Article:

Olayiwola, Olufemi Isaac orcid.org/0000-0002-2915-2193, Elsden, Miles and Dhimish, Mahmoud (2024) Robotics, Artificial Intelligence, and Drones in Solar Photovoltaic Energy Applications—Safe Autonomy Perspective. Safety. 32. ISSN 2313-576X

https://doi.org/10.3390/safety10010032

safety

Perspective

Robotics, Artificial Intelligence, and Drones in Solar Photovoltaic Energy Applications—Safe Autonomy Perspective

Olufemi Olayiwola [1,*], Miles Elsden [1] and Mahmoud Dhimish [2]

[1] Institute for Safe Autonomy, University of York, York YO10 5DD, UK; miles.elsden@york.ac.uk
[2] School of Physics, Engineering and Technology, University of York, York YO10 5DD, UK; mahmoud.dhimish@york.ac.uk
* Correspondence: olufemi.olayiwola@york.ac.uk

Abstract: While there is evidence of substantial improvement in efficiency and cost reduction from the integration of Robotics, Artificial Intelligence, and Drones (RAID) in solar installations; it is observed that there is limited oversight by international standards such as the International Electrotechnical Commission (IEC) in terms of the hazards and untapped potentials. This is partly because it is an emerging application and generally burdened with social acceptability issues. Thus, the safety regulations applied are adaptations of device-specific regulations as deemed fit by individual companies. Also, due to the fast-paced technological development of these platforms, there is huge potential for applications that are not currently supported by the device-specific regulations. This creates a multi-faceted demand for the establishment of standardized, industry-wide polices and guidelines on the use of RAID platforms for Solar PV integrations. This work aims to address critical safety concerns by conducting a comprehensive high-level system examination applicable to the monitoring and maintenance of Solar PV systems. Standard safety assurance models and approaches are examined to provide a safe autonomy perspective for Solar PVs. It is considered that, as RAID applications continue to evolve and become more prevalent in the Solar PV industry, standardized protocols or policies would be established to ensure safe and reliable operations.

Keywords: robotics; artificial intelligence; drones; autonomous systems; photovoltaics; safety; autonomy; policies

Citation: Olayiwola, O.; Elsden, M.; Dhimish, M. Robotics, Artificial Intelligence, and Drones in Solar Photovoltaic Energy Applications—Safe Autonomy Perspective. *Safety* **2024**, *10*, 32. https://doi.org/10.3390/safety10010032

Academic Editor: Raphael Grzebieta

Received: 21 August 2023
Revised: 3 March 2024
Accepted: 13 March 2024
Published: 18 March 2024

1. Introduction

Recent advancements in robotics, artificial intelligence (AI), and drone technologies have enabled the development of sophisticated systems capable of performing tasks with minimal human intervention. These technologies have been deployed in various sectors of the economy, such as healthcare [1], transportation [2], agriculture [3], construction [4], power systems [5], and manufacturing [6]. They are fast becoming a part of our daily living, and our activities are now more dependent on their functionalities. Examples of these include Full Self-Driving (FSD) AI technology in electric vehicles [7], surgical robots [8], and crop monitoring with drones [9]. The reduction in human intervention associated with some of these applications has resulted in the new class of systems termed “autonomous agents” [10]. The energy sector is not left out of this revolution and has a conservative cumulative annual growth rate (CAGR) of 23.6% and revenue of USD 49.54 billion forecasted for artificial intelligence applications between 2023–2032 [11].

The energy sector encompasses various applications, including smart grids, energy management systems, oil and gas exploration and production, and renewable energy. The renewable energy sector, in particular, continues to develop new applications utilizing robotics, artificial intelligence, and drones to overcome challenges that limit the benefits of renewable energy. It is widely known that renewable energy technologies face several challenges, including the availability of the main energy source for conversion, limited installation space, high energy storage costs, natural disasters, and maintenance issues. To address these challenges, strategies have been developed, such as wind turbine inspection with drones, robotic arms for renewable energy equipment manufacturing, and AI-platforms for energy management. For solar photovoltaic energy generation, drones equipped with sophisticated cameras and AI algorithms can inspect solar panels to detect faults and damages [12,13], enabling timely maintenance and repair. Autonomous robots can clean solar panels [14], and AI can optimize the operation of Solar PV systems [15]. Additionally, machine learning algorithms can analyse data from solar panels, weather forecasts, and energy markets to predict energy production and consumption patterns, allowing for the system's optimal operation [16,17].

It is observed that, with the emergence of various RAID platforms, many companies tend to define safety within their operational environment solely by acceptable practices on the use of individual RAID devices, as there are currently limited industry-wide policies for Solar PV integration of autonomous systems. This can be expected, as several of these technologies are in their early adoption stage by a significant number of Solar PV installation companies. However, the absence of specific regulations often creates several gaps or loopholes in such high-level system integration, as indicated by [18,19]. In their research, Ref. [18] described the gaps as semantic gaps, responsibility gaps, and liability gaps. Identification of these gaps would provide information and clarification on sources of errors arising from system integration, as well as the party that bears the liability during the disaster management process. These gaps are inevitable since the integration of autonomous platforms into an existing facility creates new fault points and can lead to varying failure scenarios.

It is worth noting that policies from regulatory authorities (IEC, International Robotics Federation—IFR, and Country-specific Unmanned Air Vehicle—UAV regulators) are not entirely oblivious to the use of RAID platforms for Solar PV site maintenance. For example, the European Union Operations and Maintenance best practice guideline v5.0 [20] granted recognition to thermography inspection using UAVs for Solar PV site monitoring, as supported by IEC TS 62446-3:2017 [21]. However, the scope of this guideline is limited to the use of UAVs for thermography applications as it relates to procedures to obtain valid imagery. As described in Section 3.3, the recent use of UAVs extends beyond thermography. Also, the guidelines have yet to provide standard operational procedures as they relate to safety and hazard management. This is expected to cover instances of recent robotics integration and autonomous interactions within the site.

Furthermore, some of the current policies on the use of some autonomous platforms limit viable application of the technologies for solar photovoltaics integration. An example is the beyond-visual-line-of-sight (BVLOS) regulation, which is designed to protect uninvolved persons during drone flights. A downside of this is that it severely restricts the possibilities and ease of monitoring of building-attached photovoltaics (BAPV). Due to exponential increases in energy demand in several countries, commercial rooftop photovoltaic installation has gained significant legal recognition, and there are several installations on rooftops of commercial buildings, such as very large malls and industries. Several of these installations are over 500 kWp, fully installed with over 1000 high-wattage solar modules. Oftentimes, the allowed rooftop Solar PV system size could be up to 1MWac or more (the legal limit varies per country) [22,23]. This implies that there is the need for monitoring of a significantly higher number of solar modules spread out over a very wide area, at different orientations and substantial height from the ground. UAV (drones) monitoring can be highly beneficial as it reduces fall-from-height risk and damage to roofs from frequent climbing by operations and maintenance staff. However, this application is currently limited, with several UAV regulations yet to be considered in terms of this specific application. Thus, the research question is to identify whether there are new advances to be made or guidelines to enable application at such scale.

Consequently, regardless of the need to apply beneficial technologies where necessary, when the trustworthiness of the overall system is not adequately examined, it acts as an impediment to companies willing to adopt autonomous systems in emerging industries, as the perceived risk may outweigh the benefits.

To address this issue, this work aims to assist industry experts in exploring and identifying critical aspects that ensure the safe implementation of autonomous systems in the Solar PV industry and recommend the provision of tailored guidelines for failure management that can be considered standard industry practice.

In summary, the issues raised in this work are mainly as follows:

- Motivate a review of conventional practices and policies associated with the use of RAID devices that currently limit the broad utilization of various Solar PV installation systems.
- Highlight the need for a review of high-level systems assurance guidance or policies that will serve as the industry standard on the emerging use of RAID devices within solar installations.
- In view of the above, the contribution of this work is perceived as follows:
- To identify areas where conventional RAID device practices and policies could be reviewed and standardized for specific applications (use case), such as with solar farm integration.
- To examine several potential hazards associated with the use of RAID devices and provide insight into areas that may require policy review for industry-wide standardization.
- To provide insight into salient areas that could assist with this specific use case safety guidance, such as the autonomy level categorization and the need for an incident register section dedicated to activities related to the use of RAID devices.

For clarity and uniformity, the use of the word 'device' or 'platform' in this work refers to the AI subsystem or individual robots and drones; the use of the word 'system' takes this a step further to indicate the integration of the robot, drone, or AI platform into the solar photovoltaic installation.

2. Safe Autonomy and Solar Photovoltaics

Autonomous systems by definition extend beyond just robotics and automation to software development, sensors, control algorithms, and systems development [10,24,25]. According to [25], autonomous systems can make their own decisions and take their own action without real-time human interference. These definitions can be considered as the difference between robotics and drone applications that are fully controlled by humans and tasks that are autonomous. In fact, once a system has been pre-programmed to act in a particular manner, there is a level of autonomy involved.

In view of this, we acknowledge that there are different levels of autonomy in systems applications. For autonomous transportation, there are five (5) levels of autonomy in addition to full manual control [26]. These levels of automation describe the various levels of the driver's assistance provided by the sensor-enabled artificial intelligence integrated into the vehicle management system, where the final level describes a fully autonomous vehicle that does not require any human assistance. The classification applied for autonomous road vehicles on levels of autonomy serves as a very vital step in defining the term "safety" and, therefore, the expected reliability of the system. In contrast, there is still a need for such clarity, in particular for energy systems application, and this will be addressed under Section 3 of this work.

As previously discussed under Section 1, autonomous systems deployment has been applied in various renewable energy applications, such as in [27–29]. However, due to the emerging nature of the applications, safety measures are usually considered only at the RAID device level, based on the risk analysis of the operator/company and not at a standardized system integration level code of conduct. This creates a loophole for dangerous practices and preventable system failures. This work aims to highlight critical aspects of safety in autonomous platforms, particularly as they apply to system-level integrations into solar photovoltaic energy installations.

