A review of the attributes of successful agriphotovoltaic projects

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ABSTRACT

Climate change is causing massive environmental disasters, which increasingly damage human civilization. To cope with climate risk, the world is progressively converting its energy dependence from the fossil fuel base to renewable energy such as photovoltaic solar farms. Successful photovoltaic (PV) projects have demonstrated various benefits and positive effects in all environmental, economic, and social aspects. However, conventional photovoltaic projects tend to have a serious land-use conflict issue with agricultural farmlands in that solar farms require huge land areas to install PV panels. Responsively, the concept of Agrivoltaic (APV), a mixed system that deploys photovoltaic panels over farmlands, emerged and have been implemented. Although numerous studies demonstrate the multiple benefits of APV, there is a lack of studies analyzing the influential attributes that may lead to the success or failure of the APV project. Thus, this paper aims to review and analyze the influential attributes of APV that may be relevant to its success or failure, based on the triple bottom lines-economic-environmental-social aspects. This paper also aim to review the opportunities and challenges that may arise when implementing APV into the urban environment.

Keywords: *agrivoltaic, productive landscape, co-location, renewable energy, future energy landscape.*

INTRODUCTION

Extreme weather events have been increasingly occurring in recent years across the world, which is leading to major and minor damages in human life and property. In 2016, The United Nations established seventeen Sustainable Development Goals (SDGs) to address poverty, health, and other social problems under climate change. The primary goal within the SDGs is to protect the environment while, simultaneously, promoting sustainable growth in a cooperative way by alleviating climate change. One of the main principles shared within the SDGs is to reduce carbon emissions. Throughout the world, countries have been striving to observe Certified Emission Reductions (CERs) designated from the Kyoto protocol. As a result, the world is now facing a new era of converting energy infrastructure from conventional fossil fuel systems to renewable energy practices. Many countries have increased their number of renewable energy infrastructures, such as photovoltaic (PV) farms and wind farms, to fulfil the 2012 Paris Global Carbon Agreement that begins to take effect soon.

Despite constructive efforts, several serious issues have occurred while implementing renewable energy technologies. The main conflict revolved around land-use, and it was mainly triggered by two conflicting land-use demands between agriculture and the land-use needs of solar farms (González-García et al., 2020). In fact, major renewable energy technologies, such as solar and wind farms, require a huge land area to install photovoltaic panels or wind turbines, respectively. In particular, solar farm sites are preferred on flat land with appropriate access to sunlight. This standard used to conflict with farmland needs, where sunny plants, such as rice and wheat, are ideal for growth.

The concept of Agrivoltaic (APV) emerged to mitigate this land-use conflict. APV is the dual land-use concept that enables agricultural lands to be situated under photovoltaic arrays. APV is expected to address the land-use conflict by establishing agricultural activities underneath solar energy production simultaneously upon the same land area (Schindele et al., 2020). Nowadays, interest in APVs is increasing with rising demands for renewable energy and adequate food production.

The benefits and effects of APV have been addressed by numerous studies. Notably, APV's dual land-use characteristics may promote land-use efficiency and increase land productivity (Lobaccaro et al., 2019; Scognamiglio, 2016).

The APVs vertical structure can increase maintenance and operation efficiency by inducing synergies between PV panels and agricultural activities (Elamri et al., 2018; Scognamiglio, 2016). For example, its vertical deployment can increase water use efficiency for both solar energy production and crop cultivation by enabling PV cleaning water to be reused as irrigation for crops. Also, suspended PV arrays place shades on the crops, which can reduce direct sunlight. This help soil moisture on crops maintain longer. Alongside these studies, there have been numerous studies revealing the benefits of APV in regards to bio habitats, decreased environmental and soil degradation near PV panels (Ravi et al., 2016), and carbon sequestration (Lobaccaro et al., 2019).

Even though numerous studies have examined multiple benefits of APVs by focusing on each APV attribute respectively, there has been few studies that comprehensively incorporate APV attributes into planning and design. In fact, previous studies have mentioned influential factors that could influence either the success or failure of APV projects. However, these influential attributes were discussed separately under different geographical contexts and scales, so it was difficult to comprehensively understand which APV attributes affect the success, in terms of the actual project implementation. In addition, most, if not all, APV projects were executed in rural or suburban areas of farmlands, which makes us question why APVs have been implemented in rural areas and what impacts APVs may have in urban areas.

