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Article

Building Integrated Photovoltaics 4.0: Digitization of the Photovoltaic Integration in Buildings for a Resilient Infra at Large Scale

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Abstract: Building integrated photovoltaic (BIPV) systems have gained a lot of attention in recent years as they support the United Nations' sustainable development goals of renewable energy generation and construction of resilient infrastructure. To make the BIPV system infra resilient, there is a need to adopt digital technologies such as the internet of things (IoT), artificial intelligence (AI), edge computing, unmanned aerial vehicles (UAV), and robotics. In this study, the current challenges in the BIPV system, such as the rise in the temperature of the PV modules, the occurrence of various faults, and the accumulation of dust particles over the module surface, have been identified and discussed based on the previous literature. To overcome the challenges, the significance and application of the integration of these digital technologies in the BIPV system are discussed along with the proposed architecture. Finally, the study discusses the vital recommendations for future directions, such as ML and DL for image enhancement and flaws detection in real-time image data; edge computing to implement DL for intelligent BIPV data analytics; fog computing for 6G assisted IoT network in BIPV; edge computing integration in UAV for intelligent automation and detection; augmented reality, virtual reality, and digital twins for virtual BIPV systems with research challenges of real-time implementation in the BIPV.

Keywords: BIPV system; digitalization; IoT; artificial intelligence; renewable energy; UAV; digital twin; edge computing

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1. Introduction

The United Nations' sustainable development goals (SDGs) emphasize the need to implement sustainable technologies by 2030 to support socio-economic development and human well-being [1]. The adoption of sustainable and renewable energy technologies upgrades building infrastructure and it results in the creation of resilient infrastructure for sustainable cities and communities [2,3]. In the SDGs, the United Nations also recommended increasing the contribution of renewable energy to global energy by 2030. Infrastructure development and technological advancements are essential to provide modern and sustainable energy services. In the current scenario, photovoltaic (PV) technologies emerged as the fastest growing technology in increasing the sustainable renewable energy practice worldwide. Solar PV is on course to account for 60% of global renewable power growth in 2022, followed by wind and hydropower technology [4]. To increase the PV penetration, the wide spread of PV plants installed on open fields, water surfaces as a floating PV system, and rural and urban buildings has been increased.

The installation of PV technologies on buildings has been practiced from the early 1990s when the opaque panels were simply integrated into the building envelopes, also termed "BIPV". Initially, the technology was mainly focused on remote applications, but as the population rose the per capita demand also increased. Therefore, the penetration of these technologies with grid connection has increased in the last two decades [5]. Irrespective of the capacity of installed BIPV technologies, the energy generation from the PV modules is very sensitive to internal and external parameters. The internal parameters include poor encapsulation of cells, broken interconnection between the cells, and cracks in cells [6]. The external parameters are adjacent shading, ambient temperature, humidity, and dust accumulation. These parameters decrease/deteriorate the power output from the PV system and increase the degradation rate [7]. Therefore, there is a need to increase and improve its maintainability, operating costs, availability, reliability, safety, life cycle, etc. As per the above discussion, there is a necessity to adopt innovative and sustainable technologies in developing resilient infrastructure to enhance the performance and reliability of BIPV systems. Currently, IoT, AI, robotics, edge computing, and drones are the emerging technologies recognized as key players to achieve energy-efficient digitalized BIPV infrastructure [8]. The main motivation for this work is to explore the potential of digital technologies in the BIPV system. The technologies overcome the different issues related to the performance of the BIPV system with real-time monitoring and control. One advantage is that these technologies will improve the efficiency and life expectancy of the BIPV system. The current study covers the various issues related to the BIPV system identified in the previous literature and emphasizes the role of digitalization in the BIPV systems using emerging technologies. The main contributions of the study are:

- A brief overview of the BIPV system along with different types of integration of PV modules with building envelopes represented pictorially.
- A discussion of various issues related to the performance of the BIPV system. The issues include the rise in PV modules' temperature, different types of faults in PV modules, accumulation of dust particles over the modules, etc.
- A discussion of the significance and application of the digital technologies implementation for overcoming the different issues related to the BIPV system with the proposed architecture.
- Vital recommendations including ML and DL for image enhancement for flaws detection in real-time image data; edge computing to implement DL for intelligent BIPV data analytics; fog computing for 6G assisted IoT network in BIPV; edge computing integration in UAV for intelligent automation and detection; augmented reality, virtual reality, and digital twins for virtual BIPV system as a part of future directions. Research challenges are also discussed.

The structure of the study is as follows: Section 2 covers the overview and challenges/issues of the BIPV system; Section 3 covers the digitalization of the BIPV system; Section 4 covers the measures to overcome the challenges with the proposed architecture; Section 5 covers the future directions and research challenges of the study, and the final section presents the study conclusions.

2. Overview of BIPV System

The PV modules integrated or attached to the conventional building envelopes are called BIPV. The BIPV system involves different PV technologies and their applications as a building envelope as shown in Figure 1. The PV technologies in the BIPV system can be classified as conventional and emerging solar cells in nature. In application, the integration of different PV technologies such as a crystalline, thin film, and organic technologies on the different building envelopes are covered [9]. Building envelopes are the outer part of the buildings which separate the internal environment from the outer one. The building roof, facade, and window are the primary envelopes of the system [10]. Further, it can be classified as flat/pitched PV rooftop, PV-DSF, semi-transparent PV glazing, etc. The integration of technologies mainly depends upon the building demand, size, and climatic conditions [11]. The PV modules used in the BIPV system convert between 13–20% of incident solar radiation to electricity under ideal operational conditions [12,13]. The remaining amount of radiation absorbed by the cells is transformed into thermal energy, causing an increase in its temperature. Temperature plays an important role in PV system efficiency, as the performance of the PV module is directly related to the operating temperature of its cells. Further, the rise in temperature leads to several types of degradation such as delamination, hot spots, corrosion, glass fracture, electrical migration between module layers/interconnections, and discoloration.

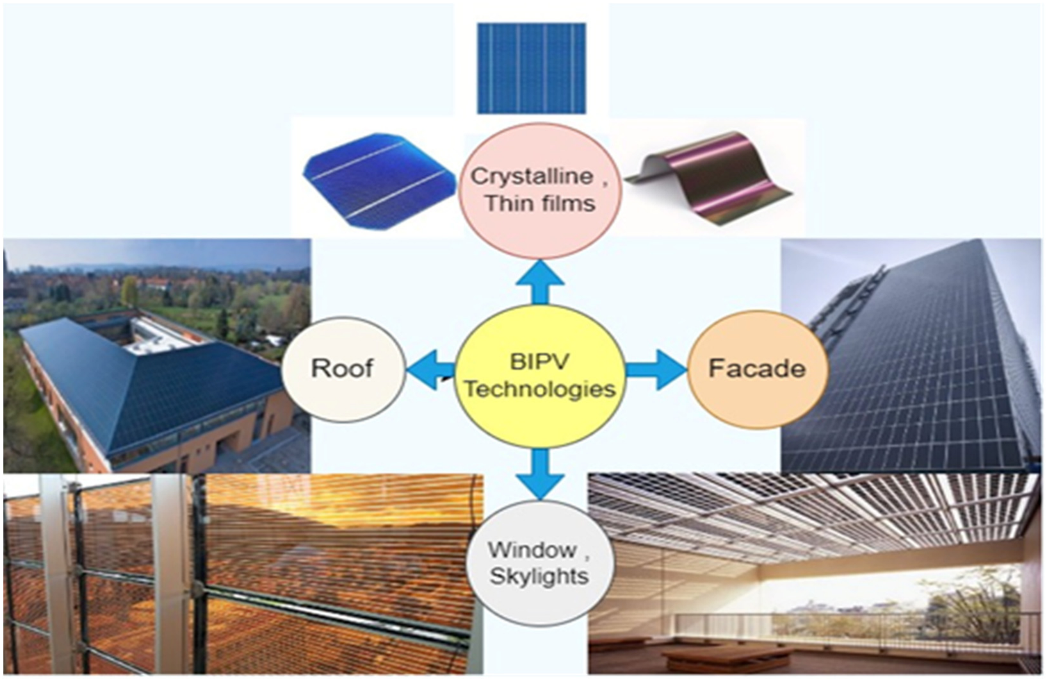

Figure 1. Categorization of BIPV system.

In hot environments, the BIPV system temperature can reach as high as 80 °C [14], which affects the system efficiency. An effective way to counteract the rate of thermal degradation of a PV module is by reducing its surface temperature. This can be achieved by using natural or forced ventilation which prevents the modules from heating during operation [15]. The performance of the modules is also affected by shading from the adjacent buildings and dust accumulation on the PV modules. In countries such as the UK, high-rise buildings mainly depend upon glazing technologies for regulating the building temperature and maintaining thermal comfort [16]. The opaque PV modules were integrated on the front face of the facade with some air gap provided to reduce the heat flux penetration in buildings as well as lowering the PV module temperature [17]. The different types of the BIPV system envelopes (Figure 1) are discussed as follows:

(a) BIPV roof

The rooftop envelope of a building protects the building from the outdoor environment. The PV modules are attached to flat or tilted roofs [18]. In Figure 2, the PV modules attached to a sloped roof are provided with a certain air gap from the rear side. The roof was provided with forced ventilation above the cavity opening.

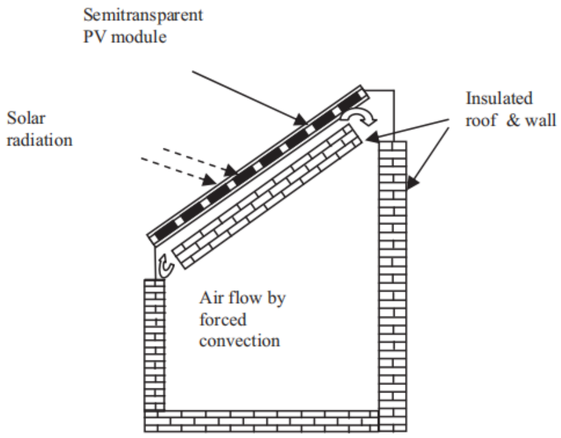

Figure 2. Schematic presentation of the tilted BIPV roof with semi-transparent PV with forced ventilation [19].

(b) BIPV facade

This is the outer wall of a building and contains window glazing and shading devices. Generally, an air gap is provided between the outer skin of the building and the PV modules, and such an attachment of PV modules with a facade is termed a double skin facade (DSF). The cooling was provided either by natural or forced ventilation (Figure 3). Further, the ventilated hot air can be utilized in the buildings during the winter season.

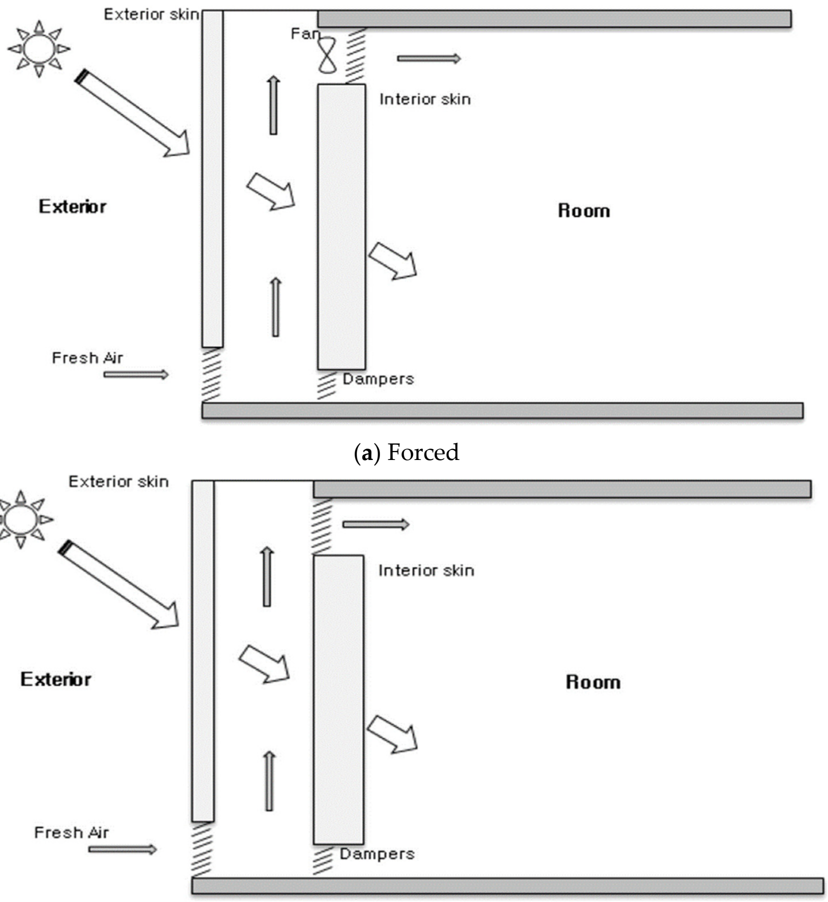

Figure 3. Schematic presentation of the DSF (**a**) forced (**b**) natural [17].

