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TOPICAL REVIEW

A Concept of Smart Agro-Photovoltaic Tunnels

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ABSTRACT This paper is a review of chosen reports on the integration of photovoltaics and agrotechnics and also presents the concept of an agro-photovoltaic foil tunnel module. This concept assumes the possibility of integrating modules into intelligent agro-photovoltaic fields. The proposed solution combines cultivation in a foil tunnel with a photovoltaic farm. The paper reviews electronic solutions to control ambient parameters, particularly those influencing the rate of photosynthesis in foil tunnels. The article also presents an analysis of the energy and water balances of the module in 4 different climate zones, including locations in Poland, Spain, Algeria, and Colombia. The module's water requirements include drip irrigation and fogging systems. Water is assumed to be obtained from rainfall, desalination, non-conventional (treated, desalinated) resources, groundwater, and sub-artesian wells. The module's energy needs include electricity consumption for pumping freshwater, desalination and water treatment, irrigation and fertilization, additional lighting and heating of plants, folding and unfolding of foil covers, and energy consumption related to automation. The article also analyzes crop shading by solar panels and its impact on the selected crop. The functionality of the presented solution was assessed for tomato cultivation in the four selected areas. A 240 m^2 foil tunnel was considered. 60 m^2 of the tunnel was covered by PV panels. The analysis results show that the most energetically effective agro-photovoltaic cultivation of tomatoes appears to be in the Saharan region of Africa where a 16 MWh annual energy surplus was obtained. Cultivations in Spain (Cartagena) and Colombia (Cali) seem to be slightly less effective, with approximately 15.5 MWh/a. The least effective agro-photovoltaic cultivation of tomatoes proved to be in Poland where the energy surplus reached 8.5 MWh/a. However, the economic return from cultivation strongly depends on local energy and tomato prices. The system of smart tunnels proposed by the authors combines photovoltaics with controlled protection of crops against unfavorable and extreme climatic conditions. In addition, the system allows plants to be grown with the maximum possible days with natural growing conditions, i.e. with uncovered tunnels, with natural bio-fertilization, and with natural sunlight.

INDEX TERMS Smart agriculture, agro-photovoltaics, foil tunnel, photosynthesis, fertilizer, greenhouse, drip irrigation, control system, water management, energy balance, monitoring.

ABBREVIATIONS

Af	Tropical rainforest climate.
Am	Tropical monsoon climate.
APV	Agro-photovoltaic.
APVT	Agro-photovoltaic tunnel.
ATP	Adenosine triphosphate.
Aw	Tropical savanna climate.
BSh	Hot semi-arid climate.
BSk	Cold semi-arid climate.
BWh	Hot desert climate.
BWk	Cold desert climate.

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C_{ar}	Ambient CO_2 concentration.
CC	Cloud Computing.
Cfc	Subpolar oceanic climate.
Chl A	Chlorophyll A.
Chl B	Chlorophyll B.
C_i	Intercellular CO_2 concentration.
Csc	Cold-summer Mediterranean climate.
Cwc	Cold subtropical highland climate.
Dfa	Hot-summer humid continental climate.
Dfb	Warm-summer humid continental climate.
Dfc	Subarctic climate.
Dfd	Extremely cold subarctic climate.
Dsa	Mediterranean-influenced hot-summer humid continental climate.
Dsb	Mediterranean-influenced warm-summer humid continental climate.
Dsc	Mediterranean-influenced subarctic climate.
Dsd	Mediterranean-influenced extremely cold subarctic climate.
Dwa	Monsoon-influenced hot-summer humid continental climate.
Dwb	Monsoon-influenced warm-summer humid continental climate.
Dwc	Monsoon-influenced subarctic climate.
Dwd	Monsoon-influenced extremely cold subarctic climate.
ET	Tundra climate.
EF	Ice cap climate.
E_{SOL}	The amount of kWh of energy obtained annually from photovoltaic panels.
E_{CROP}	The amount of kWh of electricity needed in a calendar year to maintain the crop.
$E_{S/N}$	The amount of kWh of electricity saved (positive $E_{S/N}$) or needed to be delivered (negative $E_{S/N}$) per year.
I_{PAR}	The intensity of sunlight in the range of 400-700 nm (3.1 … 1.77 eV), reaching the plant [W/m^2].
I_{PPFD}	The intensity of photosynthetic flux density [μmol(photons) $\cdot$ m^{-2} $\cdot$ s^{-1}].
I_{TOTAL}	Total sun radiation [W/m^2].
IoT	Internet of Things.
I_{12}	Intensity of Sun Light in the noon.
IR	Infrared.
LC	the point defined as the value of the intensity of flux **I** activating molecules of chlorophyll A, B and carotene, at which the rate of photosynthesis is the same as the rate of respiration.
NADPH	Nicotinamide adenine dinucleotide phosphate.
NPK	Nitrate, phosphorus and potassium.
PAR	(see I_{PAR}).
Pn	The net rate of photosynthesis driven by the photon stream I_{PAR} activating chlorophyll and carotene molecules.
PPFD	(See I_{PPFD}).
PVP	Photovoltaic panel.
VIZ	Visible light.
WSN	Wireless Sensor Networks.
W_{DES}	Water from desalination [m^3].
W_{TR}	Water from wastewater treatment [m^3].
W_{PUMP}	Water from other conventional resources [m^3].

I. INTRODUCTION

In recent years, existing limitations in land use rooted in the expansion of industrial and urban areas and the desire to increase the efficiency of land use, have motivated an initial search for co-production of electricity and agricultural biomass on the same land. Since the beginning of the 20th century, windmills fitted with electrical generators have been located on fields or pastures for off-grid electricity production. This was later followed by the development of big wind farms, both on-grid and off. A new system of this kind combined a photovoltaic farm with agricultural production. Such ideas and models appeared at the beginning of the millennium [1]. In recent years, new systems of what is known as ''agro-photovoltaic'' (APV) construction have been developed and tested [2], [3].

Striving to increase the use of solar energy, it turns out that self-sufficiency in the field of electricity production is not possible without limiting the land intended for agriculture [2]. This is due to the dispersed nature of solar energy, with an average production of 4-11 W/m^2. The concept of incorporating solar energy production into the agricultural process has been proposed in various construction forms over the past few decades [2], [4], [5].

Marrou found that although APV is promising, without major changes in agricultural methods, the loss of solar radiation on crops is a major factor in reducing yields, and, therefore, mitigating solar reduction should be the subject of future APV implementation and work [2], [4]. The Fraunhofer Institute has tested various solutions within experimental APV projects, showing a 60% increase in the efficiency of land use. Hybrid production seems to be promising: the observed reduction in agriculture crop production is not higher than 20%, and, at the same time, the reduction of electricity is not higher than 20%, as compared to a system where agricultural and electricity production are separated. The hybrid system (APV) also has another advantage: it preserves the agricultural character of farmland, which would become industrial areas if fully covered with solar panels [2]. Photovoltaic panels (PVPs) are a renewable energy source and should be widely used in agriculture, where the energy supply for food production is crucial [3].

The scope of global research work carried out in the field of agro-photovoltaics so far is very wide. This paper focuses only on the review of works on the integration of photovoltaics and foil tunnels. The result of reviewing solutions used in this field and the authors' own experience is the novel concept of a universal, intelligent APV tent that allows for plant production and generation of electricity, combined with effective water management and plant monitoring. Electric energy produced off-grid or on-grid can power devices such as sensors, cameras, automatic valves, water pumps, plant lighting devices, etc. Particularly important is the possibility of using electricity for water pumping or desalination, as part of the integrated water management, in order to increase water supply and enable expansion of agricultural land. This seems especially imperative for the Saharan countries like Algeria where solar energy is the most abundant natural resource. The insolation time in almost all of Algeria exceeds 2000 h annually and may reach 3900 h in the Sahara [6].

In addition, the APV tent concept makes it possible to collect rainwater from the surface of the foil and panels. The collected water might be used for crop (drip) irrigation. In addition to collected rainwater, pumping from natural freshwater sources, and desalination, an important source of water extraction for agriculture is treated household wastewater. According to the AQUAREC international project, between the years 2000 and 2006, more than 3300 wastewater facilities were registered worldwide. These wastewater facilities were characterized by different water treatment quality levels and use types, agriculture being the primary wastewater user [7]. The countries with the greatest number of reuse facilities were Japan and the United States (1800 and 800, respectively), followed by Australia and the European Union with 450 and 230, respectively. In the Mediterranean and Middle East regions, approximately 100 wastewater treatment facilities were identified, whereas Latin America was reported to have 50 facilities, and Sub-Saharan Africa had 20 [7].

Bixio et al. [8] analyzed the amount of wastewater used in agriculture: The European continent reused 963 Mm^3/year of untreated wastewater, whereas Latin America discharged approximately 400 m^3/s (c.a., 12614 Mm^3/year) of wastewater and subsequently used it to irrigate different crops [9]. However, reports from the Food and Agriculture Organization of the United Nations (FAO) stated that approximately 10% of the total global irrigated land area receives untreated or partially treated wastewater, approximately 20 million hectares in 50 countries [10]. Jiménez and Asano [11] have reported the estimated wastewater-irrigated area determined by country and by water treatment conditions.

Using treated wastewater in agriculture benefits human health and the environment, and the prevention of water pollution is an associated benefit [12], [13], [14]. The nutrients naturally present in wastewater allow for savings on fertilizer expenses ([15], [16]), thus ensuring a closed and environmentally favorable nutrient cycle that avoids the indirect return of macro- and microelements to bodies of water. Depending on the nutrients, wastewater may be a potential source of macro- (N, P and K) and micronutrients (Ca, Mg, B, Mg, Fe, Mn or Zn) [17], [18], [19].

Another benefit of agricultural wastewater reuse could be the avoided cost of extracting groundwater resources. The energy required to pump groundwater can represent up to 65% of the costs of irrigation activities [20].

Besides water needs, proper plant lighting also plays a crucial role. This is more important because PVPs which cover agricultural or horticultural tunnels shade crops, thus limiting sunlight directed at the plants. In some cases, this is an advantage of the system (e.g., in the case of excessive evapotranspiration). In other cases, where sunlight should not be limited, the proper design of the APV is crucial [1], [2].

The plant's response to light is a key factor throughout the plant's life cycle. Light serves not only as an energy source for photosynthesis, involving the photophysical and photochemical reactions by which plants convert light energy (with the participation of H_2O and CO_2) into carbohydrates and oxygen, but light also acts as information for the plant about the surrounding environment and therefore influences various types of reactions, from germination to fruiting. All these functions are possible because plants can accurately perceive intensity fluctuations, spectral changes, diffusion, and the diurnal and seasonal progression of light. All of this is encoded in specific photoreceptors. Therefore, shading should be approached with caution and local conditions should be taken into account [21], [22].

The subsequent sections describe this concept of an agro-photovoltaic tunnel (tent) which provides both conditions for optimal plant growth and simultaneous energy production from PV panels. This APV concept was assessed in four climate zones in Europe, Africa, and South America. The presented case studies focus on tomato cultivation (Lycopersicon esculentum).

In particular, sections II and III present and discuss the key parameters of electronic devices and systems for tracking plant growth. These systems allow for continuous recording of data (for example in the cloud), which are subsequently subject to automatic analysis, and then, in accordance with the proposed algorithms, the systems adjust climatic conditions in real time. In chapters IV and V, based on the literature and the authors' own experience, irrigation systems as well as methods of effective water and fertilization management are described. In the following sections, VI, VII, and VIII, we present estimated values of parameters calculated from the photosynthesis rate curve, based on the model. Using these estimated parameter values, we have proposed a method of controlling the climatic conditions in the tunnel. Among other things, sample measurements were used to calculate estimates of uncertainty of measurement for solar radiation in various time intervals and to determine the thresholds of solar underexposure from the point of view of maintaining the rate of photosynthesis. They were also used to determine the maximum area that can be covered by solar panels without the rate of photosynthesis falling below the established average rate for tomatoes. We have described and discussed the problem of real-time photosynthesis rate measurement, as well as the reasons why large-area farming should attach importance to spectroscopic analysis of leaves.

We have also proposed algorithms for data collection and automatic control in the tunnel. Section IX proposes our innovative idea of a tunnel with appropriately placed photovoltaic panels, which has a rewinding foil and combined meshes with different transmission, light diffusion, vapor permeability, and varying degrees of airiness. Section X presents the construction of the agro-photovoltaic tunnels which we have proposed and used in Poland. In Section XI, on the basis of the literature and our own experience, data on tomato cultivation for four locations are compiled and compared. The choice of cultivation was intentional as we had sought a photophilous and demanding plant, which could be grown in the conditions of the partial shade created by the panels. The abovementioned data were used to analyze the energy efficiency of the crop under the proposed shading system. In addition, the chapter includes an economic analysis of the profitability of tomato cultivation in agro-photovoltaic tunnels and attempts to generalize the proposed model to climate zones that have not been analyzed in detail in the article.

Currently, in the field of agro-photovoltaic vegetable crops (e.g., tomatoes), high-performance industrial greenhouse crop production, isolated from the environment in large greenhouse facilities, dominates, which is the method proposed in most works on this subject [23]. Industrial vegetable production is increasingly being carried out in multi-storey agro-photovoltaic greenhouses. For example, [24] describes research conducted in a high-tech greenhouse with six identical compartments at Wageningen University & Research in Bleiswijk, the Netherlands. The testing area was arranged on several floors, each of which measured 96 m^2. It was equipped with technology comparable to commercial high-tech greenhouse buildings. Growing tomatoes in agro-photovoltaic greenhouse buildings has the same advantages and disadvantages as any commercial high-tech greenhouse. Production is highly efficient and relatively cheap. The sanitary conditions are high, and hydration and fertilization are precise. The taste and appearance of tomatoes from standard commercial greenhouse buildings should be the same as that of tomatoes from agro-photovoltaic greenhouses. As some consumers prefer the taste of tomatoes cultivated in the fields, the proposed system of intelligent agro-photovoltaic tunnels may be the solution to meet the demand for both better tasting vegetables and more energy efficient cultivation.

The system of intelligent agro-photovoltaic tunnels (APVT) proposed by the authors combines photovoltaics with controlled protection of crops against unfavorable and extreme climatic conditions. Additionally, this model allows crop production with the maximum possible number of days with natural conditions, i.e., grown in natural soil, with a minimum amount of crop protection sprays, with natural bio-fertilization, and with sunlight.

II. PARAMETERS FOR PLANT CULTIVATION IN AGRICULTURAL MANAGEMENT

The Food and Agriculture Organization (FAO) estimates that in the near future, agricultural production will increase to meet the rising food demands due to population growth, especially in developing countries. The production increase will be attributable to new methods of land cultivation, in particular, changes from dry to irrigated land, and more efficient land management and modern agricultural practices, most of these due to technological development.

However, plant cultivation and plant growth dynamics are not limited solely to crop types. Complex interrelationships between plant, water, soil, and meteorological parameters, as well as other elements of the ecosystem, must also be taken into consideration.

