Review on Photovoltaic Agriculture Application and Its Potential on Grape Farms in Xinjiang, China

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Abstract: Photovoltaic industry has become extremely important in China as a strategic emerging policy since 2012, and how to widen the domestic demand to overcome the problem of overcapacity has drawn much attention. The so-called "Agrivoltaic", or, photovoltaic agriculture, could provide a possibly superior approach to providing green and sustainable electricity simultaneously. Xinjiang province, located in Northwestern China, is abundant in renewable energy resources such as wind power and solar radiation; on the other hand, Xinjiang is famous for its growth of grapes with high-intensity of sweetness. Hence, in this paper we firstly introduce some new opportunities for photovoltaic agriculture applications in China, such as photovoltaic greenhouse, photovoltaic water pumping and photovoltaic water purification. Then we focus on one of the applications – the Agrivoltaic potential on grape farms in Xinjiang, and investigate the potential co-develop between the grape production and the solar PV farms, so that the farmers could use the electricity generated from the PV station and simultaneously got the second income from selling the electricity to the grid, without noticeable influence on the crop production output. The results indicate a positive economic value from this hypothesis agrivoltaic system, with green electricity generation, village electrification and the maintenance of the approximately same production of grapes. However, more researches and empirical explorations should be implemented further to draw some unified standard on the agrivoltaic system, so that the output could be stabilized and more and more farmers would be convinced and join the program.
Keywords: Solar photovoltaic; PV agriculture; Agrivoltaic; Renewable energy; Land use.

1. Introduction

The traditional fossil fuel usage has been creating severe environmental problems such as greenhouse gas (GHG) emissions, acid rain and energy shortage, resulting in global ecosystem imbalance and threatening the future generations as well as international economics [1-5]. Fossil fuels are considered unsustainable being depleted year by year, and another more serious side effect is the negative environmental impact with time going on, demanding larger proportion of de-carbonized renewable energy in the whole energy-supply portfolio [6-10].

Solar energy has the reputation of being safe, reliable and clean, and PV electricity generation would be one of the most popular utilization of solar energy in the world. Continuous technical improvements have been taken place in the past few years [11,12], ensuring a more stabilized and cost-efficient application in solar PV technology [13,14]. The International Energy Agency (IEA) has made a prediction that by the year 2050, 16% of the global energy demand, i.e. approximately 6000 TWh, would be generated by solar PV plants [15].

China, with relatively low labor cost and raw material expenses, has witnessed an incredible development in the solar PV products manufacturing within the past decade, becoming one of the most significant countries providing solar PV products [16-18]. Nevertheless, the suddenly weakened demand for solar energy in Europe and US due to the global financial crisis in the year 2008 affected the Chinese solar PV industry to a great extend, and the following anti-dumping and anti-monopoly survey launched in the end of 2011 by the western world officially brought the Chinese solar PV industry to a winter time. Chinese government, from then on, has established a series of subsidy and incentive policies to stimulate the domestic solar PV market, and one of the future possible applications would be photovoltaic agriculture.

Modern agriculture heavily depend on electricity and energy generated mainly from traditional fossil fuels nowadays, thus solar PV technology could be an ideal substitute energy recourse that would provide sustainable and clean energy with low GHG emission [19]. The operation of applying solar PV technology to agriculture activities is called PV agriculture, or agrivoltaic, utilizing the power generated from solar PV plants to fulfill the electricity demand in agricultural production activities such as watering, planting and irrigating. Many scholars have conducted the economic feasibility study of this application in the past 20 years and the experiments were conducted as well [20,21].

Beyond those studies mainly integrating the solar PV plants on agricultural machines to provide services, solar PV farms could also be deployed on the agricultural area to dual-use the land. Solar photovoltaic stations could be deployed both on building and on ground, while the massive deployment of the ground-mounted PV plants can be a theoretical land-use conflict with agricultural production, especially those full sun crops such as grapes, which would compete the sunlight with the PV panels. Fortunately, this problem could be solved by agrivoltaic, which, by the name, could be interpreted as a combination or so-called co-development of sunshine land areas for both agriculture and solar PV plants [22,23]. The agrivoltaic concept has been experimented and proven successful in several systems including Aloe vera in dry and semi-arid regions, lettuce, and cherry tomatoes [24-27]. However, those studies mainly focused on shade tolerant crops that would not be affected by the shading areas from the PV panels, while this study would provide a hypothesis agrivoltaic system on the potential of a shade intolerant plant (grape) in Xinjiang province.

