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Agrivoltaic systems and its potential to optimize agricultural land use for energy production in Sri Lanka: A Review

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Abstract

The demand for food and energy is increasing at a fast rate and their security has become the prime issue in especially developing countries like Sri Lanka. Conventional fossil fuel-based electricity generation has become a challenging task for the economy as well as for the environment. Therefore, moving to renewable energy has currently grown in the world than ever before as a result of the Paris agreement launched in 2015 and in line with Sustainable Development Goal 7. Photovoltaic based electricity generation is one of the best options for the country as it blessed with an ample amount of solar radiation. Rooftops of houses, buildings, and other suitable infrastructures would be the best places to establish the PV panels. Nevertheless, it needs to expand up to a considerable area of land of photo-voltaic panels to cater to the increasing demand for energy which is available to feed the ever-increasing population. Agri-voltaic system has been proposed as a mixed system, combining photovoltaic with agriculture at the same time on the same land to capture solar energy, for both energy generation and food production while maximizing the solar efficiency on the land. The main eco-physiological constraint for the crop production under the Photovoltaic is the light reduction. Since the inadequate information about most of the crops under the shade conditions, it is extremely difficult to recommend some crop species for their ability to shade tolerance. The use of shading (PV panels) requires more crop-specific research to determine the optimum percentage of panels and their arrangement that do not reduce agricultural production. Crop yield variation with panel shading and practicalities to maximize the system need to be studied extensively. This paper reviews the potential of the Agri-voltaic system and identifies the research gaps in selecting suitable crops under the PV panels.

Keywords: Agrivoltaic, Photovoltaic, Food, Energy, Shade, Tolerance

Introduction and Background

World population is expected to increase up to 9.6 billion in 2050 [1]. Meanwhile, people are searching for basic needs for their compatible life which always increases the demand for food and energy [2-3]. Increasing the population also affects per capita land availability as well as land quality. Some of the lands that are available to feed the ever-increasing population, are becoming unproductive or degraded due to the many reasons [4], such as desertification, salinity building and waste

Disposal [5]. According to the World Oil Outlook, Energy demand is anticipated to increase by around 33% between 2015 and 2040 with an expanding global population. Almost one billion people still lacking access to electricity and three billion wanting access to clean fuels and efficient technologies for cooking, there will be a variety of sufficient energy resources including renewable energy to meet this demand growth and the crucial needs to reduce energy poverty in the world [6].

On-site renewable energy use has been developed in past decades [7] due to unpredictability and increasing prices of conventional energy sources day by day. Renewables are expected to see the largest annual

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average growth rate [8]. It should be noted that many Oil Producing and Exporting Countries (OPEC) are making significant investments on renewables giving their immense solar and wind resources [9]. These conventional fossil fuel-based electricity productions have influenced the greenhouse gas emission, acid rain, and energy shortage [10], continues depletion of fossil fuel resources [11] thereby creating detrimental impacts on global warming and consequently leading to climate change [12-13] threatening the future generation as well. Now people are concerned about climate change, global warming and trying to produce electricity from renewable energy [14-15-16]. As a result of that, the Paris agreement has been launched to control the rise up of global temperature. According to that, many countries are trying to promote renewable energy which is zero or low-emission of CO_2 and other greenhouse gasses [17]. In addition to that, fossil fuel is being exhausted rapidly and as a result of these circumstances, people have to find renewable energy sources [18]. There are several sources of renewable energy such as solar, wind, geothermal, biomass, seawater and hydropower [19].

Energy from biomass is considered as a possible substitute for fossil fuels for the future. However, the land area that would be required for replacing fossil fuels with biofuels will largely replace the cropland area of the planet [20] which are available to feed the population. The low efficiency of the photosynthesis process of most energy crops which is *c.a.* 3% will not be able to cope up with increasing energy demand to replace fossil fuels. In contrast, commercially available photovoltaic (PV) panels have an efficiency of 12 – 15 % and can supply future increasing energy needs [21]. In the long term, it may be questioned what the best option for producing energy is; whether it is Photovoltaic panels or Biofuel?

Renewable energies will play a vital role to meet this increasing demand for energy in a sustainable and environmentally friendly manner. Solar power is the most abundant and available source among all renewable energies. Solar energy has the reputation of being safe, reliable and clean. Continuous technical improvements have been taken place in the past few years [21] ensuring a more stabilized and cost-efficient application in solar PV technology [22] and becoming more affordable (Green and sustainable energy/ electricity). The cost of solar panels has dropped by 10% for the past thirty years, while production has risen by 30% [8]. International Energy Agency (IEA) has made a calculation that by the year 2050, 16% of the global energy demand (approximately Terawatt-hour (TWh) 6000) would be generated by solar PV plants [23].

Solar power generation avoids pollution and decreases water use and employs smaller land-use footprints compared to other forms of energy production [24]. However, in Sri Lanka, the electricity traditionally/currently comes from fossil fuel like sources that create negative environmental impacts. Solar power can be used to diversify our energy supply and provides protection against unpredictable fuel prices, avoids the need for new transmission infrastructure, decreases stress on existing distribution and transmission lines, increases opportunities for rural electrification, and produces much-needed economic development benefits [24].

