6 shows the temporal variation of rainfall patterns in Pakistan. For instance, in 2015 average annual rainfall was observed at about 546 mm while 407 mm in 2016, indicating considerable shifting of rainfall patterns throughout the country. Consequently, less rainwater availability necessitates further improvement of farming and irrigation infrastructure. On the other hand, the shifting of seasons triggers a relatively long monsoon season in which high rainfall may cause floods throughout different regions of the country. Nonavailability of storage facilities like dams and

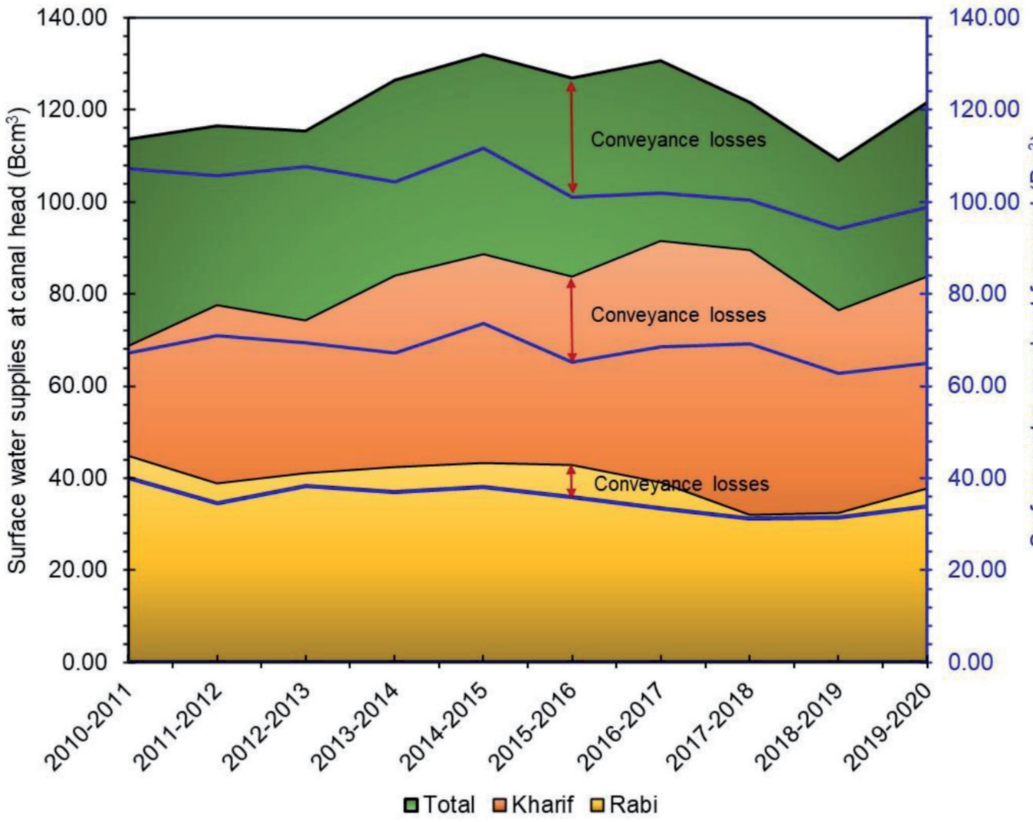


Figure 5.
*Temporal variation of the surface water generated in Pakistan at canal and farm ends reproduces here from the Pakistan Bureau of Statistics (***Figure 11***: Overall water availability).*

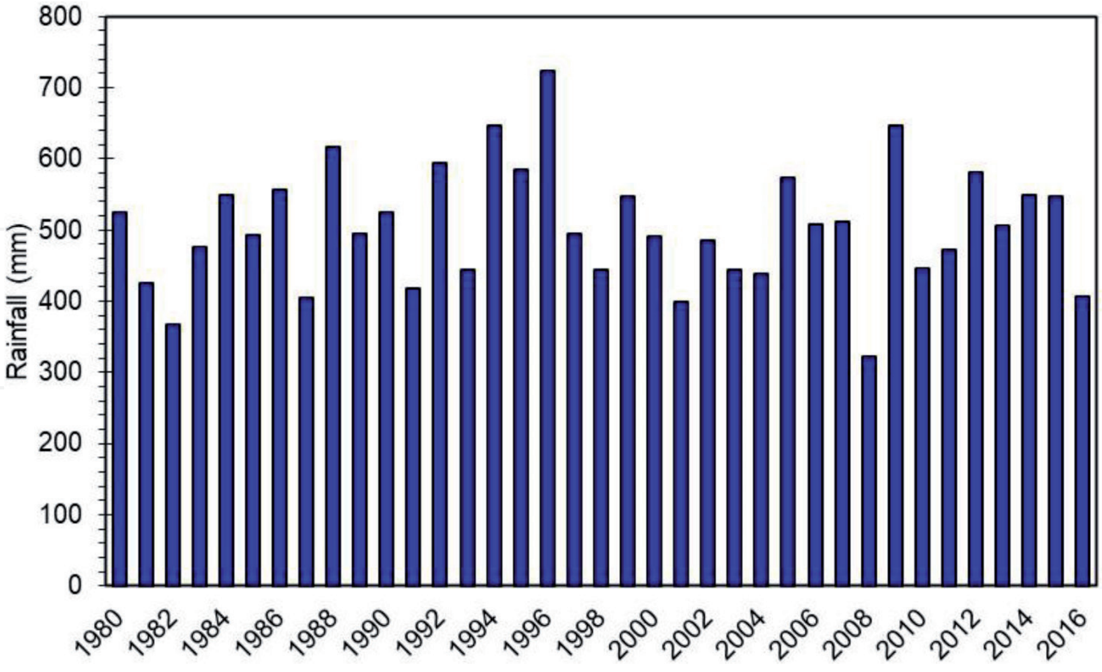


Figure 6.
Rainfall patterns in Pakistan reproduce here from [36].

other water management infrastructures directed a huge amount of water to the sea. In this regard, farmers are being shifted toward the utilization of groundwater in order to fulfill the crop water requirements.

