



Integrating Solar Cells, Arduino, and Sensors for Vocational Science Education: A Scoping Review

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Abstract

Vocational science learning requires contextual, hands-on experiences that reflect real-world technological applications. Solar cell systems integrated with Arduino and various sensors represent low-cost technological platforms with strong potential to be adapted as learning media for renewable energy topics in vocational education. Numerous studies have developed solar-Arduino-sensor systems for monitoring, tracking, acquiring data, and experimenting in a laboratory; however, these developments have not been systematically mapped from an educational perspective. This study employed a scoping review to map the landscape of existing research on solar cell–Arduino–sensor system designs. The initial literature research was conducted using Publish or Perish (PoP) based on Google Scholar indexing, followed by iterative searching and reference tracking during the review process. A total of 20 articles published between 2015 and 2025 were selected for data charting and thematic analysis. The results revealed several major clusters of system development, including solar tracking mechanisms, sensor-based photovoltaic monitoring, Internet of Things (IoT) architectures, portable photovoltaic laboratory instruments, and immersive solar education technologies. Although most studies were conducted in engineering and monitoring contexts, the identified designs demonstrated strong potential to be adapted as contextual science learning media aligned with the characteristics of vocational education. This mapping provides a comprehensive overview of technological designs that can support the development of vocational science learning tools based on solar cells, Arduino, and sensor integration.

Keywords: Arduino, Scoping Review, Sensor Integration, Solar Cell, Vocational Science Education.

Introduction

The demand for electrical energy continues to increase over time. This has resulted in high consumption of electrical energy sources, particularly fossil fuels, as the primary energy source for power plants. Fossil fuels have a direct negative impact on the environment. This has driven humanity to innovate continuously in developing electrical energy sourced from renewable energy, one of which is solar energy

converted into electricity using solar cells. Solar cells operate by harnessing photons from sunlight and converting them into electrical energy in the form of current and voltage (Fonash, 2015). Generally, there are four stages in the photovoltaic conversion process of solar cells (Conibeer & Willoughby, 2014): (1) transfer of solar photons to the active part of the system; (2) absorption of the photons and energy transfer

to the electronic system; (3) selective extraction of electrons to contacts (at least two); (4) the transfer of e-free energy to a useful load whose impedance is adjusted.

Solar cell systems involve measurable electrical parameters, such as voltage, current, and power, that vary with environmental conditions and system configurations. These characteristics allow solar cells to function as observable physical systems rather than abstract concepts, making them suitable for exploration through direct interaction. In vocational and science education contexts, learning activities that engage students with tangible systems have been shown to support conceptual understanding and the development of practical skills through hands-on experiences.

In the context of Technical and Vocational Education and Training (TVET), such hands-on activities are not merely practical exercises but represent core pedagogical principles. Vocational learning is grounded in work-based learning, where knowledge is constructed through activities that resemble real technical work (Sudira, 2017). This perspective is closely related to life-based learning and work-integrated learning, in which learning occurs through meaningful interactions with tools, systems, and real-world technologies. Solar cell systems integrated with microcontrollers and sensors reflect the techno-scientific learning environment, as students engage in assembling systems, measuring physical parameters, interpreting data, and directly observing system performance. These characteristics position solar cell-embedded system designs within the fundamental framework of TVET pedagogy rather than as merely technological devices.

Several studies have demonstrated the use of immersive technologies, portable photovoltaic laboratory instruments, Arduino-based monitoring systems, and wireless sensor architectures in learning-related or exploratory contexts involving solar energy systems, as conducted by

Machado et al. (2025), Zahra et al. (2023), and Khalid et al. (2024). Nevertheless, these studies are commonly situated within engineering, monitoring, or system optimisation contexts rather than being explicitly discussed from an educational perspective. As a result, the educational potential of these technological designs, especially for vocational science learning, has not yet been systematically mapped. To address this gap, a mapping of existing research is required to understand what types of solar cell-Arduino-sensor systems have been developed, how these systems are instrumented, and how they could be adapted as contextual science learning media.

Based on this objective, the study is guided by the following research questions: (1) What types of solar cell-Arduino-sensor systems have been developed in existing studies? (2) What physical parameters are measured, and how are these systems instrumented? (3) In what contexts are these systems applied (engineering, monitoring, laboratory, or educational settings)? (4) What educational potentials can be inferred for vocational science learning from these technological designs?