As a result, in this study, we aim to conduct a literature review on influential attributes for successful APVs in general. We also aim to explain the APV's potential opportunities and challenges in terms of both planning and design.

METHOD

The success of APV projects usually have been discussed from an economic aspect, such as whether an APV site can make profits by selling enough amount of solar energy and crops. In order to find key attributes among several APVs characteristics, we firstly searched studies on APV with the following keywords through Google Scholar and Science Direct: Agrivoltaic, Agrovoltaic, Agriphotovoltaic, and Agrophotovoltaic. Next, we selected twenty studies that empirically investigated the effect of certain attributes of APV on energy yields, crop quality, and crop quantity. Through reviewing these papers, we grouped key characteristics of APVs based on the triple bottom lines-Environmental-Economic-

Social dimensions. We then reviewed the key attributes of how they could affect either success or failures of APV projects, and organized the finding in this paper.

RESULTS AND DISCUSSIONS

1) Environmental aspects

The APV project's success may be measured by whether the APV triggered detrimental environmental impacts on existing land. Simply put, the less environmental impacts may be evaluated as more successful APV design and implementation. However, negative environmental impacts, such as soil erosion and vegetation degradation, could occur throughout the construction process depending on land-use history and landscape characteristics. In the case of soil erosion, while some studies have argued that APV projects provide advantages in preventing soil erosion, others have suggested erosion may get worse if APVs are constructed on unstable ground with more than moderate slopes and sandy soils. In conclusion, the following questions may be evaluated to lead planners and designers to higher APV success earlier on; whether the site characteristics are proper to develop APV, and whether the appropriate site evaluations have been made. In fact, an elaborate site analysis is important to evaluate the project feasibility. The analysis should be conducted by considering various factors such as annual solar insolation, slope, environmental pollution, microclimate, seasonal change, and much more.

2) Economical aspects

The success of APVs can be discussed by whether APV projects have profitability through the sales of energy and crop yields. In particular, the success of APV can be defined by the time APVs start making net-income. It could be identified as APV's increase in cumulative earnings from crop and energy sales over the sum of initial investment funds and operation costs. This economic estimation could be explained with the Levelized Cost of Electricity (LCOE). One study mentioned that APV has 38% higher LCOE, as much as €0.0226 kWh−1, than that of conventional PV solar farms because of the extra installation cost (Schindele et al., 2020). Additionally, it stated that the operating expenses of APV are lower than ground-mounted PV farms because of synergetic effects and benefits from co-location, such as significant decrease in land-cost, management cost and labor (Schindele et al., 2020). Therefore, the economic success of APVs would depend on how much energy and good quality of crops could be produced in APV while having low operational costs. To be more specific, producing energy and crops in APVs can be specifically explained by three associated factors: PV density ratio, crop characteristics, and the trade-off between PV systems and agricultural activities.

First, the success of PV systems in APV could be defined as both the APV's solar efficiency in relation to maintenance energy costs and the APV's capacity to making a profit by selling solar energy to an energy company. The following questions would be helpful to evaluate APV in the energy sector; how long an APV project should be operated to make net-income, and how much energy APVs can produce annually or monthly. The selling price of solar energy keeps decreasing due to expanding solar farms and decreasing prices for raw materials for PV panels. It makes the operation period longer, which may lead to an increased risk of failure.

Second, the success of crop cultivation in APV depends on the quality of yields of the harvested crops. APVs have a distinct physical feature compared to conventional agricultural land in that crops grow under PV arrays. As a result, APV crops are getting less sunlight due to the shades of PV arrays over the field, which is likely to result in a failure of cultivation.

Influential factor (1): PV density ratio

PV density is the ratio of how many PV panels cover land area. It is closely related to the energy yield as well as the crop quality and yield in that the amount of shade on crops may vary depending on the PV density. The PV density could be decided depending on the context of which aspects, either energy or crop cultivation, are more concentrated in APV projects. In general, PV density may be decided as many panels as possible so that it may produce a large volume of potential solar energy. The higher the PV density, however, is directly correlated with the more increase of shades, which could end up negatively impacting crop quality. Although various studies have been investigating PV density to find an optimum proportion, the debate is still ongoing (Aroca-Delgado et al., 2018; Weselek et al., 2019). While the studies show different results on density, several studies reported that fifty percent of PV density was adequate in balancing both energy and crop production (Dinesh & Pearce, 2016; Dupraz et al., 2011; Weselek et al., 2019). They also mentioned that the optimum PV density may vary depending on conditions such as local climate, annual solar insolation by geographical location, and the type of PV panels. In the case of the PV panel type, one of the earlier studies empirically showed that using a long and narrow shaped PV panel (4*9 or 3*12 cell array) can allow slightly more sunlight to reach the ground, while slightly decreasing potential energy yields (Solarfarm Co., 2019). However, they also pointed out that using this configuration of PV panels will cause additional cost in APV installation (Solarfarm Co., 2019).

