

# Autonomous and Collaborative Robots for Energy Systems: State-of-the-art Review

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## Abstract

Energy systems are becoming larger, more complicated and distributed system. Such environments make manual operation and investigation based on unsafe, slow and inefficient operations. The independent and cooperative robots have been realized as viable systems in energy infrastructures to monitor, maintain and assist in operating the facilities. Recent research indicates a gradual increase in automated, energy-sensitive work and combined task performance of robots. Simultaneously, energy systems have severe limitations in safety, reliability and power efficiency. According to research explained in recent surveys, energy-efficient movement planning, smart power controlling and collaborative working among robots in energy-based tasks are most important. This paper reviews autonomous and collaborative robots in energy systems. It considers energy infrastructures as robotic workplaces, discusses autonomous and collaborative robots and reviews energy consumption modelling and optimization plans. The system integration and real-life implementations are also discussed. Finally, the main problems and future study directions are described. This survey aims to provide a brief and methodical source of data for researchers and engineers working on robotics and energy systems.

**Keywords:** Autonomous robots; Collaborative robots; Energy systems; Energy efficiency; Robotic inspection; System integration.

## 1. Introduction

Energy systems support the production, transmission, storage and distribution of power are the foundation of modern society. These systems are developing at a rapid rate because of increased usage of smart grid technology and renewable energy sources. The operational needs in energy system increases in size and complexity. Many energy plants are constructed in isolated, hazardous or secluded areas that human access may be limited due to operational costs and safety risks. The application of robotic solutions in energy systems has been encouraged by these factors. Autonomous robots are currently used for tasks including maintenance, monitoring and investigations. When compared to traditional automated systems, autonomous robots can detect the environment and make decisions without human intervention. Research, [1] explains the autonomous robotic systems have been developed to work with complex service tasks within structured and semi-structured settings. In energy systems, autonomy minimizes human exposure to potentially hazardous environments and enables them to operate continuously in the long term.

Robots can safely operate by humans. Collaboration improves job productivity and adaptability within industries according to the review done in [4]. The collaborative operation has advantages for maintenance, research and rapid reaction in energy systems. Robots are capable of task transfer, movement control and condition adaptability. Numerous robots are operated by large-scale energy facilities. Energy efficiency is the primary issue in the robotic implementation of energy systems. Furthermore, robots depend on limited on-board power sources to consume energy. According to the study reported in [3] and [11], robotic energy usage is significantly influenced by work allocation, movement planning and control method. This problem is even more critical in large energy plants, where it is necessary to explain long distances or have 24-hour operations in robots. The design of power supply and storage systems emerged as a research priority considered in [16].

Robots and energy systems interact with sensors, communication networks and energy management systems to improve monitoring and decision-making, electronic representations of robotic systems are also being researched. The research [6] illustrates that digital twins can be applied for automated robotic operations based on artificial data and learning-based control. Preventive maintenance and integrated energy use are made simple for the result. Energy infrastructure has to satisfy advanced safety and dependability standards. Severe climatic conditions, power limitations and communication problems can affect robotic performance.

