A Surface Energy Balance Model for Agrivoltaic Applications in Arid Regions

Isabela Lima Ribeiro Walter

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A Surface Energy Balance Model for Agrivoltaic Applications in Arid Regions

by

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at

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Abstract


The co-location of photovoltaics (PV) and agriculture - Agrivoltaic (APV) system - is an economically viable solution to address the land competition between two distinct productions and simultaneously maximize energy harvesting and agricultural yield. APVs are expected to possess the greatest results in arid regions where the solar resource is potential and there is a need for marginal land regeneration and improvements in food production. Particularly, APV systems can modify surface heat fluxes by increasing latent heat flux and consequently reducing sensible heat flux, which is expected to enhance PV panels' performance and boost crop productivity.

This thesis simulates dynamical Agrivoltaic Energy Balance (APV-EB) to assess the potential of conventional photovoltaic technology compared with its performance in the bare soil scenario. The model is parameterized for the UAE’s characteristic climatic conditions. One of the significant limiting climatic factors that compromise photovoltaic performance in arid and desertic regions is extreme heat, which this project will focus on.

The study concluded that the PV natural cooling from crops under the panels in an APV setup could be a valuable addition to improve PV thermal behavior and, consequently, power yield.

Indexing Terms: Agrivoltaic, photovoltaic, crop, quinoa, energy balance, sensible heat, latent heat, evapotranspiration, power.
Acknowledgment

In the first place, I am grateful to God for allowing me to keep in physical and mental health to complete this thesis work.

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Declaration and Copyright

Declaration

I declare that the work in this thesis was carried out in accordance with the regulations of Khalifa University of Science and Technology. The work is entirely my own except where indicated by special reference in the text. Any views expressed in the thesis are those of the author and in no way represent those of Khalifa University of Science and Technology. No part of the thesis has been presented to any other university for any degree.

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Author Signature: [signature]

Date: July 15th 2022

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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Surface area</td>
<td>m²</td>
</tr>
<tr>
<td>(d_l)</td>
<td>Module layer thickness</td>
<td>m</td>
</tr>
<tr>
<td>(\rho_l)</td>
<td>Module layer density</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>(C_l)</td>
<td>Specific heat capacity of module layer</td>
<td>J kg⁻¹ K⁻¹</td>
</tr>
<tr>
<td>(C_{\text{module}})</td>
<td>Heat capacity of PV panel</td>
<td>J K⁻¹</td>
</tr>
<tr>
<td>(T_{\text{module}})</td>
<td>Photovoltaic module temperature</td>
<td>K</td>
</tr>
<tr>
<td>(T_{\text{air}})</td>
<td>Air temperature at 2m</td>
<td>K</td>
</tr>
<tr>
<td>GHI</td>
<td>Global Horizontal Irradiance</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(SW_{PV})</td>
<td>Total shortwave radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>DNI</td>
<td>Direct Normal Irradiance or Beam Solar Radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>DHI</td>
<td>Diffuse Horizontal Irradiance</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(LW_{PV})</td>
<td>Photovoltaic net longwave exchange</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(L_{\text{sky}})</td>
<td>Downwelling longwave radiation as a function of the module's sky view factor</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(L')</td>
<td>Incoming sky longwave radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(L_{PV,\text{top}})</td>
<td>Upwelling longwave radiation output from the top side of the module</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(L_{PV,\text{btm}})</td>
<td>Downwelling longwave radiation output from the bottom side of the module</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(SH_{PV})</td>
<td>Sensible heat flux from the module</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(P)</td>
<td>Power production from the photovoltaic module</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(SW_{cell})</td>
<td>Shortwave radiation transmitted through the glazing and absorbed by the PV cell</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>SVF</td>
<td>Sky view factor</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>GVF</td>
<td>Ground view factor</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>Stefan Boltzmann constant</td>
<td>W m⁻² K⁻⁴</td>
</tr>
<tr>
<td>(\varepsilon_{\text{top}})</td>
<td>Module top side emissivity</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\varepsilon_{\text{btm}})</td>
<td>Module bottom side emissivity</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\varepsilon_{G})</td>
<td>Ground emissivity</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Incidence angle</td>
<td>°</td>
</tr>
<tr>
<td>(\theta_z)</td>
<td>Zenith angle</td>
<td>°</td>
</tr>
<tr>
<td>(\alpha_{\text{r}})</td>
<td>Reflectivity or albedo of the top side of the module</td>
<td>°</td>
</tr>
<tr>
<td>(\alpha_{s})</td>
<td>Ground reflectivity or albedo</td>
<td>°</td>
</tr>
<tr>
<td>(\alpha_s)</td>
<td>Solar altitude angle</td>
<td>°</td>
</tr>
<tr>
<td>(\gamma_s)</td>
<td>Solar azimuth angle</td>
<td>°</td>
</tr>
<tr>
<td>(\gamma_{PV})</td>
<td>Photovoltaic surface azimuth</td>
<td>°</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Tilt angle of the module</td>
<td>°</td>
</tr>
<tr>
<td>(\delta)</td>
<td>Solar declination</td>
<td>°</td>
</tr>
<tr>
<td>(\omega)</td>
<td>Hour angle</td>
<td>°</td>
</tr>
<tr>
<td>N</td>
<td>Day of the year (DOY)</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\phi)</td>
<td>Latitude</td>
<td>°</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Turbulent convection coefficient</td>
<td>W/ K m$^2$</td>
</tr>
<tr>
<td>$Eff_{PV}$</td>
<td>Maximum electrical energy conversion efficiency of the module at standard conditions: reference solar radiation 1000 W/m$^2$ and at 25°C</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>$M$</td>
<td>Air mass modifier</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>$(\pi \alpha)_{dir}$</td>
<td>Transmissivity ($\pi$) absorptance ($\alpha$) product of the module glazing for the direct radiation</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>$(\pi \alpha)_{diff}$</td>
<td>Transmissivity ($\pi$) absorptance ($\alpha$) product of the module glazing for the diffuse radiation</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>$(\pi \alpha)_G$</td>
<td>Transmissivity ($\pi$) absorptance ($\alpha$) product of the module glazing for the ground reflected diffuse radiation</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>$RH$</td>
<td>Relative humidity of the air at 2m</td>
<td>%</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Mean air density at constant pressure</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Water density</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Air heat capacity</td>
<td>J kg$^{-1}$ °C$^{-1}$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Latent heat of water vaporization</td>
<td>J kg$^{-1}$</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Gradient of the saturation vapor pressure with temperature</td>
<td>Pa °C$^{-1}$</td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td>Psychrometric constant</td>
<td>Pa °C$^{-1}$</td>
</tr>
<tr>
<td>$e_{as}$</td>
<td>Actual saturation vapor pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$e_s$</td>
<td>Actual vapor pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$P_{atm}$</td>
<td>Atmospheric pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$z_{ref}$</td>
<td>Reference height</td>
<td>m</td>
</tr>
<tr>
<td>$d$</td>
<td>Zero-plane displacement</td>
<td>m</td>
</tr>
<tr>
<td>$z_{0h}$</td>
<td>Roughness length governing heat and vapor transfer</td>
<td>m</td>
</tr>
<tr>
<td>$r_a$</td>
<td>Aerodynamic resistance from the surface to the air layer at reference height of 2m</td>
<td>s m$^{-1}$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Von Karman’s constant</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>$u_{ref} = u$</td>
<td>Wind speed at a 2m</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$h$</td>
<td>Crop height</td>
<td>m</td>
</tr>
<tr>
<td>$ET$</td>
<td>Potential evapotranspiration</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$\lambda ET$</td>
<td>Latent heat flux</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$R_{net}$</td>
<td>Incident radiation over the crop</td>
<td>W m$^{-2}$</td>
</tr>
</tbody>
</table>
1. Background and Motivation

1.1 Concept and Importance of Agrivoltaic Systems

Agrophotovoltaic or Agrivoltaic (APV) is the co-location of photovoltaic (PV) technologies and crop production simultaneously. Goetzberger & Zastrow (1982) are the pioneers in approaching this combined system. They propose setting a distance between PV rows to achieve nearly uniform radiation and elevate the solar collectors around 2 – 4 m above the ground, allowing workers and machines to circulate below. Figure 1 illustrates the concept of the APV system.

![Figure 1: Schematic of APV system (Dos Santos, 2020).](image)

This innovative system has been proposed as an efficient and economically viable solution for marginal land reclamation, promoting local food security in hot-desert regions (HDRs) and potentially increasing crop yield. At the same time, APV systems exploit their potential for solar power production and successfully implement a decarbonization agenda in drylands by cutting down the emission of greenhouse gases - a primary and anthropogenic cause of climate change, which has become a significant concern of this century. (Adeh et al., 2019; Barron-Gafford et al., 2019; Ravi et al., 2016).

Most of the commercial and experimental APV plants have been deployed in the last few years (Weselek et al., 2019), with the majority of sites placed in the northern hemisphere. Some of the countries that already registered the implementation of APV facilities are located in Europe, such as Italy (Corditec, 2017; Praderio & Perego, 2017), France (H. Marrou et al., 2013), and Germany (Weselek et al., 2019); Asia, such as India (Patel et al., 2018), China (REM TEC, 2017; Tonking, 2018), and Japan (Movellan, 2013); and America, in which USA (Tricole,
2017) and Chile (Fraunhofer, 2017) are instances. Among the diverse range of planted crops are fruits (watermelon), cereals/grains (wheat, maize, rapeseed, beans, rice), and several vegetables (tomatoes, cucumber, lettuce, broccoli, cauliflower, coriander, kale, potato, pumpkin, peppers). Lastly, the usual types of photovoltaic technologies applied are polycrystalline silicon and bifacial PV modules. However, in greenhouse applications, semi-transparent PVs (Yano et al., 2014) and CPVs (H. Apostoleris & Chiesa, 2019) are a trend.

Sustainability is one of the most challenging issues in the current century (Helliwell et al., 2021). In the light of this, the United Nations together with 178 countries developed 17 Sustainable Development Goals (SDGs) (Figure 2), a global partnership for sustainable development to improve human lives and protect the environment (Nations, 2022). The goals are designed to facilitate the development of the economy, ecosystem, and social life (Le Blanc, 2015).

![Image of the United Nations Sustainable Development Goals (SDGs) (Nations, 2022).](image)

Figure 2: The United Nations Sustainable Development Goals (SDGs) (Nations, 2022).

Agrivoltaic systems work in accordance with the SDGs. To illustrate, APVs agree with SDG 1 (No poverty) and SDG 2 (Zero hunger) by contributing to access to basic energy and food; SDG 7 (Affordable and clean energy), and SDG 8 (Decent work and economic growth) by increasing energy supply reliability and affordability and contributing to employments globally; SDG 11 (Sustainable cities and communities) by minimizing pollution; SDG 12 (Responsible consumption and production) by reducing waste and supplying cleaner and safer
energy; and lastly APVs enhance SDG 13 (Climate action) by contributing to mitigate climate change and decreasing GHGs emissions (Obaideen et al., 2021).

