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Agrivoltaic System Potential to Mitigate Effects of Climate Change in Viticulture

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ABSTRACT

Viticulture already faces several climate-related risks, which will be even more severe in the future. If Agrivoltaics (APV) can help to mitigate challenges associated to climate change still has to be investigated. To address this, we analyze historical meteorological data, onsite measurements, and climate projections to summarize the effect of climate change on wine yield for two wine-growing sites: Hatzenport, Germany, and Laujar, Spain. We compare projected ambient temperature, precipitation, and global horizontal irradiance to the effects of various APV installations on these parameters. Since 1970, temperatures at both locations have risen by about 2.5°C, and future scenarios show further warming, especially in Hatzenport, where average yearly temperatures are predicted to increase up to 5.8°C under 8.5 W m^{-2} radiative forcing until 2100. The climate projections indicate that heat waves and droughts are increasingly likely to occur in Laujar by 2100. Phenological stages might occur about 10–20 days earlier in the year 2100, which increases the risk of hail damage and shortened dormancy periods. APV systems have the potential to mitigate those risks by providing protection for the crops, improving microclimate below the photovoltaic modules by reducing air and soil temperatures, and simultaneously generating renewable energy on agricultural land.

1 | Introduction

In order to achieve a "net zero" CO_2 economy, a transition of both the energy system and the agricultural and food sector is required [1].

Agrivoltaic (APV) installations offer a promising solution to the growing challenges of global food and energy security [2]. APV is the simultaneous usage of land for solar energy and agricultural production, e.g., installing photovoltaic (PV) modules above crops. It not only provides clean energy but also contributes to the development of a sustainable and circular food economy in rural regions and farming communities. By installing PV modules over arable land, the competition for land between solar energy and agriculture can also be reduced. In addition, APV can mitigate the negative effects of climate change on agricultural productivity that can be expected in a warmer and drier climate. APV installations can significantly reduce greenhouse gas emissions while having only a minor impact on agricultural income [1].

Several studies investigated the influence of climate change on viticulture in different regions. One recent review paper [3] showed that about 90% of traditional wine regions in coastal and lowland Italy, Spain, Greece, and southern California might be at risk of disappearing by 2100 due to increased frequencies of droughts and heat waves. The authors summarize strategies to support viticulture resilience against climate change effects, e.g., by cultivar shifts, increase of the varietal diversity, relocation of vineyards, enhancements in water, and soil management and pest control or modification of the canopy [3]. Also, shading nets might be integrated to decrease the risk of excessive solar irradiance to prevent sunburn or to alter the microclimate below.

1.1 | APV Installations in Viticulture

In addition to traditional measures, integrating APV into vineyards could provide a controlled shading effect, mitigate heat and drought or water stress on crops, and therefore potentially enhance crop growth.

Through regional modeling of APV systems and their influence on microclimate and plant growth, it has been found that APV systems offer clear advantages in the Mediterranean region of Spain, characterized by its dry climate and high average annual global horizontal irradiance sum of up to 1950 kWh/m^2/y [4, 5]. They can increase agricultural productivity, improve the water use efficiency of the agricultural area and create a more favorable microclimate for the plants due to the additional shading. Particularly in dry periods or in extreme weather conditions, this leads to less evaporation. In the long term, APV systems can also promote soil health and strengthen the resilience of plants to climate risks, making it a sustainable solution for arid and semi-arid regions [6].

In literature, different experimental results of APV installations in vineyards have been documented. In Spain, several projects have been realized already since 2022 in the region of Toledo, and Castilla la Mancha and in 2025, an experimental pilot (0.012 ha) has been installed in Laujar, Southern Spain [6, 7]. In Germany, the first grid-connected "VitiVoltaics" installation on 0.15 ha has been in operation since 2023 [8].

Authors [9] analyzed 3 years of grapevine growth data under a fixed-tilt south-oriented APV system of 0.015 ha with an average shading ratio of 75% in Northern Italy (Veneto region). The authors found that the APV systems improved the microclimate in the vineyard by lowering air and soil temperatures and reducing water stress on the vines. Under the modules, the vines showed higher transpiration and photosynthesis rates at midday than in full sun, while these were lower in the morning. Yield and quality parameters were slightly reduced in the grapes under the PV modules. Another study [10] investigated a fixed-tilt south–north oriented APV system with a ground cover ratio of 43% in the Puglia region, Italy, and found that the shading by the APV system increased soil moisture and moderate soil temperature, which benefited the plants. Under the PV modules, the vines produced 277% in comparison to the yields in full sun. While the system had little effect on the air temperature, it reduced the wind speed and the vapor pressure deficit, creating a more favorable microclimate for the vines. A research group [11] found a significantly reduced wind speed below the APV system in winter, and generally reduced soil temperatures compared to an open field. The same authors found no significant difference in carbohydrate storage, budding, shoot growth, grape weight, sugar content, or acidity, but the harvest under the APV system was delayed by about 7–10 days due to later veraison. Additionally, it has been shown [12] that intermittent shading of vines in Southern France promotes delayed ripening, which can be beneficial for maintaining acidity, balancing sugar accumulation, and improving overall grape quality in a warming climate. However, this experiment was performed with potted grapevines.

Several APV designs featuring different shading patterns have been implemented in vineyards worldwide and are currently under evaluation. These approaches include elevated fixed-tilt systems equipped with opaque or semi-transparent PV modules [8], vertical configurations, pergola-type structures with adjustable shading ratios,[1] mobile and flexible systems [13], one- and two-axis tracking installations (such as the APV installation[2] at Oberrhein Germany, "Vegetal Welfare" by PowerfulTree[3] or "Wine Solar" by Iberdrola),[4] as well as trellis-integrated systems [14]. While all concepts aim to combine electricity generation with viticulture, they differ substantially in their effects on microclimatic conditions, agronomic performance, operational management, and overall economic viability.

1.2 | APV System Influence on Ambient Temperatures Below PV Modules

It has been observed that an APV system reduced maximum air temperature below the PV panels by about 1°C–2°C [9]. Another study [15] showed in a conventional fixed tilt PV park a cooling effect of up to 5.2°C during summer months in the UK. Other authors [16] found a reduced daily ambient temperature of up to 2.16°C on days with temperatures above 35°C for different shading treatments with shading nets in 50 cm above the canopy in Adelaide, Australia, over Shiraz vines. In a high-elevated APV system in Southern Germany, about 1.1°C lower daily temperatures have been recorded [17]. Under a dynamic APV system in South of France over apple trees with variable shading between 4% and 88% during the day and a mean shading rate of 50%–55%, a reduced daily temperature of 1.2°C–3.8°C has been measured [18]. A French APV company [19] claims that their 4.5 m elevated APV system above apple trees deployed in the transitional Mediterranean climate of the Durance Valley in France reduced the ambient temperature by 2°C–4°C. With their dynamic APV system, the company reaches a temperature reduction of up to 5°C [20]. A further study [21] analyzed ambient temperature difference below an elevated APV system over rice in Japan and found a temperature reduction of around 0.8°C. Lower air temperatures were observed below PV modules in the "VitiVoltaics" [8] installation in Germany in comparison to a reference zone without PV modules. On hot and sunny days during the summer months, air temperature was up to 4°C lower during daytime during the growing season, while at night temperatures were the same or even slightly increased on the APV plot. During winter months or on days after drastic temperature reductions, the APV system showed higher temperatures compared to the non-shaded control during daytime. A similar behavior has also been observed in the experimental site in Laujar (Spain) [6]. During the first growing season in 2025, a decrease of on average 0.5°C and up to 0.85°C during daytime has been measured between June and August. This value is slightly lower than that reported in other studies, probably due to the fact that Laujar's APV system is smaller, which causes boundary effects.

1.3 | APV System Influence on Other Microclimate Parameters Below PV Modules

In addition to ambient temperature, other microclimate parameters, like soil temperature, soil moisture, water retention, and availability or irradiance levels, can be altered due to overhead APV installations.

Soil temperatures have been reduced in different experiments by around 1.5–1.7°C [22], 1.2–1.4°C [17], and 0.5–2.3°C [23]. APV systems can decrease soil temperatures of up to 6°C in warm periods and can promote water retention up to 20%–30% in the case of elevated systems, a benefit especially favorable in semi-arid regions with limited water availability [24, 25].

Concerning soil moisture and irrigation needs, around 2%–3% higher soil moisture values have been derived in comparison to a reference plot without APV shading [17]. And a decrease of 6%–31% in irrigation needs has been reported [18]. Soil moisture measurements [8] showed increased soil moisture levels in an APV system in comparison to a control plot during the growing season in 2023. Especially during hot summer months, the control plot experienced a faster soil drying process. This result was confirmed for the year 2024, where the APV installation had a positive impact on water status and availability [26]. A similar behavior has been observed with volumetric water content measurements in different depths in Laujar, Southern Spain, where a higher volumetric water content was maintained below the APV installation after rainfall events in comparison to the control area [6].

1.4 | Economic Considerations

Recent studies have begun examining the economic benefits of APV in vineyard environments. A key study established an economic evaluation framework for vineyard APV systems, explicitly integrating viticultural and energy production parameters through simulated scenarios [27]. The study indicates that under Germany's current cost structure and energy prices, the systems cannot achieve a positive net present value over a 20-year period due to high capital expenditures (CAPEX) and relatively limited combined revenue from grape and energy production. Key factors influencing profitability identified include: CAPEX levels, electricity prices, potential feed-in tariff policies, and self-consumption strategies. Economic viability potential emerged only in scenarios featuring premium wine pricing, higher feed-in tariffs, and increased self-consumption ratios. This underscores the need for cost reduction and supportive policy frameworks to enhance implementation feasibility.

Existing APV literature (beyond viticulture systems) also highlights critical economic challenges. For instance, APV techno-economic models in other agricultural contexts, like, e.g., apple farming, demonstrate that APV can significantly reduce investment cost as the main driver of the cost reduction is the partial substitution of the hail net system. But these savings are not enough to significantly reduce the overall cost of the APV system [28].

Another study highlights that the additional costs for APV systems, which depend on size and height of the system, in comparison to ground-mounted PV installations, cannot completely be balanced by additional agronomic yields [29]. But the results of economic evaluations differ for APV designs [30]. A further study estimated the electricity production costs between 7 and 12 € cents per kWh, which enables APV to be competitive with other renewable energy sources [31]. Recent studies of APV systems emphasize that economic and policy factors are central to achieving large-scale adoption [32, 33]. While these reviews do not focus specifically on vineyard scenarios, they consistently indicate that current economic viability primarily depends on regulatory frameworks, incentive mechanisms, and the long-term stability of revenues from both agricultural and energy markets.

In summary, the current scientific consensus is that robust economic evidence for APV systems in vineyards is still emerging. The most advanced published research indicates limited feasibility under existing cost and price structures, while also suggesting that future studies could improve outcomes through specific pathways. Therefore, the core task for prioritizing development in this field lies in conducting more in-depth empirical and longitudinal economic analysis, ideally integrating real-world vineyard operational data with dynamic electricity market information.