(c) STPV glazing/windows

STPV technology is a glass-to-glass technology, where opaque c-Si cells are equally spaced and encapsulated between the transparent glasses using ethyl vinyl acetate (EVA). STPV can replace the conventional window glazing and roof skylight (Figure 4) [18]. Apart from energy generation, the technology is also advantageous in reducing lighting loads and heat gain [19].

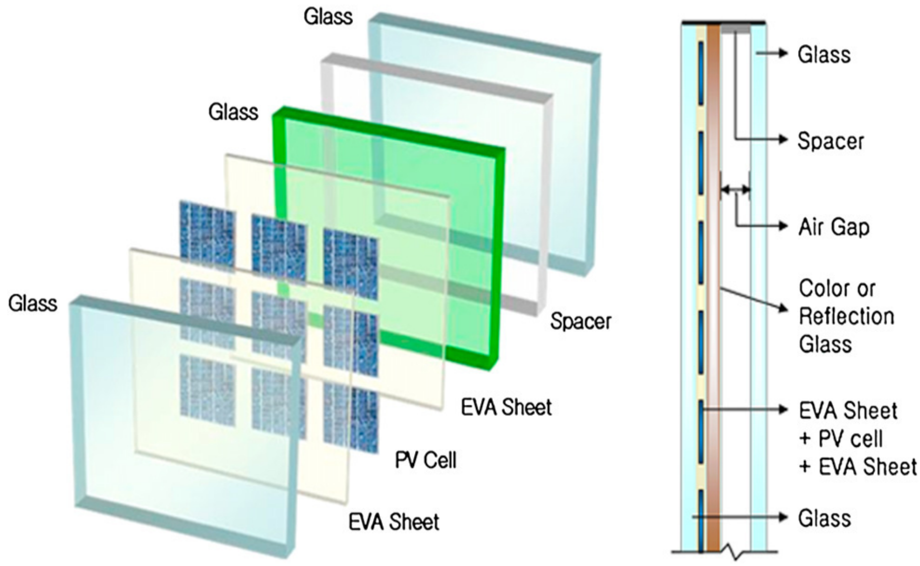

Figure 4. Different layers of the encapsulated STPV modules [18].

Issues/Challenges in the BIPV Systems

The issues of BIPV systems that are discussed in the previous studies are detailed and presented. The primary issues of the BIPV system are:

- The system attains a high temperature during the sunshine hours, which reduces power generation. It also affects the building envelope temperature and the building thermal comfort. For preventing the heating of the modules, an uncontrolled high-power forced ventilation is used, which consumes much energy leading to an overall reduction in system efficiency.
- In a large BIPV system, different types of optical, electrical, and non-classified faults occur, depending on the ambient condition, type of integration, and adjacent shadings on buildings that need to be analyzed regularly.
- Regular and safe cleaning of dust-accumulated PV modules in large buildings, roofs, facades, and fenestration is challenging, which reduces the overall efficiency of the BIPV system and daylight availability in buildings.

3. Digitalization for BIPV

Currently, the digitalization of any field is achieved with the assistance of emerging technologies such as IoT, AI, edge computing, UAVs, and drones. The adoption of digital technologies empowers us to create value from new, advanced technologies by exploiting digital network dynamics and the giant digital flow of information. The implementation of digitalization in the BIPV system improves the system performance by establishing automation and a digital network.

(a) **IoT:** IoT was first proposed at the end of the twentieth century, and it was developed using radiofrequency technology [20,21]. The GSMA estimates that the number of IoT connections will reach 25 billion worldwide by 2025 [22,23]. IoT is a collection of devices with embedded systems connected to the internet's telecommunications network with the ability to generate and send data without the need for human interaction. IoT consists of machine-to-machine (M2M) networks, in which intelligent devices communicate with one another and make independent decisions based on created and transmitted data [24,25].

Figure 5 illustrates the IoT-based architecture that is discussed in [26], which comprises four-layers, namely, the perception layer, network layer, cloud computing layer, and application layer. The perception layer is part of IoT architecture, as it is the primary layer for obtaining the data of physical things through sensors, radio frequency identification (RFID), actuators, and camera modules. The different sensors that are suitable for the BIPV system are presented in Table 1. The network layer comprises different wireless communication modules that establish the network with the cloud server.

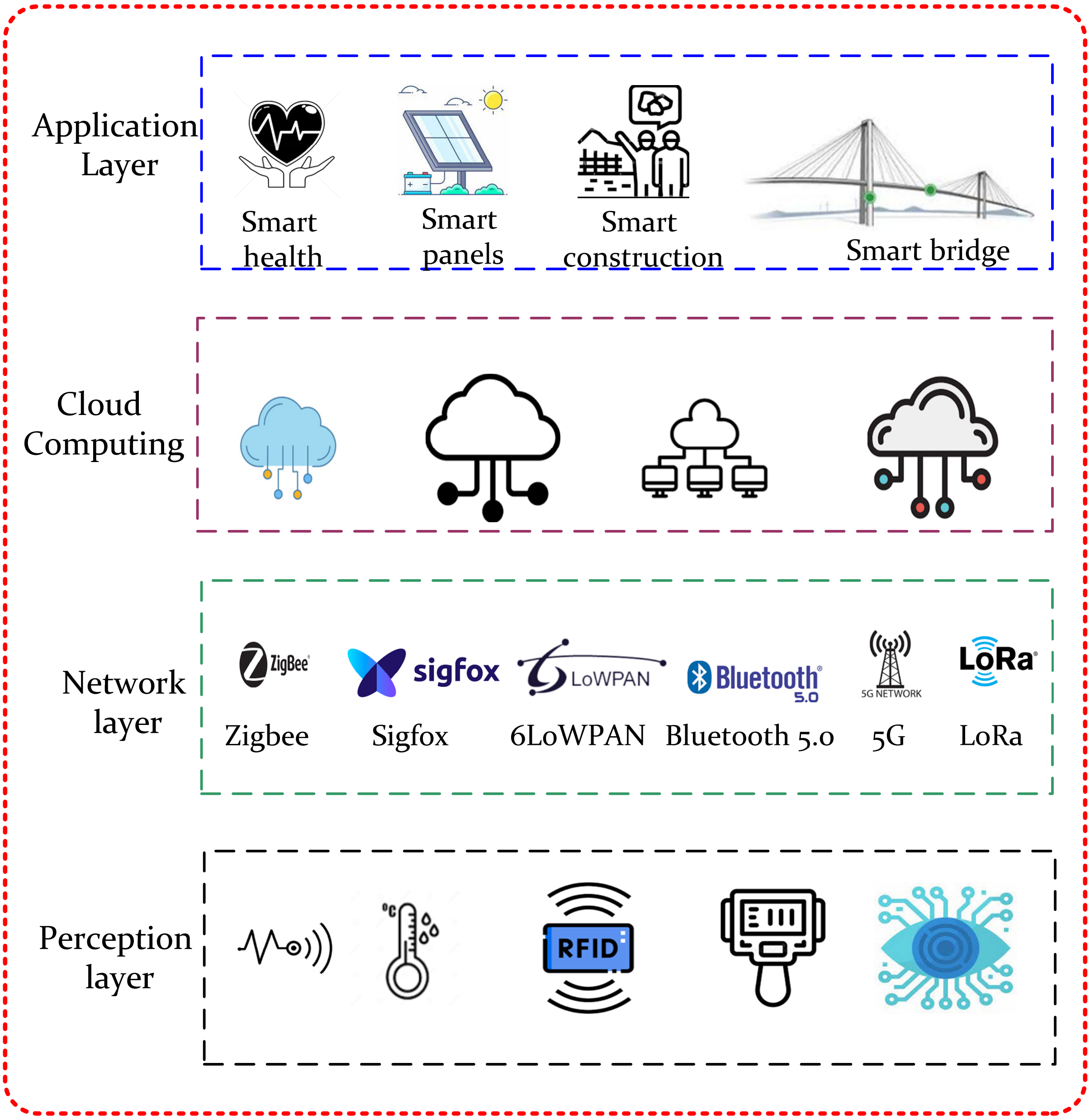

Figure 5. IoT architecture.

Table 1. Different sensing devices used in digitization.

Sensing Device	Function
Current	Detects and converts current to an easily measured output voltage, which is proportional to the current through the measured path.
Voltage	The input is the voltage and the output is its analog voltage signal, a current signal, or an audible signal.
Optical	Measures the physical quantity of light rays and converts this into electrical signals which can be easily read by the instruments.
Radiometric	Measures the UV irradiance or illuminance with the radiometer. In the case of non-vertical irradiation, the diffusers inside the sensors ensures the cosine correction.
IR	Emits or detects infrared radiation in its surroundings and also measures the heat emitted by the objects.
Lux meter	Converts the amount of light that falls on the photodiode into a current form. The amount of current measured will give the approximate value of lux radiation falling on the surface.
Pyranometer	Measures the potential difference developed due to the temperature difference between two surfaces of the thermopile. The gradient of temperature is used to measure the sum of solar radiation.
Anemometer	Measures the input power required to maintain the temperature of the hot wire cooled down due to the flow of air. The input power is utilized as the measurement of airspeed.
Temperature	Measures the temperature through an electrical signal using the thermocouple. The thermocouple will change electrical resistance indirectly proportionally to changes in the temperature.
Humidity	Measures the change in electrical permittivity of dielectric material and change in the resistivity value of this resistive material for predicting the change in humidity.

During the implementation of the IoT network, the wireless communication protocol plays a vital role in connecting the perception layer to the network layer and also in controlling and monitoring [27]. Currently, different wireless communication protocols are used to establish IoT networks as shown in the Table 2. Sigfox, Narrowband IoT (NB-IoT), and LoRa are the wireless communication protocols that establish the low power wide area network (LPWAN) between the perception layer and network layer [28]. These communication protocols are capable of communicating the sensory data over a long range with minimum energy consumption. The previous studies concluded that the LoRa is preferred over Sigfox and NB-IoT in building applications due to the following aspects: long battery life, bi-directional communication, large-scale deployment, and mobility [29]. Bluetooth low energy (BLE) and Zigbee are low-power communication protocols that transmit short-range data. Along with this, wireless fidelity (Wi-Fi) is the communication protocol that enables the perception layer to connect directly over the internet. MQTT (message query telemetry transit) is a machine-to-machine network protocol that is lightweight and publish/subscribe. It is built for communications with remote sites that have limited network bandwidth or devices with resource limits.

(b) **AI:** AI is the process of creating intelligent devices out of massive amounts of data [31]. Human-like tasks are performed by systems that learn from previous learning and experiences. Human efforts are improved in terms of speed, precision, and efficacy. To create machines that can make judgments on their own, AI uses complicated algorithms and methodologies. Figure 6 illustrates the subsets of AI, and they are machine learning (ML), deep learning (DL), expert systems, natural language processing (NLP), robotics, vision, and speech recognition [32]. ML is a branch of AI that offers intelligence to computers by allowing them to learn from their experiences without being explicitly programmed [33].

Table 2. Wireless Communication Protocols [30].

