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AGRO-PV Dome - Developing Agrivoltaics Solution Suitable for OR through Multidisciplinary Hands-on Student Design Project

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Dr. Budiman has been specializing in the advanced materials characterization techniques for nanoscale and other emerging (additively-manufactured, AI-enabled) materials design/development since his Ph.D (Stanford, 2008) time. Over the years, he has applied that to enhance materials performance and reliability in structural (mechanical, nuclear, space/aerospace) and functional (semiconductor/microelectronics, renewable energy, biomedicals) applications in academia and industry alike – Los Alamos National Laboratory (LANL), Massachusetts Institute of Technology (MIT), Singapore University of Technology and Design (SUTD), Advanced Micro Devices (AMD), Hewlett-Packard (HP), Spansion and SunPower. Dr. Budiman is currently serving as the Director of Oregon Renewable Energy Research (OREC) where he oversees a wide range of applied research/technology programs for accelerating the pace of transition to renewable energy especially in the state of Oregon (from photovoltaics, agrivoltaics, wind and energy storage all the way to hydrogen production, including the use of Artificial Intelligence/AI and Machine Learning/ML for advanced renewable energy systems), apart from being a tenure-track Faculty Member in the Mechanical Manufacturing Engineering Technology (MMET) department in Oregon Tech (OIT). Most recently, he has also been utilizing Machine Learning (ML) approaches to accelerate materials design and reliability for enabling nascent industrial applications in extreme environments (cutting-edge solar PV manufacturing – with REC Singapore, radiation-tolerant space thinfilm coating – with BOEING, and novel 3D nano-architected energy storage electrodes – with NBRI/CATL).

AGRO-PV DOME –
Developing Agrivoltaics Solution Suitable for OR through Multidisciplinary Hands-on Student Design Project

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ABSTRACT

Achieving the Net Zero Emissions scenario by 2050 requires more solar energy production – but it must not be at a cost to traditional agricultural land uses. We report an innovative photovoltaic configuration to optimize solar energy generation in agricultural settings without compromising or competing with agricultural production (also known as Agrivoltaics). It indeed enhances the outcome quality of agricultural production. Polymer-based greenhouse structures (or solar domes) are typically part of the agricultural ecosystems, especially for those economically important crops in Oregon (OR) state, such as potatoes, corn, and tomatoes – which may need cultivating at an optimum condition (usually moderately high temperature low relative humidity, well-drained soil and moderately high sunlight intensity) for the crops to achieve their premium market qualities. The greenhouse structures function as the cultivating place of the crops with controlled conditions (within a range of temperature, humidity, soil condition and sunlight intensity), relying on solar energy and radiation through the transparent polymer dome structures. This is what we called the AGRO-PV Dome. Our AGRO-PV Dome concept integrates the existing dome structure with the most powerful (highest efficiency) form of solar cell technology, which is the monocrystalline

silicon solar cells. This will increase solar energy production, which could, in turn, be used directly for the agricultural uses of the overall farm or for other energy uses in the complex without taking any additional land/space for agricultural purposes – it simply uses the space occupied already by the existing solar dome structures. The key enabling technology here is the light-weight Polycarbonate-Polycarbonate (PC-PC) based mono-crystalline silicon solar cell mini-modules – which is a technology that our group had developed previously in the lab scales, as has been reported widely in the literature. This represents a form of the dual-use farming concept which could be a promising solution to the combined increase in demand for solar energy with the agricultural use of the land. In this report, we document the building of the AGRO-PV Dome prototype that would demonstrate the efficacy of the concept and the promise for scaling it into large-scale standard photovoltaics structures that meet the demand for flexibility, modularity, scalability, minimum land occupation, mechanical performance, and that can be deployed in farms without hindering crops growth and farmer activities. This concept is an opportunity for developing new PV configurations that use off-the-shelf materials to optimize solar energy generation in agricultural settings without compromising or competing with agricultural production. The AGRO-PV Dome project was a Final Senior Capstone Design assignment conducted by multidisciplinary students from the Mechanical Engineering, Electrical Engineering, Renewable Energy Engineering, Biological Sciences and Business/Management departments at the Oregon Institute of Technology (OIT). It recently won the Oregon Tech IDEAFEST 2024 Award in June 2024, as well as a research project supported by the OR State Legislature through the Oregon Renewable Energy Center (OREC). OIT has been known for its hands-on, integrated (multidisciplinary approach) engineering program – and it was reflected well in this AGRO-PV Dome project.

I. INTRODUCTION

Achieving the Net Zero Emissions scenario by 2050 in US requires more solar energy production — but it must not be at a cost to traditional agricultural land uses. While promoting the large-scale development and deployment of solar technology to support a transition to a decarbonized electricity system by 2035 and decarbonized energy sector by 2050, accelerating innovative research and development (R&D) of technologies to ensure the equitability of such transition is crucial. According to the Solar Futures Study [1], meeting the 2035 capacity number will require about 5.7 million acres, or 0.3% of the U.S. contiguous land area, rising to about 10 million acres (0.5% of U.S. contiguous land area) in 2050. Solar energy deployment can conflict with agriculture because the same attributes that make land appropriate for agriculture (large, sunny, flat areas) are also attractive for solar energy. This scenario presents opportunity and challenge in seeking solutions to reduce land use conflicts and provide additional benefits to farmers, rural communities, and the solar industry.

An emerging strategy is to co-locate photovoltaic arrays with traditional agricultural land uses, a strategy dubbed “dual-use farming” or agrivoltaics. In agrivoltaics, both solar energy and agricultural crops are produced in the same space. Crops (or livestock) are cultivated beneath or besides a special configuration of solar photovoltaics (PV) panel arrays. This relationship can improve farming productivity and the overall production quality of the crops [2].

Agrivoltaics systems are typically classified into two categories: 1) open systems including inter-space PV and overhead PV; 2) close systems including PV greenhouses and opaque buildings [3]. The former is simply a combination of agricultural lands and PV farms and is more feasible to large scale machinery operation. While the latter creates a controllable microclimate for growth of crops and a distributed solar power generation station for generating electric power with a potential to support a distributed and fully renewable energy powered power grid system. The closed systems, in particular the agricultural greenhouses, provide opportunities for implementation of solar energy technologies on greenhouses [3]. The configuration of the greenhouses also allows exciting opportunities for more direct integration with solar energy technologies in which novel (non-conventional) PV modules could be directly integrated on the roofs of greenhouses. Typical greenhouses as parts of the agricultural complex are shown in Figure 1.