According to the Food and Agriculture Organization (FAO), the world population tends to grow by around 20% by 2050. Consequently, there is an increased global demand for food to be expected in the coming decades, requiring agricultural yield leverage by more than half of the current production (Pawlak & Kołodziejczak, 2020; Silva, 2018) to fulfill growing human needs.

In parallel, the global population growth and a more energy-intensive industrial sector significantly impact the world's demand for energy, which is responsible for about 80% of CO₂ emissions and almost 70% of greenhouse gases emission (Sciubba & Toro, 2011). Researches attest that global energy demand has grown exponentially (Mostafa et al., 2019). In the meantime, the threat of climate change is altering the global energy strategy, in which renewable energies are gradually replacing non-renewables. Scaling up electricity from renewable sources is decisive for decarbonizing the world's energy system. In this case, photovoltaic energy has the potential to offset a considerable percentage of fossil fuel demand globally. Nowadays, solar PV is the technology with the fastest-growing power generation, and it expects to continue driving overall renewables development in multiple regions over the following years (IRENA, 2019).

Solar resource is considered the most abundant energy source on the globe. Moreover, solar energy has shown a significant reduction in the Levelized Cost of Electricity and an increase in the Net Capacity Factor, two crucial indicators for the energy sector that expect further improvements (Feldman et al., 2016). The tendency for higher solar farm installation demands more physical space. Therefore, it leads to land competition, especially in densely populated areas and small cities. One feasible solution may be the APVs, which involve dual use of land between solar energy production and agricultural purposes (Hélène Marrou, 2019).

One of the APV development strengths is the increase in Land Equivalent Ratio (LER). The LER is a parameter that quantifies the land yield. Combined cropping systems generally present LER ranging from 1.0 to 1.3. An LER higher than one means that the hybrid system is beneficial. In the case of agrivoltaic systems, the LER is higher than in combined cropping systems, as shown by Dupraz et al. (2011) study. They computed the LER agrivoltaic systems in France, and for full-density APV systems, the estimated LER is 1.7. Accordingly, an LER equal to 1.7 indicates that the production of 100 ha for an APV farm will generate as much food
and power as a 170-hectare farm with separate productions. Such considerable yield improvement is attractive and explains the actual trend in investigating APV systems, which promote a complementary use of resources and a synergetic process when one component benefits from the other (Dupraz et al., 2011). Adeh et al. (2019) further explored this concept, showing that APVs may alleviate land competition for solar power production, displaying significant opportunities for future energy sustainability. They claim that solar production would offset global energy demand if even less than 1% of cropland converts into an agrivoltaic system. Amaducci et al. (2018) also confirmed that agrivoltaic systems could effectively maximize land productivity.

From the APV system, crops can also adapt against climate change since the modules above provide shade and protection for the plantation. Climate change triggers more frequent natural disasters such as hails and heatwaves that can hazard agricultural production (Dos Santos, 2020). The PV shade prevents the culture from burning from the direct radiation effect and avoids water stress by reducing plant evapotranspiration.

Encouraging preliminary results showed that farms may increase land economic value by 30% as well as promote diversification of farmer’s income by adopting the APV solution, as contrasted with conventional dryland agriculture practices (Dinesh & Pearce, 2016).

Other advantages of APVs can be highlighted. For instance, APV could help reclaim degraded lands with vegetation insertion by altering the near-surface energy and water balance. Moreover, vegetation reduces dust generation since the green cover and soil moisture may control soil erosion by wind. Therefore, air quality is improved by reducing soil erosion and dust emissions (Ravi et al., 2016).

1.2 Agrivoltaics in Arid Regions

Prevalent clear-sky conditions, high insolation, and land availability are typic features of arid regions. As a result, these places possess an excellent potential for large-scale solar power production. In contrast, drylands are affected by a series of drawbacks, like endemic water scarcity, land degradation, saline soils, dust, as well as harsh climatic conditions such as extreme heat and evaporation. The mentioned constraints limit drylands capacity mainly for local agricultural production. Besides, aridity and land degradation expect to intensify under climate change, posing an additional threat to food security and sustainable development in drylands (The Arab Water Council, 2009).
Drylands, which englobe arid regions, account for nearly 30% of the world’s land area (Koch & Missimer, 2016). In these regions, competition for land may not be significant, but the availability of irrigation water is considerably limited.

Barron-Gafford et al. (2019) tested APV systems at a small experimental site in Arizona using different drought-resilient crops. They concluded that solar panel shading could reduce excessive evapotranspiration, drought stress, and plant heat stress. These effects combined enhance plant productivity (Herbert, 2018). Furthermore, solar panels above crops are cooler than those installed over bare soil in daylight. Namely, the presence of vegetation below the PV modules promotes evaporative cooling and enhances PV efficiency.

However, soiling of panels may lead to a 15-25% decline in annual electricity production. Hence, weekly cleaning of panels is vital in drylands. Ravi et al. (2016), after a detailed Life Cycle Analysis (LCA) in APV systems, concluded that the amount of water needed to clean solar panels in most drylands is similar to irrigation required for desert plants. They thus proposed recycling water in these integrated systems. Water use efficiency may be a crucial outcome of APV applications, especially in arid regions, where water is a limited resource and irrigation accounts for approximately 80% of the water use. Technologies that require no water for operations, such as photovoltaics, could provide a solution for enhanced resilience under uncertain water resource conditions.

The highest potential for the APV system is expected in arid regions where the shading effect induced by APV greatly ameliorates extreme radiation. Thereby, it produces substantial water savings that could boost the crop yield and increase PV performance derived from evaporative cooling (Weselek et al., 2019). Moreover, the water savings produced by APV could attenuate the problem of rising groundwater salinity by reducing the need for irrigation water coming from desalination. In addition, APV aids in improving power independence and connectedness to the power grid leading to improving the economic situations of farmers.
1.3 The Interest in Modeling Agrivoltaics

The UAE has launched an Energy Strategy 2050 plan to meet the growing energy demand and ensure sustainable growth for the country's economy by 2050, aiming for an energy mix of renewable, nuclear, and clean energy sources. There are plenty of solar energy projects (Mokri et al., 2013) and one of the benchmark energy projects is the world’s largest single-site solar power plant in Abu Dhabi, the Al Dhafra Solar PV plant. The project aims to deliver electricity with high efficiency and at a world record-low tariff under the UAE irradiation conditions. Once fully operational, the Al Dhafra plant promises to increase the solar power capacity of the capital city to approximately 3.2 GW (WAM, 2020).

The Covid-19 pandemic negatively intensified the agricultural scenario, disrupting food supply chains globally. The Gulf Countries, particularly challenged by their international dependence, raised an urgent necessity for policy changes, local production incentives, and more controlled environment agriculture. In terms of agriculture in the UAE, the country has made substantial investments in boosting food production and security in the past few years. The Abu Dhabi plan for agricultural sustainability and food systems innovation is a recent project that supports the UAE's Net-Zero by 2050 initiative. It is in line with global trends to promote climate-smart agriculture (Tolley, 2021).

Until now, there are not many farming areas in UAE. Nevertheless, by spreading new technologies such as agrivoltaics, this reality could be improved and then deploy more agricultural sites.

Considering all the beneficial services agrivoltaic systems can offer, as previously discussed, it is relevant to comprehend better the dynamics of them. This research's interest consists in assessing the potential of APVs in arid regions through a dynamical energy balance model accounting for the partitioning of energy and water at the land surface.

The APV Energy Balance Model (APV-EBM) is parametrized for the characteristic soil, climatic, and UAE's hydrological conditions, accounting for irrigation and soil water content effects on energy partitioning. It helps enhance understanding of the interactive relationship between crops and solar panels under stress factors in the UAE as poor and saline soils, low rainfall, lack of natural waterways, high temperatures, high humidity, and dust.

Simulating energy fluxes in solar panels and improving photovoltaic efficiency by cooling encourages the APV system to spread out in the UAE and other desertic and arid places.
2. **Photovoltaic Investigation**

Photovoltaic (PV) is an electric power system designed to produce clean, renewable, and useable solar power. These systems come in a wide range of sizes, from large utility-scale power plants to small rooftop or portable systems. They consist of one or more solar modules, an inverter, and other electrical and mechanical components that transfer sunlight into a usable form of power. Photovoltaic panels comprise solar cells with semiconductor properties housed in a weather-resistant material. Moreover, an anti-reflection coating minimizes reflection losses and protects the cells from a harsh environment.

It is important to clarify the difference between efficiency and performance for a clear reading. Efficiency consists of the ratio between the actual power output and the input of absorbed radiation. On the other hand, performance means the ratio of the actual power output and the theoretical power output under standard conditions (Edalati et al., 2015).

The PV cell is an energy harvesting technology with various shapes and sizes. However, all types of PV cells rely on semiconductors to interact with the photons received by the sunlight. This interaction generates an electric current that transforms the solar radiation into electrical power through a process called the photovoltaic effect. The photovoltaic effect happens whenever the flow of electrons occurs in the cell due to its exposure to sunlight. This discovery was made by Edmond Becquerel back in 1839 when he observed an increase in the cell voltage whenever the silver plates were exposed to the sunlight (Boyle, 2004).

In a PV cell, the most critical layer is the semiconducting layer, composed of two different types (p-type and n-type) joined together to form a p-n junction (band gap). By forming a p-n junction, electrons flow from the positive p-side to the negative n-side, which creates an electric field. As a result of this electric field, the negatively charged particles start to flow in one direction while those with positive charges flow in another. By exposing these cells to sunlight, photons with a specific wavelength transmit their energy into electrons in the semiconducting layer, causing them to leap to a greater energy state known as the conduction band. In the conduction band, electrons are excited, and their movement generates an electric current (Kazem, 2019).

PV cells can be made from different materials with various manufacturing methods. Regardless of their differences, they all have the same goal: capture solar energy and turn it into usable
electricity. Generally, PV systems are classified into on-grid and off-grid if either connected with the local power grid or not.

2.1 Crystalline Silicon Photovoltaic Technologies

Crystalline Silicon (c-Si) is the first generation of photovoltaic technology, together with Gallium arsenide (GaAs) (Du et al., 2016). Silicon, which possesses semiconducting properties, is the most used material for PV cell manufacturing. Crystalline Silicon PVs are composed of single-junction solar cells.

Monocrystalline silicon, polycrystalline silicon, and thin-film are the three main types of PV cell technology that currently dominate the global market. However, they are more likely to lose efficiency at higher temperatures, usually during hot sunny days (Stefan, 2015).

Monocrystalline silicon (mono-c-Si), also known as single crystalline silicon, was the first commercially manufactured solar module. This PV type consists of a highly pure form of silicon with almost no defects. Although mono c-Si has a better light conversion efficiency than polycrystalline, its initial cost is relatively higher, mainly due to its complicated manufacturing procedure which is slow and labor-intensive (Nogueira et al., 2015; Peake, 2018).

The best efficiency recorded from mono c-Si reached 26.6%, with an average efficiency ranging from 15% to 20% (Green et al., 2017). The monocrystalline silicon cells can last over 25 years. However, they are also known as mechanically vulnerable, and their efficiency decline with time by approximately 0.5% annually (Fedkin & Dutton, 2021).