1.5 | Novelty of This Study

Although several studies address the impacts of climate change on crop development and the potential of APV to tackle them, most of them have focused on individual sites or experiments. Site-specific comparative studies using standardized methods do not exist so far. Therefore, it is still unclear to what extent the results of the studies are transferable to different sites and to what extent local climatic conditions affect the effects of APV.

The novelty of this study is the intention to fill this gap by analyzing two contrasting site examples to identify possible similarities and differences between climate change and the effects of APV applications. The study aims at helping to better understand the challenges and potential of specific sites and analyzes historical, measured, and projected climate data to compare the potential benefits of APV installations in two European viticulture regions in Germany and Spain. The novelty of our study is the comparison between two sites with distinct climates by synthesizing the insights from experiments in literature. We evaluate how viticultural practices might benefit from APV systems, considering an influence on microclimate, water demand, and yield under future climate conditions. Section 2 describes the investigated sites as well as the analyzed data sets. In Section 3, the results of this study are presented, and they are discussed in Section 4. Section 5 concludes the findings and suggests future research efforts.

2 | Materials and Methods

This study examines climate change impacts on agriculture and the role of APV systems in mitigating these effects across Europe. The aim of the investigation is to assess the diverse impacts of climate change on wine yield, including different future climate change scenarios. For this purpose, two sites in Europe are compared by analyzing meteorological measurements, reanalysis datasets, and different climate projections until the year 2100. The evaluated datasets are also summarized in Table 1.

TABLE 1 | Analyzed datasets.

Dataset	Parameters	Analyzed period	Temporal resolution	Source
Onsite measurement Laujar	*T*, *p*, *GHI*	2009–2024	Daily, monthly, yearly	[34]
Onsite measurement Hatzenport	*T*, *p*, *GHI*	2009–2024	Monthly, yearly	[35]
ECMWF ERA5 -Land reanalysis	*T*, *p*, *GHI*	1970–2024	Monthly, yearly	[5]
CMIP6 climate projection Scenarios: SSP1−1.9, SSP2−4.5, SSP5−8.5, EC-Earth3-Veg model	*T*, *p*, *GHI*	2015–2100	Monthly, yearly	[36, 37]
EURO-CORDEX: Climate indicators for Europe from 1940 to 2100 derived from reanalysis and climate projections, regional model CCLM4-8-17, Global Climate Model MPI-ESM-LR	IPCC hazard category parameters: Hot days, heat waves, frost days, total precipitation, consecutive dry days, duration of meteorological droughts	2015–2100	Monthly, yearly	[38, 39]
Wine production and crop yield	Wine production in l ha^{-1} for Germany and Spain; crop yield in t h^{-1} for Cortijo el Cura in Laujar (Spain)	1995–2024 2005–2024 (Laujar)	yearly	[40, 41]

2.1 | Investigated Sites

Two exemplary sites, relevant to European viticulture, are investigated (Figure 1). The first site is the Moselle River region surrounding Hatzenport in Rhineland-Palatinate in Germany (50.23°N, 7.42°E, 156 m a.m.s.l.). Grapevine cultivation in the Moselle River region was already implemented by the Romans [43]. The predominant grapevine variety in the region is Riesling, which is cultivated in this region of steep slopes (Figure 1, left), due to the present temperate oceanic climate ("Cfb" Köppen–Geiger category [44]), as grapevine varieties differ in temperature, precipitation, sunshine duration demands [43]. The region plays a significant role in German viticulture [45].

The second site examined is in the Laujar–Alpujarra wine region in Andalusia, Spain (36.97°N, 2.92°W, around 920 m a.m.s.l.) in currently hot-summer mediterranean climate ("Csa" Köppen–Geiger category [44]). This region has a long-standing tradition of viticulture [46, 47]. Laujar is already experiencing noticeable impacts of climate change, like increased temperatures and reduced water availability (see analysis in Section 3), and the future of viticulture in this region is uncertain, posing challenges for local wine producers and the broader Spanish wine industry [6, 7]. In the organic vineyard Cortijo el Cura [40] in Laujar, a 10.8 kW APV pilot plant was installed in December 2024 (Figure 1, right). The APV installation is an overhead system covering 120 m^2, providing additional shading to the red variety of Merlot vines in a checkerboard layout with a ground cover ratio of 38% [6, 7]. The ground cover ratio describes the percentage of land area covered by the vertical projection of the PV modules relative to the total area occupied by the APV system [48].

2.2 | Onsite Measurement Data

To evaluate and preprocess historical reanalysis and projection data, they are compared to onsite measurements to scale the data according to local measured values.

For Laujar, measurements of the average daily ambient air temperature (*T*, measurement performed with a Pt1000 sensor), the total daily precipitation (*p*) and the total daily global horizontal irradiance (*GHI*) are provided from 2009 until 2024 and monthly and yearly averages are derived (Figure 1, middle) [34].

For Hatzenport, monthly data of *T*, *p*, and *GHI* is provided [35] and additionally yearly mean values are calculated. The

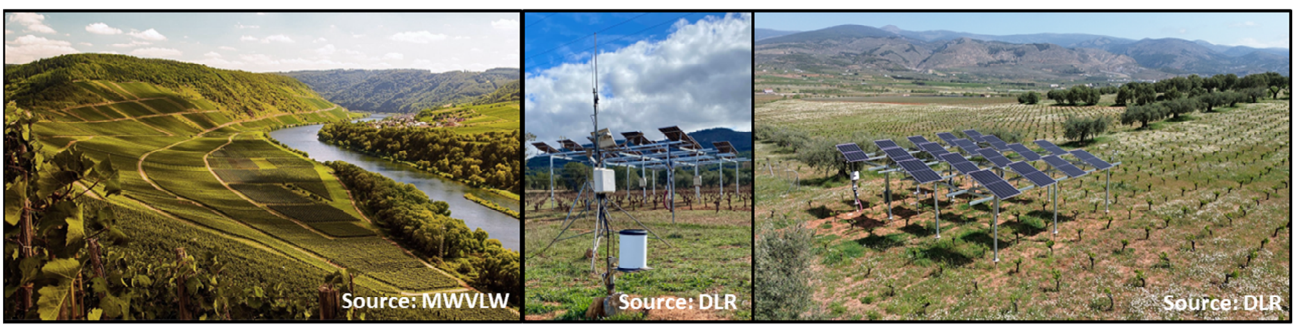

FIGURE 1 | (Left) Viticulture region Hatzenport, Germany; (middle) meteorological station in Laujar; (right) APV system installed in an ecological vineyard in Laujar (Spain). Reproduced with permission from ref. [40, 42].

measurements are performed with a meteorological measurement station of Lambrecht, using the sensors TA200, NN050, and GS200 for T in 2 m height above ground, p, and GHI, respectively.

2.3 | ERA5 Reanalysis Dataset

Historical data for both sites have been extracted from the ERA5 land dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF), which covers the period from 1950 to present (here only analyzed from 1970–2024) with a horizontal grid resolution of 9 km (0.1° x 0.1°grid) [5]. ERA5 land is based on climate reanalysis and combines model data with observations from across the world into a globally complete and consistent dataset. Monthly averaged data is provided by ECMWF. The GHI is defined as the surface global horizontal irradiance downwards given in Wm^{-2}, daily precipitation p in millimeters, and T at 2 m height above ground in °C. For both investigated sites, data from the closest available grid point (longitude and latitude coordinates) in the ERA5 dataset are extracted.

2.4 | Climate Projection Scenarios

2.4.1 | CMIP6

To investigate future climate conditions, global climate projections for 2015–2100 based on three scenarios with low, medium, and high radiative forcing of the sixth phase of the Coupled Model Intercomparison Project (CMIP6) have been considered [36, 37]. The scenarios are understood in terms of a Shared Socioeconomic Pathway (SSP) and a representative concentration pathway (RCP). The second and third digits represent the RCP radiative forcing, while the first digit represents the SSP storyline for the socioeconomic mitigation and adaptation challenges leading to this RCP. SSP1−1.9 stands for a low radiative forcing of 1.9 Wm^{-2} (RCP1.9) by 2100 induced by SSP1 with low challenges to mitigation and adaptation. SSP2−4.5 represents the intermediate pathway SSP2 with moderate challenges and a radiative forcing of 4.5 Wm^{-2} (RCP4.5), reflecting a mid-range scenario of plausible future developments. SSP5−8.5 is based on the fossil-fueled development path SSP5 with high mitigation challenges and a radiative forcing of 8.5 Wm^{-2} (RCP8.5), representing the high end of plausible future forcing trajectories.

The EC-Earth3-Veg-LR model (250 km resolution), which integrates atmospheric and land surface models (ECMWF model IFS 36r4 and HTESSEL), ocean and sea ice model (NEMO3.6 and LIM3) and the dynamic vegetation model LPJ-GUESS was selected to analyze climate-biosphere interactions under various future scenarios [49]. This EC-Earth3-Veg-LR model estimates the vegetation changes caused by climate change and therefore aims to cover feedback processes between the atmosphere and vegetation, like albedo or evapotranspiration.

For all chosen scenarios, the GHI is provided by CMIP6 as the surface downwelling shortwave irradiance which can be converted into an average daily GHI in W m^{-2}, the temperature T in °C, and the precipitation as monthly mean precipitation flux in kg m^{-2} s^{-1}, which can be converted to an average daily precipitation sum p in millimeters.

2.4.2 | EURO-CORDEX

For the here analyzed climate indicators (see Table 1), the RCP scenarios RCP1.9, RCP4.5, and RCP8.5 are provided by [38, 39]. The regional model CCLM4-8-17 was used here, and the Global Climate Model selected is MPI-ESM-LR, the “Moderate Resolution Earth System Model - Low Resolution” of the Max Planck Institute for Meteorology. The dataset [38] is based on the CMIP5 intercomparison. CMIP5 served the Fifth Assessment Report of the IPCC (International Panel for Climate Change) and worked with the RCP scenarios, used around 40 climate models with typical resolutions of 100–200 km, focusing primarily on greenhouse gas emissions and their climate impacts. CMIP6 (used for the dataset of Section 2.4.1) forms the basis for the Sixth Assessment Report, comprises over 100 models, works with the new SSP scenarios, which also take socioeconomic developments into account, and offers a much more detailed representation of climate and extreme events with higher resolutions and more complex Earth system components.

In this study, the scenarios of the EURO-CORDEX dataset [38, 39] are referred to RCP scenarios and the scenarios of the CMIP6 dataset [49] (Section 2.4.1) are named SSP scenarios.

2.5 | Meteorological Data Preprocessing

The ERA5 analyses may deviate from accurate meteorological measurements because they represent grid fields with a horizontal resolution of about 31 km and therefore only depict large-scale averages. Local site factors, such as slope or distance from water bodies, are therefore not resolved. In addition, ERA5 works with smoothed terrain heights, which may result in systematic differences. ERA5 is also generated by a mixture of observations and model calculations, so that measured values are not adopted on a one-to-one basis. Small-scale phenomena such as convective precipitation events, inversions, or fog are therefore usually not adequately captured or not captured at all. The same accounts for the CMIP6 climate model simulations due to the coarse spatial resolution of 250 km, where only mean area values are provided. Topographical details such as slope gradients, valley structures or small-scale differences in land use are not taken into account or are only taken into account in a highly smoothed form. Furthermore, the model results are not derived from a direct assimilation of observations, but from coupled physical simulations of the climate system, meaning that local measured values cannot be reproduced exactly.