Wireless Communication	Transmission Area	Bandwidth	Transmission Rate	Network Topology	Authentication
Sigfox	9.5 km	868 MHz (Europe); 915 MHz (US)	100 bps	Star	Private key signature Encryption
NB-IoT	15 km	LTE bands	250 kbps	NA	3GPP S3 security
LoRa	7.2 km	433 MHz (Asia), 868 MHz (Eu) and 915 MHz (US)	0.25–5.5 kpbs	Star of stars	Distinctive key distribution,
BLE	150 m	2.4 GHz	1 Mbps	Star, bus	Secure pairing before the key exchange
Zigbee	30 m	2.4 GHz	250 kbps	Star, Peer 2Peer (P2P), mesh, tree,	AES-128b, Network key
Wi-Fi	100 m	2.4 GHz	54 Mb/s	Point-to-hub	
MQTT	Machine 2 Machine (M2M)	2.4 GHz	2 Mbps		TLS/SSL

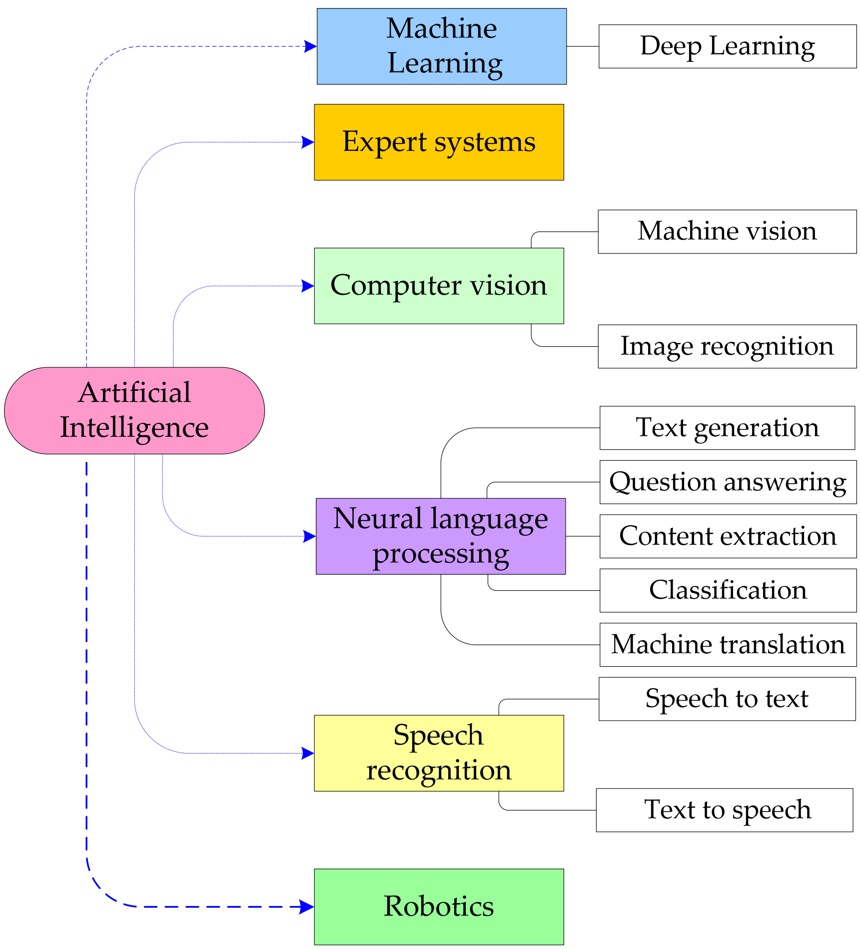

Figure 6. Subsets of AI.

ML is founded on the premise that computers can learn from prior data, recognize patterns, and make judgments using algorithms. ML algorithms are built in such a way that they can automatically learn and improve their performance. DL is a subset of ML that allows machines to execute human-like activities without human intervention. DL is implemented through neural network architecture, also called a deep neural network. An expert system is a type of AI application that relies on acquiring knowledge from human experts and implementing that knowledge into a system [34]. Expert systems simulate human decision-making abilities. Instead of traditional procedural code, these systems are designed to tackle complex problems using bodies of knowledge.

(c) **Edge computing:** In IoT, many computing paradigms such as edge computing, cloud computing, and mobile ad hoc cloud (MAC) are employed to provide various services based on the application requirements [35]. Real-time delay-sensitive applications cannot accept prolonged delays generated by a wide area network during IoT installation. IoT devices have limited processing power, making them inadequate for computationally intensive workloads [36]. Edge computing is a decentralized computing platform that offers cloud computing capabilities to IoT devices at the network edge. However, IoT devices with limited resources can enhance their capabilities by utilizing the resources of edge servers. Latency minimization, network management, cost optimization, energy management, resource management, and data management are the advantages of edge computing implementation [37].

(d) **UAV:** The technology can be customized and used for fast mobile applications that can be employed in a variety of smart city applications. UAV technology is developed to match smart city criteria and functions that will productively connect UAVs to smart cities [38]. By enabling a UAV with monitoring sensors, cameras, as well as software, we can perform smart city infrastructure inspection and control applications [39]. Furthermore, one of the emerging fields of UAVs is their involvement in smart city applications, which results in a variety of benefits. UAVs, as compared to manned planes, can be more cost-effective. They are more adaptable and can function in a variety of environments and settings, including those that are difficult or dangerous to people. Traffic monitoring and management, health emergency services, security and crowd monitoring, UAV-based infrastructure inspections, agriculture management, environmental monitoring, tourism support, and UAV-aided wireless communications are the applications of UAVs [40].

The significant characteristics of digitalization implementation in the BIPV system are illustrated in Figure 7 and are as follows:

- **Sensing:** Sensing technology enables the establishment of an ecosystem for connecting the physical and virtual worlds. Sensors collect signals, convert them to digital data, and process them. Further, the information on the present status of the physical environment is converted into usable data.
- **IoT:** IoT is built on the integration of many standards and supporting technologies such as sensors, communication protocol, storage, computational, and other capabilities. At present, the advancement in sensor technology and communication protocol empowers us to implement IoT in various applications for real-time analysis. The application of IoT in the BIPV system enables us to monitor and control the BIPV system from any remote location in real-time.
- **AI:** The implementation of IoT generates a large amount of sensor and visual data. The evolution of AI simulates human intelligent behavior with computers and trains computers to learn human characteristics such as judgment, learning, and decision-making. The application of AI with IoT enables us to predict events based on real-time data.
- **Data Analytics:** Advanced data analytics reveals computing approaches, allowing for the interpretation of data. It is critical for converting huge data into usable data for better decision-making.
- **Edge Computing:** Data is currently being increasingly generated at the edge of the network, and it would be more effective to handle the data there as well. Edge computing refers to the technologies that enable computation to be conducted at the

network's edge, on downstream data for cloud services and upstream data for IoT services.

- **Drone Technology:** A drone is a type of unmanned aircraft. A drone is effectively a flying robot that can be operated remotely or autonomously by software-controlled flight patterns in its embedded systems, which work in concert with onboard sensors and GPS.
- **Robotics Technology:** An autonomous robot is a system that operates in an unpredictable and partially unknown environment, and it is able to navigate without interruption and avoid any obstacles placed within the mobility confinement. The integration of IoT with robotics enables the realization of the robotics-based automated system for different applications in the BIPV system.
- **Human to BIPV interaction:** The digitalization of the BIPV system is relevant to controlling the performance of the system and rectifying the issues. Interaction of humans with the BIPV system is important to manage its performance.

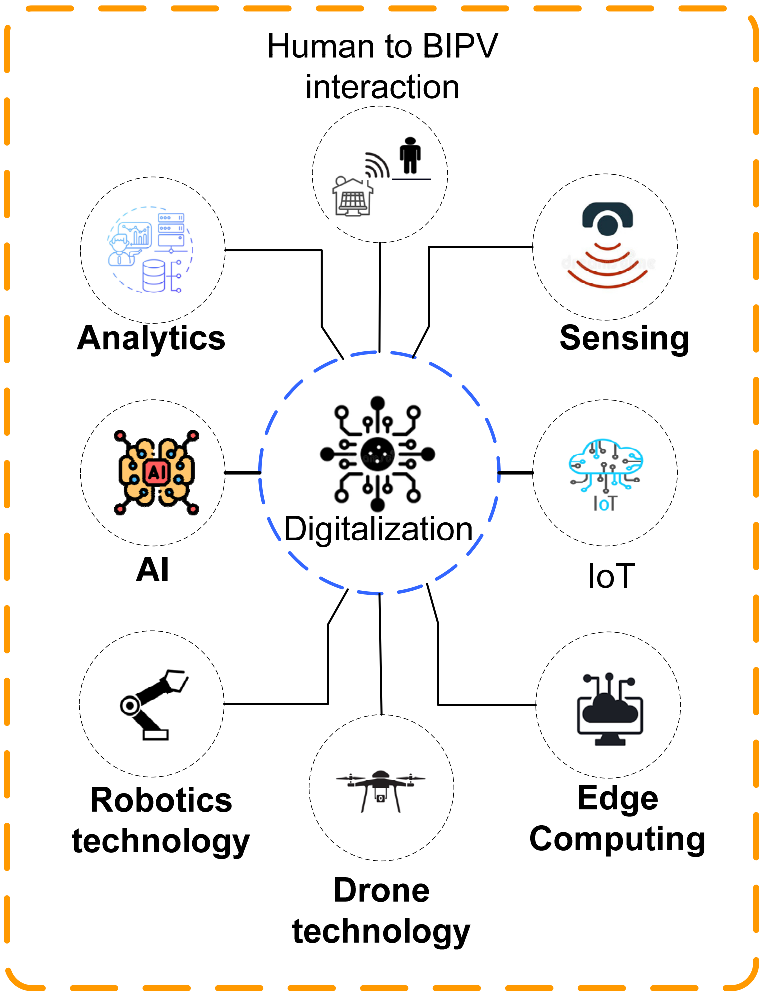

Figure 7. Digitalization in the BIPV system.

Table 3 illustrates the different digitalization elements used in sensing and monitoring the PV system. It can be observed that all the elements were applied to PV systems on the open field. IoT is one of the elements that has been widely adopted in monitoring the PV system such as power, energy, solar radiation, and weather condition. Drones with IoT and image processing are implemented in a PV system for detecting dust accumulation, faults, and weather conditions.

Table 3. Recent technologies and applications of digitalization involved in PV systems.

Ref.	Elements	Sensors	Monitoring	Outcome
[41]	IoT	Temperature, radiance, humidity, pressure, wind speed, etc.	Instant power and energy	• Increases the scalability security of the monitoring system • Dependency on intermediate devices is reduced.
[42]	IoT	Temperature sensor, voltage transducers, current transducers,	Instant power and energy	• Reduction in time for manual supervision and plant management.
[43]	IoT	Current, voltage, irradiation, and temperature.	Solar radiation, instant power, and energy	• Low-cost edge sensing methods, open-source software, and processing technologies used were found to be cost-effective.
[44]	IoT	Current sensor temperature and humidity sensor, optical dust sensor	Instant power level, and weather condition	• Reduces the number of sensors and computation complexity of data. • Easy and low cost of human interaction with the PV system.
[45]	Drones, IoT	Radiometric sensors, thermographic camera	Dust accumulation on PV modules	• The results of dust accumulation through the radiometric sensors seem to be feasible compared to thermographic image results.
[46]	Drones, image processing	IR camera	Dust accumulation	• The developed fault detection algorithm is feasible compared to electrical measurements.
[47]	Robotic cleaning	voltage and current sensor	Dust accumulation	• The robotic system cleans the dust on the solar panels and increases the power output versus the weekly-cleaned controls.
[48]	Robotic cleaning	Illuminance sensor, voltage, and current sensor; temperature and humidity sensor, dust sensor.	Dust accumulation	• Beneficial in semi-arid areas, with frequent cleaning. • Generates the revenue in accordance with plant size.
[49]	IoT, Cloud	Temperature sensor, voltage transducers, current transducers,	Dust accumulation, open circuit, shading effect	• Have fault detection potential. • Cost-effective IoT technology recorded the real-time data through the cloud which can browse all recorded data in real-time. • Have the potential to significantly reduced the potential for fault detection through the historical data analysis.
[50]	Drones, IoT, image processing	voltage and current sensor; an optical and thermal camera	Instant power level, faults, weather condition	• Digitalization of PV plant using sensored drones, monitoring O and M task. • Developments of PV database and human interaction tools. • Increases the O and M accuracy and saves time in real-time.

4. Measures to Overcome the Challenges

In this section, the challenges in the BIPV system are discussed in detail. Along with the discussion of challenges, the proposed architecture is presented to overcome the challenges.

4.1. High Temperature of BIPV System

The author [51] experimentally examined the developed unglazed transpired collector (UTC) prototype with black-framed PV modules of 70% area, and the remaining area has a porosity of 0.6% to allow fresh air to enter as shown in Figure 8. It can be observed that a fan was provided at the top of the facade duct for cooling the PV modules and providing pre-heated air for other purposes. A study also experimented with a DC fan on the wall upper vents, and it was reported that PV cell temperature was reduced by 1.28 °C, and the pre-heated air was further utilized as per the thermal comfort requirement (Figure 9) [52].