On the other hand, polycrystalline silicon, also known as multi-crystalline (multi c-Si), presents a cheaper and easier manufacturing process with high mechanical brittleness (Afework et al., 2018). In 2015, due to its low manufacturing cost, multi-c-Si cell production dominated other technologies, which reached up to 70% of the total PV production worldwide (Peake, 2018). Multi-c-Si reaches maximum efficiencies of around 21%, slightly lower than mono c-Si (Green et al., 2017). Its power degradation is similar to mono c-Si (Jordan & Kurtz, 2011).

The major factors affecting c-Si PV performance include cell temperature and solar radiation intensity (Arvizu et al., 2011). According to experimental studies regarding efficiency and power production in hot regions, the monocrystalline module performs better during the year compared to polycrystalline. For instance, Emziane & Al Ali (2015) tested mono and multi c-Si modules for one year in Abu Dhabi, UAE. They found that mono-c-Si PVs present a more
significant capacity factor over the year, even though they tend to be more sensitive to temperature variations (Mirzaei & Mohiabadi, 2017; Mussard & Amara, 2018).

For power conversion, conventional PV modules utilize direct radiation and diffuse light scattered mainly by clouds and dust (Abiko et al., 2018). Therefore, c-Si PV systems are suitable for regions with high global radiation.

2.2 Concentrated Photovoltaic Technology

Following the increasing demand for power generation based on renewable and sustainable energy, concentrated photovoltaic (CPV) systems have evolved as a highly efficient power generation technology (Saito et al., 2013). Concentrated photovoltaic (CPV) is part of the third generation of PV technologies, along with dye-sensitized and organic PV types, after thin-film technologies as a second generation (Du et al., 2016).

A CPV system is a photovoltaic power generator that concentrates the direct radiation on solar cells through a convex lens commonly working as concentrators (Abiko et al., 2018). There are two classes of CPV: The high concentrated photovoltaic (HCPV) and the low concentrated photovoltaic (LCPV). The HCPV is the object of study and it has a 300-1000 typical concentration ratio, 2-axis tracking, and multi-junction solar cells, with a global massive installed capacity of over 90% (Philipps et al., 2015).

CPV works with wider bandgaps made of different semiconductor materials. Each spectral band will produce an electric current in response to different light wavelengths. Multiple semiconducting materials absorb a broader range of wavelengths, improving electrical energy conversion efficiency. Due to the multi-junction cells, CPVs report very high peak efficiencies reaching 46%, while the mean conversion efficiency ranges from around 33% to 36%, representing about double the efficiency of conventional c-Si modules (Abiko et al., 2018). Recently, scientists have fabricated a six-junction solar cell with an efficiency of 47.1%, which holds the world record for the highest solar conversion efficiency. The six-junction solar cell now holds the world record for the highest solar conversion efficiency (Geisz et al., 2020).

Moreover, CPV technology optimizes manufacturing costs by substituting silicon, a costly material, for gallium arsenide (Dobos, 2019). Therefore, CPV shows a higher light absorption coefficient and can operate at elevated temperatures without significantly declining performance (Peake, 2018).
Some drawbacks of CPV modules are less competitiveness for their higher cost and limited market since they are interesting financially in sun-rich regions with high DNI values (usually more than 2000 kWh/m²). (Philipps et al., 2015) For being one of the most recent PV technologies, there is still a lack of technology standardization. The system also relies on tracking, which should be accurate and reliable to avoid power production losses (Philipps et al., 2015).

Diverse studies converge that CPVs are largely more productive than conventional photovoltaic systems (Abiko et al., 2018; Burhan et al., 2016; Philipps et al., 2015; Saito et al., 2013). Abiko et al. (2018) evaluated a CPV power plant located in Morocco (a suitable region for solar resources) in terms of power output performance in comparison with a nearby conventional c-Si PV system. They concluded that the CPV surpasses the conventional system regarding power density at 1.97 times and rated power at 1.23 times.

CPVs have shown a step toward a recyclable future on photovoltaic technologies. The new idea starting on CPV systems is that the PV module degradation occurs mainly on the cell level. Thus, to reduce the material to be processed and recycled, CPV modules can be ameliorated by replacing just the cells without modifying the other components and layers (H. N. Apostoleris & Chiesa, 2020). This idea was applied in Saudi Arabia (Khonkar et al., 2019), supporting the circular economy. In addition, due to the improved use of semiconductor material, CPV modules are one step further on the Life Cycle Analysis (LCA), considerably reducing manufacturing energy relative to conventional PVs (Fthenakis & Kim, 2010).

The CPV work as a natural light splitter. Lately, transparent CPVs have been recommended to afford a fairer sunlight sharing between agriculture and PV power production. CPV with transparent layers can split direct and diffuse radiation. While direct radiation is captured onto tiny cells, diffuse light is transmitted to the ground. Thus, transparent CPVs are suitable for APV setups as they can harvest large quantities of electrical power based on the DNI and retain the DHI to crops. Thereby, the main advantage of transparent CPVs (conceptual drawing in Figure 3) is the capacity to recover the diffuse component for other purposes, when normally DNI is wasted in concentrator systems, and then allow the dual-use of land and solar resources (H. Apostoleris & Chiesa, 2019).
CPV systems concentrate only direct radiation on cells, differing from c-Si PV modules, which harvest the global radiation. Due to these characteristics, CPV deployment is justified in areas where DNI is stronger than scattered light (Abiko et al., 2018). To deploy the most appropriate module type, it is pivotal to account for the location and weather conditions, including available radiation, dust problems, and cloudy periods.

Concerning the UAE context, the amount of diffuse radiation is extremely high over the year, owing to the permanent dusty condition of a desertic country. Connecting this reality with the idealization of APV systems in the region, crops under a PV system are supposed to have sufficient light needed for growing. With plenty of scattered light, conventional PVs are suitable for an APV system even partially shading the crop, as well as financially more viable. Simultaneously, global irradiance reaches high values during the entire year, which is an advantage for conventional PVs.

APVs in UAE have not been founded in the literature so far, either as experimental or commercial. Besides, it would be more feasible to first assess the energy balance on these new systems using consolidated technologies. Moreover, in terms of having a minimum comparison of power generation with another power plant, taking into account that the massive number of solar farms in UAE are from c-Si PV modules. Hence, for the aforementioned local-dependent reasons, crystalline silicon PV technology was selected to be assessed in this present work.
2.3 Photovoltaic Performance in Hot Deserts and Arid Regions

Due to the favorable global radiation levels in the Arabian Peninsula, a sunny belt region with a typical daily average solar radiation exceeding 6 kWh/m² (Alnaser & Alnaser, 2011) and 80-90% clear skies throughout the year (Masdar Institute, 2013), substantial solar power generation is expected. Nevertheless, the Gulf countries are known as hot deserts with harsh climatic conditions, like soiling, elevated air temperatures, and humidity.

Besides the PV tilt angle and orientation that play a role in the electrical power performance, the environment and its climatic conditions are direct disturbing causes the PV performance (Maghami et al., 2016; Regulation & Supervision Bureau [RSB], 2017). In this way, the parameters mentioned above play an enormous impact on PV modules' performance and degradation rate, being essential to consider them when deploying a PV setup under such conditions (Al Siyabi et al., 2021; Mussard & Amara, 2018).

Heating Effect

When radiation reaches the solar panel, it splits: part is reflected into the atmosphere; part is transmitted through the module, and part is absorbed, totaling 100% (Duffie et al., 2013). Regarding the absorption fraction of light, the big junk is converted into heat due to the material heat capacity, leaving a minor faction to the main goal, which is power generation. Consequently, it overheats the panel and compromises photovoltaic performance (Rahman et al., 2015).

The impact of the temperature on the performance of different photovoltaic technologies has been observed and experienced over the past decades. Studies show that the heating effect varies with the module characteristics such as panel temperature, manufacturing materials, and design parameters, for example, tilt angle, orientation, and latitude (Du et al., 2016; Rahman et al., 2015).

In addition, the temperature of photovoltaic modules is extensively influenced by weather parameters such as solar irradiance intensity, air temperature, wind speed, and humidity (Du et al., 2016; Mussard & Amara, 2018; Rahman et al., 2015). Studies related to the performance of solar schemes indicate that photovoltaic power output configures as linearly proportional to the radiation levels (Labed & Lorenzo, 2004).
In hot deserts and arid regions, irradiance and air temperatures commonly reach higher values in contrast to other locations. For example, UAE presents around 3570 hours of annual sunshine and an average annual global radiation of nearly 2285 kWh/m² (Hejase & Assi, 2013). A justification for such discrepancy is the minimum dense cloud cover, predominant in these hot areas, with clear skies over the year. Once clear days are uppermost, there is less irradiance fluctuation. Thus, better light levels increase electricity generation (Mussard & Amara, 2018). However, on the other hand, it rises PV module temperatures.

Oppositely, wind speed is a cooling agent on solar panels (Ghabuzyan et al., 2021). Particularly in Abu Dhabi, UAE, where meteorological records are assessed in this work, wind speed is considered low and then insignificant to PV modules' cooling effect.

Humidity also exerts influence on the radiation reaching the PV arrays. Elevated air humidity negatively impacts efficiency since water vapor reflects or refracts solar light away from solar cells and, consequently, the photovoltaic power output is compromised (Mussard & Amara, 2018). High humidity also creates a thin layer of water on the PV panel surface that when combined with dust, enhance PV losses.

The electrical power output of PV solar cells is a function of module/cell temperature. It is proven that as higher temperatures reach the solar cell, as less productive the PV panel becomes. Therefore, it is essential to characterize the module temperatures since it is directly connected to the long-term reliability of these technologies (Dobos, 2019).

The UAE Innovation Centre carried out a field experiment in the UAE to estimate the actual performance of a PV setup, and the results reveal a linear increase in the PV current with irradiance. Nevertheless, the photovoltaic efficiency decreased by around 3% to 4% compared to standard test conditions. This diminution was attributed to the elevated temperatures reached by the panels (around 60 °C), followed by an electrical yield decrease (Radhi, 2010).

Al Harbi et al. (1998) conducted a PV-thermal experiment under the climatic conditions of Saudi Arabia. During the summer season, the exceptionally high operating temperatures of the solar cells during the peak sun hours (around noon) caused PV power output depletion of more than 30%. On the other side, the PV arrays generated more during winter than in the hot period.
Soiling Effect

Soiling loss is the process of dust accumulation and the consequent negative effect on photovoltaic power production. Dust significantly deteriorates the PV system performance by impeding light penetration on the PV surface. Under the soiling effect, shaded cells perform as a current resistance, inducing heat. Since a group of cells starts to heat up, it forms a hot spot capable of spoiling the module (Ngan & Tan, 2011). Site experiments attest that soiling compromises the power yield of PV installations from a short (daily, monthly) to a long-term basis (seasonal, annual) (Maghami et al., 2016; Mussard & Amara, 2018).