Influential factor (2): crop characteristics

Crop characteristics, such as shade tolerance and drought resistance, are also closely related to crop yield and quality. APV lands have a less irradiated solar environment due to PV arrays. Multiple studies have pointed to the importance of appropriately selecting a crop (Adeh et al., 2018; Dinesh & Pearce, 2016; Scognamiglio, 2016; Weselek et al., 2019). Some studies have proposed that planting shade-tolerant species in APVs may be conducive for both producing energy and crops together (Dupraz et al., 2011; Elamri et al., 2018). Conversely, other studies have surprisingly revealed that plants preferring sunshine, such as lettuce, eggplants, and tomatoes, grow well even under limited light conditions (Wang et al., 2018; Weselek et al., 2019). Also, APVs have the benefits of increasing water-use efficiency by dual water uses for PV cleaning and irrigation (Adeh et al., 2018; Barron-Gafford et al., 2016; Elamri et al., 2018). The water used to clean the PV panels fall on the ground, which could be used as irrigation but it might cause uneven water irrigation on crops without a small water distributor under the panels. In addition, shade from PV arrays can decrease evapotranspiration rates on crops, allowing the moisture on the crop leaves to potentially persist longer than typical farmlands. This benefit would contribute to increasing the APV's adaptability in arid and semi-arid climates (Adeh et al., 2018; Weselek et al., 2019).

Influential factor (3): inherent trade-offs in land-use

APVs require a structure that can hold PV panels over a productive field. The columns supporting the structure causes some land-use losses, which will reduce the potential maximum crop yield. A report from a South Korean APV company revealed that APVs should aim to secure at least 80 percent of the entire site for arable lands. It is because the lands lost by the columns occurs up to 20 percent (Solarfarm Co., 2019). APVs have faced criticisms that their respective energy or crop yield is lower than the typical solar farm and farmland. However, this criticism has not been considered when regarding land-use efficiency and productivity. Even though APVs have slightly lower potential yields in producing energy and growing crops, it may expand the overall use of the land while establishing sustainable development. As a result, this dual utility of the land will contribute to increasing land productivity and land-use efficiency. Therefore, in planning APVs, estimating potential yields will be important to anticipate when APV projects start to produce net-profits.

3) Social aspect

The final challenge of APVs becoming successful are the social conflicts and the lack of relevant laws and regulations. Governments and agencies are increasingly interested in APVs for their potential of dual benefits from energy and agricultural production. However, unlike the typical ground-mounted solar farms that are widely accepted, APVs are still in an early stage of implementation. Due to the lack of regulations and standards regarding APVs, there is a rise in conflict between energy companies and local farmers, hindering wide spread implementation of APVs.

Social conflicts

The social conflicts originate from the disproportionate profit-sharing between energy companies and individual energy producers. This uneven distribution of profits discourages people from implementing APV. The revenue model of APV, which is directly related to the profit distribution, is linked to the following three subjects: (1) the government, as the top-end, provides subsidies and pressure to increase renewable energy; (2) major energy companies responding to the pressure from the government seek potential land areas (farmlands) to install PV panels. (3) As the bottom end, the farmers earn money through the land rental charges and energy sales to energy companies.

The uneven profit distribution usually occurs in-between major energy agencies and individual energy producers. One of the major causes of the profit inequity is the decreasing price of the Renewable Energy Certificate (REC). The decreasing REC is reducing the energy unit price, which results in decreasing individual producers' potential profits that could have been obtained by selling their produced energy. Particularly, this would be much worse in the case of APVs, as APVs need a huge amount of initial investment costs than the typical ground PV farms (Kim et al., 2018) and it may take more than 10 years to generate a net profits from APVs. Also, farmers are concerned about the decreasing REC and variables, such as environmental disasters, that might lead APVs to failure (Kim et al., 2018). These widening risks and concerns discourage farmers from embracing APV implementation. In fact, a study showed that people living in rural areas tend to agree with the overall energy shift to renewable energy systems, but they tend to disagree with implementing it on their lands such as NIMBY (Kim et al., 2018).