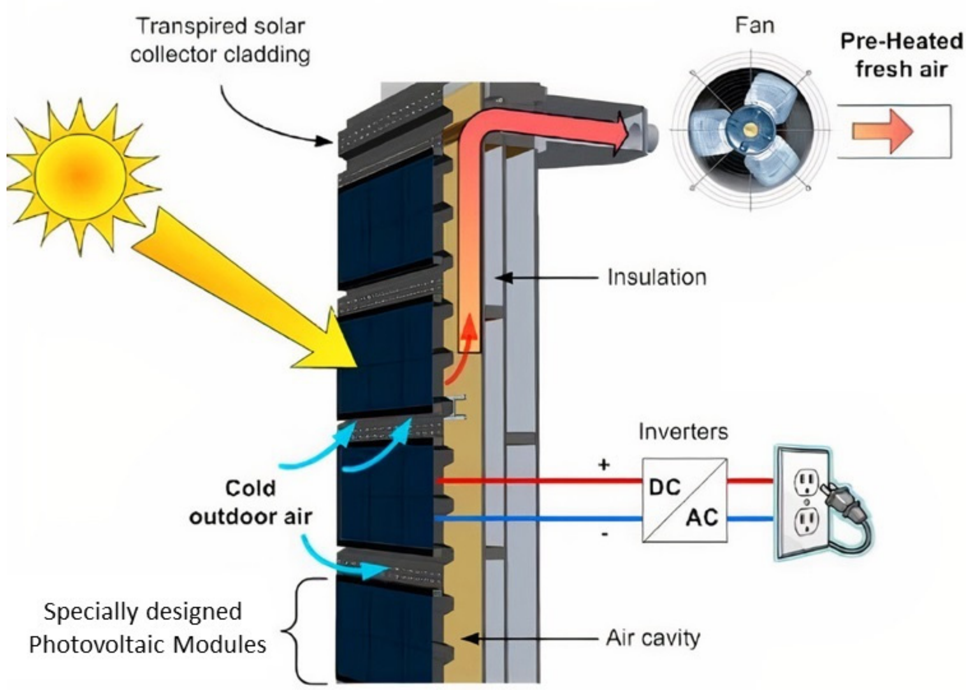

Figure 8. Schematic for BIPV/T system [51].

It was found that the DC fan electrical efficiency of the PV modules was 10% to 11%. The author [53] experimentally performed cooling of the PV module through a DC fan controlled by the PIC18F4550 microcontroller, which depends on the average value of module temperature (Figure 10). It was seen that cooling can increase the electrical conversion efficiency by 7–8% compared to without cooling. The energy consumption required during forced ventilation was not reported by the researchers which needs to be considered when applied on a large-scale basis. Moreover, as the solar radiation, wind velocity, and ambient temperature are intermittent parameters, the duct width and airflow therefore have to be controlled as per the average temperature of the PV arrays and the optimum temperature requirement for the thermal comfort in the buildings.

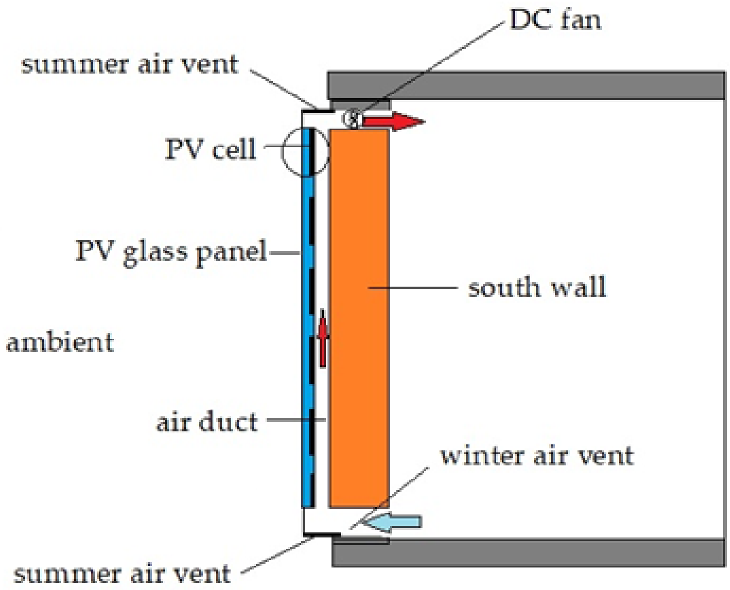

Figure 9. BIPV facade provided with vents and DC fan [52].

Figure 10. (**a**) Development of DC fan cooling mechanism and temperature distribution through the front surface PV panels for different mode operation PV panel temperature, (**b**) rear side of the panel having a (**c**) DC fan [53].

In the above discussion, there are different methods implemented for cooling the PV panels through the fans manually. To implement IoT in automating the fan to cool the panels based on sensory data. Figure 11 illustrates an IoT-assisted architecture for cooling the fan through sensors and wireless communication protocol. The 'n' number of sensor nodes and fan controller units are the two different units that will be embedded in the building for the automation of fans to cool the solar panel temperature. The number of sensor nodes and fan controlling units can be customized depending on the building area. The sensor node embedded in the PV panels monitors the temperature and in case the temperature exceeds the normal range, the sensor node alerts the fan controller unit to turn on the cooling fan through LoRa communication. The fan controller unit controls the cooling fan through the relay.

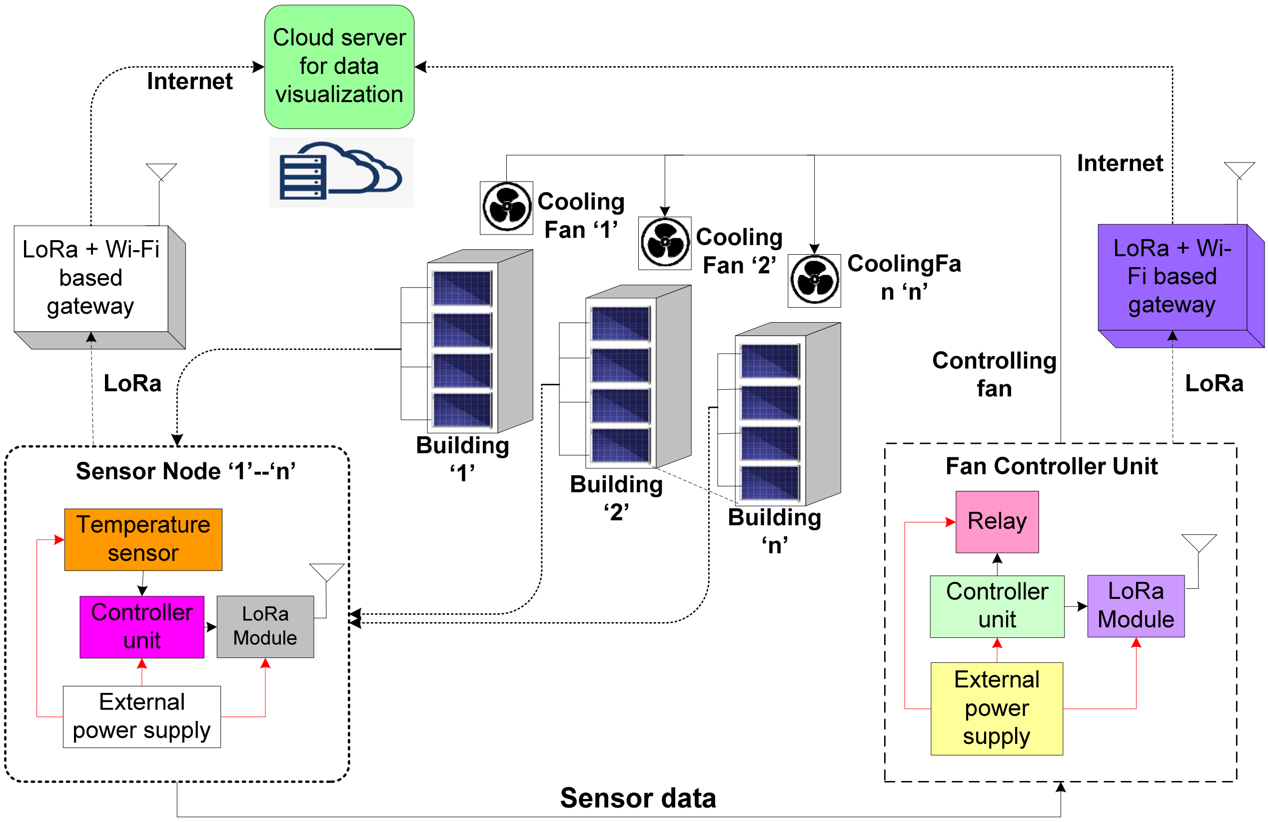

Figure 11. Proposed architecture for automatic fan cooling using IoT and LoRa.

The sensor node connects the PV panel temperature monitor and cooling to the cloud server through the LoRa-based gateway. The LoRa connection is established among the sensor node, fan controller unit, and the LoRa-based gateway enabling long-range transmission of data along with low power consumption. As LoRa can transmit the data in the long-range, it is feasible to place a LoRa-based gateway in such a location where the internet connectivity is stable. The Wi-Fi module in the gateway enables connection to the internet and logs the information on the cloud server that is received from the sensor node. The cloud server is managed by the authorities, and they can monitor the PV panel's temperature and cooling fan on the digital platform from any location in real-time through internet connectivity.

4.2. Faults Occurrence in the BIPV System

The different types of faults that arise in the module are the optical degradation in a PV module, electrical mismatches and degradation, and non-classified faults. The optical degradation occurs mainly due to the formation of bubbles, and discoloration of the encapsulation. This can occur internally as well externally, internally poor quality of encapsulation and externally high outdoor temperature and humidity are significant factors [8]. In electrical degradation and mismatch, the cracks occur in cells, the interconnection is broken, short-circuiting of cells and shading on the cell are some of the common factors that can arise. In non-classical faults, the bypass diode becomes defected or short-circuited or the submodule becomes open-circuited [8]. The diagnosis of such faults can be performed through infrared thermography conducted to access the condition of the PV modules in a free standing or building attached manner. From the combination of the different IR images, various types of faults and their effect on the I-V curve can be seen. The gathered

IRT can predict the geometry and area of hot spots formed on a single or multiple cells of PV modules, known as a region of interest (Figure 12).

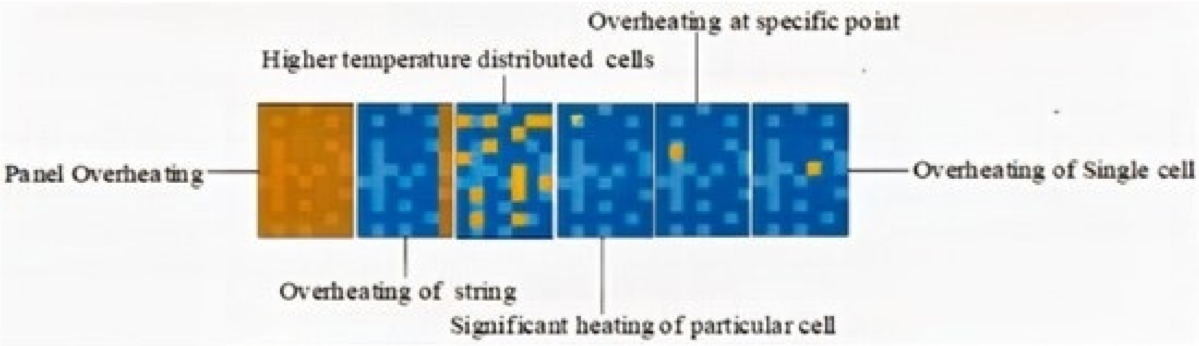

Figure 12. Schematic diagram of infrared images and possible defects [8].

The manual capturing of IR images (Figure 13) of a small-scale PV plant of a few kW is possible, however, at a large scale the PV system on building rooftops or integrated on the facades of high-rise buildings requires more reliable and faster technologies [54]. Recently, aerial technologies have evolved to capture the IR images of large PV plants installed on open fields. Using the thermal orthophotoplan, a uniform scale of the captured images is converted into IR maps for predicting different faults that occur in a system.

Figure 13. A manually captured thermographic image of small-scale PV modules [55].

The thermal signatures of PV modules in the IRT mapping were implemented with the help of aero triangulation, photogrammetry, and global positioning system (GPS) data processing (Figure 14). All types of faults detected from the mapping were successfully validated and diagnosed [54]. A digital twin technology can also be developed by these drone aircraft which includes thermal imagery, of both potential PV sites and installed facilities for operational management and troubleshooting (Figure 15) [56]. The operation and maintenance team can scan the serial numbers of the module and can perform an inspection of the PV modules.