In dusty and dry environments, soiling is one of the main concerns on PV efficiency. (Hachicha et al., 2019), since it can damage PV performance from 15 to 30%. This situation is peculiar from operational sites surrounded by an atmosphere full of fine sand particles in desert locations and exposed to sand storms. (El-Nashar, 2003). Globally, the Middle East and North Africa (MENA region) comprehend the worst dust accumulation zones (Ghazi et al., 2014).

Problems of dust deposition on solar panels require regular cleaning, which normally is done with water, a scarce resource in arid and desertic regions. Sarver et al. (2013) studied distinct approaches to facing dust problems on PVs, many of them without water, such as treating the surface to make it dust repellent or even using jet air mechanical cleaning with robots.

Hachicha et al. (2019) conducted experiments in Sharjah under UAE weather conditions, aiming to assess dust accumulation on solar panels. Based on the PV tilt angle, dust over the PV surface is the highest on a flat module, around a 38% increase compared to a clean module. For a 25° tilted configuration, dust increases around 14%, while for a 45° tilted configuration, the dust deposition is the lowest at about 11%. Besides, after five months of dust accumulation in the test field, the soiling loss increased by 13%.

Al Siyabi et al. (2021) conducted measurements on a 2 MWp PV plant in Oman to investigate the soiling effect on the PV performance. They concluded that electrical output decreased due to dust by around 5% at the end of 1 week of operation, 18% in 3 weeks, and 38% after five weeks. Moreover, the results showed that a 7.5% increase in dust deposition compared to a clean module could reduce the monthly power production by 6%. In the case of 12.5% of dust accumulation, the losses in monthly power production could reach about 11%.

El-Nashar (2003) studied the dust accumulation result on a PV plant performance in Abu Dhabi, UAE. It was found that the module performance is also dependent on the annual seasons.
Especially during the Summer months, when sandstorms are usual and the dust level increases, there is a significant drop in the PC performance.
3. Crop Investigation

3.1 Crop Selection Criteria for Agrivoltaics in Arid Regions

The implementation of APV systems involves changes in agricultural practices. Harsh climatic conditions that should be considered for growing crops in arid regions like UAE are extremely high temperatures, high soil salinity, and drought with few annual rainy episodes (Abdelfattah & Shahid, 2007).

The crop choice must rely on criteria consistent with the prevalent climatic conditions in arid regions. Thus, a study based on a literature review was performed to highlight the principal crop traits to be assessed based on APV systems in arid regions such as the UAE and then determine the most suitable crops for this scenario (Abuolwan, 2020).

Therefore, the crop selection criteria in arid regions may be performed at four primary levels based on significant stressors that limit agricultural productivity in arid regions. In addition, there is a 5th level serving as a supplementary check of the economic and nutritional value of the selected crop. The traits that are used to assess the suitability of crops in the UAE environment include (1) Soil pH requirements, (2) Salinity tolerance, (3) Drought tolerance, and (4) Shade tolerance. The assessment priority is soil condition (pH and salinity), followed by drought tolerance and then shade tolerance. The selection criteria aim to maximize salt tolerance values and minimize irrigation water needs and water footprint.

Soil pH Requirements

The soil pH is the first inspection for cultivating crops. It is specific to crops cultivated in the UAE environment, considering that UAE soils are mostly alkaline, with high values reaching 8.5 in some locations (Qureshi & Shoaib, 2017). Hence, it is important to assess the compatibility of the crop with the pH in the first place before other criteria. A pH range of 7 to 8.5 is considered satisfactory.

Salinity Tolerance

Soil salinity usually comes from three main sources: (1) saline soils, (2) soils with a high saline water table, or (3) irrigation water containing salt (USDA-NRCS, 2011).
Salinization issues lead to the rupture of biochemical processes between soil particles and plant roots. There is a disruption in the ion-exchange mechanism between soil moisture and plant cells. Consequently, plant cells dry out. In addition, salinity alters the selective capacity of crop nourishment on soil particles. Harmful quantities of trace minerals (such as B, Cu, Mn, and Zn) may damage or completely destroy the crop. In such a situation, fertilizers can even intensify it. Lastly, salinity can modify the electrochemical balance of soil particles, which compromises physical soil properties, decreasing soil percolation and intensifying evaporation and soil erosion (Wiede, 2005).

A salinity turns into a problem when the salt concentration in the root zone provokes a yield decrease. Yield reductions occur when the crop can no longer extract sufficient water from the soil, reducing water quality and plant growth (USDA-NRCS, 2011).

Soil salinization is a widespread problem in the UAE. Particularly in the Abu Dhabi Emirate, there are natural and anthropogenic salinity causes. Seawater and salt adherence in marine sediments is a natural cause of salinization, mainly affecting the coastal area of Abu Dhabi. On the other hand, artificial causes for salinity in Abu Dhabi comprehend (1) constant irrigation over long periods, depleting the water table and allowing seawater intrusion; (2) brackish and saline groundwater used for irrigation purposes; and (3) poor water management in farms and cultural practices in irrigated agriculture (EAD, 2017). These factors intensify soil salinization with adverse consequences on agriculture as most of the commonly cultivated crops are not highly salt-tolerant, except date palm (Rao & Shahid, 2012).

In terms of salinity tolerance, the absolute salinity tolerance - measured as soil salinity in electrical conductivity (target: ECe above 4 dS/m) - and the irrigation water salinity (ECw) tolerance should be the main evaluating features, while sodium and chloride tolerance (target: values greater than 500 mg/L) will serve as secondary selection criteria to check if the mainly salt-tolerant crops can tolerate sodium and chloride as well (Qureshi & Shoaib, 2017).

Drought Tolerance

Water shortage is another severe environmental constraint to crop productivity. Drought stress can limit leaf size, stem extension, and root growth, as well as harass plant-water relations and diminish water-use efficiency (WUE) (Farooq et al., 2009).
In this manner, for drought tolerance assessment, the main selection criteria to be considered are:

1) Daily irrigation water needs. It should be less than 5L/m²/day.

2) Time from sow to harvest. It should be less than 90 days.

3) Water footprint, which is the sum of the direct and indirect freshwater used in all activities involved in crop production. It should be less than 900 m³/ton.

Daily irrigation needs and time to harvest complement each other in determining the total water needs of crops over the growth periods, so they can be evaluated together. The selected crops should satisfy at least two of the three parameters mentioned for drought tolerance (R. G. Allen et al., 1998; Brouwer et al., 1992).

Soil Moisture

Soil moisture is connected to atmospheric moisture through evapotranspiration, a fundamental process in the energy exchange between the ground surface and the atmosphere (Henn et al., 2018). Soil moisture alterations are fundamental for hydrology, ecology, and meteorology, and it is central to the interactions between land and climate. The evapotranspiration process usually happens in the top 10 cm of soil. As vegetation cover reduces, evapotranspiration becomes more related to the surface soil moisture (Wang et al., 2021).

The crop health also depends on an adequate supply of moisture and soil nutrients. As soil moisture availability reduces, the vegetation's normal function and growth are disrupted, and crop yields are compromised. In arid regions the soil moisture level is low so it is necessary to account for full irrigation (Wang et al., 2021).

Changes in soil moisture tend to occur owing to periodic rainfall recharge. McColl et al. (2017) studied that the soil surface usually retains around 14% of precipitation after 3 days of precipitation. Moreover, the surface soil moisture is more preserved in arid regions and places with low groundwater replenishment rates, for having sparse rainfall and more complex soil moisture distribution. Soil properties and topography also play a role as physical control factors of soil moisture changeability.
Studies presented that potential evapotranspiration pursues the main contributing factors as sunshine duration, relative humidity, and wind speed with rates of about 33%, 25%, and 22%, respectively (Liu et al., 2008).

Relative Humidity

Humidity is important to become photosynthesis happen. When vegetation loses too much water, the stomata close since the photosynthesis process stops. If this happens, no further CO2 can be absorbed (IMAC & Anthura, 2016).

Crop temperature on a hot day is primarily regulated by cooling through evaporation. Evaporating water can release plant heat, being an efficient way of cooling. Therefore, by closing the stomata, the plant temperature will often increase quickly. To keep the stomata open, it is important to reduce the evaporation of the plant when there is more irradiation (IMAC & Anthura, 2016).

With high humidity, the plant can keep its stomata open. Then, CO2 is absorbed and the plant temperature can be regulated through evaporation. Moreover, the crop could be slightly moistened so that the evaporating water cools the crop. Keeping the stomata open is more important than the optimal amount of light since photosynthesis will be possible even with low light values. To make photosynthesis possible, the stomata should be open to being able to absorb CO2. If the stomata are closed due to higher light values, photosynthesis does not happen. In very high humidity, it may create the growth of mold and bacteria, causing plants to die and crops to fail, as well as conditions like root rot (IMAC & Anthura, 2016).

The faster the transpiration process, the faster the plant absorbs water and nutrients. When evaporation stops, the same happens to the water uptake. This is where humidity connects with plant growth. Humidity directly affects the transpiration from the leaves. Most plants require about 60% of relative humidity. Tropical plants require higher relative humidity, reaching about 90% of relative humidity. On the other side, desertic plants endure much lower humidity, around 30% but sometimes as low as 20% (IMAC & Anthura, 2016).
Shade Tolerance and Crop Light Needs

A crop selection should also account for PV shadowing effects since the main concern of the PV plant installation above agriculture is creating shade (Dupraz et al., 2011). Thus, it is essential to select crops that survive and grow under lower light conditions.

The main criteria to be assessed is the crop light needs for photosynthesis, represented mainly by the Light Saturation Point (LSP). LSP is the point of maximum photosynthesis efficiency, after which no further increase in light absorption results in more photosynthetic CO2 assimilation. LSP varies with different crops, as well as growing conditions. It essentially represents the light use efficiency (LUE) of plants.

In terms of sun exposure, full sun crops are the ones that need 8 hours or more of direct sunlight. Partial sunlight crops need from 4 to 8 hours, while those with 4 hours or less are defined as shade plants. The necessary conditions to fit APV systems are low LSP (less than 1100 µmol/m2/s selected for conventional APV setups) and low direct sunlight requirements, less than 8 hours. LSP is featured in a light-response curve that illustrates a plant's photosynthetic activity when subjected to light, as shown in Figure 4 (Anpo et al., 2019).

The radiation harnessed by the plants is diffuse radiation (DHI) (H. Apostoleris & Chiesa, 2019). Particularly in the UAE, the DHI is extremely high over the year, especially in Summer, when the dust increases considerably, and more radiation is scattered as a diffuse component. In this case, the PV shading still allows sufficient light to cover most of the daily light requirements of many crops.