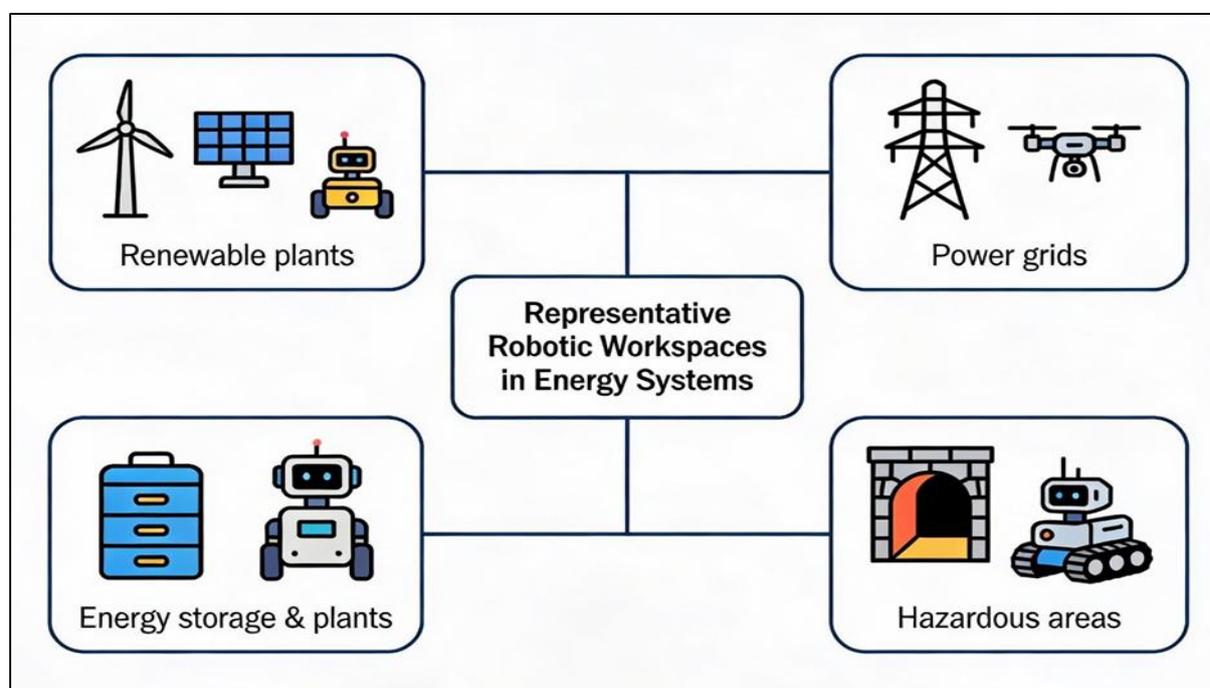
Large-scale implementation cause problems with cybersecurity and scalability. Reviews [15] and [21] suggest that the requirements for the long-term application of robotic technology in energy systems is being able to manage these difficulties.

This review used a systematic approach to find and collect research on autonomous and cooperative robots used in energy systems particularly focuses on energy-aware operation, modelling and integration. A keyword-based search was utilized for search terms such as autonomous robot, collaborative robot, multi-robot, inspection, maintenance, energy systems, power grid, wind/solar, energy consumption, motion planning, energy optimization and digital twin in the large research databases (IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar). There are three stages of evaluation were applied to these initial records: (i) duplicates were eliminated; (ii) title/abstract evaluation was done to make sure that the study included technical data related to the review elements (autonomy, collaboration, energy modelling/optimization, system integration, or field deployment); and (iii) full-text evaluation was done. The studies included in the collection of papers published in English scientific journal or conference focused on robotic operation in an energy-based infrastructure or industry. They were removed from studies that described robotics energy system that lacks sufficient technical depth or non-peer-reviewed publications to compare the approaches, limitations and unresolved problems of the energy environments. The result data was created using the concept-based methodology that matches with the text structure.

## **2. Energy Systems as Domains of Robot Applications**

In energy systems, the application of robotics in both necessary and challenging across a wide range of environments. Such locations include renewable power plants, power transmission systems, energy storage facilities and large industrial power plants. All these fields have unique physical and operational conditions. They have a direct impact on the development and implementation of robotics. The results indicate that energy systems are spread, operate 24/7 and require high reliability. Renewable energy plants e.g., wind farms and solar plants are normally located in remote or open locations. The robots in such places have to operate on hilly surfaces, changing weather conditions and large spaces [5]. According to the discussion, manual monitoring within such settings is expensive and unsafe to the workforce and exposes staff to accidents. Another method can be provided by robotic systems conduct periodic inspections and monitoring with no disruption of the energy production. The

other area of application is in transmission and distribution systems of power. To prevent faults and outages, transmission lines, substations and grid components should be monitored regularly. The size and complexity of present power grids is an added challenge to manual inspection, according to [19].



**Figure 1.** Technical Workflow of Autonomous Robotic Operation in Energy-System Environments

The robots in farm places have to operate on hilly surfaces, changing weather conditions and large spaces. Accuracy and dependability are the significant requirements. Other limitations are generated by industrial power plants and energy storage plants. Such circumstances are normally linked with a restricted field, low visibility and extreme safety measures. The limitations demand the robotic systems must be reliable, have minimal contact with device and minimal risk to human beings. The comparative analysis of the structures of systems in the energy system is illustrated in [21], depicts a high need in automated monitoring solutions that will integrate with the existing infrastructure. The energy systems significantly limit the use of robotic platforms in all these areas. The need to work 24/7, minimize the accessibility to the robot and have high safety standards determines the design of autonomous and collaborative robots.

