IOSUD - Universitatea Politehnica Timişoa
Şcoala Doctorală de Studii Inginereşti

Contributions to the Electrical and Thermal Modeling and Simulation of Greenhouses Using Transparent PV. Experimental Validation.

Doctoral Thesis – Abstract

for the scientific title of Doctor at
Universitatea Politehnica Timișoara
in the doctoral field of Electronic Engineering, Telecommunications and Information Technologies

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<u>Engleză:</u>

Motivation

Interest in renewable energy sources has seen a significant increase over the past decades, leading to a historic level of investment in their development. From the perspective of conventional energy systems, renewable sources are often classified as alternatives; however, when viewed from a broader historical perspective, it becomes evident that these sources have been exploited by humanity in one form or another for millennia. In contrast, technologies associated with the exploitation of fossil fuels have only developed in the last 150–200 years.

Solar energy harnesses sunlight to generate electricity through photovoltaic cells or solar thermal systems. It has made significant progress, making it an attractive choice for both residential and industrial applications [1] [2]. Solar energy systems benefit from the widespread availability of abundant sunlight, although their efficiency can be affected by geographic location and weather conditions.

A photovoltaic panel consists of an array of solar cells interconnected either in series or in parallel, depending on the system requirements. These arrays convert the radiation received from the sun into electrical energy. Among the defining characteristics of a photovoltaic system are modularity, energy autonomy, operational safety, and the fact that it uses a free and inexhaustible energy source – the sun. Additionally, photovoltaic systems offer high versatility, as they can be designed and adapted for a wide range of applications compared to conventional electricity generation systems.

The energy generated by photovoltaic panels can be used to heat the greenhouse during cold periods or ventilate it during hot periods; furthermore, it can power an integrated irrigation system, temperature and soil humidity measurement systems, as well as air temperature and humidity sensors. These measurements enable efficient plant development by maintaining an appropriate microclimate inside the greenhouse. Moreover, the generated energy can also be used to implement an intelligent video monitoring system for plants to ensure proper development.

For a greenhouse, light is a significant and crucial factor for plant growth. The global solar radiation entering a greenhouse consists of Ultraviolet (UV), Photosynthetic Active Radiation (PAR) – which is essential for plant growth and photosynthesis – and Near-Infrared (NIR). Plants use various photosensitive receptors and pigments to absorb specific wavelengths that help regulate their growth and development [3].

Objectives

A greenhouse equipped with photovoltaic panels must find a balance between two contradictory elements: maximizing the absorption of PAR (Photosynthetically Active Radiation) inside the greenhouse by reducing the shading effect of the photovoltaic panels, while also increasing energy production, which grows with the expansion of the opaque surface area of the panels. The main challenge in a greenhouse covered with PV panels is achieving equilibrium between the panel-covered roof and the plants. Transparent PVs offer an advantage here by reducing the opaque panel-covered areas and maximizing PAR absorption at the plant level.

The main objectives of this thesis are focused on two major directions:

1. Electrical and thermal modelling and simulation:
   - Development of electrical models for DSSC cells
   - Simulation and comparative analysis between DSSC and Silicon models
   - Development of thermal models for DSSC cells
   - Simulation and analysis of results between DSSC and Silicon
2. Practical implementation of the greenhouse structure and experimental validation of the developed models:
   - Development of a hardware system for greenhouse monitoring and control
   - Development of a software system for greenhouse monitoring and control
   - Experimental validation and comparative analysis of the electrical behaviour of DSSC and monocrystalline silicon cells
   - Experimental validation and comparative analysis of the thermal behaviour of DSSC and monocrystalline silicon cells

To achieve the objectives defined above, the thesis is organized into six chapters, which I will briefly present below.

Chapter 1 – "Introduction" details the relevance of the chosen topic and the motivation behind the research. Based on these elements, the thesis objectives are formulated, which subsequently determine the structure of the work.

Chapter 2 – "Current State of Energy-Autonomous Greenhouse Implementation" presents the thesis topic in the context of recent developments and research in the field of energy-autonomous greenhouses. It defines the types of energy-autonomous greenhouses available on the market or in the research phase. It identifies and analyses the types of photovoltaic panels available and used in the development of energy solutions for autonomous greenhouses. It also presents and analyses the types of sensors used for greenhouse monitoring and the existing electronic modules for intelligent greenhouse control using IoT – Internet of Things.

Chapter 3 – "Greenhouse Modelling" presents the types of models developed and the results of their simulation. It details the procedures used to develop electronic models for transparent Dye-Sensitized Solar Cell (DSSC) photovoltaic panels. It also describes the methods used to develop energy models for the entire monitoring and control system used in the greenhouse, as well as the development of a thermal model for the greenhouse and the transparent DSSC photovoltaic panels.

Chapter 4 – "Proposed Greenhouse Structure" includes details about the experimental construction of the greenhouse from both a mechanical and hardware/software implementation perspective. It details the mechanical elements considered for the greenhouse structure, the hardware components used for the monitoring and control system, and the software elements, including the rationale for the programming languages used and the software solutions developed for the monitoring and control system.

Chapter 5 – "Experimental Results" presents the results obtained from the electrical and thermal analysis of the photovoltaic panels. It compares the performance differences between transparent photovoltaic panels (DSSC – Dye-Sensitized Solar Cell) and monocrystalline silicon panels. It analyzes the results obtained from partial shading of the photovoltaic panels and the impact of this shading on performance. It also examines the thermal behavior of different types of photovoltaic panels, both DSSC and monocrystalline silicon, when exposed to solar radiation.

The final chapter, "Conclusions", summarizes the results obtained, the author's contributions, and the dissemination of these results in scientific publications. The chapter concludes with a list of future research directions.