3.3 Groundwater

Groundwater is one of the most essential sources of irrigation in Pakistan. Total groundwater availability in Pakistan is about 73 Bm^3 while 62 Bm^3 is being extracted annually. In Pakistan, agriculture has shifted from surface water to groundwater-fed irrigation over the previous 50 years. The groundwater share of the total irrigation water supply has increased from 8% in 1960 to 60% in 2010 due to the continuous expansion of agricultural lands [37]. Based on arid and semiarid climates that prevail in most of the areas of the country making irrigation is necessary for efficient and long-term crop production because evapotranspiration is high while rainfall is scarce and unpredictable [38]. The groundwater extraction is mostly done by means of electricity or diesel-operated tube wells. These tube wells consume a huge amount of primary energy directly or indirectly to lift groundwater from the water table. In this case, the cost of pumping 1000 m^3 of water from shallow and deep tube wells varies between 5$ and 15$ owing to varying energy prices in different regions of the country [39]. On the other hand, the availability of energy resources is challenging for developing countries like Pakistan. Furthermore, irrigation through groundwater is not possible in remote areas of the country where electricity is unavailable. In this perspective, a sustainable solution like Agrovoltaic is principally required to overcome the energy-nexus dilemma.

4. Energy status of Pakistan

4.1 Fossil fuel reserves

In developing countries, an increase in energy consumption is directly linked with population growth and industrial development. In recent decades, energy demand has risen faster than energy supply or energy production in the country. In Pakistan, total energy consumption exceeded from 139.56 TWh in 1986 to 606.74 TWh in 2020 with a 4.4% annual compound growth rate, and this consumption is predicted to reach 1162.07 TWh by the end of 2030 [40]. The country is highly dependent on non-renewable energy resources that primarily include fossil fuels e.g., coal, oil, natural gas, and peat for energy production. The rising energy demand and limited supply of energy due to the presence of fewer energy reserves have become a major challenge in Pakistan. On the other hand, being an oil importing country about 6.6 million tons of oil worth 3.4 billion dollars were imported in 2019 [41]. Another important aspect that impacts the economy of fuels and ultimately all sectors is the inflation rate. Energy generation and the agriculture sector are affected by the rise in fuel prices. In response to rising fuel prices and the depletion of fossil fuel reserves, the world is turning to renewable energy sources like solar thermal, wind, and biomass/biogas [42, 43]. Unfortunately, Pakistan has not been successful in implementing modern technologies for the use of renewable energy sources particularly for agrarian tasks. However, some renewable energy projects like solar, wind, and biomass have been initiated recently in some areas of the country [44–46].

4.2 Sever electricity shortfall

Pakistan is experiencing severe electricity shortages. Electricity consumption has increased throughout all economic sectors particularly the agriculture sector because

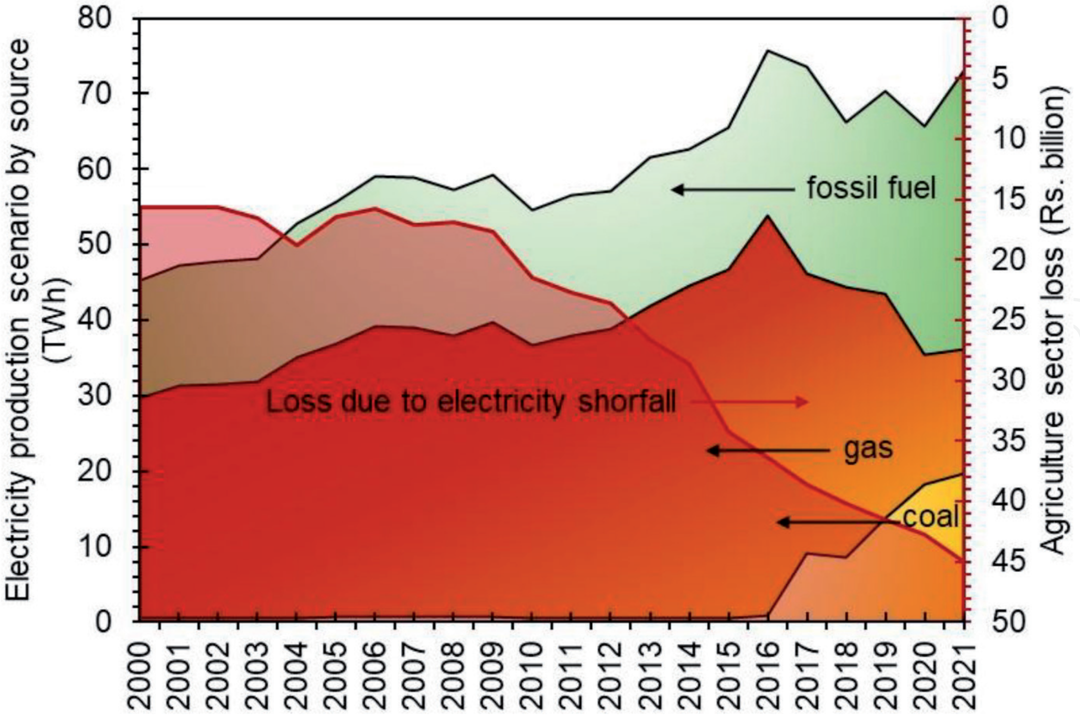


Figure 7.
Electricity production scenario by source and the cumulative loss to agriculture sector due to electricity shortfall reproduce here from [51, 52].

