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Agri-photovoltaics: first experience above Riesling vines

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Abstract. Agri-photovoltaics (APV) describes the dual use of an agricultural area for food production and solar power generation. In large parts, they still allow mechanical cultivation and other positive side effects of an APV system were observed in addition to the increase in utilization in the form of electricity and food: Effects on the water balance and passive protection against extreme weather events. The VitiVoltaic system, with special focus on Vitis cultivars, is currently being developed at Hochschule Geisenheim University to investigate the possibilities, effects and protective impact of APV partial shading on vines. The increase in sunshine hours and global radiation, together with the higher temperatures, are already leading to increased risks in viticulture. As a result, vine development is significantly accelerated. The early budding increases the risk of late frost. Together with the accelerated ripening over the course of the year, this also results in increasingly earlier harvest dates, higher TSS and lower total acidity. High temperatures combined with intense sunlight also increase the risk of sunburn. First experiences establishing such a system and their impact on white Riesling (*Vitis vinifera* L.) have shown that the microclimate can be positively influenced and that this may also be reflected in healthier grapes. The innovative research platform offers the opportunity to investigate further synergies over time and to develop ways of using energy.

1. Introduction

Agri-photovoltaics or short agrivoltaics (APV) describes the dual use of agricultural land in which the production of agricultural goods is preferably the focus. To reach our goal of renewable energies all sectors need to grow so does solar energy. However, the expansion of further ground mounted PV could cause a use conflict with agriculture and food production. The fairly new concept of APV by simultaneously producing both goods, electricity and food, on the same land could overcome this conflict. Several studies have been conducted mainly with horticultural or field crops but only little with special fruit crops even though this combination of perennial crops is believed to be very promising [1]. The combination of agriculture and solar power production could create synergies on many levels. For example, it could bring electricity to rural regions, provide a reliable income for farmers or even increase the efficiency of the modules through the transpiration cooling of the plants [2], [3]. Knowledge has been accumulated, that many crops under the solar modules can benefit the most. Positive aspects include that shading can in increase soil moisture by decreasing soil temperatures and therefore evapotranspiration [4] and in consequence reduce the irrigation demand [3]. Moreover the modules could mitigate heat waves by lowering the air temperatures and protect the crops from excessive radiation [5]. Especially soft fruits and berries could benefit from the shading by APV and increase yields [6] and during periods of extreme weather conditions the protection by the APV even increased the yield of some crops [7]. In addition, the moderate shading of vines by APV could also delay ripening [8], [9] and maintain or increase acidity [10]. Within the challenges of climate change such aspects may create benefit for some varieties or wine profiles.

However, agrivoltaic itself bears challenges that need to be targeted. The water distribution under an APV system is very heterogenous [7]. The rain water runs of the modules and creates a dripping edge. Erosion can be prevented by covering the ground with vegetation, but the run off needs to be handled. Collecting the rain would be possible, and irrigation needs to be scheduled. Furthermore, it is not yet clear which system design and light availability is most suitable for which crop. Many different designs strategies are currently being developed and tested. And various crops are also undergoing trials under different climatic conditions. However, the gaps in knowledge are still large and there is a need for research.

Climate change is ongoing and impacting viticulture since many years. In the recent decades changes in the climate were not only causing problems in viticulture but also altering wine quality. However, in the last years the problems caused by global warming are no longer neglectable and more difficult to overcome. Drought is a major threat in many growing regions [11]. The demand on irrigation will increase and not be confined to the southern regions. Extreme drought and heat lead to yield and quality losses threatening the wine industry. Moreover, harsh weather events like hail and heavy rain, as well as spring frost damage, repeatedly cause major yield losses.