Weather-related factors influence agricultural management of crop water needs throughout the different growing stages (e.g., irrigation demand). Whereas geographical location is the main factor for local climatic conditions, the most important weather parameters for the type of vegetation in a region, plant growth, development, and crop yield are:

i) rainfall, which increases soil water for root growth; ii) air temperature (most plants grow in temperatures between 12°C and 32°C); iii) solar radiation, also called insolation, for the photosynthetic activity of the plant; iv) atmospheric humidity, which regulates plant transpiration; and v) wind direction and speed (e.g., constant wind may lead to closing the leaf pores to reduce water loss).

Soil texture and structure (distribution of mineral grain size) set the conditions for water infiltration. Hydraulic, physicochemical, and mineralogical properties affect soil, water content (wetting–drying), nutrient needs (fertilizers), and nutrient transport to roots. Hydraulic properties (hydraulic conductivity) determine crop access to water uptake and nutrient transport. The main physico-chemical soil properties are pH and salinity. Soil pH determines nutrient availability for plants and soil microorganisms. The presence of salts in the soil reduces the ability of plants to uptake water due to increased osmotic pressure.

New technological developments may allow automated control of most of these parameters to improve agricultural management practices. These developments are reviewed in the subsequent sections.

III. SENSOR SYSTEMS USED IN AGRICULTURE

In order to effectively manage most of the plant cultivation processes such as irrigation, fertilization, temperature regulation, artificial lighting, and shading, it is necessary to obtain continuous information on the climate, soil conditions, and plant conditions. Such information is provided by sensor systems. Automated agricultural support systems use a wide variety of sensors to measure the parameters necessary to maintain optimal conditions [25], [26], [27], [28], [29]. This section presents examples of affordable electronic systems for commonly available control modules as well as highly specialized sensors for photosynthesis rate control.

A. AIR HUMIDITY AND TEMPERATURE SENSORS

Undoubtedly, the most important sensors in agricultural management are those which measure temperature and air humidity. Some popular examples of this type of sensor are DHT11, DHT21, BME280, SHT3x (with digital outputs), and LM35 (with analog output). These humidity

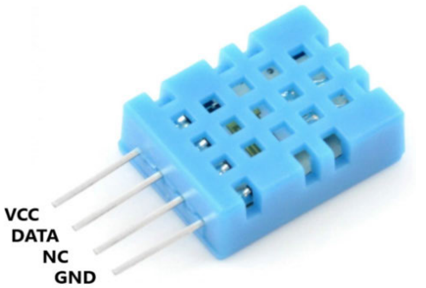

FIGURE 1. Temperature and air humidity sensor (type DHT11) [30].

measurement sensors use the capacitive method (with a hygroscopic polymer layer), whereas the temperature is measured via a thermistor (e.g., DHT21) or a diode junction (e.g., BME280). Although modern processors are usually equipped with ADC converters, due to possible interference, it is much more convenient to use a sensor that uses digital buses such as SPI, I2C, or 1-Wire. They facilitate easier application because modern microcontrollers possess built-in serial interfaces that enable easy connection of the sensor. Some sensors not equipped with a hardware 1-Wire port can be easily operated using the UART port.

One of the sensors most often found in the literature is the DHT11 system (e.g., [26], [27], [28]). DHT11 (Fig. 1) is a temperature and air humidity sensor with a digital, single-wire interface (despite a similar connection, it is not a 1-wire bus). The measuring range for air humidity is limited. Also, temperature measurement is limited to temperatures above 0°C, so it is useless for measurements in some climate zones where winter temperatures are negative.

The accuracy of humidity measurements and the repeatability of DHT11 sensors is relatively low (±4%). More detailed testing of various temperature/humidity sensors (including DHT11) can be found on the producer web page dedicated to sensor calibration [31]. Certainly, it is one of the cheapest sensors available for measuring humidity, hence its great popularity.

In recent years, some more precise sensors have been offered and their price is currently acceptable (especially taking into account the cost of control and communication modules).

If automation control systems require precise temperature measurement, other sensors than the DHT11 must be applied. The easiest solution is the replacement of the DHT11 with the DHT21 sensor. DHT21 (Fig. 2) has the same bus as DHT11. This modification of the reading protocol is minimal (due to the need to take into account the temperature sign and the ability to read decimals of measurements - which may be unnecessary in many applications). DHT21 (or AM2320) measures both air temperature and humidity and has a digital, single-wire interface (similar to DHT11).

The sensors described above are usually used as measuring elements in do-it-yourself systems. There are also integrated wireless sensors that use ZigBee or BTLE standards, which

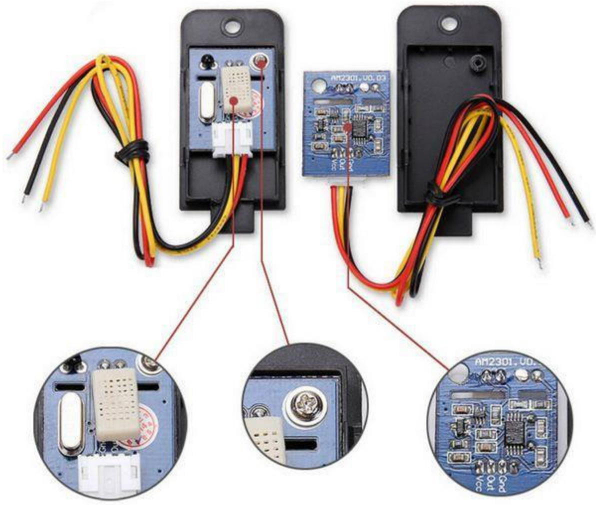

FIGURE 2. Temperature and air humidity sensor (type DHT21) [32].

FIGURE 3. ZigBee Xiaomi Mi wireless temperature and humidity sensor [33].

can be easily connected wirelessly with a designed system. An example solution may be the Xiaomi WSDCGQ01LM sensor (Fig. 3). This sensor is powered by a replaceable CR2032 battery that allows for 2 years of operation. The sensor has small dimensions (its diameter is 36 mm).

B. ATMOSPHERIC PRESSURE SENSORS

The most exemplary sensor for temperature, humidity, and, at the same time, pressure is the BME280 (Fig. 4). It uses a 2-wire I2C bus to read data. The system can work with voltage ranging from 1.71 V up to 3.6 V. Modules can additionally be equipped with voltage converters, enabling operation with voltage of 5 V.

A problem of the BME280 is that calculating its measured values can be quite complicated, although this can be simplified using libraries available on the Internet (e.g., on Arduino).

C. SOIL MOISTURE SENSORS

Proper measurement of soil moisture is very important for effective drip irrigation. One of the most popular and affordable soil moisture sensors is the FC-28 (Fig. 5), used in many projects dedicated to automation and drip irrigation [25], [26], [27], [28].

FIGURE 4. Module with BME280 sensor [34].

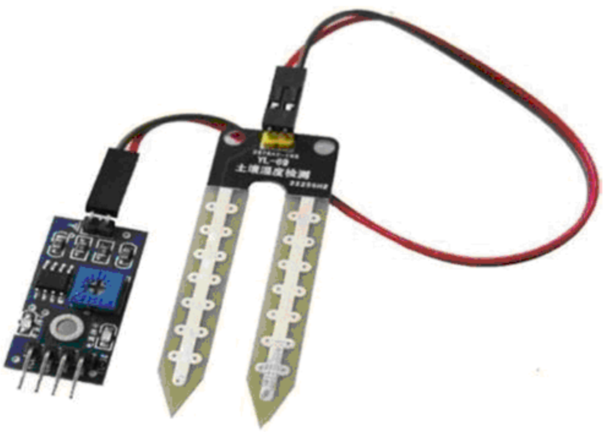

FIGURE 5. FC28 soil moisture sensor [35].

FIGURE 6. HONDETEC Soil PH Sensor [36].

FIGURE 7. MLX90614 contactless temperature sensor [37].

The principle of operation of the FC28 sensor is simple. Two large exposed electrodes act as sensor probes, between which a variable resistance resistor (depending on soil moisture) is formed. The more water there is in the soil, the better the conductivity between the electrodes. A signal proportional to the measured resistance is fed to an analog output. This voltage is also applied to the input of the comparator with an adjustable threshold. The comparator output is derived as a digital signal.

Unfortunately, a well-known problem with this design of soil moisture sensors is their short service life in a humid environment.

D. SOIL PH METERS

Another group of sensors are those used to measure the pH of the soil. An example is the HONDETEC Soil pH Sensor module (Fig. 6). It uses the RS485 bus to connect with control modules (it is also available with a current or voltage output).

E. LEAF TEMPERATURE SENSORS

The temperature measured inside the tunnel can differ significantly from the temperature of the plants. For advanced analysis of the photosynthesis process, it is necessary to measure leaf temperature. For this, it is necessary to use a non-contact temperature sensor that analyzes infrared radiation. One possible solution is to use the MLX90614 sensor (Fig. 7).

This sensor system integrates a highly sensitive thermoelectric detector and a processing part containing a low-noise amplifier, an ADC converter, and a DSP processor. The sensor has a wide measuring range from -70 to 360 °C. In the required leaf temperature range from 0 to 50 °C, measurement error does not exceed 0.5 °C. For temperature measurement, the system uses a 17-bit ADC converter and

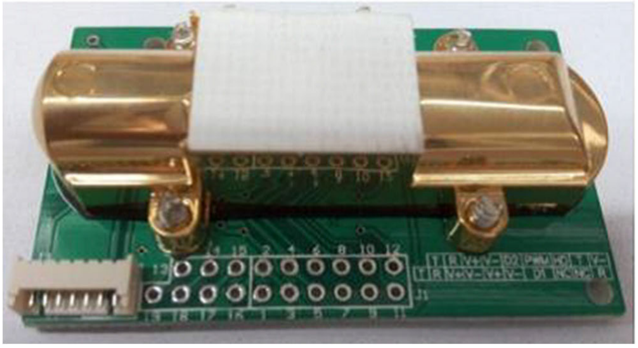

FIGURE 8. MH-Z14A CO2 sensor [38].

for data transmission, it uses a digital SMBus. The sensor is supported by the Arduino platform.

F. CO_2 SENSORS

Correct measurement of the photosynthesis rate, as well as the analysis of shading, also requires precise measurement of CO_2 concentration. The most commonly used type of sensor for measuring carbon dioxide concentration is NDIR. The principle of operation is as follows: The light from an IR (infrared) source is directed through a tube filled with a sample of tested air towards a detector located behind an optical filter. The band of IR radiation produced by the source is close to the absorption band of CO_2, i.e., 4.26 micrometers. As infrared light passes through the tube, CO_2 gas molecules absorb a specific band of infrared light while transmitting light at different wavelengths. At the end of the detector, the remaining light falls on the optical filter, which only transmits light at the wavelength absorbed by the CO_2 particles. The IR detector measures the remaining amount of light that has not been absorbed by the CO_2 particles or the optical filter, depending on the CO_2 concentration.

Modern sensors are designed with complex structures of waveguides, which makes it possible to minimize the dimensions while increasing the sensitivity of the sensor. The LED sources and semiconductor detectors that are used make it possible to reduce energy consumption, enabling battery or solar power supply. An example of this is the MH-Z14A sensor (Fig. 8). Its sensor in the useful range of 0-2000 ppm (the CO_2 starvation concentration is from 150-200 ppm, whereas optimal concentration equals 700-900 ppm) maintains an accuracy of ± 50 ppm. Temperature can be measured in a wide range of -10-50 °C and humidity from 0-95% RH. The maximum measuring range of the sensor (with lower accuracy) is 0-10000 ppm. It has both an analog output, PWM, and a digital UART interface.

G. SENSOR PARAMETERS

Sensor parameters are summarized in Table 1. Many sensors can measure two or more parameters. Usually sensors that measure temperature are also used to measure relative humidity. It is important to use the sensor whose measurement range corresponds with the range of values that can occur in the environment. Some of them are not suitable for monitoring temperatures below 0 °C.

H. COMMUNICATION PROTOCOLS

Sensors connected directly to the controller use popular wired buses (i2c, 1-wire), whereas the frequent need to arrange sensors over a relatively large area is conveniently managed using wireless links. One possible solution is to use the 802.11 standard, or WiFi (Table 2). The introduction of the SoC ESP8266 system (processor + WiFi) has contributed to the popularization of solutions using this standard. Unfortunately, the problem in this case is the relatively high power consumption of the radio system, which makes it impossible to use a sensor on battery power. The advantage is quite a long range, but all sensors must be within the range of the access point.

Currently, the market of wireless sensors is dominated by solutions using Zigbee and BLE (Bluetooth Low Energy) standards. Both of these standards have been optimized for low power consumption, so they can run on battery power for many months. An additional advantage is the ability to work in mesh networks, which can extend the range of the wireless network (remote devices can use other indirect sensors to connect to the controller)

IV. DRIP IRRIGATION AND FERTILIZATION SYSTEMS

Proper plant growth depends largely on the required water being supplied to the root system of a plant and on the correct application of fertilizers. With the increase of drought worldwide and the worsening problem of water scarcity, it is becoming increasingly important to use existing water resources sparingly. Appropriate drip irrigation systems, the type of applied water (surface, groundwater, treated wastewater), and plant fertilization are key factors.

A. IRRIGATION

Water supply is crucial for agricultural field management. Among the most critical issues, water management, usually combined with accurate fertilization, is fundamental. Recently, innovative technologies have improved water management and monitoring in agriculture. The Internet of Things (IoT), Wireless Sensor Networks (WSN) and Cloud Computing (CC), have been recently used for this purpose. One of the irrigation systems utilizing the above mentioned technologies was proposed by Khattab and co-workers [39] as a hardware prototype. The authors proposed a cloud-based IoT architecture composed of 3 layers. At the front-end layer, their proposal uses a Raspberry Pi 2 as a microcontroller, responsible for data collection: wind speed, rain volume, air temperature, and humidity. Communication between the nodes is performed via a gateway layer using an nRF24L01 wireless communication module operating at the frequency of 2.4 GHz. The cloud platform architecture is composed of both Apache and MySQL. Google data sheets are used for data visualization.

TABLE 1. Parameters of popular sensors most often used in agriculture 4.0.

Sensor type	Measured parameter	Measurement range	Accuracy	Supply voltage (power)	Data transmission protocol
LM 35	temperature	-55-150 °C	0.5-1 °C	4-30 V	Analog
DHT11	temperature relative air humidity	0-50 °C, 20-90% RH	± 2 °C ± 4% RH	3-5.5 V	Pseudo 1-wire
DHT21	temperature relative air humidity	-40-80 °C, 0-100% RH	± 1 °C ± 3% RH	3-5.5 V	Pseudo 1-wire
XIAOMI WSDCGQ01LM	temperature relative air humidity	-20-50 °C 10-90%	± 0.3 °C ± 3%	Battery CR2032	wireless ZigBee
BME280	temperature relative air humidity atmospheric pressure	-40-85 °C 10-80% RH 300-1100 hPa	± 1 °C ± 3% ± 1 hPa	1.71-3.6 V 5 V (with voltage converter)	I2C, SPI
MLX9061	contactless temperature	-70-380 °C	0.5 °C in range 0-50 °C	3-5 V version	SMBus, PWM
FC28	soil moisture	need the individual calibration in the environment	3%	3.3-5 V	Analog/Digital (0/1)
HONDETEC	soil pH	3-9 pH	0.3 pH	5-30 V	RS 485
MH-Z14A	CO_2	0-10000 ppm	50 ppm in range 0-2000 ppm	4.5-5.5 V	PWM, UART

TABLE 2. Communication protocols for sensor data transmission and storage in the cloud.