Therefore, a bias-adjustment procedure is applied to the ERA5 and CMIP6 datasets with the help of the onsite measurements. This individual bias-adjustment helps to better capture small-scale local patterns.

To bias-correct the ERA5 dataset, an average adjustment factor is calculated for each site. To do so, average annual values for GHI, T, and p are calculated from the onsite measurements and for the ERA5 dataset and the calibration period of 2010 until 2022. The adjustment factor is then derived by averaging the ratio of the average annual values of ERA divided by the average annual values of the measurements. Similarly, the adjustment factor for the CMIP6 dataset is derived for the period of 2015 to 2024.

The adjustment factors for each dataset (ERA5, CMIP6 SSP scenarios) and parameter (T, p, GHI) $AF_{\text{dataset, parameter}}$ is calculated as follows:

$$AF_{\text{dataset,parameter}} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\overline{\text{parameter}}_{\text{dataset},i}}{\overline{\text{parameter}}_{\text{meas},i}}\right)$$

where i is the year within the adjustment period (2010–2022 for the dataset ERA5 and 2015–2024 for CMIP6). N is the number of years used for the calibration (14 years for ERA5 and 10 years for CMIP6). $\overline{\text{parameter}}_{\text{dataset},i}$ is the average annual temperature from one dataset and $\overline{\text{parameter}}_{\text{meas},i}$ from the onsite measurements for year i. The adjustment factor $AF_{\text{dataset},\text{parameter}}$ is the mean of the annual ratios over the full period. This adjustment factor is used to adjust the ERA5 and CMIP6 data to better match local measurements as follows:

$$\text{parameter}_{\text{dataset adjusted}} = \frac{\text{parameter}_{\text{dataset}}}{AF_{\text{dataset,parameter}}}$$

This linear bias-adjustment was chosen due to reduced computational effort compared to more complex bias correction methods such as quantile mapping, still ensuring sufficient data precision to address the issues explored in this work.

Figure 2 shows for illustration of the bias-adjustment method the average annual temperature T for Hatzenport (Germany) of the measurement data, the ERA5 originally extracted data and the adjusted ERA5 data. For the adjusted ERA5 data, the average adjustment factor for the whole period has been applied. The annual adjustment factor and the average adjustment factor are also shown in Figure 2.

To evaluate the performance of the adjustment for the adjustment period, the mean absolute deviation (MAD) is calculated as follows:

$$MAD_{\text{dataset,parameter}} = \frac{1}{N}\sum_{i=1}^{N}\left|\text{parameter}_{\text{meas},i} - \left(\frac{\text{parameter}_{\text{dataset},i}}{AF_{\text{dataset,parameter}}}\right)\right|$$

The average adjustment factors for each dataset and site, as well as the MAD of the adjusted modeled data from the measurements, are summarized in Table 2.

It can be seen that the deviations between local measurements and ERA5 or CMIP6 data are greater for p than for T or GHI. Precipitation is highly variable in space and time and is influenced by small-scale processes such as convection or orography. The spatial resolution and smoothed topography of the models used in ERA5 and CMIP6 can therefore only represent these effects in parameterized form. For CMIP6 scenario data, the differences are high, as the climate models have a much coarser horizontal resolution, do not include the assimilation of observations, and thus generalize precipitation processes even more.

For the monthly analysis performed in Section 3.2.3, an appropriate monthly adjustment method was applied to the SSP5−8.5 T data. The derived monthly adjustment factors and the MAD between adjusted monthly SSP5−8.5 T data and measurement data are listed in Table 3.

2.6 | Crop and Wine Yield Data

To investigate the crop yield and the according wine yield and trend, annual yield data [41] is extracted for the countries Germany and Spain from 1995 until 2024 in liter per ha. Further, for one local winery in Laujar (*Cortijo el Cura*) the annual crop yield data in kg for 2005 until 2024 is provided [40].

3 | Results

The impact of climate change on wine production is analyzed for each site individually. Among other factors, we identified several climate-related risks impacting viticulture yields:

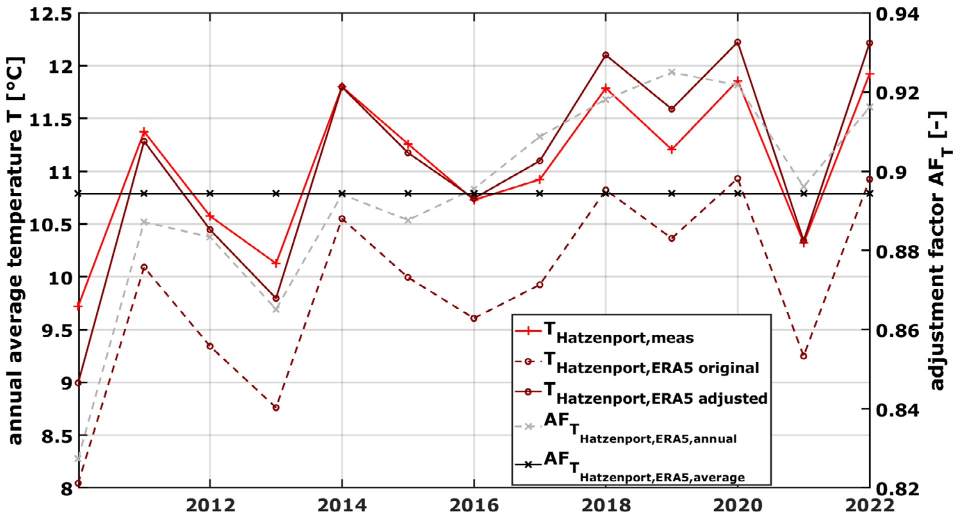

FIGURE 2 | Left y-axis: Average annual temperature T for Hatzenport (Germany) and the measurement data (light red), the ERA5 original data (dark red dashed line) and the adjusted ERA5 data (dark red solid line). Right y-axis: Annual adjustment factor AF (light gray dashed line) and average adjustment factor (black solid line) for 2010–2022.

TABLE 2 | Adjustment factors for the ERA5 and CMIP6 datasets for Hatzenport (Germany) and Laujar (Spain) and the according MAD of the adjusted modeled data from the measurements.

		Hatzenport		Laujar		
Dataset	**Parameter**	**Adjustment Factor AF**	**MAD between measurements and adjusted modeled data**	**Adjustment Factor AF**	**MAD between measurements and adjusted modeled data**	**Period**
ERA5	*T*	0.89	0.23	0.88	0.37	2010–2022
	p	1.35	0.11	1.33	0.20	
	GHI	1.06	4.14	1.02	5.64	
SSP1-1-9	*T*	0.84	0.61	1.28	0.44	2015–2024
	p	1.79	0.24	1.09	0.29	
	GHI	1.05	6.27	0.99	3.35	
SSP2–4.5	*T*	0.86	0.71	1.28	0.44	
	p	1.88	0.23	0.75	0.33	
	GHI	1.06	5.38	1.03	5.39	
SSP5–8.5	*T*	0.83	0.73	1.28	0.57	
	p	1.80	0.30	0.99	0.22	
	GHI	1.04	9.745	1.01	4.51	

TABLE 3 | Adjustment factors for the monthly temperature parameter of the CMIP6 SSP5–8.5 datasets for Hatzenport (Germany) and Laujar (Spain) and the according MAD of the adjusted modeled data from the measurements.

	Dataset SSP5–8.5, Parameter T				
	Hatzenport		Laujar		
Month of year	**Adjustment Factor AF**	**MAD between measurements and adjusted modeled data**	**Adjustment Factor AF**	**MAD between measurements and adjusted modeled data**	**Period**
January	0.9940	2.42	1.0307	0.91	2010–2022
February	0.9931	1.99	1.0260	1.32	
March	0.9930	1.77	1.0206	1.16	
April	0.9937	1.61	1.0155	1.28	2015–2024
May	0.9921	1.79	1.0054	1.30	
June	0.9905	1.74	0.9995	1.60	
July	0.9907	1.22	0.9960	1.26	
August	0.9915	1.30	1.0020	0.95	
September	0.9972	1.92	1.0134	0.94	
October	0.9951	1.73	1.0172	1.19	
November	0.9932	1.27	1.0258	1.59	
December	0.9929	1.69	1.0284	1.04	

- frost days after budburst
- hail events between budburst and harvest
- droughts between budburst and harvest
- heat waves between budburst and harvest.

The definitions of budburst and these factors are summarized in Table 4. Further, extreme precipitation events between budburst and harvest, as well as too short cold periods during winter to induce the vines into their winter dormancy, play a role, but are not analyzed in detail in this study.

This work analyses several risk factors for viticulture with regard to climate change scenarios, discussing how APV systems can mitigate or reduce those risks.

3.1 | Historical Data

Figure 3 shows calibrated ERA5 reanalysis data and onsite measurements for both sites with derived linear trends for *T*, *p*, and

TABLE 4 | Definition of budburst and risk factors (EURO-CORDEX).

Risk factor	Definition	Reference
Frost day	day with daily minimum temperature below 0°C	[38, 39]
Budburst	Date (typically in spring), when the buds of plants break out of their cocoons and new leaves or inflorescences begin to grow	
Consecutive dry days	The index of consecutive dry days reports the longest dry period per month with daily precipitation of less than 1 mm	[38, 39]
Drought duration (*dd*)	The duration of a meteorological drought is the total number of months with abnormally low precipitation conditions for at least two consecutive months during a specified period of time, based on the Standard Precipitation Index (SPI). The SPI used here is based on 3 months of total precipitation, which is generally considered suitable for agricultural applications when compared with a 30-year reference baseline (1981–2010). A drought event begins when the SPI is below −1 (i.e., one standard deviation below the mean) for at least two consecutive months, and ends when the SPI returns above zero.	[38, 39]
Heat wave	The count of climatological hot days in a year. A climatological heat wave is a period of at least three consecutive days exceeding the 99th percentile of the daily maximum temperatures of the May to September season during a reference period between 1971 and 2000 (EURO-CORDEX definition)	[39, 50]

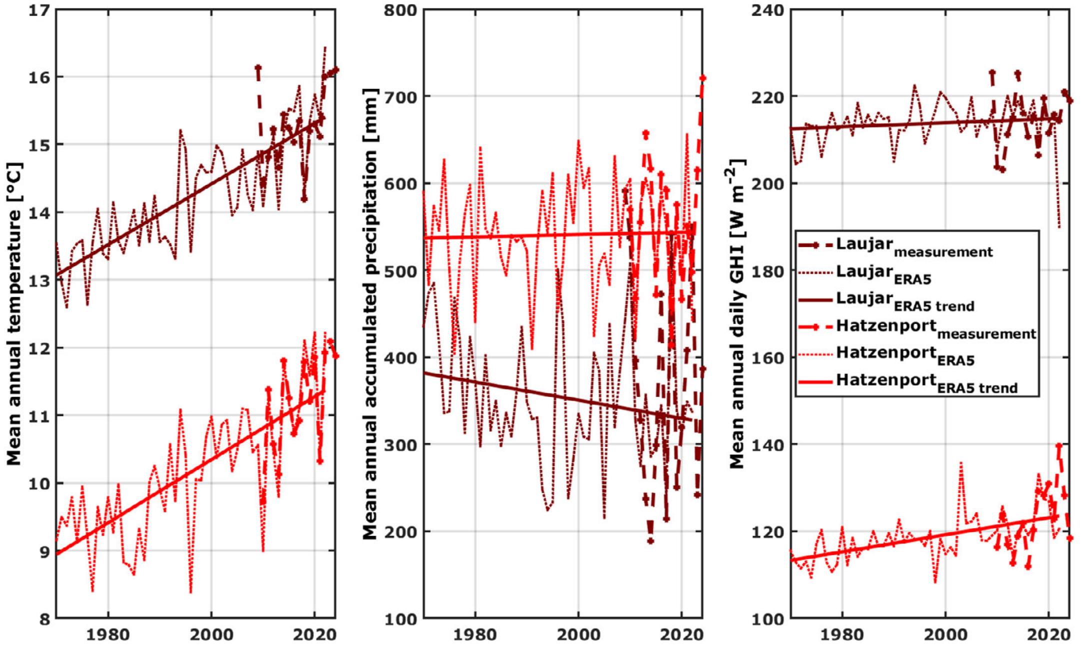

FIGURE 3 | ERA5 calibrated reanalysis (point line), according linear trend (straight line) and measurement data (dashed line) for: left) annual mean ambient temperature T; middle) annual accumulated precipitation p; and right) annual mean daily *GHI* for Laujar, Spain (dark red) and Hatzenport, Germany (red) from 1970 until 2024.