The main reason why solar PV technology could be integrated with the traditional agriculture operations gradually is technological improvement and cost reduction [28,29]. This co-development could not only help the transformation from the traditional agriculture to modern agriculture, but also help to reduce the GHG emission, enhance environmental protection and energy saving. Moreover, this would be an effective way to expand the domestic solar PV market and solve the overcapacity problem in the long run.

2. Current conditions of solar energy resources and development in Xinjiang, China

2.1. Overview

High-energy demand and large population have always been the greatest challenges in China, adding the incredible consecutive growth of GDP in the past few decades, China is facing a severe situation of energy shortage and environment damage [30]. To cope with the problem, the State Council in China has launched the 12th Five-year Plan for Energy Development, announcing to establish five national-level integrated energy bases, referring to the thermal power and sustainable energy portfolio including hydropower, wind power and solar power, in Shanxi, Ordos Basin, Eastern Inner Mongolia, the Southwest and Xinjiang [31]. Take Hami in Xinjiang province for example, it has not only large reserves of traditional high quality fossil fuels but also rich volume of wind power and solar radiation; moreover, both the traditional resources and the clean energies are well-developed on large-scale basis [32].

In September 2013, Chinese President XI Jinping announced the “Silk Road Economic Belt”, which would cover an area of around 50 million square kilometers and influence a total population of about 3 billion people. Xinjiang, a traditional significant energy base in China, is one of the most important strategic provinces in this policy that connects different areas in East China within the country and links western areas abroad. On the other hand, Xinjiang plays a critical role in providing national energy supply with top reserves of a variety mainstream energy sources such as traditional fossil fuels and renewable energy resources including wind power, solar radiation, biomass and dry air energy, ensuring its outstanding development status. In particular, the solar radiation and wind power resources have been widely utilized in different projects, gaining remarkable achievement in various aspects, making Xinjiang the potential central engine in promoting new energy in Northwest and Central China [33].

2.2 Solar Energy

Generally speaking, Xinjiang is quite rich in solar energy comparing to other areas in China. Table 1 justifies the common classification of solar energy resources [34], and we can see that most southern areas in Xinjiang could reach the Class 1 area with the highest amount of sunshine radiation, while the other areas in Xinjiang fall in the second Class.

Taking Xinjiang province as a whole, the average annual sunshine duration is around 2500-3500 hours, and the annual total radiation is 5430-6670 MJ/m2, ranking the second place in China [34]. The percentage of sunshine in East and South Xinjiang is around 60-80% while the percentage is around 60-70% in the rest of the province. The value in the east areas is higher than in the west areas, and July is generally the month with the highest value of sunshine in most areas except for south Tianshan piedmont where August is even higher. On the other aspect, East Xinjiang enjoys the most days with sunshine exposure of more than 6 hours per day, and the average value is 270-325 days [35], as shown in the following Table 2.

Table 1 Classification of solar energy resources.

Description	Equivalent standard coal (kg)	Annual total radiation (MJ/m^2)	Annual cumulative sunshine hours (h/a)	Class
Abundant areas	225-285	6680-8400	3200-3300	I
Rich areas	200-225	5852-6680	3000-3200	II
Middle areas	170-200	5016-5852	2200-3000	III
Poor areas	140-170	4180-5016	1400-2200	IV
Poorest areas	115-140	3344-4180	1000-1400	V

Table 2 Sunshine exposure value in Xinjiang.

Days with sunshine exposure of more than 6 h/d	Area	Name
300-325	East Area	Resource-rich belt
250-280	Southern Tianshan Piedmount – Southern Xinjiang	Resource-poor belt
250-280	Northern Tianshan piedmount	Belt with relatively rich resources
250-270	Edges of Junggar – Altai Mountains	Belt with fewer resources

It could be noticed clearly that the solar energy resources are abundant in Hami, Ruoqiang, Qiemo, Turpan and the east areas, with the maximum sunshine percentage as high as 80%. The annual total solar radiation in Hami could reach 6400 ML/m2, providing a possibility to co-develop the grape production and the solar power stations. Also, most sunshine exposure areas in Xinjiang are desert or located in Gobi desert with flat landform, which are quite suitable for large-scale ground-mounted solar power stations to be established [36-39].

2.3 Current development of solar energy in Xinjiang

According to a report generated by Xinjiang Power Grid Company, the overall capacity of power generated from renewable energy resources in Xinjiang was 18.3 billion kWh during the period of January to November in 2015, and the increasing rate was 14.31% comparing to the same period before [40]. The on-grid new energy resources installed in Xinjiang province met 14.94 million kW by the end of November 2015, occupying 22.5% of the total power generation, ensuring Xinjiang the third place in this criteria following Gansu and Inner Mongolia.