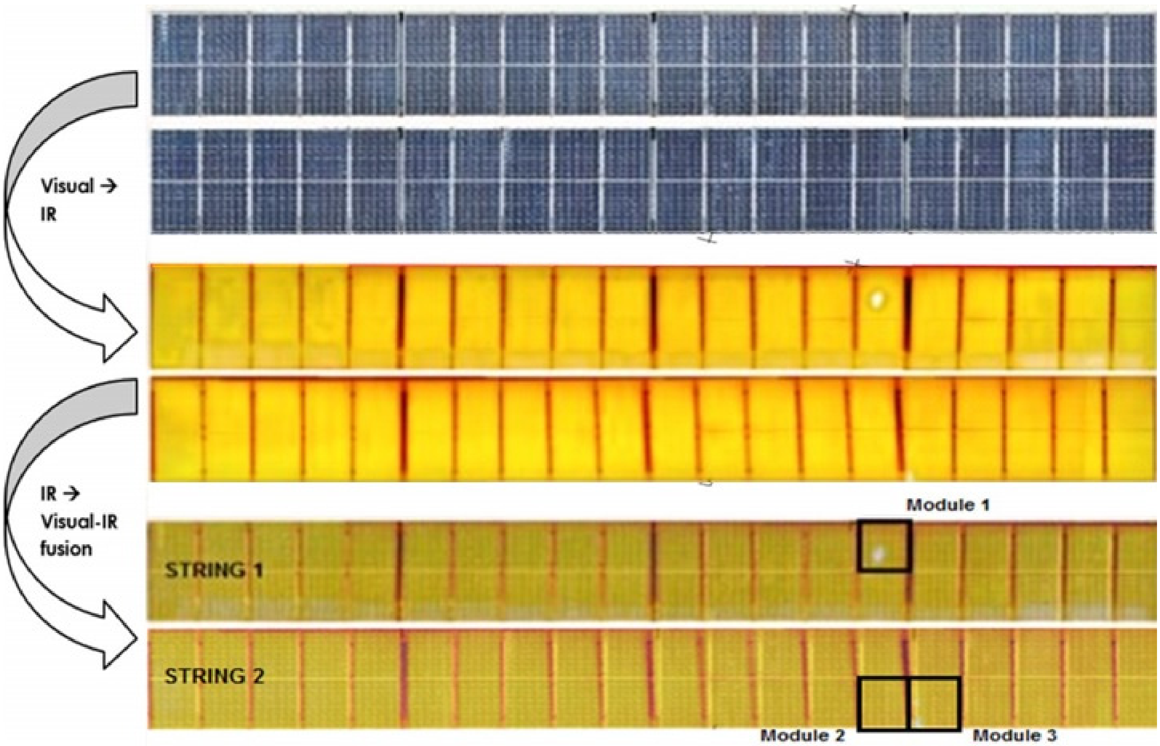

Figure 14. Implementation of a thermal orthophotoplan technique, for IRT mapping and fault detection in a PV plant [56].

Figure 15. A Raptor Maps drone gathers inspection data on a Borrego solar facility [57].

Real-time fault detection in BIPV systems is urgently required to enhance the infrastructure with intelligent technologies for minimizing the loss of PV panels for late detection and diagnosis. In previous studies, a sensing-based system is implemented to detect a fault on the ground-level PV panels. In the case of a building, the area is very large, and it is difficult to identify the different types of faults with the sensing-based system. In this study, an architecture is proposed with the integration of drone technology, edge computing, and AI to realize real-time fault detection. Figure 16 illustrates the working of this real-time fault detection system, where the drones capture the BIPV panel images with the assistance of a thermography camera. The thermography images are immediately transmitted to the edge device which is placed on the ground level of the building through LoRa communication.

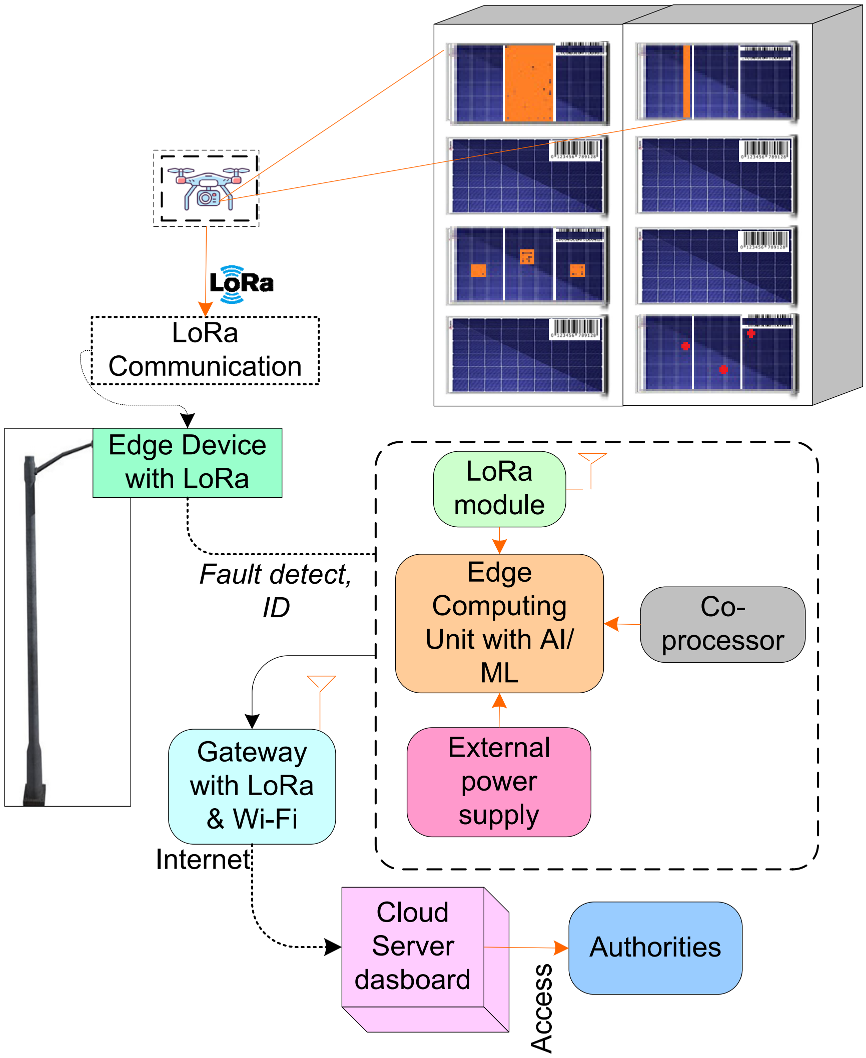

Figure 16. Proposed architecture for fault detection using edge computing with AI/ML.

The edge device is based on edge computing, where it performs the computation process with the help of a co-processor by applying AI/ML models for identifying the faults from the thermography images. If the fault is identified, then the edge device updates the type of fault and ID of the panel that is obtained from the thermography images to the authorities connected to the cloud server. To connect to the cloud server, the edge device establishes a LoRa connection with the gateway. The gateway connects to the internet with the help of a Wi-Fi module and updates the fault details on the cloud server in the form of internet protocol packets. The information available in the cloud server boosts the authorities to diagnose the fault of PV panels in real-time for overcoming further damage to the PV panels. With the assistance of this architecture, the authorities can predict the faults in the PV panels early.

4.3. Dust Accumulation on BIPV

The accumulation of dust on PV modules can deteriorate the energy output of the PV modules by around 20% to 40% [58]. It has become essential to rectify the problem of dust accumulation and significant losses in the PV system. The percentage or rate of dust accumulation may vary as per the wind pattern and ambient condition of the surroundings. Practically, the accumulation rate was higher in areas with dry winds and high vehicular movement, dust storms, etc. After the accumulation of dust, a layer was formed over the surface of the PV modules This affects the performance of the PV modules. Figure 17 shows the scenarios of the BAPV system on the rooftop with and without scheduled cleaning. In Figure 18 the variation in PV module efficiency due to the dust accumulation on modules was shown, it can be observed that the reduction in efficiency varied from 10% to 80%. In general, manual cleaning of PV panels whether installed on building roof or facade was performed within a certain time interval The cleaning can be performed manually using the long stick brushers or through the washing technology (Figure 19). However, manual cleaning of a panel on buildings is a high concern for safety.

Figure 17. The Solar PV plant was installed at the Science and Technology Park, in Doha (State of Qatar) (**a**) scheduled cleaning and (**b**) dust particles accumulated on PV modules [59].

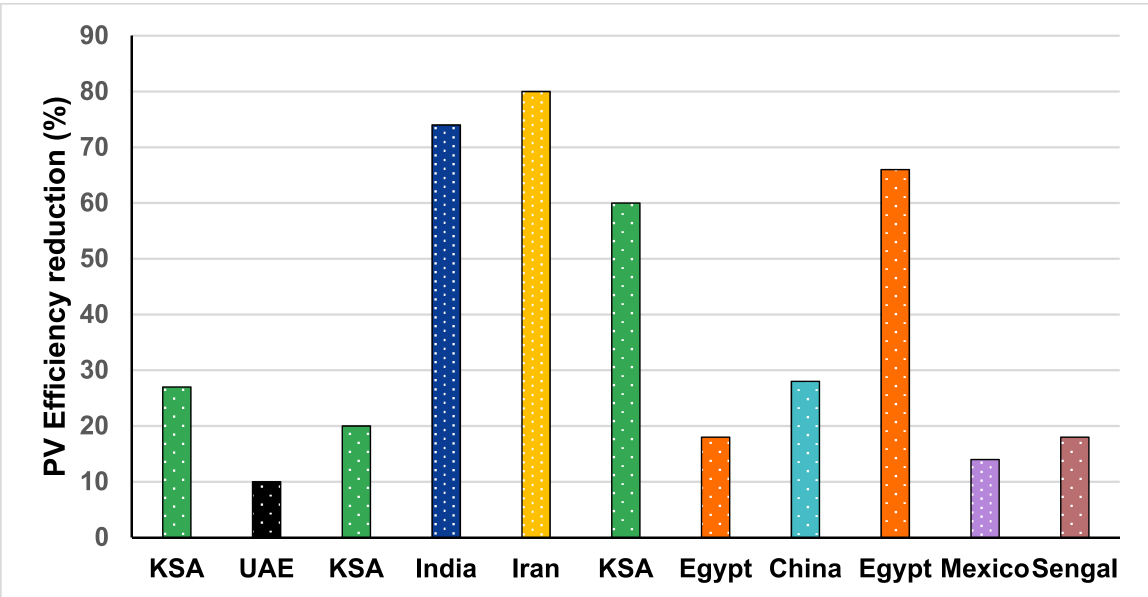

Figure 18. The monthly reduction in PV module efficiency due to the dust accumulation [58].

In automated cleaning, fully or partially automatic robots were used. The robotic cleaning can be water-based or water-free. Robotic cleaning demands low consumption of fuel, and no labor cost and with no intervention of a human, it also resolves the safety concerns of manual cleaning. It was reported that with fully automated cleaning the soiling rates can be reduced by 95% [58]. The researcher experimentally studied the potential of cleaning solar panels using a low-cost automated robotic cleaning system (Figure 20) [47]. The system consists of a silicon rubber brush foam mounted on an aluminum core. It was observed that the robotic arm was capable of minimizing the solar panels' dust and providing an increase in power output compared to weekly-cleaned PV modules.

Figure 19. Manual cleaning of PV modules on the building rooftop [60].

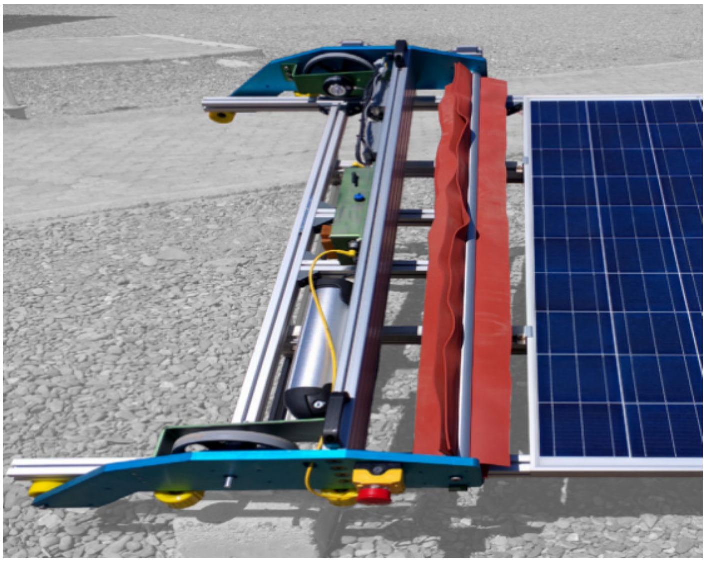

Figure 20. The robotic cleaning system was installed in the test field [47].