Agri-Voltaic system

In view of the future requirement of increasing energy and food production, Agri- voltaic systems (AVS) have been identified as a mixed system combining photovoltaic with agriculture at the same time on the same land [21-25-26]. Most of the areas of Sri Lanka receives ample amount of solar radiation though not properly utilized. To date, the ways by which solar efficiency can be maximized on the same land is not sufficiently addressed globally. Establishing PV panels at a location that is already in use, such as agricultural land, rooftops, parking garages, or other sites like wind farms, affords dual-use opportunities, taking advantage of the productivity of land use [24]. Agricultural lands provide ideal opportunities for dual-use of lands as solar panels can intentionally be placed to provide energy while allowing continued productive agricultural use of the site.

Good climate with the availability of adequate sunlight year-round is ideal for AVS to capture solar energy on solar cells for energy generation and food energy through photosynthesis. The use of sunlight is shared by the solar panels and crops under the panels by separating the radiation spectrum with respect to electricity production and plant photosynthesis consequently increase the Land Equalling Ratio (LER), (Figure 1). In other words, use the same unit of land for agriculture and electricity generation simultaneously [27]. For some crops, solar radiation is frequently too intensive in high-irradiation temperate regions and especially during the summer. Accordingly, shade screens are used to reduce or moderate the light intensity [27] which can be replaced by solar panels like semi-transparent PV panels. A potentially serious conflict of land-use between agricultural production and clean energy generation, on the other hand, is of great importance to find a way to combine these two.

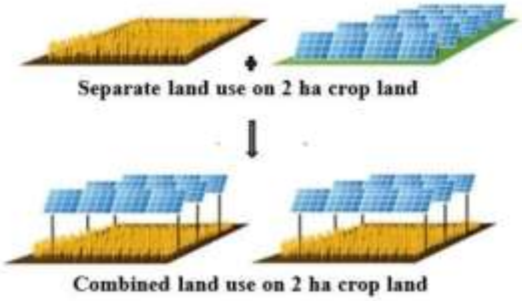

Figure 1. Schematic Simplified diagram of land-use in an Agri-voltaic system

Solar power provides many benefits over conventional fossil-fuel-based electricity generation. For example, the establishment of such a system may provide additional income from the sale of electricity in addition to the sales of the crops [25]. Agri-voltaic systems have been predicted to increase global land productivity by 35–73% [21], and increase the value of the energy production system by 30% [22].

Solar geometry

Climate zones, seasonal and daily temperature changes are mainly determined by changes in the amount of energy received at a particular area on the earth surface [28]. Generally speaking, the amount of energy obtained at a particular place on the earth's surface is decided by several factors such as, the angle at which solar radiation strikes the surface, clouds, and atmospheric particles. The angle at which solar radiation strikes a surface strongly affects the amount of energy received by a particular surface. Therefore, understanding the geometrical relationship between the earth and the sun is very important when work with the Agri-voltaic dual use concepts. There are some parametric angles distinct under solar geometry (Figure 2). It is well known that; the earth is almost spherical in shape and it rotates slightly elliptical orbit around the sun. The earth's axis of rotation is tilted 23.45^o from the normal to the plane of the ecliptic. The angle between the plane of the earth's equator and the ecliptic (or the earth - sunline) is the declination and it varies between +23.45^o on June 22 (Northern solstice) and -23.45^o on December 22 (Southern solstice, Fig. 3).

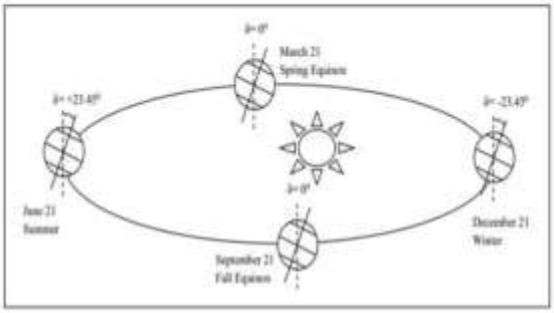

Figure 2: Solar declination angle, Source: [28]

Figure 3: 2D section of earth’s orbit, showing the two extreme declination angles,
Source: [29]

Application to Sri Lanka

Sri Lanka is an upper-middle-income earning country. Approximately 21.67 million people live in a total area of 65,610 km^2. Population density is about 346/ km^2 [30]. About 18.2 percent of the population is urban, with the remain 77.4% living in rural and 4.4% in the state [31]. Increasing food and energy demand as a result of increasing population, has always been the greatest challenge in Sri Lanka. The better living condition creates energy shortage in Sri Lanka due to the inability of fulfilling the rising energy demand every year. The country is facing a critical situation of both energy shortage and environmental threat due to over dependency on imported fossil fuels and locally generated hydropower. Imports of fossil fuel have been increased during the last few years and a considerable amount is going to electricity generation [32]. According to the [30], the shares of hydro, fuel oil, coal and non-conventional renewable energy (NCRE) were 34, 24, 31 and 11% respectively, of the total power generation in 2018.