In the period of “12th Five-Year Plan”, solar PV plants contributed remarkable capacity of power generation with rapid development of project technology and diversification. Statistics from authority institute declared that by the end of year 2015, the total on-grid installed renewable energy resources has reached 22.19 million kW in Xinjiang [41].

Thanks to its geological and climate feature, thermal power takes up most of the renewable energy power generation volume in Xinjiang, reaching as high as 69.27% in the year 2014, followed by wind power, hydropower, photovoltaic and biomass as shown in Fig. 1. The installed solar PV projects was 3.26 million kW at that time, increasing by 490,000 kW compared to one year before, witnessing a 17.69% increase [42]. Actually, the utilization of solar photovoltaic energy generation gained the most remarkable increase from zero level in 2011 in Xinjiang, with 144 million kWh in 2012 and 737 million kWh in 2013, jumping by 411.36% within just one year. The capacity of generation by solar PV was as high as 4.024 billion kWh in 2014, witnessing another annual increase of 447.36% [43,44].

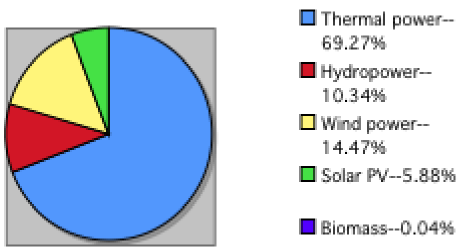

Fig. 1. Installed structure of renewable energy sources in Xinjiang in 2014

3. Application modes of PV agriculture system

Considering the huge capacity of solar PV power generation potential, increasing demand for energy in agriculture activities, limited source of traditional fossil fuels and negative environmental impacts in the past years, Xinjiang province could encourage the industrialization process of PV agriculture in the following applications suitable in Xinjiang to gain a all-win situation

3.1 PV agricultural greenhouse

One of the most popular and intuitive applications to utilize the solar PV agriculture is to incorporate PV panels to the greenhouses. For one thing, higher economics income could be gained by flexibly creating proper temperature and environment for high value-added crops; even anti-season plants could be achieved thanks to the inner artificial environment in greenhouse [45]. For another thing, the transparent and semi-transparent PV panels could actually allow more sunlight enter the greenhouse [46.47], and by selecting different kinds of plastic films, various of wavelengths of light could be absorbed to fulfill the demand for different plants [48]. The third advantage is to adjust the daylight inside the greenhouse by providing supplementary lights powered by PV systems [49], or it could extend the light providing time for the crops growth by establishing an LED lamb inside the greenhouse, using the stored electricity generated during the daytime [50]. According to the statistics, the total installation of PV greenhouse in China by May 2014 has already reached more than 612 MW [51].

3.2 PV wastewater purification

Wastewater, or sewage, has become an increasingly serious problem in China, especially in those rural areas where agriculture production takes places [52,53]. According to the literature [54], the excessive emissions of agricultural pollutants such as COD and TN have done critical damage to the water pollution in those rural areas in China. However, solar PV wastewater purification system with no battery and no storage system could utilize solar PV electricity generation into the wastewater treatment process with no extra pollution and energy transferring [55]. Without battery installed inside, the system would work during the daytime and stop wording after sun goes down, which would be an ideal condition for nitrogen and phosphate to release from the wastewater. This is not just a theoretical hypothesis, since experiments have been taken place and indicated that the system could achieved average removal of 88% COD, 98% NH4+-N, 70% TN and 84% TP. Nowadays, more and more such PV wastewater purification system have been established in China such as Yangzhou 9.7MW PV wastewater treatment project and Taizhou 5 MW PV wastewater treatment project [56,57]. It is conservatively predicted that the total capacity of such PV wastewater treatment project could reach 60 MW in China by 2020, and Xinjiang could enjoy the benefit from this technology in the long run.

3.3 PV water pumping

Every kind of agricultural crops need watering, thus how to use the water in a saving and environmental way is a big challenge. PV water pumping could be a green and sustainable solution to provide water in an economical way for irrigation; it can also halt grassland from desertification and degradation, promoting farmland conservation in China [58], especially in Xinjiang where the climate is dry and the temperature is high most of the years. Chandel et al. [59] conducted a review indicating that the PV water pumping system surpassed the traditional electricity-driven pumping machines in ways that the PV water pumping system would not emit any GHG and at the same time the operational costs were much lower, with the investment payback period of 4-6 years. Campana et al. [60] did a detailed investigation on the payback period of PV water pumping system with a sensitivity analysis, indicating that the investment payback period of such systems would vary between 5-14 years following the variation of PV module price between $0.8-2.0/Wp at the lowest forage price, while 2-5 years at the highest forage price. By the year 2016, the total installed capacity of PV water pumping systems in vast remote rural areas in China has reached 280 kW to supply water for residents, livestock and crop-irrigation, and the capacity could surpass 6 MW by the end of 2018 [61].