In this work, we define safe autonomy in solar photovoltaic (PV) energy applications as the use of automated systems, including robots, artificial intelligence, and drones, in a way that ensures safe and reliable operations with minimal human intervention. For the purpose of this discussion, the emphasis will be on safe autonomy for RAID applications.

It is important to note that safety in autonomous systems can be viewed from two standpoints. One is the reduction of risk to humans, since the tasks involved are now carried out by autonomous systems, such as is observable in [25,30,31], where RAID equipment are used to perform hazardous tasks in space (on satellites) and at heights to install or repair solar panels. Autonomous robots and drones equipped with sensors and AI algorithms can perform these tasks more efficiently and safely, with minimal risk of injury to human workers. The second standpoint is the safety of system operations, to prevent avoidable issues that can lead to injuries/death for those involved or within the vicinity of the operation or damages to the facility operated on (or interconnected ones), as well as the RAID equipment itself [32].

Due to the increased use of RAID platforms, such as UAVs on solar, there have been increased reports of mishaps [33], which are probably undocumented. An example seen in [33] indicates a possibility of mechanical/battery failure (explosion) while a solar farm monitoring exercise was ongoing. The UAV operator states categorically that they were unable to locate the drone at the report time. This could have resulted in a worse scenario if the UAV crash landed into the Solar PV asset or another human on site during the inspection. In this case, the UAV itself would have sustained significant damage (or possible asset loss).

To ensure safe operations of autonomous systems, researchers are exploring various methods to develop safe autonomy within the Solar PV space. One approach is to use sensors and cameras to enable autonomous robots to perceive their environment and detect potential hazards [32,34]. Another approach is to implement safety protocols and fail-safes to ensure that the system can respond appropriately to unexpected situations or malfunctions [35–37]. These are effective measures to prevent operational failures and loss of income associated via capital expenditure, downtime reduction, irrecoverable loss, and, in cases of loss of life and permanent injuries, legal and insurance costs.

There exist several autonomous RAID applications in solar photovoltaics, ranging from solar cell wafer production to cell arrangement to form a solar module, mechanical testing of the final product before packaging, packaging, installation, and maintenance [29,38–41]. As mentioned earlier, on a frequent basis, the safety protocols are implemented as best understood by the company utilizing the application or solely based on the device manual. This approach oftentimes does not adequately consider fault points introduced by the integration of the device into the overall system, ease of transfer of knowledge (to operations staff), or Solar PV-specific issues, and, as such, there is a need to start providing frameworks and policy guidelines that can serve as the industry standard for the safety of humans (involved and non-involved), adequate asset management, ease of regulatory inspection, conflict resolution, and warranty and insurance claims resolution.

In view of the above, this work aims to identify critical issues in the integration of autonomous systems, particularly RAID application within the Solar PV industry, with an attempt to provide possible solutions and a guiding framework. In the next section, we look into different RAID platform classes and the levels of autonomy.

3. Autonomous RAID Applications in Solar Photovoltaics

3.1. Autonomy Levels

In Table 1, we provide a description of the levels of autonomy used in autonomous vehicles according to the Society for Automotive Engineers (SAE). This classification makes it easier to define regulatory roles for adequate rider or passenger safety and asset management.

Table 1 is a summarized extract of the automated driving levels recommended by the SAE for surface vehicles [42], and it can be further simplified as Level 0 (No Automation—Manual), Level 1 (Driver Assistance—A single automated feature can be activated per time while the driver performs the remaining tasks), Level 2 (Partial Automation—The

Advanced Driver Assistance System is available for combined longitudinal and lateral functions; however, the human driver is fully involved at all times), Level 3 (Conditional Automation—The automated driving system is able to perform all driving functions when activated; however, the human driver should be ready to take over during failures or complex tasks).

Table 1. Levels of Automated Driving [43].

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You <u>are</u> driving** whenever these driver support features are engaged—even if your feet are off the pedals and you are not steering			**You <u>are not</u> driving** when these automated driving features are engaged—even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake, or accelerate as needed to maintain safety			When the feature requests you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do the features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	Automatic emergency braking, blind spot warning, lane departure warning	Lane centering **OR** adaptive cruise control	Lane centering **AND** adaptive cruise control at the same time	Traffic jam chauffer	Local driverless taxi, pedals/steering wheel may or may not be installed	Same as level 4, but feature can drive everywhere in all conditions

The blue section on the table indicates where basic functionalities are mostly to support driver actions while the green section indicates levels of autonomy where the driving can be performed by the system and not the driver.

Level 4 (High Automation—Self-driving is available, and the vehicle intervenes when things go wrong; however, the human can override if desired or based on legislation), Level 5 (Full Automation—Driving does not require any human oversight) [44,45].

While this classification approach has successfully enabled the current regulatory oversight for on-road motor vehicles, we observe that applying the same principle for Solar PVs may not provide a robust solution. This is because the approach applied above can be considered a single device scenario when compared with the range of interacting systems applicable on a single Solar PV installation/farm. However, since EVs and RAID applications have similarities in terms of the inclusion of autonomous systems, we consider leveraging the basic principles used in the automotive sector. To achieve some form of generalization for RAID applications in solar photovoltaics, we propose consideration of the autonomous processes/applications and the various anticipated failure points/processes. To perform this, we first consider the existing classifications or categorization of the RAID platforms and their applications within the Solar PV sector.

3.2. RAID Classification and Application

3.2.1. Robots Classification

A robot can be defined as an automatically controlled, reprogrammable, multipurpose manipulator capable of carrying out a complex series of action [46–48].

According to [49–51], there are different classifications of robots for industrial applications, based on different criteria, such as mechanical structure, degrees of mobility (number of joints 'L'—number of independent constraints 'c') [52], useful configuration, and operational mode. For the purpose of this work, a classification based on operational mode will be applied for clarity and generalization across various devices. In terms of operational mode, robots can be classified into six types [49].

- Autonomous Mobile Robots (AMRs): These are robots that are able to move around with the aid of sensors and machine vision. They have onboard processors that allow them to make smart decisions on the move.

- Automated Guided Vehicles (AGVs): These robots rely on pre-programmed paths and are operated only when under full supervision.
- Articulated Robots: This refers to robotic arms used mostly in manufacturing plants. They have different degrees of motion based on the number of joints and coordinates of motion at each joint.
- Humanoids: These robots perform human-centric tasks and are therefore designed with human forms. They are essentially a subset of AMRs.
- Cobots: The term Cobots implies Collaborative Robots. These robots perform tasks alongside or directly with humans. They are designed to significantly reduce arduous tasks for human workers.
- Hybrids: These robots are a combination of any of the classes described above. This is to enable them to perform more complex tasks than the single categories.

3.2.2. Artificial Intelligence (AI) Platforms

Artificial intelligence refers to any platform/process that is implemented to execute tasks or make decisions like human beings. It is also defined as the ability to plan, reason, learn, or provide information via a combination of concepts from a broad field of science, such as computer science, psychology, philosophy, linguistics, and many others [53,54].

AI is often classified in terms of capabilities as Narrow/Weak AI (single task), General AI (multiple tasks as well as a human) and Super AI (multiple tasks better than a human), or in terms of functionality, as described below [55,56].

- Reactive AI: This type of AI is programmed to only provide a predictable response based on the input/stimuli it receives. This form of AI does not store the input and does not learn with continuous usage.
- Limited memory AI: This level of AI functionality learns from previous use to improve its output or response. Model training under this level can either be prompted by developers or the AI platform pre-built to automatically update the training. An example is the training of computers in playing games.
- Theory of mind: This level of AI functionality not only has memory, but it also begins to interact with human thought and emotions. This is a very high level of human-behaviour mimicking, and an example is Sophia, the humanoid robot created by Hanson robotics in Hong Kong. The fluidity of human nature and emotions, however, makes this very difficult to attain for now.
- Self-awareness: AI at this level would have achieved human-like intelligence and self-awareness. The AI platform would be aware of itself and others' emotions and needs. There is currently no AI at this level; however, with continuous advancement in technology, this is considered achievable.

3.2.3. Drones (Unmanned Aerial Vehicles)

In the context of this work, we refer to drones as aerial vehicles that do not carry human beings on board but that are, rather, controlled remotely or through pre-programed on-board systems or from remote facilities. Generally, drones refer to a larger range of devices, ranging from small (1mm wingspan) unmanned battery-powered aerial vehicles to large (61 m wingspan) unmanned underwater or aerial vehicles that use a fuel engine, often used in the military [57–59].

Drones can be classified in terms of their size/weight and wing mechanism (fixed wing, rotary wing) [60,61]. In terms of operational functionality, drones are usually designed to carry payloads for different applications. These could include ordinary cameras, specialized cameras, LIDAR systems, or missiles in military application. This work will only discuss drones used to carry non-combatant payloads for Solar PV applications.

3.3. Specific RAID Applications in Solar Photovoltaics

In order to gain a deeper understanding of the levels of autonomy and associated risks in the applications of RAID devices, we present a comparative analysis of RAID applications in the Solar PV system context. The objective is to explore the breadth of applications and assist in defining the varying levels of autonomy and risk associated with these applications. This will provide insights on decision making.

Table 2 provides a snapshot of some of the RAID applications in Solar PV systems [4,12–17,62,63]. It is important to note that this list is not exhaustive and serves as a representative sample of the diverse range of system implementations that exist, depending on the developers and their specific objectives. Each application in the table represents a unique combination of RAID technologies integrated into Solar PV systems to perform specific tasks.

Table 2. RAID application in solar photovoltaics.