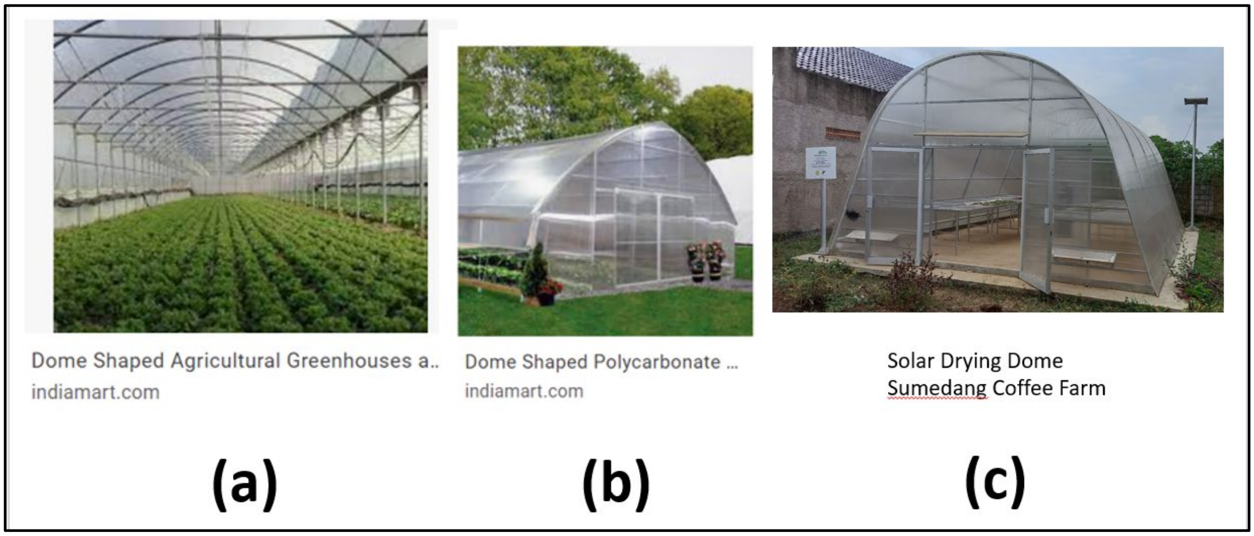

Fig 1. Dome-shaped agricultural greenhouse structures typically made out of high strength polymers such as polycarbonates are used in agricultural settings, typically for crops that need cultivation at certain optimum conditions (temperature and relative humidity). Reproduced with permission from Elsevier B.V [3] and Springer [4].

For the category of Agrivoltaics systems in which PV modules are directly integrated on the roofs of greenhouses, the major and most obvious impact is that the PV modules reduce the average available light for the crops at ground level. It is shown that plants react differently to changing light conditions. A sun-loving and a more shade-tolerant crop react to increasing light intensity differently. In general, on the light response curve at canopy level under field conditions, at low light levels, the rate of photosynthesis increases linearly with increasing light intensity. As the light intensity rises, the growth of assimilation rate starts leveling off until a species-specific light saturation point is reached. Further increases in light intensity do not cause a change in the rate of photosynthesis as the capacity of light-harvesting reactions is finite [4,5]. The light saturation points under field conditions differ from plant to plant. The light saturation point is a crucial criterion for defining the shading ratio of an agrophotovoltaic system.

When PV modules are directly integrated on the roofs of greenhouses, incident sunlight is shared for purposes of crop growth and electric power generation [3]. For photosynthesis of crops, a certain level of sunlight illumination must be guaranteed. The shading generated by the PV modules on the roofs of greenhouses will negatively impact the growth of crops inside of the greenhouses. Fortunately, responses of most crops to the intensities of sunlight illumination saturate at relatively low levels [4,5]. This fact provides a theoretical foundation for integrating PV modules onto the roofs of greenhouses. It is therefore one of the important outcomes of the present study to validate this hypothesis – that for certain crops, their cultivation (and thus their productivity) is not significantly hindered by the PV module integration onto the rooftop of the greenhouses.

A greenhouse structure (often in the shape of a dome) is typically found as an integrated part of many agricultural farms all over the world (such as shown in Fig. 1), although more typically farms with crops that need optimum drying and storing conditions (temperature and relative humidity), like coffee or tea, have such greenhouses or solar drying domes. They are typically made out of strong, stiff and transparent polymeric materials (such as polycarbonate sheets), thus allowing sun radiation to help move the humidity away from the crops placed inside the dome, while protecting them from other unwanted environmental conditions (raining, wet or humid air, or even insects, etc.) [6].

In the “AGRO-PV Dome” concept, we integrate this existing dome structure with the most powerful (high efficiency) form of the solar cell technology in the market today, which is the monocrystalline silicon solar cells [7]. Figure 2 shows an illustration of the basic idea of the AGRO-PV Dome system as an Agrivoltaics solution. By integrating the monocrystalline solar cells directly onto the strong, stiff and transparent polymeric sheets (often polycarbonate) that form the dome structures, solar PV energy production may be realized and used for the daily operations of the agricultural farms without occupying any extra land in the farms. The individual solar cells will be placed on the dome structure, such that there would be still spaces in between them, such that it would still allow sufficient sunlight intensity and radiation to come inside the dome and do the function of drying the crops, such as illustrated in the Figure 2 below. The idea would certainly work for existing domes used for drying and storing agricultural products [8,9], but it might be further extended to non-drying agricultural crop growth purposes. The basic idea is that the photovoltaics arrays could be further designed and configured to be on the roof structures of the agricultural land used for crop growth. Crops (or even livestock) may be cultivated beneath or besides this special configuration of solar photovoltaics (PV) panels arrays.

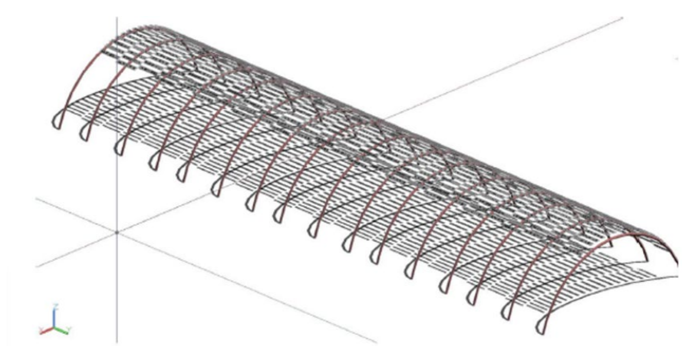

Fig 2. Illustration for the “AGRO-PV Dome” Concept – Polycabonate-based, dome-shaped greenhouse structures for agricultural purposes integrated with silicon monocrystalline solar cell

technology enabling dual-use farming which could be a promising solution to the combined increase in demand for solar energy with the agricultural use of the land.

The use of monocrystalline silicon solar cells here is justified based on their highest efficiencies, compared to other technologies existing in the market today, like organic solar cells, or thinfilm [7]. In addition, the silicon solar cells (mono or polycrystalline) are also the most mainstream off-the-shelf technology available in the market todays at scales. The challenge is of course integrating them onto the surfaces of the polycarbonate materials of the greenhouse structures. We know that silicon is naturally a brittle material, and silicon solar cells (especially the latest, cutting-edge generation is cut almost razor-thin, at 120-180 microns [10]) are indeed fragile. They break easily – how could we laminate them onto some curved surfaces of the polycarbonate materials? Here, we identify two key technical challenges here. First, integrating brittle silicon solar cells onto curved surfaces, and secondly, integrating them onto polycarbonate sheets (front and back, ie. instead of glass front sheet and PET backsheet of typical PV module design [7], here both front and backsheets will have to be made out of polycarbonates).