The author [46] used an image processing technique for predicting the accumulation of dust on PV modules. The high-resolution images were captured from the aerial robots. The dust detection algorithm was developed, and performance was assessed in the MATLAB image processing toolbox. Further, the algorithm is validated against electrical measurement where it showed a variation of 5% to 5.5% of detection variation in the developed algorithm. The author [45] develop a central monitoring system for detecting the dust accumulation over the PV panels using drones as shown in Figure 21. A radiometric sensor was connected with the Arduino platform. The sensor detects the emissivity level of the PV modules, which determines the presence of dust over the modules, further the results were validated through IR images taken during the analysis. The results were sent and analyzed through IoT. However, different angles and height of the UAV have to be monitored for analysing the accuracy. Further controlling the data acquisition from the sensor (ON/OFF) with the help of a Wi-Fi-enabled switch according to the requirement can save around 58% of energy as well as the life of sensors [61].

Figure 21. A new CMS uses a radiometer sensor embedded in a UAV to detect dust on PV panels [45].

It was found that most of the module cleaning studies were performed on the horizontal and tilted PV panels installed either on the building rooftop or on the open ground. For high-rise buildings, the cleaning of panels can be implemented as discussed by [62], and the cleaning robots can be installed on the top or bottom of the envelope edge. The robots will be provided with sensors to sense the level of dust and moisture on the surface. The robot will move in an upward/downward direction on the rails provided on the side of the envelopes (Figure 22).

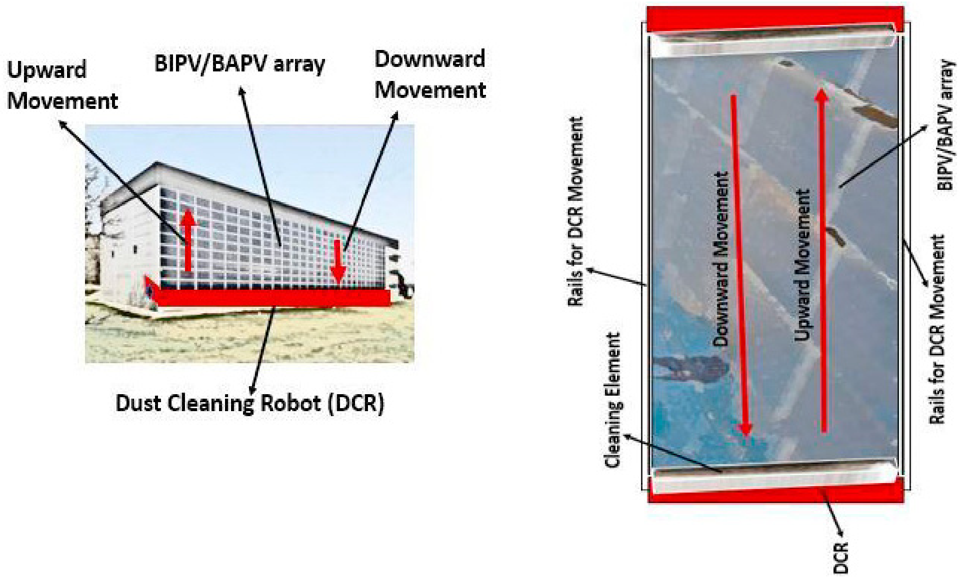

Figure 22. Adjustment of DCR on BIPV facade [62].

The implementation of DCR as shown in Figure 23 can rectify the dust accumulation issue on the BIPV system on the roof. The practical implementation of such technology on building facades was not reported. The combination of cleaning robots over the BIPV system and aerial robots for dust prediction on modules can play a significant role in resolving the issue on a large-scale basis. As discussed earlier, the dusting of the BIPV panels is challenging in terms of safety and vertical height. The current advancement in sensing technology and communication boost the applicability of drone and robotics-powered automatic system for the identification and cleaning of dust on BIPV panels.

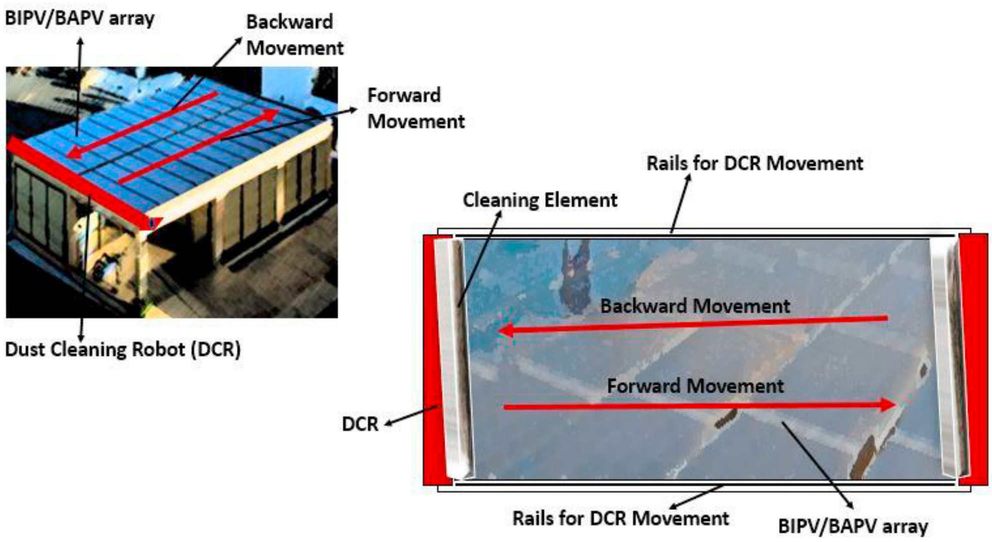

Figure 23. Adjustment of DCR on BIPV roof [62].

Figure 24 presents an amalgamation of multiple technologies and a LoRa-based network establishment for an automatic dust cleaning system. Drone-based mote, PV panel mote, robotic wiper mote, and drone yard are the components of the proposed architecture that are connected to the cloud server through a LoRa-based gateway. In this, the authorities initiate the instructions to the drones located in the drone yard to proceed with the inspection of the dust status on BIPV panels through the LoRa-based gateway. As the LoRa-based gateway is based on LoRa and Wi-Fi, so it can receive the instructions from the cloud server through the internet and communicate the instructions to the drones through LoRa.

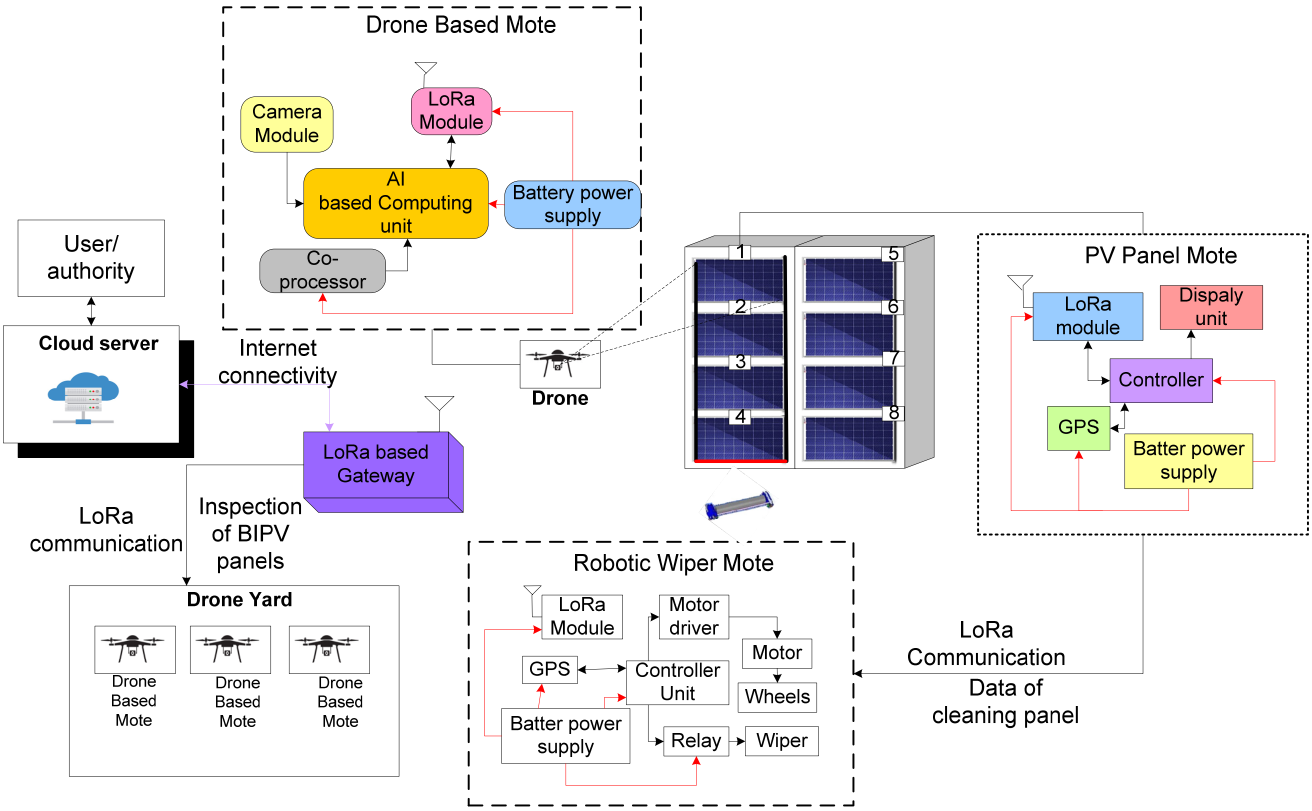

Figure 24. Proposed architecture for the robotic and drone-based automatic wiper system.

Drone-based mote embedded in the drones enables to detect the dust based on visuals obtained through the camera module. The obtained images are computed on the AI-based computing unit with co-processor to identify the dust in real-time. If the dust is identified, then the drones instruct the PV panel mote to send the GPS location to the robotics wiper mote through the LoRa communication. Here the PV panel mote is embedded in every panel so that every panel will be connected with the drone-based mote and robotic wiper mote through LoRa communication. Based on the request from the particular PV panel mote, the robotic wiper mote enables the robotic wiper system to locate and clean the dust on the BIPV panels. Simultaneously, it receives the request from the other PV panel mote, then it moves to that location and performs a cleaning activity. Along with building structure and area, the complete system can be customized.

5. Future Directions and Research Challenges

This study has discussed the significance of the digitalization implementation in BIPV for achieving a resilient infrastructure. Initially, we presented an overview of the BIPV system, and later on, the discussed digital technologies that are suitable for digitalization. A high temperature of BIPV system, fault identification in BIPV system, and dust accumulation of BIPV system are areas where the significance of digitalization is identified and the proposed architecture is relevant. However, few parameters can be improved for the better implementation of digitalization in the BIPV system. Below, the discussion and recommendations are provided to enhance the few parameters, and they are as follows:

Next Generation Computing for Digitalization of the Photovoltaic Integration

(a) **Future directions**

According to the findings of the above analysis, digitalization integration in the BIPV system is minimal. The adoption of digitalization has previously been proven in a variety of applications, where it facilitated the realization of robust infrastructure with a sustainable system. IoT, AI, ML, DL, edge computing, fog computing, UAV, and robotics technologies allow for real-time monitoring and control with intelligent analytics on the digital network [63]. Recently, the use of AR, VR, digital twins, and metaverse has increased in popularity in order to establish a virtual environment in which to visualize and feel everything in a realistic manner.

- **ML and DL for image enhancement for flaws detection in real-time image data**

In the scenario of the PV panels, the UAV with the assistance of an IR thermography camera captures the images of the PV panels during the aerial inspection. This image consists of noise and is unclear due to different environmental and technical parameters. From the previous studies, it has been concluded that by using adaptive histogram equalization grayscale and histogram equalization, the thermal solar panel images can be enhanced [64]. Moreover, with the different models such as artificial neural network (ANN) and convolutional neural network (CNN), the support vector machine achieved the highest accuracy in identifying the hotspot of faults in the enhanced images [64–66]. The above facts will encourage the implementation of the same models in the field of BIPV.