Robots	AI	Drones
Inspection	Maximum power point tracking	Site inspection before system design
Cleaning	Plant yield forecasting	Construction monitoring
Ribbon disconnection failure detection	Parameter estimation in modelling	Site commissioning
Panel installation	Defect detection	Module maintenance inspections
Industrial production of solar cells/modules	System design	Thermal imagery assessment
Thermal imaging	Model optimization	PV transmission lines inspection
Bird control	Solar plant control	Shading assessment
Carrying payloads for solar farm inspection	Data analytics	Asset security monitoring
	Plant maintenance	Solar module cleaning
	Cybersecurity	
	Cell material optimization	
	Embedded system control of robots and drones	
	Fault detection	

One key observation from the analysis is the significant variance in the level of autonomy exhibited by these applications. While some applications are still in the early stages of development and considered basic prototypes, others have already been implemented on operational solar farms, albeit with full human supervision. This variance in autonomy levels reflects the current stage of development and adoption of RAID technologies in the Solar PV industry. It is important to recognize that the level of autonomy directly impacts the associated risks in these applications. Applications with higher levels of autonomy, where the RAID devices operate with minimal human intervention, may introduce additional risks that need to be carefully managed and mitigated. On the other hand, applications with lower levels of autonomy, where human supervision is prevalent, may have a different set of risks associated with human–machine interactions and the potential limitations of human oversight.

The next level is venturing into full scale autonomy for individual devices and then full-scale autonomy at the whole solar plant level. This may be inevitable as the devices become more sophisticated and need to manage large utility-scale farms.

3.4. Approach/Models to Safe Autonomy

Table 3 presents a comprehensive overview of recent models, approaches, and guidance related to safe autonomy for the use of RAID. By examining the content of this table, it becomes evident that a significant portion of the research and guidance available in this domain either takes a broad approach, encompassing a wide range of applications involving RAID platforms, or focuses on the individual components of RAID systems.

Table 3. Safe autonomy approach for RAID applications.

Reference	Model Name/Approach Type	Methodology Description	Domain/Industry
[64]	Risk level	4 levels of risk in AI in general and regulation to ensure minimal risk	AI platforms
[65]	Risk based regulation and certification	12 years empirical data in Norway for clarification of human and autonomous systems role to propose security and risk-based regulation	All autonomous transport systems
[66]	Self-diagnostics via semantic modelling	Runtime verification and certification of autonomous systems to prevent hardware failure within any operational condition or environment	AI + robotic platforms
[67]	Self-certification	In situ verification, validation, and certification of runtime operations with continuous modelling of environment	AI + robotic platforms
[68]	Subsystem data verification/validation	Provides a model for detecting subsystems fault via quality and delay of exchanged data from the real-time data field	AI (railway system)
[69]	Self-optimization	Providing multi-layered strategy for reorganization and flight plan for swarm of drones through its navigation control centre (NCC)	AI + swarm of drones
[70]	Environmental risk assessment	Simulation validation by integrating a safety unit consisting of a safety unit that incorporates external environment sensory and fallback layer	UAVs
[71]	behavioural assessment/self-verification	Software based analysis of system behaviour using unrestricted extended finite state machines approach	Multipurpose systems verification
[72]	behavioural assessment/self-verification	Use of behavioural tree and differential logic to verify system operation and inform decision process	Multipurpose autonomous agents
[73]	Risk assessment	Hierarchical task analysis for collision avoidance systems. Human Reliability Analysis (HRA) is used to identify and assess human-related errors in autonomous systems oversight, which can lead to developing management strategies	Autonomous vehicles/transport
[74]	ML safety assurance	Provided a six-stage closed-loop safety assurance model for any platform using machine learning. It covers all aspects of ML assurance, verification, and deployment	Any platform using Machine learning
[75]	ML safety assurance	This model provided upgrade to Hawkins, R. et al. (2021) for real-time ML safety verification and deployment	Any platform using Machine learning
[76]	Safety Assurance	Provides a comprehensive model for safety assurance of autonomous systems in complex environments	All autonomous systems
[77]	Safety Assurance	Provides comprehensive guideline for autonomous systems integration from algorithm level to system-of-systems integration. Also provides broad guidelines on where responsibility lies in cases of faults or anomaly behaviour (either the human supervisor or actual autonomous system)	All autonomous systems
[78]	Reliability and risk-based assessment	Detailed information about autonomous systems, and various aspects to be considered for safety and system assurance	All autonomous systems

While these existing models and approaches provide valuable insights and guidance, it is important to note that they may not directly address the specific considerations and requirements of the integration of RAID technologies in Solar PV applications. The unique characteristics and challenges associated with the Solar PV industry necessitate a tailored approach to ensure the safe and effective utilization of autonomous systems. Therefore, it becomes apparent that further research and development are required to bridge the existing gaps and provide more specialized guidance for the integration of RAID technologies in the context of Solar PVs. This new application-based guidance should consider the specific requirements and challenges posed by Solar PV systems, including aspects such as monitoring, maintenance, safety protocols, and environmental considerations.

By developing application-specific guidance, we can ensure that the unique needs of the Solar PV industry are adequately addressed. This approach will enable the establishment of comprehensive safety frameworks and protocols that account for the particular nuances of Solar PV installations and their interaction with RAID technologies. The uniqueness of the Solar PV application is inherent in the operational architecture. For example, if we consider different stages in the life cycle of a utility-scale solar plant, the preconstruction, construction, and life-time system operation, some applicable RAID applications found are highlighted in Figure 1.

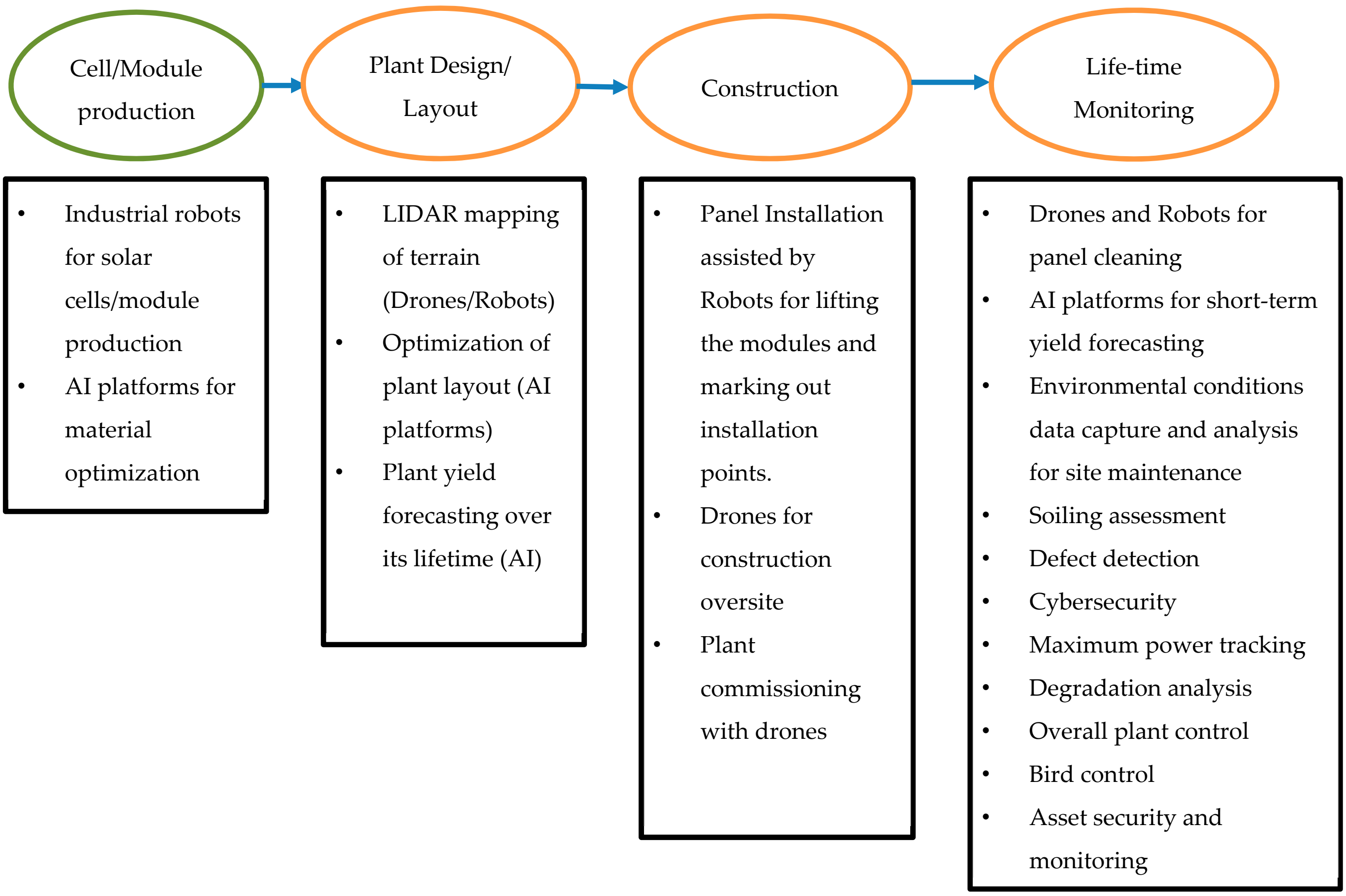

Figure 1. Autonomous tasks within Solar PV life cycle.

While several of the applications highlighted in Figure 1 [4,12,15,29] may have been treated individually for safety considerations, most of the procedures during the life-time monitoring were essentially built as autonomous systems performing tasks based on information provided by other autonomous systems. An instance of this occurrence is when the soiling sensor platform or autonomous drone inspection indicates that the solar panels require cleaning and provides the information to the robots responsible for the cleaning. The robots will require other autonomous decision-making processes from weather analytics platforms and path-planning guidance on when to perform the task of panel cleaning. This process indicates an interdependence of the autonomous systems, which must be accurately measured/predicted for safe maintenance. Any deviation or low accuracy/prediction by any of the systems could lead to unpredicted action by the next sub-system.

In terms of risks associated, faulty path planning from a robotic inspection can lead to collision with any part of the module, causing a sudden cable breakage or cable sheathing peel and leading to open wires, which may cause a short circuit with another part of the system. This alone can result in system downtime, high fire risk, loss of plant yield, asset destruction, and financial loss and could impact any human being in close proximity. This is a ripple cause and effect that can be avoided as we approach the era of full autonomy within Solar PV plant maintenance.