Methodology

This study employed a scoping review methodology following the framework proposed by Arksey and O'Malley (2005) and further refined by Levac et al. (2010) to map the landscape of technological designs that integrate solar cells, Arduino, and sensors. This scoping review was conducted through the following: (1) Identifying the research question; (2) Identifying relevant studies; (3) Selecting the studies; (4) Charting the data; and (5) Collating, summarising, and reporting the results. The consultation stage was not conducted, as the review focused on mapping published technological designs rather than stakeholder validation.

The initial literature search was conducted using the Publish or Perish (PoP) software based on Google Scholar indexing

with the keyword query “solar cell, Arduino, science, vocational education”. Following the scoping review approach, the searching process was iterative, and additional relevant articles were incorporated through complementary searches and reference tracking during the review process. After identifying core studies from the initial search, additional relevant articles were incorporated through reference tracking and complementary searches to ensure a

comprehensive mapping of solar cell–Arduino–sensor system designs.

To determine the eligibility of studies included in this scoping review, predefined inclusion and exclusion criteria were applied. In line with the scoping review approach, these criteria emphasised topic relevance and system characteristics rather than database indexing, journal quartile, or access type. The inclusion and exclusion criteria used in this study are summarised in Table 1.

Table 1 Inclusion and Exclusion Criteria.

No	Criteria	Inclusion	Exclusion
1.	Period	2015–2025	Before 2015
2.	Language	English	Not English
3.	Topic Relevance	Discuss solar cell systems integrated with embedded systems, microcontrollers, or sensors	Not related to solar–Arduino–sensor systems
4.	System Focus	Present system design, monitoring, tracking, data acquisition, or laboratory applications	Pure theoretical discussion without system implementation
5.	Application Context	Engineering, monitoring, laboratory, or educational context	Unrelated application context
6.	Educational Potential	Demonstrates potential for experimental or learning media adaptation	No potential for experimental or learning use

Results and Discussion

The initial literature search produced a broad set of studies relevant to solar cell systems integrated with embedded platforms and sensors. Using Publish or Perish (PoP) with the keyword combination “solar cell, Arduino, science, vocational education,” the search captured studies spanning technological, experimental, and educational contexts. Although the initial query emphasised the term “Arduino,” subsequent screening and mapping revealed that many relevant studies employed other microcontrollers and embedded systems (e.g., ESP8266, ESP32, Raspberry Pi) with similar functional roles in solar cell

monitoring and experimentation. Based on these findings, the scope of the review was broadened to include solar cell systems integrated with various embedded platforms and sensors.

This search yielded approximately 200 articles from various sources and criteria. These records served as the starting point for identifying relevant studies. VOSviewer was utilised only as a visual tool to explore keyword relationships within the initial records, supporting the understanding of research trends rather than serving as a formal screening instrument.

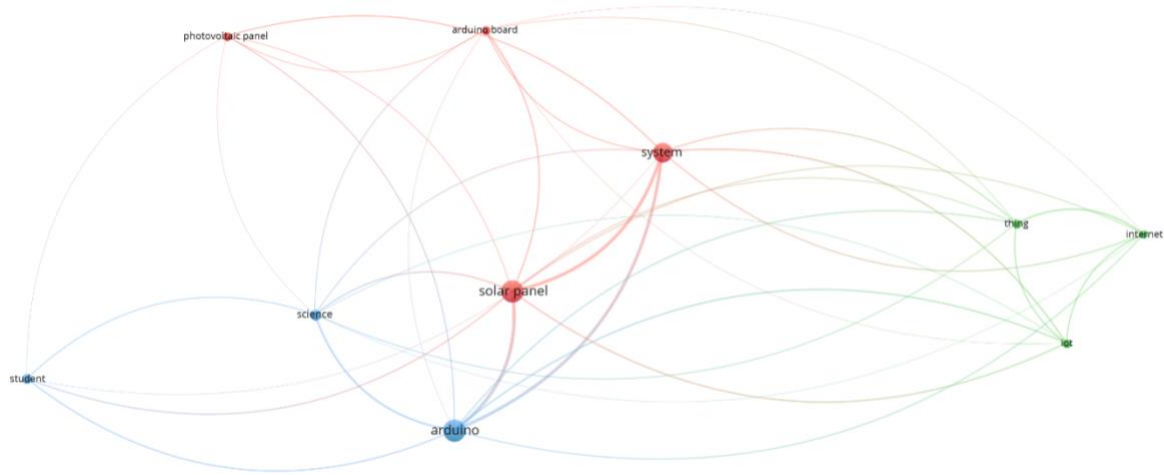


Figure 1. VOSviewer Keyword Screening.