Standard	Range	Power Consumption	Topology	Remarks
GPRS	Very large (limited by the range of the GSM provider)	Large (up to 2A peak)	Star (connection to BTS)	active SIM card required (additional costs), useful for connecting the system to the Internet
WiFi	Medium (several hundred meters)	Large (tens of mA)	Star (connection to AP)	Used mainly in home automation (line powered)
ZigBee	Small (several dozen meters, can be enlarged thanks to mesh topology)	Low (designated for battery supply)	Star and mesh	A coordinator is required to read the sensors
BLE	Small (several dozen meters, can be enlarged thanks to mesh topology)	Low (designated for battery supply)	Star and mesh	The sensors can be read, for example, using a mobile phone

Dobrescu et al. [40] proposed real-time control of an irrigation system based on an IoT platform. The system was based on three main advanced technologies: IoT, cloud computing and a middleware mechanism for interaction between them (a context-aware platform). IBM's BlueMix cloud platform was used for data storage and real-time supervision. The monitoring unit sends the collected data to the BlueMix6 cloud platform using the MQTT protocol.

B. FERTILIZATION

The agricultural yield primarily depends on soil fertility, the moisture level of the soil, and the use of appropriate fertilizers (organic, mineral, liquid, or solid).

The study done by Zainal Abidin et al. [41] explored the potential of innovating the fertilizer distribution on crops in the agriculture sector through the implementation of automation and artificial intelligence (AI) technology. The study focused on the fertilizer application process. The proposed system, iFeeder, uses a mobile application, sensors, and microcontrollers in dispensing fertilizer on crops and monitoring soil condition. It allows users to conduct quick soil analysis, observe the results and apply fertilizer to crops via a mobile application. Shylaja and Veena [42], proposed a smart farm management system based on the IoT and soil nutrient analysis using WSN. The wireless sensors measure the presence of macronutrients in the soil and transmit the data to the cloud. The user can view the soil fertility by means of their mobile application. The software system automatically regulates the types and amounts of the required nutrients to be applied to fulfill crop needs, thus improving the quality of the soil and in turn, increasing the yield. Overall, the proposed system helps farmers gather real-time information on their soil and its fertility level, as well as recommending crops and nutrients via the mobile app. Wang et al. [43] in their experiment also created an integrated intelligent water and fertilizer management system based on IoT and WSN. Their sensors collected soil temperature and humidity, air temperature and humidity, lighting conditions, and other environmental information, with data storage in a cloud server. The cloud platform was used for data collection and analysis, and formulation of vegetable water demand, dose (NPK, i.e., nitrate, phosphorus, and potassium), fertilization timing, and other agricultural management. The results showed that the ratio of nitrogen, phosphorus, and potassium fertilizer was optimized by this management, and the absorption of NPK by vegetables and fruits was more complete. Other authors [44] analyzed data acquisition for precision agriculture based on remote sensing. They presented a program which updates, edits, and presents data, as well as offering management decision-making support, etc. to provide precision agriculture data quickly to the end-user. There are some obstacles regarding data acquisition for precision agriculture, limiting its wide applicability, so research on data acquisition for precision agriculture based on remote sensing is necessary.

Some companies provide ready-to-use smart agriculture systems for fertilization and irrigation. "AMI Penta-Milex" is an exemplary fertilizer application and irrigation control system [45]. The "AMI Penta Controller Fertilizer Computer" application offers a cost-effective alternative to purchasing completely new software and equipment (a fertilizer and irrigation mixer). The central software, SUPERLINK 5 For Windows, from the Danish company SENMATIC, is available for PCs and compatible with other hardware and software such as "Completa Fertilizer Mixer" and "Completa Climate Computer." The complete control system provides advanced management of plant growth, flexible setup of 100 irrigation groups, and pre-programming of up to 20 ingredient sets, designed for user needs.

The HortiMaX MultiMa has been the leading greenhouse environmental controller for years now [46]. This control computer is versatile and easy to operate thanks to its advanced Synopta software. The controller collects data from sensors such as the HortiMax PAR Sensor, which measures light in the photosynthetic spectrum. It is compatible with other systems (Clima500 and MultiMa) offered by the same producer [46].

An automatic and precise dosing fertilization system is offered by the Italian producer SPAGNOL SRL [29]. EvoJet is a fertigation unit with an injection dosing system. EvoJet can be configured to be installed in parallel with the pump that supplies water to the irrigation system (SP version) or connected directly to the main irrigation supply pipe (SL version). Equipment is available in two sizes, based on the capacity of the dosing channels: up to 600 l/h or up to 1000 l/h per dosing channel. The possibility of using two different types of dosing channels (with a high definition electronic flowmeter or a variable area flowmeter) provides application versatility. It uses the latest generation computerized system, ensures accurate nutrient dosing in irrigation water, and allows connection with multiple sensors for automating irrigation processes like Gravimatic and/or a weather station to control irrigation, fog, or anti-frost systems. In the case of long distances between EvoMix and the irrigation valves, these can be managed in two ways, either via radio thanks to Spagnol Radio System or by using the data bus Spagnol S-Bus. With the MC-Net, MC-Cloud, MC-SMS services, the user can remotely control the entire system via smartphone, tablet, or PC.

The Climate Corporation, based in the USA, offers Climate FieldView™- a crop management system [47]. The Climate FieldView™system supports farmers in collecting and analyzing field data, measuring performance, monitoring nitrogen, and building tailored seeding prescriptions. Data are collected and stored on one digital platform that can be accessed from the field, office, or home. The insights from field data are delivered by imagery and performance analysis tools, so farmers can make the best input decisions for their fields. The system supports building and developing a customized plan for any field application to manage variability and maximize yield with variable rate planting prescriptions and nitrogen monitoring tools. The greenhouse control system, ORION-MC, is offered by HOTRACO company [48], consisting of a communication interface between the horticulture computer (for crop management) and the Input-Output Interface (IO) units in the field, for example, the H1MC. The ORION-MC communicates through the CAN-local bus with the IO units. The ORION receives control commands from the horticulture computer and converts them into relevant control commands to the IO units through the CAN-local bus. With the ORION-MC, it is possible to create motor groups to control aeration and screens. Several motors can be assigned to each motor group. The climate computer controls aeration on the sheltered side of a separation by means of a climate group through the ORION-MC. The ORION-MC uses the IO units to control all aeration motors that belong to that climate group and reports this back to the climate computer. It is also possible to assign the ORION-MC motor groups to different controls [48], for example, to control the aeration and the screens, resulting in such effects as sequential or simultaneous run, two screens on a wire bed, post-pulse control on the screens, and frequency-based controls for aeration and screens. The producer also offers the PC management program, "The Rainbow+," which is part of the Orion-GC system. This visualizes the greenhouse data graphically in charts and diagrams on the user's PC. "The Rainbow+" application allows users to remotely control the Orion-GC system with a tablet or smartphone. It gives the farmer direct access to all greenhouse processes, such as screening, water supply, or climate control.

V. WATER MANAGEMENT

The most fundamental issue for the correct operation of irrigation and fertilization systems is the efficient extraction of water. In addition to the traditional methods of obtaining water from rainfall and natural freshwater sources, intense activities are currently being undertaken around the world to obtain water for irrigation from desalination processes and the treatment of water used in households.

A. WASTEWATER: TREATMENT AND REUSE

Wastewater reuse in agriculture is considered an efficient tool for dealing with water pollution and managing water resources [49], which involves treating wastewater for crop irrigation [50]. Nevertheless, quality standards for respective applications have not always been met. In the 19th century, transportation and final disposal of untreated wastewater into open peri-urban fields triggered epidemics of diseases such as cholera and typhoid fever [51].

Consequently, wastewater reuse has been a global concern due to the associated risks to public health and the environment. In 1973, the World Health Organization (WHO) drafted the document "Reuse of effluents: methods of wastewater treatment and health safeguards," with the aim of protecting public health and facilitating the rational use of wastewater in agriculture and aquaculture. The [52] drafted guidelines for safe use of wastewater, excreta, and greywater constitute a tool for the preventive management of wastewater in agriculture, providing clear guidance for decision-makers on wastewater application in different local contexts [53].

In 1987, the FAO developed guidelines for using wastewater in agriculture. These guidelines dealt with the degree of limitation of water consumption depending on salinity, infiltration, and toxicity parameters of specific ions [54], indications the quality of wastewater for agricultural use. The new EU Regulation EU-2020/741 [55], compulsory for Member States, on minimum requirements concerning water reuse for agricultural irrigation, is applicable to reclaimed water from wastewater gathered in collecting systems and treated in urban wastewater treatment plants.

Wastewater treatment is a complex process for removing existing contaminants in water with the objective of returning the effluents to the water cycle for further water reuse. Standard treatment in plants, based on physical characteristics and constituents of domestic water, consists of three main stages: primary (for settlement of solid particles), secondary (to degrade the biological content through aerobic biological processes), and tertiary (to raise the quality of water to defined standards and remove pathogens). For urban/domestic wastewater, several processes are involved: physical (sedimentation or flotation, to remove solids), biological, or chemical (to remove organic pollutants, bacteria, and pathogens). The outflow of highly treated water from a plant for its reuse is known as reclaimed water.

B. DESALINATION

Desalination, based on Reverse Osmosis technology (RO), is currently extensively applied in response to the problem of water scarcity. Large seawater desalination plants have rarely been considered for agricultural purposes due to the high costs of the water supply. Private small desalination plants, processing brackish water originating from natural saline aquifers or treated wastewater, with outputs of 15 or 20 m^3/h, have been promoted for agricultural irrigation of crops in water-scarce areas. Brackish water has a lower level of dissolved salts (2000-6000 μS), which prolongs the life span of RO membranes. A facility for agricultural management consists of a proper intake, a pond, and a desalination plant. Solar desalination, powered by solar energy, can be direct (thermal) and indirect (photovoltaic).

Desalination is a process of removing salts from water with a certain concentration, to obtain water with a very low salt content suitable for further consumption. The intake can be located at a seashore or in a pumping well. The final outcome of the desalination process is the brine. Nowadays, the leading process is RO technology based on the use of semi-permeable membranes to remove ions, molecules, and particles from water.

The characteristics of the water to be treated by desalination largely determine the most appropriate process to use, as well as the requisite pretreatment. Among the cited water characteristics are physical parameters, important in seawater desalination (turbidity, algae, absorbance, etc.), chemical parameters (such as salinity, temperature, pH, alkalinity, TOC, and DOC), and the presence of nutrients (the most important parameter). Brackish water (either natural or from wastewater treatment) does not require pretreatment for turbidity or other compounds.

VI. ARTIFICIAL LIGHTING FOR GROWING PLANTS

The fundamental biochemical process taking place in plant organisms is photosynthesis, thanks to which the plant produces oxygen and carbohydrates. This process requires water, carbon dioxide, and light. In the process of photosynthesis, the plant basically uses the visible light spectrum, ranging from 400 to 700 nm, i.e., photosynthetically active radiation (PAR) [56]. Plants absorb light in the PAR range, however, red and blue light is best absorbed, while absorption of green light, which is reflected to the greatest extent, is worse. Each plant has different molecules involved in photosynthesis.

In the temperate climate zone, the amount of sunlight reaching plants in the autumn and winter is significantly limited due to the short duration of the day. Moreover, due to the structure of a given greenhouse or agro-photovoltaic farm, it is often impossible to provide optimal light conditions for the cultivated plants [57]. Crop cultivation, based solely on natural light and existing weather conditions, is complex, and sustainable development is the basic criterion for a modern farm to be profitable [58]. As indicated in the literature, the lack of sunlight can be successfully supplemented with the use of artificial light [58], [59], [60].

The use of artificial lighting brings a number of significant advantages, including better control over plant development, predictable crop yields, and greater independence from climatic conditions [61]. Cultivation with the use of artificial light is more efficient and profitable, and artificially lit fruits and vegetables are more numerous, ripen much faster, are larger, and are of better quality and taste [62], [63], [64]. Plant illumination is especially beneficial in the winter when the prices of fruit and vegetables are high due to difficult growing conditions and the lack of conventional crop harvesting.

There are many types of electric light sources. A detailed description of their structure and operation principles can be found in [65]. Among the technologies of light sources for plant illumination, conventional incandescent lamps, fluorescent lamps (fluorescent lamps), metal-halide lamps, low-pressure and high-pressure sodium lamps, and LED semiconductor sources are most often used [66]. In addition to the above-mentioned types of light sources, there are also solutions using carbon arc lamps and solar lamps [65]. High-pressure sodium lamps (HPS) have commonly been used to provide additional illumination for plants in greenhouses, but they are characterized by low efficiency and generating large amounts of radiant heat. Currently, greenhouses are increasingly using lighting systems based on LED (light-emitting diode) technology, which is replacing older technologies [60], [63], [64].

The advantages of artificial lighting using different light sources for tomatoes have been repeatedly demonstrated. In Japan, an experiment was conducted to illuminate tomato crops with red, blue, and white light [67]. Individual sections of the crops were lit with each of these light sources separately, in such a way as to ensure the same energy consumption for each of them. Under the influence of white and red light, yield increases (fresh crop) of 12% and 14% were observed as compared to the yield obtained without additional artificial lighting. Red and green components were clearly visible in the spectrum of white light. Artificial lighting is also important on an agro-photovoltaic farm, where additional shading is introduced, which means that the amount of light reaching the plants is even smaller and definitely insufficient. In this case, the influence of artificial lighting on the yield of a selected plant, e.g., a tomato, seems to be even greater. It is worth noting that only a small part of the energy generated by photovoltaic panels would be used for artificial plant irradiation [67].

Increasing the exposure to blue light does not significantly increase the obtained tomato yield [68]. For artificially lighting tomatoes, LED intracanopy lighting (ICL) towers bring much better results compared to high-pressure sodium (HPS) overhead lighting (OHL). The costs of artificially lighting tomatoes in a greenhouse with LED ICL's can be over four times lower in terms of yield [69].

Recently a broad variety of lamps specialized for agriculture applications have emerged. One of them, Fluence's VYPR 3p lamp, offers high fixture PPFD up to 2330 μmol/s and high efficiency up to 3.8 μmol/s, enabling the direct replacement of a 1000W HPS fixture with more than 40% energy savings. The optional reflector kit provides a wide light pattern and uniform PPFD for the plants. Fluence's main propositions are following:

- The DUAL Spectra Lamp features two narrow spectral bands that maximize energy efficiency, aiming at further reduction of energy costs and operational expenses.
- The BROAD Spectra Lamp offers photon emission across the PAR 400-700nm continuous wavelength range, balancing energy efficiency with quality of light for desired plant response and human work environment.