3.4 Rural solar power station

Solving the problem of the enhancement of rural electrification rate is one of the most critical improvements for the living quality of rural population in China, especially for the remote villages where the national power grid cannot be linked or the electricity service is unsustainable. Although the lightening project and other programs have already contributed much to cope with the situation, there are still towns and villages with absolutely no access to electricity supply at all in some remote rural areas in China [62-64]. Solar PV power stations could be a suitable solution to this issue. As a matter of fact, such policies have been launched with remarkable success in the past years, for example, the Township Electrification Program aiming to provide electrification in poor and remote areas in western China initiated by NDRC in 2002 has gain a total installed capacity of PV power stations of 20 mw with a total investment of $0.71 billion [65], and the total distributed PV stations for rural electrification is predicted to reach 10 GW by the year 2020 [66]. This application could be an ideal solution in Xinjiang where there is plenty of sunshine and platform landscape, while at the same time many poor and remote areas with no electricity services at all.

4. Agrivoltaic potential on grape farms in Xinjiang

4.1 Background

According to the previous discussion, Xinjiang could establish many kinds of PV agriculture projects to enhance economical value and at the same time eliminate GHG emissions. Besides the ordinary PV agriculture projects, Xinjiang, especially Hami district where solar radiation is superior with large areas of grape farms, could investigate the possibility to establish the so called Agrivoltaic potential on grape farms to simultaneously benefit from two projects on one piece of land.

Grape farms in Xinjiang could be ideal spots for agrivoltaic experiment. For one thing, grape farms in Xinjiang are generally established in areas with moderate-to-high temperatures and reasonable duration of sunlight, for example Hami [67,68]. Geometrically speaking, grapes are grown on trellises lining up straightly with a unified unutilized gap of about 1.5-2.5 meters between. For another thing, although grapes are normally considered as shade intolerant crop, it is still possible to grown grapes with approximately same harvest output even if the sunlight can not cover the plant continuously, and a more extreme case could be seen that the grapes could be grown properly even with mostly shade and limited sunlight as well, with some preparation and forethought [69]. At the same time, the remote grape farms in Xinjiang would always suffer from electricity shortage and unsustainability.

4.2 Method

One method to simultaneously fully utilize the wasted sunlight between the trellises and to self-satisfy the utility usage is to mount and install solar PV modules between the trellises with no shading areas on modules to ensure the proper operation. For farmer's convenience to take care of the grapes as well as do the daily main maintenances to the solar PV systems such as cleaning and checking, the PV modules should be mounted in an alternate manner with the length (vertical height of the modules) mounted on the trellises.

In a recent study investigating the Agrivoltaic potential on grape farms in India [70], the author chose the Trina Solar 310W TSM-310-PD14 polycrystalline silicon module as the installed target, with efficiency of 15.7% and dimensions of 1956mm * 992mm * 40mm [71]. The modules were considered mounting on the same height as that of the grapes for convenience, and the side length of the 1 acre grape farm would be 63.6 m, allowing to arrange 32 modules along the sideway. The inner-trellises spacing was 1.8 m, providing 17 rows of solar PV modules in an alternative way. Moreover, this arrangement of the solar PV modules, though sacrificed some desired array output comparing to the fully arranged solar module filed, could further ensure that there would be little overlap shading area between two rows of solar panels, and the height of the panels would be designed in a way that there is no shading problem of the PV modules from grape vines. Figure 2 is the side view of the arrangement of solar modules between grape trellises by Malu [70], indicating the width and tilt angle of the alternative modules as well as their relationship with the trellises. The Figure 3 is the bird view of the grape farm with the solar modules installed inside [70].