Continuous increase of energy demand and depletion of fossil fuel has caused a major impact on climate change and energy security respectively. Following the Paris agreement launched in 2015, many developing countries, including Sri Lanka, also try to promote renewable energy, which has zero emission of greenhouse gasses [19]. In line with the goal 7 of the Sustainable Development Goals (SDG) of the UN, the policy changes in Sri Lanka will also contribute to reduce the requirement of Sri Lanka on fossil fuels below 50% of the primary energy supply by 2030 [34]. Parallel to the global energy transition, Sri Lanka is adhering to the sustainable energy revolution taking place across the country in order to assist to meet her energy requirements in a sustainable manner. According to the national energy policy and strategies of Sri Lanka, the country is aspiring to become a carbon-neutral country by 2050 by using renewable energy available and emerging sustainable energy resources [34]. Sri Lankan sustainable energy industry is anticipated to facilitate a number of economic activities and continue to grow rapidly in the coming years by novel energy generators, solar power, in particular. There is an incredible economic opportunity to develop these clean energy technologies, and great economic advantages which utilize the clean and renewable energy in the country.

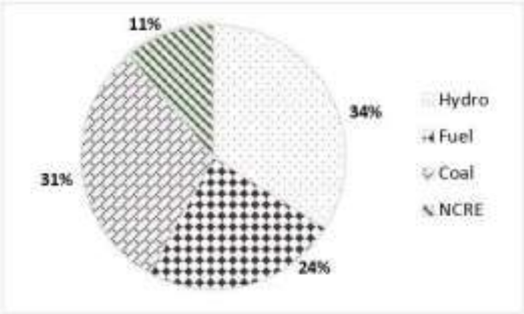

Figure 4: different sources of power generation in Sri Lanka, Source: [30]

Depending on the feature of geo-climatic settings, Sri Lanka is blessed with several types of renewable energy resources including hydropower, wind, biomass, and solar, in the pursuit of sustainable development energy access, energy security and low-carbon economic growth and prosperity [37]. Such technologies have identified as new renewable energy (NRE) technologies since, they were not used frequently in the past.

Hydropower generation is a technology which is used to generate electricity in Sri Lanka for more than a century. It is also known as "conventional" power generation plans that usually work with a dam and reservoir for storage [37]. However, hydropower generations are almost acquired its potential in the country though still there is an energy gap. As a result of climate change, the rainfall pattern is decreased and consequently increases the demand for petroleum imports and has become a challenging task for the economy of the country as well as the environment. Recently, the country has experienced an island-wide power cut due to the inability of producing required energy by hydropower as a result of a severe drought. Therefore, we have to restore to other means of generating power among which, the grid connection of wind power generating schema and solar projects are receiving much attention.

By the end of the 2015, 98.5% of the households in the country has been provided with the electricity. The average per capita electricity consumption was at 535 units (kwh/person) and the total gross electricity generation was 13,154 GWh and is expected to increased dramatically in future [32]. To cope up the energy problem that the country is facing, the government has launched several programs especially solar power generation. Many applications of solar energy are currently in use to meet the remote electrical loads through much of the nonelectrified regions of Sri Lanka. The "*Surya Bala Sangramaya*" (battle for solar energy) is one of the major government projects currently working on promoting solar energy solutions in Sri Lanka. The project aims to promote the setting up of small solar power plants on the rooftops of households, religious places, hotels, commercial establishments, and industries (48).

In order to cater to the growing needs and demands of electricity, measures have been taken to encourage the use of solar energy which is a healthy option that would prevent environmental pollution and in parallel, would meet the high-end electricity needs of general public. Nevertheless, the country is facing and energy crisis. Therefore, it needs to expand up to a considerable area of land of photo voltaic panels mainly in agricultural lands.

Solar energy potential in Sri Lanka

Solar electricity is generated converting sunlight into electricity with the help of devices such as "solar photovoltaic (PV) modules". Solar electricity generation takes place well under tropical climatic environments where dry weather patterns create the electricity generation process easy and gainful.

Sri Lanka is an island in the Indian ocean and located between 6^0 and 10^0 Northern latitude and 80^0 and 82^0 Eastern longitudes [30]. The country lies within the equatorial belt where considerable solar energy is available throughout the year**.** The extent of solar resources in Sri Lanka has been estimated by several parties and some studies have shown that the distribution of annual solar radiation varies from 15-20 MJ/m^2 day (4.2 to 5.6 kWh/ m^2/ day) across the country with the lowest values occurring in the hill country in the South-central region [35-36]. The results of another study showed that, the country does not experience clear seasonal changes in solar resources and the variability in global horizontal solar resources is relatively small across Sri Lanka despite terrain characteristics on cloud formation [35].

Sri Lanka is divided in to three major climatic zones namely, wet zone, Intermediate zone and dry zone [38]. The seasonal climate is depicted as four major regimes: The Northeast monsoon (NE- December to February) the Southwest monsoon (SW- May to September) and two inter-monsoonal periods (March to April and October to November) [39].