3.5. System-Level Consideration

In view of the system-level approach being explored in this work, we consider system-level autonomy levels, as described in Figure 2.

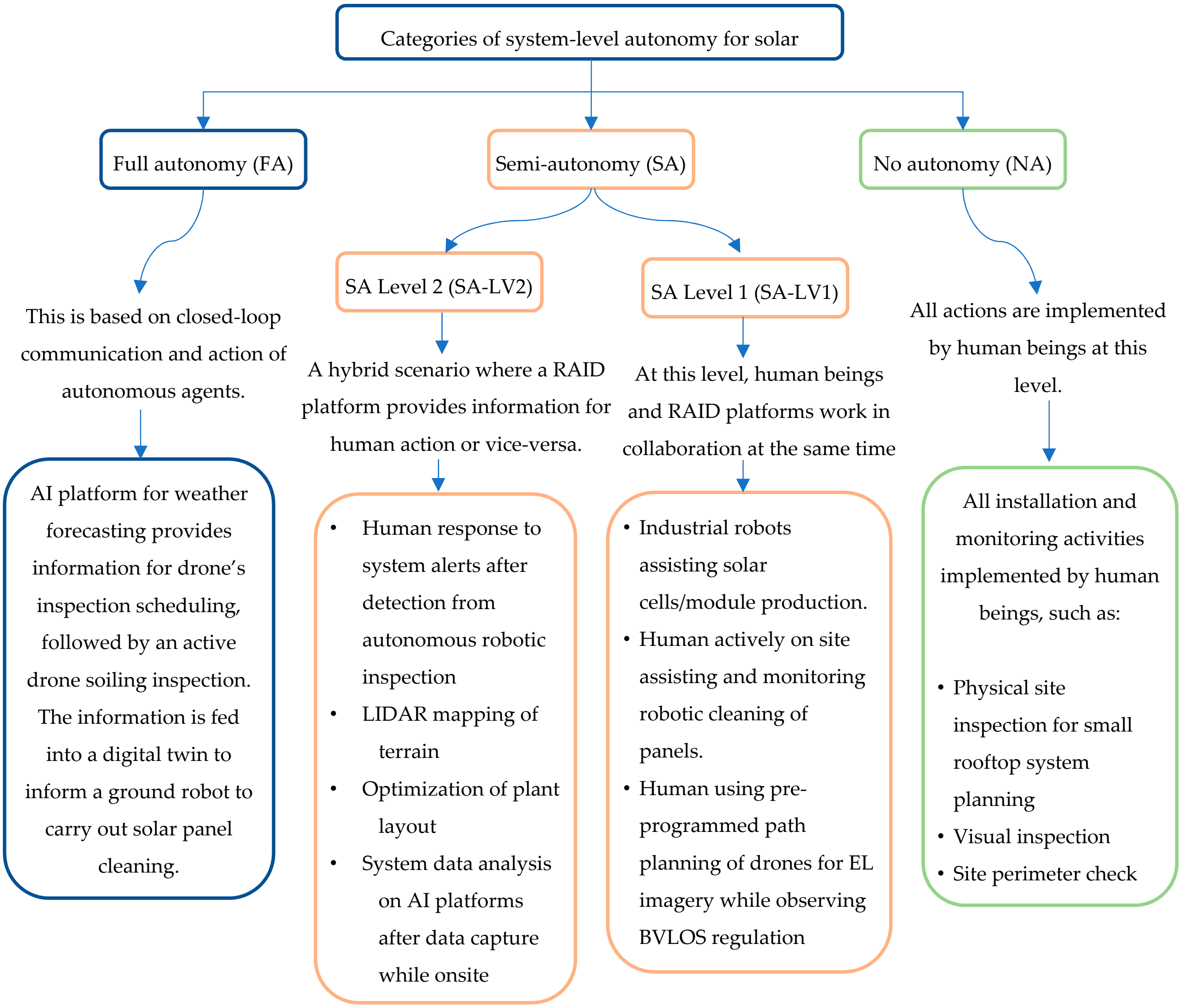

Figure 2. System-level autonomous categories in solar photovoltaics.

It is essential to note that a system-level approach is recommended for the guidance of autonomous RAID implementation for solar photovoltaics for three (3) main reasons.

- **Existing regulations for individual platform use:** There exist various regulations guiding the use of the RAID devices/platforms in different countries. If carefully followed, a huge proportion of device-level risks can be managed. Thus, there is no need for regulation duplication. However, most of the regulations generalize the implementation aspect and lose the resolution of system integration. This creates a loophole in terms of the responsibility of involved parties when a risk occurs. This is an obvious situation with regards to the solar photovoltaic system integration as various forms of implementation are just evolving.
- **Enabling ease of implementation at all levels:** Solar PV energy is a renewable energy source that is highly scalable and, at best, highly socially integrable. This means that a Solar PV system of any size can be installed based on the energy demand required. Also, since various means have been achieved to enhance its social appeal and minimize its intrusiveness, it is being installed in various locations, such as residential rooftops, commercial building rooftops, carparks, commercial ground mounts, building-integrated and building-attached systems, floating systems, farmland-integrated and utility-scale locations. Thus, while there are several existing rules guiding application of the RAID devices individually, it is observed that some of the regulations make it impossible for application in some of the areas where the Solar PVs are installed and where the RAID application will be very useful for system developers and monitors. An example is found in the regulations guiding the autonomous use of drones for Solar PV monitoring in densely populated areas such as commercial buildings (malls). While the regulations are generally not in favour of such application, being able to implement autonomous monitoring is also highly beneficial, as it averts the risk of workers always having to climb rooftops (in fact, they may damage the roof sheeting and cause roof sheeting warranty issues) and is cost saving.
- **Ensure system of system level assurance**: In addition to the device-level regulations that exist, system-level guidance will ascertain a higher level of asset and life protection, thereby boosting investor confidence. This is because, at this level, the impact on the environment and uninvolved persons within the scope of operations will have been adequately considered. This reduces the legal issues and risks associated with the rights of uninvolved persons.

4. Safety in Autonomous RAID Applications

4.1. Research in Solar PV RAID Safety

To emphasize the increasing significance of safety guidance in the integration of RAID applications in Solar PVs, we conducted an analysis of the research trend in this field. This analysis, depicted in Figure 3, aimed to examine increasing interest and the need for safety guidance on the integration of autonomous systems in solar photovoltaics. The data for this analysis was sourced from the Web of Science database, and the search was conducted on 10 April 2023.

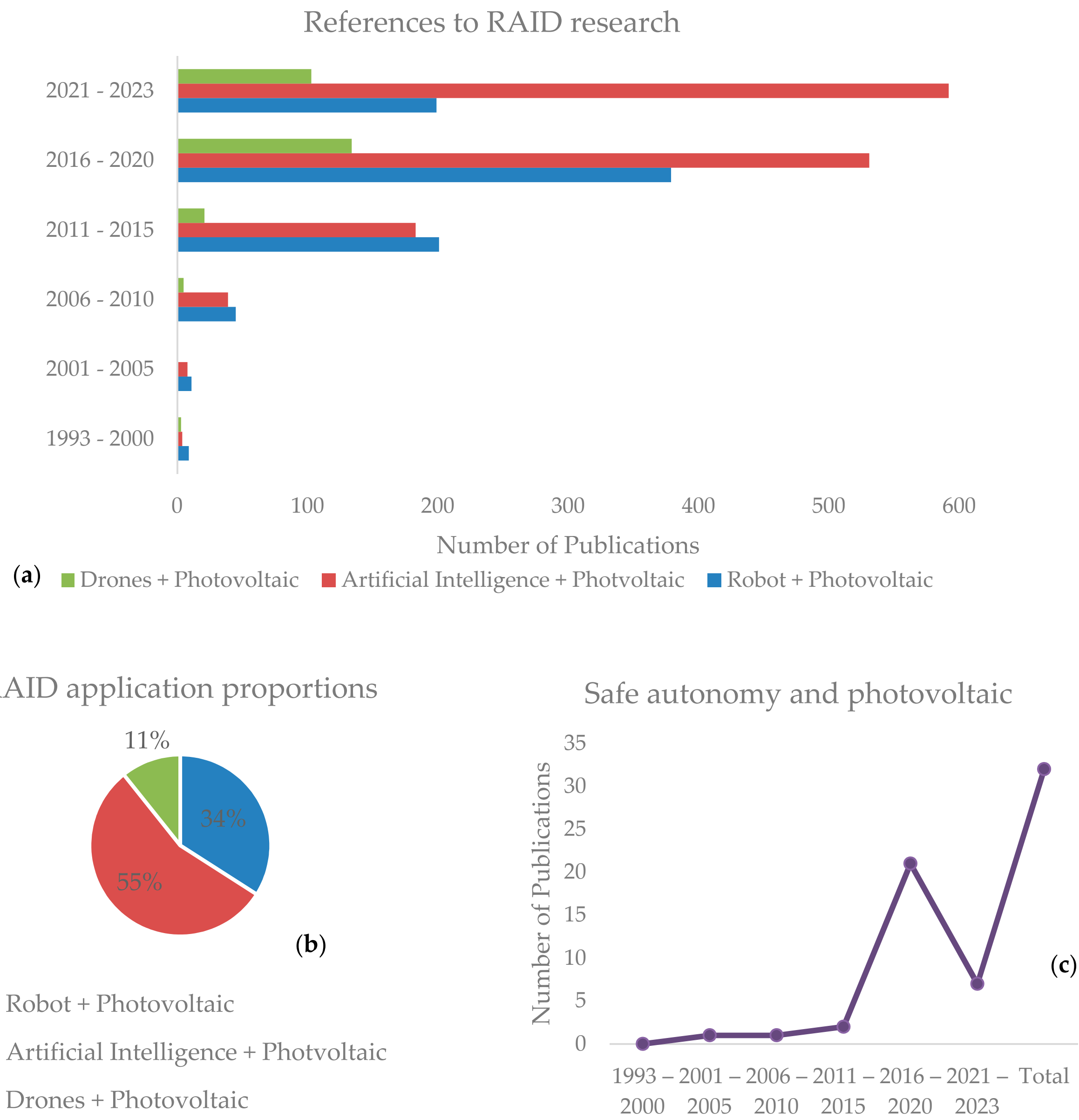

Figure 3. From Web of Science [79]: (**a**) References to RAID and photovoltaics research; (**b**) Spread of RAID application; and (**c**) Reference to safe autonomy.