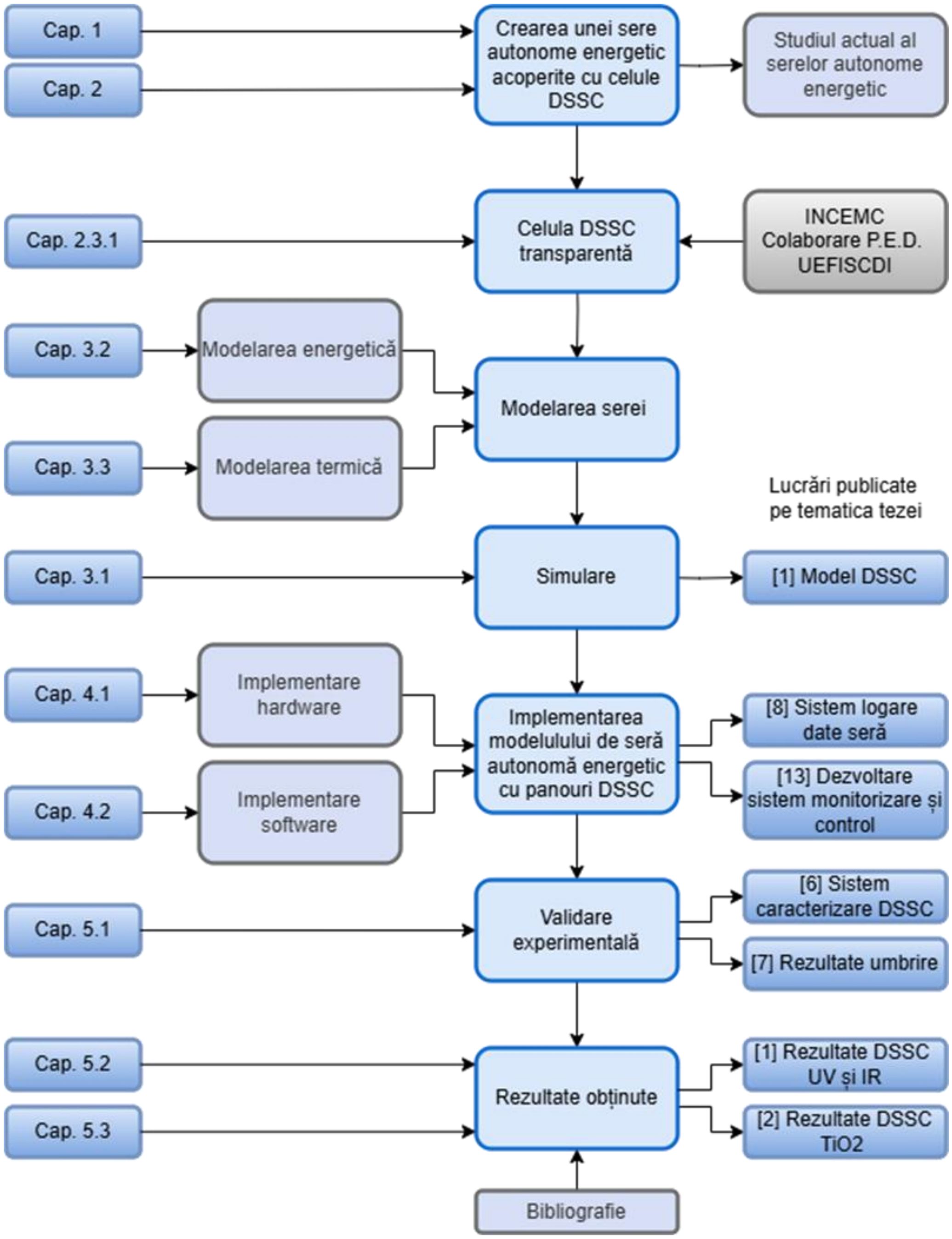


Figure 1: Thesis structure diagram

Current State of Energy-Autonomous Greenhouse Implementation

Greenhouses with photovoltaic (PV) panels integrate solar panels into their structure, allowing crops to benefit both from light for photosynthesis and from electrical energy for uses such as irrigation, heating, and ventilation systems. By efficiently harnessing sunlight for dual purposes, this design significantly reduces energy costs and promotes sustainable practices [4], [5], [6]. Majidi et al. discuss how sustainable photovoltaic systems can help greenhouses achieve net-zero energy consumption by using locally available resources and designing systems adapted to specific environmental conditions [7]. Similarly, Jiang et al. emphasize how optimizing solar energy in greenhouses, especially in cold climate regions, can lead to significant reductions in both energy consumption and operational costs [8]. The integration of photovoltaic panels into greenhouses represents a major advancement in both sustainable agriculture and renewable energy utilization. The types of greenhouses covered with photovoltaic panels vary depending on the method of panel integration, the types of crops grown, and the climatic conditions of the location.

There are three main types of greenhouses with photovoltaic systems: On-Grid PV greenhouses, Off-Grid PV greenhouses, and Hybrid PV greenhouses.

On-Grid PV greenhouses use an energy management system that is permanently connected to the electrical grid. In this setup, photovoltaic panels generate direct current (DC) electricity during the day when solar radiation is at its peak. This energy is directed to an inverter that converts DC into alternating current (AC), which can be used by the greenhouse's electrical equipment. Any electricity produced but not consumed locally is fed into the national distribution grid, where it can be used by other consumers.

Off-Grid PV greenhouses use an energy management system that is not connected to the electrical grid and stores all the energy generated by the photovoltaic panels on sunny days in batteries. A solar controller is connected between the battery and the photovoltaic panels to monitor the battery's charge status. When the controller detects that the battery is fully charged, it stops the energy supply to prevent overcharging, extend battery life, and ensure efficient system operation.

Hybrid photovoltaic systems combine the advantages of both grid-connected and autonomous configurations, offering an efficient and flexible energy supply solution. This type of system is connected to the national distribution grid but also includes an energy storage system in the form of batteries. The energy generated by the photovoltaic panels during high solar radiation days is stored in these batteries and later used during periods when grid supply is interrupted or during unfavorable weather conditions, when photovoltaic production is insufficient to meet the consumption needs of users connected to the system.

Following the analysis of all existing types of photovoltaic systems, it was concluded that the most suitable system for a greenhouse is an Off-Grid photovoltaic system. This type of system is ideal for a greenhouse because it provides energy independence regardless of the greenhouse’s geographical location. It does not require the greenhouse to be positioned near an electricity source or the national power grid, meaning it can be placed virtually anywhere.

DSSC Cells

For greenhouses, dye-sensitized solar cells (DSSC) offer several advantages compared to monocrystalline silicon solar cells, especially in the context of the agrivoltaic industry. This integration not only meets energy needs but also enhances agricultural productivity by optimizing light conditions for plant growth.

DSSCs also show significant potential in the agrivoltaic industry, a field that aims to synergistically use land for both agriculture and solar energy production, thereby increasing land-use efficiency [9], [10]. In this context, integrating DSSCs into agricultural systems offers multiple benefits.

DSSCs can be designed to allow selective light transmission, enabling part of the solar radiation to reach the crops below, while another portion is converted into electrical energy [11]. This property is particularly beneficial in arid regions, where maximizing the use of sunlight for both energy production and agriculture is essential. The use of DSSCs could encourage landowners to adopt renewable energy practices without compromising valuable agricultural land [12], [13]. The relatively low installation costs compared to conventional solar technologies further enhance the attractiveness of these systems for integration into the agricultural sector [14], [15].

Another crucial advantage of DSSCs used in the agrivoltaic industry is their superior performance under diffuse lighting conditions. Unlike silicon-based solar cells, which often struggle in low-light scenarios, DSSCs can efficiently capture solar energy even under cloudy skies or through vegetation [16], [17]. This adaptability makes them particularly appealing for agricultural environments, where optimal lighting conditions are not always guaranteed.

Due to all the benefits that DSSC cells offer for use in agrivoltaic systems, I chose to focus on this type of photovoltaic cell. Additionally, we won and received funding from the Executive Unit for Financing Higher Education, Research, Development and Innovation (UEFISCDI) for a Demonstrative Experimental Project. The prototype developed under project number 479 PED from 05/11/2020 is titled “Intelligent greenhouse with selective absorption of solar radiation using dye-sensitized solar cells (DSSCs), autonomous and automated”, and was carried out between 2020 and 2022, with a total funding of 599,888 RON, of which UPT’s share was 185,078 RON.