Our group has developed the key technology solutions to enable the integration of silicon solar cells with curved polycarbonate sheets [11,12]. The first issue is how to integrate brittle silicon solar cells onto curved surfaces, and Budiman et al. [11,12] demonstrated the enabling solution using all off-the-shelf (commercially available) materials typically used in a conventional PV module design, except of course the front and backsheets. Lab-scale prototypes of silicon solar cells (1x1 and 1x2 cells) integrated successfully onto curved surfaces were demonstrated in Figure 3 (a,b) below [11]. The second issue relates to the rather poor adhesion of Ethylene Vinyl Acetate (EVA) encapsulant [12] with the polycarbonate surfaces. EVA as we know was developed in the PV industry for good adhesion with glass frontsheet of the traditional PV modules. Nevertheless, it is one among the most commonly used as mainstream encapsulant materials in conventional PV modules available in the global market today. Thus, the solution as reported in [12] was based on making polycarbonate materials to bond better with EVA. Figure 3 (c,d) demonstrated the success of the work reported in [12] to prove the feasibility and the efficacy of the concept.

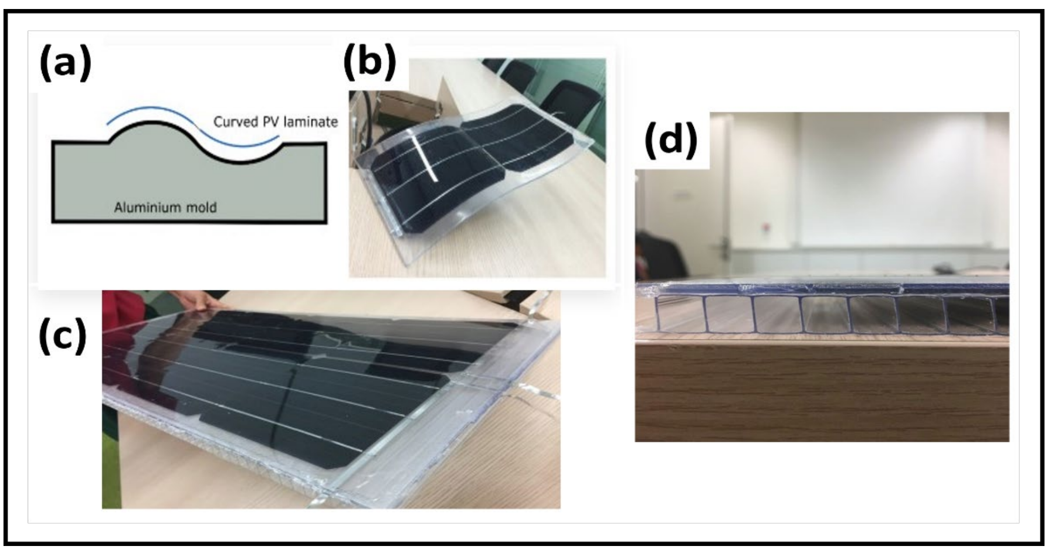

Fig 3. Lab-scale prototypes showing the technical solutions to enable direct integration of silicon solar cells onto curved polycarbonate sheets (a,b) and (c,d) comparable adhesion bonding of the

EVA-polycarbonate interfaces (with the standard EVA-glass interfaces). Reproduced with permission from Elsevier B.V [11,12].

The AGRO-PV Dome concept has a few advantages over other agrivoltaics designs. Integrating PV modules directly onto the roofs of greenhouses dramatically reduces the cost for constructing the overall systems relative to other configurations such as the normal overhead agrivoltaic systems [3], because the greenhouse structure provides sufficient support for the PV module array. It is enabled by the lightweight nature of the PC-PC sandwiched PV laminate concept. The normal overhead agrivoltaics design needs strong, and thus heavy, metal structures/pillars to support the heavy conventional PV modules (with glass-based, metal-framed PV module design). Furthermore, this also almost always means that the supporting metal structures are new, additional structures that the farmers need to build, which will result in large expenditures (economic cost). Creating such large, strong metal pillars on the ground could also take valuable land space which then cut the crop productivity of the farm. Expensive costs can have an impact on the sustainability of this system. In addition, rooftop canopies agrivoltaics solution (such as AGRO-PV Dome) also features structural designs that can enhance security against animal interference and extreme environmental aspects, especially for certain specialty crops. Lastly, this configuration could improve farming productivity and indeed the overall production quality of crops, like coffee or tea [8,9]. The energy generated from the roof of the drying dome could be further used to control the ambient inside the dome with smart and precision farming techniques – Internet of Things and Artificial Intelligence (AI) – often allowing even faster drying process and higher quality crops, as has been successfully demonstrated in our group's previous work [8,9]. In addition, of course, the farmers will generate clean energy which they could use to offset the meter from the electricity company, or simply use it directly for daily operation of the farms.

This manuscript reports the development and building of a model experimental greenhouse system integrated with our novel, custom-made lightweight PC-PC sandwich PV modules. At this stage, we focus on validating the most important hypothesis – that crop growth/cultivation is not significantly hindered by some of the sunlight blocked by the solar cells. This is in fact an important validation, not only for our AGRO-PV Dome concept, but also for all kinds of agrivoltaics systems. For this stage, we measure the performances of our model (ie. small scale) AGRO-PV Dome in terms of crop growth and PV power generation. We then discuss further on the design aspects and other considerations (market, social/economics, etc.) of the AGRO-PV Dome system, if it were to be built on real scales.

II. MATERIALS AND METHODOLOGY

The aim of this project is to develop and build a small-scale (model) AGRO-PV Dome to provide the proof-of-concept that we can have both productivity of crop growth/cultivation and clean energy (PV power) generation on the same plot of land. The materials and methodology discussed here are only specific to the AGRO-PV Dome model we build and report in the present manuscript, not necessarily of the general (real-scale) implementation of the AGRO-PV Dome concept in a real-world setting.

II.1 Model AGRO-PV Dome Design

The model AGRO-PV Dome was built on a wooden cart of 1.22 m in length and 1.07 m in width, as illustrated in Fig. 4(a). The model dome structure is built on top of the cart with steel strips of 3.175 mm in thickness and the overall dome frame dimensions of 1.22 m in length, 1.07 m in width and 0.76 m in height, as illustrated in Fig. 4(b). The overall frame-cart integration is as illustrated in Fig. 4(c). Total weight of the AGRO-PV Dome base structure is about 40 kg. Polycarbonate sheets (of 2.38 mm in thickness) are used to cover all sides of the model AGRO-PV Dome. For this model version, the semi-circular dome shape is not chosen for ease and simplicity of fabrication of the base structure, as well as subsequently the fabrication of the PV laminates (semi-circular dome shape would require curved PV laminates), given the limited fabrication facility available to us in Oregon Institute of Technology, especially on PV lamination side.