GHI. In order to calculate the trend line, linear regression analyses were carried out for each parameter from the calibrated ERA5 data for both locations. While Spain already has a warm, dry climate in many wine regions ("Csa" Köppen-Geiger), Germany is characterized by cooler, temperate climate ("Cfb" Köppen–Geiger). At both sites, the *T* and *GHI* trend shows an increase and *T* has risen by approximately 2.5°C since 1970, while the increase in *GHI* has been less pronounced. The annual total precipitation decreased in Laujar and rose slightly in Hatzenport which is also visible in the linear trend lines, although strong interannual fluctuations are observed.

3.2 | Future Scenarios

3.2.1 | Annual Trends: Temperature, Precipitation, GHI (CMIP6)

In Figure 4, 10-year moving yearly averages for three climate scenarios and various parameters are displayed. In Figure 4 (left), it can be seen that for the SSP2−4.5 and SSP5−8.5 scenarios, *T* rises steadily until 2100 at both sites while the average daily *GHI* levels remain almost constant (Figure 4 (right)). For the SSP5−8.5 scenario, predicted temperature levels in Hatzenport rise up to similar levels as in Laujar until 2100.

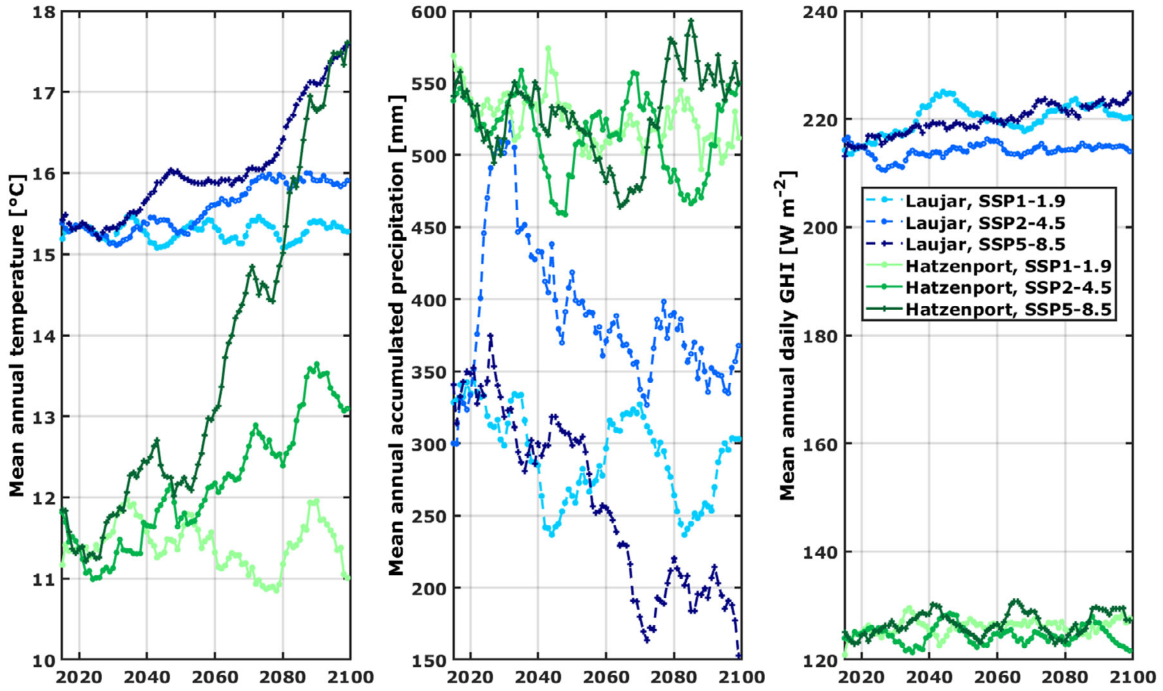

FIGURE 4 | CMIP6 calibrated climate projections yearly 10-year moving averages for 2015–2100. Left, mean ambient temperature T; middle, accumulated precipitation p; and right, annual mean daily GHI for Laujar, Spain (blue colors) and Hatzenport, Germany (green colors).

In Figure 4 (middle) it can be seen that while in Hatzenport precipitation levels stay at a similar level, they decrease until 2100 for the SSP1−1.9 as well as for the SSP5−5.8 scenario in Laujar. Interestingly, the SSP2−4.5 scenario shows even an increase in precipitation until 2032, followed by a decrease until 2100.

3.2.2 | Annual Trends: Hail Events (EURO-CORDEX)

Main hail events occur on both sites during summer months (June, July, August), which are a great risk for ripening grapes. But also hail events before budburst can affect grape yield. The hailstones can break the terminal meristem (the zone of growth of the stem), which can cause a blocking of the plant and the growth of secondary, smaller stems which later prevent ventilation of the bunches [43]. Analyzing average grape yield in years where hail occurred in Laujar indicated a reduction in yield of over 60% [40], which shows the relevance of hail events. Considering that APV solutions (depending on the APV design and operation strategy) are able to protect the vines from hail [28], the predicted yield loss due to hail might be avoided. Therefore, we extracted the hail probability for different climate scenarios for both sites from published literature, which investigated the hail frequency change probability in Europe considering RCP4.5 and RCP8.5 scenarios and comparing the results to 1971–2000 [51]. The authors described the conditional probability that large hail (hailstones larger than 2 and 5 cm) will also occur if lightning occurs to monitor the evolution of the fraction of storms that produce a hazard. The study did not model absolute frequencies per location per year, but relative increases under similar lightning conditions for future climate scenarios. They found that historically, hail events with hailstones diameters larger than 2 cm could be observed 0.4–0.8 times per year if lightning occurred at both sites, and 0.07–0.14 times for hail larger than 5 cm (with models diverging). For Laujar (2071–2100), the probability of hail over 2 or 5 cm increases by 20%–40% for both scenarios. In Hatzenport, the model ensemble showed a 10%–40% increase under RCP4.5 and 40%–80% under RCP8.5.

Fixed-tilt PV modules installed above vineyards could provide a degree of hail protection as a physical barrier. However, in tracked APV systems, automated operation strategies must be considered, as the tracking controller may move the PV modules to a stow position during hail events [52]. Since PV modules typically require hailstones significantly larger than grapes to cause damage as their design aims a withstanding at least 11 impacts of hail stones larger than 25 mm according to international product qualification standards [53, 54], maintaining the PV modules in a protective orientation during small to medium hail events might achieve protective effects without increasing risks to the APV system.

3.2.3 | Monthly Trends: Temperature (CMIP6)

Figure 5 shows the 10-year moving average monthly averaged ambient temperatures in °C for Laujar, Spain, and Hatzenport, Germany, according to the SSP5−8.5 scenario for 2015 until 2100 [36, 37]. The first value shown in Figure 5 is for the year 2024 due to the calculation of the 10-year moving average. In Laujar, around 7°C in January between 2015 and 2030 and around 25°C in July between 2015 and 2030, can be observed, which are predicted to rise up to around 8°C in January and 29°C in July in 2099. In Hatzenport, summer average temperature between 2015 and 2030 was around 19°C–20°C, but average temperatures of up to 28° are expected by the end of the century according to the SSP5−8.5 scenario. Additionally, the period of months with average monthly temperatures exceeding 21°C is projected to extend into earlier months of the year. If the cold winter periods are too short, the vines may no longer be able

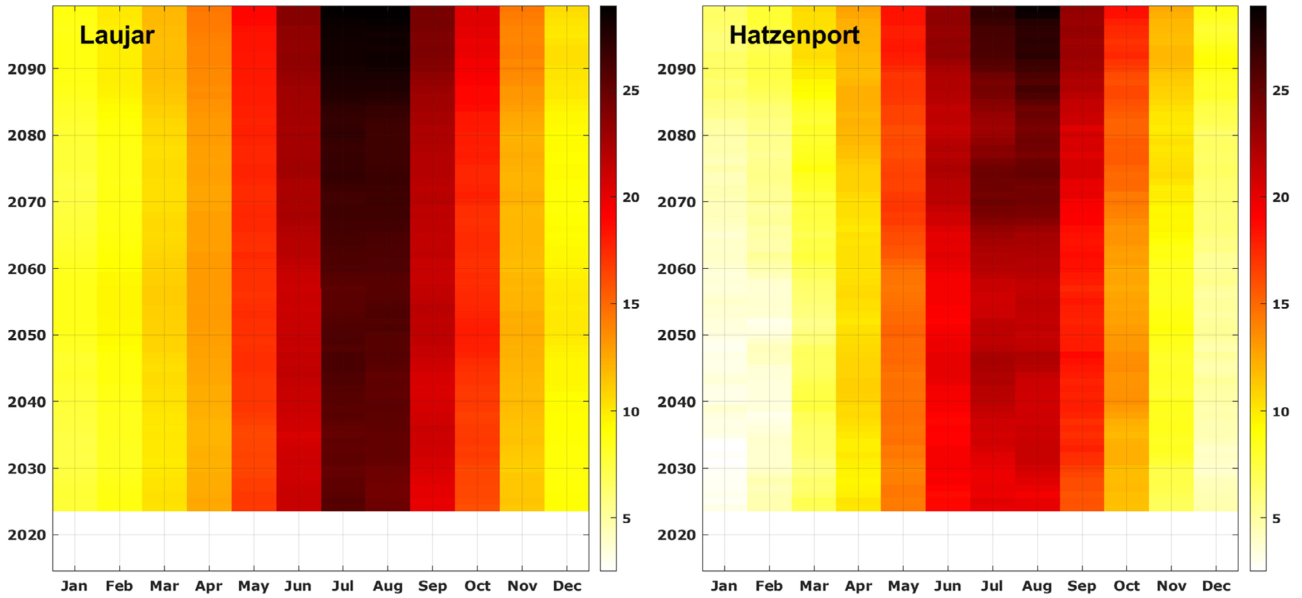

FIGURE 5 | 10-year moving average of monthly averaged ambient temperatures in °C for Laujar, Spain (left) and Hatzenport, Germany (right) according to the SSP5–8.5 scenario for 2015–2100..

to fully enter their winter dormancy. Without sufficient cold stimuli, physiological processes remain active for too long, which can lead to irregular or delayed budding in spring, lower resistance to late frost and overall lower vitality and yield stability. Sufficient winter dormancy is important to reset the growth cycle and ensure uniform development in the following season [3].