Sensors Used for Monitoring

The sensors used for monitoring and control can be divided into four categories:

1. Soil Monitoring Sensors

To monitor soil temperature and moisture, we used three S-Soil MTEC-02A sensors for humidity, temperature, and electrical conductivity. These sensors are equipped with a MODBUS-RTU RS485 communication module and support supply voltages from 3.6V to 30V. The S-Soil MTEC-02A sensor allows us to monitor the soil's electrical conductivity, enabling accurate measurement of the volumetric water content in the soil regardless of soil type, with high precision and accuracy [18].

2. Indoor Greenhouse Environment Sensors

To monitor temperature and humidity inside the greenhouse, we used a DHT22 humidity sensor, which digitally measures humidity using a capacitive sensor and temperature using a thermistor. We chose this type of sensor due to its familiarity, having been used in multiple projects over time, and because it has low current consumption (0.3 mA) during measurements and a versatile supply voltage range from 3.3V to 5.5V, making it ideal for a greenhouse powered by photovoltaic panels.

3. Outdoor Climate Monitoring Sensors

Monitoring the external weather conditions of the greenhouse is necessary as it informs us about wind speed, allowing us to protect the DSSC photovoltaic panels on the roof. Additionally, by monitoring precipitation levels, we can control the opening and closing of the greenhouse roof to maximize solar energy absorption by the DSSC panels and protect the greenhouse and its systems from water damage.

All this information is provided by a DS-15901 weather monitoring system, which consists of three elements: an anemometer, a rain gauge, and a wind vane.

4. Solar Radiation Monitoring Sensors (Exterior and Interior)

Due to the variation in solar irradiance throughout the year caused by seasonal changes, we used the Delta Ohm LPPYRA03S sensor to measure Photosynthetically Active Radiation (PAR), with RS485 MODBUS-RTU communication. This sensor belongs to Class C pyranometers and can measure in a range from 0 to 1600 W/m^2 with an accuracy of ±5% [18].

Additionally, to monitor UV radiation both outside and inside the greenhouse and create a suitable environment for crop development, we used the Delta Ohm LPUVA03BLS sensor with RS485 MODBUS-RTU communication. The UV radiation measurement range is between 315 nm and 400 nm.

Development of a Transparent PV Model

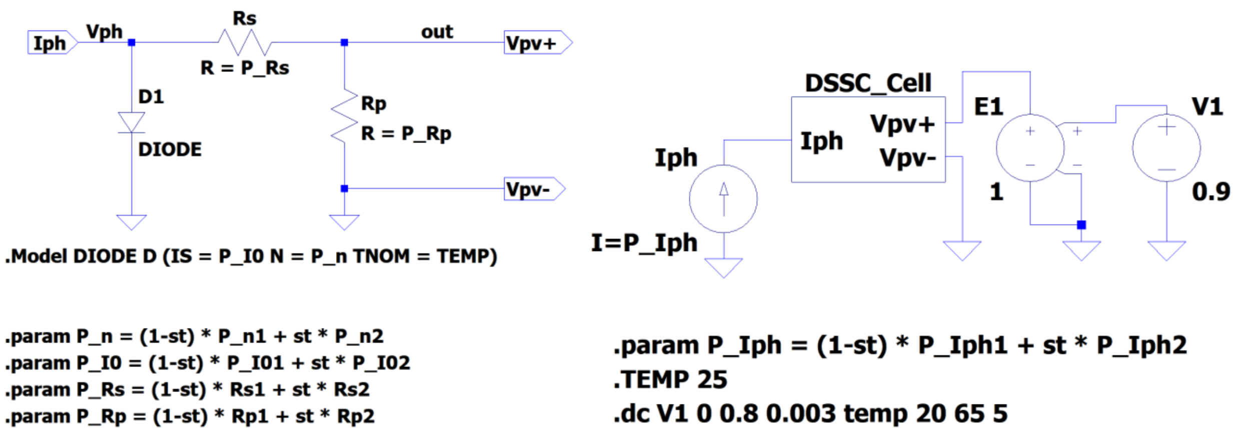
To efficiently simulate photovoltaic (PV) cells, it is essential to establish a comprehensive schematic model that accurately reflects the operational characteristics of PV systems under varying environmental conditions.

The single-diode model with a series resistor and a parallel resistor, schematically illustrated in Fig. 3.2, is the most commonly used equivalent model for photovoltaic cells in the scientific literature, as shown in [19], [20], [21], [22], and for this reason, we chose to use it.

The five-parameter equivalent model, typically used for modelling conventional silicon photovoltaic cells, will be adapted for DSSC cells. Even though the two types of cells differ in terms of components and manufacturing processes, I will demonstrate that this model is valid for DSSC cells.

Using both calculated values and those provided by the DSSC cell manufacturer, we developed the equivalent circuit of the DSSC cell, shown in Figure 2-a.

This model was later transformed into a DSSC component used for simulation. Both the implementation described above and the final simulation schematic shown in Figure 2-b were implemented in LTspice.



a. **b.**

Figure 2: **a.** Diode, parallel and series resistance model; **b.** Final implementation of the simulation model of the DSSC [original]

After simulating the circuit using a temperature variation starting from twenty-five degrees Celsius to sixty-five degrees Celsius with a temperature increment step of five degrees Celsius, we obtained the following results.

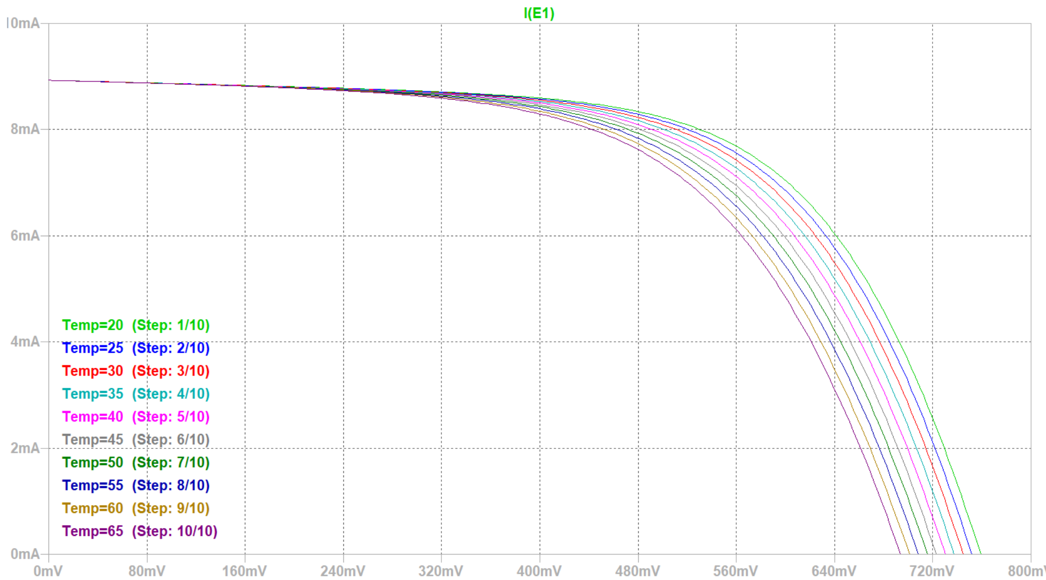


Figure 3: I_{SC} obtained results after the SPICE simulation of the DSSC cell [original]