During the SW monsoon, the airflow generally is from Southwest to Northeast. The lee side of the country receives high solar resources. During the NE monsoon, the Southern and Western portion of the country shows higher resources. However, the highest solar resources occur during the period which the transition between the NE and SW monsoon occurs. The highest resources are in the Northern and Southern regions and the lowest resources generally vary spatially at most 20% to 30% during any given season [28]. Typically, the amount of solar radiation depends on the amount of cloud cover [7]. The high level of solar resources throughout the entire country makes it well suited for island-wide solar power generation except for certain time of the year. It could be noticed clearly that solar energy resources are abundant in Northern and Southern regions, with the maximum sunshine percentage is as high as 80% [35].

Since Ceylon Electricity Board (CEB), the official solar electricity services provider in Sri Lanka has a rapid growth in power demand, the power generation from a thermal energy source has become an alternative even though that introduces many challenges for the environment, energy security and economy. As an Island where the land is limited, the demand for energy and food is increasing as well as the use of renewable energy is crucial for the protection of the ecosystem, this AVS is a very important alternative for the food and energy production at the same time in the same land.

Photovoltaic component in an AVS

Solar panel is a module which has an ability to produce electricity in Agri-voltaic systems as the major output. Planning the density of photo-voltaic (PV) panels is very crucial because of the number of solar panels or photovoltaic area in a given land determines the amount of light received by the crops which are grown below the panels [21]. Productivity of the solar panel is described by the amount of electricity generated from unit area per unit time. Several designing parameters such as the number of photovoltaic panel strips, length, height inclination Southward, spacing and size of individual PVPs [21] are important when the productivity is considered.

These design parameters for establishing solar panels in AVSs are slightly different from those for conventional solar power plants [25]. Calculation of solar position angle or sun path is critical when fixing the solar panels to intercept more light which are perpendicular to the surface (Figure 5, and 7).

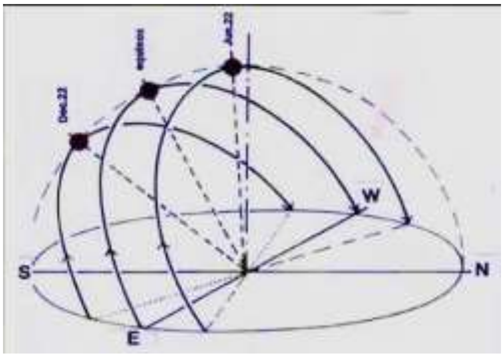

Figure 5: Annual variation of the sun's apparent path in northern hemisphere (drawn for 27^0 and -27^0 latitude, Source: [29]

Solar panels are generally installed over a mounted structure at an elevated height from the ground surface with an inclination of 25^0 facing the South which is equal to the latitude of the location (Figure 8), as, perpendicular incident light always increases the efficiency of electricity generation. Due to this angle of solar panels, if the panels are closely arranged, a shade of PV modules is generated at the leeward side by shading adjacent PV modules [25], **t**hereby reducing the efficiency of the shaded PV panel. Therefore, PV arrays should be established with some separation distance between two arrays [40]. In general, 6-12 m space between two rows of PV arrays is kept in conventional solar power plants to avoid shade casting on the next row.

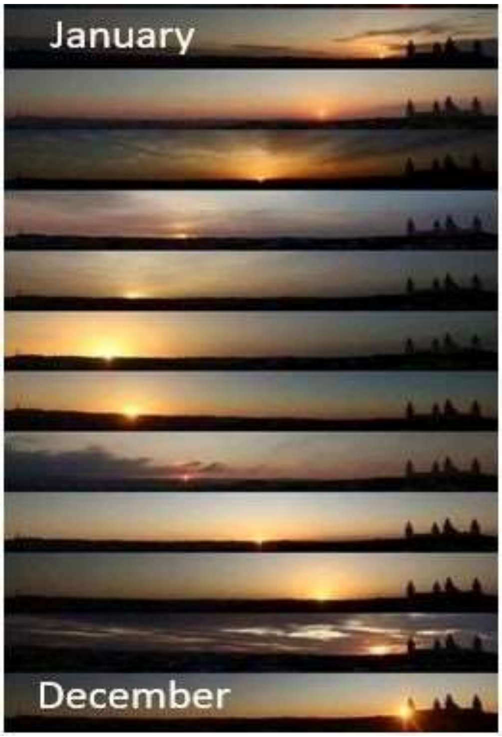

Figure 6**:** Picture of changing solar position angle within a year in Sri Lanka (January to December)

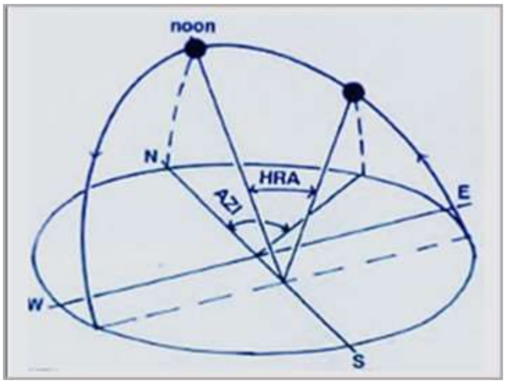

Figure 7: Sun's hour angle changes in a day, Source: [29]