Light reduction is not necessarily harmful to crops that can adapt and improve radiation interception efficiency (H. Marrou et al., 2013). In the UAE and arid regions in general, shade provided by PV panels could prevent agriculture from receiving excessive light from direct radiation (DHI) (Dos Santos, 2020). In this way, partial or full shading tends to work as a crop relief by reducing evapotranspiration losses (Santra et al., 2017).
Crop Economic Feasibility

A 5\textsuperscript{th} level examines the economic feasibility of harvesting the selected crops. The 5\textsuperscript{th} level is a check step rather than a selection, performed after completing the crop selection criteria. This level involves looking into fertilizer requirements and the market value of crops. Fertilizer requirements should be minimized, and the market value should be high to make local agriculture feasible and cheaper, the

In addition, for the best fit of the crop in an APV setup, crop height should not be tall, limiting to around 2 m since the average clearance below PV modules is 3.0 m. In this way, all fruit trees are excluded since their growth height exceeds 2.0 m. Ideally, crops for APV sites should be perennial (life cycle is more than a year) and easily spread below the PV arrays.

According to the stated criteria, from around 100 crops assessed for the UAE environment, the most suitable crops to be set in an APV system in arid regions are Sugar beet; Artichoke; Asparagus; Basil; Cabbage & Cauliflower; Celery; Cherry Tomato; Cucumber; Quinoa; Marrow/Squash; Pea; Pepper; Potato; Spinach; Tomato.

3.2 Quinoa as a Suitable Crop for Agrivoltaics in Arid Regions

The future of food security has been faced as a world challenge. One of the most promising crops for forthcoming food and nutrition security is quinoa. Originating in the Andes, South America, quinoa grows in elevated altitudes (around 5 km), making it frost tolerant. Quinoa withstands wide temperature ranges, produces under minimum annual rainfall rates, and yields in reduced timeframes (from sow to harvest: 90 to 120 days). There are more than 3,000 quinoa
ecotypes whose potential and nutritional value have not been yet explored outside the Andes (Hena et al., 2016).

Quinoa's positive features have been rising global endeavor in growing it. Quinoa is a highly nutritive grain, presenting great protein quality and content (12-20%). The balance of essential amino acids in quinoa is superior to wheat, barley, and soybeans and comparable with milk protein. Furthermore, quinoa content of vitamins and several minerals, such as calcium (Ca), magnesium (Mg), iron (Fe), and zinc (Zn) (Bhargava et al., 2006).

With multiple uses as nutrition for humans and animals and potential food for the industry, quinoa seeds are generally used to make flour, soup, and breakfast cereal. Moreover, quinoa is a source of dietary fiber. Quinoa leaves can be eaten as a vegetable, such as spinach.

Over the globe, the Arabian Peninsula, where UAE is located, is one of the most barren and hottest regions, with rare rainfall episodes and temperatures in summer reaching more than 50°C. Due to the hot climate, soil organic content is insufficient to support crop growth. Consequently, only a limited number of plants can thrive under these conditions (Rao & Shahid, 2012).

There is an increasing effort to introduce quinoa in marginal agriculture production systems of the world, owing to its large endurance to abiotic stresses such as soil salinity and drought (Choukr-Allah et al., 2016). Quinoa thrives where other crops no longer yield (Hena et al., 2016). Therefore, the outstanding characteristics of quinoa make this grain an exceptional alternative for the diversification of future agricultural systems in the UAE and other areas with similar extremely environmental conditions. (Rao & Shahid, 2012).

Bosque Sanchez et al. (2003) assessed the relative influence of drought and salinity stress on growth, plant-water relations, and the photosynthesis rate of quinoa. They found that salt stress contributed to better growth rates. Moreover, quinoa presented adaptation mechanisms to drought by improving water use efficiency (WUE) and root-shoot ratio (roots weight over the plant canopy weight, RSR).

Due to quinoa's high nutritional value and medicinal application, it is recognized as a pseudocereal with a complete nutritional composition. The Food and Agriculture Organization of the United Nations (FAO) has understood quinoa as the "grain of the future." Considering the exceptional nutritional qualities, adaptability to various growing conditions, and potentially
significant contribution against hunger and malnutrition, FAO declared 2013 as the International Year of Quinoa (FAO, 2011).

In this scenario, since quinoa has been shown as a climate-resilient crop of exceptional value, quinoa was selected in this project to be assessed in terms of evapotranspiration under a virtual APV system modeled in the UAE.
4. Modeling Methodology

4.1 Photovoltaic Energy Balance (PV-EB)

The Energy Balance parameterization of photovoltaic panels (PV-EB) is described by Heusinger et al. (2020), which evaluated a PV surface energy balance model and implemented it on the UCRC-Solar model developed with recent meteorological data from Arizona (USA) over nine months (Broadbent et al., 2019). Jones & Underwood (2002) first stated the PV surface energy balance model by covering a range of geophysical processes. The model as described in Equation 1 involves a balance among the PV net shortwave radiation ($SW_{PV}$), the PV net longwave radiation ($LW_{PV}$), the sensible heat flux ($SH_{PV}$), and the electrical power produced by the PV panel ($P$), each component assessed in the $W/m^2$ unit. Such balance is directly proportional to the module heat capacity ($C_{module} \left[ J/K \right]$) and to the gradient of the PV module temperature ($T_{mod} \left[ K \right]$) concerning the time ($\frac{dT_{mod}}{dt}$). The PV-EB is a dynamic model assessing how the thermal regime of the PV energy budget system changes in time.

$$C_{module} \frac{dT_{mod}}{dt} = SW_{PV} + LW_{PV} - SH_{PV} - P \tag{Equation 1}$$

The module heat capacity ($C_{module} \left[ J/K \right]$) is defined according to Equation 2 as the sum of the specific heat capacity of each layer ($C_l$), weighted by the area ($A \left[ m^2 \right]$), the thickness ($d_l \left[ m \right]$), and the density ($\rho_l \left[ kg/m^3 \right]$) of the module layer.

$$C_{module} = \sum A \ast d_i \ast \rho_i \ast C_i \tag{Equation 2}$$

Total Shortwave Radiation Component

The total shortwave radiation ($SW_{PV}$) reaching the PV module is represented in Equation 3:

$$SW_{PV} = DNI \frac{\cos \theta}{\cos \theta_z} (1 - \alpha_{PV}) + DHI + GHI \ast \alpha_g \frac{1 - \cos \beta}{2} \tag{Equation 3}$$

Where:

GHI: Global Horizontal Irradiance from the Sun [W/m²].

DNI: Direct Normal Irradiance or Beam Solar Radiation [W/m²].
DHI: Diffuse Horizontal Irradiance [W/m²].

θ: Incidence angle [°].

θz: zenith angle [°].

α_ω: Reflectivity or albedo of the top side of the module.

α_γ: Ground reflectivity or albedo.

β: Tilt angle of the module [°].

The direct radiation (DNI) considered as input for the module is the absorbed one, which means the reflected parcel is deducted. The second term is the diffuse component (DHI), considered in its totality. Finally, the global shortwave radiation (GHI) reaching the module accounts for the reflected global shortwave from the ground on a tilted surface.

Meteorological stations usually obtain the global radiation on a horizontal plane. On the other side, the amount of incident radiation over the PV module at a certain latitude/ longitude is a function of the azimuth and tilt angle of the PV system (Al Siyabi et al., 2021).

Solar and Module Positioning

To precise the solar energy reaching a certain point where the solar system is deployed at a specific time, it is important to define and calculate the related angles. The calculation through the corresponding mathematical expressions requires information such as latitude, declination, and hourly angle (Kayfeci et al., 2019).

The solar panel’s shade on the ground surface may not be a concern to the PV module itself, but to what is below the PV arrays. In the agrivoltaic study, agriculture is the parallel yield to PV energy production. Shade from PV modules depends on Sun’s position, which is mainly defined by the azimuth angle and zenith angle.

The position of the Sun to a given place on Earth is set by physical parameters, the solar altitude angle (α_s) and the solar azimuth angle (γ_s) (Kayfeci et al., 2019). The first one is the angle between the horizontal and the Sun direction (0° ≤ γ_s ≤ 90°), complementary to the zenith angle (θz), which is defined by the vertical and the line to the Sun. The solar azimuth is set on the
horizontal plane and consists of the angular displacement from the south of the solar ray projection. Commonly is adopted displacement zero if equals south, $\gamma_s < 0$ if turned east, and $\gamma_s > 0$ if turned west (Kayfeci et al., 2019). Different conventions may also be found in the literature. A graphical representation of solar and PV surface angles is illustrated in Figure 5.

![Diagram of solar and PV surface angles](image)

**Figure 5: Relevant angles. Solar position on sky: Solar azimuth ($\Upsilon_s$), solar altitude ($\alpha_s$) and zenith ($\theta_z$) angles. PV tilt surface ($\beta$) and PV orientation ($\Upsilon = \Upsilon_{PV}$) (Rosa-Clot & Tina, 2018).**

Zenith and incidence angles are calculated after Braun & Mitchell (1983), being the zenith angle function of the Sun declination ($\delta$, angle between the Sun rays and the plane of the Equator [°]), the latitude ($\phi$ [°]), and the hour angle ($\omega$ [dimensionless]). The incidence angle is a function of the previously described zenith angle ($\theta_z$), the tilt angle ($\beta$), the solar azimuth, the PV surface azimuth ($\Upsilon_{PV}$), and the solar azimuth ($\Upsilon_s$).

The PV surface azimuth ($\Upsilon_{PV}$) is the projection on a horizontal plane of the normal to the PV surface from the local meridian, varying from $-180^\circ$ to $180^\circ$ (Duffie et al., 2013). If the module is in the best orientation facing the south for north latitudes, then $\Upsilon_{PV} = 0^\circ$. The solar azimuth is a function of the declination of the sun ($\delta$), the hour angle ($\omega$), the latitude ($\phi$), and the zenith angle ($\theta_z$). The declination ($\delta$) and hour angle ($\omega$) are a function of the day of the year ($N$), calculated as:

$$\delta = 23.45 \sin \frac{360}{365} (N + 284) \quad \text{Equation 4}$$

$$\omega = 15N \quad \text{Equation 5}$$

Being:

$N=1$, for Jan 1st. $N=365$, for Dec 31st.

**Net Longwave Radiation Component**
The PV net longwave exchange ($L_{W_{PV}}$) described in Equation 1 is calculated in Equation 6:

$$L_{W_{PV}} = L_{sky} + L_G - L_{PV, top} - L_{PV, btm}$$  \hspace{1cm} \text{Equation 6}

Where:

$L_{sky}$: Downwelling longwave radiation as a function of the module's sky view factor (SVF) [W/m$^2$].

$$L_{sky} = L^i \ast SVF$$  \hspace{1cm} \text{Equation 7}

$L^i$: Incoming sky longwave radiation [W/m$^2$].

$L_G$: Fraction of the longwave radiation from the ground surface received by the module [W/m$^2$].

$L_{PV, top}$: Upwelling longwave radiation output from the top side of the module [W/m$^2$].

$L_{PV, btm}$: Downwelling longwave radiation output from the bottom side of the module [W/m$^2$].