Flexibility is also required because energy systems should be flexible to accommodate variable demand and production. It has been stated in modelling reports like the one in [2] that the explained flexibility is one of the key features of the modern energy systems and it is considered when deploying robotic solutions. The common energy system where the robots used such as renewable systems, grid systems, storage systems and hazardous areas are represented in Figure 1. In particular, sensing/perception blocks (Figure 1) are associated with monitoring applications (Section 3), but the planning and execution blocks represent movement planning and autonomy needs in a complex energy plant. Energy-aware operation is the final step is directly connected to the modelling and optimization formulas presented in Section 5. This discussion highlights the variety of operating conditions that autonomous and collaborative robots must consider in energy-related tasks.

### **3. Energy Applications of Autonomous Robotic Systems**

Automated robotic systems are important and these systems are designed to operate in complicated and dynamic situations to complete tasks with a minimal amount of human involvement. Energy automation minimizes the need for continuous medical treatment in remote or unsafe locations. It may also be used to work continuously for a long time. According to the survey [1], the primary need for service robots in large-scale and safety-based uses is autonomous. Depending on the needs of the application, robotic activities in the energy system have various levels of mobility. Certain robots operate under control having human operators implementing high-level decisions. Others are autonomous and capable of independent sensing, navigation and task execution [13].

According to the review in [15], it increases detection levels and decreases operating delays. The autonomous operation is preferred for renewable energy location task and grid maintenance due to its extensive coverage of space and limited access. Robots are provided with sensors to understand their environment such as cameras, LiDAR, heat sensors and inertial units. These sensor systems enable robots to identify mistakes, challenges and structural variations in energy resources. According to the results presented in [3], perception accuracy directly affects both energy usage and navigation efficiency. The robots' control and decision-making algorithms determine to be an observed data. In energy systems, autonomous robots must be able to adjust in changing conditions such as external interference, system failures and communication limitations.

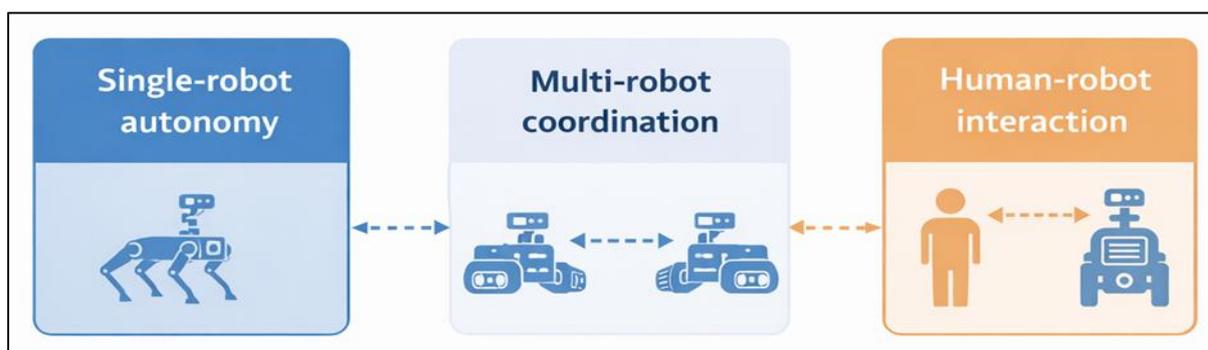
According to the study [17], adaptive control techniques can change actions of robot depending on the task conditions and energy availability. They will improve the effectiveness of operations. These techniques are useful for in-depth research. The lack of control in robotic energy applications requires energy awareness. The robots have to maintain an appropriate balance between task efficiency and energy consumption to improve work time. Communication, sensing frequency and speed are limited by the power's capability. Power-efficient hardware design and operational preparation are critical to ensure execution based on the research of mobile autonomous robots currently summarized in [16]. Sustainable automation prevents robots from shutting down before completing their mission. Autonomous robots with energy capabilities need to manage with unexpected problems. Sensor noise, sudden problems and changes in the environment are common. Robust autonomous devices are made to operate safely in these kinds of situations. The visible decision-making and energy awareness of autonomous robotic systems make them useful in energy applications.