With a compact form factor, flexible mounting options, and various spectra, the VYPR 3x series offers design flexibility to growers who previously were unable to install supplemental lighting. The VYPR 3x and 3×2 deliver a high light output and consistent uniformity, with market-leading efficacies up to 3.8 μmol/J. This is a good solution for year-round crop production [70].

The use of artificial lighting should take into account the above fundamental information on photosynthesis in terms of matching lamps to the correct frequency and intensity of light for a specific plant. For northern geographical locations (e.g., northern Europe), one should provide additional lighting that extends the period of active photosynthesis to 10 hours a day in the period from March 1st to April 15th and from September 15th to November 15th (assuming no shading, e.g., by PV panels).

In order to estimate the energy needed for artificial lighting per one m^2 a simple approximation can be made:

1) $I_{12} \cdot \cos^2$ (sunangle) $= \mathrm{I}_{\mathrm{real}}$,
   where: I_{12} is the flux of sunlight at noon on average 750-1000 W/m^2 (about 1500-2000 μmol$\cdot$m$^{-2}\cdot$s^{-1} PAR) depending on the geographic location.
   If $I_{\mathrm{real}} < 350$ μmol$\cdot$m$^{-2}\cdot$s^{-1}then the artificial lighting starts.
2) Artificial lighting must be sustained for 2 to 5 hours daily in the period from March 1 to April 15 and from September 15 to November 15 (2.5 hours on average).
3) Fluence proposes side-top mounting of their VYPR3x lamps is proposed (in the case of PV panels directly below them). Assuming the height of 2 m and an opening angle of 120°, the lamps provide 80 W/m^2, and accepting a quantum efficiency of 3.8, plants are illuminated with a stream of 304 μmol$\cdot$m$^{-2}\cdot$s^{-1} PAR. Small, linear power control, e.g., using the Dimming Source Signal driver, enables effective illumination of plants by regulating the intensity of illumination from 10% to 100%.
4) Supplementing sunlight with artificial lighting requires (assuming a linear increase in dimming) an average of 60 W/m^2 over the period under consideration. This is due to the formula:

$$y = ax + 20(W/m^2), \tag{1}$$

where:
y – the needed illumination, which, with the above assumptions, changes from 20 W/m^2 to 80 W/m^2 (75 μmol$\cdot$m$^{-2}\cdot$s^{-1}PAR to 300 μmol$\cdot$m$^{-2}\cdot$s^{-1}PAR) for the VYPR 3p Lamp;
a – a dimming rate of 32 W/m^2/hour;
x – the artificial lighting period (from 0 to 2.5 h).

The formula (1) is adapted to the controllability of the VYPR 3p lamp.

The energy consumption in supplementary hours needed for additional lighting (up to 10 hours) in the period from March 1 to April 15 and from September 15 to November 15 for the northern location estimated with the above assumptions is approximately 16 kWh (105 days $\cdot$ 2.5 hours $\cdot$ 60 W/m^2) per 1 m^2 of plant cultivation area in the tunnel.

VII. TEMPERATURE CONTROL

Providing the proper air temperature and the soil in which the plant has optimal growth conditions allows for high yields and protects, to some extent, against different tomato diseases. The most evident influence of the temperature is plant evapotranspiration (ET). The higher the temperature is, the higher the ET will be. Evapotranspiration directly determines plant water needs, which are different in different climate zones. Assumed average daily water needs for tomatoes per 1 m^2 in the four analyzed locations are as follows: 1.6 l for Tarnów (Poland), 3 l for Cartagena (Spain), 5.7 l for Bechar (Algeria), and 4.3 l for Cali (Colombia).

Temperature also affects different tomato diseases and growth disorders. One of them is fusarium wilt – the most serious in the temperatures 26 to 32 °C when growing in sandy soil. Another disease favored by high humidity and soil moisture and temperatures between 29 °C and 32 °C is southern blight. High soil moisture also causes buckeye rot, occurring in temperatures over 26 °C. Another factor contributing to this disease is the contact of fruit with soil. Lower temperatures cause bacterial spots to injure leaves, stems, and fruit at any growth stage when temperatures range from 23 to 29 °C and plants are wet. Another disease favored by lower temperatures is bacterial speck, occurring at temperatures between 12 °C and 25 °C. There are many more tomato diseases, but their description is beyond the scope of this paper. More information on this topic can be found in the literature [71].

It should be noted that photosynthesis significantly depends on the relationship between ambient temperature, the intensity and spectral distribution of light radiation, and air humidity. This fact must take into account the process of controlling the parameters both inside and outside the foil tunnel. Ideally, the information from sensors, for example a PAR sensor or a plant surface moisture sensor, would be independent of the ambient temperature and humidity data by using appropriate physico-electronic bridge compensation solutions.

The diagram in Fig. 9 shows how a pyrometer can be organized with a temperature compensation system, with mV output. Additionally, to prevent condensation of water vapor inside the sensor, under certain climatic conditions, one can put moisture absorbing silica gel tablets inside.

Depending on the needs of the plant, the temperature in the tunnel can be raised or lowered using a control system. It should be noted that the temperature in the tunnel increases spontaneously during the day compared to the ambient temperature. This is due to the greenhouse effect. Therefore, additional heating of the tunnel is used mainly in northern climatic zones (e.g., in Poland) in the late autumn and winter period, most often at night, when the temperature may drop below the value that ensures plant survival. Occasionally, additional tunnel heating can also be used in the cold desert climate zones (e.g., in regions of northern Algeria) in the autumn-winter period, when the temperature fluctuates around 0 °C. There are various ways of heating the tunnel, but usually, convection methods (electric fan heaters) or radiation methods (lamps) are used.

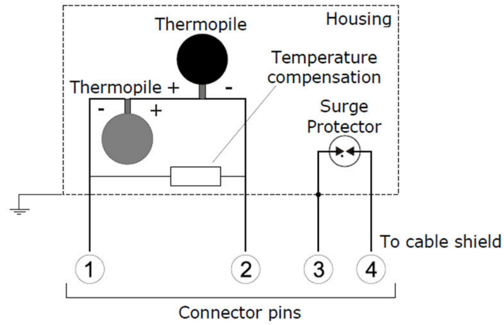

FIGURE 9. Diagram showing the idea of a temperature-compensated pyrometer.

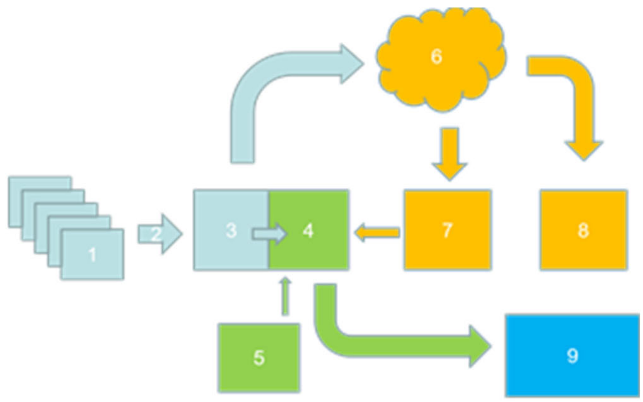

FIGURE 10. General concept of the control system in an agro-photovoltaic tunnel.

In hot climate zones (Spain, Algeria, Colombia) and in summer, in cold climate zones (e.g., in Poland) there is a problem of the temperature in foil tunnels being too high. In the case of the proposed solution, it should be noted that the temperature in the tunnel will be reduced to some extent due to shading through the photovoltaic panels. However, this may not be enough, and therefore additional means should be applied. The most popular are natural or mechanical ventilation, the use of shade nets, and fogging systems. It should be also emphasized that the adverse effects of high temperature on plants can be minimized to some extent by more abundant irrigation.

VIII. AUTOMATION CONTROL IN TUNNELS

The general scheme for automatic control in the tunnel is shown in Fig. 10. The presented system consists of the following blocks:

1) Network of sensors (temperature/humidity, soil moisture, irradiation) with local microcontroller (sensor reading, preliminary data analysis, wired or wireless data transmission);
2) Wired (RS485) or wireless (WiFi, BLE, Zigbee) data exchange system;

3) Data collection module with a logger (SD card) and a communication system with the "cloud" (WiFi, GPRS);
4) Central control module (irrigation, fertilization, ventilation, lighting, possibly additional heating, energy control in autonomous systems) - this can be a separate block or can be integrated with block 3 (modification of settings from the local keyboard or the analyzing system);
5) A vision module (Raspberry Pi / webcam / software package) that analyzes the image from the webcam, making it possible, e.g., to detect yellowing of leaves or some other changes;
6) Data collection and exchange system in the cloud;
7) A PC server that analyzes data from the cloud (optimization algorithms) in order to modify the controller settings;
8) Android application for reading data from the cloud (and possibly allowing manual remote control);
9) Block of actuators (motors, pumps, solenoid valves).

This system can be implemented using a broad range of microcontrollers. Exemplary microcontrollers which are often used to control agro systems are based on Arduino Uno modules [27], [72]. This is due to the user friendly system software and the large number of available libraries, which greatly simplify the operation of sensors and actuators as well as communication. In the first control systems, an 8-bit Atmega328 processor was used, with computing power sufficient only to implement simple controlling systems [73]. More advanced systems require the use of more powerful modern controllers (32 bit). Currently, the Arduino system supports many 32-bit STM32 series processors as well as other manufacturers (e.g., NRF52832 which, in addition to the 32-bit CPU, has an integrated BLE5.0 communication module). In the case of very complex systems, a PLC controller should certainly be used, e.g., the SIMATIC series from Siemens. This solution ensures high reliability and resistance to weather conditions but is also more expensive. A good compromise between features/price could be to use a Raspberry Pi microcomputer as a control unit [28], [73]. The latest versions have high computing power and integrated communication systems (wifi 2.4 / 5 GHz and BLE 5.0).

The authors believe that the Raspberry Pi platform version 3b or 4 is a good basis for building an intelligent and affordable agro-photovoltaic system. This platform has a fast processor, sufficient memory, GPIO, and extensive software support in the form of numerous available libraries that enable implementation of modern algorithms based on predictive models, fuzzy logic, or neural networks. Such algorithms can support the learning process of this intelligent system to optimally regulate plant cultivation processes based on the photosynthesis rate curve.

The authors have not encountered a similar control method based on the photosynthesis rate curve in real time. Developing this is the subject of the authors' current research. The results will be presented in the next publication.

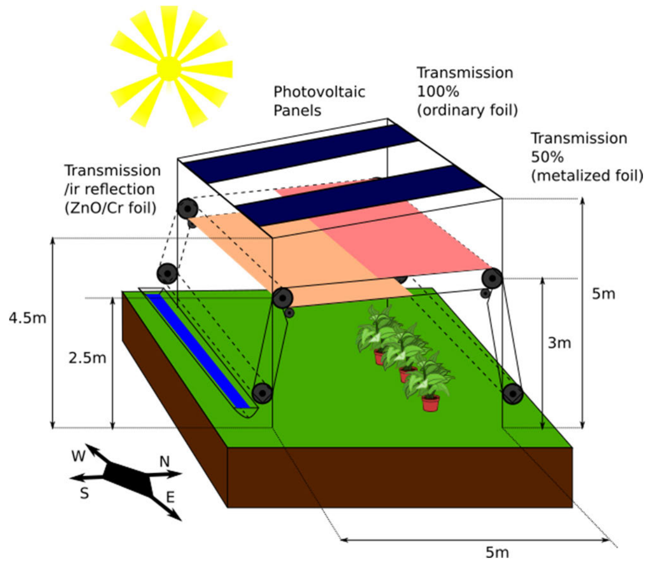

FIGURE 11. The idea of an experimental agro-photovoltaic system.

IX. AGRO-PHOTOVOLTAICS

The authors have concluded that the increased surface area of PVP panels, which shade plants, does not linearly correlate with a decrease in expected yield. In other words, agro-photovoltaic systems (APV) can be designed to optimize PVP power output and, at the same time, to optimize the expected crop yields. Future work in this area should take this optimization into account and implement the latest solutions.

Fig. 11 shows a proposed experimental tunnel. This system should enable optimizing the relationship between radiation, temperature, and the rate of photosynthesis, and use the maximum possible surface area of photovoltaic panels without adversely affecting plant growth by overshading.

Fig. 11 presents the idea of an experimental APV system, consisting of a structurally solid tent with highly placed PVP (optimally positioned and with appropriate geometry). In the foil tent, the conditions for plant growth are monitored and controlled. The foil covering of the tent can be moved or uncovered automatically, depending on the time of day or night, sunshine, temperature, or rainfall. This covering is partly a breathable mesh and partly a metalized foil with transmission and reflection of, for example, 50%. It can also be covered with a layer that reflects IR radiation and transmits VIZ (visible light) radiation. The aforementioned foil tent is constructed in such a way that it can be hung anywhere on the reinforced structure of the system or disassembled, depending on the needs.

The target experimental project assumes the use of continuous shading through the use of scrolled films and thin-film flexible panels with different light transmissions to control sunlight fully. It is imperative to determine the degree of shading when the panels are optimized for electricity production, without limiting the flux of photons falling on the plants. This flux should not fall below a certain minimum, based on the necessary speed of photosynthesis for a productive harvest over a certain time period.

An accurate assessment of the rate of photosynthesis is fundamental to determining the minimum intensity of sunlight (I_{min}). It is important to understand the photochemical efficiency of the process, as well as to determine the relationship between the intensity of sunlight in the range of 400-700 nm reaching the plant (I_{PAR}) and the net rate of photosynthesis (Pn) driven by the photon stream I_{PPEF} activating chlorophyll and carotene molecules.

Chlorophyll is a green fat-soluble pigment that comes in two main forms, chlorophyll A (Chl A), which absorbs waves of approximately 430 and 662 nm, and chlorophyll B (Chl B), which absorbs waves of approximately 453 and 642 nm [74].

In contrast, carotenoids and anthocyanins act as an additional pigment, capturing light and transferring its energy to chlorophylls A and B. In general, the light energy absorbed by the pigments is transmitted to reaction centers where the electron-hole charge separation takes place: positively charged holes reduce water to molecular oxygen (O_2), while electrons are used in light-dependent reactions, leading to the production of NADPH (nicotinamide adenine dinucleotide phosphate) and ATP (adenosine triphosphate). In the next step, NADPH and ATP reduce carbon dioxide (CO_2) in order to produce a wide range of organic molecules necessary for the functioning and metabolism of the plant cell [56], [75].

A. PHOTOSYNTHESIS RATE MEASUREMENT

There are different methods of measuring the rate of photosynthesis. Most of these methods are stationary. This section reviews some real-time automatic control systems.

The physiological status of the plant can be indicated by its photosynthesis parameters. These parameters can be estimated by means of rather simple digital sensor measurement. There are automation systems based on simple sensor measurements that optimize plant growth conditions such as: watering, fertilization, ventilation, shading, etc. For the experimental tunnel, some sophisticated measurements can be also applied to determine the influence of solar irradiation on the plants.