The search strategy involved using specific keywords to retrieve relevant publications. As shown in Figure 3, the primary search words included "robotics", "artificial intelligence", and "drones." However, for the term "drones", we expanded the search to include synonymous terms such as "unmanned aerial vehicles" and "unmanned aerial systems", along with their respective abbreviations. This expansion was necessary as these terms are frequently used interchangeably in the literature.

By examining the research trend, we aimed to gain insights into the level of attention and focus given to RAID applications in the context of solar photovoltaics. The analysis provides a quantitative measure of the scholarly output and interest in this field over time, allowing us to identify potential gaps or areas that require further exploration.

Our analysis revealed a remarkable trend in academic research publications related to RAID applications in the Solar PV domain over the past five years. In fact, the volume of research conducted in this field during this relatively short period has more than doubled compared to the cumulative research output since the establishment of publication records in 1993. This significant increase highlights the growing interest and recognition of the potential of RAID technologies in Solar PV applications. However, despite the substantial growth in the research output, our examination of the literature, as depicted in Figure 3c, indicates that there has been limited attention given to the risks associated with autonomous systems in this area. While the advancements in robotics, artificial intelligence, and drones offer exciting opportunities for the Solar PV industry, it is crucial to recognize and address the potential risks and challenges that come with their integration.

4.2. Associated Hazards and Risks, with Examples

To conceptualize the associated risks with Solar PV system integration and autonomous RAID platforms, we present the analysis using a trigger, hazard, consequence approach, termed "bowtie" diagrams/graphs [80]. Furthermore, we use the same model to present the current state of affairs and the proposition of this work. Note that the analysis in this section is focused on autonomous RAID applications for the monitoring and maintenance of Solar PV systems of various scales. As we integrate RAID in rooftop, commercial, agri-voltaics, floating PV, and other utility-scale Solar PV systems, we need to be aware of the hazards. This will guide policymakers and stakeholders on safety principles to employ to avoid or significantly minimize incurring losses of any form.

In Table 4, we present an initial list of potential triggers, hazards, and consequences. We define the hazard as a source of harm and the trigger as the cause of a potential hazard, while the consequences are adverse effects that could easily occur as a result of the hazard being triggered. Note that as systems size and degree of autonomy increases, the probability of a hazard occurring may increase. This is because, with larger systems, information for an autonomous device may be obtained from another autonomous platform for decision making, leading to a ripple effect scenario.

Also, the relationship defined in Table 4 should not be considered as a one-to-one causative or consequential scenario. Rather, it should be noted that there could be multiple causes for a single hazard, while a single hazard could also have multiple consequences and vice-versa. Let us consider a few of the relationships in the description below:

- Proximity (hazard) when a computer vision-guided robot has its vision compromised by light reflection/glare (cause/trigger) from solar panels during daytime operation. The glare would alter the perceived imagery of the robot, and it could collide (consequence) with any object or human within a short time span if it is unable to instantaneously halt its actions during an operation.
- Terrain separation decreasing (hazard) could exist for faulty path planning or path scheduling (cause) of robots and drones. This leads to collision (consequence 1) of the devices concerned and will in turn cause damage to the asset (consequence 2). In addition, any human on site may be involved in the collision, and injuries may occur (consequence 3).
- Fire hazard (hazard) is imminent for a drone/robot during operation with a damaged battery from over-charging or heating from erratic weather conditions (cause). This can lead to the crash of the drone/robot (consequence 1) and fire on the farm at the crash area, which could in turn affect the whole site (consequence 2).
- Cybersecurity hazards (hazard) also exist where the RAID equipment like a drone can be hacked (cause) by external parties or repurposed by a human controller (cause) to performed illegal operations such as hacking data centres (consequence).

Table 4. Real-time hazards, triggers, and consequence for autonomous RAID integration.

Causes/Triggers	Hazard	Consequences
Electromagnetic interference affecting RAID operations.	Close proximity to human, solar module, or other equipment, such as weather monitoring stations and IoT devices	Destruction of solar module
Loss of GPS signal	Terrain separation decreasing	Destruction of equipment and IoT devices
Accuracy of prediction	Potential battery fires from robots, drones, and other monitoring devices	Loss of data/data collection gaps
Periodicity of data and prediction update	Fire	Injuries (mild or severe)
Faulty planning	Incursion into forbidden zone	Potential negative impact on wildlife and biodiversity in the region
System training procedure and unexpected interactions during real-time operation (especially for machine vision applications)	Ground damage	Asset loss from fire
Unauthorized hacking and control of drones or robots	Crash/breakdown during operation for robots and drones	Crashes and asset destruction
Unexpected human interference or other emergency situations	Electromagnetic interference	Malfunctioning of IoT and other electronics in the vicinity
Human error	Environmental hazards such as adverse weather conditions	Disruption of automated analytics
Control error Reflection of light off solar panels and other equipment on site	Water ingress/high humidity during operations/storage	Insufficient data for continuous and valid decision making (either autonomous/manual)
Mechanical failure	Falling	Illegal use of device/platform
Time pressure	Noise	Major disruption of airplane navigation
Environmental sources	Unauthorized usage/access	Disruption of drones' or robots' navigation
Power system failures or malfunctions	Cybersecurity	Dropping payloads on people
Improper assembly or installation		

4.2.1. Risk Probability and Severity

As with any potential hazard, it is important to consider the severity of the consequences to determine suitable guidelines or professional requirements for implementing the procedures in a way that reduces the likelihood of the cause of the hazard or reduces the severity of the consequences [19,81]. Table 4 highlights a list of consequences ranging from skin cuts to equipment fires to fire outbreaks on the whole farm, which could be worse if a human is on site at the solar installation/farm or nearby. A fundamental approach to preventing hazards that could lead to severe consequences may be to ensure that platforms are only equipped with a certain functionality or that professionals trained for such specific purpose oversee the operations.

4.2.2. Trade-Offs

While there is a need to regulate the use of artificial intelligence (AI) and AI-enabled platforms (robots and drones), there is also a need to ensure that the regulations preferably act more as guidelines to enable the desired advances in systems operations, rather than hamper beneficial applications [82]. This is observed in the scenario highlighted under Section 2 on the use of drones on building-attached PV (BAPV) installation monitoring. Aside from such scenarios, with the exponential advancements in AI, subtle instances may occur, which would require a trade-off in terms of the benefits and associated risks.

General guidelines with provisions for risk/disaster management, including the possible responsibilities of involved parties, may be required. This will provide some guidance during instances of fallout or hazard that may be inevitable.

4.3. Proposed Perspective on System Integration

In this section, we discuss the current industrial practice and proposed safety practice/model. As shown in Figure 4a, the current industry practice is based solely on individual device regulation adapted into company operational practice. This implies that the safety protocols or guidelines applied by companies is based on risk assessments adapted from standard UAV or robotics policies interpreted in a manner suitable to the application. This assists various companies to reduce risk as much as possible in the absence of industry-wide guidance for Solar PV integration. As previously mentioned, this situation is inevitable because of the recent adoption of autonomous systems in Solar PV integration due to the recent capabilities and assurance cases around the systems. As such, there is a gradual improvement in the trustworthiness associated with the application from both installers and clients.

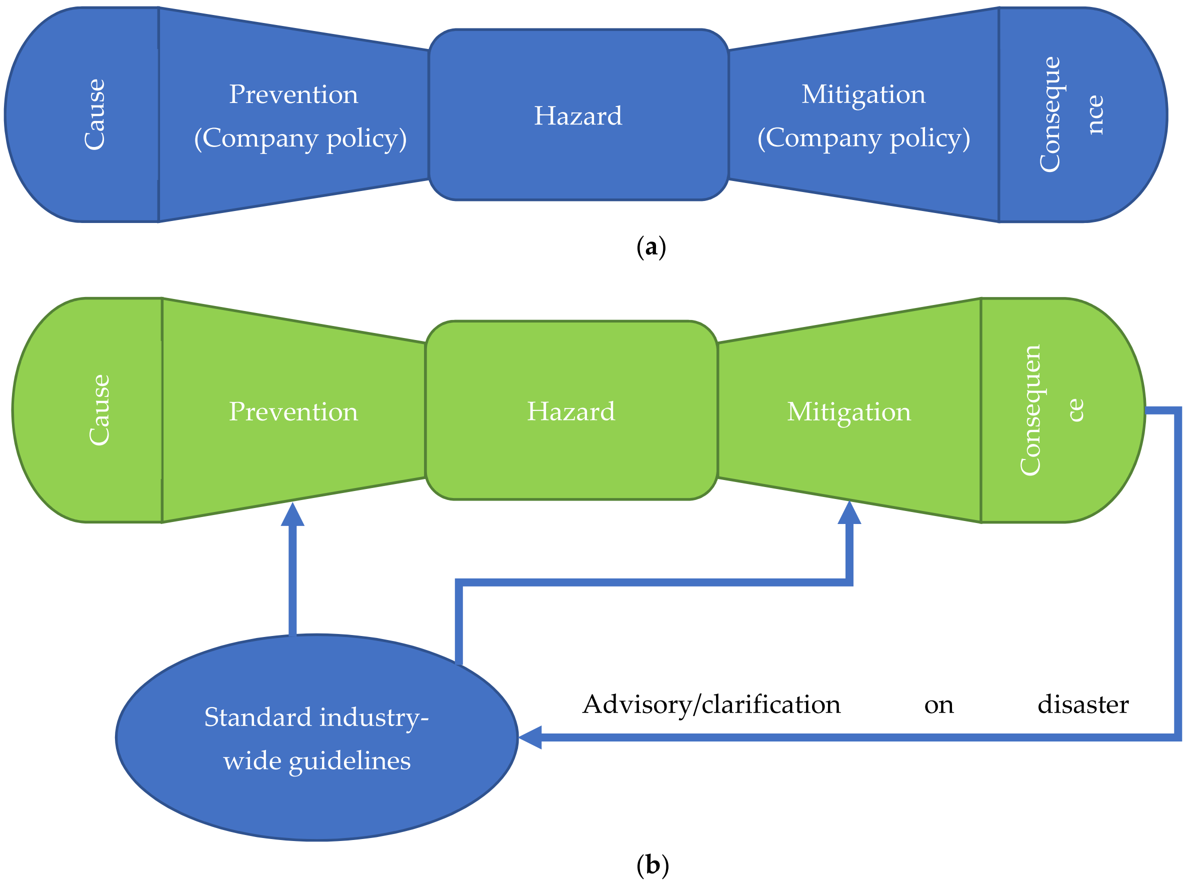

Figure 4. Safety model basis: (**a**) Current dynamics; (**b**) Proposed model.