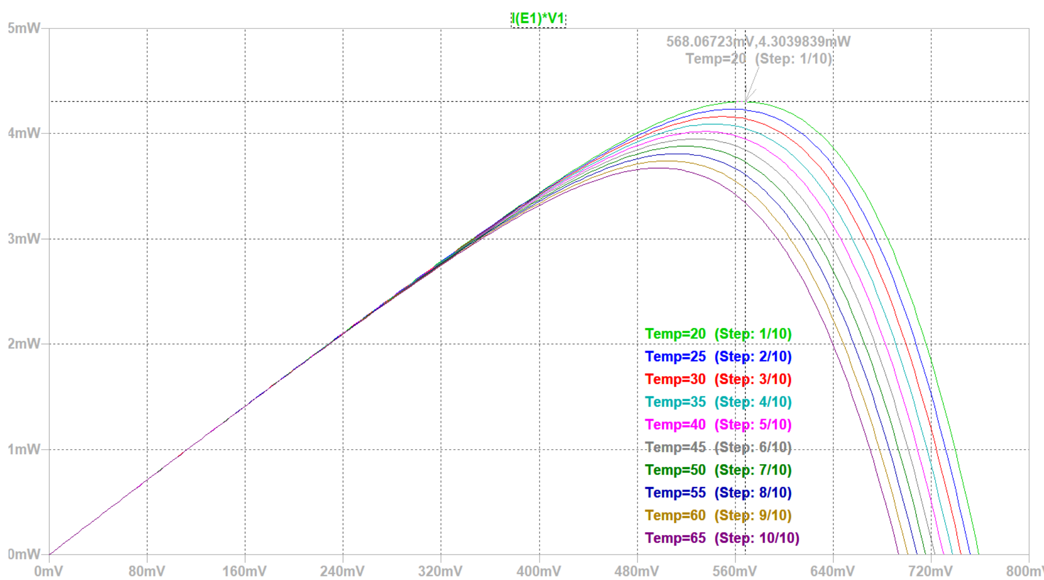


Figure 4: P_{MAX} obtained results after the SPICE simulation of the DSSC cell [original]

Energy Modelling of the Greenhouse

Energy modelling for a greenhouse powered by photovoltaic panels is essential, as it enables the optimization of energy consumption and ensures efficient operation. Depending on the greenhouse's energy requirements, energy modelling helps determine the optimal number of panels and the battery capacity needed for energy storage.

The simulation of the equivalent circuit is performed for two voltage levels, since some components of the greenhouse system are powered directly from a 12-Volt battery, while others are powered through a converter that steps down the voltage from 12 Volts to 5 Volts.

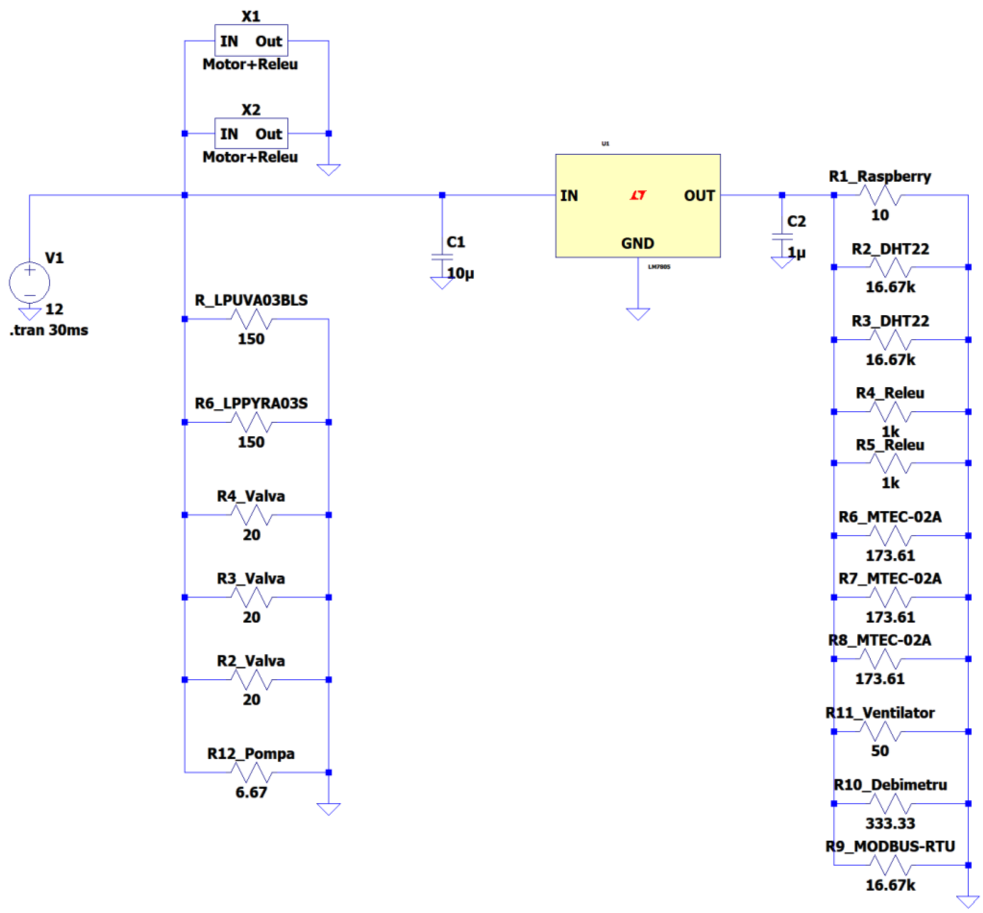


Figure 5: The equivalent circuit with all the loads of the greenhouse system [original]

Following the simulation of the equivalent circuit, an instantaneous energy consumption of 113.2 W was recorded for the entire greenhouse when all components are active simultaneously. Once the motor starts, the consumption stabilizes at 61 W, and when the actuators are turned off, the instantaneous energy consumption with all other consumers active drops to 53.7 W.

If we consider that the only elements permanently connected to the battery powering the system are the UV and PAR radiation sensors, the Raspberry Pi board, and the soil and air temperature and humidity monitoring sensors, the resulting instantaneous energy consumption for the simultaneous operation of all sensors is just over 9 W. This occurs rarely, at 30-second measurement intervals (120 measurement cycles per hour), for a period of no more than one second, when data is acquired from all sensors.

Due to the periodic operation of the sensors, the energy consumption is further reduced, reaching a level of approximately 3 W.