The keyword visualisation indicated strong relationships between solar panels, Arduino, sensors, monitoring systems, and IoT-related terms, illustrating the technological focus of the initial literature landscape. In particular, explicit educational terms such as “vocational education” were not dominant in the keyword network. The study selection process followed the stages of identifying relevant studies, screening based on eligibility criteria (Table 1), and charting the data as described in the scoping review framework. The initial search returned approximately 200 records, which served as the starting point for identifying relevant

studies. These records were screened based on title and abstract relevance, resulting in 60 articles for full-text review. Rather than limiting the selection based on database indexing or access type, the screening focused on identifying studies that presented relevant solar cell–embedded system–sensor system designs. During the full-text review and data charting process, additional relevant articles were identified through reference tracking and complementary searches. This iterative process resulted in a final set of 20 articles utilised for mapping and thematic analysis.

Table 2. Selected Article.

No	Author & Year		Criteria			
	Language	Topic Relevance	System Focus	Application Context	Educational Potential	
1	Abichandani et al. (2019)	English	Solar–VR learning environment	Virtual PV simulation system	Education	Immersive PV learning media
2	Organtini & Tufino (2022)	English	Arduino-based lab apparatus	Experimental lab instrumentation	Education	Inquiry-based lab tool
3	Mayub et al. (2024)	English	Solar power bank with Arduino	Solar charging prototype	Education	Solar kit for literacy

4	AlQallaf et al. (2024)	English	VR solar system design	Immersive solar training system	Education	Immersive solar training system
5	Belik et al. (2025)	English	PV parameter measurement	Portable PV laboratory stand	Laboratory	PV instrumentation kit
6	Muñoz et al. (2024)	English	PV I–V characterisation	Arduino I–V tracer	Laboratory	PV characterisation tool
7	Machado et al. (2025)	English	PV panel characterisation	Arduino I–V curve tracer	Laboratory	Low-cost PV tracer
8	Baouche et al. (2022)	English	Solar tracking mechanism	Arduino tracker prototype	Engineering	Replicable tracker model
9	Laseinde & Ramere (2019)	English	Multi-axis solar tracking	Arduino tracking design	Engineering	Low-cost tracker design
10	Morón et al. (2017)	English	Dual-axis solar tracking	Arduino mechanical–electronic tracker	Engineering	Mechanical tracker model
11	Zahra et al. (2023)	English	PV monitoring system	Arduino-based battery charging monitoring	Monitoring	Monitoring system model
12	García et al. (2022)	English	PV fault detection	ESP-based PV diagnosis	Monitoring	Sensor-based PV diagnosis
13	Oberloier & Pearce (2018)	English	Power monitoring	Arduino data logger	Monitoring	Open-source monitoring tool
14	Beltrán Castañón et al. (2025)	English	Wireless PV monitoring	Arduino Nano monitoring system	Monitoring	Wireless monitoring model

15	Salamone et al. (2015)	English	Wireless solar control	Arduino ZigBee control	IoT / Monitoring	PV control architecture
16	Hameed & Kurnaz (2024)	English	Long-range PV monitoring	LoRaWAN PV monitoring	IoT / Monitoring	Long-range monitoring model
17	Khalid et al. (2024)	English	IoT PV SCADA system	Arduino + ESP32 SCADA	IoT / Monitoring	SCADA learning model
18	Panagopoulou & Argiriou (2022)	English	PV data acquisition	ESP32 MQTT DAQ system	IoT / Monitoring	IoT data architecture
19	Paredes-Parra et al. (2018)	English	Standard PV monitoring	Arduino + Raspberry PV system	Monitoring	IEC-compliant monitoring
20	Cámara-Díaz et al. (2021)	English	PV electronic behaviour	Low-cost PV electronic design	Engineering	PV behaviour model

The mapping of the reviewed studies revealed five dominant clusters of system development: (1) solar tracking mechanisms; (2) sensor-based photovoltaic monitoring systems; (3) IoT-based monitoring architectures; (4) portable photovoltaic laboratory instruments; and (5) immersive

solar education technologies. These clusters represent recurring patterns in the integration of solar cell systems with embedded platforms and sensors. The thematic mapping derived from the data charting process answers the first research question regarding the types of developed systems.

Table 3. Thematic Mapping of Solar-Embedded System Designs.