about 1 GW of energy is consumed annually by the irrigation practices only [47, 48]. In 2020, electricity generation was about 22 GW compared to a peak demand of about 25 GW, however, this peak demand is continuously increasing every year, therefore, the whole country is subjected to daily blackouts of about 3–4 h [49]. The electricity shortfall is mainly caused by multiple issues including inadequate power policies, exploitation of indigenous resources, high transmission and distribution systems, and persistent utilization of continuous antiquated thermal power plants that consume fossil fuels [50]. The severe electricity shortfall triggers a reduction in GDP growth of the country by 4%, because of closures of hundreds of manufacturing plants and less agricultural production [47]. **Figure** 7 shows the electricity production scenario by different sources (coal, gas, and fossil fuels) that is not enough to meet the peak demand and the cumulative loss to the agriculture sector due to electricity shortfall and this shortfall is increasing every year. For instance, cumulative loss to the agriculture sector in 2020 was observed at Rs. 42.74 billion while in 2021 this loss was observed at about Rs. 45 billion (PKR).

5. Agrovoltaic concept for irrigation and potential in Pakistan

Recently, scientists and renowned engineers introduced a unique concept named "Agrovoltaic" for addressing food insecurity and on-farm energy constraint in tandem. The concept is to harness solar energy by putting photovoltaic (PV) modules into the same agricultural area that is already being cultivated to produce agrarian commodities. The approach promotes sustainable rural development, and the preservation of biodiversity and the ecosystem by forming synergies between renewable energy and agriculture. In addition, the PV modules shielded the crops from harsh weather conditions. The concept might be expanded to develop an intelligent vision-based irrigation system. **Figure 8** shows the generalized conception of AVIS. The AVIS concept mutually resolves the water and energy problems specifically for the countries that have groundwater reserves and solar energy harvesting potentials. The AVIS integrated Internet of Things (IoT) with the solar-driven irrigation system. The IoT comprising of soil sensors, weather sensors, crop sensors, and microcontrollers. The solar-driven irrigation system contains PV modules, AC or DC batteries, motors and pumps, sun trackers, etc.

The microcontroller is the computational hub of the AVIS which computes, planed, and regulates the components of the solar-driven irrigation system. The microcontroller collects data from the different sensors and executes the data processing activities. For instance, the soil sensor captures agricultural field information such as soil type, water holding capacity, and, most significantly, detects available moisture in the ground. The collected data aid in determining of irrigation volume needed in the field. Similarly, meteorological sensors included within the AVIS capture weather data such as solar radiation, daylight hours, ambient temperature, rainfall, etc. The obtained data will be used to evaluate the solar energy generation capacity and to cut off the irrigation system if the rain will forecast. The cropping data was utilized to calculate water demand based on crop water requirements and crop coefficients. The water data contains surface water availability as well as an estimate of the water shortage that can be met by pumping groundwater. Once the prerequisites were computed, the microcontroller equipped with AVIS actuated the solar pump to extract groundwater for a predetermined period of time.

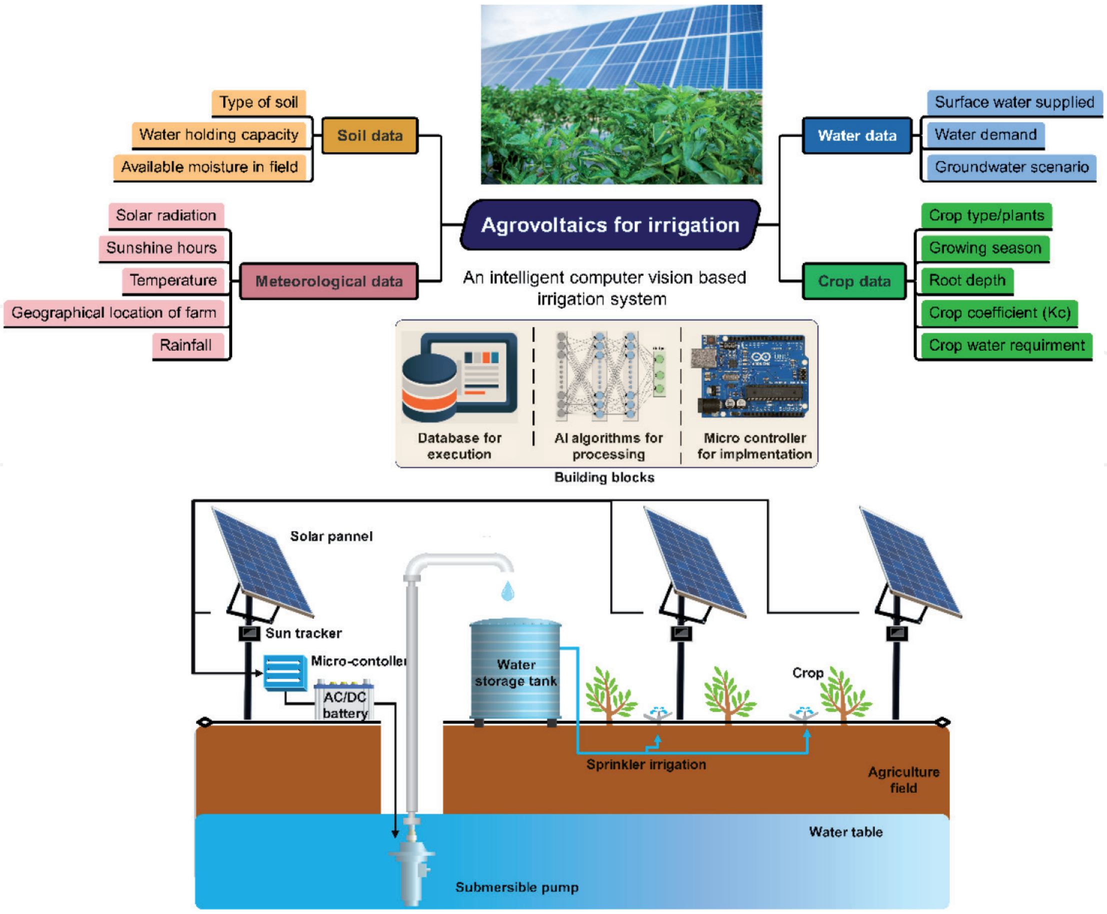


Figure 8.
Agrovoltaic irrigation system (AVIS) conception.