Climate change is not only affecting grape yields but is also increasingly compromising their quality, often for the worse. Rising average temperatures are expected to accelerate the grapevine's phenological stages, meaning bud break, ripening, and harvest will occur earlier in the year. This earlier bud break in early spring heightens the risk of spring frost damage[12], while the earlier onset of veraison have a significant impact on berry quality, leading to faster degradation of organic acids and increased sugar accumulation. Resulting in more unbalanced wines with high alcohol contents, low acidity as well as reduced microbiological stability of juice and wine [13]. White wines like Riesling which is the most common cultivar in Germany is jeopardized to lose its typical light and fresh taste [14].

As a consequence of extreme weather conditions, many adaptation methods are already being tested today. For example, canopy management strategies determining position, severity and timing of the application as well as protecting the bunch zone through other means including the application of kaolin make big differences. At the same time, a number of shading experiments have already been carried out, some with promising results [15]. There was less sunburn damage, slower ripening, lower sugar concentrations and therefore less alcohol in the wine as well as higher acidity levels. In addition, the reduced photosynthetic activity can increase water use efficiency. However, phenol concentrations were reduced under shading.

Yet little agrivoltaics studies have been conducted in viticulture or other special crops. In addition, research into possible synergies with regard to mitigating the effects of climate change has rarely been the focus of attention, but has been identified more by chance. For this reason, a so-called VitiVoltaic research platform was created over a Riesling vineyard in Geisenheim, which is intended to make the best possible use of the synergy potential for the vines below. Semi-transparent modules were installed, which make it possible to erect a dense protective roof of solar modules and still provide sufficient light for the vines below. Moreover, the system has dynamic modules that can be adjusted to follow the sunlight in order to maximize the energy yield or to optimally adjust the microclimate and light availability for the vines below.

2. Material and methods

2.1. Plant material and site description

The VitiVoltaic system of Hochschule Geisenheim University is located in the Rheingau Valley, Germany (49°59'12.4 "N 7°56'50.5 "E). The trial plot covers an area of 0.3 ha where half of the area covered with PV modules.

According to the mapping by HLNUG [16], the soil is classified as loess-rich with an available water capacity of 246 mm and pH 7.2.

The vineyard was planted with *Vitis vinifera* L. cv. Riesling (clone 326 Gm) and rootstock SO4 (clone 47 Gm) in 2021 before the APV system was established in fall 2022. Accept for the APV itself a further factor regarding the management strategy is included in the experimental design. The integrated treatment was managed according to the code of good practice [17]. The organic plot was managed according to Regulation (EC) No 834/2007 and Regulation (EC) No 889/2008. In the following, only the integrated rows are considered.

The vines are trained in a vertical shoot positioning system (VSP) and 8-10 buds were pruned per vine. The vineyard is north-south aligned with a row spacing of two meters and a row spacing of 0.9 m. The vines bore fruit for the first time in 2023. Soil cultivation was carried out according to best practice. Every second row was sown with cover plants. The shoot tips were cut twice during vegetation and no further canopy work was carried out. The vineyard was rain fed.

2.2. VitiVoltaic system

The galvanized support structure of the system was rammed into the soil providing a concrete free anchoring. Modules are positioned above every row of vines and at least three meters above ground which keeps almost all options open for cultivating the vineyard. The modules (Mono crystalline, 175 WP Sonnenstromfabrik, CS Wismar GmbH, Germany) have a 50% transparency and can be rotated from east to west using a hexagonal axis. The panels can therefore be continuously tracked according to the position of the sun, used either to optimize the electricity yield or to improve the microclimate in the vineyard. If the modules are in horizontal position, the gap between the modules is about 30 cm. In total 552 modules, each with a power output of 172 Wp, are mounted, yielding in a nominal output of 94 kWp (kilowatt peak).

2.3. Climatic conditions

During the vegetation measurement period, the average temperature was 17°C, which was 1.4°C warmer than the long-term average from 1991-2020. Total precipitation of the year was 587 mm, which was around 60 mm more compared to the long-term average. The sunshine duration was 1882 hours, about 180 hours more than the long-term average.