To further accelerate the adoption and trustworthiness, we recommend the development of standard industry-wide guidelines/policies to outline safety use cases for autonomous system integration with Solar PV installation.

Figure 4b illustrates the potential impact of the proposed guideline in three major areas: hazard prevention, hazard mitigation, and disaster management of hazardous consequences. These areas encompass various aspects of ensuring safety and addressing risks associated with autonomous systems in Solar PV applications.

Hazard prevention is a crucial aspect of the proposed guideline. By identifying and addressing potential hazards early on, the guideline aims to prevent accidents, incidents, or hazardous situations from occurring in the first place. This proactive approach can significantly enhance the overall safety of autonomous systems in Solar PV applications, reducing the likelihood of adverse events.

Hazard mitigation is another essential focus of the proposed guideline. Despite preventive measures, certain hazards may still arise. In such cases, the guideline aims to provide strategies and protocols for effectively mitigating the impact of these hazards. By outlining appropriate response actions, the guideline assists in minimizing potential harm to humans, the environment, and the system itself. Prompt and effective hazard mitigation can limit the severity of consequences and aid in restoring normal operations swiftly.

Disaster management of hazardous consequences is a critical component covered by the proposed guideline. In the event of a major incident or disaster, the guideline offers guidance on managing the aftermath and any hazardous consequences. This includes strategies for containment, evacuation procedures, emergency response plans, and coordination with relevant authorities. By providing a structured framework for disaster management, the guideline aims to minimize the impact of such incidents and facilitate a more efficient and effective response.

Implementing the proposed guideline would not only enhance safety but also have broader implications. Clarity provided by the guideline can facilitate the allocation of liabilities in the event of unwarranted occurrences. This means that responsibilities and accountabilities can be clearly defined, making it easier to determine who is liable for specific incidents or damages. This clarity enables more predictable financial management of the system, allowing stakeholders to better assess and manage risks and allocate resources accordingly.

By promoting safety, clarifying responsibilities, and facilitating financial management, the proposed guideline makes the operation and management of autonomous systems in Solar PV applications more viable and sustainable. It provides stakeholders with a comprehensive framework to address risks, prevent hazards, mitigate consequences, and effectively manage disasters. Ultimately, the implementation of the guideline can contribute to a safer and more reliable integration of autonomous systems in the Solar PV industry.

4.4. Potential Challenges and Mitigation

Implementing an industry-wide safety regulation is a non-trivial procedure and therefore must include various stakeholders. In this case, potential challenges envisaged include social acceptability issues, geopolitical issues, country-specific approvals on Solar PV system installation, technical capabilities of RAID platforms [83–85] applied for Solar PV inspection, and security concerns on the types of RAID applications allowed within each country. Thus, aside from standard global regulations such as the ISO/IEC TS 22440 standard currently under development for safety of AI enabled systems, there may be need for country-wide amendments.

In addition to the above, social acceptability issues arising from privacy concerns, safety risks, and job displacement [81,86] could impact the implementation of these regulations. While potential strategies for mitigating job displacement and safety risk issues are curbed through upskilling workers and the enforcement of technical capability and regulation of RAID platforms, data privacy appears to be a priority particularly for urban RAID applications. For applications related to Solar PVs in urban areas, a potential mitigation for privacy concerns could be the enforcement of human detection and blurring algorithms. This implies that even when operating in real-time, once the RAID platform identifies human features, the image/video frames (or portion thereof) will be blurred or deleted and not be stored. This can be achieved via optimization of advanced computer vision algorithms such as YOLO (You-Only-Look-Once) that can easily detect human features in real time.

To mitigate deviation from standard regulations, conventional approaches, such as the use of risk registers and safety officers, can be applied [85]. This can later be transformed using safety technology capabilities based on observed risk occurrences.

4.5. Safe Autonomy Pillars

In the context of the highlighted hazards for autonomous systems integration in Solar PV applications, we consider the following core principles (pillars) as minimal requirement for safe autonomy. These pillars identify the various aspects that must be verified in such system.

- **Hazard identification and risk assessment:** This forms an essential aspect of ensuring the safe operation of autonomous systems in Solar PV applications. It is crucial to design these systems to identify potential hazards, such as obstacles or adverse environmental conditions, that could potentially impact their operation. Furthermore, a comprehensive risk assessment should be conducted to evaluate the likelihood and consequences of these hazards causing harm to humans or the environment. This enables the development of effective risk mitigation strategies and the incorporation of appropriate safety measures into the system design.
- **Safe operation design of autonomous systems:** These systems should be designed to operate safely under normal conditions, as well as in abnormal situations. Safety features, such as advanced sensors, robust safety protocols, and fail-safe mechanisms, should be integrated to ensure the system can detect and respond to potential hazards or malfunctions, thereby minimizing risks to humans and the environment.
- **Cybersecurity**: This is a critical consideration in the design of autonomous systems for Solar PV applications. To maintain the safety and reliability of the system, measures should be implemented to prevent unauthorized access or control. Cyberattacks targeting these systems can compromise their functionality and potentially lead to harmful consequences. Robust cybersecurity measures, including encryption, authentication mechanisms, and intrusion detection systems, should be integrated to protect against such threats.
- **Interaction between autonomous systems and human operators/workers:** When humans are required to work alongside autonomous systems in Solar PV applications, it is vital to design the system with human–machine interaction in mind. Safety protocols and interfaces should be established to facilitate safe collaboration and communication between humans and autonomous systems, minimizing the risk of accidents or incidents.
- **Maintenance and repair procedures:** These should also be considered in the design of autonomous systems for Solar PV applications. The systems should be designed for ease of maintenance and repair, with clear guidelines and safety protocols in place. These measures ensure that maintenance or repair activities can be conducted safely, minimizing risks to human workers and preventing potential harm to the environment.
- **Environmental impact (EI)**: EI mitigation is another critical consideration when designing autonomous systems for Solar PV applications. Efforts should be made to minimize the system's environmental footprint. This can include reducing the use of hazardous materials during production, operation, or disposal phases, as well as implementing measures to minimize waste generation. By prioritizing sustainability and environmental stewardship, autonomous systems can contribute to a cleaner and greener energy ecosystem.

In summary, ensuring the safe and reliable operation of autonomous systems in Solar PV applications involves several key considerations. These include comprehensive hazard identification and risk assessment, safe operation design, cybersecurity measures, human–machine interaction protocols, maintenance and repair procedures, and environmental impact mitigation strategies. By addressing these aspects, stakeholders can promote the safe integration and use of autonomous systems in the Solar PV industry.

5. Conclusions

In the realm of Solar PV applications, existing regulations govern the usage of individual devices or platforms. However, it has been observed that numerous implementations combine multiple procedures, techniques, or platforms. This convergence of different elements results in combined implementation, which subsequently leads to the integration of these components into the Solar PV system. Unfortunately, this integration introduces additional layers of complexity and potential points of failure that demand careful attention.

To address these challenges, we propose the establishment of a risk register—a systematic tool that identifies, assesses, and manages risks associated with the integration of autonomous systems in Solar PV applications. This risk register would be accompanied by an assurance case, comprehensive documentation that provides regulators with the necessary information to prioritize interventions in critical areas. By setting up such a structured approach, we can proactively identify and address potential risks, thereby enhancing the overall safety of autonomous system implementation.

Furthermore, in order to safeguard valuable assets, preserve human life, and protect investments, it is crucial to give due consideration to the safety practices surrounding the integration and utilization of autonomous systems in solar photovoltaic systems. This entails implementing stringent safety protocols, adhering to industry standards, and continually evaluating and updating safety measures in response to technological advancements and emerging applications.

In summary, it is imperative to acknowledge the propensity for combined implementation and integration of various procedures, techniques, and platforms in the Solar PV industry. To navigate this complex landscape, the utilization of a risk register, accompanied by an assurance case, can provide regulators with the necessary information to prioritize interventions effectively. Furthermore, to ensure adequate protection of assets, life, and investments, a meticulous focus on safety practices surrounding the integration and use of autonomous systems is of paramount importance. By embracing these measures, we can foster a safer and more resilient environment for the integration of autonomous systems in solar photovoltaic applications.

Author Contributions: Conceptualization, O.O. and M.E.; methodology, O.O. and M.E.; writing—original draft preparation, O.O.; writing—review and editing, O.O., M.E. and M.D.; funding acquisition, M.E. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for this work was provided by Research England under the UKRPIF: Net Zero funding scheme.

Informed Consent Statement: Not Applicable.

Data Availability Statement: The data analyzed in Section 4.1 is the number of articles available at Web of Science [http://webofscience.com], reference number [79].