#### **4. Multi-Agent Operation and Collaborative Robotics**

The important factor is cooperation of robotic implementations in energy systems. Although autonomous robots are capable of operating independently with a substantial amount of energy-related activity requires a secure involvement of human operators or the coordination of several robots. Humans and robots work together to assign tasks and exchange knowledge. In complicated industrial environments, such as energy infrastructures, cooperation increases efficiency and adaptability was reviewed in [4]. In energy facilities, complete automation is not achieved that proposes the human-robot collaboration method. Robots are frequently utilized to help humans in performing harmful or repetitive tasks in transmission lines, power plants, storage facilities in different locations. Collaborative robots have safety features enabling close contact without physical challenges.

The previous studies described in [14] explains that shared decision-making and adaptive interactions due to their common features to enable cooperative functioning with energy efficiency. These features make it possible to maintain a high level of safety and improve productivity. Mission tasks usually exceed the abilities of a single robot such as monitoring transmission lines, renewable energy sources and restricted infrastructure areas. In this case, a group of robots may be used to carry out specific tasks, distribute work and plan operations. According to research by [7] and [9], collaborative assigned tasks require less

energy from people and improves system performance. As an example, consider the combination of autonomous and collaborative modes in energy systems. Figure 2 depicts the interaction between human administrators, integrated robot teams and single autonomous robots in an environment connected to energy. It highlights the cooperation that improves individuality rather than destroys it. While cooperation will enable coordination, safety and sharing of tasks across complex infrastructures, autonomous decision-making will enable robots to make decisions.



**Figure 2.** Multi-Agent Collaboration Architecture for Robotic Inspection and Maintenance in Energy Systems

Collaborative operation creates new communication and synchronization requirements, as seen in Figure 2. The task assignment, coverage control and resolution of conflicts technique has been commonly utilized in multi-robot maintenance and investigations are described as the coordinating layer in Figure 2. The explanation of network dependability and energy limitations combined to affect collaborative performance was explained by the description of the communication and synchronization channels. It is used to promote the section 5 discusses the environmental optimization. They need to communicate with each other regarding robots to be secure and avoid conflicts. Communication failures or delays have an impact on coordination in large operations or remote areas. Effective communication methods are also required when collaborative robots perform in unsafe and limited energy locations explained in the study [18], [20]. Time loss and redundant motions can be decreased with integrated movement scheduling and task sharing. However, the coordination and communication increase the usage of power. Thus, connecting these elements is an important design element.

The studies have been implemented in the [7] suggest that the energy conscious cooperation methods need to be introduced in order to achieve the operational efficiency during

the long-term. Collaborative robotics improves the autonomy systems of energy applications. The operation and the ability to act in concert can ensure the robots will be able to address the scale, security and intricacy of the energy system more effectively.

#### **4.1 Failure Modes and Risk Factors in Multi-Agent Collaboration**

Due to sensing unpredictability, communication limitations and coordination faults, failure modes in distributed operation leads to a breakdown in collaborative performance. One of the possible failures is a communication loss or latency that delays the transmission of status and intent data, resulting in inaccurate models and harmful navigation decisions. Duplicate work, insufficient coverage during evaluation and incomplete or missing assignments can be caused by network failures and bandwidth limitations. Another major challenge is localization drifting and perceptions inconsistency that makes the robots to maintain inconsistent views on the locations of challenges or resources causes coordination problems and path conflict. When the device is energy-limited, partially malfunctioning or disconnected, task collection failure is seen in dynamic setting leads to an imbalance workload and execution failure. Additionally, the asynchronous updates may cause the devices differ on tasks that develops to a synchronize failure and resolution with unstable reset cycles. The possibility of malicious interference (such as spoof signals or cyber infiltration) can lead to misleading cooperative behavior shows the critical implementations require authentication, redundancy and secure alternative behavior in the safety concerns.

#### **4.2 Classification of Coordination Methods for Multi-Agent Collaboration**

The collaboration of multiple agents in the energy system may be categorized according to the decision-making process of formation and sharing within the robot team.

The first step to centralized coordination for all robot tasks and paths are assigned by monitoring unit with global awareness of situation (centralized control, edge server or ledger robot). In regard to scheduling and coordinated coverage, this system is effective (in a global sense), but it is sensitive to communication delays, single-point failure and the scalability of huge energy plants.

Secondly, the decentralized or distributed coordination of each robot uses reduced neighbour communication and local sensing to make decisions that include distributed task

assignment, behavioural coordination (collision avoidance and priority rules) and consensus-oriented control (consensus in common variables like data formation state or coverage region). This model improves the fault tolerance and function in periodic connection when it is common in power plants, tunnels and wind farms. These distributed methods can result difficulties in infrastructure or poor global distributions without specific conflict resolution.