Thermal Modelling of Photovoltaic Cells

During the process of converting sunlight into electrical energy, conventional silicon solar panels are capable of transforming approximately 15–20% of solar light into electricity, while the remaining 80–85% of photon energy is converted into heat, which accumulates in the solar panel. This temperature increase directly affects both the panel's performance and its lifespan.

In the thermal modelling process of photovoltaic panels, it is necessary to consider both the internally generated heat from the panel's components and the thermal transfers occurring at the panel's surface, specifically between the panel and the surrounding environment. From a thermal transfer perspective, two types of heat transfer must be considered for photovoltaic panels: convection and radiation.

Thermal Simulation of a Silicon Photovoltaic Cell

To establish a benchmark for comparing the performance of transparent DSSC cells, we developed a thermal simulation of an equivalent solar panel composed of conventional silicon photovoltaic cells. Using the Ansys simulation software, we performed the thermal simulation of a single silicon cell.

In Figure 6, we can observe all the materials that make up the silicon cell, how these materials are layered, and which surfaces come into contact. The calculated thermal fluxes are applied to the layers of the photovoltaic panel module in such a way that it becomes easier to understand how they interact..

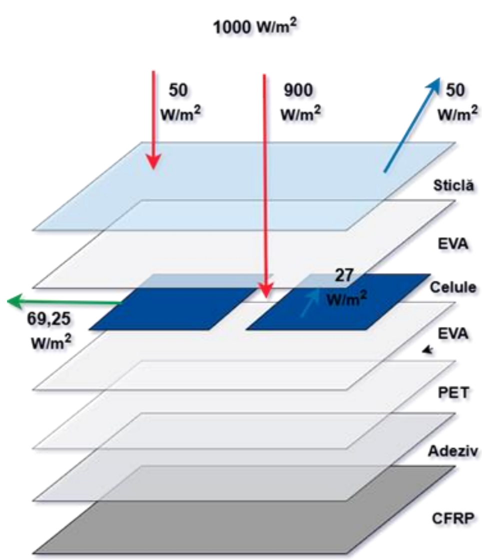


Figure 6: Thermal fluxes applied to the layers of the silicon photovoltaic module [original]

Following the simulation of the silicon photovoltaic module exposed to solar radiation of 1000 W/m² and an ambient temperature of 25°C, we obtained the results shown in the figures below. From Figure 7, the thermal behaviour of the two silicon cells forming the photovoltaic module can be observed. In this case, the thermal values range between 36.48°C and 37.35°C..

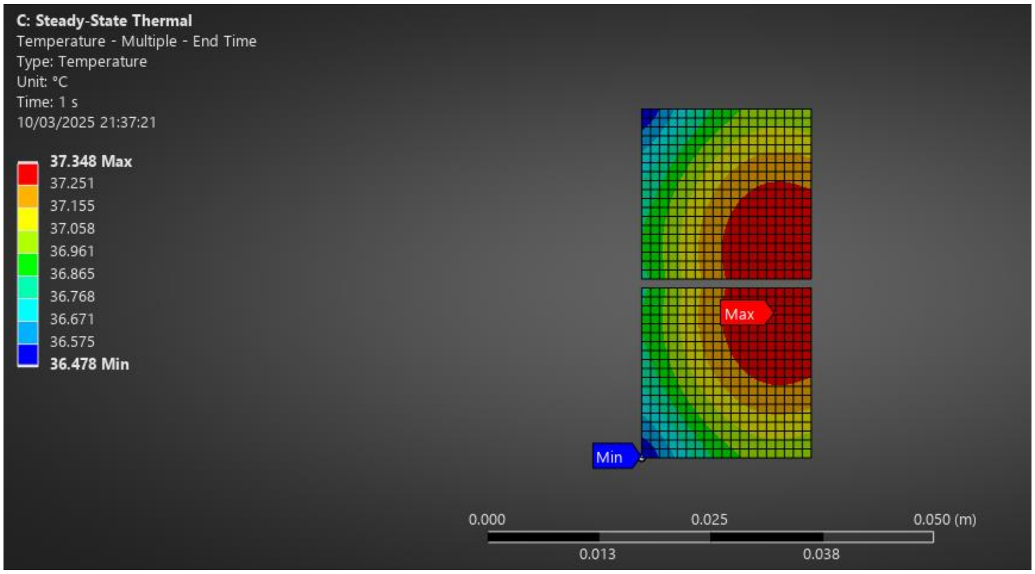


Figure 7: Thermal simulation of the layer with silicon cells [original]

Thermal Simulation of a DSSC Photovoltaic Cell

The simulation of the DSSC cell followed the same steps as the simulation of the silicon module. Compared to the silicon module, the DSSC cell has a much simpler structure, consisting of only three layers: two FTO glass layers on the top and bottom, which encapsulate a TiO_2 layer in the middle.

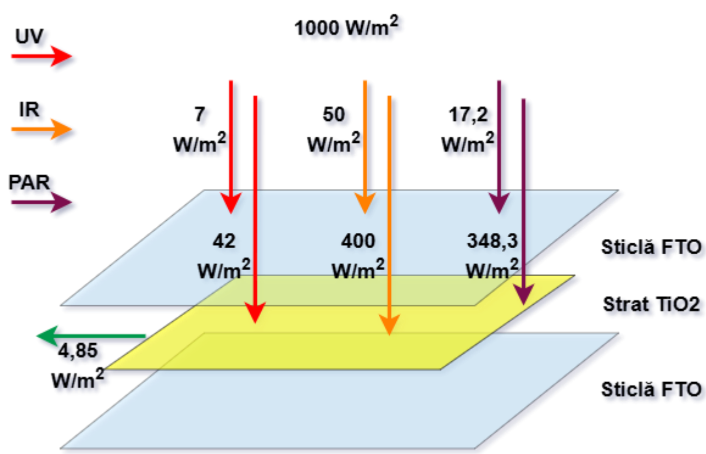


Figure 8: Thermal fluxes applied to the layers of the DSSC photovoltaic module [original]

In Figure 9, we can observe the thermal behaviour of the TiO_2 photoanode layer of the DSSC, where the thermal values range between a minimum of 31.47°C and a maximum of 32.05°C.