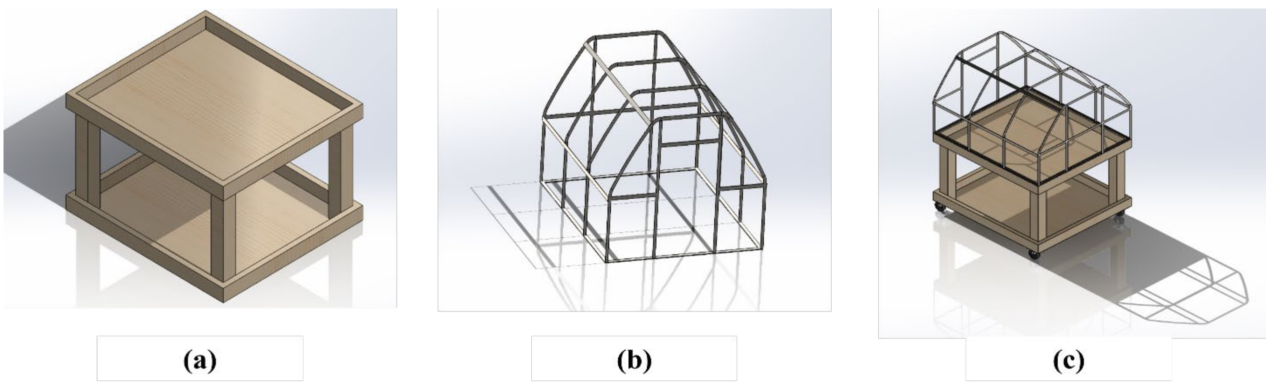

Fig 4. Model AGRO-PV Dome Base Structure Design: (a) the cart design, (b) the frame structure and (c) the overall frame-cart integration designed with caster wheels for easy mobility.

II.1.1. Polycarbonate (PC) Sandwiched PV Laminates

Solar PV mini modules using PC as front and back covers/sheets were integrated using customized lamination process parameters. PC sheets of 2.38 mm thickness were used both for front as well as back covers/sheets of the PV mini modules. We used bifacial silicon monocrystalline solar cells (156 x 156 mm) – in a 2x1 cell arrangement in each mini-module, as shown in Fig. 5(a). Commercially available Ethylene Vinyl Acetate (EVA) was used as encapsulants. These PC-sandwiched PV mini modules were laminated using optimized process parameters involving the need to have lower lamination temperatures (due to PC properties) vs. achieving the fullest extent of curing of the EVA materials possible in the set-up. Glass transition temperature of the PC material is approximately 147 ℃ [12].

(a) (b)

Fig 5. (a) PC-PC Sandwiched PV Mini Module in a 2x1 cell arrangement. Bifacial silicon monocrystalline solar cells were used and interconnected in series; (b) Total 15 mini modules were tested in an array.

The final optimized process parameters used in all the samples reported in the present study are as follows:

- Laminating temperature = 140 ℃ (this is below the typical lamination temperature of Glass-Backsheet PV module, which is 150 ℃)
- Laminating time = 600 s
- Laminating pressure = 0.1 MPa

The solar cells in the PC-sandwiched PV mini modules were interconnected using the process parameters as follows:

- Soldering power – 65 W
- Soldering time – 3 s
- Cell gap (Edge to edge) – approximately 5 mm

More detailed fabrication processes and parameter optimizations have been discussed elsewhere [12]. All surfaces were thoroughly cleaned before the lamination and during lamination, the layers were fixed at their corresponding position using Kapton tape. After lamination, the edges of the PC-sandwiched PV mini modules were fully sealed with typical sealant materials such as silicone (following the sealant product's instructions).

Bifacial silicon monocrystalline solar cell technology was chosen in the present study for its added power production advantage, compared to its monofacial counterpart. Our own test results (I-V curve) of bifacial vs. monofacial silicon monocrystalline solar cells of the same brand (commercially available in the market) are shown in Table 3.

Table 1. Comparison of mono-facial crystalline and bifacial crystalline silicon solar cells

Type	Dimension(mm)	V (V)	Power output (nominal)	Efficiency	Power output (IV test)	I_{SC} (A)
Monocrystalline	156X156	0.56	5.45W	22.30%	4.8W	9.45
Bifacial	156X156	0.55	6.45W	20.00%	5.033W	9.50

All the solar cells were integrated successfully into the PC-PC sandwich PV mini modules – without any cell cracks (tested using Electroluminescence/EL imaging after integration) and with fully cured EVA (visual inspection of no bubbles and delamination). A total of 15 PV mini modules (with total 30 cells) were made, tested and then integrated onto the AGPV Dome base structure. All the modules were interconnected in series to form an array, as shown in Fig. 5(b) – and were tested with the open circuit voltage and short circuit current are measured 16.87 Volts and 8.23 Amps respectively under the typical max sunlight intensity during the day (between 11am and 2pm) in Klamath Falls, OR, in summer time. The total power production was just under 5% below the rated specification of the solar cells, which is considered reasonable given the interconnection was done with manual soldering. The PV mini modules were mounted on the dome PC cover using transparent adhesives. Total power production was monitored for 2 months (about 8 weeks) during summer (June-July) in Klamath Falls, OR in 2023.

Since in the present study, the model AGRO-PV Dome was only studied primarily for the validation of the main hypothesis as stated above, the power produced was measured/monitored (in term of power production/capacity), however was mostly not used, for instance for optimizing the conditions (temperature, humidity, etc.) inside the greenhouse structure, such as stated as an example earlier in the manuscript. It is certainly an advantageous feature of the AGRO-PV Dome design concept and will be applicable in the real implementation of the concept. The PV mini modules here were connected to a battery mostly to provide power for the use of measurement/monitoring instrumentations that were run 24/7, and other incidental needs.

II.2 Crop Selection

For the purpose of validating the primary hypothesis in the present study – that for certain crops, their cultivation (and thus their productivity) is not significantly hindered by the PV module integration onto the rooftop of the AGRO-PV Dome model/prototype – crop selection is crucial. Primarily, it must be a crop that nominally requires substantial sunlight intensity for its full growth rate. Secondarily, given our monitoring period was limited to 2 months, we need a crop that we could observe its growth within the timeline. The monitoring period was constrained by the logistics available to us within Oregon Institute of Technology during summer (it is mostly a holiday period where campus is usually deserted).

We chose beets for the crops in the present study with the model AGRO-PV DOME for the performance monitoring (both power production as well as the crop growth/cultivation) during summer (June-July) in Klamath Falls, OR in 2023. Beets nominally require substantial sunlight intensity [13,14], and their growth timelines fit our constraints reasonably well. In addition, they are crops of moderate economic importance to the state of Oregon [15], are easily scalable, could benefit from being grown indoors (in greenhouse structures) [16] and have reasonable ease of implementation (low cultivation cost). These are all obviously important aspects for consideration in the implementation of the AGRO-PV Dome concept in the real applications. An automatic water irrigation system was also designed to ensure that crop cultivation was not affected by lack of water, especially given the summer conditions in Klamath Falls, OR could be very hot and dry. The need to power the automatic irrigation system here was considered part of the incidental needs (using power stored in the battery).

III. RESULTS AND DISCUSSION

In this section, we aim to provide the results – in term of the demonstration of the model AGRO-PV Dome built in the present study, as well as in term of the performance monitoring (PV power generation vs. crop growth/cultivation productivity). We then discuss the results of the model AGPV-Dome studied in the present study, and explore potential implementation issues of the AGRO-PV Dome concept in the real world and at real scales, based on the model study, as well as some further design considerations.