2.4. Monitoring microclimate

2.4.1. Sensors for air temperature and relative humidity

A close measuring network of sensors was installed in the VitiVoltaic vineyard. The Dragino LSN50v2-S31 LoRaWAN temperature and humidity sensors were installed outside the canopy at a height of 2 meters. The data is captured via LoRaWan. The sensors report every 20 minutes. Daily average values from the sensors in the APV and the reference area were calculated from all measured values after installation on 01.06. to 31.10.2023.

2.4.2. Soil water measurements

Soil moisture content was determined using a capacitance measurement technique (Diviner 2000, Sentek Pty Ltd, Stepney, SA, Australia). In May 2023, three access tubes were installed in the inter-vine space of two vines for each treatment. Soil moisture was measured weekly from May to October 2023, with data collected down to a depth of 1 meter at 0.1-meter intervals. To calculate the percentage difference between the control and APV areas, the ratio of the absolute values (APV/control) was used, indicating the percentage of soil moisture in the APV area relative to the control.

2.4.3. Light conditions

The cumulated global radiation reaching the canopy under the APV as well as control was determined using light-sensitive films (OptoLeaf R-3D, Taisei-Environmental & Landscape Group, Tokyo, Japan). The procedure was as described in [18].

The electromagnetic spectrum was examined using the Jaz UV/Visible Spectrophotometer from Ocean Optics (Orlando, FL, USA). The spectrometer was positioned horizontally at the highest position of the sun and placed close to the ground. The mean value was calculated from three measurements.

2.5. Monitoring of grape health status

After a series of hot days with daily maximum temperatures exceeding 30 °C, sunburn damage was evaluated on September 05, 2023. For each treatment and each canopy side, the degree of damage was assessed on four hundred grape bunches using a percentage scale from 0-100%.

Botrytis was assessed in the same way at a time close to harvest, September 09, 2023 (EPPO-guideline, https://pp1.eppo.int/standards/PP1-054-3).

3. Results and discussion

3.1. Microclimate

3.1.1. Air temperature

In the experimental plot, multiple temperature and humidity sensors were positioned at a height of two meters, with data collection from the first of June 2023 on. The difference of the daily mean temperature, derived from two sensors of each treatment, to visualize the differences in daily mean temperatures throughout the growing season (Figure 1). The overall trend indicates that the daily mean temperatures under the agrivoltaic system are generally lower compared to control. However, temperature differences are often subtle, and there are instances where daily mean air temperatures under the agrivoltaics are higher, particularly during the harvest period at the end of September and the beginning of October.

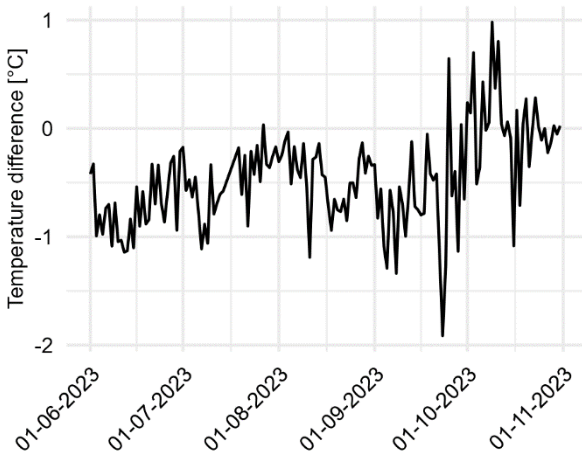

Figure 1. Differences in the daily mean temperature) TControl - T_{APV}).

Distinct diurnal patterns of air temperature were observed between the control and VitiVoltaic plots (Figure 2). On sunny and hot days, the air temperature beneath the photovoltaic modules remained up to four degrees Celsius cooler during the day, whereas at night, temperatures equalized or even slightly increased under the VitiVoltaic system. Conversely, on cooler and cloudier days, the VitiVoltaic plot tended to maintain slightly higher temperatures than the control plot. Overall, the cooling effect of the VitiVoltaic system, reaching up to four degrees, surpasses the warming effect, which has a maximum of two degrees.