In Figure 6, the monthly temperature difference ΔT in comparison to 2024 for the 10-year moving average of the monthly averaged ambient temperatures in°C according to the SSP5–8.5 scenario for 2024–2100 for both sites is displayed. It can be seen that a greater increase of monthly temperatures is expected under this scenario for Hatzenport (around 3.1°C in winter and 8.7°C in summer months) in comparison to Laujar (around 1.1°C in January and 4.4°C in summer/autumn months).

3.2.4 | Monthly Trends: Grape Phenology and Frost Days (EURO-CODEX)

The timing of the phenological stages, such as budburst, is closely related to frost risk, making its relationship with the probability of late frost an important aspect of climate impact studies in agriculture. We analyzed the current knowledge from literature about temporal shifting of phenological stages for grapevine with respect to climate change by looking at modeled results about the expected grapevine budburst period considering the RCP8.5 scenario for Europe [55]. We extracted the corresponding model results for the two sites of interest of this study, Laujar and Hatzenport, and compared them in Figure 7. The phenological data for Laujar and Hatzenport show clear differences between the

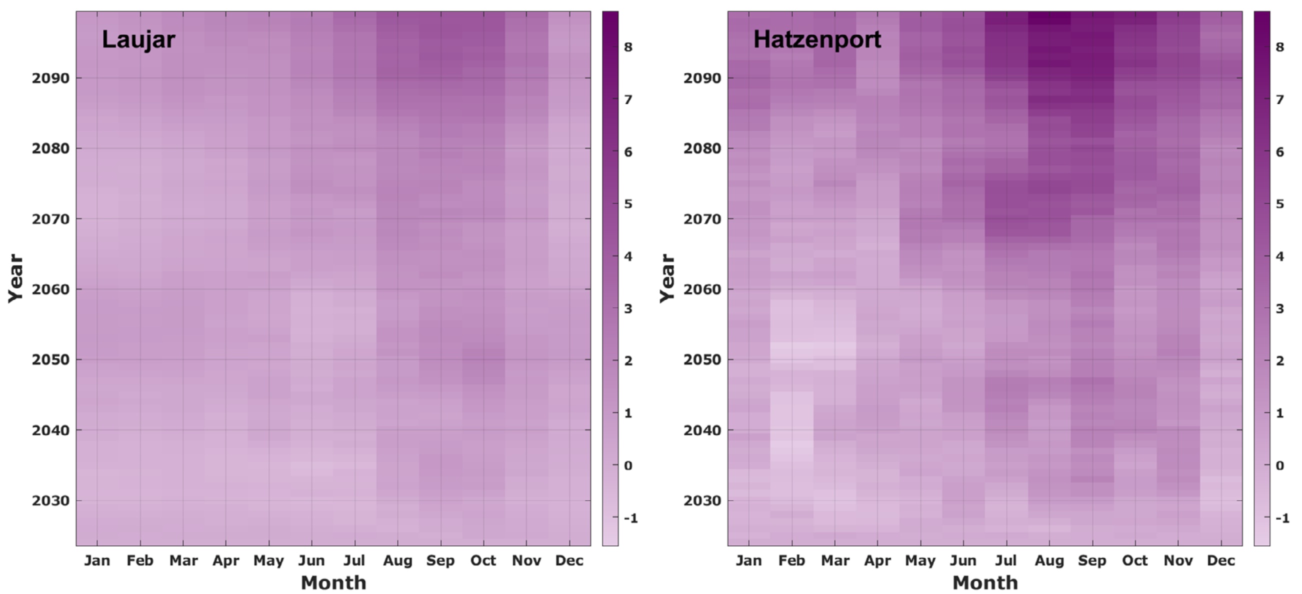

FIGURE 6 | Monthly temperature difference ΔT in comparison to 2024 for the 10-year moving average of monthly averaged ambient temperatures in °C for Laujar, Spain (left) and Hatzenport, Germany (right) according to the SSP5–8.5 scenario for 2024–2100.

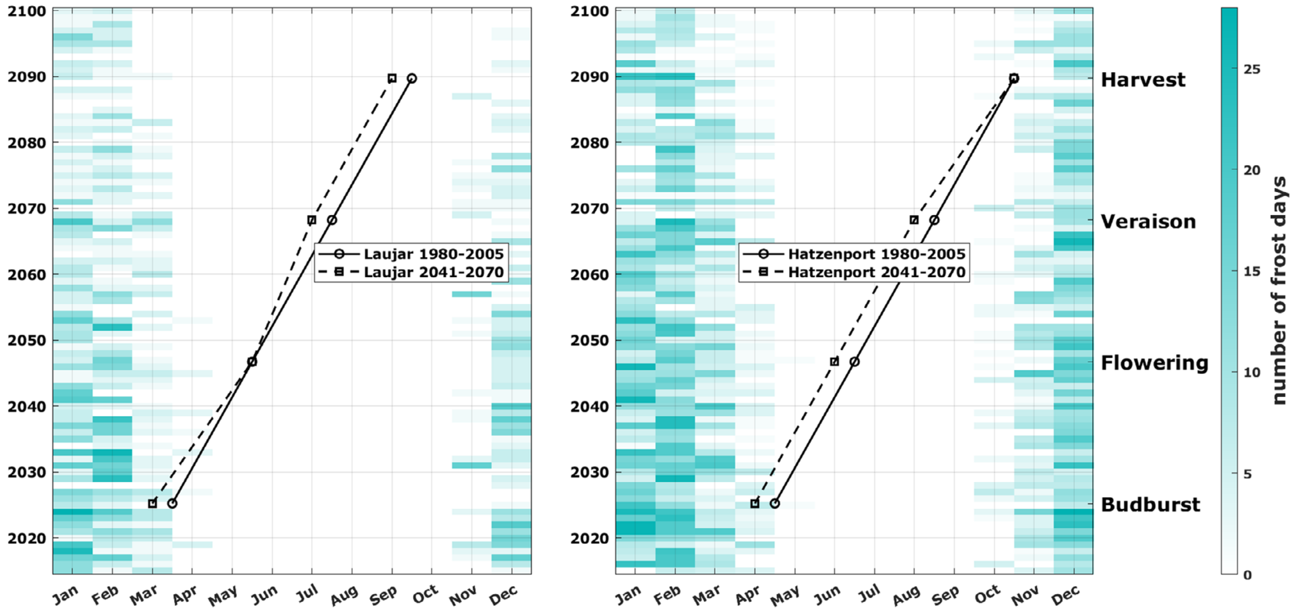

FIGURE 7 | Expected grapevine phenological stages (black curves) for the period 1980–2005 (solid line) and 2041–2070 (dashed line) extracted from [44] considering the RCP8.5 scenario for Laujar, Spain (left) and Hatzenport, Germany (right). The heatmap shows the predicted number of frost days per month and year according to the RCP8.5 scenario [38, 39].

historical period of 1980–2005 and the projected future period between 2041 and 2070. The projections indicate a consistent shift of grapevine phenology in both regions due to changing climatic conditions which is shown in Figure 7. Historically, budburst occurred between 15 March and 1 April in Laujar and between 15 April and 1 May in Hatzenport. Under the future projection with the RCP8.5 scenario, it is expected that budburst will occur 10–20 days earlier on both sites in 2070. A similar shift is expected for most other phenological stages like flowering in Hatzenport (historically from 10 to 20 June), veraison (historically between 20 and 30 July in Laujar and 20–30 August in Hatzenport) and harvest in Laujar (historically between 15 and 30 September). In Laujar, no shift in flowering (20–30 May) and in Hatzenport, no shift in harvesting time (15–30 October) is projected.

This result is in line with literature analyzing the regional climate and phenological stages of different grapevine varieties between 1951 and 2005 in Southwestern Germany [43]. It has been found that budburst and flowering dates shifted already between 1951 and 2005 to about 2 weeks earlier. Similar results are also documented in other studies [56]. According to literature [43], accumulated degree days (measure of a cumulative temperature deviation per day from a reference temperature for crop growth) in March, the mean daily maximum temperature in April, and the number of frost days from January to March mainly drive the budburst. Flowering dates correlated best with accumulated degree days in April and May, the mean daily maximum temperature in June, and the date of budburst.

In Figure 7, we derived the number of frost days (definition see Table 4) from 2015 until 2100 according to the EURO-CORDEX projection [38, 39] and combined them with the temporal shift of phenological stages of grapevine. To clarify if the reduced likelihood of late frost events until 2100 fully offset the effect of earlier budburst dates (see Figure 7), we calculated the frost day sum for the growing periods per year, which are expected under the RCP8.5 scenario. The 5-year moving average values are displayed in Figure 8. For Hatzenport, we assumed that the growing period starting with budburst will be from beginning of April until end of October. In Laujar, we considered beginning of March until end of August. It can be seen that the number of frost days decreases until the end of the century. If the timing of the phenological stages does not shift to even earlier dates in the year, the risk of frost during the growing season will likely be reduced according to RCP8.5.

3.2.5 | Annual Trends: Drought Duration (EURO-CORDEX)

Further, the duration of droughts *dd* [38, 39] has been extracted here for the two sites of interest, Laujar and Hatzenport, and is shown in Figure 9. We calculated the 10-year moving average in *dd* per year for each location and the RCP8.5 EURO-CORDEX scenario. With the help of a linear regression analysis, the trend was calculated using projected annual values of *dd* for the period 2015–2100. The result is a trend line describing the multi-year change in *dd* and providing information on the possible long-term development under this climate scenario. The analysis indicates that the duration of droughts is expected to increase for Laujar (but not for Hatzenport) under the RCP8.5 scenarios (Figure 9). Similarly, the simulations [55] from literature also emphasized that water stress will become the key limiting factor for viticulture in Laujar in the future.