The third method is combining hybrid coordination with local authority and global scheduling. A centralized organizer assigns missions (coarse level, sector-wise investigation, repair sequence) when the robots handle the actual navigation, safety and replanning under energy limitations. It is suitable for energy systems because hybrid coordination can maintain efficiency, resilience and safety. In recent years, multi-agent learning-based coordination used when the collaborative policies are modified to change unknown situations. However, the alternative techniques have effective and verified limitations for use in safety energy plants.

## **5. Energy Consumption, Power Supply and Optimization**

One of the key issues when deploying autonomous and collaborative robots to the energy systems is energy consumption. Robots are powered by limited onboard sources of power and this directly limits the duration of operation, frequency of sensing and capability of communication. Robots usually cover long distances in large energy infrastructures and are engaged in continuous activities. The operation is dependent on effective energy consumption. The surveys of the literature, including those conducted in [11] and [15], highlight the idea that the efficiency of energy plays a crucial role in determining the viability of long-term application of robots.

The initial step is optimization for the accurate energy consumption modelling. The energy use varies based on the structure of robots, payload, movement patterns and task assignment. The modelling techniques evaluate the correlation during the process of combining movements, actuator effort and power usage. It also describes in paper [12] that operation-based energy models can be used to provide real-time predictions for consumption during industrial operations. It defines the process for energy-intensive and decision controls with the help of this models.

In majority of works, the initial step involves the total energy extension during the task as the time integral of the instantaneous power of the robot:

$$E = \int_0^T P(t) dt \quad (1)$$

In the case of articulated robots, this power is usually associated with the mechanical work combined along with a base consumption and other terms of loss:

$$P(t) = \sum_{i=1}^n \tau_i(t) \dot{q}_i(t) + P_{\text{base}} + P_{\text{loss}}(t) \quad (2)$$

In this case,  $n$  represents the number of joints,  $\tau_i(t)$  and  $\dot{q}_i(t)$  is the torque and angular velocity of joint  $i$ ,  $P_{\text{base}}$  implies the power which the robot is not moving,  $P_{\text{loss}}(t)$  is the friction and electrical loss dependent on the operating condition. The application of mechanism-based formulations has to be examined the nature of movement, payload and speed profiles affect the use of consumption in industrial and collaborative robots.

A second category of literature uses called operation-aware models, in which the energy of a task is modelled as a sum of the contributions in separate segments of motion or processes:

$$E_{\text{task}} = \sum_{k=1}^K \alpha_k C_k \quad (3)$$

Here  $C_k$  is a property of operation  $k$  (such as its duration, path length or the number of cycles executed), whereas  $\alpha_k$  is an energy coefficient determined experimentally. The model is required to estimate fast at cell or line level because it does not involve extensive dynamic modeling, but the primary trends in consumption are considered.

Energy-conscious motion planning typically incorporates the model into a cost functional that is minimized along the path. Another typical method will be challenging for the squared joint torques during the time:

$$J = \int_0^T \left( \sum_{i=1}^n \tau_i^2(t) \right) dt \quad (4)$$

Reducing the cost, accelerations and control effort helps to balance the movement and improves energy efficiency compared to time-optimum paths.

In the reviewed literature, these models usually verified by using error measures such as mean absolute error or root mean square error to compare the predicted energy or power values with actual robot experimental measurements of real robot performance with comparable tasks or production. Model parameters are determined using experimental datasets and the models' ability to extend the calibration data is evaluated by testing them under new

conditions. Motion planning affects the robotic energy consumption. The shape of the trajectory, the speed curves and the length of the path affect the power consumption. As research including in [8] and [10] indicates energy-conscious motion planning can be used to decrease consumption through preventing sudden movements and unnecessary acceleration. It has been demonstrated that planning techniques are based on polynomials and the optimization process can improve efficiency without affecting the accuracy of the tasks. Nevertheless, there is a risk that these techniques can cause extra processing load needs to be offset by protection of energy.

The use of control strategies is also important in optimization of energy. Adaptive and predictive control techniques vary the behavior of the robot according to task conditions and system conditions. According to Choi et al. [17], adaptive control schemes enhance energy efficiency in the variable operating conditions by minimizing excessive actuation. Coordinated control may also be used in teamwork environments to control the amount of energy consumed through workloads allocation between robots as reported in [7] and [9]. Robots based power supply and energy storage solutions can work in duration without the need to recharge. Mobile robots have batteries as the main power source, which has been a challenge due to its low capacity to allow continuous running of the robot. Surveys like [16] explains the significance of proper battery technology selection and hybrid storage systems in the case of long missions. The design of energy storage should consider the charging time, weight and safety of operation.