These interspace areas are used for the cultivation of crops since these areas receive enough light as panels are arranged from East to West direction which is the path of the sun (Figure 8). Length of the PV array depends on the number of solar panels connected in a series [25]. Additionally, the area under the PV modules can also be used to cultivate some specific crops which are shade tolerant [25-42]. Especially, area in between the panels and below the panels which are available for the cultivation of crops changes as per the design of the installation. In a typical Agri-voltaic system, area in between the panels and the area under the panels are about 49% and 29% of the total block area, respectively [25]. Areas utilized by the crop and PV component in the AVS are not precisely decided because ratio between PV component to crop component varies depending on several factors, such as plant species going to be cultivated, amount of electricity produced, geography, meteorology, season and objectives [27].

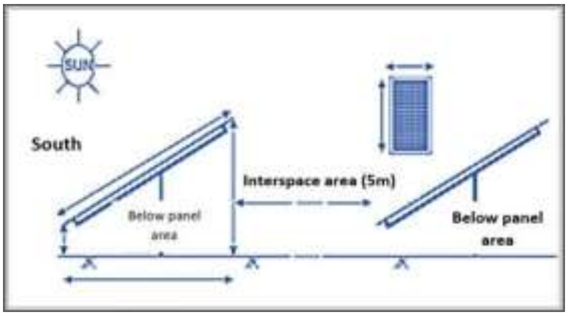

Figure 8: Panel inclination angle to the south, Source: [41]

Two different light gradients can be identified in the AVSs; direct light and indirect/diffuse light. Direct light is available in between the PV panels and near to the borders whereas indirect light is available under the PV panels. This light gradient should be taken into consideration in modelling AVSs. Time of the day and the year, and situation under the solar panels decide the radiation availability for crops under the array [21]. Irradiation level significantly varies within the AVS and more homogeneous and heterogeneous radiation can be identified in the East-west direction and North-south directions respectively. However, heterogeneity of light also depends on the panel height from the ground. In other words, higher the panel height, more homogeneous the light level at the ground level is.

Solar panels should be lifted to an elevation that allows people to go into work and for the easy cultivation practices of the crops [23]. Usually, a 4 m clearance is considered satisfactory, if the mechanical operations are encouraged under the panels (e.g. tractors etc.). The cost of building a structure that would support the fixed panels in that height should be carefully evaluated. Supporting pillars must also be well spaced out to allow cultural practices of the crops (Figure 9).

Figure 9: Installation heights of solar panels: a) Tradition way, b) and c) In the dual system

As Figure 10 shows, there are several field arrangements of PV panels such as straight lines, staggered rows, staggered giants and checker-board [27-43]. The different designs create different spatial and temporal radiation distribution in a day under the panels. Apart from that, the electricity generation also varies with the type of design.

Figure 10: Possible field arrangements of PV panels a) Continues rows, b) Staggered, c) Checker-board, d) Staggered

Of all, the most appropriate design for AVs which create more uniform radiation distribution is checker-board because, it creates alternating shadows under the AVS system as well as places that are getting shadows may vary with time of the day according to the sun's position [27]. Therefore, all the plants under the panel receive uniform light and inhibitory growth effects of the shading are reduced by this design. However, other designs create shadows on the same groups of plants continuously during the cultivation. In general, considering the above dimensions of the AVS, a solar panel system that generates 1 MW of electricity can be established in a 2 ha of crop field while assuring the crop yield [41]. However, the capacity may vary with radiation availability of the area, energy conversion efficiency of the solar panels and design.

Rain water harvesting

In this AVSs, PV panels water run-off from the panel surfaces. Water moves quickly due to no infiltration and panel angle. Rainwater can be harvested from the top surface of PV modules in AVS [41] by fixing a suitable gutter at the bottom of the panel and thereby creating a possibility to use that harvested water for cleaning and irrigation, after storage (Figure 11). The potential capacity of rainwater harvesting from AVS depends on the mean annual rainfall received at a particular area, the area of PV array and the type of designing. According to [42], the potential capacity of harvested water from an AVS system is about 350,000 L covering an area of 1 ha of land.

Figure 11: Rainwater harvesting system, source: [42]

Dust deposition on the PV panels with time is a common problem especially during dry seasons and in arid regions. Dust reduces the transparency of panels thereby reduces electricity generation. Therefore, regular cleaning of deposited dust is essential. A considerable amount of water is required and also those water can be again used to irrigate the plants [42]. Periods in which the water is scarce, this stored harvested rain water can be very useful for irrigation as well as for cleaning purposes of PV panels [44]. Dry cleaning of solar panels also becoming popular using specially produce brush and also could be automated. It has been reported that, in temperate regions, during the winter period, the formation of a sticky dust layer on the PV module after fixing with the dew at the night can be a problem [44]. Same authors reported that, cleaning of PV modules is important for efficient and economical electricity generation. Water requirement for one-time cleaning is about 20,000 L per 0.5 MW block. Four-time and two-time cleaning has to be done during the summer and winter respectively.