3.2.6 | Monthly Trends: Heat Waves and Consecutive Dry Days (EURO-CORDEX)

In this section, the climatological heat waves and consecutive dry days are analyzed (for definition, see Table 4). The monthly heat waves and consecutive dry days length under the RCP8.5 scenario have been extracted for the locations of interest from the available datasets [38, 39]. We calculated the 10-year moving averages for the period of 2015 to 2100 and for each month of the year. In Figure 10, the results are shown for the months May to

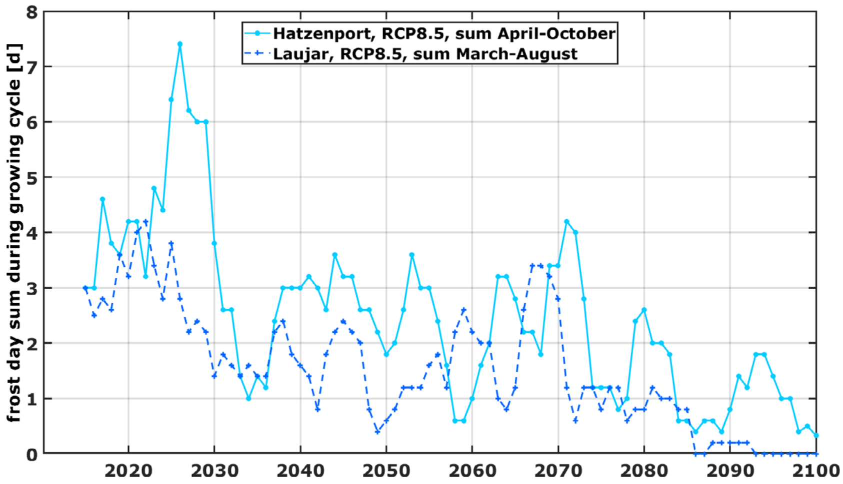

FIGURE 8 | Expected sum of frost days during growing cycle (April to October for Hatzenport and March to August for Laujar) considering the RCP8.5 scenario for Laujar, Spain (solid light blue line) and Hatzenport, Germany (dashed dark blue line).

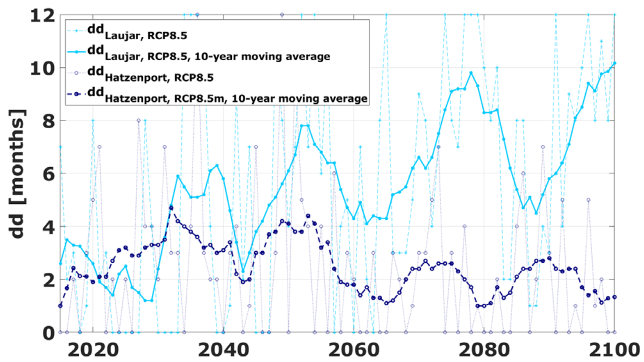

FIGURE 9 | EURO-CORDEX climate projections for 2015–2100. Drought duration dd [38, 39] for the RCP8.5 scenario extracted for Laujar, Spain (light blue colors) and Hatzenport, Germany (dark blue colors).

August. The RCP8.5 scenario shows that the probability of longer consecutive dry days is likely to increase across the months May to August in Laujar, with the most pronounced increase expected in June and July by 2100. Furthermore, the probability of more than 5 heat waves in July and August is projected to rise from approximately 2065 onwards, with a noticeable increase in June starting around 2085. In Hatzenport, no clear trend is observed for increasing probabilities of consecutive dry days during grape growing season. However, the RCP8.5 scenario indicates a rising probability of more than 3 heat waves in August starting around 2055 and in July starting around 2067.

3.3 | Crop Yield and Quality

The analysis of the amount of wine produced (l ha^{-1}) for Germany and Spain [41] as well as the grape yield (t ha^{-1})

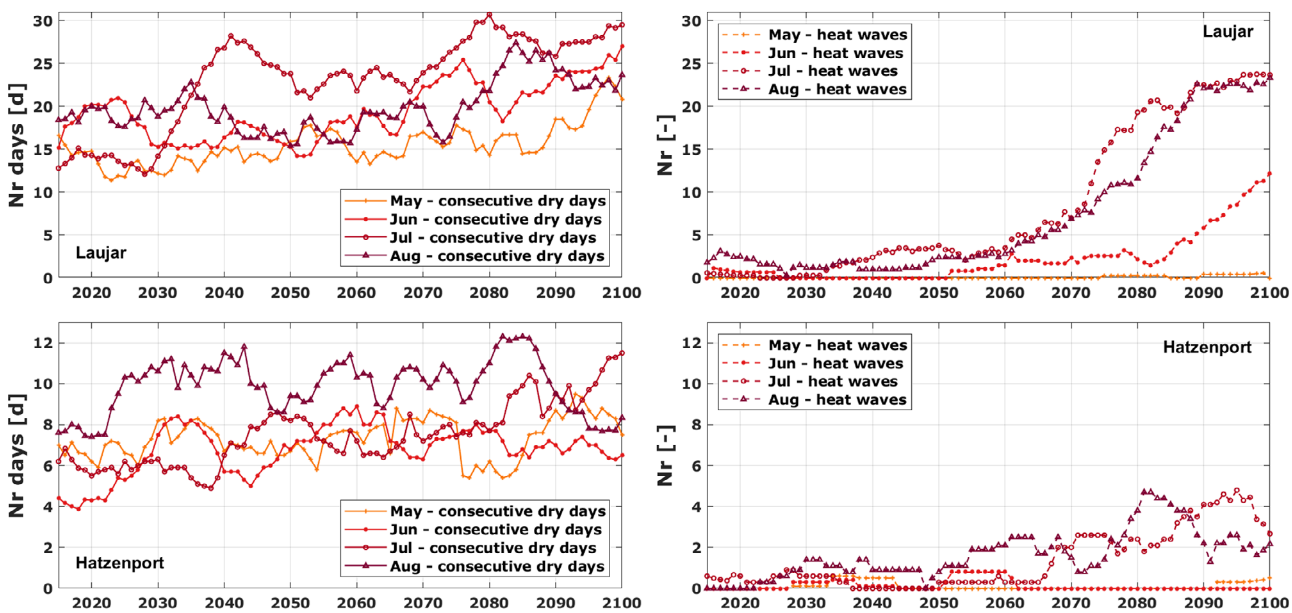

FIGURE 10 | 10-year moving averages of consecutive dry days and heat wave days for the months from May to August in the years 2015–2100 for Laujar, Spain (upper plots) and Hatzenport, Germany (lower plots) under the RCP8.5 scenario [38, 39].

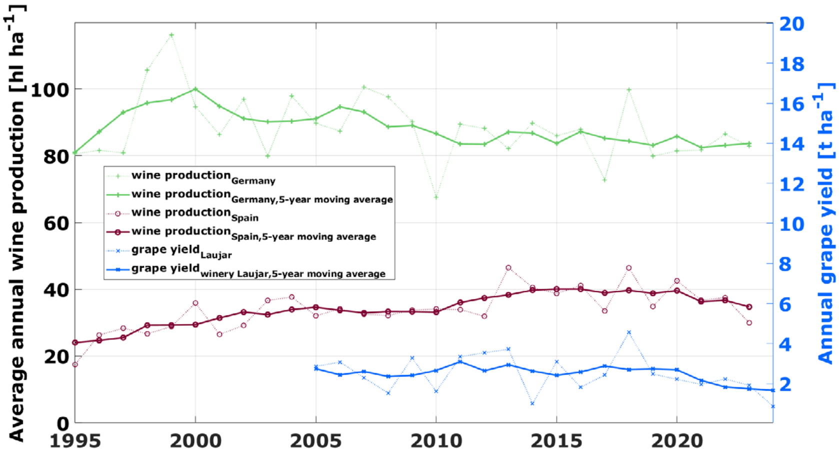

FIGURE 11 | Wine production for Germany and Spain [41] (left *y*-axis) and grape yield for the analyzed vineyard in Laujar, Spain (right *y*-axis) [40] and 5-year moving average of wine production for 1995 until 2024 and grape yield for 2005 until 2024.

for the vineyard in Laujar, Spain (Cortijo del Cura) [40] is shown in Figure 11 together with the calculated 5-year moving average on a comparative plot illustrating the variability of yields from year to year. The analysis of the temporal evolution of yield data in this manuscript demonstrates that the observed trends already reflect the influence of a changing climate. Both for Germany and Spain, the 5-year moving average in wine production per hectare seems to slightly decline since 2015 (Spain) and since 2000 (Germany) with a few outliers in specific years. A similar trend behavior can be observed for the vineyard in Laujar, where a trend decline can be observed since 2012. In 2018, higher wine yields have been achieved both in Germany and Spain. This is mainly due to the early high temperatures in Germany in combination with enough soil water content from the previous year in Southwestern Germany where most vineyards are located and few precipitation events which decreased the risk of plant diseases [3]. In Spain, temperatures were milder in 2018 in comparison to 2017 and above average precipitation in 2018 favored an increase in grape and wine yield.

The analysis shows that production trends vary for the different locations and from year to year. These differences can be attributed to differences in climatic conditions and management practices. The observed trends could be caused by the here discussed changing climatic conditions (e.g., shorter growing seasons or late frost events) at the respective locations. However, other factors could also play a role. In order to achieve higher yields, some winegrowers in Germany carry out targeted pruning to improve quality, which leads to lower yields per hectare. Also, a change in cultivation philosophy could play a role. More and more grape varieties with lower yields may also be cultivated in Germany, which are suitable for higher-quality wines. A possible more pronounced quality-oriented viticulture deliberately strives for lower yields. These aspects could have a combined effect on the previously falling yields per hectare in Germany compared to the still more yield-oriented growing regions in Spain. It should be noted that yield data are provided for descriptive purposes only. Due to the strong site and variety specificity of existing yield-climate models [57–59], this study does not attempt to directly attribute yields to specific climate variables.

4 | Discussion

4.1 | Viticulture Under Future Climates Without APV

The here presented analysis shows that changes in rainfall pattern might increase droughts in Spain, making irrigation often essential. On the other hand, Germany might experience potentially similar or more rainfall. Heavy rainfall events might come with a higher risk of erosion and fungal diseases, e.g., by causing lesion in the berry skin, which increases the risks for yield losses due to rot [60]. In Spain, extreme weather events like heat waves and prolonged droughts might be more pronounced, while in Germany, late frosts, heavy rainstorms, and altered rainfall patterns can pose significant risks for wine cultivation. Further, the risk of sunburn, especially for white varieties, has to be considered.

The traditional warm-climate grape varieties in Spain might not be fully adaptable to further heat stress. In Germany, cool-climate varieties like Riesling might suffer, and climate change might require a greater flexibility to introduce new varieties [3, 56]. Spain might suffer from higher wine production costs due to irrigation and adaptation measures, and Germany might have potential economic benefits from higher yields compared to Southern Europe [3]. On the other hand, in viticulture, the origin of a wine is closely linked to the grape variety. While the introduction of more heat-tolerant varieties in Germany could represent an adaptation strategy to climate change, the market acceptance of such products remains uncertain.

Young vines in viticulture are particularly sensitive to the effects of climate change because they are not deeply rooted and are therefore more susceptible to drought stress, water stress, extreme temperatures, and excessive solar irradiance. Consequently, establishing new vineyard plantations will heighten the risks involved in managing the field sites.

Different soil characteristics in both countries alter the possible climate change effects, e.g., in Spain, often dry limestone-rich soils are present with poor water retention, while in Germany, more fertile soils with better water-holding capacity might be advantageous during droughts. On the other hand, the steep-slope vineyards in Germany, where soils have only limited water-holding capacity and deeper layers consists of rocks may be particularly vulnerable to droughts [61]. Even if other varieties may appear in the Riesling area in the future, it is important to consider the close relationship between the adaptability of the variety and the quality of the soil, a direct transfer would have to be done with careful consideration.