Acknowledgments: The authors hereby acknowledge the contributions and support of various colleagues at the Institute for Safe Autonomy and the Department of Computer Science at the University of York, especially Ibrahim Habli and Phillipa Ryan of the Assuring Autonomy International Program (AAIP) for their valuable insight to the questions raised by the authors.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Morgan, A.A.; Abdi, J.; Syed, M.A.Q.; El Kohen, G.; Barlow, P.; Vizcaychipi, M.P. Robots in Healthcare: A Scoping Review. *Curr. Robot. Rep.* **2022**, *3*, 271–280. [CrossRef] [PubMed]
2. Niestadt, M.; Debyser, A.; Scordamaglia, D.; Pape, M. *BRIEFING EPRS | European Parliamentary Research Service*; European Parliamentary Research Service: Brussels, Belgium, 2019.
3. Parmaksiz, O.; Cinar, G. Technology Acceptance among Farmers: Examples of Agricultural Unmanned Aerial Vehicles. *Agronomy* **2023**, *13*, 2077. [CrossRef]
4. Liang, H.; Lee, S.-C.; Bae, W.; Kim, J.; Seo, S. Towards UAVs in Construction: Advancements, Challenges, and Future Directions for Monitoring and Inspection. *Drones* **2023**, *7*, 202. [CrossRef]
5. Wang, G.; Xie, J.; Wang, S. Application of Artificial Intelligence in Power System Monitoring and Fault Diagnosis. *Energies* **2023**, *16*, 5477. [CrossRef]

6. Arents, J.; Greitans, M. Smart Industrial Robot Control Trends, Challenges and Opportunities within Manufacturing. *Appl. Sci.* **2022**, *12*, 937. [CrossRef]
7. Badue, C.; Guidolini, R.; Carneiro, R.V.; Azevedo, P.; Cardoso, V.B.; Forechi, A.; Jesus, L.; Berriel, R.; Paixão, T.M.; Mutz, F.; et al. Self-driving cars: A survey. *Expert Syst. Appl.* **2021**, *165*, 113816. [CrossRef]
8. Attanasio, A.; Scaglioni, B.; De Momi, E.; Fiorini, P.; Valdastri, P. Annual Review of Control, Robotics, and Autonomous Systems Autonomy in Surgical Robotics. *Annu. Rev. Control Robot. Auton. Syst.* **2021**, *4*, 651–679. [CrossRef]
9. Gokool, S.; Mahomed, M.; Kunz, R.; Clulow, A.; Sibanda, M.; Naiken, V.; Chetty, K.; Mabhaudhi, T. Crop Monitoring in Smallholder Farms Using Unmanned Aerial Vehicles to Facilitate Precision Agriculture Practices: A Scoping Review and Bibliometric Analysis. *Sustainability* **2023**, *15*, 3557. [CrossRef]
10. Müller, M.; Müller, T.; Talkhestani, B.A.; Marks, P.; Jazdi, N.; Weyrich, M. Industrial autonomous systems: A survey on definitions, characteristics and abilities. *Automatisierungstechnik* **2021**, *69*, 3–13. [CrossRef]
11. Emergen Research. *Artificial Intelligence in Energy Market by Application and By Region, Forecast to 2028*; Emergen Research: Surrey, BC, Canada, 2021.
12. Ramírez, I.S.; Chaparro, J.R.P.; Márquez, F.P.G. Unmanned aerial vehicle integrated real time kinematic in infrared inspection of photovoltaic panels. *Measurement* **2022**, *188*, 110536. [CrossRef]
13. Morando, L.; Recchiuto, C.T.; Calla, J.; Scuteri, P.; Sgorbissa, A. Thermal and Visual Tracking of Photovoltaic Plants for Autonomous UAV Inspection. *Drones* **2022**, *6*, 347. [CrossRef]
14. Yang, J.; Zhao, X.; Gao, Y.; Guo, R.; Zhao, J. Research on Mechanism Design and Kinematic Characteristics of Self-Propelled Photovoltaic Cleaning Robot. *Appl. Sci.* **2023**, *13*, 6967. [CrossRef]
15. Romero, H.F.M.; Rebollo, M.G.; Cardeñoso-Payo, V.; Gómez, V.A.; Plaza, A.R.; Moyo, R.T.; Hernández-Callejo, L. Applications of Artificial Intelligence to Photovoltaic Systems: A Review. *Appl. Sci.* **2022**, *12*, 10056. [CrossRef]
16. Kurukuru, V.S.B.; Haque, A.; Khan, M.A.; Sahoo, S.; Malik, A.; Blaabjerg, F. A Review on Artificial Intelligence Applications for Grid-Connected Solar Photovoltaic Systems. *Energies* **2021**, *14*, 4690. [CrossRef]
17. Kim, E.; Akhtar, M.S.; Yang, O.-B. Designing solar power generation output forecasting methods using time series algorithms. *Electr. Power Syst. Res.* **2023**, *216*, 109073. [CrossRef]
18. Burton, S.; Habli, I.; Lawton, T.; McDermid, J.; Morgan, P.; Porter, Z. Mind the gaps: Assuring the safety of autonomous systems from an engineering, ethical, and legal perspective. *Artif. Intell.* **2019**, *279*, 103201. [CrossRef]
19. Hindriks, F.; Veluwenkamp, H. The risks of autonomous machines: From responsibility gaps to control gaps. *Synthese* **2023**, *201*, 21. [CrossRef]
20. Solar Power Europe. *Best Practice Guidelines Maintenance Operation &Maintenance*, Version 5.0; Solar Power Europe: Brussels, Belgium, 2021.
21. *IEC TS 62446-3:2017*; Photovoltaic (PV) Systems—Requirements for Testing, Documentation, and Maintenance—Part 3: Photovoltaic Modules and Plants—Outdoor Infrared Thermography. International Electrotechnical Commission (IEC): Geneva, Switzerland, 2017; pp. 1–37.
22. NERSA. *NERSA Generation-Licensing-and-Registration-Frequently-Asked-Questions*; NERSA: Pretoria, South Africa, 2019.
23. Ofgem. *Guidance for Renewable Installations Overview*; Ofgem: London, UK, 2021.
24. Royal Academy of Engineering. *Innovation in Autonomous Systems*; Royal Academy of Engineering: London, UK, 2015.
25. Cardoso, R.C.; Kourtis, G.; Dennis, L.A.; Dixon, C.; Farrell, M.; Fisher, M.; Webster, M. A Review of Verification and Validation for Space Autonomous Systems. *Curr. Robot. Rep.* **2021**, *2*, 273–283. [CrossRef]
26. Parekh, D.; Poddar, N.; Rajpurkar, A.; Chahal, M.; Kumar, N.; Joshi, G.P.; Cho, W. A Review on Autonomous Vehicles: Progress, Methods and Challenges. *Electronics* **2022**, *11*, 2162. [CrossRef]
27. Khalid, O.; Hao, G.; Desmond, C.; Macdonald, H.; McAuliffe, F.D.; Dooly, G.; Hu, W. Applications of robotics in floating offshore wind farm operations and maintenance: Literature review and trends. *Wind. Energy* **2022**, *25*, 1880–1899. [CrossRef]
28. Roggi, G.; Niccolai, A.; Grimaccia, F.; Lovera, M. A Computer Vision Line-Tracking Algorithm for Automatic UAV Photovoltaic Plants Monitoring Applications. *Energies* **2020**, *13*, 838. [CrossRef]
29. Niccolai, A.; Grimaccia, F.; Leva, S. Advanced Asset Management Tools in Photovoltaic Plant Monitoring: UAV-Based Digital Mapping. *Energies* **2019**, *12*, 4736. [CrossRef]
30. Kas, K.A.; Johnson, G.K. Using unmanned aerial vehicles and robotics in hazardous locations safely. *Process. Saf. Prog.* **2020**, *39*, e12066. [CrossRef]
31. Iqbal, J.; Al-Zahrani, A.; Alharbi, S.A.; Hashmi, A. Robotics Inspired Renewable Energy Developments: Prospective Opportunities and Challenges. *IEEE Access* **2019**, *7*, 174898–174923. [CrossRef]
32. Martinetti, A.; Chemweno, P.K.; Nizamis, K.; Fosch-Villaronga, E. Redefining Safety in Light of Human-Robot Interaction: A Critical Review of Current Standards and Regulations. *Front. Chem. Eng.* **2021**, *3*, 666237. [CrossRef]
33. Drone Deploy. Phantom 4 Pro V2 Crash with Drone Deploy-No Logs. 2023. Available online: https://forum.dronedeploy.com/t/phantom-4-pro-v2-crash-with-drone-deploy-no-logs/20724 (accessed on 28 February 2024).
34. Cognex Corp. *Cognex In-Sight®2D Robot Guidance Plug-in User Guide*; Cognex Corp.: Natick, MA, USA, 2018.
35. Safa, A.; Verbelen, T.; Ocket, I.; Bourdoux, A.; Catthoor, F.; Gielen, G.G.E. Fail-Safe Human Detection for Drones Using a Multi-Modal Curriculum Learning Approach. *IEEE Robot. Autom. Lett.* **2021**, *7*, 303–310. [CrossRef]