The working principle of the AVIS is based on the PV modules, which convert solar energy into electrical energy. The PV panels are interlinked with the solar motors either AC or DC motors to produce mechanical energy, which is then turned to hydraulic energy by the surface pumps or submersible pumps. The energy supply to the solar pumps will automatically be disconnected once the field requirements are accomplished. During off sunshine hours, AC or DC batteries are integrated into AVIS as a backup energy supply. The ability of a solar pumping system to pump water is determined by three major variables: pressure, flow, and pump power. For design reasons, pressure may be defined as the effort done by a pump to raise a specific amount of water to a storage tank, which is estimated by the elevation head (difference between water source and storage tank). The water pump will need a specific amount of electricity, which must be supplied by a PV array. The irrigation efficiency may be adjusted by using a high-efficiency irrigation system (HEIS) that is powered by PV modules. The benefits of the AVIS are as follows:

- Avoid permanent wilting of the crops due to the nonavailability of the surface water
- Precisely computes the amount of water need to supply from groundwater after subtracting the rainfall water and surface water
- Scavenge pumping energy freely from solar radiations
- Avoid the overexploitation of the groundwater reserves
- Cut off the pressure on the fossil fuels for irrigation activities
- Timely detect the water demand
- Reduction of evapotranspiration and evaporation from the soil
- Minimize the effect of temperature extremes on the crops
- Produce electricity that could be supplied to the national electricity grid
- Eco-friendly, reliable, and durable with longer operating life

Pakistan is geographically positioned in the domain of the sunny belt of the world having long sunshine hours and receiving high solar irradiation, which makes it an ideal locality for solar energy-driven technologies. The daily mean global radiation on the horizontal surface in Pakistan ranges between 1900 and 2200 kWh/m^2, which can potentially generate 1.9–2.3 MWh of energy [53, 54]. The sunshine hours vary between 2000 and 3000 h per year, which reflects massive solar energy harvesting potential. The average solar radiation intensity ranges between 36.05 and 287.36 W/m^2 in the country. Solar radiation intensities of more than 200 W/m^2 were recorded in Sindh from February to October; in practically all parts of Balochistan from March to October; in NWFP, Northern Areas, and Kashmir from April to September; and in Punjab from March to October [55]. During the course of the year, the average solar radiation intensity in Pakistan, namely in the southern parts of Punjab; Sindh; and Balochistan, ranges from 1500 to 2750 W/m^2 day^{-1} for a period of 10 hours every day. In the locations listed