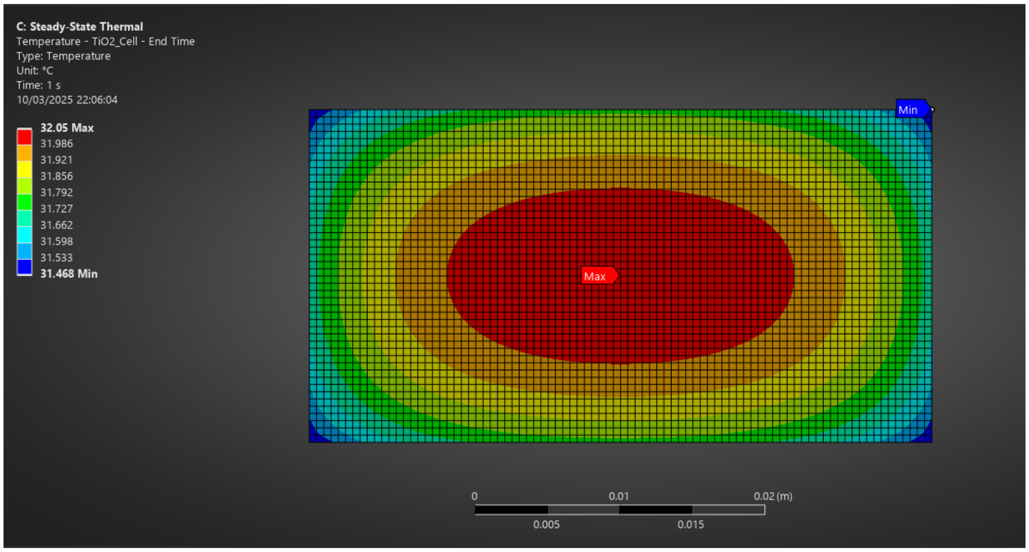


Figure 9: Thermal simulation of the layer of TiO_2 [original]

The thermal simulation of both monocrystalline silicon cells and DSSC cells demonstrates that the thermal variations on the surface of the DSSC cell layer materials are significantly smaller compared to the silicon module. Furthermore, from the thermal modelling, we can observe that the silicon model is more complex than the DSSC model, which results in better thermal behaviour for DSSC cells.

Tabel 1: Temperature variation on similar layers for DSSC and monocrystalline silicon cell [original]

Layer	**Temperature Monocristaline Silicon**			**Temperature DSSC**		
	Material	**Min.**	**Max.**	**Material**	**Min.**	**Max.**
Superior	Glass	33.8°C	37.2°C	FTO Glass	31.5°C	32.07°C
Active layer	Silicon	36.5°C	37.4°C	TiO_2	31.5°C	32.05°C
Inferior	CFRP	34.9°C	36.8°C	FTO Glass	31.2°C	32.05°C

Following the simulation of the DSSC cell, we can observe that the thermal variations on the surface of the cell's layer materials are significantly smaller compared to the previously presented silicon module. The TiO_2 photoanode layer shows a thermal variation of only 0.58°C across its entire surface, while the silicon layer of the silicon module exhibits a thermal variation of 0.87°C across its surface.

Energy-independent agrivoltaic greenhouse – Proposal

To select the best solution for the greenhouse structure, we analyzed several specific factors for Timişoara and its surrounding area, such as monthly average temperature and monthly solar radiation, expressed in kWh/m².

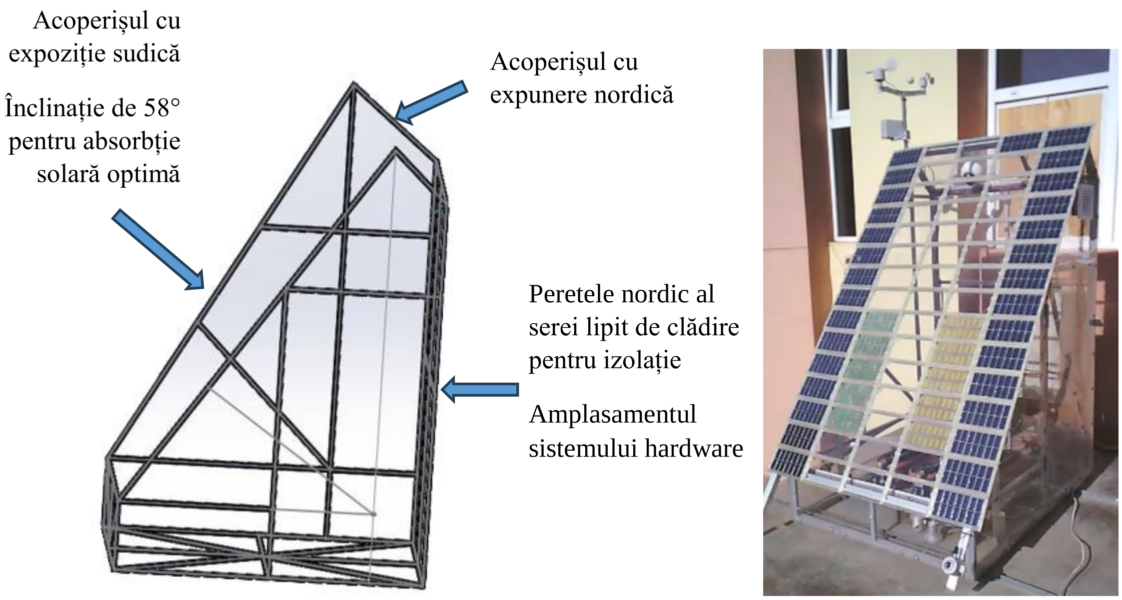


Figure 10: Structura propusă a serei

We also considered the analemma for the geographical area of Timișoara (Latitude 45°44'50"N and Longitude 21°13'36"E). The analemma is a diagram that illustrates the apparent path of the sun in the sky at the same time each day throughout the year..

Implementation of the Monitoring and Control System

The monitoring and control system implemented on the greenhouse prototype includes several hardware elements, starting with sensors for acquiring environmental conditions both inside and outside the greenhouse, sensors for monitoring photosynthetically active radiation (PAR), ultraviolet radiation, soil moisture, and for controlling the drip irrigation system, as well as the roof tilt control via two actuators.

For the software implementation of the greenhouse monitoring and control system, two programming languages were used: Python for the hardware component drivers, communication management, and data structuring and also Node-RED for building the graphical user interface (GUI) and managing the display and control system.

The main Python script handles access to all drivers and function libraries installed so that all sensor-acquired data and software functions are available for the application’s functionality, which accesses and processes all information.

The main Node-RED script is responsible for receiving data from the TCP/IP server, categorizing sensor data for proper display and logging, and managing control from the graphical interface for the actuators present in the control system.