Quantitative description of the photosynthesis process requires the measurement of chlorophyll, CO_2, humidity, and temperature, determination of the solar flux density of photons in the radiation bands relevant to the speed of photosynthesis, and the study of the luminous response. For example, Fig. 10 shows the measurement system of basic parameters commonly used in tunnels.

In our opinion field cultivation of many plants can be more and more unpredictable and highly affected in the future due to the climate change currently underway. Recently agriculture crops have been being exposed to extremely variable weather conditions.

It therefore seems necessary to control conditions in real time. The sample measurements shown in Fig. 12, made at the Academy of Applied Sciences in Tarnow [Poland], were used

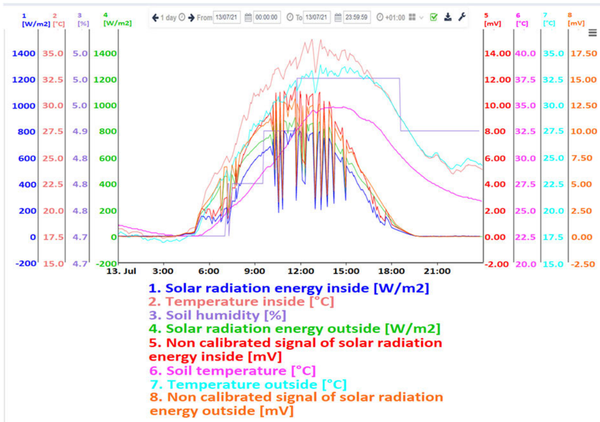

FIGURE 12. **Exemplary measurement data used to control climatic conditions in an experimental tunnel [76].**

to create a real-time control system in the currently developed experimental APVT. They are also being used to test shading systems with PV panels and to determine the threshold of plantation underexposure.

The authors consider the measuring systems described in [76], [77], and [78], and the data presented in Fig. 12 insufficient for plant growth control. To ensure effective control, quick *in situ* NIR-VIS-UV spectroscopic measurements should be taken into account, considering the photosynthesis rate [76], [79], [80], [81], [82], [83], [84], [85], [86], [87].

At present in commercial agriculture the quick test of real-time leaf spectroscopy is not used. Such a system should be taken into consideration in the experimental field or with greenhouse crops. This technology is quickly developing and in the near future such an automatic test system may also be available in commercial agriculture. This may improve plant growth and better meet plants' needs.

The authors' thesis is that commercial agriculture should monitor leaf spectroscopy in real-time. For proper tomato cultivation, it is necessary to get VIS and NIR signals of the reflectance and the absorbance spectra out of the agri-photovoltaic tunnel. Various technical and measuring solutions for implementing this can be found in the literature [79], [80], [81], [85], [87].

Many plant physiologists describe the dependence of Pn on I as well as non-rectangular hyperbolas [88], [89], [90]. These works, however, do not sufficiently take into account the relationship between excess and often harmful solar radiation in different frequency ranges. They also fail to consider that Pn is influenced not only by the number of photons absorbed by the leaves but also by the energy supplied by the photons that causes the temperature of the biochemical system to rise. The temperature associated with this energy is different from the ambient temperature. The blue photon supplies one electron to the system, but much more heat than the red photon, which also supplies one electron.

The intensity of the sun's photon flux and its energy not only directly triggers photosynthesis, but also stimulates a number of reactions accompanying photosynthesis, including those leading to the production or absorption of O_2 and CO_2.

Typically, the rate of photosynthesis Pn is measured as O_2 production or CO_2 absorption, which are most influenced by the environment and the variability of light intensity, usually expressed as photosynthetic photon flux density (PPFD) in $\mu mol \cdot m^{-2} \cdot s^{-1}$ [91].

The typical curves of photosynthesis, as a function of PPFD, show negative values for CO_2 released from the leaf in the case of respiration and positive values for CO_2 absorption. Therefore, the point (LC) can be defined as the value of the intensity of flux I activating chlorophyll and carotene, at which the rate of photosynthesis is the same as the rate of respiration. Its determination makes it possible to determine I_{min} and thus the maximum shadow [88], [92], [93].

At low light intensities above the LC point, the rate of photosynthesis increases linearly. With excessive radiation, the photosynthesis rate curve becomes saturated. Reactive forms of oxygen are formed that can damage created molecules.

For example, the stationary measurement of chlorophyll content can made by determining the absorbance with a spectrophotometer around 663 nm, 646 nm, and 470 nm. For this purpose, a sample of 4-8 leaves from a tomato top should be placed in a glass test tube with acetone, ethanol, and water in a volume ratio of 4.5: 4.5: 1 respectively for 48 hours. Chl A, Chl B, and C_{ar} content can be calculated by the method described in [94]. Three repetitions of measurements are made for each object: on the second and fourth days during radiation stress and on the fifth day after stress.

Measurements of I_{PAR}, intercellular CO_2 (C_i), and ambient $CO_2(C_{ar})$ can be performed with the Bioscience LI-6400 portable measurement system, LI-COR or equivalent at Deltaohm, during stress and every five days in the period after regeneration. Among other things, this method was used to calculate the value of the gas limit (Ls):

Ls = 1 - Ci/Ca. This method is described in Berry and Downton's work [95].

Pn can be read from a scaled model of non-perpendicular hyperbola as a function of the changing flux of radiation activating photosynthesis with the following values: 2000, 1800, 1500, 1200, 1000, 800, 500, 200, 100, 50, 20, 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The model can be determined for average values of ambient temperature, a leaf chamber assumed at 25 ± 1 °C, ambient CO_2 concentration at approximately 370 ± 10 μmol/mol, a relative humidity setting of 60 ± 2%, a leaf-to-air vapor pressure deficit setting of 1.1 ± 0.1 kPa, and for soil moisture 31–33% (soil volumetric moisture content). Under such conditions, the optimal I_{PFDF} was determined to be 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and for the northern regions, 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [96].

The rate of photosynthesis Pn can be measured automatically at any irradiation level after 3-5 minutes of exposure to light. Pn / PPFD curves can be modeled by fitting the data to a non-rectangular hyperbola. This is characterized by: α - which is the initial slope or apparent photosynthesis and a - defined as the Pn / PPFD ratio at low PPFD. The Pn / PPFD ratio is called quantum yield, whereas PPFD or I_{PPFD} is the photosynthetic photon flux density [μmol (photon)]. The second parameter defining this model is Pn_{max}. This is the rate of photosynthesis at saturation with radiation [$\mu mol(CO_2) \cdot m^{-2} \cdot s^{-1}$]. The third parameter is k, which is the convexity of the curve (dimensionless). During the measurements, P_D is also determined, which is the breathing rate in the dark [$\mu mol \cdot m^{-2} \cdot s^{-1}$]. The method described here was developed by Prioul and Chartier [88].

The authors believe that special attention should be paid to quasi-continuous automatic analysis of the photosynthetic rate. For this purpose, in addition to the standard measurements and sensors for measuring the volumetric parameters and averaged environmental parameters described in the previous paragraphs, direct-surface measurements are needed. They will enable the continuous creation of a non-rectangular hyperbola curve modeling the speed of photosynthesis and the real-time reading of the resulting speed of photosynthesis. Summarizing the above, the following series of measurement activities are proposed:

The surface temperature of a leaf is best measured with a very thin thermocouple, where a thin wire wraps around the leaf like a spider's web. The wire is less than 0.1 mm thick and terminates with inputs to the HD39 EDW radio micro-recorder. Leaf surface moisture can be measured by the capacitive method using a tennis racket-type microelectrode strapped to the leaf with outputs to the radio micro-recorders mentioned above. The third parameter that should be determined on the surface is the surface CO_2 concentration. The authors believe that this can be done quasi-continuously by measuring the sucked gas through a mini-nozzle from the leaf surface and measuring changes in concentration in an infrared (NDIR) recorder, followed by radio data transmission. These measurements and the corresponding measurements of the radiation intensity described in the previous paragraph enable dynamic analysis of the photosynthesis process.

X. THE AGRO-PHOTOVOLTAIC FOIL TUNNEL CONCEPT

Based on the analysis of the state of technology in modern agriculture presented in the previous sections, an agro-photovoltaic tunnel was conceptualized which would allow for the optimization of electricity and plant energy production. The block diagram of the systems used in the agro-photovoltaic tunnel is shown in Fig. 13.

For use in such an agro-photovoltaic tunnel, the authors believe that in the near future the most advantageous panels will be microcrystalline silicon layers on transparent and flexible substrates. They can be produced of various thicknesses, so they can be used as a foil to cover the tunnel, with a designed transmission that does not degrade the growth rate of plants, while producing electric power. Currently, these cells can be produced cheaply in low-temperature conditions.

Fig. 14 shows the spectral reflectance curves of transmission and absorption, which in the manner indicated in this figure modify solar radiation passing through a thin-film photovoltaic panel located on the agro-technical tunnel.

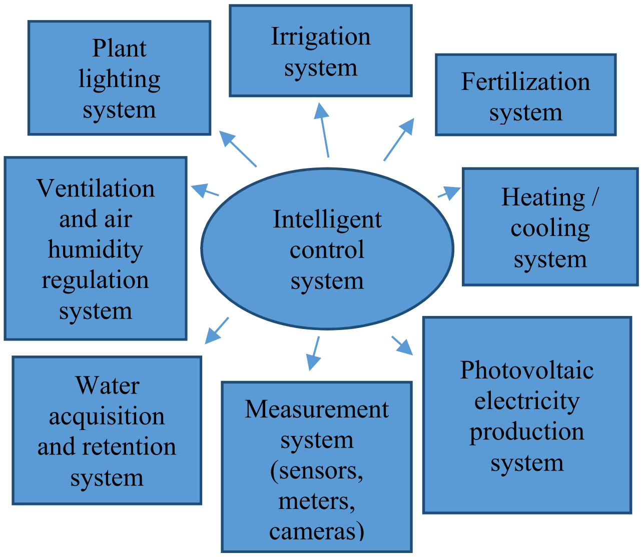

FIGURE 13. Block diagram of the agro-photovoltaic tunnel.

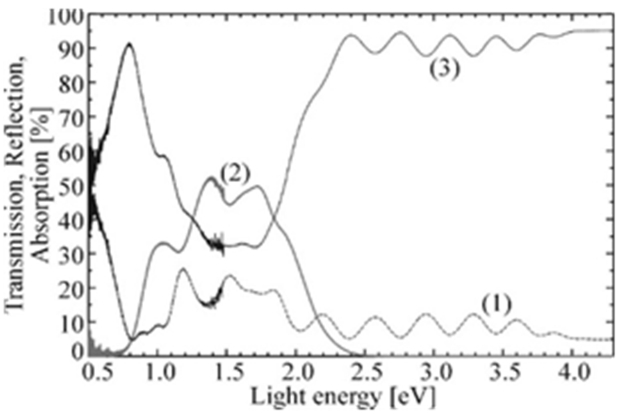

FIGURE 14. The reflection (1), transmission (2), and absorption (3) of the thin silicon cell (poly-Si:H) [97].

Low temperatures are required due to organic substrates, but therefore the panels have low efficiency, not exceeding 10%. Such panels are offered by Kaneka in Japan. Information on these types of cells can be found in the works of Kołodziej and Wronski [97], [98], [99]. It is also important that due to the 1.8 eV bandgap, the panel significantly transmits radiation in the range of 600 – 800 nm (Fig. 14). This is in the range of active photosynthesis. The advantage of these cells is that they increase efficiency with increasing ambient temperature, as opposed to monocrystalline cells.

Due to the demand in agro-photovoltaics, the production of photovoltaic films with a hybrid thin-film silicon-perovskite cell with increased efficiency is currently being intensely researched, but also, importantly, it is very much expected by the agro-technical market [97], [98], [99], [100].

Despite the undoubtedly many advantages of perovskites, they are not yet widely available. Therefore, in the considered construction of the agro-photovoltaic tunnel, the use of standard monocrystalline PV panels was assumed. Currently, silicon monocrystalline PVPs are the most popular, with an energy conversion efficiency of about 20%. Some exemplary silicon monocrystalline panels can be found in the producer catalog of Bruk-Bet Fotowoltaika [101].

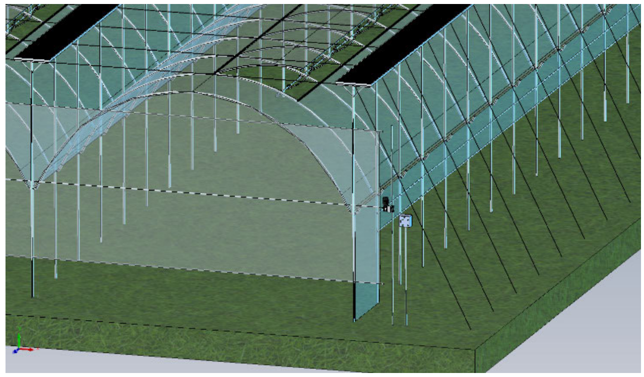

FIGURE 15. Solar panels arrangement.

Monocrystalline PVPs can be arranged in 1 m wide strips longitudinally or 2 m wide in a transverse arrangement along the north-south direction and inclined alternately every second row in the east and west direction with a 10% slope. The panels are positioned 5 m above the ground, as shown in Fig. 15. The distance between 2 PVP strips is 7 m for 1 m strips, which allows for an average of 80% of the incident radiation to reach the crop, while for strips with a width of 2 m, the distance between the strips is 6 m, which allows an average of 75% of incident radiation to reach the crop. PVP arrangement is shown in Fig. 15. In the considered tunnel construction, the 2 m wide strips have been assumed.

Fig. 15 and Fig. 16 also show the construction of the automated and affordable agro-photovoltaic tunnel. These tunnels are optionally equipped with control packages with various control options. It is possible to automatically uncover the tunnel front and sides, as shown in Fig. 15, as well as to lift the ventilation flaps – as shown in Fig. 16. Energy obtained from PVPs can be used for the various services (irrigation, fertilization, heating, ventilation, measurements, control, artificial lighting, and water production) shown in Fig. 13. These services are required for tomato cultivation. The electrical energy consumption for their support in different climate zones has been calculated and is presented and analyzed in the subsequent sections.

XI. CASE STUDIES. APPLICATION TO TOMATO CULTIVATION

The assessment of the functionality of the proposed agro-photovoltaic tunnel was carried out for tomato cultivation (*Lycopersicon esculentum*) with drip irrigation. The tomato is the second most cultivated vegetable in the world after potatoes [102]. In order to estimate water and energy consumption when growing tomatoes, the thermal, light, soil, and water requirements for this plant should be taken into

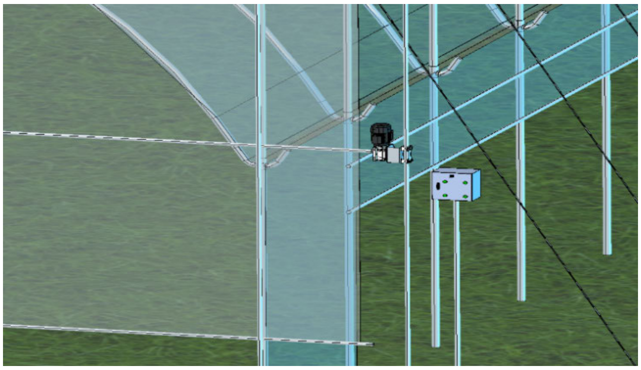

FIGURE 16. View of the agro-photovoltaic tunnel.