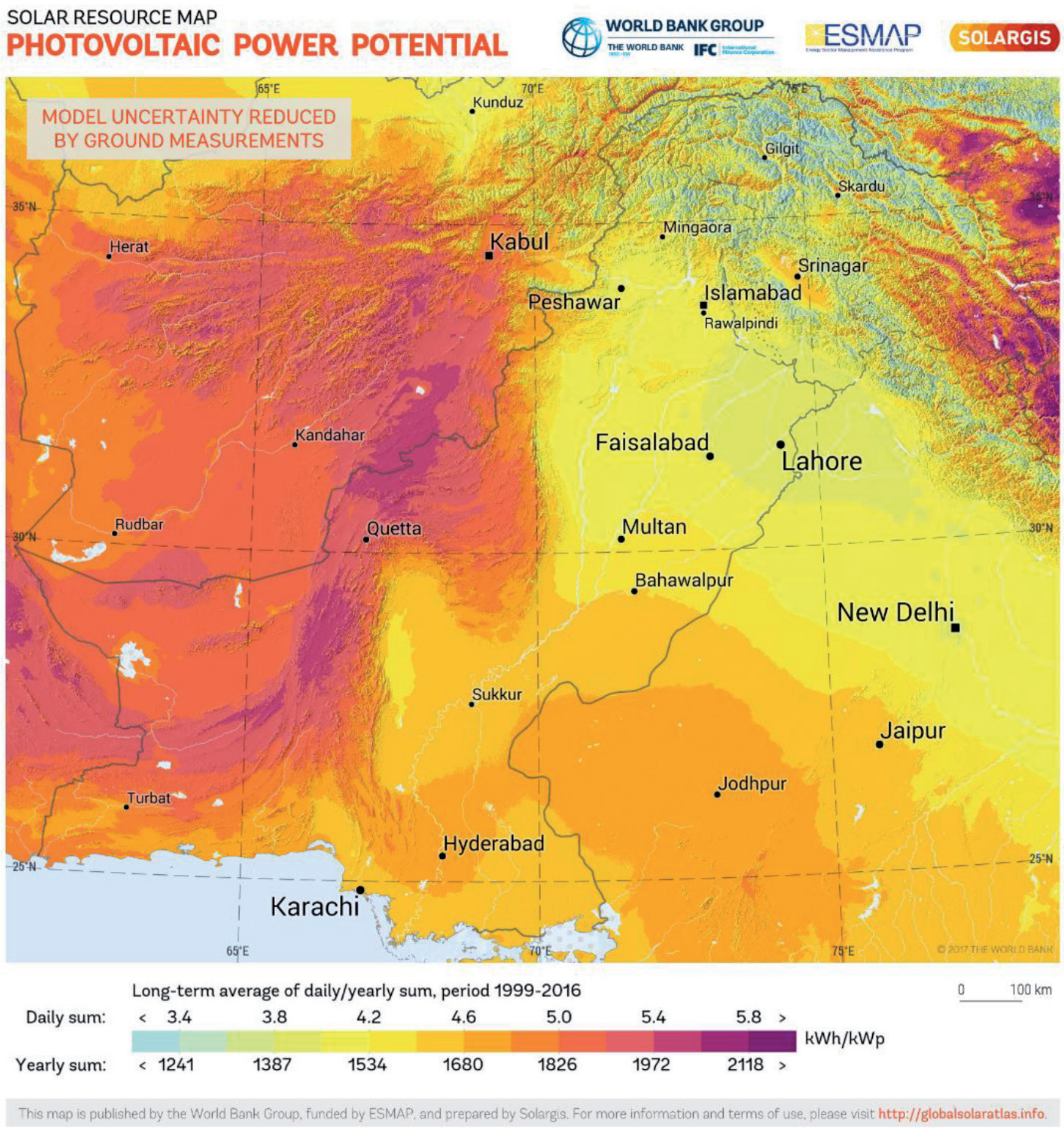


Figure 9.
Photovoltaic power potential in Pakistan is taken from the global solar atlas.

above, it is possible to generate between 45 and 83 megawatts (MW) of power every month through an area of 100 m^2 [55, 56]. **Figure 9** presents a solar resource map of PV power potential, which indicates generating electric power between 3.4 and 5.6 kWh day^{-1}. In this spectrum, the abundant supply of solar energy is promising to supply primary energy to AVIS.

6. Components of Agrovoltaic irrigation system

In this section, the authors of this chapter provide a detailed discussion of the components of the Agrovoltaic irrigation.

6.1 PV cell/generator

The term PV refers to electricity generators consisting of two semiconducting layers principally used in the construction of the PV cells. The negative layer of the

PV cell releases electrons under sunlight. If an external circuit is present, the free electrons move to the positive layer and create an electrical current. So far, the PV cell material science has led toward the 4th generation (4G) PV modules as described in **Figure 10**. The 1G PV cells are thick monocrystalline and multi-crystalline silicon films, which not only leads to highly efficient but also expensive. The efficiency of the thick monocrystalline and multi-crystalline PV cell materials was reported at 26.3% and 21.3%, respectively [58]. The 2G PV cells are synthesized from thin amorphous silicon or polycrystalline Si (silicon), CIGS (copper-indium-gallium-selenium), and CdTe (cadmium telluride) aimed to minimize the cost by employing thin film materials. In comparison to 1G, the performance of the 2G filmed PV cells are inadequate thereby lowering the efficiency. For instance, the thin film chalcogenide such as CdTe has an efficiency range between 19.5% and 21% whereas, in the case of CIGS (minimodule) the efficiency further drops to 18% [59]. In the case of amorphous silicon, the efficiency declined to 10.2% [58]. In this context, a larger surface area will be required to produce electricity equivalent to 1G PV cells. However, the 2G PV cells dramatically reduced the unit cost of electricity generation, which was the key achievement. The 1G and 2G PV modules are highly penetrated in the solar markets having 85% of the market share [60, 61]. The 3G PV modules use nanocrystalline films staked with multilayers of inorganics based on III-V materials such as Gallium arsenide (GaAs), Germanium (Ge), and gallium indium phosphide (GaInP) aimed to improve the efficiency of the system with significantly low production cost [62]. The efficiency of GaAs and GaInP was reported at 37.9% [58]. Despite the acceptable success of 3G cells, major improvements in device performance are necessary if this technology is to compete in terms of cost per watt with prior PV generations. The 4G PV cells introduced the polymers aimed to improve the optoelectronic properties and

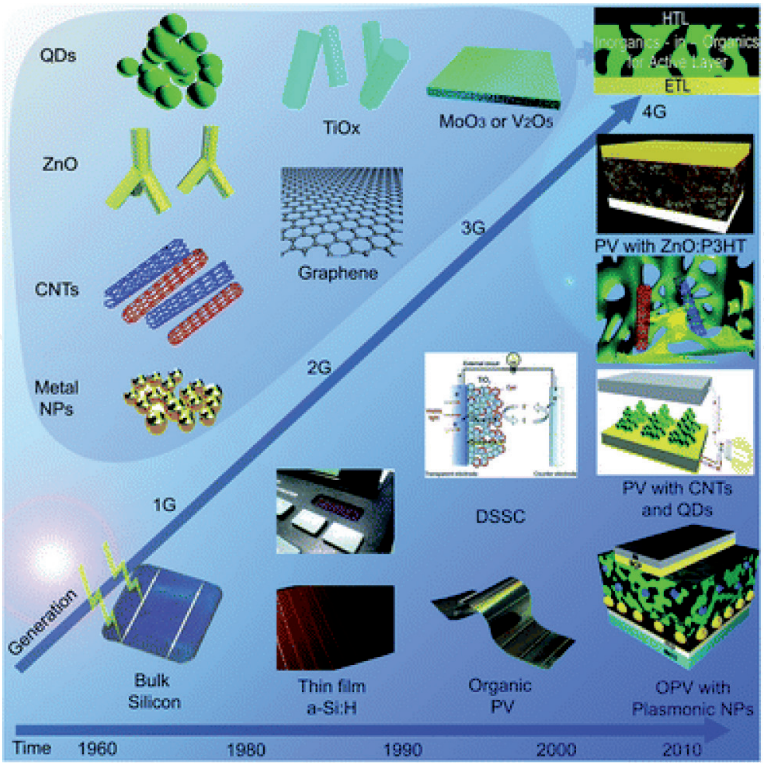


Figure 10.
Timeline of photovoltaic device generations, from 1G to 4G, with nanomaterial components that make up half of 4G devices [57].

low-cost thin PV panels/modules. Solar cells having several p-n junctions constructed of various semiconductor materials are known as multi-junction (MJ), which has been widely investigated in the literature. In reaction to different wavelengths of light, the p-n junction of each material will create an electric current. In this case, the cell efficiency was reported beyond 45%. **Figure 11** presents the temporal improvement of the cell efficiency developed by the National Renewable Energy Laboratory, Golden, Co.