In order to provide a brief overview of the energy-related strategies, Table 1 summarizes the most important strategies reported in the literature.

**Table 1.** Energy Consumption and Optimization Approaches in Robotic Systems for Energy Applications

<b>Aspect</b>	<b>Approach</b>	<b>Key Observations from Literature</b>	<b>Limitations</b>	<b>Future Research Direction</b>
Energy modelling	Mechanism-based and operation-aware models	In [12], the research works provide precise estimation of robotic energy consumption during the work.	Requires detailed system parameters	EMI resilient sensors

Motion planning	Energy-aware trajectory optimization	In [8] and [10], the power consumption is reduced by using smooth trajectories.	Higher computational cost	Fusion of LiDAR, UWB modalities
Control strategies	Adaptive and predictive control	Findings in [17] exhibit efficiency in dynamic conditions.	Sensitive to model accuracy	Energy-aware scheduling
Collaborative operation	Task sharing and coordination	The results in [7] and [9] suggest reduced personal energy charge.	Coordination overhead	Robust communication
Power supply	Battery and hybrid storage systems	Other surveys include [16], which points out enhanced autonomy and streamlined storage.	Limited lifetime and recharge time	Secure Robotic models

The accuracy of the modelling, the efficiency of the planning, the strategy of the control and the design of the power system explains influence the amount of energy used in the robotic systems. This will require actors to be considered in order to maximize them. The architecture of autonomous and collaborative robots with energy consciousness in the modern energy systems is necessary.

## 6. Smart Energy Management and Control

The technical energy system needs automated collaborative robots to interact with sensors, control platforms, communication networks and energy systems. In the study [21] highlights the automated robot control limits, the efficiency and scalability of the system. The energy management system provides real-time data for consumption and production. The real demand of operations within the integration of robotic system is to schedule the evaluation and maintenance process. It allows to prevent unnecessary operations and perform predictive maintenance for the devices. The methods of modelling presented in [2] explains the capacity to increase the energy systems using the combined system based decisions.

Digital twin is the representation of robotic system used to help in integration process. It enables the monitoring, simulation and optimization of robotic tasks explained in [6]. These

representations compare the scheduling, energy consumption and cooperative behavior under various conditions allowing the operators to reduce risk and increase scheduling accuracy.

Energy awareness is also facilitated by smart coordination. Depending on the availability of power and constraints of the system, robots are able to change the way they implement tasks. Adaptive scheduling and load balancing of robots and control centers is achieved through communication between the two. Studies presented in [14] indicate that edge-level intelligence may enhance the performance of collaboration, besides minimizing the overhead of communication. It is important to discuss the cybersecurity issues, communication dependability and connectivity of current energy systems. The review [15] explains the large-scale deployment requires high integration structures. The implementation of network sensing, human robot interfaces and remote supervision in collaborative situations enhances the space for cyber-physical attacks. These routes can be used by an attacker to change paths of robots, destroying safety systems and reducing evaluation and monitoring data affects the both human safety and security of the system infrastructure. The current system-based studies highlight the design principles for authentication, encryption, network isolation and continuous monitoring compared to autonomous capability and cooperative robots in major energy-systems.

## **7. In-Field Deployments and Case Studies**

Real-world implementation of autonomous and collaborative robots gives an understanding of the effectiveness and weaknesses of robots. A variety of applications in various areas of energy have been achieved. Such applications show that robotic systems can be used in practice with all its limitations. The analysis in [15] explains the role of robots in inspection, monitoring and maintenance in the process of transition to energy. One of the most widespread deployment environments is the installation of renewable energy. Inspection of wind turbines and solar panels is conducted by robots, saves time and increases the safety of work. Robots assist in fault detection and assets management in power transmission and distribution systems. According to the analysis in [20], specialized robotic platform can be used in constrained and dangerous infrastructure settings that limit human access.