III.1 Model AGRO-PV Dome Demonstration

As shown in Fig. 6, a model AGRO-PV Dome is constructed by mounting the PC-PC based bifacial mono-crystalline silicon solar cell mini module array on the top of the model dome type greenhouse and forming some certain coverage. The transparent dome of the model greenhouse is designed with two inclined side flat surfaces and a flat top surface to facilitate the integration of the bifacial mini-PV modules. As clearly visible in Figs 6(a,b), two trays with soil are arranged at the bottom of the greenhouse to grow two crops arugula and beets; the rest area of the ground is covered with a white sheet to reflect the penetrated sunlight for the absorption of the ceiling formed by the backside of the bifacial mini modules. Shown in Fig. 6(c) is the side and top views of the model AGRO-PV dome, where five 1x2 mini modules are mounted on each side of the dome and form a PV coverage rate about 80% of all the top surfaces (two inclined side flat surfaces and a flat top surface). Fig. 7 and Table 2 show that the AGRO-PV Dome generated electricity is used to charge battery through a solar charging controller – the controller (Fig. 7) shows 133 W of actual power produced and Table 2 shows more detailed average measurements (as well as comparison with the theoretical numbers as specified by the solar cell manufacturer) . The generated electricity is used to power the automatic irrigation system to irrigate the crop beets inside the greenhouse (shown in Fig. 9(b)).

(a) (b) (c)

Fig 6. The model AGRO-PV Dome demonstration: from (a) the side, (b) the front and (c) the top views.

Fig 7. Power produced by the model AGRO-PV Dome as shown in the measurement display of the solar charging controller. The power is used to charge a battery as shown in the bottom floor in the figure

Table 2**.** Comparison of specified performance of the bifacial solar cells (from the manufacturer) vs. our actual measurements of the PV array (15 modules, each of 2 solar cells).

	Theoritical calculations	Actual measurements
Current	9.120 A per cell	8.23 A
Voltage	0.552 V per cell	16.87 V
Total power (V*I)	151 W	138.84 W

III.2 Agrivoltaics Performance Monitoring

While the last section (Section III.1) has demonstrated that the model AGRO-PV Dome works overall according to our design (the power production/storage/use, the crop growth inside, etc.), the following sub-sections (Sub-Sections III.2.1 and III.2.2) focus on the performance monitoring of our AGRO-PV Dome as an Agrivoltaics solution – that is both the PV power production performance as well as the crop growth productivity performance. The monitoring period was between June 5, 2023 and July 28, 2023 (for two months) while the AGRO-PV Dome was located outside our OREC (Oregon Renewable Energy Center) Lab, in Cornett Building complex, in a place of maximum sunlight intensity in Klamath Falls, OR.

III.2.1 Photovoltaics (PV) Power Production Performance

The nominal performance of the 15 PV module arrays (consisting of a total of 30 bifacial solar cells connected in series) was measured and total power was calculated as shown in Table 2 above. Subsequently, the energy generated by the 15 PV modules on the Model AGPV Dome was measured using a solar charge controller (Brand: Ampinvt, and Type: 10A MPPT) that passed the energy directly to the battery for energy storage. The monitoring was done daily at a time within the range of 11AM – 2PM (Monday to Fri in a week) for two months (between June 5, 2023 and July 28, 2023). The Charge Controller displayed the Daily energy generated in KWh and the data for the period of the monitoring was shown in Figure 7.

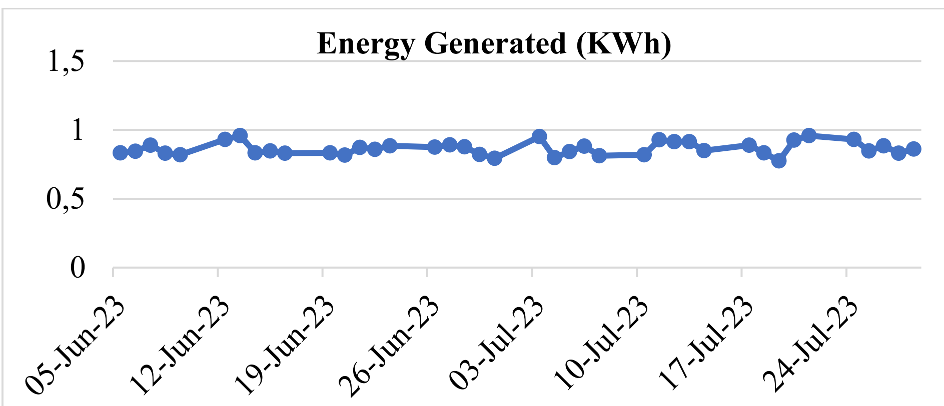

Fig 8. The daily generated energy data over the monitoring period (between June 5, 2023 and July 28, 2023).

Summer months in Klamath Falls, OR have typically bright, long days. The sun rises around 6AM in the morning and sets around 8PM in the evening. As shown in Figure 7, our Daily Energy Generated displays the mean value of 0.865 KWh, which is equivalent to around 6.230 hours of equivalent max sunlight intensity (based on nominal power of the PV arrays of 138.84W) – a reasonable number given the average equivalent hours in that geographical region is around 6 hrs. The energy generated daily was relatively stable (with mean = 0.865 KWh and standard deviation = 0.047 KWh) throughout the 2 months of the monitoring period (in June and July of 2023). The data was collected and automatically stored in the Charge Controller but was also inspected manually (by a research staff member of our group), periodically (around a few times in a week).

III.2.2 Agricultural Performance (Crop Growth/Productivity)

The crop growth productivity performance was measured qualitatively and based on comparison with a control group which consisted of exactly the same crops grown on same soils (bought from the same commercial store on the same day) but put outside the greenhouse (in direct exposure to the environment). Photos in Fig. 9 show how the crop beets inside the AGRO-PV Dome have grown during the monitoring period (between June 5, 2023 and July 28, 2023). They have grown comparably similar with the control group (not shown), certainly within reasonable crop growth experimental uncertainties. In fact, the crops inside the AGRO-PV Dome have grown better (as a whole) as the control group had parts that were affected by the outside environmental (eaten by insects, bugs) and weather conditions (rain and extreme sunlight intensity), which were quite normal for climate and conditions in Klamath Falls, OR during summer time.