TABLE 3. The four case studies Climate Zones.

Location	latitude	longitude	Climate zone according to Köppen
Poland, Tarnów	50.0173	20.9922	Dfb
Spain, Cartagena	37.6267	-1.0022	BSh
Algeria, Béchar,	31.9189	-2.4851	BWh
Colombia, Cali	3.2870	-76.5174	Af

Climate zones according to Köppen: Dfb - warm-summer humid continental climate, BSh - hot semi-arid climate, BWh: Hot desert climate, Af - tropical rainforest climate.

account. These requirements are presented in detail later in this chapter. The use of smart agriculture tunnels in agricultural areas with different climate conditions (temperate, Mediterranean, arid, and tropical) is presented here as well.

A. CROP REQUIREMENTS

1) AIR TEMPERATURE

The optimum temperature for tomato growth is between 18 °C and 25 °C during the day and from 10 to 20 °C during the night, although a number of varieties growing in colder environments also exist. However, large differences between day and night temperatures have a negative effect on the yield. The crop is very sensitive to frost, and the plant dies when the temperature is below 0 °C. Temperatures above 25 °C, combined with high humidity (higher than 70%) and strong winds, reduce yields. Night temperatures above 20 °C in combination with high humidity and little sunshine lead to excessive vegetative growth and poor fruit production [102].

2) SOLAR RADIATION

It is assumed that the light compensation point for tomatoes, depending on the season, may vary between 30-100 μmol/m^2/s in the region of the chlorophyll and carotene bands, i.e., between 400 and 600 nm.

3) ATMOSPHERIC HUMIDITY

High air humidity above 80% leads to more pests, diseases, and fruit rot (fungal disease, blossom drop, bacterial disease, among others). Therefore, a dry climate is preferable for the production of tomatoes [102].

4) WIND

Wind lowers atmospheric humidity. Cold wind leads to the withering of plants.

5) WATER AND NUTRIENT NEEDS

The total water requirement (ETm) of field-grown tomatoes for 90 to 120 days after transplanting is between 400 and 600 mm, depending on climatic condition. The reference evapotranspiration water demand (ETo) in mm / period determines the crop coefficient (Kc) for the different stages of the development of the crop: in the initial phase 0.4-0.5 (10 to 15 days); development 0.7-0.8 (20 to 30 days); mid-season 1.05-1.25 (30 to 40 days); late 0.8-0.9 (30 to 40 days); and when harvesting 0.6-0.65 [102].

Water imbibition increases the incidence of diseases such as bacterial wilt. The demand for fertilizers (NPK) for high-yielding varieties ranges from 100 to 150 kg/ha of N, from 65 to 110 kg/ha of P, and from 160 to 240 kg/ha of K.

6) SOIL TYPE

Tomatoes can grow in many different kinds of soil. According to FAO, well-drained, slightly loamy soil with a pH of 5 to 7 is preferred [102], although there are reports of studies carried out on soils with a pH above 8 [103].

Cultivation is moderately sensitive to soil salinity. The decrease in crop productivity (yield) for different values of the electrical conductivity of the soil (ECe) is: 0% at ECe 2.5 mmhos/cm, 10% at 3.5, 25% at 5.0, 50% at 7.6, and 100% at an ECe of 12.5 mmhos/cm. The period most sensitive to salinity is sprouting and early plant development, so it is often necessary to wash out salt during pre-irrigation or to over-irrigate during the first irrigation [102]. Soil temperatures below 12 °C negatively affect root development.

B. CASE STUDIES

Case studies of smart agriculture simulation have been carried out for four climate zones (with locations in Poland, Spain, Algeria, and Colombia). Characteristics are shown in Table 3.

The analysis and simulations include water and energy balance, assuming that the optimal water and nutrient needs for tomatoes are met.

All the calculations were carried out for a cultivation tunnel area of the size 8 m × 30 m = 240 m^2. Tomatoes were assumed to be transplanted by hand in double rows, 100 cm apart between double rows, 60 cm apart between rows, and 50 cm apart between plants, corresponding to (100 cm × 60 cm × 50 cm) Fig. 17.

This results in 600 plants in a tunnel, corresponding to a plant distribution of 2.5 plants/m^2. The same or similar plant distribution can be found in the literature [103] and [104]. The natural period of tomato cultivation depends on the climate

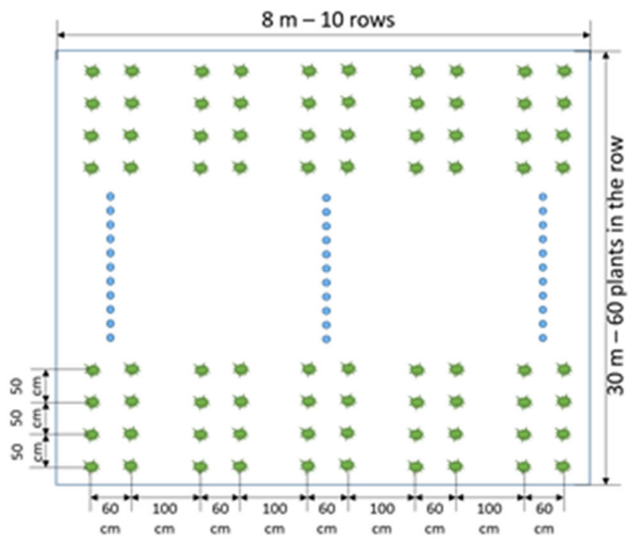

FIGURE 17. Arrangement of tomato seedlings in the tunnel.

zone. In Poland (Tarnów), this is a period between mid-May and the end of September. In Spain (Cartagena), the tomato cultivation period ranges from the beginning of April to the end of October. Algeria (Béchar) is a bit troublesome for tomato cultivation because of winter night temperatures which can sporadically approach 0 °C and very hot summers with temperatures above 35 °C. Therefore, the most optimal season for tomato cultivation in Algeria is between the beginning of February and the end of June. The least problematic cultivation seems to be in Colombia (Cali), where the tomato can be cultivated all year. However, the most optimal season in Cali is between March and July. For the case study, in every location, the most optimal tomato cultivation period has been chosen and its length was assumed at 150 days.

1) ANALYZED CLIMATE ZONES

Climatic zones include four diversified locations presented in Table 3.

2) WATER BALANCE

The most fundamental issue for consideration in the concept of the agro-photovoltaic tent is the agricultural management of water balance. The water balance expression, generally applied at the yearly rate for crop growth is:

$$W_{\mathrm{RAIN}} - W_{\mathrm{CROP}} = W_{\mathrm{S/D}}$$

where:

W_{RAIN} - water from rainfall or from the condensation of water vapor [m^3];

W_{CROP} - The amount of water needed to maintain crops [m^3];

$W_{\mathrm{S/D}}$ - Water surplus (positive $W_{\mathrm{S/N}}$ value) or deficit (negative $W_{\mathrm{S/D}}$ value) per considered period of balance (yearly) [m^3].

TABLE 4. Estimated amount of Water collected Annually (W_{Rain}) For the tunnel 240 m^2.

Location	Annual precipitation [mm]	Collected water (W_{RAIN}) [m^3]
Poland, Tarnów	836	200.64
Spain, Cartagena	518	124.32
Algeria, Béchar,	80	19.2
Colombia, Cali	3298	791.52

For water deficit, supply from sources (irrigation) other than rainfall, is needed. The external water supply includes desalination from saline water (seawater, brackish), treated wastewater, or water from other sources (groundwater, rivers, lakes). The amount of water that needs to be delivered to the agro-photovoltaic tunnel can therefore be expressed as:

$$W_{\mathrm{S/D}} = W_{\mathrm{DES}} + W_{\mathrm{TR}} + W_{\mathrm{PUMP}}$$

where:

W_{DES} - water from desalination [m^3];

W_{TR} - water from wastewater treatment [m^3];

W_{PUMP} - water from other conventional resources [m^3].

Annual precipitation for the considered locations are presented in Table 4 [105].

When determining the water needed for tomato cultivation in the tunnel, the four plant growth stages have to be considered. Water demand in every growth stage is different. The estimated average amount of water for one plant per day depends on the climate zone because of different evapotranspiration rates. It was assumed that the average water consumption (liters per day) per plant is 1.6 for Tarnów (Poland), 3 for Cartagena (Spain), 5.7 for Bechar (Algeria), and 4.3 for Cali (Colombia). The cultivation period for tomatoes was assumed to be 150 days from transplanting to the final harvest.

Taking the above assumptions into account, the crop water needs for different locations can be calculated using the formula:

$$W_{\mathrm{CROP}} = W_{\mathrm{PLANT}} \cdot N \cdot T$$

where:

W_{PLANT} – water needs of one tomato plant per one day;

N – number of plants (600);

T – cultivation period (150 days).

The values of W_{CROP} and the water balances for the different climate zones are presented in Table 5.

3) ENERGY BALANCE

Another important issue is the estimation of the energy balance. The annual balance of energy consumption is expressed by the formula:

$$E_{\mathrm{SOL}} - E_{\mathrm{CROP}} = E_{\mathrm{S/N}}$$

TABLE 5. Water Balance ($W_{S/D}$) For the tunnel 240 m^2 [105].

Location	Crop water needs (W_{CROP}) [m^3]	Collected water (W_{RAIN}) [m^3]	Water balance ($W_{S/D}$) [m^3]
Poland, Tarnów	144	200.64	56.64
Spain, Cartagena	270	124.32	-145.68
Algeria, Béchar,	513	19.2	-493.80
Colombia, Cali	387	791.52	404.52

TABLE 6. Estimated amount of energy produced annually (E_{SOL}) For the tunnel 240 m^2.

Location	Annual energy production [kWh]
Poland, Tarnów	10532
Spain, Cartagena	17359
Algeria, Béchar,	19933
Colombia, Cali	17387

where:

E_{SOL} - The amount of kWh of energy obtained annually from photovoltaic panels;

E_{CROP} - The amount of kWh of electricity needed in a calendar year to maintain the crop;

$E_{S/N}$ - The amount of kWh of electricity saved (positive $E_{S/N}$) or that needs to be delivered (negative $E_{S/N}$) per year.

The amount of electricity needed per year to maintain the crop includes energy consumption for obtaining water, irrigating and fertilizing plants, heating / cooling the air in the tunnel, artificial lighting for plants (if necessary), maintenance of the controls, and the measurement system. The amount of energy that needs to be delivered annually to the agro-photovoltaic tunnel can therefore be expressed by the formula:

$$E_{S/N} = E_{WATER} + E_{I/F} + E_{H/C} + E_{LIGHT} + E_{CNTRL}$$

where:

E_{WATER} – Annual energy consumption for water acquisition (desalination, wastewater treatment, fresh water pumping);

$E_{I/F}$– Annual energy consumption for irrigation and fertilization;

$E_{H/C}$ – Annual energy consumption for heating and cooling; E_{LIGHT}– Annual energy consumption for artificial lighting; E_{CNTRL} – Annual energy consumption for maintenance of the control and measurement system.

The energy production from PV silicon crystalline was simulated for all four locations using the Photovoltaic Geographical Information System (PVGIS) tools. It was assumed that the PV system is grid-connected and, in the simulation, most energy is consumed in situ (overproduction might be sent to the power system, and missing energy can be taken from the power system). The system was calculated for the 60 m^2 of PV cells, per every agro-photovoltaic tunnel. In such an area, about 12 kWp PV cells can be installed (typical size and efficiency of the panels). The analyzed technology is crystal silicone, the efficiency of which in converting solar radiation into electrical energy is about 20% (and the whole system energy loss is 14%). The PV panels orientation: slope angle [Â°]: 0, azimuth angle [Â°]: 10.

PVGIS web interface is a tool for producing calculations of solar radiation and Photovoltaic (PV) system energy production. Most of the solar radiation data used by PVGIS have been calculated from satellite images. There are a number of different methods to do this, based on which satellites are used. The choices that are available in PVGIS at present are: PVGIS-SARAH - this data set has been calculated by CM SAF and the PVGIS team. This data cover Europe, Africa, most of Asia, and parts of South America; PVGIS-NSRDB - this data set has been provided by the National Renewable Energy Laboratory (NREL) and is part of the National Solar Radiation Database; PVGIS-CMSAF - this data set has been calculated by the CM SAF collaboration for the area covering Europe and Africa, as well as parts of South America. The data cover the period of 2007-2016. As for the other PV calculation tools in PVGIS, the outputs consist of annual statistical values and graphs of monthly system performance values. The PV calculation tools in PVGIS provide the output data as a graph showing: a) the monthly average of the daily energy output, b) calculation of the energy production, and other information.

The results achieved with the simulation data are useful for planning energy production for agriculture systems to use locally. The data presented in Fig. 18 show that in all the locations, PV systems might be used flexibly to cover the yearly energy consumption. The calculated average energy shows that in the wintertime months in Poland and in Spain the system is not efficient and this corresponds with the crop rest needs.

Energy production in the four locations is presented in Fig. 18.

Total annual energy production in the four locations is presented in Table 6:

Energy Required for Water Production:

In order to estimate the amount of energy required for the calculation of the E_{WATER} value, the energy consumption to produce 1 cubic meter of water should be known. This energy consumption depends on the chosen method of obtaining fresh water as well as other factors. The zero energy-consuming method of obtaining fresh water is rainwater collection. More energy-consuming is pumping the water. The energy required for pumping 1 cubic meter of water at a height of 1 m can be estimated at 0.003 kWh. This means that for a 100 m deep sub-artesian well, the estimated energy consumption to pump 1 m^3 is about 0.3 kWh.