Specifically, in Laujar, the plot of Cortijo el Cura has a calcareous soil with a certain amount of gypsum, but also a high proportion of sand. The soil is loose and has a structure that is not very compacted due to the sand content, although it can easily become compacted during prolonged rainfall. It is necessary to increase water retention in the soil and to protect the soil and provide it with sufficient organic matter to store the water necessary for optimal plant growth [40]. In Hatzenport, the soils consist of clay and silty slate, often interspersed with limestone, quartzite, or sandstone, which comes with a higher water retention capacity [62].

Our findings are consistent with observations from the last century described in the literature. By the end of the 20th century, signs of climate change, such as rising temperatures, more frequent heat waves, and changing precipitation patterns, were already visible.

It has been found [43] that the meteorological conditions, especially concerning sunshine duration, number of days without frost, and mean temperatures for white wine cultivation, surpassed on average the required minimums between 1951 and 2005 in the Upper Moselle region. Further, it has been observed that the budburst and flowering date shifted to earlier dates (on average 2 days per decade) [43]. Similar trends have been found worldwide [3]. Earlier growing and ripening season comes with higher temperatures during the growing season which typically leads to increased alcohol and pH levels and decreased acidity [3]. Analyzing [63] the spatial and structural shifts for viticultural potential for five different regions in France, Germany, Spain, Romania and England due to climate change dynamics between 1951 and 2010, it has been found, that in Bordeaux (France) climatic conditions shifted toward favorable conditions for Mediterranean varieties and in the Rhine–Main–Nahe region in Germany, where traditionally white wine has been produced, climate has become also suitable for red varieties. In all studied regions, the climate suitability for viticulture shifted to higher altitudes. Therefore, wine regions with higher topography allow for better climate change adaptation.

It has been found [3], that coastal and lowland regions of Spain, which can still be considered suitable for viticulture, might be at high risk of unsuitability with high confidence levels for a global warming scenario of 2°C–4°C until 2100. In the currently suitable region of the Rhine and Moselle rivers, the suitability of viticulture might be improved (medium confidence) for a 2°C global warming, while there might be a slight risk for unsuitability (low confidence) for 2°C–4°C until 2100.

Investigating [64] the water availability in vineyards in five different wine cultivation regions worldwide with respect to rising average temperatures due to climate change and the assumed changes in evapotranspiration, the author concluded that the consequences of global climate change scenarios has to be investigated individually for each region because the complex evapotranspiration processes are individually influenced not only by potentially higher evaporation due to higher ambient temperatures, but also by altered precipitation conditions at the different locations. We assessed the climate change impacts on water availability at a regional scale by comparing two different locations, and our results support the conclusion of the study [64].

4.2 | APV Potential to Mitigate Climate Change Effects on Microclimate in Viticulture

This section evaluates the potential of APV systems to mitigate the effects of climate change on vineyard microclimates, which indirectly influence grapevine growth performance. It does not assess their direct impact on yield or grape quality. Several APV installations in vineyards have already been installed, and their performance in terms of crop yield and microclimate changes have been investigated. Those studies are summarized in Section 1, and the studies are also listed in Table A1 in Annex A.

The effect of APV systems or additional shading of the vines on ambient temperature, soil temperature, and soil moisture below the PV modules depends highly on the system design: the height of the mounted PV modules, the area covered (due to boundary effects), and the corresponding airflow below the PV modules and the resulting prevented convection. In the case of low-mounted PV modules and low wind speeds, the average air temperature as well as humidity below the PV modules may be even increased. Therefore, no general conclusion can be derived about the temperature effect of APV systems. On the contrary, however, it has been found that air temperature around agrivoltaic installations is significantly lower than with stand-alone PV systems because of the presence of crops [65].

4.2.1 | Discussion of APV Potential to Mitigate Climate Change Effects Looking at Ambient Temperatures Below PV Modules

Experiments reported in literature (see Summary in Section 1) indicate that most APV installations reduced ambient temperature below the PV panels during summer months, looking not only at grapevines, but also at different crops. But it has to be noted that a wide range of temperature reduction is reported due to the high variety of investigated APV system designs, crops, and climatic conditions of the experiments.

In Section 3.2.2, the monthly average temperature difference for the SSP5−8.5 scenario in comparison to the year 2024 is presented (see Figure 6). To compare the theoretical APV potential to mitigate temperature increase due to climate change, we calculated the average temperature difference ΔT of the summer months May, June, and July for the periods 2030–2039, 2060−2069, and 2090−2099 for both locations and the SSP5−8.5 scenario. For Laujar, the projected temperature difference in comparison to the year 2024 during the summer months is projected to be −0.08°C, 0.95°C, and 2.92°C for 2030–2039, 2060−2069, and 2090−2099, respectively. For Hatzenport, the temperature increase is modeled to be 0.72°C, 2.47°C, and 6.04°C. It can be seen in Figure 12, that predicted temperature increase during summer months until 2099 in Laujar might be possible to be compensated with the help of adequate APV systems for some studies analyzed [16, 18, 20]. For Hatzenport, higher temperature increases are modeled until the end of the century and a theoretical temperature reduction below APV systems might not be sufficient, considering experimental data from different studies in literature.

It has to be noted that the publications considered in Figure 12 reported on temperature reductions; however, the underlying variables were not consistent across studies. Some analyses focused on maximum daily temperatures for summer months

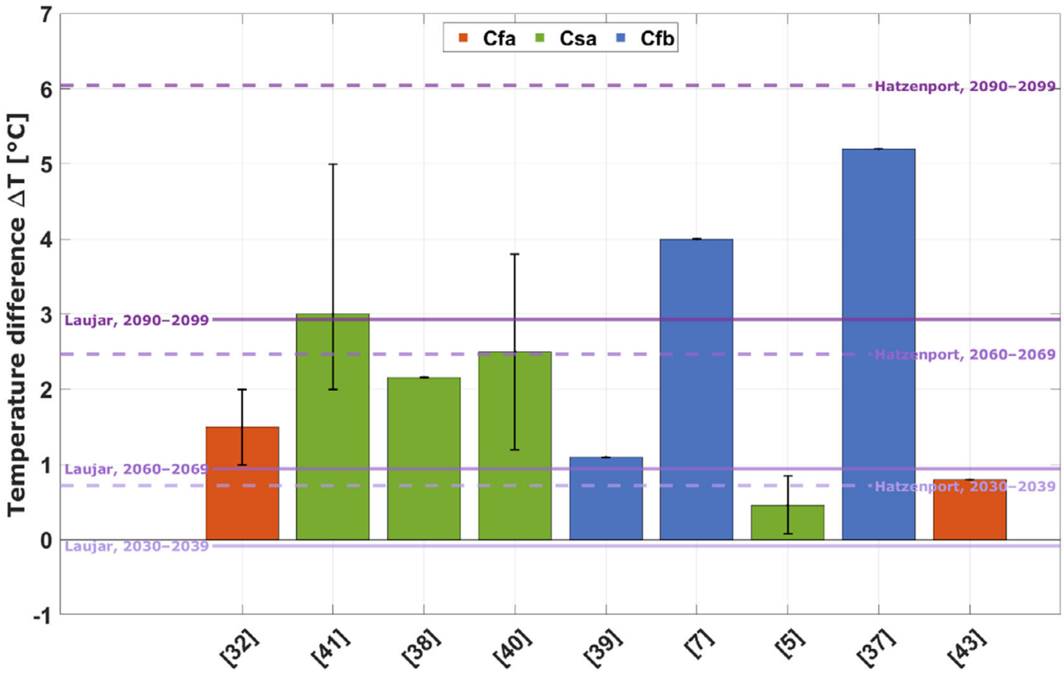

FIGURE 12 | Temperature reduction below APV systems reported in different publications found in literature (vertical bars). Temperature ranges given in literature are marked with vertical range bars. Average summer months (May, June, July) temperature difference ΔT (horizontal lines) in comparison to 2024 under the SSP5–8.5 scenario for Laujar (solid line) and Hatzenport (dashed line) for the periods 2030–2039, 2060–2069, and 2090–2099. Filling color of the bars is according to the Köppen-Geiger climate classification [44]..

[8, 9, 21], while others did not specify and referred to general ambient temperatures [20], daily ambient temperatures above 35°C [16], or daily mean air temperatures [17]. Other methods included evaluating temperatures near solar noon (±2 h, June through late August) [6]. Therefore, comparative values do not always refer to the same temperature index and should be taken into account when interpreting the results.

This theoretical analysis focuses only on temperature increases, mostly during the summer months. In reality, there are many other factors at play. During the colder months, temperatures underneath APV installations may increase, which can provide frost protection but may also alter plant phenology in other ways. Further, irradiance levels at crop/canopy level are changed by APV systems. In addition, the actual mitigation potential of an APV system is highly dependent on the system design and local meteorological conditions. Generalizations are not feasible due to the limited number of data points in the literature covering different designs and locations.

4.2.2 | Discussion of APV Potential to Mitigate Climate Change Effects Looking at Other Microclimate Parameters Below PV Modules

Other microclimate and water balance parameters (soil temperature, soil humidity, water retention, irradiance availability) are also affected by APV installations. A brief overview of results from literature is presented in Section 1, and these effects are not analyzed here specifically, but are briefly discussed. Based on these insights, the question of how to ensure water availability will become increasingly important, particularly given greater variability in precipitation due to climate change. This highlights the need for methods to efficiently manage rainfall in APV systems by, e.g., smart tracking solutions or water collection systems, addressing both more frequent and longer drought periods (Spain) and intense rainfall events (Germany). Water recycling and treatment will also play a significant role. If APV installations over vineyards can help to reduce drought stress in vineyards, especially in step terrain, or if such systems might increase soil erosion processes due to increased concentrated rainwater run-off, has to be still investigated in detail.

Due to the complexity of vine growing conditions for different grapevine varieties and their ability to adapt to altered light availability, the impact of APV systems above vineyards, especially regarding yield and quality of primary and secondary compounds, is still not fully understood [12, 27, 65, 66]. Long-term field studies are still necessary to evaluate the potential impact of APV systems on the vine, particularly for white and red wine production. The results published so far from APV experiments worldwide show a reduction in both ambient and soil temperature, as well as a positive effect on soil moisture below the PV modules. However, APV shows potential to partially mitigate the expected temperature increases in the context of climate change, especially in hot and dry regions like Southern Spain.

4.3 | Implementation of APV in Existing Vineyards and Economic Considerations

Not considering new PV technologies with higher module efficiencies and smarter tracking algorithms, it is expected that the electricity generation of APV systems will slightly decrease over the investigated time interval till 2100 due to the relatively consistent projected GHI combined with higher ambient temperatures and hence lower PV efficiencies. Hence, technologies for cooling the modules may become increasingly important.

Similar life expectancies of grapevines and APV installations allow for coordinated long-term planning. Since the type and dimension of machinery typically remain constant over the lifetime of the vineyard, the design of the APV structure and its components can be adapted accordingly. Further, the support structure of the APV system might also be used for the vineyard trellis system [14, 27].