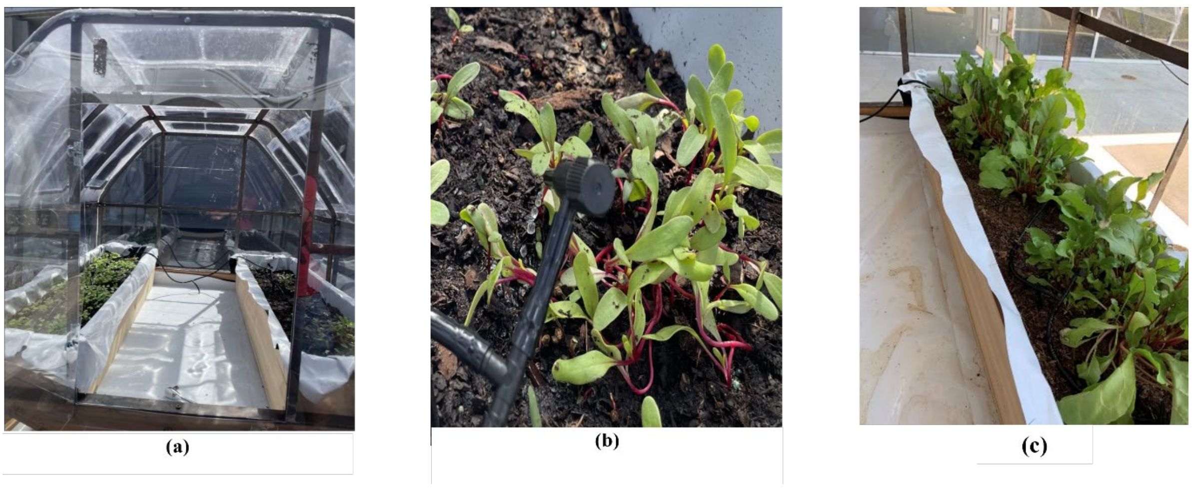

Fig 9. Photos of the crop (beets) grown inside the AGRO-PV Dome greenhouse: (a) in the beginning of the monitoring period (June 5, 2023), (b) a few days after, also showing the automatic irrigation system for watering the plants, and finally (c) close to the end of the monitoring period (circa July 28, 2023).

III.3 Model AGRO-PV Dome Discussion

The last section (Section III.2) has demonstrated that the model AGRO-APV Dome has performed both well in terms of PV power production as well as the agricultural (crop growth) productivity. The PV power production data as discussed in Section III.1 (nominal performance) shows that the novel PC-PC PV laminate design integrated onto the model AGRO-PV Dome produces power just under 5% below the rated specification of the solar cells, which is considered reasonable given the interconnection was done with manual soldering (and by amateur students), and the extra loss of photons associated with the use of PC as front sheets (instead of glass front sheets). In addition, the power production data as discussed in Sub-Section III.2.1 (performance over a period of time) has also shown that the novel PC-PC PV laminate design produces power consistently and reliably (over the period of monitoring). The novel PC-PC PV laminate design is a key, important enabler of the AGRO-PV Dome concept here – which involves non-commercially available PV laminate design integration onto existing greenhouse structures. Obviously, when implemented in real scale and applications in real world of agriculture, professional PV fabrication services could be utilized and further PV process/engineering improvements could be employed to further enhance the power productivity of the PV technology and its integration with existing greenhouse structures at scales. The present manuscript provides feasibility findings or proof of concept of the AGRP-PV Dome vision at lab or pilot-line scales.

As an Agrivoltaics solution, the model AGRO-PV Dome concept has also proven its feasibility and advantages of the concept over nominal crop cultivation or growth method in normal agriculture of beets. The findings here provide that the beets growth inside the greenhouse structure is comparable to outside (direct exposure to the environment), which means the PC (Polycarbonate) greenhouse design in the present study transmit sufficient sunlight intensity and hence the beets growth inside the greenhouse was not affected significantly, or if at all. In fact, our present findings show the greenhouse could provide additional protection of the economically important crop productivity, quality and harvesting yield by environmental and extreme/harsh climate conditions in the real agricultural settings. This could be further justification of the greenhouse structure installation, in addition to the fact that it could then be further installed by the novel PC-PC PV laminate design as demonstrated in the present study. The limited scale feasibility data provided by the present study obviously need to be further verified at larger or close to real scales needed in the agricultural industries. Nevertheless, the AGRO-PV Dome concept has hereby demonstrated the potential to turn agricultural lands into photovoltaic power generation station to support fully renewable energy transition in our society, at certainly no significant expense or disadvantages of the agricultural world. In fact, our findings in the present study have indicated that there could be advantages for the agricultural industry players, not only in terms of renewable energy power production, but also in terms of their agricultural productivity (yield) and harvest quality.

The Model AGRO-PV Dome has also been developed as an agrivoltaics solution suitable for the Oregon (OR) state's economic and geographic conditions through the multidisciplinary hands-on student design project as part of Oregon Institute of Technology's Senior Capstone Design Project 2023. The team who developed this Model AGRO-PV Dome consisted of final year students from Electrical and Renewable Energy Engineering (EERE) and Manufacturing and Mechanical Engineering & Technology (MMET) departments, with consultations from Natural Sciences department in Oregon Institute of Technology (OIT), especially for the agricultural aspects of the project (crop selection, crop growth rate in OR climates, etc.). The solar PV systems design and testing as well as the overall system considerations were naturally performed by the EERE students in the team (as highlighted in Figs. 5, 7 and 8 in the manuscript). However, a significant part of the AGRO-PV Dome concept relies on the successful and effective integration of the solar cells into the AGRO-PV Dome roof (which is made out of transparent polycarbonate sheets, as shown in Fig. 6 in the manuscript). This part was conducted by the MMET students in the team as illustrated in Figs. 3, 5 and 6 in the manuscript. Another aspect of any successful development of any Renewable Energy system is the structural design and testing of the overall system. The AGRO-PV Dome solution has to be structurally robust especially as it will need to withstand the often extreme climate of OR with gusty winds and snow storms. Some structural design and testing were conducted also by the MMET students in the team, as highlighted in Fig. 4 in this manuscript, while more complete structural simulation and considerations will certainly need to be implemented when the AGRO-PV Dome solution is realized in the real world and scales.

III.4 AGRO-PV Dome Concept – Further Design Considerations

In addition to providing the lab scale feasibility findings or proof of concept of the AGRO-PV Dome, in this section, we also offer some further design considerations which could enable the real scale development of the AGRO-PV Dome concept. for when the concept will be implemented at real or larger scales in the agricultural world or industries. The AGRO-PV Dome concept represents a breakthrough solution which increases solar energy production, reduce capital and installation costs of agriculture, align with current supply chains, work in diverse real-world conditions, and make life easier for farmers. It is a form of the dual-use farming concept which could be a promising solution to the challenges associated with combined increase in demand for solar energy with the agricultural use of the land. Our aim is to develop the AGRO-PV Dome concept to the real scale, implementable solutions that would demonstrate the efficacy of the concept in real settings, and deliver the promise for scaling it into large-scale standard agricultural structures that meet the demand for flexibility, modularity, scalability, minimum land occupation, mechanical performance, and that can be deployed in farms without hindering crops growth and farmer activities. We fervently believe this concept is an opportunity for developing new PV configurations that use off-the-shelf materials to optimize solar energy generation in agricultural settings without compromising or competing with agricultural production.

To this end, we intend to provide further design considerations for the AGRO-PV Dome concept to extend into the forms that it could be implemented beyond the availability of the existing greenhouse structures in the real agricultural settings. Greenhouse structures are typically already parts of regular agricultural complex – they may serve as drying or storage of agricultural harvests in more controlled (temperature, humidity, sunlight intensity, etc.) and protected environments (from insects or animals or dust/pollutants) [17-19]. So, naturally our AGRO-PV Dome concept could be integrated immediately within these existing infrastructures. We call this the primary forms for AGRO-PV Dome implementation in real agricultural settings.