6.2 Cooling and cleaning mechanism

The PV system's output dropped as the panels' temperature climbed over 25°C. Dirt on solar panels might have a negative impact on their performance. In order to reverse this declining trend and improve field performance, the solar panels' surfaces must be cleaned and cooled in some way. A tiny sprinkler mounted in front of the system is used as a cooling mechanism that could improve the system performance by 7–9%.

6.3 Batteries

Batteries are an important component of the AVIS in order to supply the power to the motor during off sunshine hours. Generally, lead-acid batteries and deep cycle batteries of types AC and DC are most frequently used in solar-powered irrigation systems [63]. The lead-acid battery is 80% efficient which reflects in storing 25% more energy in the battery. However, in most studies deep cycle batteries are recommended for solar energy storage due to their prominent attributes such as being discharged to a low energy level, rapid recharged, and no regular maintenance or topping-up required. The capacity of the battery should be sufficient enough to bear the load and smoothly run the connected appliances. If properly maintained, a deep

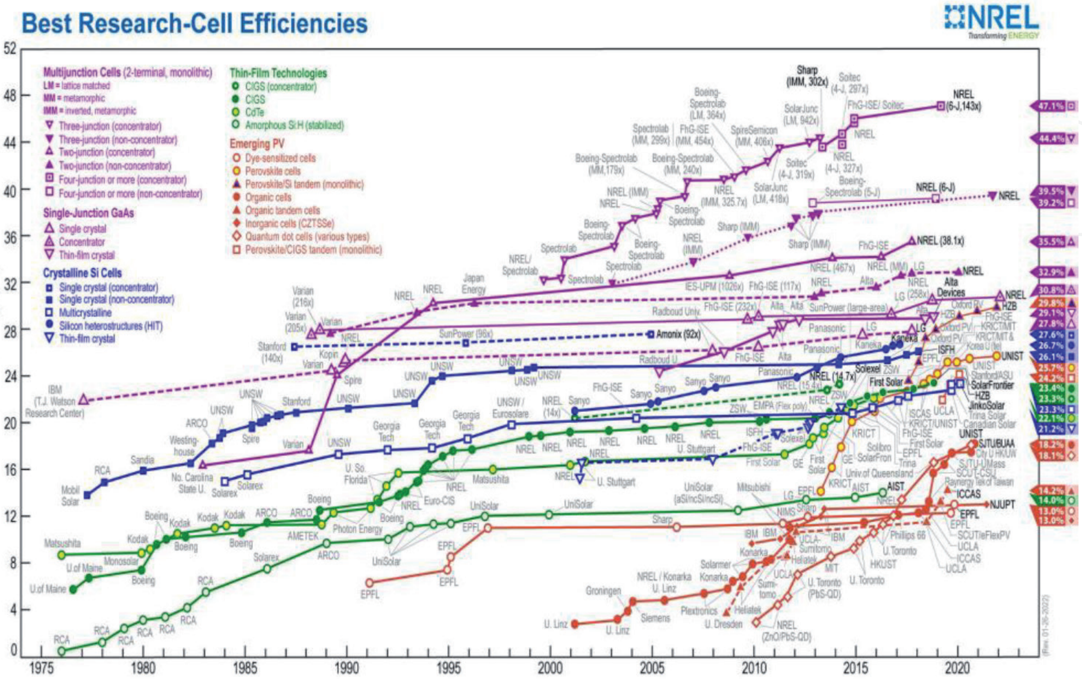


Figure 11.
National Renewable Energy Laboratory graph on best solar PV cell efficiencies.

cycle battery can prolong up to 3–4 years compared to the lead-acid battery, which is limited to 2–4 months.

6.4 Solar motors and pumps

Solar-driven pumps either surface or submersible are the heart of the AVIS. The harvested solar energy is directly being utilized to drive the AC or DC motors, which mainly transform the electrical energy into mechanical energy. The mechanical energy is then utilized to develop hydraulic energy for lifting the groundwater from the deep levels. If compared submersible pumps lift groundwater from more depths as compared to the surface pumps. However, surface pumps or centrifugal pumps are more often adopted due to their special attributes. The selection of the pumping unit is mainly dependent upon the groundwater depth. Higher groundwater depth needs high power pumps and vice versa. Different vendors are available in the market such as Shurflo, Grundfos, Lorentz, Dankoff, SolarJack, etc., [63] which produce different capacities of the solar pumps.

6.5 Sun tracker

The earth revolves around its orbit thereby, the solar radiation incident on the solar collector changes. The sun tracking device is vital in this case since it aims to direct solar energy perpendicularly to the sun during the entire sunshine hours. The device is capable to improvised the solar energy extraction 10–70% [19]. The cited study reveals that the sun tracker generates 57% more, however, increases the installation and maintenance cost of the irrigation system [64]. The sun trackers are classified based on the single axis and dual axis differentiated based on the degree of freedom **Figure 12**. The sun trackers are coupled with photo sensors, which create voltage difference when solar radiation incident on it and accordingly adjust its best orientation. Dual axis sun tracker entails two axes, primary axes and a secondary axis. The primary axis adjusts the solar panel with respect to ground rotation whereas the secondary axis provides tilt movement of the solar panel. However, it has been equipped with installation complexities and also mounts the project cost.

