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The potential of agrivoltaic systems

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ABSTRACT

In order to meet global energy demands with clean renewable energy such as with solar photovoltaic (PV) systems, large surface areas are needed because of the relatively diffuse nature of solar energy. Much of this demand can be matched with aggressive building integrated PV and rooftop PV, but the remainder can be met with land-based PV farms. Using large tracts of land for solar farms will increase competition for land resources as food production demand and energy demand are both growing and vie for the limited land resources. This land competition is exacerbated by the increasing population. These coupled land challenges can be ameliorated using the concept of agrivoltaics or co-developing the same area of land for both solar PV power as well as for conventional agriculture. In this paper, the agrivoltaic experiments to date are reviewed and summarized. A coupled simulation model is developed for both PV production (PVSyst) and agricultural production (Simulateur mulTIdisciplinaire les Cultures Standard (STICS) crop model), to gauge the technical potential of scaling agrivoltaic systems. The results showed that the value of solar generated electricity coupled to shade-tolerant crop production created an over 30% increase in economic value from farms deploying agrivoltaic systems instead of conventional agriculture. Utilizing shade tolerant crops enables crop yield losses to be minimized and thus maintain crop price stability. In addition, this dual use of agricultural land can have a significant effect on national PV production. The results showed an increase in PV power between over 40 and 70 GW if lettuce cultivation alone is converted to agrivoltaic systems in the U.S. It is clear, further work is warranted in this area and that the outputs for different crops and geographic areas should be explored to ascertain the potential of agrivoltaic farming throughout the globe.

Contents

1. Introduction

Both the continued depletion of fossil fuel resources [1] and the detrimental effects of burning them for energy such as climate

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change [2–4] has put an onus on decarbonization [5] by switching to renewable and clean sources [6–9] of energy such as solar power [10]. There has been significant progress in solar photovoltaic (PV) technology to utilize the vast, clean and sustainable source of energy to satisfy humanity's energy demands [11,12]. The IEA predicts approximately 6000 TWh of PV power will be generated in 2050 to supply society's needs, which would be around 16% of the total energy generated [13]. To meet that predication and provide the concomitant greater portion of total global demand with PV, large surface areas are needed because of the relatively diffuse nature of solar energy. Much of this demand can be met with aggressive building integrated PV (BIPV) and rooftop PV [14–17], and the remainder can be met with land-based PV farms [18–21]. Using large tracts of land for solar farms will increase competition for land resources as food production demand and energy demand are both growing and vie for the limited land resources [22–24]. This land competition becomes particularly acute in densely populated regions, mountainous areas, and small inhabited islands and is further fueled by the increasing population of 1.15% per year [25]. These coupled land challenges can be ameliorated using the concept of agrivoltaics or co-developing the same area of land for both a solar PV power station as well as for conventional agriculture.

This paper first reviews the theoretical and experimental work on agrivoltaics and analyzes the potential crop yields and solar power output as a function of the incoming solar radiation. For fixed tilt agrivoltaic farms, the optimal tilt angle of the PV is normally determined with an objective of maximizing solar power output and the pitch is determined by the spacing requirements of a given type of crop harvesting. As the PV create some shading on the crops planted between the rows, the sensitivity of the crop yield with respect to the shading effect is examined. The PV power output and crop yields are compared against that of an optimized PV power station and crop yields of conventional large-scale monocrop farms. A sensitivity analysis is performed based on the review of agrivoltaic research using the potential economic value of agrivoltaic farms to determine viability and for guiding future dual use farms.

2. Background

The precursor to the agrivoltaic system was the agroforestry system, which involved intercropping between crops and trees [26]. In the past the solution for the issue of competition for land resources between food and energy production has been addressed by the division of a piece of land for food and energy production [27]. Now following the example of agroforesty, it is possible to combine food and energy production on the same piece of land [28]. This is now known as agrivoltaics and was conceptualized as a solution to the increasing land competition between food and energy production [22]. Although agrivoltaics have been theorized in the early 1980s using the space between PV rows for crops (Fig. 1A), the first detailed agrivoltaic farm experiments were only recently performed in Montpellier, France in 2013 [29,30]. This system consisted of stilt mounted PV modules which were 0.8 m wide, mounted at a height of 4 m and tilted at an angle of 25° [29,30]. A rough schematic of this setup is shown in Fig. 1B. Lettuce crops were grown beneath the stilts and the lettuce yields and the behavior of the lettuce crop under shading were analyzed. The results have shown that shading for this crop has no significant effect on the yield due to the adaptive capabilities of lettuce to adjust to the shading caused by the PV arrays. Thus, the same area of land was used to produce both, electricity and food successfully.

Dupraz et al. were then able to prove that the yields from the agrivoltaic farm experiment were higher than their respective monosystem equivalent with the use of the LER methodology [31]. LER is used to measure the efficacy of the agrivoltaic system when compared against a monocrop system [31]. Similarly, the LER for the PV output is obtained by comparing the power output of the agrivoltaic system against a standard PV farm. The LER for the solar power output is obtained by taking the ratio of the agrivoltaic system PV output and that of a regular PV farm. One of the primary factors that influence the output of both the PV modules and crop yield is shading, which is not necessarily always negative effect on the latter (as will be discussed below). In addition to shading, the crop output also depends on the photosynthesis process of the crops in converting the incoming solar radiation into biomass [32]. It is difficult to predict the manner in which each plant behaves under shading [33] as shade tolerance of plant depends on the type of foliage and there appears to be co-relation between the leaf structure and plant tolerance to environmental conditions [34]. For example, lettuce can adapt itself to shading by increasing its leaf area to maximize its ability to tap the reduced solar radiation levels without significantly affecting yields [30], whereas, shading causes a reduction in wheat yields as it cannot adapt to the reduced light conditions [35]. Experiments conducted on the Paulownia variety wheat grown under shade showed a reduction in wheat yield by 51% [35]. Some of the experimentally verified shade tolerant crops are less common in conventional mass agriculture such as hog peanut, alfalfa [36] yam, taro, cassava and sweet potato [37].

Fig. 1. Agrivoltaic farm schematic having ground mounted PV modules with the area between the panels being used for farming. The spacing between the PV modules has been kept wide enough to allow standard sized farming equipment to pass between the rows.