$L_{PV, top}$ (Equation 8) and $L_{PV, btm}$ (Equation 9) are calculated from the Stefan Boltzmann Law of radiation, depending on the PV module temperature ($T_{PV}$ [K]) in time and the module emissivity from the top side ($\varepsilon_{top}$) and bottom side ($\varepsilon_{bttm}$). $L_G$ (Equation 10) is also solved through Stefan Boltzmann Law, inserting the contribution of the ground view factor (GVF).

$$L_{PV, top} = \sigma \ast \varepsilon_{top} \ast T_{mod}^4$$  \hspace{1cm} \text{Equation 8}

$$L_{PV, btm} = \sigma \ast \varepsilon_{bttm} \ast T_{mod}^4$$  \hspace{1cm} \text{Equation 9}

$$L_G = \sigma \ast \varepsilon_G \ast T_G^4 \ast GVF$$  \hspace{1cm} \text{Equation 10}

Where:

$T_G$: Ground temperature [K], also known as land surface temperature (LST), is the theoretical temperature required to satisfy the surface energy balance. It represents the temperature of the uppermost surface layer, which has no heat capacity and can respond instantaneously to changes in surface fluxes (Muñoz Sabater, 2019).

$\varepsilon_G$: Ground emissivity;

$\sigma$: Stefan Boltzmann constant [W m$^{-2}$ K$^{-4}$].
The SVF and GVF are dimensionless parameters as a function of the PV geometry, solved by trigonometry.

Sensible Heat Component

Sensible heat flux from the module (\(SH_{PV}\)) is parameterized for both sides of the module:

\[
SH_{PV} = 2 \times h_c \times (T_{mod} - T_{air})
\]

Equation 11

Where:

\(T_{mod}\): PV module temperature [K].

\(T_{air}\): Air temperature [K].

\(h_c\): Turbulent convection coefficient [W/ K m^2]; \(h_c\) is a function of the wind speed (u). Calculated after four correlations (Jürges, 1924; Kumar & Mullick, 2010; Sharples & Charlesworth, 1998; Test et al., 1981).

The sensible heat is then computed as an average based on four different parametrizations for the turbulent convection coefficient.

Electrical Power Production Component

The power production from the PV module (P) described in Equation 1 is calculated as follows:

\[
P = SW_{cell} \times Eff_{PV} \times \min [1, 1 - 0.005 \times (T_{mod} - 298.15)]
\]

Equation 12

\[
SW_{cell} = M \times [DNI \times (\pi \alpha)_{dir} \times \frac{\cos \theta_1}{\cos \theta_2} + DHI \times (\pi \alpha)_{diff} \times \frac{1 + \cos \beta}{2} + GHI \times (\pi \alpha)_{G} \times \alpha_{G} \times \frac{1 - \cos \beta}{2}]
\]

Equation 13

Where:

\(Eff_{PV}\): Maximum electrical energy conversion efficiency of the module at standard conditions: reference solar radiation 1000 W/m^2 and at 25°C.

\(SW_{cell}\): Shortwave radiation transmitted through the glazing and absorbed by the PV cell [W/m^2].

\(M\): Air mass modifier [-], the parameter which considers changes in the spectral distribution of the incident radiation (King et al., 2004);
\(\pi\alpha\): Transmissivity (\(\pi\)) absorptance (\(\alpha\)) product of the module glazing for the direct radiation \((\pi\alpha)_{\text{dir}}\), diffuse radiation \((\pi\alpha)_{\text{diff}}\), and ground reflected diffuse radiation \((\pi\alpha)_{G}\).

The PV-EB inputs and outputs from the module and the ground (bare soil) are illustrated in Figure 6.

\[\text{Figure 6: Schematic of the PV Energy Balance in bare soil. Inlet and outlet energy fluxes of the PV module and ground.}\]

The PV-EB in bare soil (Figure 7) is previously applied in Arizona conditions, which is also considered a desert. It is a flexible model, that is been reparametrized for the UAE meteorological conditions. The PV-EB reproduces a system with no latent heat contribution, since rainfall and groundwater evaporation are minimum in the UAE. Basically, the solar model needs meteorological data to run with additional setups of location, ground, and PV module. Multi-Crystalline type is selected. For the meteorological inputs the characteristics of interest are: radiation reaching the panels, air temperature, relative humidity, wind speed, and atmospheric pressure.

However, when we think on EB for APV systems application, we should consider the contribution of the convective fluxes coming from the ground with the introduction of the crop in the system, as it will be discussed further.
4.2 Evapotranspiration Model

Evapotranspiration Concept

The evapotranspiration from plants combines two different processes: the evaporation directly from the soil and vegetation surface and the transpiration through plant leaves, in which water is extracted by the plant's roots, transported upwards through the stem, and diffused into the atmosphere. Water losses from the leaf are driven by a gradient in water vapor concentration.
Penman first introduced the potential evapotranspiration concept (Penman, 1948), defined as the amount of water transpired in a given time by any short green crop completely shading the ground of uniform height when moisture supply is not limiting.

On the other hand, the reference evapotranspiration is defined as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance \( r_s \) of 70 s/m and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground”. In the reference evapotranspiration definition, the grass is defined as the reference crop, and this crop is assumed to be free of water stress and diseases (R. G. Allen et al., 1998).

Lastly, actual evapotranspiration is the sum of plant and ground ET when the soil is at its actual specific humidity, and the plants are at a specific stage of growth and health. As the soil dries out, actual evapotranspiration drops below its potential level. Actual evapotranspiration is a field measurement (R. G. Allen et al., 1998).

**Evapotranspiration Process and Factors**

The evaporation component comes from the energy balance linkage with the mass transfer. Afterward, by introducing resistance factors, the transpiration from the vegetation was coupled with the evaporation. One important resistance factor is the aerodynamic resistance \( r_a \), which represents the transport properties of the cropped surface (Figure 8). Aerodynamic resistance is a term that accounts for the turbulent flux of water vapor from the evapotranspiration mixing with a potentially drier atmosphere above it, describing the resistance from the vegetation upward and involving friction from air flowing over the vegetative surface. The factors depend upon the crop height \( h \) and canopy architecture. With observations of wind velocity \( u_{ref} \) and air temperature at the reference height \( T_{air, ref} \), the aerodynamic resistance can be obtained (R. G. Allen et al., 1998).

The main factors governing the evapotranspiration process are (1) energy supply, (2) vapor transport, and (3) soil moisture. Therefore, the principal parameters affecting evapotranspiration are conventional measured weather data: incident radiation, air temperature, water vapor content, and wind speed (R. Allen, 2005).
Daily Time Step

Calculation of ET on 24h time scales will generally provide accurate results. The required meteorological data consist of:

- Air temperature: maximum (Tmax) and minimum (Tmin) daily air temperatures.
- Relative humidity: mean daily data
- Wind speed: daily average for 24 hours of wind speed measured at 2 m height (u2).
- Radiation: daily integral of measured net radiation (Rn)

As the magnitude of daily soil heat flux (G) beneath the reference grass surface is relatively small, it may be ignored for 24h time steps (R. G. Allen et al., 1998).

Evapotranspiration Computation

The potential evapotranspiration calculation (Penman, 1948) is as follows:

\[
ET = \frac{\Delta R_{net} + \rho_a \cdot c_p \cdot e_{as} - e_a}{\frac{\lambda}{\rho_w} \cdot (\Delta + \gamma)}
\]

Equation 14

Where the parameters are calculated below:
\[
\Delta = \frac{\delta e_{as}}{\delta T_{air}} = \frac{4098\cdot e_{as}}{(237.3+T_{air})^2}
\]

Equation 15

\[
e_{as} = 611 \cdot e^{\frac{17.27+T_{air}}{237.3+T_{air}}}
\]

Equation 16

\[
e_a = e_{as} \cdot RH
\]

Equation 17

\[
\Upsilon = \frac{c_p \cdot P_{atm}}{0.622 \cdot \lambda}
\]

Equation 18

\[
\lambda = 2.501 \cdot 10^6 - 2370 \cdot T_{air}
\]

Equation 19

\(R_{net}\): Incident radiation over the crop [W/m²]. Net radiation (\(R_{net}\)) comprises the shortwave and longwave incomings from the atmosphere. We may utilize the PV array geometry for conventional modules (Si-c) (the module's length, width, and height above ground, length, and width of the PV rows) to estimate a shade fraction over the crop.

\(\rho_a\): mean air density at constant pressure \([\text{kg/m}^3]\), \(\rho_a = 1.293 \text{ kg/m}^3\) (Beven, 1979).

\(\rho_w\): water density \([\text{kg/m}^3]\), \(\rho_w = 1000 \text{ kg/m}^3\)

\(c_p\): Air heat capacity \([\text{J/kg °C}]\), \(c_p = 1013 \text{ J/kg °C}\) (R. G. Allen et al., 1998).

\(P_{atm}\): Atmospheric pressure \([\text{Pa}]\)

\(\Delta\): Gradient of the saturation vapor pressure with temperature \([\text{Pa/°C}]\).

\(T_{air}\): Air temperature \([\text{°C}]\).

\(e_{as}\): Actual saturation vapor pressure \([\text{Pa}]\).

\(e_a\): Actual vapour pressure \([\text{Pa}]\).

\(RH\): Relative humidity \([\%]\).

\(\Upsilon\): Psychrometric constant \([\text{Pa/°C}]\).
\( \lambda \): Latent heat of water vaporization [J/kg].

\( r_a \): Aerodynamic resistance from the surface to the air layer at \( z_{\text{ref}} \) [s/m]. Equation 20 is restricted for neutral stability conditions, where temperature, atmospheric pressure, and wind velocity distributions follow nearly adiabatic conditions

\[
 r_a = \frac{\left[ \ln \left( \frac{z_{\text{ref}} - d}{z_{0h}} \right) \right]^2}{(\kappa^2) \ast u_{\text{ref}}} \\
\text{Equation 20}
\]

\( z_{\text{ref}} \): Reference height [m].

\( d \): Zero-plane displacement [m], height within the canopy at zero wind speed (\( u = 0 \)).

\( z_{0h} \): Roughness length governing heat and vapor transfer [m].

\( \kappa \): Von Karman’s constant, [0.41].

\( u_{\text{ref}} \): Wind speed at a 2m [m/s] reference height.

Zero displacement heights and roughness lengths are considered in the aerodynamic resistance calculation when the surface is covered by vegetation, which is the APV system case. For a wide range of crops, the zero-plane displacement height (d) and the roughness length for heat and vapor transfer (\( z_{0h} \)) are commonly estimated from the crop height (h) by:

\[
d = \frac{2}{3} h \\
\text{Equation 21}
\]

\[
z_{0h} = 0.0123h \\
\text{Equation 22}
\]

**Salinization and Evapotranspiration**

Throughout the globe, salt-affected soils account for nearly 10\% of the total land surface of our planet. Salinization is a common issue in arid and semiarid parts of the world (FAO, 2015; Perri et al., 2018), where it represents a significant threat for subsistence agriculture and food security. In salt-affected soils (as the sandy soils of the UAE), salt stress decreases crop transpiration with time. The increase in salt concentration (C) tends to reduce soil moisture, thus returning less water content to crops, which causes water stress and consequently less evapotranspiration rate. The magnitude of this process also depends on the crop's tolerance.
level. As highly salt-tolerant, as longer the crop performs in the maximum capacity for ET, as depicted in Figure 9. Salt-resilient species (halophytes) under saline conditions are more efficient in water use and transpire more than conventional crops (Perri et al., 2018).