No	Cluster	Focus of Design	Representative Studies	Application Context	Educational Affordance
1	Solar Tracking Mechanisms	Light sensors, actuators, and microcontrollers for dynamic panel orientation	Baouche et al. (2022); Laseinde & Ramere (2019); Morón et al. (2017)	Engineering	System assembly, sensor calibration, actuator control, and performance comparison between fixed and tracked panels

2	Sensor-Based PV Monitoring Systems	Measurement of V, I, P, temperature, and light intensity using low-cost sensors and Arduino	Zahra et al. (2023); Oberloier & Pearce (2018); Beltrán Castañón et al. (2025); García et al. (2022)	Monitoring	Real-time measurement practices, data logging, and observation of environmental influence on PV output
3	IoT-Based Monitoring Architectures	Wireless transmission of PV data via MQTT, HTTP, LoRaWAN, ZigBee, SCADA	Khalid et al. (2024); Panagopoulos & Argirio (2022); Hameed & Kurnaz (2024); Salamone et al. (2015)	IoT / Monitoring	Integration of hardware-software systems, remote data observation, and network configuration and verification
4	Portable PV Laboratory Instruments	I-V curve tracing, Voc, Isc, MPP measurement, portable PV test stands	Belik et al. (2025); Muñoz et al. (2024); Machado et al. (2025); Paredes-Parra et al. (2018); Cámara-Díaz (2021)	Laboratory	Experimental characterisation of PV behaviour, controlled measurement, and interpretation of electrical parameters
5	Immersive and Explicit Educational Technologies	VR solar simulation, Arduino-based lab learning, solar prototype kits	Abichandani et al. (2019); Organtini & Tufino (2022); Mayub et al. (2024); AlQallaf et al. (2024)	Education	Direct manipulation of systems, conceptual visualisation, and inquiry-based experimental learning

Cluster 1: Solar Tracking Mechanisms

In the studies by Baouche et al. (2022), Laseinde and Ramere (2019), and Morón et al. (2017), solar panels are treated as parts of systems that move and respond to light. Light sensors, actuators, and microcontrollers are integrated into a single unit that continuously adjusts the panel's position in response to the direction of incoming sunlight. The assembly process requires careful attention to both mechanical and electronic aspects, including frame construction, sensor placement, and

actuator control. System performance is tested by comparing energy output between fixed panel positions and light-following positions. These stages involve direct observation, adjustment, and repeated testing. The sequence of activities follows a workflow commonly encountered in a laboratory practicum.

Cluster 2: Sensor-Based Photovoltaic Monitoring Systems

Zahra et al. (2023), Oberloier and Pearce (2018), Beltrán Castañón et al. (2025), and

García et al. (2022) present approaches focused on continuous measurement of electrical and environmental parameters. A relatively consistent system structure appears: the solar panel is connected to sensors, data are processed by a microcontroller, and the results are displayed or recorded. The main attention is directed toward acquiring real-time data and observing photovoltaic behaviour directly. In this context, the solar panel becomes an object whose performance can be interpreted through measured values. The instruments used are simple and easy to reassemble, allowing experiments to be repeated at any time. The workflow reflects measurement activities commonly carried out in physics experiments.

Cluster 3: IoT-Based Monitoring Architectures

Khalid et al. (2024), Panagopoulos and Argiriou (2022), Hameed and Kurnaz (2024), and Salamone et al. (2015) extend monitoring systems into data communication networks. Information from sensors is not limited to local displays; instead, it is transmitted to servers or dashboards through various communication protocols. Users engage in tasks that include sensor installation, configuration of communication modules, and setup of data-receiving software. The system consists of multiple interconnected layers, ranging from hardware components to digital interfaces. Its construction requires an understanding of how these parts interact within the system. Throughout the process, testing and parameter verification remain essential steps.

Cluster 4: Portable Photovoltaic Laboratory Instruments

Belik et al. (2025), Muñoz et al. (2024), Machado et al. (2025), Paredes-Parra et al. (2018), and Cámara-Díaz et al. (2021) position solar panels as test objects similar to laboratory samples. The developed devices enable full I–V curve measurement to examine the electrical characteristics of the panel. The equipment typically includes

automated load control and measurement displays within portable frames. The primary focus lies in observing electrical characteristics in detail rather than energy utilisation. Users operate these devices in the same way laboratory instruments are used during practicum. The testing environment is arranged in a controlled manner so that measurement results can be carefully analysed.

Cluster 5: Immersive and Educational Technologies

Abichandani et al. (2019), Organtini and Tufino (2022), Mayub et al. (2024), and AlQallaf et al. (2024) directly bring solar energy systems into learning activities. Students interact with the devices, make observations, and interpret the results obtained. Some studies employ virtual simulations, while others utilise Arduino-based physical devices. Learning takes place through the manipulation of equipment and examination of measured parameters. The activity pattern resembles what is found in engineering and monitoring clusters. The difference lies in the explicit intention to support learning from the outset.