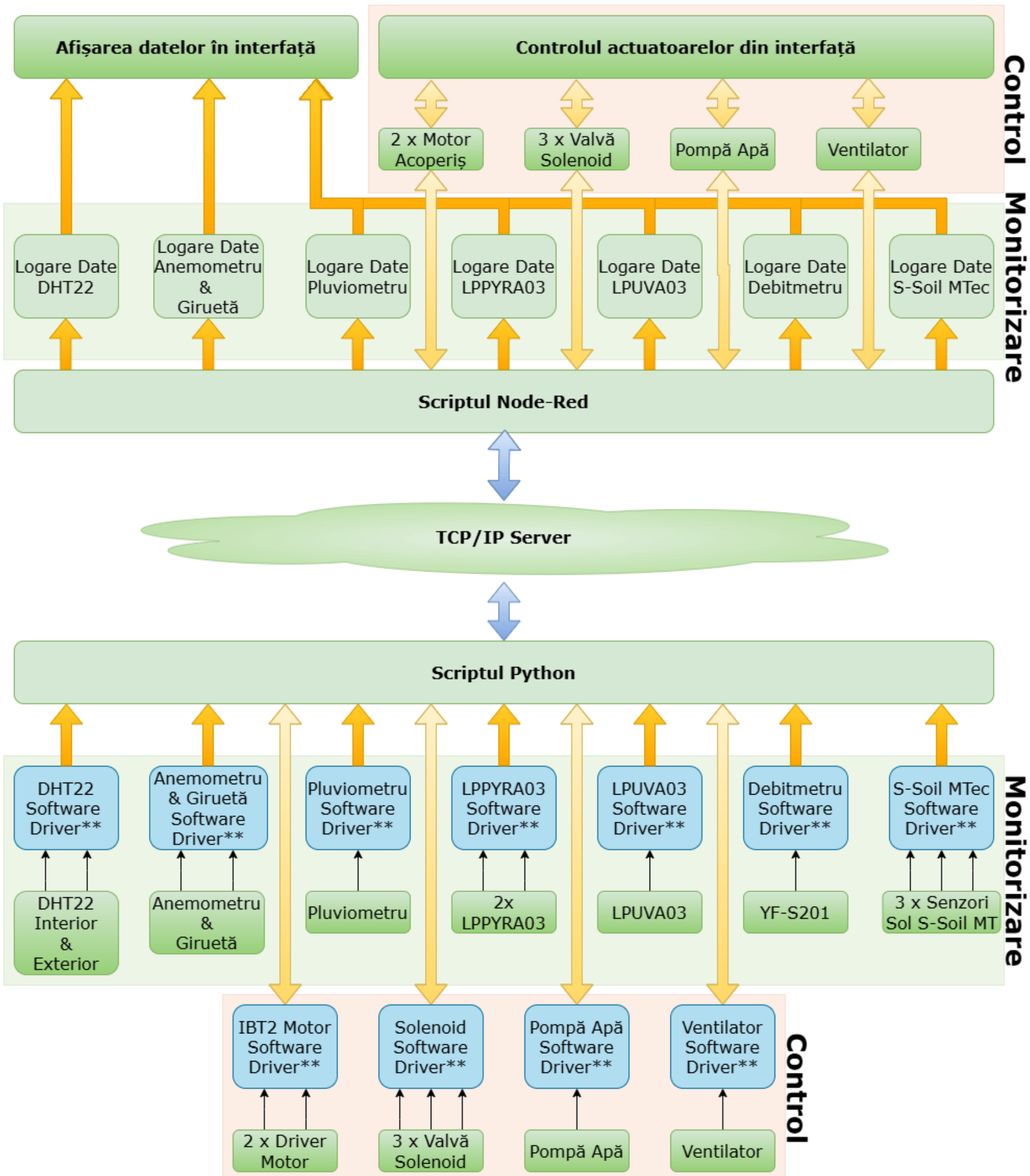


Figure 11: Software structure of the monitoring and control system
(green - original/ blue - ** created by the members of the PED project)

The entire interface with all data blocks can be seen in Figure 12, where on the left side of the figure we have the menu from which we can select the data we wish to view. These include data from the greenhouse sensors, the greenhouse control panel, external images provided by the FLIR camera, as well as interior images of the greenhouse provided by the IP camera.

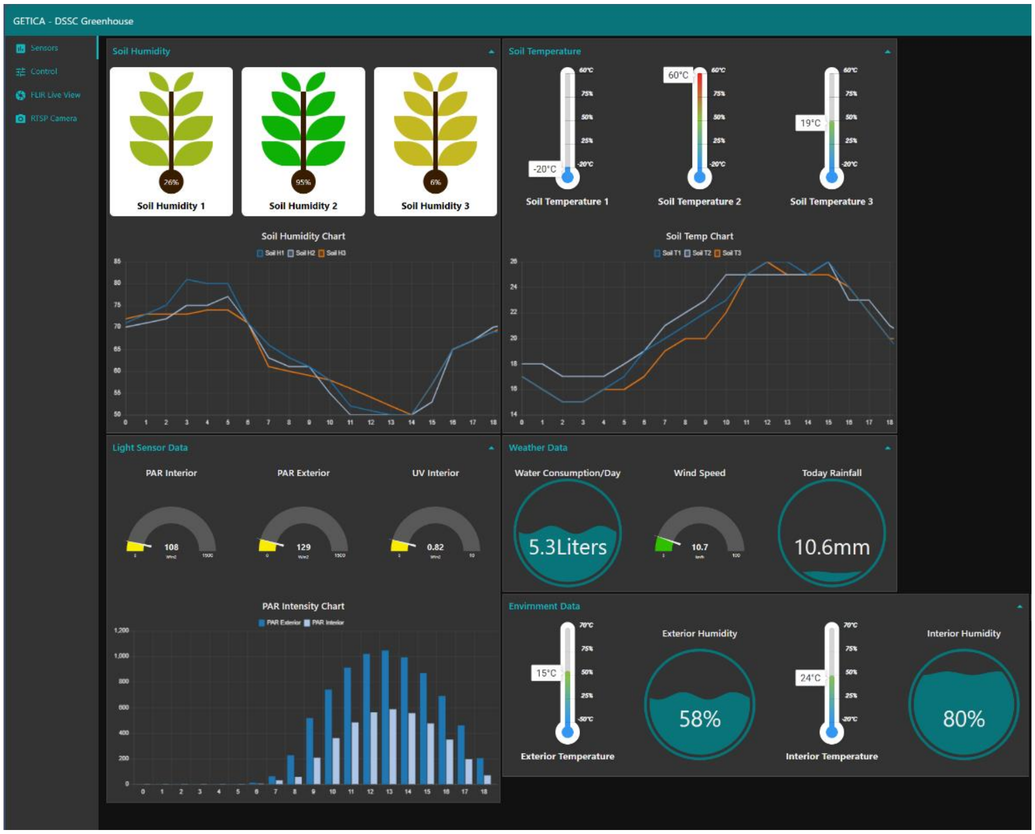


Figure 12: Complete graphical user interface with displaying of all data from greenhouse sensors, side menus and title [original]

Experimental Results

Performance Comparison: Transparent PV vs. Monocrystalline Silicon

The data collected for this experimental validation was gathered in March, around 12:00 PM, on a partly cloudy day, where we measured a maximum solar radiation value of 189 W/m² using the Amprobe 4000 sensor. Both the solar radiation sensor and the photovoltaic cells were positioned at a thirty-degree angle.

Tabel 2: Results of the measured power outputs of different DSSC cells [original]

Cell type	**Maximum power** ***mW***
UV	12.2
IR	16.5
PAR	26.8
Si Monocristalin	98.3

In Table 2, we can observe that among the three types of DSSC cells tested, the four-cell PAR module is the one that generates the highest maximum power point, managing to deliver 26.87 mW. At the other end, the DSSC UV module reaches its maximum power point at only 12.2 mW. The four-cell DSSC IR module ranks in between, in terms of generated power, with DSSC PAR cells producing the highest output and DSSC UV cells the lowest. This DSSC IR module reaches its maximum power point at 16.5 mW.