On the other hand, social acceptance could be challenged, as the traditional viticultural landscape is usually highly valued by society [67]. While discussing the integration of APV systems in winegrowing regions, it is also necessary to consider the social acceptance of the visible changes to the landscape [68], as in several regions, ground-mounted PV installations already provoked protests [69]. On the other hand, a recent study on social acceptance of integrated trellis-based configurations of APV systems in South–Eastern Spain found that 94% of surveyed wine tourists supported integrating solar panels within vineyard trellises. Especially low-height, trellis-integrated APV designs were preferred for their landscape compatibility [70].

To ensure that especially young vines take root in the field and to address the challenge of social acceptance, temporary protection systems to provide shading and evaporation protection might help to bridge the critical rooting stage and ensure the long-term viability of the vines. In the "VitiCULT PV-mobil" pilot project [13], a mobile APV system is being developed that uses PV modules that can be easily assembled and disassembled to provide shade and protection for young vines. Due to the modular and lightweight design, the system is flexible enough to move between new planting areas, while the module's auto-retraction feature provides extra security in strong winds.

In an economic performance of agrivoltaic systems in German vineyards, the authors found that APV systems for vineyards are under current boundary conditions in Germany not economically viable [27]. Revenues from grape and energy production cannot cover the high investment costs. Nevertheless, factors like premium wine pricing, higher electricity prices, e.g., due to falling land availability for conventional PV parks and benefits due to increased energy self-consumption have not been included in this feasibility study [27]. Further, a rather conservative high assumed yield reduction has been considered in this study. The authors highlight that further long-term experiments are necessary to evaluate the viticultural impacts and synergistic benefits between renewable energy and sustainable agriculture.

5 | Conclusion

In viticulture, APV offers the potential to mitigate climate change-related risks such as heat stress, dry periods, and late frosts by protecting vines from extreme weather conditions and creating more favorable microclimates. At the same time, APV enables the production of renewable energy on agricultural land, thereby conserving resources and mitigating land use conflicts between agriculture and energy production. In practice, APV opens up new adaptation strategies in viticulture by stabilizing yields and quality and reducing operating costs for irrigation and energy. However, current studies also show potentially detrimental effects, for example, on grape quality or ripening time. This leads to the key site-specific question: under what conditions and to what extent the observed effects of APV systems on vines (whether positive or negative) will interact with the increasing impacts of climate change, and when this balance will bring overall benefits to viticulture.

5.1 | Summary Results

The present study examined various challenges that winegrowing regions in Germany and Spain will have to face as a consequence of climate change. Both reanalysis data (ERA5), onsite measurements, and projections from CMIP6 and EURO-CORDEX future scenarios for Laujar in Southern Spain and Hatzenport in Germany were evaluated. Traditional warm-climate grape varieties in Spain may struggle to adapt to increasing heat stress, while in Germany, cool-climate varieties like Riesling could face challenges as well. Although climate change may create opportunities to introduce new grape varieties, the overall impact remains uncertain. Ensuring long-term water availability will become increasingly important, particularly given greater variability in precipitation. This highlights the need for advanced methods from breeding to the management of the vineyards to efficiently manage rainfall, e.g., with the help of APV systems, addressing both more frequent drought periods (Spain) and intense rainfall events (Germany).

Current results show that reduced air and soil temperatures and improved soil moisture levels can be expected under PV modules in APV systems. The extent of the cooling effect varies depending on APV system design, climatic conditions, and grapevine adaptation. It has been found that the moderate predicted increase in temperature at Laujar can be mitigated by proper APV design, while the higher increase in temperature at Hatzenport may exceed the current potential, according to the experimental results found in literature. Results vary by site and design, and generalizations are limited by the scarcity of data, but APV can be a promising technology to mitigate increasing heat, especially in already in hot and dry regions. The results of this study also show that APV systems can be used to flexibly adjust crop management in viticulture to achieve optimal yield levels and ensure stability of harvest, despite the projected time shifts of the phenological stages.

5.2 | Limitations of the Study and Future Research Directions

Although initial investigations are promising, systematic long-term studies to understand the interactions between APV and vine physiology, grape quality, water, and soil balance and biodiversity in different climate zones are still lacking. Further research applying standardized methods for measuring yield, the impact on microclimate and water use efficiency is needed to fully assess the potential of APV. Comparable databases are essential to establish APV as a sustainable adaptation strategy in agricultural environments. In addition, socioeconomic analyses are needed on the acceptance, economic viability, and optimal integration of APV into existing operations. Future research should therefore combine both experimental and model-based approaches in order to develop site-specific recommendations for the implementation of APV in viticulture and to determine the point at which APV systems achieve net positive effects under progressive climate change.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] Familia Torres launches agrivoltaic pilot installation in the Penedès as part of the SOLARWINE project | Familia Torres | Familia Torres launches agrivoltaic pilot installation in the Penedès as part of the SOLARWINE project | Familia Torres |

[2] Photovoltaikmodule im Weinbau: eine Antwort auf die Herausforderungen des Klimawandels - Interreg

[3] Tecnología - Agritechnovoltaics - Powerfultree

[4] Iberdrola España to build the first agrovoltaic system to boost apple cultivation in the Basque Country - Iberdrola España

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APPENDIX A

TABLE A1 | List of studies from literature providing information on the effect of APV systems in microclimate.

Ref.	Location	Years	Köppen–Geiger classification [44]	Crop variety	APV/PV configuration	Observed impact on microclimate	Impact of APV system on crops
[9]	Veneto, Italy	2017–2019	Cfa	Vitis vinifera L. cv. Riesling	fixed-tilt south-oriented APV system, 75% shading ratio, 0.015ha	lower air temperature; lower soil temperature; reduced water stress; higher transpiration	yields and quality parameters slightly reduced (−20% yield)
[10]	Puglia, Italy	2023	Csa	Vitis vinifera L. cv. Riesling	fixed-tilt south-oriented APV system, 43% ground cover ratio	increased soil moisture and moderate soil temperature; little effect on air temperature; reduced wind speed	+277% yield
[11]	Incheon, South Korea	2021–2022	Dwa, Cwa	Vitis labruscana L.	fixed-tilt APV system, parallel to vines, ~30% ground cover ratio	reduced wind speed; reduced soil temperature	no significant difference in carbohydrate storage, budding, shoot growth, grape weight, sugar content or acidity; harvest delayed by about 7–10 days

(Continues)

TABLE A1 | (Continued)

Ref.	Location	Years	Köppen–Geiger classification [44]	Crop variety	APV/PV configuration	Observed impact on microclimate	Impact of APV system on crops
[12]	Montpellier, France	2018–2019	Csa	Vitis vinifera L. cv. Syrah	2 m-wide horizontal PV panels placed 2.4 m above ground, ~50% shading ratio	not significantly modified air temperature	delayed veraison by up to more than 30 days under well-watered conditions
[15]	Westmill Solar Park, UK	2013–2014	Cfb	–	fixed-tilt PV park, 12.1 ha	5.2°C reduction in summer, 1.7°C increase in winter; diurnal variation in both temperature and humidity during summer was reduced	above ground plant biomass + species diversity lower under PV arrays; photosynthesis and net ecosystem exchange in spring + winter lower under PV arrays
[16]	Adelaide, Australia	2012–2014	Csa	Vitis vinifera L. cv. Syrah (Shiraz)	only shading treatment, no PV or APV system	daily ambient temperature reduction of up to 2.16°C on days with temperatures above 35°C	higher chlorophyll concentration in leaves; higher net CO_2 assimilation at saturating light; higher midday stem water potential but similar sap flow and leaf transpiration
[17]	Hegelbach, Germany	2017–2018	Cfb	winter wheat, potato, grass-clover	fixed-tilt angle of 20°, row width 3.4 m, row distance 6.3m, clearance height 5 m, 0.3 ha	soil temperature decreased under APV in summer; soil moisture + air temperature reduction; altered rain distribution; mean daily soil temperature reduction under APV of about 1.2°C in 2017, 1.4°C lower in 2018; soil temperatures reduction by ~1.2–1.4°C; ~2%–3% soil moisture increase	yield −19 to + 3% for winter wheat, −20 to + 11% for potato and −8 to −5% for grass-clover in 2017; in hot and dry summer of 2018 --> crop yields increased by AV by 2.7% (winter wheat) and 11% (potato)
[18]	La Pugére, France	2019–2021	Cfb	Apple trees	tracked APV system, variable shading between 4% and 88% during the day, mean shading rate 50%–55%, 5 m height, 1.5 m above the top of the apple trees	daily temperature reduction of 1.2°C to 3.8°C; relative 14% humidity increase; irrigation decrease between 6% and 31%	higher proportion of trees bearing fruit (+31%) under PV panels; higher number of fruits per fruit-bearing tree (+44%) in 2021; fruit size less sensitive to shading than fruit number; fruit size reduced by 17% in 2019 but maintained in 2020 and 2021 probably due to better water status
[19, 20]	Durance Valley, France	2019–2021	Csa	Apple trees	SunAgri's dynamic APV system, 4.5 m elevated	ambient temperature reduction by 2–4°C	–

(Continues)

TABLE A1 | (Continued)

Ref.	Location	Years	Köppen–Geiger classification [44]	Crop variety	APV/PV configuration	Observed impact on microclimate	Impact of APV system on crops
[21]	Chikusei, Ibaraki, Japan	2018–2023	Cfa	Rice (Oryza sativa L.)	27% ground cover ratio	maximum air temperature reduction by 0.8°C; no difference for minimum air temperature	grain yield decreased by 23%
[8]	Geisenheim, Germany	2023	Cfb	Vitis vinifera L. cv. Riesling	fixed-tilt APV system, 50% transparency, 3 m height	air temperature reduction up to 4°C lower during daytime in summer, night temperatures same or even slightly increased; higher temperatures on cooler/cloudier days; increased soil moisture levels	no sunburn damage if grapes under APV system, 13% of grapes affected in control area, with average damage level of 20%; significantly lower Botrytis infestation under APV system
[6]	Laujar, Spain	2025	Csa	Vitis vinifera L. cv. Merlot	fixed-tilt south-oriented APV system, 38% ground cover ratio, checkerboard pattern, 0.012ha	ambient temperature around solar noon (+−2 h) 0.5°C reduced between June and end of August; higher volumetric water content	results not yet available
[22]	Wuwei in Gansu Province, China	–	BSk	–	fix-tilt south-oriented PV system, only simulation	Soil moisture content increased by 59.8%–113.6% in Middle and Front zones; soil temperature decreased by 1.47–1.66°C in intermittent shade	–
[23]	Montpellier, France	2010–2011	Csa	lettuces – Lactuca sativa spp., durum wheat (Triticum durum L.), cucumbers (Cucumis sativus L.)	fix-tilt south-oriented APV system, 50%, 70% and 100% shading ratios	Soil temperatures reduced by ~0.5–2.3°C; mean daily air temperature and humidity similar	same growth rate for lettuce and cucumber under APV system, but lower growth rate at the beginning of plant life cycle
[24]	Minnesota, USA	2019–2021	Dfa / Dfb	native grasses	utility-scale solar PV facility	air temperature and relative humidity similar; lower wind speeds	–