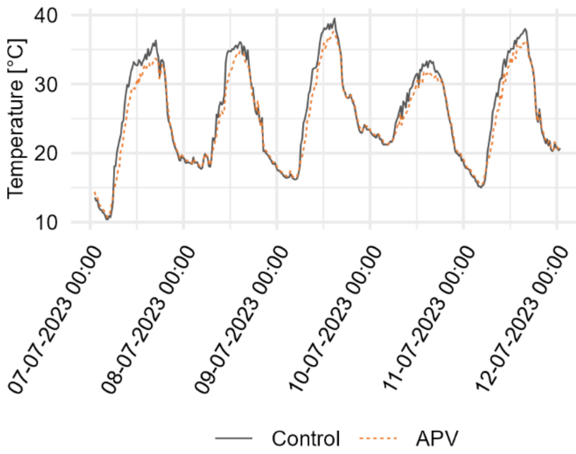

Figure 2. Temperature records over the course of several days and nights during a hot period (07.07.-11.07.2023)

It can be hypothesized that the buffering of temperature drops during the night and on cooler days is attributable to the warmed soil beneath the photovoltaic modules, which releases its heat more gradually or accumulates it before dissipating. This altered temperature pattern may have implications for grapevine physiology and could potentially influence the ripening process.

Reports from other agrivoltaics also indicate that air temperatures remain cooler under the modules, primarily due to the shading effect [5], [7]. Conversely, there are observations suggesting that during frosty nights, the air beneath the modules does not cool as drastically, thereby reducing the risk of frost damage [19]. These findings highlight the potential of agrivoltaics to moderate temperature extremes, offering a dual benefit in mitigating both heat stress and frost damage.

3.1.2. Air humidity

Humidity levels were recorded from June to the end of October, and the analysis of daily mean values over this period reveals that humidity trends under the VitiVoltaic system closely follow those observed in the control area (Figure 3). Notably, the humidity under the VitiVoltaic system is generally higher than that in the control area, with an average increase of 1-3 percentage points.

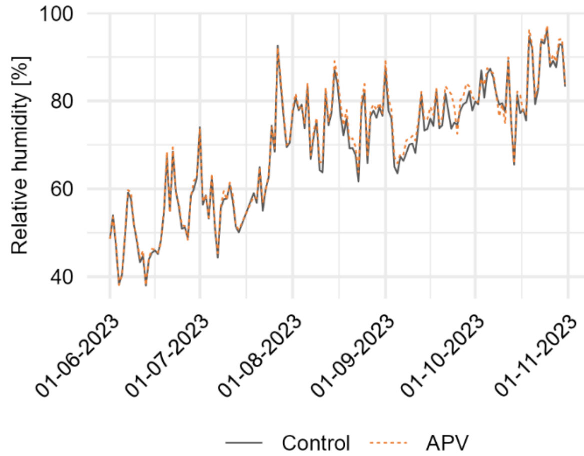

Figure 3. Daily mean relative humidity in the control field and under the agrivoltaics.

The photovoltaic shelter through the modules appears to limit moisture dissipation, leading to slightly higher humidity levels, which could create a microclimate favorable to fungal infections. However, the modules also keep the canopy drier during rain, potentially reducing the risk of other pathogens. Based on the short period of data records and microclimate observations, it is not possible to draw final conclusions regarding pathogen susceptibility. The results from trials involving protected cultivation of table grapes also do not reveal a consistent trend. The microclimate created by the protective modules may favor certain pathogens while potentially inhibiting others, indicating that pathogen responses to such environments are variable and pathogen-specific [20].