Not only that, open lands with buildings and tall trees and other obstacles which can potentially cast shading on the panels are not suitable when deciding an area for AVS. Nevertheless, some small bushes, medium size trees and tall trees which are located in a distance might be advantageous because those can act as a barrier for the dust and winds. The electricity generated from the system can be directly supplied to the local grid system through the net metering system thereby the generated electricity is directly sold to the Electricity Board. In addition to that, the farmer can use electricity for agricultural activities such as irrigation (Figure 12), automation and for the machines as well.

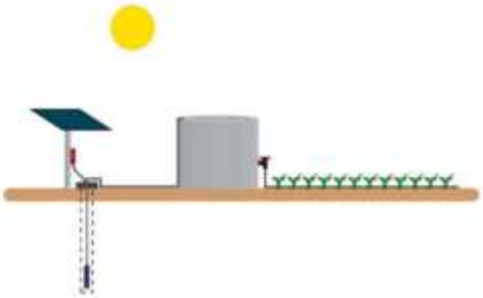

Figure 12: solar irrigation, source: [45]

Crop component

Solar panels are mounted by alternating distance between the panels to avoid the mutual shading of panels above the ground on columns. These elevated PV panels facilitate the types of machinery used under the panels. Panel holding columns also should be well spacious to allow cultural practices of the crops [41]. In addition to the cultural practices, operability of Agri-voltaic systems in terms of radiation use efficiency, shade effects on crops and water flow in the system should also be assessed. [45] have mentioned that the key challenge when adopting the AVS is achieving higher productivity and quality, while reducing the environmental impacts. Therefore, crop selection for AVSs is of paramount importance and it should carefully be done by a crop specialist with sufficient knowledge about the shade effect on crops.

Shade effects on crops

Radiation is the major ecosystem-level decider of productivity [46] and has a linear association among plant productivity and the amount of light intercepted by the canopy [47]. The productivity of the crop component in AVSs also is primarily decided by the light availability under the PV panels. PV component in the Agri-voltaic system creates intermittent shading and reduces the average available light for the crop which is below [23]. This low solar radiation availability below the PV module is one of the key challenges when adopting the Agri-voltaic systems. “Shade tolerance” is the plant trait that defines as the capability to survive and grow under low light in the field of crop ecology [21]. Nevertheless, the term Shade tolerance is used in a wide range of disciplines beyond ecology such as, plant physiology, Forestry, Agriculture and Horticulture, Landscaping & gardening [49]. This term of shade tolerance is extensively studied and is a very important concept in AVS as well. Limited evidence is obtainable on the tolerance to the shade of most crop species as very few screening studies of the tolerance of the crops to shade have been done.

Different species of plants have an optimum range of light requirements for best performance and it varies among the species. A low amount of solar energy is supposed to reduce the rate of photosynthesis and a below a certain minimum light intensity called light compensation point (LCP), the plant growth will be ceased. Simple field measure of shade tolerance is the whole-plant light compensation point (WPLCP) [50] which is a good predictor of the minimum light setting occupied by most of the species. [49], have mentioned that, dark respiration is the strongest determinant of whole plant light requirement of tropical tree saplings and it was considered as a reliable and simple estimate of shade tolerance. The correspondence with low-light mortality rate provides further evidence that the whole plant compensation is a reliable measure of shade tolerance of a species.

The Relative Growth Rate (RGR) of most species are directly and strongly linked to total mean daily photon flux than to the direct or diffuse component, that is the amount of incident light received by plant leaves [51]. Therefore, many researchers have studied how different level of incident radiation influences the plant photosynthesis. Physiological ecologists try to find this point by reviewing how various morphological and physiological properties concede a plant to grow and survive successfully in certain environments, but not in others. When we adopt the AVSs, it is very important to know how various features of plant morphology and physiology contribute to photosynthesis under low light environments. Tolerance to any given stress depends on specific structural and physiological traits, but it is also strongly affected by the status of other environmental factors which is light, in here. Therefore, an optimum light requirement by a particular crop must be determined but most commercial crops were never studied under shade. It is therefore extremely difficult to recommend some species for their adaptation to shade tolerance thereby for the AVSs.

Different plant species show different adaptations to shade. In fact, a certain plant can exhibit varying degrees of shade tolerance. Plant performance is enhanced through morphological and physiological acclimation to the light environment [52]. Some plants can produce more than one phenotype when exposing to different environmental conditions. It could be behavior, morphology, and physiology in response to a unique environment. Phenotypic plasticity is a key mechanism with which the organism can cope with the changing environment. Plasticity for certain traits, particularly the morphological features optimizing light capture, can be high in those ‘plastic’ plants. Various plant strategies to intercept more radiation at low irradiance and to enhance radiation use efficiency, have been reported before. Basically, morphological changes involve as increase of total leaf area and optimized leaf area arrangements to capture radiation more efficiently [23]. Acclimation of the photosynthetic light response is crucial in interpreting adaptation to irradiance in many traits. Photosynthetic light response of leaves which acclimated to different light levels must be determined when adopting species in the AVSs.