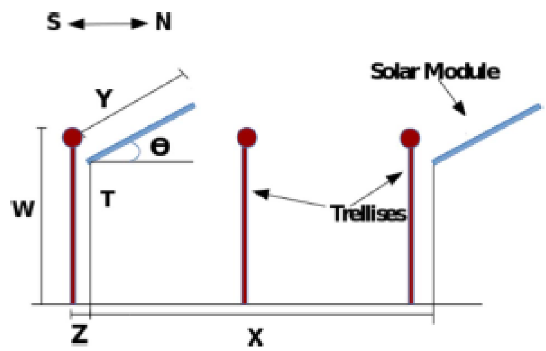

Fig.2. Side view arrangement of solar modules between grape trellises with approximately same height. X is the width between two solar modules, Z is the width between a solar module and the next trellises. W is the height of the trellises. T is the vertical distance from ground to the bottom edge of the solar module. Y is the length of the solar module. Θis the tilt angle of the solar module.

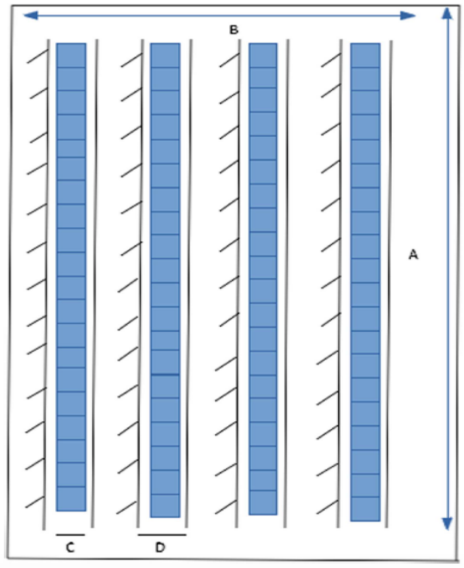

Fig. 3. The bird view of the grape farm-based PV agriculture system. A is the width of the farm. B is the depth f the farm. C is the horizontal width of the PV module on the ground, which could be calculated as Ycos(Θ). D is the inter-trellises spacing.

According to Malu et al. [70], a 1-acre grape farm could arrange the solar PV modules in 17 rows and 32 columns and the potential project electricity output could be calculated to be 168.64 kW, with the hypothesis of using the Trina Solar TSM 310PD14 modules. Another critical factor regarding the installed tilt angles of the solar panels was also investigated in the same study, indicating that a fixed optimal tilt angle of 21° could maximize PV output, resulting in an electricity generation of 259,826 kWh/year in an agrivoltaic farm set up in Nagpur [70], where the shading on the solar modules could be neglected in such situation. Further similar study could be conducted in Xinjiang Hami as well, finding out the optimal tilt angle with the local sunshine condition as well as the grape trellises arrangement.

4.3 Future work

The most critical work to be done in future is to conduct empirical experiments to proof the theoretical concept discussed above. Appropriate grape farms should be selected in Xinjiang and sensitivity analysis regarding tilt angle, module direction, module type, columns arrangement method and other related factors should be done to generate a more suitable and economical-efficient way to promote the agrivoltaic in Xinjiang. What's more, this study only consider the PV part, with neither plant-biology consideration nor farmer's concern related to phycology and tradition, which could be a possible barrier when promoting the concept to remote areas.

A simple filed pilot study could be done in national supported grape farms in Xinjiang first, and the pioneer result could be a solid encouragement to the local farmers. In the long run, the environmental benefit of lower GHG emission and the second income of selling the extra electricity generated from the solar PV array could be more and more noticeable, and new generation of integrated systems could be developed further

5. Conclusions

Xinjiang is one of the five critical energy bases in China with high strategic status, and it is also the key area in President Xi Jinping's "Silk Road" economic belt policy in China. Apart from the traditional fossil fuels, Xinjiang is rich in renewable energy sources as well, especially thermal power, wind power and solar power, which have been utilizing to some extend in the past few years. Solar PV plants are of great potential thanks to the remarkable sunshine radiation in most areas and the flat landform there.

Xinjiang is famous for its agricultural industry, thus to develop the PV agriculture, such as PV water pumping and PV greenhouse, could be a suitable way to not only enhance farmer's economic income but also solve the electricity shortage problem in some remote areas. What's more, establishing PV project could also contribute to the environmental improvement target and enhance the residents' living condition in the long run.

Apart from the traditional PV agriculture application, a new suggestion of agrivoltaic has been made to establish PV arrays inside the grape farm in an alternative way. For one thing, electricity generated from the PV arrays could offer daily usage for the grape farm, with the excess power sold to the grid to earn more income for the farmers, and for another thing, the output of the grape farms would not be influenced by such activity while the overall environment could be enhanced in the long run.

Future work including empirical experiment and sensitivity analysis should be conducted in Xinjiang to verify the result of this conceptual study, and more detailed investigation should be conducted to maximize the overall benefit in the long run.

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