Experimental studies have shown that above a crop-specific salt concentration threshold ($C_T$), crops start to linearly decrease relative crop yield rate ($\frac{\text{Actual yield}}{\text{Potential yield}}$) in response to increasing salt concentration over weeks to months. Hence, it is reasonable to understand that ET and plant growth are linearly related (Perri et al., 2018).

![Figure 9: Typical transpiration patterns for highly salt-sensitive (black line), moderately tolerant (red line), and highly tolerant (blue line) species (Perri et al., 2018).](image)

4.3 Agrivoltaic Energy Balance (APV-EB)

From bare soil to cropland conditions, evapotranspiration performing as evaporative cooling is added as a weighty component. Connected to that, sensible heat flux (warming component) from the PV module, together with the heating of land and atmosphere, tends to decrease with the introduction of vegetation,

In addition, solar PV arrays shade the ground where they are placed, reducing the land surface temperature compared to the condition without solar panels present. Shade from the PV arrays may enhance the cooling process at the surface and reduce crop water consumption (Hélène Marrou, 2019).
It is known that conventional PV panels, due to their darker color, absorb solar radiation more effectively than do ground surfaces, leading to a warming effect in the surrounding areas as the absorbed radiation is released as heat. This process is known as Photovoltaic Heat Island (PVHI) (Barron-Gafford et al., 2016). However, vegetation below the panels tends to increase evapotranspiration benefiting from the shade. Such an increase in ET cools down the modules. Therefore, a synergy between the vegetation and PV panel can be established.

In this way, evapotranspiration from the crop is incorporated into the PV-EB model as latent heat flux ($\lambda ET \frac{W}{m^2}$) to access the PV energy balance under the APV system. Figure 10 reproduces the hybrid system of crops under PV panels and shows a reduction in the sensible heat from the panel and the ground caused by the latent heat incorporation. This energy budget was developed for conventional photovoltaic panels and did not differentiate between direct and diffuse radiation.
Figure 11 illustrates the evapotranspiration (ET) model inputted in the PV-EB and obtaining the agrivoltaic energy balance system (APV-EB) with its outputs. The inputs in the PV-EB remain the same, with some changes in ground inputs: the albedo and emissivity of a vegetative area substitute the albedo and emissivity in bare soil. The APV-EB model expects some reduction in the PV module temperature and a consequent increase in PV performance, followed by a slight improvement in electrical power production (P). Both the PV-EB and the APV-EB model are run in a Python system. We are considering here the need for full irrigation since rainfall is completely scarce in the UAE.

It is crucial understanding the Energy Balance and the alteration in the thermal regime of the panel under a new system, the APV, by incorporating the patterns of evapotranspiration to the EB considering the ground inputs. It will allow to understand the partitioning of sensible and latent heat and how these fluxes are affecting the temperature of the air.

Sensible heat is subtracting heat from the PV module. The panel cools down depending on the temperature of the air. The capacity of the panel to cool down depends on the gradient of temperature between the panel and the atmosphere, as we can see from Equation 11 previously presented. In order to add the latent heat component on the system, it would require data from the ground, which unfortunately is not available. Then, new air temperatures generate sensible heat fluxes from the panels in an APV system.
Figure 11: Flowchart of the APV Energy Balance.
5. Data Description

5.1 Meteorological Data

Land Surface Temperature (LST) was obtained from the Copernicus Climate Database as hourly resolution (Muñoz Sabater, 2019) for Masdar City - UAE location (latitude: 24.4267° N, longitude: 54.6150° E) for 2018, 2019, and 2020.

UAE albedo was obtained for the vegetated area (latitude: 24.4425° N, longitude: 54.3795° E) and bare soil (desert: latitude: 23.2273° N, longitude: 54.8542° E) from the Moderate Resolution Imaging Spectroradiometer (MODIS) MCD43C3 Bidirectional Reflectance Distribution Function and Albedo (BRDF/Albedo) (Schaaf, C., Wang, 2015). Albedo dataset is produced in a 0.05-degree Climate Modeling Grid (CMG). MCD43C3 provides black-sky albedo (directional hemispherical reflectance) and white-sky albedo (bi-hemispherical reflectance) at local solar noon. Both values are available as a separate layer for MODIS spectral bands from 1 to 7 and the visible, near-infrared (NIR), and shortwave bands. From 2012 monthly data, it calculates an average for each site, resulting in:

Albedo for a vegetated area in the UAE: 0.160
Albedo for a desert area (bare soil) in the UAE: 0.376

The input meteorological data used in the EB Model are from the Masdar City sensors in Abu Dhabi, UAE. The variable inputs are detailed in Table 1:

<table>
<thead>
<tr>
<th>Meteorological Parameter</th>
<th>Abbreviation</th>
<th>Unit</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Radiation</td>
<td>GHI</td>
<td>W/m²</td>
<td>Irradiometer</td>
</tr>
<tr>
<td>Diffuse Radiation</td>
<td>DHI</td>
<td>W/m²</td>
<td>Irradiometer</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Tair</td>
<td>°C</td>
<td>Airphoton Nephelometer</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>RH</td>
<td>%</td>
<td>Airphoton Nephelometer</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>u</td>
<td>m/s</td>
<td>Ultrasonic Wind Anemometer</td>
</tr>
</tbody>
</table>

The selected data is from 2018, 2019, and 2020 with a one-minute resolution. Considering data issues and gaps from power shutdown, tracking, working instruments, and maintenance, the chosen years showed better confidence in terms of data resolution.
It is also essential to consider the environmental and weather conditions for the data assessment. Masdar City is a construction site located in a desertic country. Therefore, the site is surrounded by dust all year round and high humidity typical of the UAE.

Data assessment and cleaning were performed to ensure that the data was free of incorrect information and outliers. Below is the graphical description of the input parameters from Masdar City. The average of all days was computed per minute for each month and picked the month’s maximum, mean, and minimum values. The peak values were obtained from the day with the highest record of each month. The diurnal mean ranges from 8 am to 5 pm for the radiation plots. The daily mean of sunlight is 10h over the year which agrees with other studies (Das, 2014; Mas’ud et al., 2018), but hours of sunlight can reach more than 12h in Summer.

The GHI depicted in Figure 12 presents high average monthly values and peaks for the region, with an 1174 W/m² maximum average in June and a 1260 W/m² peak in July, during the summer season.

The DHI illustrated in Figure 13 shows high average monthly values and peaks for the region, with a 346 W/m² maximum average and 571 W/m² peak in July. DHI is shown as very high in UAE, mainly due to dust and humidity, adding that Masdar City is a construction site.
Air Temperature in Figure 14 also presents extreme average monthly values and peaks. The maximum average of 45.7 °C and the peak of 51.2°C occur in July, during Summer.

Relative Humidity is also high in the country, as presented in Figure 15, with peak values close to 100%.
Wind speed is usually low in UAE. Figure 16 shows monthly maximum averages ranging from 2.6 m/s to 4.2 m/s.

Table 2: Meteorological characterization for two representative months of Summer and Winter, respectively, June and December. Average data from 2018 to 2020.

<table>
<thead>
<tr>
<th>Meteorological variable</th>
<th>June - Summer</th>
<th>December - Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{air, peak}}$ (°C)</td>
<td>47.9</td>
<td>31.5</td>
</tr>
<tr>
<td>$T_{\text{air, mean}}$ (°C)</td>
<td>36.2</td>
<td>21.7</td>
</tr>
<tr>
<td>$T_{\text{air, min}}$ (°C)</td>
<td>30.6</td>
<td>16.3</td>
</tr>
<tr>
<td>$u_{\text{mean}}$ (m/s)</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>$\text{RH mean}$</td>
<td>54.7</td>
<td>69.3</td>
</tr>
<tr>
<td>GHI mean daily (MJ/m²)</td>
<td>32.5</td>
<td>15.5</td>
</tr>
</tbody>
</table>
5.2 Crop Data

Assuming quinoa as the specific crop for the present APV model in UAE, the quinoa data to input in the evapotranspiration (ET) model was obtained from Razzaghi et al. (2020). The experimental site locates at the Research Station at Agricultural College, Shiraz University, Iran. The texture of the soil at the research station is silty clay loam. Even though the air temperatures are not as high as in UAE in Summer, Iran is a country dominated by an arid and semiarid climate, highly affected by water scarcity and high salinity levels. Therefore, these climatic and environmental characteristics can be compatible with the UAE's condition.

The quinoa seeds (cv. Titicaca) were sown on March 31st, 2017. The 2017 growing season happened in Summer, from June 11th to July 14th. This is the period of interest since it is when the crop germinates, develops leaves, and the evapotranspiration process takes place.

Full irrigation water treatment (100% irrigation water requirement) was chosen to avoid water stress and reach better evapotranspiration values for the selected crop data.

The physiological parameter incorporated in the ET model is the crop height (cm) with daily resolution from June 11th to July 14th. The quinoa height ranges from 49.3 cm to 108.4 cm during the growing season.
5.3 PV module Specifications

The PV module applied in the Energy Balance model is a Trina Solar TSM-315PD14 type, Polycrystalline technology, similar to Heusinger et al. (2020) for comparison purposes. The PV module is set in a $20^\circ$ fixed-tilted configuration optimized for Summer and facing due south (The suitable direction for PV panels in UAE). In a future case of an experimental project in Masdar City, the selected tilt angle is supported by PV systems already implemented at $20^\circ$ in this location. The adopted tilt angle is very close to the optimum value of $22^\circ$ for Abu Dhabi (Jafarkazemi & Saadabadi, 2013). Table 3 describes further details on dimensions and operating parameters for the PV model.

Table 3: Specifications of Trina Solar TSM-315PD14 PV module used in the EB model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power (Pmax)</td>
<td>315 W</td>
</tr>
<tr>
<td>Nominal Efficiency</td>
<td>16 %</td>
</tr>
<tr>
<td>Maximum Power Point Voltage (Vmpp)</td>
<td>37.0 V</td>
</tr>
<tr>
<td>Short Circuit Current (Isc)</td>
<td>8.85 A</td>
</tr>
<tr>
<td>Maximum Power Point Current (Imp)</td>
<td>8.38 A</td>
</tr>
<tr>
<td>Cells</td>
<td>72 (6 x 12)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1.96 m x 0.94 m x 0.04 m</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°C + 85°C</td>
</tr>
</tbody>
</table>
6. Results and Discussion

6.1 Photovoltaic Panels in Bare Soil

The photovoltaic module temperature (Figure 17) and the power output (Figure 19) from January to December were modeled from the previously described PV panel and meteorological data. As already discussed, the UAE region characterizes by elevated air temperature and global radiation all the year with low wind incidence. The PV module tends to reach extremely high temperatures in this climatological scenario, especially in Summer. From the results, the maximum daily average (69.1 °C) and higher peak (75.9 °C) in Summer happen in July (with a mean of 46.5 °C and minimum temperature of 33.7 °C), followed by June (maximum daily average of 69.1 °C, a peak of 75.9 °C, and mean of 44.3 °C). In December (Winter), the module temperature reaches a peak of 47°C, a maximum daily average of 41.8 °C, a mean of 25.6 °C, and a minimum of 16.6 °C.