- **Edge computing to implement DL for Intelligent BIPV data analytics**

DL has already proven to be an efficient computation approach that has achieved high accuracy on computer vision data. DL demands high computation and memory. The inference is computationally expensive due to the very large dimensionality of high-resolution image data and the millions of computations that must be performed on the input data. The implementation of these computational tasks on a cloud server is challenging in terms of scalability, privacy, and bandwidth efficiency. Edge computing is capable of meeting the computational and memory requirements of DL with low latency [67]. Edge computing, which involves deploying a tiny mesh of compute nodes close to end devices, is a possible solution to address the high processing and low latency needs of deep learning on edge devices while also offering additional improvements in terms of bandwidth efficiency, privacy, and scalability [68]. Edge computing enables the loading of the AI and ML techniques in the edge device to perform real-time analytics regarding the BIPV system [69].

- **Fog computing for 6G assisted IoT network in BIPV**

Generally, the implementation of BIPV on a scalable building or in a scalable community comprises a massive number of IoT-connected devices. However, based on current trends, the future BIPV system will be highly interconnected, encompassing a large number of devices, progressively digitized, and data-driven. In this context, the 6G network and fog computing play a significant role in executing intelligent learning techniques to execute complex computations such as assessing aging properties, soiling effects, fault detection, detection of shading, etc., and transforming the user experience to the near real-time response [70]. The focus of communication will shift from ubiquitous connectivity to intelligent and automated connectivity. In addition to this, fog computing is crucial for the 6G implementation, as fog computing provides effective computation and storage [71]. The fog nodes assist the 6G in enabling ubiquitous connectivity and achieving extremely low latency.

- **Edge computing integration in UAV for intelligent automation and detection**

The UAV is employed to capture visual data on heights or in the air. The captured data is communicated to the edge device on the ground level, this indeed increases the infrastructure. To overcome this challenge, edge computing technology can be integrated into UAVs to analyze and compute the data gathered from the installed BIPV system through the inbuilt camera, sensors, and AI/ML algorithms [72,73]. The UAV minimizes the processing time and energy required for operating the whole process. In addition to this, UAVs have been integrated as air–ground equipment to meet the processing and storage requirements at IoT network edges because they provide low latency support for latency-sensitive applications, improve the scalability of massive mobile connectivity, and ease the distribution of big data analysis [73]. The combination of UAV-enabled edge computing with blockchain structure boosts security because the blockchain is a distributed ledger that allows UAVs to record their data as a transaction in a chain of blocks in an immutable, secure, and transparent [74]. This is a promising option for addressing the security and privacy concerns associated with UAV networks.

- **Augmented Reality, Virtual Reality, and Digital Twins for virtual BIPV system**

Augmented reality, virtual reality, and digital twins are rapidly emerging technologies that facilitate the linking of physical and virtual worlds in real-time, delivering a more real and holistic analysis of unplanned and unpredictable events [75,76]. The implementation of these technologies in the BIPV system empowers virtual visualization of the system before its installation in real-time. In addition to this, the performance of PV panels can be predicted, and can also visualize preventative measurements to avoid the further degradation of panels.

(b) **Research challenges**

- The implementation of AI in edge computing has significant advantages, along with a few challenges that require the focus of researchers, such as computational power, memory, security, and power management of the edge devices. In the area of BIPV, the energy generated by the edge devices will be based on renewable energy, however, the life of edge devices concerning the performance of computational activities is challenging because the replacement of edge devices within a short period also increases the infrastructure and adds another operating cost.
- Along with the life of the edge devices, another significant parameter that needs to be considered is the security and privacy of the data. In the context of the BIPV, the building structure data, and the panel details with location are shared on the edge network. The data is comprised during transmission from the edge to the cloud

server. Recently, blockchain has been integrated with edge computing to achieve secure authentication and collaboration with trusted distributers [77,78].
- To perform the high computational activities with AI, there is a need for additional computational hardware and this hardware consumes a lot of energy to perform the computational activities [79]. The reduction of computation immediately reduces energy consumption, where there is a need for a deeper understanding of AI computation with battery management measures, such as CPU throttling and sensor hardware modifications, which is an attractive research avenue [80]. Changes in input data, whether detected in software or hardware, can help reduce the frequency of AI runs and overall energy consumption. This challenge enables us to carry out research for better understanding of hardware chips (GPUs and TPUs) during the computation process.

6. Conclusions

Digitalization in the BIPV system plays a significant role in overcoming the challenges of the system by making it resilient through digital technologies. Initially in this study, the challenges faced by the system during the operation were identified and discussed based on the previous literature. Various conventional techniques to overcome the challenges discussed by the researchers are presented. This study addresses the digitalization of the BIPV system with the proposed architecture in order to realize real-time monitoring and intelligent analytics for controlling high rise temperature, fault detection, and dust accumulation identification of BIPV systems with digital technologies when they are deployed on a large scale. Finally, the study discusses the vital recommendations for future directions such as ML and DL for image enhancement for flaws detection in real-time image data; edge computing to implement DL for intelligent BIPV data analytics; fog computing for 6G assisted IoT network in BIPV; edge computing integration in UAV for intelligent automation and detection; augmented reality, virtual reality, and digital twins for a virtual BIPV system with research challenges of the real-time implementation in the BIPV.

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References

1. SDG 9: Industry, Innovation and Infrastructure. Available online: https://in.one.un.org/page/sustainable-development-goals/sdg-9/ (accessed on 3 June 2022).
2. SDG 7: Affordable and Clean Energy. Available online: https://in.one.un.org/page/sustainable-development-goals/sdg-7/ (accessed on 3 June 2022).
3. #Envision2030 Goal 11: Sustainable Cities and Communities | United Nations Enable. Available online: https://www.un.org/development/desa/disabilities/envision2030-goal11.html (accessed on 11 June 2022).
4. Renewables—Global Energy Review 2020—Analysis—IEA. Available online: https://www.iea.org/reports/global-energy-review-2020/renewables (accessed on 13 August 2022).
5. Singh, D.; Chaudhary, R.; Karthick, A. Review on the progress of building-applied/integrated photovoltaic system. *Environ. Sci. Pollut. Res.* **2021**, *28*, 47689–47724. [CrossRef] [PubMed]
6. Sahu, A.; Yadav, N.; Sudhakar, K. Floating photovoltaic power plant: A review. *Renew. Sustain. Energy Rev.* **2016**, *66*, 815–824. [CrossRef]
7. Singh, D.; Gautam, A.K.; Chaudhary, R. Potential and performance estimation of free-standing and building integrated photovoltaic technologies for different climatic zones of India. *Energy Built Environ.* **2020**, *3*, 40–55. [CrossRef]
8. Tsanakas, J.A.; Ha, L.; Buerhop, C. Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges. *Renew. Sustain. Energy Rev.* **2016**, *62*, 695–709. [CrossRef]

9. Paliwoda, B.; Krzysztof, W.; Biega, M. Internet of Things in Industry: Research Profiling, Application, Challenges and Opportunities—A Review. *Energies* **2022**, *15*(5), 1806. [CrossRef]
10. Singh, D.; Chaudhary, R. Impact of roof attached Photovoltaic modules on building material performance. *Mater. Today Proc.* **2021**, *46*, 445–450. [CrossRef]
11. Singh, D.; Rawat, M.; Singh, S.P.; Chaudhary, R. Performance of PV integrated wall and roof as a building material. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Punjab, India, 28–30 August 2020; IOP Publishing: Bristol, UK; Volume 1033, p. 12005.
12. Ma, T.; Yang, H.; Zhang, Y.; Lu, L.; Wang, X. Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook. *Renew. Sustain. Energy Rev.* **2015**, *43*, 1273–1284. [CrossRef]
13. Siddiqui, M.U.; Arif, A.F.M.; Kelley, L.; Dubowsky, S. Three-dimensional thermal modeling of a photovoltaic module under varying conditions. *Sol. Energy* **2012**, *86*, 2620–2631. [CrossRef]
14. Poulek, V.; Matuška, T.; Libra, M.; Kachalouski, E.; Sedláček, J. Influence of increased temperature on energy production of roof integrated PV panels. *Energy Build.* **2018**, *166*, 418–425. [CrossRef]
15. Radziemska, E.; Klugmann, E. Thermally affected parameters of the current–voltage characteristics of silicon photocell. *Energy Convers. Manag.* **2002**, *43*, 1889–1900. [CrossRef]
16. Vats, K.; Tiwari, G.N. Performance evaluation of a building integrated semitransparent photovoltaic thermal system for roof and façade. *Energy Build.* **2012**, *45*, 211–218. [CrossRef]
17. Agathokleous, R.; Kalogirou, S. Simulation-Based Investigation of the Air Velocity in a Naturally Ventilated BIPV System. In Proceedings of the Conference on Sustainable Energy, Brasov, Romania, 19–21 October 2017; Springer: Cham, Switzerland, 2017; pp. 201–217.
18. Park, K.E.; Kang, G.H.; Kim, H.I.; Yu, G.J.; Kim, J.T. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. *Energy* **2010**, *35*, 2681–2687. [CrossRef]
19. Vats, K.; Tomar, V.; Tiwari, G.N. Effect of packing factor on the performance of a building integrated semitransparent photovoltaic thermal (BISPVT) system with air duct. *Energy Build.* **2012**, *53*, 159–165. [CrossRef]
20. Al-Fuqaha, A.; Guizani, M.; Mohammadi, M.; Aledhari, M.; Ayyash, M. Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 2347–2376. [CrossRef]
21. Kimothi, S.; Thapliyal, A.; Akram, S.V.; Singh, R.; Gehlot, A.; Mohamed, H.G.; Anand, D.; Ibrahim, M.; Noya, I.D. Big Data Analysis Framework for Water Quality Indicators with Assimilation of IoT and ML. *Electronics* **2022**, *11*, 1927. [CrossRef]
22. Kimothi, S.; Singh, R.; Gehlot, A.; Akram, S.V.; Malik, P.K.; Gupta, A.; Bilandi, N. Intelligent energy and ecosystem for real-time monitoring of glaciers. *Comput. Electr. Eng.* **2022**, *102*, 108163. [CrossRef]
23. GSMA | IoT Connections Forecast: The Rise of Enterprise | Internet of Things. Available online: https://www.gsma.com/iot/resources/iot-connections-forecast-the-rise-of-enterprise/ (accessed on 6 February 2021).
24. Boyes, H.; Hallaq, B.; Cunningham, J.; Watson, T. The industrial internet of things (IIoT): An analysis framework. *Comput. Ind.* **2018**, *101*, 1–12. [CrossRef]
25. Fatorachian, H.; Kazemi, H. Impact of Industry 4.0 on supply chain performance. *Prod. Plan. Control* **2021**, *32*, 63–81. [CrossRef]
26. Ud Din, I.; Guizani, M.; Hassan, S.; Kim, B.S.; Khurram Khan, M.; Atiquzzaman, M.; Ahmed, S.H. The Internet of Things: A Review of Enabled Technologies and Future Challenges. *IEEE Access* **2019**, *7*, 7606–7640. [CrossRef]
27. Ray, P.P. A survey of IoT cloud platforms. *Futur. Comput. Inform. J.* **2016**, *1*, 35–46. [CrossRef]
28. Nižetić, S.; Šolić, P.; González-de, D.L.-I.; Patrono, L. Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future. *J. Clean. Prod.* **2020**, *274*, 122877. [CrossRef] [PubMed]
29. Mekki, K.; Bajic, E.; Chaxel, F.; Meyer, F. A comparative study of LPWAN technologies for large-scale IoT deployment. *ICT Express* **2019**, *5*, 1–7. [CrossRef]
30. Singh, R.; Sharma, R.; Akram, S.V.; Gehlot, A.; Buddhi, D.; Malik, P.K.; Arya, R. Highway 4.0: Digitalization of highways for vulnerable road safety development with intelligent IoT sensors and machine learning. *Saf. Sci.* **2021**, *143*, 105407. [CrossRef]
31. Shi, F.; Ning, H.; Huangfu, W.; Zhang, F.; Wei, D.; Hong, T.; Daneshmand, M. Recent Progress on the Convergence of the Internet of Things and Artificial Intelligence. *IEEE Netw.* **2020**, *34*, 8–15. [CrossRef]
32. Zhang, C.; Lu, Y. Study on artificial intelligence: The state of the art and future prospects. *J. Ind. Inf. Integr.* **2021**, *23*, 100224. [CrossRef]
33. Borges, A.F.S.; Laurindo, F.J.B.; Spínola, M.M.; Gonçalves, R.F.; Mattos, C.A. The strategic use of artificial intelligence in the digital era: Systematic literature review and future research directions. *Int. J. Inf. Manag.* **2021**, *57*, 102225. [CrossRef]
34. Collins, C.; Dennehy, D.; Conboy, K.; Mikalef, P. Artificial intelligence in information systems research: A systematic literature review and research agenda. *Int. J. Inf. Manag.* **2021**, *60*, 102383. [CrossRef]
35. Hassan, N.; Gillani, S.; Ahmed, E.; Yaqoob, I.; Imran, M. The Role of Edge Computing in Internet of Things. *IEEE Commun. Mag.* **2018**, *56*, 110–115. [CrossRef]
36. Shi, W.; Cao, J.; Zhang, Q.; Li, Y.; Xu, L. Edge Computing: Vision and Challenges. *IEEE Internet Things J.* **2016**, *3*, 637–646. [CrossRef]
37. Yu, W.; Liang, F.; He, X.; Hatcher, W.G.; Lu, C.; Lin, J.; Yang, X. A Survey on the Edge Computing for the Internet of Things. *IEEE Access* **2017**, *6*, 6900–6919. [CrossRef]