Influence of Partial Shading on PV Performance

To test the partial shading of DSSC cells, a module with fourteen DSSC cells in series was built, along with a reference module containing fourteen monocrystalline silicon cells. Following the tests conducted with active bypass diodes and Schottky diodes connected in anti-parallel with the cells the results presented in Table 3 were obtained.

Tabel 3: Results of partial shading on DSSC and Monocristaline Silicon [original]

Nr.	Conditions	DSSC P_{max}	Si P_{max}
1	One cell shaded 100% no bypass diode	5.38 mW	0 mW
2	One cell shaded 100% with Schottky bypass diode	8.65 mW	12 mW
3	One cell shaded 100% with active bypass diode	14.98 mW	66 mW
4	No cell shaded	23 mW	101 mW

From the results, it can be observed that DSSC cells perform better under shading conditions compared to monocrystalline silicon cells. This is due to their construction: when the upper surface is shaded, the lower surface remains transparent, allowing ambient light to pass through and excite the semiconductor, thereby enabling the generation of a small amount of energy.

Thermal Analysis of Different Types of Panels

From a thermal perspective, it is clearly evident—both from the temperature variation results of the cells and from the thermal images in Figure 13—that silicon cells reach the highest temperatures, being over four degrees Celsius warmer than the infrared-absorbing DSSC cells, and over six degrees Celsius warmer than the DSSC cells that absorb visible or ultraviolet spectrum.

Tabel 4: Maximum and minimum temperatures measured at the surface of photovoltaic cells [original]

Cell Type	Si 1	Si 2	UV 1	UV 2	VIS 1	VIS 2	IR 1	IR 2
Temp. Max. °C	30.7	30.5	24.97	24.35	24.1	24.87	26.42	26.17
Temp. Min. °C	27	26.63	23.17	22.79	23.06	23.16	24.78	24.38
ΔT °C	*3.7*	*3.87*	*1.8*	*1.56*	*1.04*	*1.71*	*1.64*	*1.79*

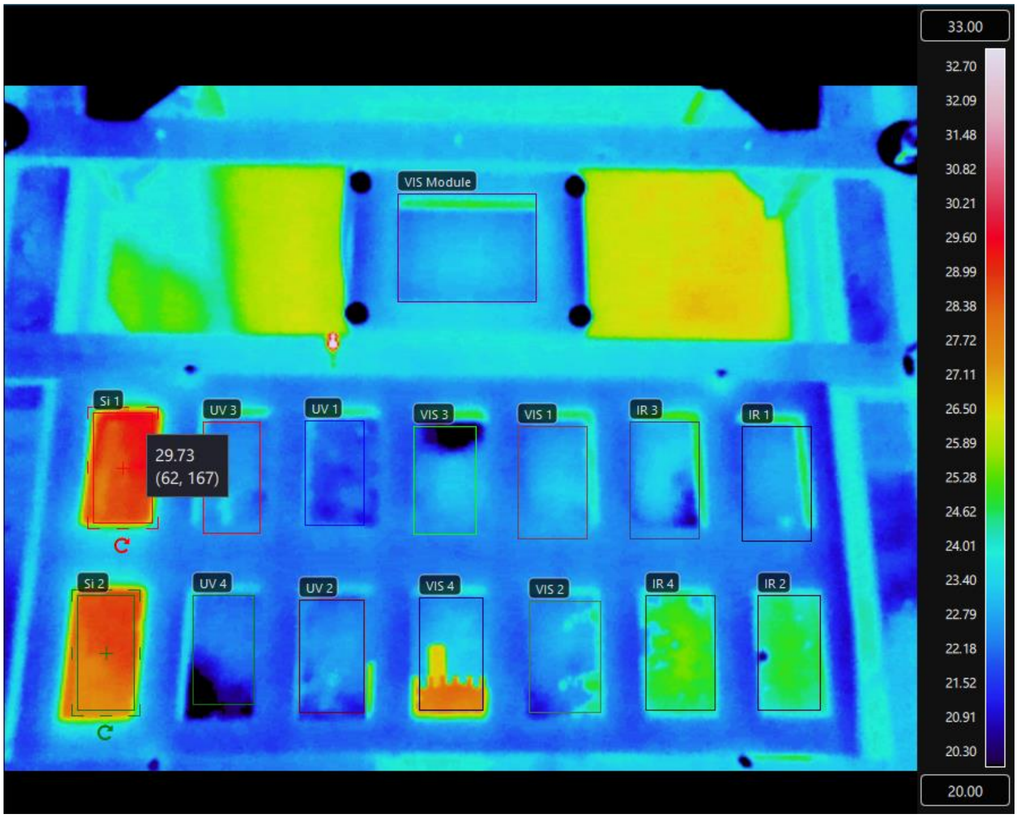


Figure 13: Image captured with FLIR A50 for thermal analysis of photovoltaic modules [original]

Conclusions

This work aimed to develop an energy-autonomous greenhouse, with a focus on sustainability, flexibility, and the integration of modern technologies in agriculture. Throughout the research, multiple directions were explored – from choosing the power supply typology, to electrical and thermal simulations of DSSC cells used to power the greenhouse, hardware and software implementation of the energy supply, monitoring, and control system, and finally the experimental validation of the thermal and electrical behavior of DSSC cells compared to monocrystalline silicon cells.

In conclusion, this work demonstrates that the integration of innovative photovoltaic technologies with intelligent automation systems can lead to the realization of a fully energy-autonomous greenhouse. The proposed project not only meets the current demands of sustainable agriculture but also offers a clear vision of the future – a future in which technology and nature collaborate harmoniously to support efficient and eco-friendly agricultural production.

Original Contributions

During the doctoral study program, I analyzed over one hundred bibliographic titles and published 17 scientific papers, of which 12 are indexed in WoS, an additional 4 indexed in IEEE Xplore, and 1 indexed in Springer. Among these, 4 papers are published in WoS journals (1 in

Q1 and 3 in Q2), and 12 are published in WoS conferences (5 as first author), with a total of 12 WoS citations.

The original contributions of this work are as follows:

In Chapter Two – Current State of Energy-Autonomous Greenhouse Implementation

1. Structuring and comparative analysis of information from current scientific literature.

In Chapter Three – Greenhouse Modeling

2. Development of an equivalent circuit model from silicon cells to DSSC cells.
3. Validation of the model through simulation of series and parallel connections of DSSC cells.
4. Development of an equivalent circuit model for the greenhouse's energy consumption.
5. Development of a thermal model for monocrystalline silicon cells.
6. Development of a thermal model for DSSC cells.

In Chapter Four – Proposed Greenhouse Structure

7. Proposal of the hardware architecture for the monitoring and control system.
8. Proposal of the software architecture and implementation of the monitoring and control system.

In Chapter Five – Experimental Results

9. Development of an experimental prototype for measuring and comparative analysis of the performance of different types of DSSC cells with selective energy absorption.
10. Study of the influence of shading on DSSC cell modules and analysis of mitigation methods for this phenomenon.
11. Experimental evaluation and validation of the thermal behavior of DSSC and monocrystalline silicon cells.

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