36. Naija, M.; Khemiri, R.; Exposito, E. Failsafe Mechanism to Hazard Analysis and Risk Mitigation in Unmanned Aerial Vehicle based on NCES. In Proceedings of the 15th International Conference on Software Technologies, Online, 7–9 July 2020; pp. 220–227.
37. Cho, D. A Study on a Flight Safe System in Unmanned Aerial Vehicles. *Int. J. Appl. Eng. Res.* **2018**, *13*, 7128–7130.
38. Otani, T.; Itoh, A.; Mizukami, H.; Murakami, M.; Yoshida, S.; Terae, K.; Tanaka, T.; Masaya, K.; Aotake, S.; Funabashi, M.; et al. Agricultural Robot under Solar Panels for Sowing, Pruning, and Harvesting in a Synecoculture Environment. *Agriculture* **2023**, *13*, 18. [CrossRef]
39. Staubli Int. *AG. Robotics | Experts in Man and Machine*; Staubli Int.: Thessaloniki, Greece, 2022.
40. ABB Ltd. *Efficient Robot-Based Automation for Solar Cell and Module Production Robotics*; ABB Ltd.: Zurich, Switzerland, 2009.
41. Clemenzi, R.A.; Siglin, J.A. Robotic Assembly of Photovoltaic Arrays. U.S. Patent US20190134822, 8 February 2022.
42. *SAE-J3016_201806*; Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE International: Warrendale, PA, USA, 2018.
43. SAE International. Levels of Driving Automation. 2021. Available online: https://www.sae.org/blog/sae-j3016-update#:~:text=With%20a%20taxonomy%20for%20SAE's,and%20their%20operation%20on%20roadways (accessed on 24 March 2023).
44. Litman, T.A. *Autonomous Vehicle Implementation Predictions*; Victoria Transport Policy Institute: Victoria, BC, Canada, 2023.
45. Synopsys. Available online: https://www.synopsys.com/automotive/autonomous-driving-levels.html (accessed on 22 March 2023).
46. Institution of Engineering and Technology. *IET Standards Michael Faraday House Six Hills Way Stevenage Hertfordshire SG1 2AY Guide to Implementing Industrial Robots Guide to Implementing Industrial Robots*; IET: Hertfordshire, UK, 2018.
47. Ben-Ari, M.; Mondada, F. Robots and Their Applications. In *Elements of Robotics*; Springer International Publishing: Berlin/Heidelberg, Germany, 2018; pp. 1–20. [CrossRef]
48. World Robotics. *Industrial Robots*; The International Federation of Robotics: Frankfurt am main, Germany, 2016.
49. Intel Corp. *Types of Robots: How Robotics Technologies Are Shaping Today's World*; Intel Corp.: Santa Clara, CA, USA, 2023.
50. International Federation of Robotic. *Industrial Robots*; International Federation of Robotic: Frankfurt am Main, Germany, 2022.
51. Staretu, I. Classification of industrial robots according to the number of degrees of mobility-structural synthesis and useful configurations. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *514*, 012023. [CrossRef]
52. Briot, S.; Khalil, W. *Dynamics of Parallel Robots*; Springer Science and Business Media LLC: Cham, Switzerland, 2015; ISBN 9781447146636.
53. Samoili, S.; López Cobo, M.; Gómez, E.; De Prato, G.; Martínez-Plumed, F.; Delipetrev, B.; European Commission; Joint Research Centre. *AI Watch: Defining Artificial Intelligence: Towards an Operational Definition and Taxonomy of Artificial Intelligence*; EUR 30117 EN; Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-17045-7. [CrossRef]
54. van Duin, S.; Bakhshi, N. *Artificial Intelligence*; Deloitte: Amsterdam, Netherlands, 2018.
55. Hewlett Packard Ent. *What Is Artificial Intelligence (AI)?* Available online: https://www.hpe.com/uk/en/what-is/artificial-intelligence.html (accessed on 29 March 2023).
56. Khan, H. *Types of AI | Different Types of Artificial Intelligence Systems*. Available online: https://www.fossguru.com/types-of-ai-different-types-of-artificial-intelligence-systems (accessed on 29 March 2023).
57. Ofcom UK. *Spectrum for Unmanned Aircraft Systems (UAS)*; Ofcom UK: London, UK, 2022.
58. Uddin, M. *Drone 101: A Must-Have Guide for Any Drone Enthusiast*; Amazon Kindle: Washington, DC, USA, 2020.
59. Kakaes, K.; Greenwood, F. *Chp1-Drones and Aerial Observation: New Technologies for Property Rights, Human Rights, and Global Development: A Primer Observation*; New America: Washington, DC, USA, 2015.
60. Stewart, M.P.; Martin, S.T. *Unmanned Aerial Vehicles*; Barrera, N., Ed.; Nova Science: Hauppauge, NY, USA, 2021.
61. Vergouw, B.; Nagel, H.; Bondt, G.; Custers, B. Drone technology: Types, payloads, applications, frequency spectrum issues and future developments. In *The Future of Drone Use*; TMC Asser Press: The Hague, The Netherlands, 2016; pp. 21–45. [CrossRef]
62. Aghaei, M.; Leva, S.; Grimaccia, F. PV Power Plant Inspection by Image Mosaicing Techniques For IR-Time Images. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 5–10 June 2016.
63. Cerra, D.; Ji, C.; Heiden, U. Solar panels area estimation using the spaceborne imaging spectrometer desis: Outperforming multispectral sensors. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *1*, 9–14. [CrossRef]
64. European Commission. *EU AI Proposed Regulation Risk Based*; European Commission: Brussels, Belgium, 2021.
65. Haugen, S.; Barros, A.; van Gulijk, C.; Kongsvik, T.; Vinnem, J.E. Safety and Reliability: Safe Societies in a Changing World. In Proceedings of the 28th International European Safety and Reliability Conference (ESREL 2018), Trondheim, Norway, 11–21 June 2018.
66. Zaki, O.; Dunnigan, M.; Robu, V.; Flynn, D. Reliability and Safety of Autonomous Systems Based on Semantic Modelling for Self-Certification. *Robotics* **2021**, *10*, 10. [CrossRef]
67. Fisher, M.; Collins, E.; Dennis, L.; Luckcuck, M.; Webster, M.; Jump, M.; Page, V.; Patchett, C.; Dinmohammadi, F.; Flynn, D.; et al. Verifiable Self-Certifying Autonomous Systems. In Proceedings of the 2018 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW), Memphis, TN, USA, 15–18 October 2018; pp. 341–348.
68. Kunifuji, T. Safety Technologies in Autonomous Decentralized Railway Control System. In Proceedings of the 2017 IEEE 13th International Symposium on Autonomous Decentralized System (ISADS), Bangkok, Thailand, 22–24 March 2017; pp. 137–142.

69. Vistbakka, I.; Troubitsyna, E.; Majd, A. Multi-Layered Safety Architecture of Autonomous Systems: Formalising Coordination Perspective. In Proceedings of the 2019 IEEE 19th International Symposium on High Assurance Systems Engineering (HASE), Hangzhou, China, 3–5 January 2019; pp. 58–65.
70. Hagele, G.; Soffker, D. Safety unit-based safe behavior assurance for autonomous and semi-autonomous aerial systems: Requirements, concept, and simulation results. In Proceedings of the 2017 IEEE Intelligent Vehicles Symposium (IV), Los Angeles, CA, USA, 11–14 June 2017; pp. 1546–1551.
71. Spislaender, M.; Saglietti, F. Evidence-Based Verification of Safety Properties Concerning the Cooperation of Autonomous Agents. In Proceedings of the 2018 44th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), Prague, Czech Republic, 29–31 August 2018; pp. 81–88.
72. Tadewos, T.G.; Shamgah, L.; Karimoddini, A. Automatic Safe Behaviour Tree Synthesis for Autonomous Agents. In Proceedings of the 2019 IEEE 58th Conference on Decision and Control (CDC), Nice, France, 11–13 December 2019; pp. 2776–2781.
73. Ramos, M.A.; Utne, I.B.; Mosleh, A. Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events. *Saf. Sci.* **2019**, *116*, 33–44. [CrossRef]
74. Hawkins, R.; Paterson, C.; Picardi, C.; Jia, Y.; Calinescu, R.; Habli, I. Guidance on the Assurance of Machine Learning in Autonomous Systems (AMLAS). *arXiv* **2021**, arXiv:2102.01564.
75. Picardi, C.; Hawkins, R.; Paterson, C.; Habli, I. Transfer Assurance for Machine Learning in Autonomous Systems. In Proceedings of the Workshop on Artificial Intelligence Safety (SafeAI), Washington, DC, USA, 13–14 February 2023.
76. Hawkins, R.; Osborne, M.; Parsons, M.; Nicholson, M.; McDermid, J.; Habli, I. Guidance on the Safety Assurance of Autonomous Systems in Complex Environments (SACE). *arXiv* **2022**, arXiv:2208.00853.
77. Defence Science and Technology Laboratory. *Assurance of Artificial Intelligence and Autonomous Systems A Dstl Biscuit Book*; Defence Science and Technology Laboratory: London, UK, 2021.
78. Leslie, D. Understanding Artificial Intelligence Ethics and Safety. *arXiv* **2019**, arXiv:1906.05684. [CrossRef]
79. Web of Science. *Data Analysed Are Derived from Clarivate^{TM} (Web of Science^{TM}). © Clarivate 202___. All Rights Reserved*. Available online: http://webofscience.com (accessed on 10 April 2023).
80. Bensaci, C.; Zennir, Y.; Pomorski, D.; Innal, F.; Liu, Y.; Tolba, C. STPA and Bowtie risk analysis study for centralized and hierarchical control architectures comparison. *Alex. Eng. J.* **2020**, *59*, 3799–3816. [CrossRef]
81. Malm, T.; Tiusanen, R.; Heikkilä, E.; Sarsama, J. Safety risk sources of autonomous mobile machines. *Open Eng.* **2022**, *12*, 977–990. [CrossRef]
82. Sanderson, C.; Schleiger, E.; Douglas, D.; Kuhnert, P.; Lu, Q. Resolving Ethics Trade-Offs in Implementing Responsible AI. *arXiv* **2024**, arXiv:2401.08103.
83. Shambo, G. Top 5 Challenges of Solar O&M and How Drones Will Solve Them—The Drone Life. Available online: https://thedronelifenj.com/solar-operation-maintenance/ (accessed on 28 February 2024).
84. National Engineering Policy Centre; Royal Academy of Engineering. *Safety and Ethics of Autonomous Systems Project Overview*; Royal Academy of Engineering: London, UK, 2020.
85. Wong, A. The Laws and Regulation of AI and Autonomous Systems. In *IFIP Advances in Information and Communication Technology*; Springer Science and Business Media: Berlin/Heidelberg, Germany, 2020; Volume 555, pp. 38–54. [CrossRef]
86. Wang, N.; Mutzner, N.; Blanchet, K. Societal acceptance of urban drones: A scoping literature review. *Technol. Soc.* **2023**, *75*, 102377. [CrossRef]