6.6 Micro controller

In order to ensure the smooth operation of the solar pump, it is essential to have both a maximum power point tracking system (MPPT) and a variable frequency inverter (VFI). Various configurations of variable frequency drive (VFD) are being investigated by coupling with and without MPPT. The VFD controller provides square wave output, which results in higher-order harmonics in the output, causing extra losses and pulsating torque in the motor. On the other hand, the maximum power point was not able to identify if the MPPT is not mounted, consequently, the system operates at a fixed DC voltage. Furthermore, the groundwater head found an influential entity for manipulating the average power tracking efficiency. Yadav et al. [67] investigated and compared the impact of sine wave MPPT and VFD on the tracking efficiency corresponding to varying the water head. It was reported that the tracking efficiency ranges between 99.30 and 99.60% when the water head fluctuates from 10 to 20 m. However, in the case of VFD tracking efficiency dropped to 72.20%. In addition, the sine wave MPPT coupled with a low pass filter eliminates the higher-order harmonics.

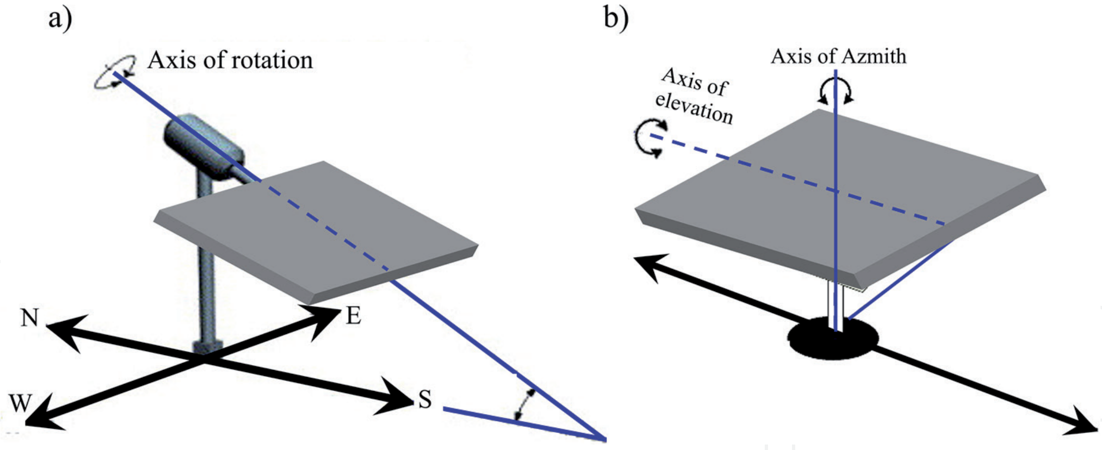


Figure 12.
Single axes (a) and dual axes (b) sun tracker [65, 66].

The MPPT was also found sensitive to environmental variables such as shading and temperature. In this context, various tracking algorithms are being investigated. The incremental conductance method (INC) works on the principle of comparing how voltage and current change. The INC technique, however, has a step size difficulty, particularly in rapidly changing weather conditions. Aside from that, the control system necessitates a costly and intricate circuit and is incapable of dealing with partially shadowed conditions, such as the shadow created by clouds and trees. Recently, it was realized that dual MPPT coupled with INC and dormant particle swarm optimization (DPSO) could handle the partial shading effect and mitigate the voltage fluctuation and spikes [68]. MPPT based on extremum-seeking control has a rapid convergence time and strong steady-state performance because the operating voltage or current of solar PV arrays can be dynamically tuned to maximize output power. Gray Wolf's optimization-based MPPT method was investigated and found efficient in terms of fewer operating parameters, higher efficiency, and outperformed under partially shaded conditions [69]. The artificial neural network (ANN) based MPPT method was also investigated for MPPT [70]. The ANN obtained records of environmental variables from sensors and give the output signal of maximum power point generating conditions. Ramaprabha et al. [71] also investigated the ANN algorithm and found it efficient for all insolation levels. Lin et al. [72] proposed a radial basis function network (RBFN) and an improved Elman neural network (ENN) for MPPT and found them effective. Similarly, another study concludes the ENN implementation due to its stable response and low fluctuation as compared to perturb and observe (P&O). One can find the details relevant to various types of ANN models from the cited articles [73, 74]. However, the variable step size-based ANN MPPT possesses high accuracy, with a quick convergence response time as compared to the step size-based ANN MPPT algorithm [73].

The microcontroller can also be used to determine the optimum irrigation requirements. Rajkumar et al. [75] investigated an automated switching mechanism of the water pump by collecting data from the temperature, humidity, and soil moisture sensors. It was reported that the microcontroller successfully regulates the pumping time. Gao et al. [76] designed a fuzzy irrigation control strategy for real-time estimation of real crop water requirements based on the data received from sensors. Based on experimental results it was realized that the system precisely regulates the solenoid valve, which turns to improve efficiency and proven food security. Normally, the sensor data contains noise that needs the preprocessing of the collected data. In this context, the recursive adaptive filter method was employed to remove the noise, handle the missing values, and normalize the data [77]. Cordeiro et al. [78] developed a deep learning model that was capable to anticipate the soil moisture availability in the agricultural land and addressing the sensor missing data and failure ambiguities. Among the studied algorithms, the k-nearest neighbors (KNN) algorithm bypasses the problems and accurately predicts the irrigation water need. Another study determined the soil moisture using gradient boosting with regression tree (GBRT) and found the best results for smart irrigation planning [79]. Abdulaziz et al. [80] utilized the Lagrange multiplier method in order to optimize the consumption of pumping power and water consumption. The model gives satisfactory results in optimizing the water consumption however, lacked in power utilization. The cited study [77] focused on the preprocessing of irrigation data and estimating plant growth using an adaptive neuro-fuzzy inference system (ANFIS) based on the soil, water level, temperature, and moisture conditions. The ANFIS proved to be optimum due to a precision value of 81% with an accuracy of 84.6% [77].