Figure 18 presents a correlation between the temperatures of the air and the PV module in Masdar City as an average for the winter and summer seasons. It is a diurnal assessment. For the both seasons there is an approximate linear and direct correlation between air and PV temperatures. In general, it is observed for the two seasons that the panel has a wider thermal amplitude than the air, as expected for the panel properties in terms of thermal capacity. Considering a nearly linear relation, the slope of the curves increases from winter to
summer. While the air temperature varies 10 degrees during the day for both seasons, the panel temperatures vary more, around 24 degrees in Winter and 28 in summer. In case that latent heat is added it would be expected messy linear patterns, which would need to be assessed first from the field measurements.

![Figure 18: PV module temperatures as a function of the air temperatures. Winter and Summer averages.](image)

The higher peaks of power output (Figure 19) occurred in May (188.5 W/m²), June (188.9 W/m²), and July (185.4 W/m²), during Summer. The maximum averages for these months were 179.2 W/m², 178 W/m², and 168.6 W/m², respectively. The diurnal means are computed from 8 am to 5 pm. The calculated diurnal means for the most productive months are 142 W/m² (May), 143 W/m² (June), and 134.7 W/m² (July). However, it is observed that for the months of Summer presenting the highest temperatures (June, July, and August), the module power production starts to decrease, presenting less performance even with high GHI indices. On the other side, during Winter, December recorded most of the lowest results, with a maximum average of 122.2 W/m², a monthly peak of 138.8 W/m², and a diurnal mean of 84.2 W/m².
The PV module temperature and power production obtained from the PV Energy Balance modeling in bare soil for the UAE condition are compared with the outputs from Arizona, USA (Heusinger et al., 2020a). The same PV panel parameters (PV type, efficiency, and geometry) are applied for the two sites. Both sites are above the Equator line. Therefore, the Winter and Summer seasons roughly occur in the same months. Thus, the months of December and June are compared. The input and output data resolution from UAE are 1 minute, while for the Arizona condition, it is 5 minutes input and 30 minutes output resolution.

Figure 20 compares the daily average PV module temperature for the Winter (December) in both locations (Masdar City and Arizona). The maximum daily average of the PV panel temperature observed in Arizona was 33.7 °C around noontime, while in Masdar City, the maximum PV panel temperature was around 8 °C higher (41.8 °C). On the other hand, in June (Summer), the solar panel reached the maximum daily average of 59.4 °C around noon in Arizona, 9.7 °C lower than in Masdar City (69.2 °C) for the same period (Figure 21).

In all the representations of module temperature (Figure 20 and Figure 21) it is observed that the line on the right side, corresponding to the evening period, is higher than the left side, the morning period. It occurs due to the heat absorbed and still being dissipated during the evening.
Figure 20: Modeled average daily behavior of PV panel temperature from two different sites and climates in December (Winter season). Left: Masdar City, UAE. Right: Arizona, USA (Heusinger et al., 2020b).

Figure 21: Modeled average daily behavior of PV panel temperature from two different sites and climates in June (Summer season).

Figure 22 illustrates the comparison of the daily average PV power production for December in Masdar City and Arizona sites. The maximum daily average PV power production observed in Arizona was 84.4 W/m$^2$ around noontime, while in Masdar City, the maximum power was 122.3 W/m$^2$ in December. On the other hand, in June (Summer), the solar panel reached the maximum daily average of 97.2 W/m$^2$ around noon in Arizona. As for Masdar City, the power output is 178 W/m$^2$ for the same period (Figure 23). We can conclude that the same panel can be more productive in Masdar than in Arizona, owing mainly to better radiation levels. It is essential consider that the real power production would be lower than the one here that was modeled since we are not accounting for the dust deposition.
Figure 22: Modeled average daily behavior of PV power production from two different sites and climates in December (Winter season).

Figure 23: Modeled average daily behavior of PV power production from two different sites and climates in June (Summer season).

Figure 24 describes air temperature influencing power production from Winter to Summer. The results show that there is an increase in power from January to May, being May the most productive month. From May on, even with continuous increase in temperatures, from the beginning of Summer the module decreases Power production essentially because extremely high temperatures start to lower efficiency. From May to July power losses of about 6% are observed from the modeling.
6.2 Agrivoltaic Scenario

From the PV system in bare soil to the agrivoltaic setup, the crop evapotranspiration (ET) is calculated as an integral of each day of the cropping season and added to the Energy Balance. The potential evapotranspiration of quinoa (PET, mm/day) was modeled during 33 days of the growing season (from June 11th to July 14th) (Figure 25). The PET monthly average values are 4.32 mm/day (June) and 4.19 mm/day (July).

Assuming there is no latent heat contribution in the model for the bare soil condition (Heusinger et al., 2020a), the PV convective heat flux accounts only for the sensible heat component, which is considered a warming parcel. As the agriculture is under the PV system, the latent heat contribution (cooling parcel) is incorporated into the convective fluxes. A trade-off happens between sensible and latent heat fluxes, in which the increase in one of them leads to a respective reduction in the other.

From the energy balance of the PV panel, modeled after Jones & Underwood (2002), the variation in the PV module temperature ($\Delta T_{mod}$) is dynamically dependent on changes in radiative and convective fluxes. In this case, a reduction in the sensible heat flux tends to create negative variations in the module temperature and, consequently, cool down the PV panel by a natural vaporization process.
Figure 25 represents the potential evapotranspiration addition to the system. During the growing quinoa season, the monthly mean for June is 4.3 mm/day, while for July, 4.2 mm/day. Even though the crop height is continually increasing, the evapotranspiration behavior showed to be more dependent on the meteorological conditions, mainly the radiation. For instance, on July 5th there is a sharp decrease in the potential ET to 3.6 mm/day compared to the other days. When investigating the reason, from the input data there was a reduction in the radiation of around 15% on the same day. Expanding more on it, the stomata is the part of the plant responsible for opening up so the plant releases water vapor to the outside. By diffusion CO2 enters the leaf to add in the photosynthesis process by fixing carbon. The stomata only opens when there is available light for the leaf. In this way, with reduced light the stomata may not open and that’s why the plant transpires less.

![Modeled Quinoa Potential Evapotranspiration during growing season](image)

*Figure 25: Modeled quinoa potential evapotranspiration (mm/day) during 33 days of the growing season.*

The next step is to incorporate the patterns of evapotranspiration to the Energy Balance considering the ground Energy Balance to have a clear idea on the partitioning of sensible and latent heat and how these fluxes are affecting the temperature of the air. Then, realistic air
temperatures can be used to recalculate sensible heat fluxes from the panels in a second context, with the green cover under the APV system.

Adding the latent heat component on the system through experiments would require data from the ground, which is not available in this project for the absence of an experimental field. The other way would be by modeling, and it would need Energy Balance of the surface. It means that it is necessary to know the partitioning between sensible and latent heat. As already discussed, as higher the latent heat flux, lower will be the sensible heat and consequently lower will be the air temperatures. Air temperature for the cooled system would be computed from the model to obtain the sensible heat from the panel and so calculate the PV panel outputs, temperature and power.
7. **Conclusions and Future Work**

The current research has been conducted by modeling the PV energy balance under two different systems, ground-mounted photovoltaic in bare soil and agrivoltaic system, both under Masdar City, UAE, climatic conditions.

The work focused on the thermal performance and analysis of power production from a polycrystalline PV panel in a fixed configuration oriented at 20°. It is vital to consider that the power output and consequent performance of the PV system not only depends on the module characteristics (such as PV type, nominal efficiency and maximum power, tilt angle, and orientation) but also relies on the environmental conditions in which the system is deployed. In locations such as UAE, the influence of climate on the PV efficiency is even more intense.

The pre-existing model from Heusinger et al. (2020a) provides the basic machinery to deal with the energy balance of conventional photovoltaic technologies. This model is implemented in Python. Further, the available climatological database from Masdar City (UAE) is incorporated into the model to simulate PV performance for UAE conditions.

Masdar City (Abu Dhabi, UAE) meteorological conditions assessed from 2018 to 2020 record extreme indices of GHI, DHI, and air temperatures, especially during Summer. These conditions agree with the studies reported in the literature. In addition, the model results showed that the highest power yield occurred during the summer months.

The introduction of quinoa under the PV setup turns it into an APV system. The adaptation from the PV-EB model to the APV-EB is made by incorporating quinoa evapotranspiration into the simulation. Thus, the new system's PV thermal and electrical performance is assessed by adopting the same input weather conditions from the bare soil scenario (radiation, air temperature, relative humidity, and wind speed). Available crop data is regarding the growing period when the evapotranspiration process happens. Hence, connected to the crop data, the APV assessment takes place in Summer, from June to July, representing the most critical period in terms of climate conditions in the UAE.

It is concluded from this work that the PV module exposure to extreme heat mainly by high radiation and temperature in hot deserts as UAE potentially reduce PV performance.

From the APV-EB it would be expected that since crops like quinoa are able to transpirate in conditions that are similar to the one in UAE, we may have a benefit from having crops under the panels. It also possibly benefits the PV thermal and electrical performance under the APV
scenario. In this way, the natural cooling from the crops under the panels is a potential addition that may ameliorate PV behavior.

The absence of an APV experimental site in similar climatic conditions limited a broader assessment of the APV system. For instance, limitations in assessing the efficiency improvement of the PV module from the bare soil to the APV scenario in actual outdoor conditions.

On the agricultural side, without the complementary of an experimental project, there was no feedback from the crop. Thus, without a physical system, it was not possible to assess the energy balance between the panels and the crops with simultaneous feedback from each and then obtain more accurate results. Therefore, it was not feasible to estimate the impact of the APV system on the quinoa growing traits, evapotranspiration changes, and agricultural production. Another constraint was the inaccessible data for validating the modeled PV output in bare soil conditions with an existing PV testing field in the exact location of the weather inputs.

These limitations could be helpful to open ways for future improvements. Based on the learning obtained from this project, the following further studies are suggested:

1) To Expand the present model to the presence of sensible and latent heat fluxes both at the surface and this should be done with direct observations by performing experimental tests

2) Add the assessment of soiling losses to the model and further compare it with the field performance. It would give a complete analysis of the PV performance in both scenarios, bare soil and under the APV system, and show if APVs can somehow help minimize soiling losses.

3) Extrapolate the photovoltaic analysis to transparent CPVs and benchmark the PV technologies, followed by a field validation to have a more comprehensive assessment of PV performance under APV systems in arid or desertic conditions. It would be more feasible to decide the most appropriate technology for APV systems in arid climates.

4) Assess the possibility of a zero-energy APV in which the system can be modeled and dimensioned based on the APV energy and agricultural demand.
References


Pawlak, K., & Kolodziejczak, M. (2020). *The Role of Agriculture in Ensuring Food Security in Developing Countries: Considerations in the Context of the Problem of Sustainable Food Production.*