Beyond the primary forms, we could envision that the AGRO-PV Dome concept could also be implemented with just minimum installations of light roofing frames or structures, and without the polymer covering sheets. The roofing frames or structures would just serve as the elevated structures on which the novel PC-PC PV laminates would be installed or fixed on – and beneath which crops (or even livestock) may still be cultivated as normally in the agricultural setting. We call this the secondary forms for AGRO-PV Dome implementation in real agricultural settings. Fig. 10 illustrates the schematic diagrams of the primary and secondary forms of the AGRO-PV Dome implementation schemes. Figs. 10(a,b) illustrate the primary forms (ie. the greenhouse structures integrated with the novel PV laminates) which may be used for drying facility of harvests (such as coffee or tea, as shown in Fig. 10(a)), or for normal cultivation of crops (especially those high value crops whose productivity or yield or quality may be prone to outside insects/animals or extreme weather conditions) as shown in Fig. 10(b).

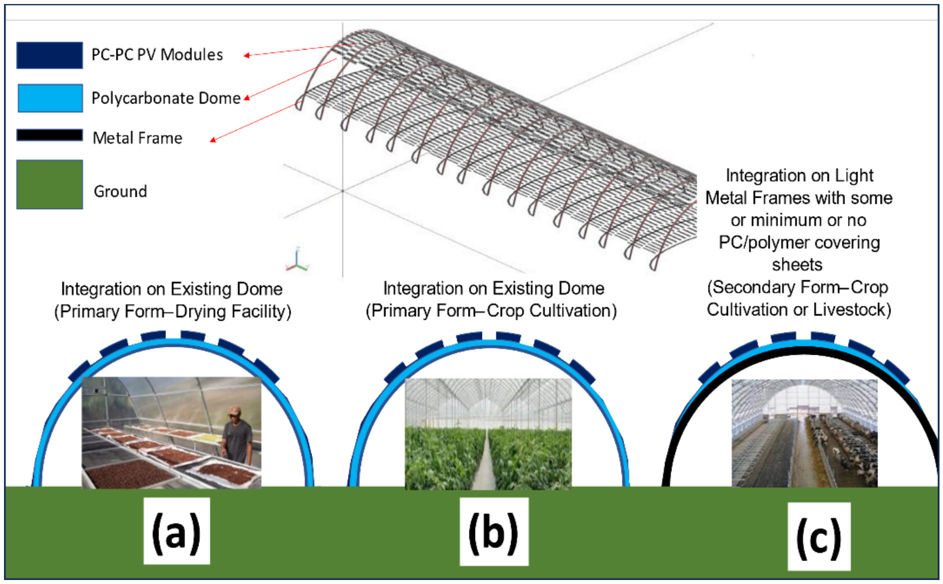

Fig 10. Illustrations of the AGRO-PV concept implementation schemes: (a) Primary Form – as a Drying Facility, (b) Primary Form – as a Greenhouse Facility for normal crop cultivation, and (c) Secondary Form – as a roof structure for crop cultivation or livestock farms.

In the meantime, Fig. 10(c) depicts the secondary forms, in which the light metal frames or structures with some or minimal amount of polymer covering sheets become simply the platform on which the novel PV laminates may be integrated. The polymer covering sheets could be installed if crops or livestock may need some cover from rain or other environmental conditions, but otherwise the secondary forms could also manifest in just light metal frames with no polymer covering whatsoever. The PV laminates could be designed with continuous fixtures on the frames of metal structures. The secondary forms of implementation schemes would provide crops that would benefit from direct exposure to the outside environment to grow optimally, as well as for livestock to roam around freely as if they are in open free range as in typical farms in normal agricultural settings. With the secondary forms, the sunlight obstruction may also be further designed to still provide as minimally required by the crops (or livestock). Nevertheless, the solar PV energy generation will require no significantly extra land/space in the agricultural settings, and minimum or low-cost installation for the PV power production, as all the overall AGRO-PV Dome structures use standard and off-the-shelf materials and processes in conventional silicon PV industry.

The novel PC-PC PV laminates, as demonstrated in our model AGRO-PV Dome, could be installed on existing greenhouse structures or domes – as long as they are made out of polycarbonate (PC) materials, or other transparent and sufficiently stiff polymeric materials to serve as covering sheets (primary forms) – or just light metal frames as infrastructures for the installation of the lightweight PV laminates (secondary forms) . The solar cells could be integrated with full modularity concept [17-20]. For instance, a 4x4 (4 rows and 4 columns) mini-PV modules of silicon solar cells integrated into PC-PC module design (such as demonstrated already in the present manuscript). These mini modules would be laminated already on a particular shape or curvature consistent with the global curvature of the existing dome or the light metal structure, as illustrated in Fig. 10. The curved PV laminates were not demonstrated in the present manuscript, but its lab scale feasibility has been successfully demonstrated in References [11,12] by our research group, and actually shown in Figure 3(b) in the present manuscript.

The modularity concept in fact allows gradation of curvature, if it is needed by the global curvature of the existing dome or frame structure (some domes/structures are only a spherical arc (with a known curvature) on the very top and might be following slightly different curvatures on other parts of the dome). In the primary forms of the AGRO-PV Dome concept, the PC-PC mini modules would then be bonded to the PC or the polymer covering sheets of the existing dome using commercially available adhesives. Such arrangement for adhesion between both PC surfaces or PC with other stiff polymeric cover sheets is known and has been part of many existing building-integrated PV technologies. More realistic illustration of the large scale AGRO-PV Dome concept in primary forms is shown in Fig. 11 below.

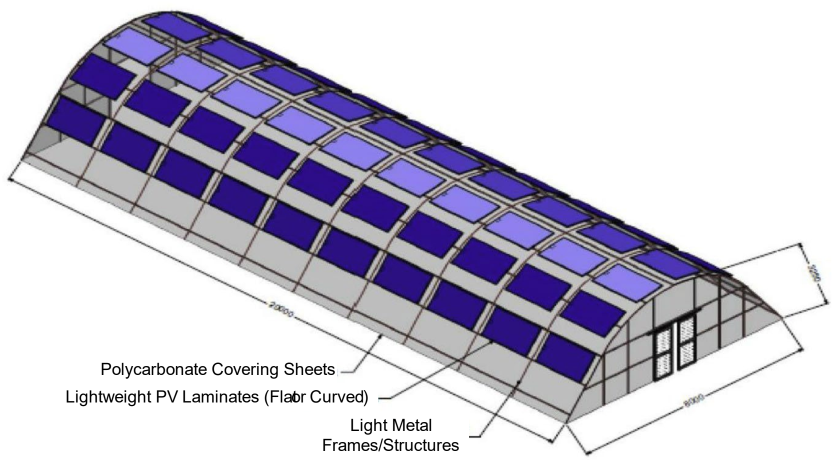

Fig 11. More realistic illustration of the AGRO-PV concept implementation scheme in the Primary Form in large or real scales such as found in typical agricultural complex. The dimensions were in arbitrary units, and only meant to illustrate the dome scale in comparison with the PV laminate size and other features in real scales (door, frame design, etc.).