Dominance of Arduino as an Experimental Platform

The mapping results indicated that Arduino appeared more frequently than other embedded platforms, including ESP8266, ESP32, and Raspberry Pi, across the included studies. In the mapped dataset, Arduino-based systems were reported in a larger proportion of studies compared to other platforms. Its simplicity, mature ecosystem of libraries, low cost, and ease of programming make it practical for a wide range of system designs. Sensors can be connected using basic circuits. Moreover, libraries are easily accessible, and the system can be rebuilt quickly when needed. This condition supports repeated testing without requiring complex equipment. Arduino is therefore often used as a medium for exploring physical parameters rather than merely as a device controller.

Educational Potential Across Non-Educational Studies

Many studies situated in engineering, monitoring, and laboratory contexts display workflows that closely resemble a vocational science practicum. Users assemble devices, install sensors, perform measurements, record data, and evaluate system performance. These sequences represent the core components of experimental learning. Although the authors rarely frame their work in educational terms, the system designs themselves already form learning-oriented processes. The practicum structure is embedded within the technological designs. From this perspective, an opportunity emerges that has not been widely discussed within educational contexts.

From a vocational education standpoint, experiential learning is widely recognised as a foundational pedagogical approach, as it emphasises learning through direct engagement with real-world systems and tools (Sudira, 2017). This emphasis is particularly relevant in the context of TVET, where previous studies have identified persistent challenges related to overly theoretical learning practices that are insufficiently connected to authentic work processes, resulting in graduates who are not fully prepared to meet industry demands (Suharno et al., 2020). In response to these challenges, hands-on and practice-oriented learning environments are known to support the development of procedural skills, conceptual understanding, and problem-solving abilities by enabling learners to connect abstract concepts with observable system behaviour. Learning activities that involve constructing, testing, and refining physical systems further foster iterative reasoning and reflective thinking, which are essential components of scientific and technical competence. Consequently, system designs that naturally require learners to engage in measurement, experimentation, and evaluation align closely with the pedagogical goals of vocational science education.

Although most of the reviewed non-educational studies did not explicitly report instructional designs or learning outcomes, their underlying system architectures demonstrate characteristics that are pedagogically transferable to educational settings. The modular construction, sensor-based measurement, and iterative testing processes observed across studies provide a practical foundation for designing vocational science learning activities grounded in experiential learning principles. This perspective is consistent with recent vocational education research emphasising that engagement with emerging technologies and authentic technological systems plays a critical role in cultivating students' professional skills and higher-order thinking skills in vocational contexts (Li & Zhang, 2024). At the same time, the absence of explicit educational framing across the reviewed studies highlights a gap between technological development and pedagogical application. This gap suggests an opportunity for future work to deliberately adapt and evaluate such system designs as structured learning media within vocational science classrooms, thereby transforming implicit educational potential into explicitly designed instructional practice.

Conclusion

This scoping review mapped existing studies that integrate solar cell systems with embedded platforms and sensors to identify their technological characteristics and educational relevance for vocational science learning. In response to the first research question, the review found that a wide range of solar cell-embedded system designs have been developed, with Arduino-based platforms appearing most frequently across the literature. Other platforms—including ESP8266, ESP32, and Raspberry Pi—were also employed, but Arduino's accessibility and suitability for experimental system development contributed to its dominance.

The reviewed studies commonly measured photovoltaic electrical and environmental parameters such as voltage,

current, power, temperature, and light intensity. These measurements were obtained through sensor-based data acquisition systems integrated with microcontrollers, enabling real-time monitoring, logging, and analysis of photovoltaic behaviour under varying conditions. Many systems were designed as portable laboratory instruments or experimental setups that support direct observation and parameter characterisation.

The application contexts of these systems were primarily situated in engineering, monitoring, laboratory, and system development settings. Only a limited number of studies explicitly framed their designs within educational contexts. Nevertheless, the workflows involved in system assembly, sensor integration, measurement, data interpretation, and performance evaluation closely resemble activities commonly found in a vocational science practicum.

This review identified substantial educational potential across non-educational studies. Although explicit instructional designs and learning outcomes were rarely reported, the underlying system architectures demonstrate characteristics that are pedagogically transferable to vocational science education. The modular construction, sensor-based measurement, and iterative testing processes align with experiential and practice-oriented learning principles central to TVET. At the same time, the lack of explicit educational framing highlights a gap between technological development and pedagogical application. This gap indicates an opportunity for future research to intentionally adapt and evaluate solar cell-embedded system designs as structured learning media, thereby transforming implicit educational potential into explicitly designed instructional practice within vocational science classrooms.

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