3.1.3. Solar radiation

Solar radiation at the height of the fruit zone was measured at two key stages of vegetative development: flowering and the onset of ripening. Light-sensitive films were used to quantify solar radiation, with the data averaged across the west and east sides for each treatment. During flowering, the canopy under the PV modules received 45% of the solar radiation compared to the control, and this decreased to 33% at the onset of ripening (Figure 4). It is important to note that exposure times varied between these measurements due to differing weather conditions, with moderate cloud cover during flowering and complete cloud cover at the start of ripening, which must be considered when interpreting these results. This means that per day the solar radiation at veraison was significantly lower than during flowering.

From these observations and those made in studies with shading nets [15] it can be assumed that the reduced solar radiation beneath the PV modules may potentially diminish photosynthetic activity, which could, in turn, influence the ripening process. Moreover, the effects of lower temperatures and moderate shading may also offer protection against sunburn in the grapes.

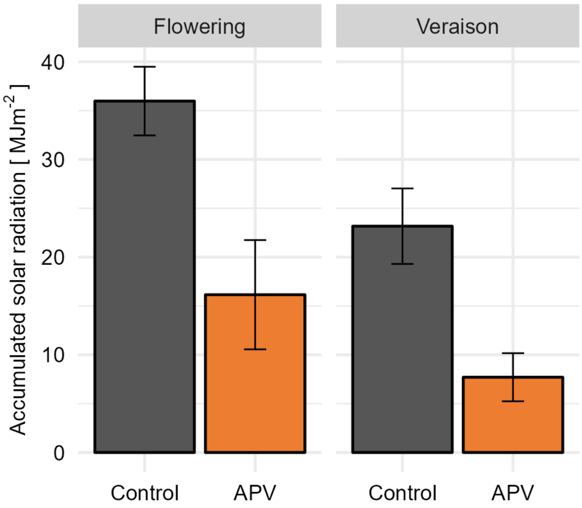

Figure 4. Accumulated solar radiation at the fruit zone throughout three days during flowering (72 hours of exposition) and five days at veraison (120 hours of exposition).

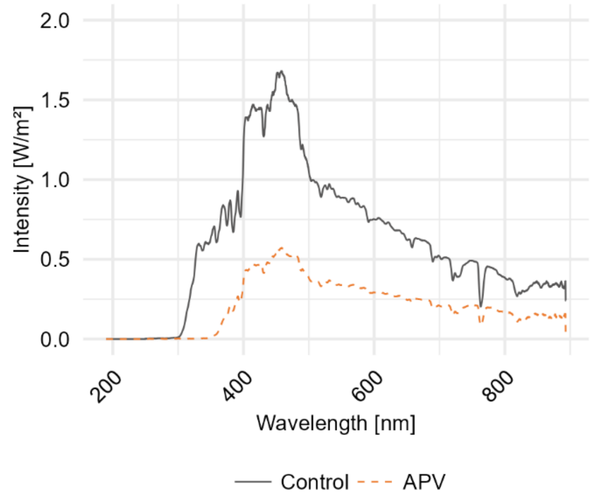

Figure 5. Electromagnetic spectrum of solar radiation of Control and APV plot.

3.1.4. Electromagnetic spectrum

The radiation passing through the solar modules alters the light spectrum. To investigate this, a comparison was made between the solar light spectrum in the control area and beneath the APV surface. At first glance, it is evident that the light intensity is significantly reduced, on average by more than 50%. Notably, the short-wave range between 300 and 350 nm is completely absent from the spectrum beneath the modules, suggesting that this range was filtered out. Across the broader spectrum, the peaks occur at the same wavelengths, though at reduced intensity.

The overall reduction in light intensity may influence growth, development, and grape quality in various ways. However, even if the missing short-wave range only has a limited influence on the growth of the vines, it could influence the formation of secondary plant metabolites and thus also aromatic substances in the grapes. In particular the synthesis of secondary metabolites such as phenols, stilbenes, and flavonoids rely on this wave length range. Consequently, this alteration in metabolite production could not only impact the composition of the must and wine, but also potentially reduce the pathogen resistance of both the vines and the grapes [21].