Plant light harvesting, the light-driven plasticity is an important trait that alters radiation interception among different shade tolerant plant species [46]. Leaf, shoot and canopy level traits contribute to light-harvesting [53] under the low photon flux density and it is crucial when increasing the canopy productivity under these conditions. Leaf level adjustments or differences in foliage chemical and structural plasticity are considered as determining factors of efficient light-harvesting in species with different shade tolerance and leaf life-span in low PPFD. Whole plant energy capture depends not only on the photosynthetic response of individual leaves but also, on their integration into effective canopy and on the cost of producing and maintaining photosynthesis capacity [54]. Specifically, foliage chlorophyll content governs the leaf absorbance hence foliage chlorophyll content per unit dry mass increases with decreasing light availability [55-56].

Branching architecture, foliage inclination angle and leaf area distribution can also importantly decide the arrangements of leaves thereby efficiency of foliage exposure to light. The efficiency of light-harvesting of foliage exposure is a function of foliage inclination angle from the horizontal. Foliage inclination changes gradually from more vertical in the upper canopy under high light habitats to more horizontal in the lower canopy under low light habitats [57]. The angle of branching has been identified as an important adaptive feature determining the degree of overlap between neighbouring branches and leaves [58]. Increasing of leaf longevity provides an important way to accumulate foliage and enhance canopy light harvesting.

Generally, this information concludes that, age- and size-dependent dynamic shoot and canopy architectural modifications in foliage play a dominant role in ontogenetic changes of morphological characteristics in plant leaf area accumulation, light-harvesting efficiency and plant survival under shade. Plant survivorship in the understory with low light decreases at the initial stages of growth and dramatically increases with plant age in shade tolerant species [59-60]. To understand the functioning of different-aged plant stands, and to be able to simulate plant stand development, it is critical to consider the age and size-dependent alterations in leaf, shoot and canopy architecture.

Plant leaves which are grown in high irradiance usually have higher photosynthesis rate per unit area than those are restricted or acclimated to low irradiance levels and vice versa [61]. The photon flux density for leaves of shade-grown seedlings showed lower compensation points, higher quantum yields and lower respiration rates (Table 1).

Shade loving plants have slow respiration and light-saturated photosynthesis [63], and higher quantum yields per unit leaf area than those of sun-grown seedlings as a function of photosynthetic response curve [64]. In addition, it has been reported that, shade-tolerant species have higher growth rates in low light than intolerant species, and especially certain morphological traits can adjust to light stronger than the shade tolerant species [62]. Little physiological activity means smaller maintenance costs, and in the way, carbon losses in the understory are reduced and potential relative growth rates (RGR) are enhanced [65-66]. Biomass accumulation is mainly driven by the capture of light resources while other resources are not limiting.

Table 1: Characteristics differences between plants adopted or acclimated to sunny v. shady extremes in irradiance level; Source: [62]

Trait	Sun	Shade
Leaf-level		
Photosynthetic light responses		
Light-saturated ratio	High	Low
Compensation irradiance	High	Low
Saturation irradiance	High	Low
Biochemistry		
N, Rubisco, and soluble protein content/ mass	High	Slightly lower
Chlorophyll a/ chlorophyll b ratio	High	Low
Chlorophyll/ soluble protein ratio	Low	High
Anatomy and ultrastructure		
Chloroplast size	Small	Large
Thylakoid / grana ratio	Low	High
Morphology		
Leaf mass /area	High	Low
Leaf thickness	High	Low
Stomatal size	Small	Large
Stomatal density	High	Low
Palisade / spongy mesophyll ratio	High	Low
Mesophyll cell surface /leaf area ratio	High	Low
Leaf orientation	Erect	Horizontals
Iridescence, lens-shaped epidemic cells	None	Rare
Reddish leaf undersides	Very rare	Infrequent
Canopy-level		
Leaf area index	High to low	Low
Phyllotaxis	Spiral	Distichous
Twig orientation	Erect	± Horizontal
Asymmetric leaf bases	Very rare	Infrequent
Plant-level		
Fractional allocation to leaves	Low	High
Fractional allocation to roots	High	Low
Reproductive effort	High	Low

According to the carbon gain hypothesis, any trait that improves the use efficiency of light and therefore improves carbon gain, increases the shade tolerance of species. Carbon gain can be increased by a number of traits spanning from tissue to whole plant scales [49-62-67]. According to revised carbon gain hypothesis, shade tolerant species achieve superior performance in low light by minimizing CO_2 losses in low light rather than by enhancing maximum potential/ carbon gain [68-69].

Plant light requirement is affected by other co-occurring stresses such as drought, flooding, nutrient availability or herbivory, thus the minimum light tolerated by any given species can vary in different ecosystems or under different experimental conditions [21]. Despite the occurrence of these multiple stresses every in nature, knowledge of the tolerance to abiotic stresses is still scarce for many important plants and tolerance to concurrent stresses are poorly understood [70]. Lack of water limits the production of many crops in the world. The shade will reduce the transpiration needs and possibly increase the water efficiency under low radiation intensity.