38. Mohamed, N.; Al-Jaroodi, J.; Jawhar, I.; Idries, A.; Mohammed, F. Unmanned aerial vehicles applications in future smart cities. *Technol. Forecast. Soc. Change* **2020**, *153*, 119293. [CrossRef]
39. Alsamhi, S.H.; Ma, O.; Ansari, M.S.; Almalki, F.A. Survey on collaborative smart drones and internet of things for improving smartness of smart cities. *IEEE Access* **2019**, *7*, 128125–128152. [CrossRef]
40. Abualigah, L.; Diabat, A.; Sumari, P.; Gandomi, A.H. Applications, deployments, and integration of internet of drones (iod): A review. *IEEE Sens. J.* **2021**, *21*, 25532–25546. [CrossRef]
41. de Arquer Fernández, P.; Fernández, M.Á.F.; Candás, J.L.C.; Arboleya, P.A. An IoT open source platform for photovoltaic plants supervision. *Int. J. Electr. Power Energy Syst.* **2021**, *125*, 106540. [CrossRef]
42. Adhya, S.; Saha, D.; Das, A.; Jana, J.; Saha, H. An IoT based smart solar photovoltaic remote monitoring and control unit. In Proceedings of the 2016 2nd International Conference on Control, Instrumentation, Energy & Communication (CIEC), Kolkata, India, 28–30 January 2016; pp. 432–436.
43. Cheddadi, Y.; Cheddadi, H.; Cheddadi, F.; Errahimi, F.; Es-sbai, N. Design and implementation of an intelligent low-cost IoT solution for energy monitoring of photovoltaic stations. *SN Appl. Sci.* **2020**, *2*, 1–11. [CrossRef]
44. Sarkar, S.; Rao, K.U.; Bhargav, J.; Sheshaprasad, S.; Anirudh Sharma, C.A. IoT Based Wireless Sensor Network (WSN) for Condition Monitoring of Low Power Rooftop PV Panels. In Proceedings of the 2019 IEEE 4th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), Chennai, India, 21–23 November 2019; pp. 1–5.
45. Márquez, F.P.G.; Ramírez, I.S. Condition monitoring system for solar power plants with radiometric and thermographic sensors embedded in unmanned aerial vehicles. *Measurement* **2019**, *139*, 152–162. [CrossRef]
46. Qasem, H.; Mnatsakanyan, A.; Banda, P. Assessing dust on PV modules using image processing techniques. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 5–10 June 2016; pp. 2066–2070.
47. Parrott, B.; Zanini, P.C.; Shehri, A.; Kotsovos, K.; Gereige, I. Automated, robotic dry-cleaning of solar panels in Thuwal, Saudi Arabia using a silicone rubber brush. *Sol. Energy* **2018**, *171*, 526–533. [CrossRef]
48. Khadka, N.; Bista, A.; Adhikari, B.; Shrestha, A.; Bista, D. Smart solar photovoltaic panel cleaning system. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Bangkok, Thailand, 11–14 December 2020; IOP Publishing: Philadelphia, PA, USA, 2020; Volume 463, p. 12121.
49. Laudani, A.; Lozito, G.M.; Radicioni, M.; Fulginei, F.R.; Salvini, A. Optimal PV Panel Reconfiguration Using Wireless Irradiance Distributed Sensing. In *ELECTRIMACS 2019*; Springer: Cham, Switzerland, 2020; pp. 525–537.
50. Niccolai, A.; Grimaccia, F.; Leva, S. Advanced asset management tools in photovoltaic plant monitoring: UAV-based digital mapping. *Energies* **2019**, *12*, 4736. [CrossRef]
51. Athienitis, A.K.; Bambara, J.; O'Neill, B.; Faille, J. A prototype photovoltaic/thermal system integrated with transpired collector. *Sol. Energy* **2011**, *85*, 139–153. [CrossRef]
52. Jie, J.; Hua, Y.; Gang, P.; Bin, J.; Wei, H. Study of PV-Trombe wall assisted with DC fan. *Build. Environ.* **2007**, *42*, 3529–3539. [CrossRef]
53. Amelia, A.R.; Irwan, Y.M.; Irwanto, M.; Leow, W.Z.; Gomesh, N.; Safwati, I.; Anuar, M.A.M. Cooling on photovoltaic panel using forced air convection induced by DC fan. *Int. J. Electr. Comput. Eng.* **2016**, *6*, 526.
54. Koch, S.; Weber, T.; Sobottka, C.; Fladung, A.; Clemens, P.; Berghold, J. Outdoor electroluminescence imaging of crystalline photovoltaic modules: Comparative study between manual ground-level inspections and drone-based aerial surveys. In Proceedings of the 32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany, 20–24 June 2016; pp. 1736–1740.
55. Thermal Imaging Camera in Solar Industry. Available online: https://www.ulirvisiontech.com/application/solar-industry.html (accessed on 11 June 2022).
56. Tsanakas, J.A.; Vannier, G.; Plissonnier, A.; Ha, D.L.; Barruel, F. Fault diagnosis and classification of large-scale photovoltaic plants through aerial orthophoto thermal mapping. In Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 14–18 September 2015; pp. 1783–1788.
57. Solar Drone Inspection Provider Raptor Maps Secures $22 Million in Funding—Pv Magazine International. Available online: https://www.pv-magazine.com/2022/04/15/solar-drone-inspection-provider-raptor-maps-secures-22-million-series-b/ (accessed on 11 June 2022).
58. Kazem, H.A.; Chaichan, M.T.; Al-Waeli, A.H.A.; Sopian, K. A review of dust accumulation and cleaning methods for solar photovoltaic systems. *J. Clean. Prod.* **2020**, *276*, 123187. [CrossRef]
59. Aïssa, B.; Isaifan, R.J.; Madhavan, V.E.; Abdallah, A.A. Structural and physical properties of the dust particles in Qatar and their influence on the PV panel performance. *Sci. Rep.* **2016**, *6*, 1–12.
60. Hudedmani, M.G.; Joshi, G.; Umayal, R.M.; Revankar, A. A comparative study of dust cleaning methods for the solar PV panels. *Adv. J. Grad. Res.* **2017**, *1*, 24–29. [CrossRef]
61. Gupta, V.; Sharma, M.; Pachauri, R.K.; Babu, K.N.D. A low-cost real-time IOT enabled data acquisition system for monitoring of PV system. *Energy Sources Part A Recovery Util. Environ. Eff.* **2021**, *43*, 2529–2543. [CrossRef]
62. Kumar, N.M.; Sudhakar, K.; Samykano, M.; Sukumaran, S. Dust cleaning robots (DCR) for BIPV and BAPV solar power plants-A conceptual framework and research challenges. *Procedia Comput. Sci.* **2018**, *133*, 746–754. [CrossRef]
63. Gill, S.S.; Xu, M.; Ottaviani, C.; Patros, P.; Bahsoon, R.; Shaghaghi, A.; Golec, M.; Stankovski, V.; Wu, H.; Abraham, A.; et al. AI for next generation computing: Emerging trends and future directions. *Internet Things* **2022**, *19*, 1–43. [CrossRef]

64. Kim, B.; Serfa Juan, R.O.; Lee, D.E.; Chen, Z. Importance of Image Enhancement and CDF for Fault Assessment of Photovoltaic Module Using IR Thermal Image. *Appl. Sci.* **2021**, *11*, 8388. [CrossRef]
65. Kurukuru, V.S.B.; Haque, A.; Khan, M.A.; Tripathy, A.K. Fault classification for Photovoltaic Modules Using Thermography and Machine Learning Techniques. In Proceedings of the 2019 International Conference on Computer and Information Sciences (ICCIS), Sakaka, Saudi Arabia, 3–4 April 2019. [CrossRef]
66. Ali, M.U.; Khan, H.F.; Masud, M.; Kallu, K.D.; Zafar, A. A machine learning framework to identify the hotspot in photovoltaic module using infrared thermography. *Sol. Energy* **2020**, *208*, 643–651. [CrossRef]
67. Chen, J.; Ran, X. Deep Learning with Edge Computing: A Review. *Proc. IEEE* **2019**, *107*, 1655–1674. [CrossRef]
68. Nastic, S.; Rausch, T.; Scekic, O.; Dustdar, S.; Gusev, M.; Koteska, B.; Kostoska, M.; Jakimovski, B.; Ristov, S.; Prodan, R. A serverless real-time data analytics platform for edge computing. *IEEE Internet Comput.* **2017**, *21*, 64–71. [CrossRef]
69. Chang, Z.; Liu, S.; Xiong, X.; Cai, Z.; Tu, G. A survey of recent advances in edge-computing-powered artificial intelligence of things. *IEEE Internet Things J.* **2021**, *8*, 13849–13875. [CrossRef]
70. Malik, U.M.; Javed, M.A.; Zeadally, S.; ul Islam, S. Energy efficient fog computing for 6G enabled massive IoT: Recent trends and future opportunities. *IEEE Internet Things J.* **2021**, *4662*, 1–22. [CrossRef]
71. Aazam, M.; Zeadally, S.; Harras, K.A. Deploying Fog Computing in Industrial Internet of Things and Industry 4.0. *IEEE Trans. Ind. Inform.* **2018**, *14*, 4674–4682. [CrossRef]
72. Zhou, Y.; Pan, C.; Yeoh, P.L.; Wang, K.; Elkashlan, M.; Vucetic, B.; Li, Y. Secure communications for UAV-enabled mobile edge computing systems. *IEEE Trans. Commun.* **2019**, *68*, 376–388. [CrossRef]
73. Yazid, Y.; Ez-Zazi, I.; Guerrero-González, A.; El Oualkadi, A.; Arioua, M. UAV-Enabled Mobile Edge-Computing for IoT Based on AI: A Comprehensive Review. *Drones* **2021**, *5*, 148. [CrossRef]
74. Kumari, A.; Gupta, R.; Tanwar, S.; Kumar, N. A taxonomy of blockchain-enabled softwarization for secure UAV network. *Comput. Commun.* **2020**, *161*, 304–323. [CrossRef]
75. Singh, M.; Fuenmayor, E.; Hinchy, E.P.; Qiao, Y.; Murray, N.; Devine, D. Digital twin: Origin to future. *Appl. Syst. Innov.* **2021**, *4*, 36. [CrossRef]
76. Barricelli, B.R.; Casiraghi, E.; Fogli, D. A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access* **2019**, *7*, 167653–167671. [CrossRef]
77. Yang, R.; Yu, F.R.; Si, P.; Yang, Z.; Zhang, Y. Integrated Blockchain and Edge Computing Systems: A Survey, Some Research Issues and Challenges. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 1508–1532. [CrossRef]
78. Guo, S.; Hu, X.; Guo, S.; Qiu, X.; Qi, F. Blockchain Meets Edge Computing: A Distributed and Trusted Authentication System. *IEEE Trans. Ind. Inform.* **2020**, *16*, 1972–1983. [CrossRef]
79. LiKamWa, R.; Priyantha, B.; Philipose, M.; Zhong, L.; Bahl, P. Energy characterization and optimization of image sensing toward continuous mobile vision. In Proceedings of the 11th Annual International Conference on Mobile Systems, Applications, and Services, Taipei, Taiwan, 25–28 June 2013; pp. 69–82.
80. Mijuskovic, A.; Chiumento, A.; Bemthuis, R.; Aldea, A.; Havinga, P. Resource management techniques for cloud/fog and edge computing: An evaluation framework and classification. *Sensors* **2021**, *21*, 1832. [CrossRef] [PubMed]