3.1.5. Soil water content

From May to the end of October, volumetric soil water content was measured using capacitance sensors at three locations near the rootstocks in each plot. In the APV plot, those are areas where the solar modules prevented direct rainfall from reaching the soil surface. Soil moisture values were integrated over a depth of up to one meter, with the data averaged across the three measurement points (Figure 6). Additionally, the relative soil moisture of the APV plot was calculated as a percentage of the control plot's soil moisture (gray line in Figure 6), with the control plot's soil water content normalized to 100%.

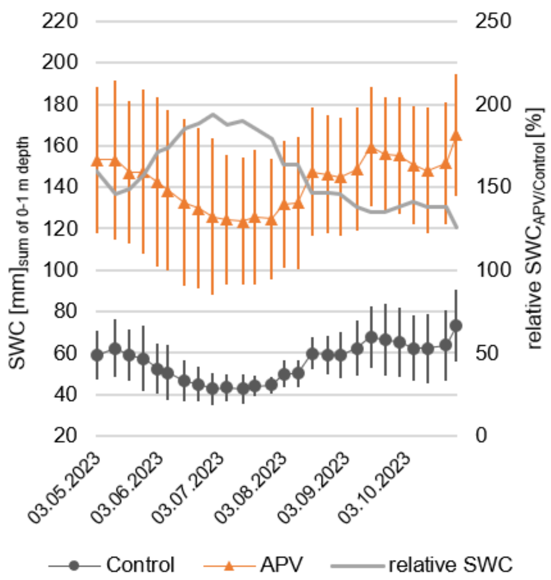

Figure 6. Development of soil moisture content (SWC) throughout the growing season 2023. Every point represents the mean of 3 measurement point in the respective area. The vertical lines giving the standard deviation. The light grey line gives the ratio of SWC_{APV}/SWCControl.

Both the APV and control plots exhibited fluctuations in soil moisture over the months; however, soil moisture levels in the APV plot consistently exceeded those in the control plot throughout the measurement period reflected by more than 100% of the control. Notably, during a dry spell in June and July, the soil in the control plot experienced greater drying compared to the APV plot, where soil moisture appeared more buffered against fluctuations. However, the higher standard deviation of the APV soil water contents suggests greater variability in soil moisture between measurement points in the VitiVoltaic compared to the control.

While studies in other APV systems similarly report higher soil moisture levels under the modules, this moisture is often distributed more heterogeneously compared to the respective control [7]. Still, there is a lack of data in the literature regarding horizontal water diffusion in deeper soil layers. Based on our findings, it can be inferred that water infiltrates the soil in a concentrated manner between the modules, subsequently dispersing through deeper soil layers and reaching the root zones beneath the modules, which do not receive direct rainfall.

3.2. Grape health

The protective effects of the PV system on grape health were extensively studied in only one season yet. No sunburn damage was observed in grapes under the agrivoltaic system, whereas 13% of the grapes in the control area were affected, with an average damage level of 20%. Additionally, the grapes under the VitiVoltaic system exhibited significantly lower Botrytis infestation compared to those in the control area. This reduction in Botrytis incidence may be attributed to a looser grape structure or reduced mechanical damage from heavy rainfall. However, factors such as lower sugar levels, altered berry structures, or higher acidity could also contribute to this effect, warranting further investigation. Numerous factors, both microclimatic and physiological, are influenced by the presence of PV systems and can either increase or decrease disease pressure. Currently, making accurate predictions is challenging, as existing literature presents conflicting data on these effects [20]. More data will be required to better report on these aspects.

4. Conclusion

With the establishment of the VitiVoltaic research platform, the potential of protected cultivation with dual land use can be investigated and synergies developed. The first year has already shown that the moderate shading can reduce the air temperature on hot days and keep the soil moisture longer. In 2023 APV also provided effective protection against sunburn damage to the grapes. In the future, further phytosanitary aspects, new possibilities in cultivation and energy use as well as parameters of ripening and quality formation in berries, must and wine will be investigated.

5. Funding

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