7. Challenges of agrovoltaic irrigation system

In Pakistan, the alternative energy development board (AEDB) has been actively involved in developing and promoting renewable energy technologies because of the massive resource potential across the country. For solar-driven technologies, the region is envisaged as highly feasible. In this spectrum, various megaprojects are being executed with collaborative efforts. One can find the details of these projects on the official website of the AEDB. In 2015, the federal government of Pakistan takes initiative to subsidize the farmers having cultivated areas greater than 5 hectares for the installation of solar-driven irrigation pumps under the project entitles solar irrigation for agricultural resilience (SoLAR). The project's worth was USD 93.2 million, providing an 80% subsidy for installing 30,000 solar irrigation pumps. However, there no such schemes/policies are being designed for AVIS despite its enormous potential. The challenges could be in the form of economic barriers, nonavailability of technical and skilled personnel, and technological barriers. In this section, the authors analyzed the potential challenges that need to ponder in order to develop successful AVIS.

7.1 Lack of awareness

Agrovoltaic itself is an emerging conception so far investigated in developed countries and possesses plenty of room for technical improvements. Lack of awareness regarding the new energy-water efficient AVIS is the potential bottleneck [9]. The farmers are not informed of relevant cost/economic, environmental benefits, and the potential barriers that need to be encountered for the concept implementation. In addition, the farmers hesitated to invest in emerging technologies due to their limited resources. The leading researchers need to execute the small projects on a university scale in order to develop local knowledge relevant to technology. After that, dissemination activities are performed to spread awareness among the farmers. It is imperative that there be a centralized information hub with a single point of contact for quick and simple access to AVIS data that is made available to all farmers in each and every district.

7.2 Lack of skilled workforce

The shortage of qualified and experienced installation workers, project managers, and engineers in both developing and developed countries is a significant barrier to the growth of AVIS. Likewise, In Pakistan, lack of qualified and semiskilled personnel has hampered the widespread use of the AVIS. This leads to inadequate support infrastructure, maintenance, and after-sales services, which significantly impacts farmers' opinions on AVIS adaptability. In addition, the farmers are not technically trained to operate and understand the complex operating mechanism of the AVIS. In this framework, training facilities that give technical expertise to farmers must be established in each area. Furthermore, short-term courses and vocational training courses must be established in order to develop a job-ready trained workforce.

7.3 Risk of declining groundwater

Recent studies reveal that groundwater is declining at a higher pace in the Indus plains of Pakistan due to climate change, low surface water supplies, installation of large-scale tube wells, over-exploitation, and lack of groundwater governance policies [29, 81, 82]. Although, farmers' access to groundwater benefited them to ensure food security and accomplished agriculture requirements. However, many farmers pump groundwater beyond their agriculture requirements thereby massive pressure, which leads to a declining groundwater table. For instance, Shakoor et al. [83] reveal that if the historical trend of groundwater pumping continues, the water table in Punjab might drop up to 18 m by 2030. Similarly in Balochistan, the groundwater is depleted at the rate of 2–3 m annually [82]. The lowering groundwater table is required to install high-capacity pumps due to depreciation of pumping efficiency beyond the depth of 500 cm [84]. In addition, if standalone solar-driven irrigation pumping systems are installed then there is fear of a more rapid drawdown of groundwater due to the assumption of being increasing pumping by the farmers. However, the Pakistan Council of Research in Water Resources (PCRWR) analyzed that actual solar energy is not capable to exploit the groundwater reserves through solar pumping, irrespective of considering the influential factors such as installation capacity and farmer behavior thereby not widely accepted [21]. The AVIS could be a potential solution to the stated problem in a manner of harvesting free solar energy and pumping the groundwater according to crop water requirement. The AVIS motor switches off the irrigation system once the field requirements are fulfilled.

8. Conclusions

Energizing the agro-food supply chain and access to sufficient water have been essential aspects that bring prosperity and stability to the agriculture sector. However, currently, Pakistan's agriculture sector is profoundly suffering from both energy and water crisis. The major culprits are the exponential growth of population, limited freshwater and primary energy reservoirs, electricity shortfalls, and dried agricultural lands, leading to food insecurity in the country. In 2021, the agriculture sector accounts for 45 billion PKR loss due to power shortages, which directly influence cultivation and irrigation activities. The groundwater and solar energy are alternative reliable solutions to accommodate water and energy shortages, respectively. In this framework, solar pumps are installed across the country however they exhausted groundwater resources in several regions of Pakistan due to inadequate irrigation technologies, irresponsive behavior of farmers, and lack of groundwater governance policies. Agrovoltaic irrigation system (AVIS) could be a remarkable solution that controls the overexploitation of groundwater by utilizing non-payable energy. The present study aimed to explore the prospects and challenges that need to encounter for local implementation of the AVIS. In addition, the study discusses and reviewed the components of the AVIS. Because of the massive solar energy harvesting potential in the country, a significant amount of solar radiation transforms into electrical energy via photovoltaic modules if installed on the land that is cultivated with the crop. The potential benefits of the AVIS include the utilization of the same land for twin benefits (i.e., energy and crop production), metering the groundwater extraction, saving crops from extreme weather conditions, and powering irrigation systems free of cost. However, the impediments such as complex operating mechanisms required skilled/technical personnel for installation, sophisticated maintenance, absence of sufficient ground knowledge, and high capital investment. In order to ensure food security and agriculture prosperity, the government takes the necessary initiatives and empowers the AVIS adaptation by involving leading researchers and engineers mutually involve in research projects that strengthen the AVIS knowledge and conduct dissemination activities and workshops to train and attract the farmers.

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Conflict of interest

The authors declare no conflict of interest.

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