In the secondary forms of the AGRO-PV Dome, either the semi dome frames or structures with just a spherical arc top as mostly roof structure (or elevated PV structure), or a complete spherical dome frames or structures could be built, provided the growth of the crops (or livestock) within the dome frames or structures would not be hindered too much by slightly less sunlight intensity. The gradation of the curvature of the curved PC laminates is technically possible, but economically might make slightly higher fabrication costs of the PV laminates. The secondary forms allow for full or more coverage with PV laminates (as illustrated in Fig. 12) or just the roof or top part (as illustrated in Fig. 13). Again, it is just a matter of design and balancing the trade-off between PV power production and agricultural productivity (crop cultivation's need of sunlight intensity and other direct exposure to the outside environment, or livestock's need for free roaming which may be important for its productivity).

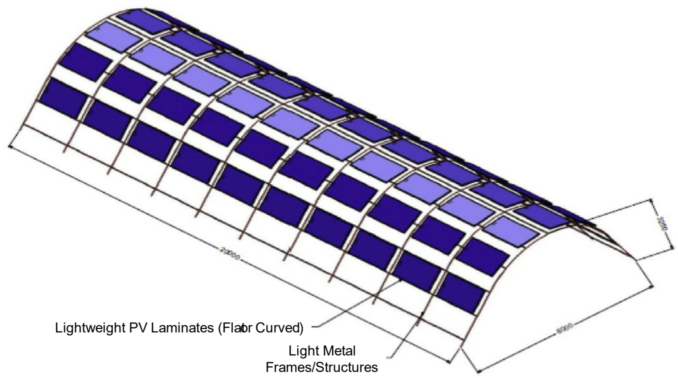

Fig 12. A more realistic illustration of the AGRO-PV concept implementation scheme in the Secondary Form in large or real scales such as found in typical agricultural complexes. The dimensions were in arbitrary units, and only meant to illustrate the dome scale in comparison with the PV laminate size and other features in real scales (frame design, etc.).

The AGRO-PV Dome concept of Secondary Form implementation scheme is completely scalable for if much larger PV power generation scales, might be needed. This is illustrated in Fig. 13 in realistic agricultural settings. In this case, the light metal frames or structures could just have the PV laminates on the roof or top of the structures hence opening more movements of farmers or livestock as if they are on regular agricultural setting without the PV power production installations (except for the fact that some sunlight will be obstructed by the opaque silicon solar cells on the PV laminates). The larger the overall scales of the metal frames/structures, the more likely the PV laminates may be just flat – no curvature is needed – which will lead to lower PV laminate fabrication complexities and thus cost. The metal frames cost of materials and installation are minimum as only light metal frames are needed (most likely aluminum strips may be sufficient). This is especially given the large PV power production that will be generated. It will certainly offset the cost of frame material and installation or lead to quick return on investment. The lightweight PV modular design is indeed key and critical here as standard glass-based PV modules will be heavy and hence much more substantial (heavier, stronger) steel frames would be mandatory. Overall, the scalability is simply a balance for tradeoff between overall installation cost and the PV power generation amount needed. This applies to any PV system installation – building-integrated, vehicle-integrated or agriculture-integrated. In addition, the power generation, control and storage could be further optimized with the advent of new technologies such as Internet of Things (IoT) and Artificial Intelligence (AI) that have indeed been more and more integrated recently with advanced renewable energy systems, including for agriculture-integrated photovoltaics systems, like what we have conducted in our own previous project "SMART DOME 4.0" in collaboration with Bina Nusantara and Trisakti Universities in Indonesia in 2020-2021 [21-24].

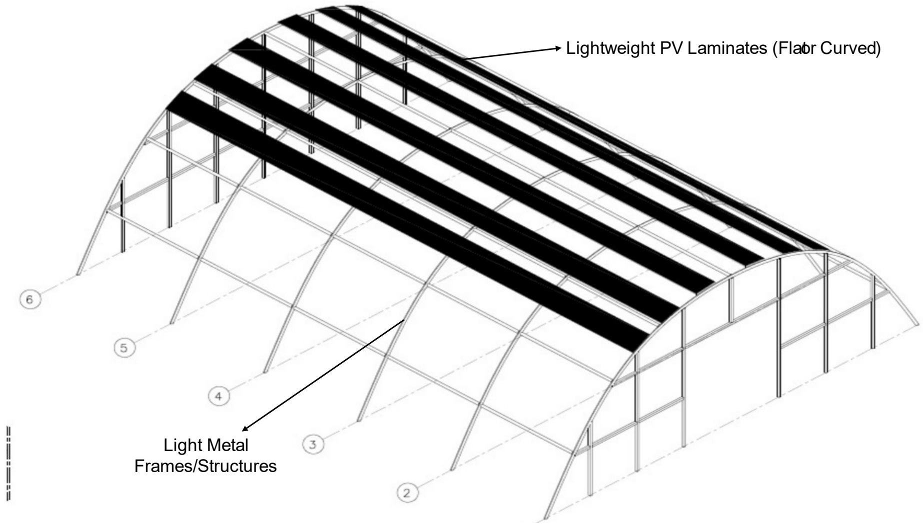

Fig 13. A more realistic illustration of the AGRO-PV concept implementation scheme in the Secondary Form for much larger scales of PV power production amount. The dimensions were in arbitrary units, and only meant to illustrate the dome scale in comparison with the PV laminate size and other features in real scales (frame design, etc.). This implementation scheme allows for more rooms for movements of farmers or livestock on the ground, as if they are on normal agricultural lands. The PV laminates which are only on quite high, elevated locations might obstruct the sunlight moderately.

IV. CONCLUSION

The present manuscript demonstrates the basic, lab scale feasibility of the AGRO- PV Dome system as an Agrivoltaics solution – leveraging agricultural production and solar power generation on the same soil. This pathway provides an opportunity to enhance agricultural production by providing a controlled environment for crop growth/cultivation or potentially for livestock productivity as well, and in addition, by maximizing the PV power production using the same the agricultural land. The AGRO-PV Dome concept here does not only mitigate the conflict of land uses for agriculture and photovoltaic power generation, but also provides an approach to improve the environment for agricultural production/yield and harvest quality. This manuscript also presents demonstrative research that successfully addresses the challenge in laminating fragile bifacial solar cells into light-weight PV mini modules using PC-based technologies for the best fit to integrating PV system onto roofs of greenhouses. The feasibility of the AGRO-PV Dome concept needs to be further verified in real scales and in real agricultural settings, for successful, full implementations for greater societal impact. Further design considerations have also been documented in the present manuscript which could contribute to enable the AGRO-PV Dome implementation in the real world.

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AUTHORS CONTRIBUTORSHIP

I.B.R: Conceptualization, Data curation, Methodology, Writing - original draft, F.S.M and C.H: Methodology, Validation, Formal analysis, Writing – review and editing, A.Z., M.A.M., V.T., K.O.M, and R.R: Conceptualization, Data curation, Formal analysis, Writing – original draft. T.P.,B.P.,D.S.,and F.S.: Supervision, Validation, Writing – review and editing, E.D and D.N.N.P: Validation, Writing – review and editing, A.S.B: Conceptualization, Methodology, Formal Analysis, Validation, Writing – review and editing, Supervision.

CONFLICT OF INTEREST STATEMENT

The authors state that there is NO CONFLICT OF INTEREST in this manuscript – as well as related to the funding agencies.

DATA AVAILABILITY STATEMENT

Data supporting this study have been included within the article.

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