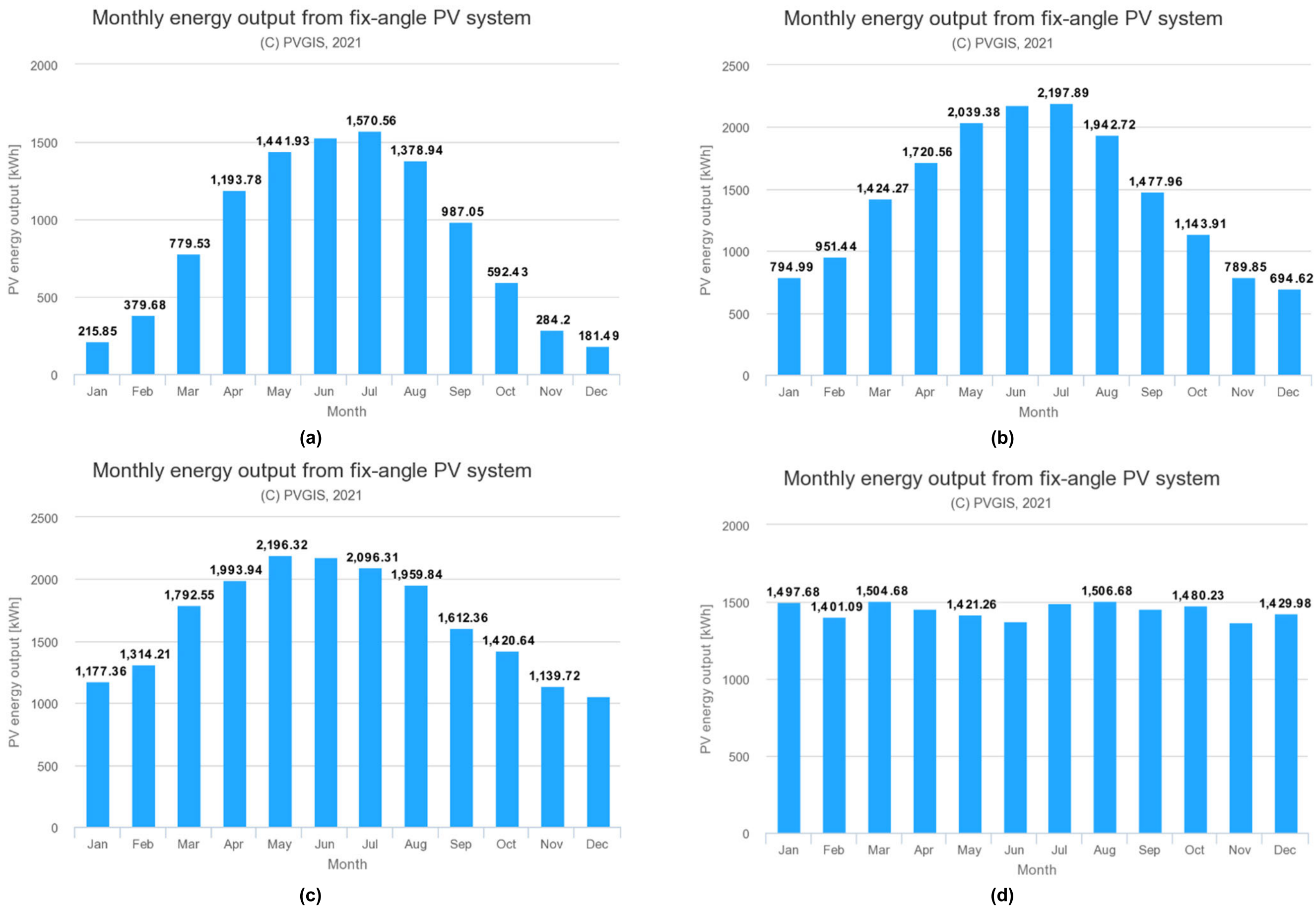

FIGURE 18. **Monthly energy production in a) Tarnów (Poland), b) Cartagena (Spain), c) Bechar (Algeria), d) Cali (Colombia).**

Desalination of treated wastewater requires more energy than pumping, and is estimated at 0.051 kWh/m^3, assuming that the treated wastewater is provided by the authorities. Desalination of 1 cubic meter of brackish water consumes 0.536 kWh electrical energy. The energy consumption of seawater desalination depends on the salinity of water and can reach up to 15 kWh/m^3 (in the case of water distillation). It should be noted that in practice some mixed methods of water production are used, e.g., desalination and pumping from a sub-artesian well.

By taking into account the water balance from Table 7, the energy consumption for freshwater production in the four considered locations can be estimated. Two locations in Tarnów (Poland) and in Cali (Colombia) do not need energy for freshwater production because all the needed water is collected from precipitation. For Cartagena (Spain), missing freshwater for agriculture is typically obtained from the desalination of seawater and from sub-artesian wells. Example energy consumption for pumping from three wells more than 100 m deep, desalination and transport to a mixing pond was 2.25, 2.45, and 2.82 (kWh/m^3), respectively for each well [106]. The most water-demanding location in Béchar (Algeria) has some natural resources of brackish water; therefore, this water source is primarily used for supplementing water scarcity in agriculture. Water for agriculture at this location is mostly collected from rainfall but can be also gained from surface water sources or from desalinating treated wastewater. Taking into account the information presented above, an estimation of the energy needed for the water production E_{WATER} can be made. Calculated values for the four considered locations are presented in Table 7.

Energy Required for Drip Irrigation:

Drip irrigation power consumption depends on the dripper flow. Increasing the dripper flow of the irrigation network from 4 to 23 l/h increases the power requirement from 17 watts for dripper 4 l/h to 106 watts for dripper 23 l/h. However, the hours of irrigation are decreased. Calculations of the energy consumption for drip irrigation $E_{\mathrm{I/F}}$ resulting from the above data are presented in Table 8. It was assumed that the energy consumption for fertilization can be neglected.

Energy Required for Heating and Cooling:

Taking into account the assumed period of tomato cultivation (150 days in the warmest period of the year), there is no need to heat the tunnel even in the coldest location in Poland. However, because of the possibility of night frost on some days at the end of September and the beginning of October,

TABLE 7. Amount of energy required per annual water production.

Location	water production method	Energy consumption per 1 m^3 of water [kWh/m^3]	Annual water demand [m^3]	Annual energy consump tion [kWh]
Poland, Tarnów	Rain harvest	n.a.	n.a.	0
Spain, Cartagena	Rain harvest + water pumping + desalination	2.51	145.68	365.66
Algeria, Béchar,	Rain harvest +desalination	0.536	493.80	264.68
Colombia, Cali	Rain harvest	n.a	n.a.	0

TABLE 8. Annual energy consumption for drip irrigation.

Location	Energy consumption with dripper flow 4 l/h [kWh]	Energy consumption with dripper flow 23 l/h [kWh]
Poland, Tarnów	612	664
Spain, Cartagena	1147.5	1244.5
Algeria, Béchar,	2180.25	2364.25
Colombia, Cali	1664.75	1783.5

TABLE 9. Annual energy consumption for maintenance of the control and measurement equipment.

device	Number of the devices	Power consumption [W]	time of operation per year [hours]	Annual energy consumption [kWh]
Air humidity temperature and atmospheric pressure sensor	4	0.0004*	8670	0.01
Soil moisture sensor	4	0.115	8670	3.99
Soil pH meter	2	0.144	8670	2.49
Leaf temperature sensor	2	0.006	8670	0.1
CO_2 sensor	2	0.425	8670	7.37
Control unit (microcontroler)	1	6	8670	52

* Average value at the frequency of measurements of 1 measurement / 1 min

it may be necessary to completely close the tunnel in order to preserve the heat during the night. Consequently, the energy needed for heating and keeping the cultivation warm is the energy to automatically unwrap the foil in order to close the tunnel.

The amount of energy for unwinding the foil and cooling the cultivation is necessary for the locations in Spain, Algeria, and Colombia, and also for summertime in Poland. Some cooling effects can be achieved through the shading of PV Panels. An additional cooling effect can be achieved by using shading nets and opening side and upper covers of the tunnel in order to enhance ventilation. Therefore, the energy cost for cooling is the cost of unwrapping shading nets and opening sides of the tunnel in order to enable ventilation.

The cost of foil rewinding in every location may be estimated at 40 kWh annually.

Energy Required for Artificial Lighting:

Another important use of energy is artificial lighting. Placing panels above the tunnel covers 25% of its area, which shades the tomato plants and lowers the effectiveness of photosynthesis. Moreover, the foil of the tunnel weakens the sunlight by at least 10% (old or dirty foil even more). Therefore, there is a need for artificial lighting in some regions in periods when the days become shorter. This is especially necessary for the location in Tarnów (Poland) in the period from August 15 to September 30. The shading effect of the PV panels and tunnel foil is additionally enhanced by the low sunlight intensity caused by the low angle of the incident light and sometimes by cloudy and rainy days. It is enough to light the cultivation on average for 2 hours a day with an intensity of 60 W/m^2. Taking into account the above considerations, the energy needed for artificial lighting of tomato cultivation in Poland can be estimated as:

$$E_{\mathrm{LIGHT}} = N \cdot T \cdot I \cdot A$$

where:

E_{LIGHT}- annual energy consumption for artificial lighting;
N - number of days needed for artificial lightning (45);
T - average period of lightning per day (2 hours);
I - light intensity (60 W/m^2);
A - area of the cultivation in the tunnel (240 m^2).

The above calculation gives an estimated E_{LIGHT} value of 1269 kWh.

It turns out that artificial lighting of the cultivation is also needed for the Béchar location in Algeria due to the atypical (compared to other locations) period of tomato cultivation (from February to June). The amount of energy needed for lighting can be calculated in a similar way as for the location in Tarnów. The calculated value for the site in Béchar is 846 kWh/year.

Energy Required for Control and Measurement

Annual energy consumption for maintenance of the control and measurement system E_{CNTRL} is the amount of energy needed for sensors and control equipment. The energy

E_{CNTRL} can be assumed to be the same in every location. Calculation of the energy is summarized in Table 9.

Summary of Energy Consumption

A summary of the energy balance is presented in Table 10. In every location there is a surplus of electric energy that can be used for the cultivation of another plant during the remaining part of the year or utilized in other ways.

4) ECONOMIC ANALYSIS

The two previous chapters show that the proposed agro-photovoltaic tunnel, in addition to income from tomato production, should also bring significant income from surplus energy. Therefore, the question arises of whether tomato production in an agro-photovoltaic tunnel is economically viable, taking into account the investment costs. To answer this question, the income from tomato cultivation must first be estimated. According to FAO data from 2020 [102], the income from tomato production in a single agro-photovoltaic tunnel in the four analyzed locations is at the levels presented in Table 11.

It was assumed that 600 tomato bushes grow in each tunnel, and 15 kg of fruit are obtained from each plant [107].

Revenue from the sale of tomatoes is reduced by production costs related to human labor, fertilization, soil preparation, etc. Based on available studies, these costs have been estimated at 30% of the income from tomatoes. Revenue from tomatoes after deduction of production costs is presented in Table 12. The price of 1 kWh of energy in individual countries was adopted on the basis of data from June 2022 [108] at the levels of \$0.178 for Poland, \$0.365 for Spain, \$0.039 for Algeria, and \$0.138 for Colombia, which results in (taking into account data from Table 10) the profits shown in Table 12. This table also shows the total income from one agro-photovoltaic tunnel.

The approximate cost of investment in the construction of the tunnel includes the components presented in Table 13. It was assumed that the cost of building one square meter of the tunnel with automation is about USD 25 [109].

A comparison of the investment costs from Table 13 and the tunnel income presented in Table 12 shows that the payback time may vary from approx. 1 year and 5 months in the location in Spain to approx. 3 years and 2 months in Algeria. The time for return on investment in Poland is 2 years and 10 months, and in Colombia it is 2 years and 8 months. However, it should be noted that the incomes given in Table 12 do not take into account the surplus of water (in Poland and Colombia), the possibility of growing a second crop in the tunnel (e.g., onions) when tomatoes are not being grown, the possibility of producing mineral salts from desalinated water, or the possibility of increasing income by exporting products (energy, tomatoes, onions, salt) to other countries. Taking these possibilities into account, the time for return on investment could be significantly shortened. In addition, growing tomatoes under cover in the form of agro-photovoltaic tunnels can paradoxically be even more profitable due to the more and more frequent increases in food and energy prices caused by political crises (e.g., the war in Ukraine) or natural disasters as a result of climate change. For example, unexpectedly heavy snowfalls in Morocco and Spain in February 2023 caused an unprecedented increase in tomato prices in Poland to as much as \$8 per kg in retail.

5) GENERALIZATION OF THE MODEL

This section analyzes the model of the agro-photovoltaic tunnel applied to tomato cultivation in four climate zones: Af, BWh, BSh, and Dfb. The question arises of whether the proposed model can be used in other climate zones and for the cultivation of other crops. The answer to this question is determined by three factors: temperature, precipitation, and insolation.

From Table 5, it can be concluded that for the cultivation of tomatoes in a 240 m^2 agro-photovoltaic tunnel in zone Af, it is necessary to provide 387 m^3 of water throughout the growing season, which corresponds to approximately 1613 mm of rainfall per year. This amount of precipitation occurs in the tropical rainforest climate zone (Af) and the tropical monsoon climate zone (Am). In the tropical savanna climate zone (Aw), precipitation may be lower than sufficient for the water needs of the tomato, and in that case, the water deficit must be supplemented by one of the methods described earlier. Temperatures in climate zone A are suitable for tomato cultivation. On hotter days, it may be necessary to lower the temperature in the tunnel, e.g., through shading nets or ventilation.

Tomato cultivation in the arid climate zone B is much more problematic. This article analyzes cases of tomato cultivation in an agro-photovoltaic tunnel in the zones of hot semi-arid BSh and hot desert climate BWh. The conclusions from this analysis are to a large extent also correct for the cold semi-arid BSk and cold desert BWh climates, which have not been analyzed. As in the BSh and BWh zones, there is a problem of water scarcity due to insufficient rainfall (or snow). The water deficit can be supplemented from alternative sources by desalination of sea or sewage water or by pumping from artesian wells if such water sources are available. In the absence of access, the only solution seems to be to increase the area that collects rainwater, e.g., by collecting it from the roofs of buildings or from additional photovoltaic panels placed in the desert. The size of the projection area from above, which in this case should be additionally reserved for rainwater collection, is expressed by the formula:

$$S_{\mathrm{RAIN}} = 1000 \cdot W_{\mathrm{CROP}}/H_{\mathrm{RAIN}} - S_{\mathrm{TUNNEL}}$$

where:

W_{CROP} - The amount of water needed to maintain crops in one tunnel [m^3];

H_{RAIN} – annual rainfall [mm];

S_{TUNNEL} – surface of the agro-photovoltaic tunnel (top view) [m^2].

As in hot arid climate zones (BSh and BWh), in cold arid climate zones (BSk and BWk) there may be a need to

TABLE 10. Annual energy consumption in the agro-photovoltaic tent.

Location	energy production [kWh]	water production [kWh]	drip irrigation [kWh]	foil rewinding [kWh]	artificial lighting [kWh]	automatic control [kWh]	Energy surplus [kWh]
Poland, Tarnów	10532	0	664	40	1269	66	8493
Spain, Cartagena	17359	365.66	1244.5	40	0	66	15642
Algeria, Béchar,	19933	264.68	2364.25	40	846	66	16352
Colombia, Cali	17387	0	1783.5	40	0	66	15497

TABLE 11. Annual revenue from sale of tomatoes from 1 AGRO-photovoltaic tunnel.

Location	Price of 1 tonne of tomatoes [USD]	Income from the sale of tomatoes from 1 tunnel [USD]
Poland, Tarnów	551.6	3815
Spain, Cartagena	363.1	4473
Algeria, Béchar	423.9	4964
Colombia, Cali	497	3268

TABLE 12. Annual income from the agro-photovoltaic tunnel.