Reduction of biomass production in low PPFD may also reduce the needs for nitrogen and consequently mitigate the nitrogen stresses. The tolerance to one stress is typically reduced by other co-occurring stresses or by biotic factors such as herbivores, pests, and competition from neighbour plants. Minimum whole-plant light requirement and the extent to which a plant can tolerate interacting stresses in low light depend on the duration of the effective growing season [70-71]. Many applications have illustrated how shade tolerance can be involved in altering species performance and distribution under globally changed conditions. Because of the inherent trade-off between shade tolerance to other environmental factors, shade tolerance influences the response of the plant to many drivers of global change such as elevated temperature and alter water availability [49-72-73].

Height and spacing of the panels may also be adjusted to grow a different type of crops in an agri-voltaic system and to facilitate more radiation received on the ground. Few crops which can be grown in the agri-voltaic system were screened based on their shade tolerance characteristics, height and, water requirement [41]. Performance of crops under different agro-climatic zones also needs to be studied through field experimentation. There are mainly two areas in AVSs according to light received by crops; between panels that have full sun light and under the panels which is shaded. Crops that have different shade tolerant abilities can be selected for both areas. More shade tolerant crops should be selected for below the panels and vice versa.

[41] reported that Cabbage (*Brassica oleracea* var. capitata) and onion (*Allium cepa*) as crops suitable for below panel area. Crops that can be successfully grown in interspaces of the established AVS include mung bean (*Vigna radiata*), moth bean (*Vigna aconitifolia*) and cluster bean (*Cyamopsis tetragonoloba*). Apart from these crops, a few medicinal plants of perennial nature e.g. *Aloe vera*, sonamukhi (*Cassia angustifolia*) and sankhpuspi (*Convolvulus pluricaulis*) can also be grown.

Several studies have mentioned that Tomato is one of the most suitable crops that is suited to AVSs. According to [74], the number of fruits per square meter did not significantly change in shaded tomato plantation (with 52% shade) when compared with those that were unshaded [75]. The tomato yield was not reduced despite low total dry matter. The shade can improve the commercial quality of the fruit by reducing burns in tomato under 30% shade. [76] observed a higher yield and a higher concentration of lycopene in tomatoes grown under 50% shade and with, lower doses of irrigated nitrogen. Another study showed that, flexible PV panels or mobile shading can improve the tomato quality and also water use efficiency [77]. As stated by [78], the increase in temperature and solar radiation reduces the nutritional quality of cherry tomato.

According to the [28], Paddy, Bean and Cowpea shows inverse proportionally decreasing yield when shading increase. Some crops like Pineapple and Corn can be cultivated shade increase until 30%- 40% and yield are decreased lightly. [79] reported that, use of a shading mesh in greenhouse melon cultivation reduces the leaf temperature by approximately 5 ^{0}C and, the size of the fruit was not affected, although the sugar acumination in the fruit did increase. Moreover, shading can substantially reduce the weed growth that can compete with the main crop thereby reduce the height of the plant [80]. Cultivation of flowers in greenhouse requires optimum temperature which can be provided by panels installed on the roof and a support system for critical hours.

In addition, the crop coverage in between PV arrays will also check the erosion of soil and thus will reduce the dust load on PV module. In order to reduce the dust settling on solar panels, there is also a need to develop shelter belts of suitable tree species of that height which do not block solar irradiance on PV panel surface. Fruit trees can be used as component plants in tree belts such as Mango (*Mangifera indica*) especially TEJC (an Alponso-type) variety for Dry and Intermediate areas as well as Bananas.

Way forward

This review was aimed to elaborate on the potential of Agri-voltaic systems in Sri Lanka where ample solar resources do exist. Rising food and energy demands associated with population growth especially in the present-day climate change situation is highly relevant for the country as well. The green energy in a green economy approach is an applicable solution to these problems thus solar power can play a vital role in sustainable energy. The agrivoltaic system is the best solution to the intense competition for the lands between food and renewable energy production through efficient use of solar radiation in the long run. Agri-voltaic system will be the future land use system from where both food and energy can be produced at once despite unsolved problems specific to the application of solar panels on the crop filed, for example regarding the acclimation of the plants to the intermittent shading which is created by panels. Selection of crops are very important that are capable to withstand shade. Shade tolerant plants which have high plasticity are more suitable for cultivation specially bellow panel areas. microclimatic effects of PVPs on crops should also be investigated. Productivity of crops and cultural practices in different local climatic conditions should be explored. It Suggests that little adaptation in cropping practices should be required to adjustment from open cropping to agrivoltaic cropping and attention should mostly be paid to light reduction mitigation [23]. Though there is low crop productivity compared to the open field, high LER can be achieved from the electricity generation. Future agrivoltaic designs should eliminate this heterogeneity by optimizing PV panel placement to create a spatially uniform shadow pattern such as checker boarder designs and semi-transparent PV panels that create uniform biomass accumulation thus compromise between electricity production and crop production. Apart from crop production, rainwater can also be harvested. The stored water can be used as supplementary irrigation to crops during dry season and also to wash the panels from dust deposition which decrease the efficiency of electricity generation. The agrivoltaic system enhances farmer’s economic income but also solve the electricity shortage problem in some remote areas thereby enhance the dwellers’ living condition in the long run.

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