Laws and regulations

Relevant laws and regulations need to be enacted and updated. Weak regulations and poor laws caused multiple falsified and unverified APV projects. What’s even worse, some local farmers experienced fraud by unethical PV panel developers, spouting lies about earning more money via installing their PV panels onto the farmers’ lands. This fraud started to negatively influence people's perception of PV development in rural areas. Also, regarding the increase of the use of APVs, some other existing rules and regulations might impede its growth. For example, in South Korea, the timeline permitting farmlands to use APVs is only eight years, which is just less than half of the 15-year that net-profit may occur. While strict regulations settled on the ordinary farmlands were to preserve agricultural values and sustain their prosperity, it may be a bit of an obstacle in expanding APVs.

Therefore, it would be important to urge the government to amend their existing regulations and laws beyond their current efforts of subsidization policy that have been commonly used for traditional PV fields. It would be important to question whether the laws and regulations support APV or not.

Table. 1

Field	Type	Stage	APV requirements or conditions
Environmental aspect	Environmental impacts	Installation	**[Absent or less environmental impacts]** Were there negative environmental impacts in the installation process? If yes, was it ecologically treated/recovered?
	Environmental consideration	Installation	**[Use existing site conditions]** Were there limited geomorphological or environmental transformations in APV installation?
	Environmental management	Operation	**[Less resource consumption for managing APV]** Were energy and resource inputs reduced compared to typical PVs?
Economic aspect	Solar energy production	Installation	**[Link to grid infrastructure]** Can APV be connected to the grid? Is it possible to selling produced energy?
		Installation & Operation	**[Energy production efficiency]** Does APV use good quality PV panels that can produce energy well? Is there regular maintenance for the installed PV panels (water cleaning on PV panels)?
		Installation & Operation	**[Stability and durability of PV supporting structures]** Can the support system withstand the weight of the photovoltaic panels and harsh exterior conditions?
		Installation	**[Geographically good solar insolation condition]** Does the site is located in a good solar irradiated area?
		Installation	**[Appropriate crop species choice]**
	Crop cultivation	Operation	**[Sufficient irrigation]** Can the PV cleaned water is reused as irrigation after the filtration process? Does irrigation happen regularly?
		Installation & Operation	**[Sufficient solar irradiation]** What is the ratio of PV density, Can crops receive the least amount of solar irradiation?
		Harvest	**[Crop quality and yield check]**
Social aspect	Social conflicts	Installation	**[Disagreement for APV installation by local residents]** Is there any disagreement for APV by residents or farmers? If yes, what is the major cause?
		Installation & Operation	**[Visible landscape degradation]** Does local residents feel the degradation of visible landscape quality?
	Laws and regulations	Installation & Operation	**[Hindering laws and regulations]** Is there any laws and regulations hindering APV implementation?
		Installation & Operation	**[Favorable laws and regulations]** Is there any policy and laws supporting APV?

Table 1: APV evaluation checklist table; the success of actual APV cases can be inferred using this conceptual framework proposed in the table. Specific elements need to be further developed depending on the different local climate zones and ecotones.

CONCLUSION

We reviewed the attributes of APV that can impact an APV project's success and introduced the opportunities and challenges of implementing APVs into urban areas. Although APV has some challenges and weaknesses in its cost and social aspect, it has strong potentials in jointly producing solar energy and crops. Most of all, APV is expected to increase the efficiency and productivity of land-use by enabling dual land-uses in a place where conflict may occur. This advantage from joint food and energy production would contribute to fulfilling SDG's Goal 2: ending hunger, and Goal 11: affordable and clean energy.

The current COVID19 pandemic situation has altered the way in which people live their lives, especially within the urban context. Social distancing is now mandatory. Going to markets to get food is not just shopping, it may be an action with risky consequences. This pandemic is more serious for people with lower incomes and socio-economic statuses. They are likely to lose jobs, and if government subsidization is politically grid-locked or cancelled, they will not be able to sustain basic lives with essential necessities. In this sense, APVs would help ease the financial burdens of lower-income people by providing them with energy and food. Even though this paper covers APV in rural context, it needs

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