Location	Income from tomatoes [USD]	Income from the sale of energy [USD]	Total income [USD]
Poland, Tarnów	2671	1512	4183
Spain, Cartagena	3131	5709	8840
Algeria, Béchar	3475	638	4113
Colombia, Cali	2288	2139	4427

cool tunnels, for example, in the Gobi Desert where summer temperatures reach 40 °C. However, the problem of cooling tunnels in summer seems to be less severe than in the case of hot arid climate zones. Occasionally, it may be necessary to protect the plants from the cold (e.g., by means of closing the tunnel or additional heating) if tomato cultivation is carried out partially at the turn of winter and spring or in autumn. To sum up, growing tomatoes in agro-photovoltaic tunnels in climate zone B seems to be a reasonable solution.

The only type of continental climate that was analyzed in this article was warm-summer humid continental Dfb. Similar conditions regarding the amount of precipitation and

TABLE 13. Cost of building one agro photovoltaic tunnel.

Location	Tunnel construction + automation [USD]	PV installation [USD]	desalination plant* [USD]	Total cost [USD]
Poland, Tarnów	6000	5600	n.a.	11600
Spain, Cartagena	6000	5600	330	11930
Algeria, Béchar	6000	5600	1130	12730
Colombia, Cali	6000	5600	n.a.	11600

* It is assumed that the water is desalinated using a 250 l/h plant that costs $5,000. The annual water yield is sufficient to irrigate c.a. 15 tunnels in Spain and 4.5 tunnels in Algeria. Therefore, the installation costs per 1 tunnel are different in individual locations.

temperatures also prevail in the climate zones Dfa, Dwa, Dwb, Dsa, and Dsb. Due to the relatively small evapotranspiration, the amount of water obtained from precipitation is sufficient to irrigate plants. Only in the Dsa zone, may there be water shortages in some areas, which can be supplemented by the previously mentioned methods. Average temperatures are relatively low in some areas, so it may be necessary to keep the tunnel closed for extended periods of time in order to achieve the greenhouse effect, and occasional reheating may even be necessary. Also, due to the low angle of the sun's rays and the rapidly decreasing day's length at the end of August and September, it may be necessary to temporarily illuminate the crops. It is only in the subarctic climate zones of Dfc, Dfd, Dwc, Dwd, Dsc, and Dsd that tomato cultivation in agro-photovoltaic tunnels raises doubts due to low temperatures and poor insolation. The analysis of tomato growing conditions in these climate zones requires further research. Analysis shows that in continental climate zone D, with hot and warm summers, tomato cultivation in agro-photovoltaic tunnels is possible. However, cultivation in subarctic continental and polar climate zones (ET and EF) requires further research and analysis.

It is also worth analyzing the possibilities of growing tomatoes in tunnels in temperate climate zone C, which has not been considered in this article. Since it is a climate at similar latitudes as the continental climate, but with warmer winter months and, in some zones, with less rainfall than the continental climate, tomato cultivation in agro-photovoltaic tunnels in zones of this climate seems very possible. Of course, due to lower rainfall in some zones, it may be necessary to mitigate for water shortages. Only cultivation in the Cfc, Csc, and Cwc zones raises doubts due to lower temperatures and the fact that these zones are too far north. Growing tomatoes in these zones requires further research and analysis.

Finally, it should be mentioned that the real profitability of tomato cultivation in agro-photovoltaic tunnels strongly depends on economic factors, mainly energy and tomato prices.

6) ANALYSIS OF CROP SHADING

Most of the works analyzing crop shading are limited to shade-tolerant crops, which only make up a small subset of commercial crops [110], [111]. Shadow-loving plants differ from photophilous plants due to a lower LC value, a lower respiration rate in the dark, and a higher net photosynthesis rate at low luminous fluxes. Moreover, the photosynthesis rate of these plants has a much lower intensity maximum at which the photosynthesis rate curve saturates. Lighting that is too intense can destroy the chlorophyll molecules and the active defense mechanisms, which manifests in deformed leaves. Unlike shadow-loving plants, photophilous plants can achieve a higher rate of photosynthesis in full sun. It is generally found that shade plants have thinner and wider leaves that maximize light absorption, while the leaves of photophilic plants often contain an extra cell layer to capture light for photosynthesis [112].

A number of works analyzing the conditions for agro-photovoltaics depending on the geographic and locally specific location have been published around the world. For example, [1] presents possible examples of shading in the USA. There are also patented solutions of APV systems (concerning polyethylene foil with improved stiffness, toughness balance, and increased solar radiation transmittance), which ensure the improvement of land use efficiency both for crop and electricity production [113]. Other works [4], [114], [115], [116] present the results of modeling an agro-photovoltaic system intended for applications in southern geographic locations. The results show that the efficiency of land use increases to 73%.

Also, a similar APV system was tested by the Fraunhofer Institute, wherein various solutions were implemented at experimental APV farms. A program has been realized in which solar panels were placed above the crops at a height of 6-8 m (cover up to 20% of the surface) in a mosaic arrangement. There is a wide blurring of edges and mild shadow changes, which are additionally softened due to lateral diffusion of light. In the proposed system there is enough space under the PVP construction to install a classical foil tunnel [2].

However, this work does not take into account the effects of the different dimensions, configurations, or designs of the panels, limiting their use. A work recently published in 2019 importantly takes up the overall problem of modeling shading of crops by solar panels [3]. The model developed by the authors allows for the studying of multiple configurations and geometric designs of panels. To mitigate the reduction in insolation, the matrix configuration and panel designs were investigated. Additionally, a ray-tracing model was developed using MATLAB, which uses the open-source PVLib library to create a spatial map of insolation integrated in one day [117]. This model treats the sun as "planar source MODELING" and uses finite elements to find the corresponding positions of a direct light ray in the field of two surface dimensions. Only direct light-catching structures are considered. Modeled PV panels are treated as rectangular flat segments with zero thickness. The shadow positions are computed from sunrise to sunset based on the apparent solar elevation from each corner of the panel at each time step, calculated using PVLIB. The line drawing algorithm of the MATLAB poly-mask function maps the locations of shadows in a binary manner onto a finite element matrix representing the field. 100% of direct light is removed from each of these shaded elements over a given period of time.

In the first stage of calculating the possible coverage of tunnels with panels, it was assumed that the shade equals the surface of the panels and its size proportionally affects the attenuation of solar radiation. In the second stage, the determination of the maximum possible shade caused by panels required an analysis of a function of the speed of photosynthesis for a chosen plant and the time-dependent distribution of the darkness. The approximate calculations made by the authors did not include temporal variable shading.

Analyzing possible plant overshading by PVP, it should be noted that the radiation intensity reaching the plant ($\mathbf{I}_{\mathrm{TOTAL}}$) consists of the direct ($\mathbf{I}_{\mathrm{DIRECT}}$) and diffuse ($\mathbf{I}_{\mathrm{DIFFUSIVE}}$) radiation:

$$I_{\mathrm{TOTAL}} = I_{\mathrm{DIRECT}} + I_{\mathrm{DIFFUSIVE}}.$$

If part of the cultivated area is obscured by panels, the I_{DIRECT} and $I_{\mathrm{DIFFUSIVE}}$ radiation will be attenuated to varying degrees. The $I_{\mathrm{DIFFUSIVE}}$ radiation will illuminate the plantation approximately uniformly and will be far less attenuated by the obscuring panels than the I_{DIRECT} radiation at the plant level.

After passing through the matrix or other screening system of the panels, I_{DIRECT} radiation at the crop level will be much weaker and will additionally illuminate non-uniformly (there will be light and dark spots). This heterogeneous lighting will no longer be the case if panels are placed higher. In the case of the cultivation location in Tarnów, the average share of $I_{\mathrm{DIFFUSIVE}}$ to I_{TOTAL} radiation is about 40%, while for Mediterranean latitudes, such as the location in Cartagena, the share of $I_{\mathrm{DIFFUSIVE}}$ to I_{TOTAL} radiation is about 10%. So, in these latitudes, photosynthesis is determined by radiation and incident. In this case, the ratio of the panels' area to the total area will approximately determine the radiation level necessary for photosynthesis and the LC point. On the other hand, in the case of Tarnów, the arrangement of the panels and the percentage of the area (up to about 30%) will not determine the lighting at the plant level to such a degree, due to the high proportion of $I_{\text{DIFFUSIVE}}$ radiation. On the other hand, the extension of the growing period into September and October will require artificial lighting due to lower lighting at this latitude.

XII. CONCLUSION

This article has reviewed works that analyze the integration of photovoltaics and agrotechnics. These issues have been considered assuming the use of a foil tunnel with panels for very different weather phenomena and climatic conditions. The maximum area of coverage with solar panels was assessed so that shading would not reduce the rate of photosynthesis. They can cover up to 25% of the surface, depending on the climate zone and type of plant. Due to the complexity of the problem, analysis was limited to tomato cultivation in four climate zones. The study also estimated energy consumption for tunnel automation, water storage and preparation, and water droplet delivery to plants. The approximate energy balance for the four climatic zones has been presented. In each case, the energy surplus was obtained while maintaining optimal plant growth conditions, in particular by ensuring the proper rate of photosynthesis. The paper has also presented a simple and affordable design of a foil tunnel which has the ability to open walls, darken, and provide artificial light, and is equipped with installations for basic measurements and control in order to obtain the desired plant growth conditions. It was proposed that in each climate zone a foil tunnel be organized with specialized measuring devices in order to build a control algorithm for a given plant, which could be used later in cheap, commonly used tunnels. This tunnel should include automation and energy management to maintain the photosynthesis rate and a positive energy balance. More detailed conclusions for each analyzed location are presented below.

The northernmost location in Tarnów (Poland) is a good site for tomato cultivation with respect to meeting the water requirement of the crops. All the water in the considered period of cultivation can be obtained from rainwater retention. This is possible due to abundant annual precipitation and the low evapotranspiration in the Dfb climatic zone. Low evapotranspiration also means low energy consumption for drip irrigation. On the other hand, there are problems with tomato cultivation in Tarnów resulting from high air humidity, relatively low insolation, and low air temperatures in early spring and late summer. Therefore, artificial lighting in agro-photovoltaic tunnels is a must from mid-August. The energy surplus is of the lowest value compared to the energy surplus in other locations.

The more southern location in Cartagena suffers from water shortage. Therefore, a significant amount of energy is consumed by pumping water from sub-artesian sources and for desalination of seawater. Energy consumption for water production in Cartagena is the biggest among the four analyzed localizations. The energy consumption for drip irrigation is twice as high as in Tarnów because of greater evapotranspiration. On the other hand, drip irrigation in Cartagena consumes twice less energy in comparison with Cali and about 500 kWh lower than in Béchar. There is no need for artificial lighting in Cartagena. Energy surplus is about 7 MWh more than in Tarnow due to the higher energy production from the PV panels.

The location in Béchar in the Algerian desert unexpectedly seems to be the best place for an agrophotovoltaic tunnel in terms of the amount of energy produced. Energy production from the PV panels is the highest from all the analyzed locations. Moreover, energy for water production is more than 200 kWh lower than in Cartagena due to low-salt brackish water sources in the neighborhood. In spite of the highest energy consumption for drip irrigation due to the highest evapotranspiration and relatively high amount of energy needed for artificial lighting, the energy surplus is largest of all the locations.

The location in Cali has the most abundant precipitation and the water needs are completely covered from the rain harvest. Similarly to in Cartagena, there is no need for artificial lighting in Cali, and the energy surplus is comparable to that of Cartagena.

As shown in Section XI-B.5, the considerations regarding tomato cultivation in agro-photovoltaic tunnels can be generalized to most climate zones, with the exception of the coldest climate zones of type C, D, and E. Evaluating the possibility of growing tomatoes in the coldest climate zones requires separate studies.

The considerations contained in Chapter XI.B.4 on the economic aspects of tomato cultivation in APV tunnels show that the amount of energy produced and the yields obtained from tomato production do not always ensure profitability. Income from agricultural production and electricity is directly proportional to the prices of tomatoes and electricity in local markets. Therefore, with low energy and tomato prices, such as in Algeria, the return on investment can be relatively long.

One of the ways to increase income from an agrophotovoltaic tunnel is to grow vegetables other than tomatoes in the autumn and winter, or to grow vegetables more profitable in a given market than tomatoes in the spring and summer. Therefore, it is reasonable to ask whether the model of the agro-photovoltaic tunnel proposed in the article allows for the cultivation of other plants than tomatoes. The answer is yes when growing vegetables with similar water and climate requirements to tomatoes. Such plants include: sweet potato, okra, pepper, eggplant, cucumber, corn, squash, zucchini, southern peas, beans, malabar spinach, ground cherry, onion, leek, carrot, beet, and basil. In addition, taking into account the possibilities of cooling, additional heating, lighting, and virtually any irrigation and fertilization, as well as protection against adverse weather conditions (wind, hail, heavy rains) offered by the described model of the agro-photovoltaic tunnel, it seems to be possible to grow any vegetable and many fruit bushes and low-growing fruit trees under these conditions. It seems, however, that the most economical approach is the cultivation of plants in tunnels in periods similar to the periods of their natural vegetation. Thus, in the autumn and winter, the following crops should be successful: alliums (e.g., onions, garlic, leeks, shallots), heading brassicas (brussels sprouts, cabbage, cauliflower, sprouting broccoli), leafy greens (brassica greens, chard and spinach, chicories, fennel, lettuce, parsley), fava beans, and root crops (carrots, parsnips, celeriac, turnips, rutabaga, radishes, horseradish, Jerusalem artichoke) [118]. It seems, however, that due to the temperatures being too high, cultivating winter vegetables in the tunnel may not be possible in climate zone A. The exact answer of which vegetables can be grown in an agro-photovoltaic tunnel requires additional analyses and research.

The described model of the agro-photovoltaic tunnel obviously has its limitations. One of the most important seems to be the lack of a qualitative and quantitative analysis of the effect of shading from panels on plant evapotranspiration. The conclusions of this analysis may turn out to be optimistic for dry climate zone B because shading reduces the evaporation of plants, and thus water consumption. Another limitation is the lack of calculations regarding the energy consumption for heating the tunnels. In the presented analysis, this was not so important because it was assumed that cultivation in tunnels takes place during the natural vegetation of tomatoes in individual climate zones and that additional heating only needs to be activated sporadically. However, this issue will be of key importance when analyzing tomato cultivation in the coldest climate zones of type C, D, and E, and in the autumn and winter periods in warmer climate zones of type B, C, and D. Another limitation is the lack of quantitative and qualitative analysis of the possibility of cooling tunnels, which is important in the hot climate zones of type A and B, but also during summer periods in the warmer climate types of C and D. As for the economic analysis, a simplification was adopted that electricity is returned to the grid, which in the case of areas that are not electrified is a serious limitation. Future research should analyze the possibility of using energy banks in the construction of an agro-photovoltaic tunnel. The model should also be supplemented with an analysis of the possibility of growing a second crop (e.g., onions) in the autumn-winter period and an analysis of the possibility of recovering salt from the desalination process. Taking into account the last two options could significantly shorten the payback time and increase the income from the agro-photovoltaic tunnel. The analysis of the above-mentioned issues will be the subject of future research.

Summing up, this paper proposes the introduction of special foil tunnels integrated with photovoltaic panels for use in areas with extreme climatic conditions in various climate zones, including post-industrial areas. They enable the expansion of arable land and the production of electricity.

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