Robotic implementation also used in industrial energy plants and energy storage facilities. In restricted areas, the robots can perform regular monitoring process. This function will reduce manual labour and increase efficiency. The provided results show the advantages of safety and efficiency in the system. Table 2 illustrates the explanation of sample

implementations by combining different cases examined in previous works. The system includes the high-performance, energy-capability and multiple sensing operations to support the operations in challenging environments. This application illustrates the advantages of autonomous and cooperative robots in energy systems. It highlights the research based on the need of scalability, integration and long-term dependability.

**Table 2.** Representative Robotic Deployments in Energy Systems

Energy Domain	Robotic Role	Deployment Characteristics	Reported Benefits	Tech. Specifications	Performance Indicators
Renewable energy	Inspection and maintenance	Indoor mobile robots	Less downtime and enhanced safety.	Climbing robots with cameras	Fault identification
Power grids	Monitoring and fault assessment	Robots used on the transmission lines and substations	Reliability improvement.	Ground robots with cameras	Fewer patrols
Energy storage	Facility inspection	Self-driving within the tight areas	Constant surveillance.	Small bases with vision sensors	Inspection frequency
Hazardous environments	Infrastructure assessment	Developed robots in sensitive or dangerous places	Less exposure to human danger.	Tough robots with hazard sensors	Area covered

## 8. Issues and Unresolved Research Problems

The current problems prevent autonomous and cooperative systems in the regular industry. These energy systems operate in a distributed environment and are spread over wide geographic areas. The challenging process of designing robots will help in different settings and developing robots can be used in many configurations over the time. The research [1] and [15] explains the system increases costs and complexity. Energy-efficient robots and communication unreliability are the another challenges found in energy systems.

Robots require a continuous dataflow to control the functions and develop over time. The communication links are unstable in power plants or crowded areas. Interruptions in

connectivity is also a risk in energy systems. In reference [20] highlights the effective operation of robots with limited infrastructure is impossible without a proper communication method.

Many optimization techniques that have been presented without accurately represent situations in real time, particularly when battery range, expiry, and unpredictable tasks are involved. The references [7] and [11] not explains the solution for the over-time system adaptation leads to reduced failure in results. The robots need to be secure and their ability to control network makes easy target for cyberattacks. System-based research in reference [21] explains that during design the security not considered. The primary areas are scalable integration models, efficient communication, long-term resource optimization and improved safety protection should be focused on future research. The future works and limitations are mentioned in the research.

**Gap 1:** The combined models of energy and communication and coordination are not provided. Future direction: The optimization structures deal with task allocation, routing and communication scheduling as a constraint on delay/loss.

**Gap 2:** The energy prediction models do not pay attention to actual degradation and field interactions.

**Future Work:** Including the battery expiry dates, change in loads, temperature and loss into predictive energy models is needed before actual implementation.

## 9. Conclusion

In this paper, the role of autonomous and collaborative robots in energy systems was reviewed. The energy infrastructures were also examined as complex and challenging robotic working environments. This review also examined various design requirements for autonomous operations. Energy efficiency and coordinated operations were also explored. The modelling, optimization and integration of the system were summarized. The review demonstrates that the robotic technologies have the possible way to increase the levels of safety, efficiency and reliability in energy systems. However, there are issues of scalability, communication, energy use and security. Hence, there is an urgent need to conduct more research to provide solutions for the existing problems. This survey provides a systematic report of the current developments and the new solutions. The identified research gaps can be effectively utilized to create effective and energy-consumption robotic solutions.

## References

- [1] Misaros, Marius, Ovidiu-Petru Stan, Ionut-Catalin Donca, and Liviu-Cristian Miclea. "Autonomous robots for services—state of the art, challenges, and research areas." *Sensors* 23, no. 10 (2023): 4962.
- [2] Gils, Hans Christian, Hedda Gardian, Martin Kittel, Wolf-Peter Schill, Alexander Zerrahn, Alexander Murmann, Jann Launer et al. "Modeling flexibility in energy systems—comparison of power sector models based on simplified test cases." *Renewable and Sustainable Energy Reviews* 158 (2022): 111995.
- [3] Wu, Mingyu, Che Fai Yeong, Eileen Lee Ming Su, William Holderbaum, and Chenguang Yang. "A review on energy efficiency in autonomous mobile robots." *Robotic Intelligence and Automation* 43, no. 6 (2023): 648-668.
- [4] Patil, Swapnil, Vishwa Vasu, and K. V. S. Srinadh. "Advances and perspectives in collaborative robotics: a review of key technologies and emerging trends." *Discover Mechanical Engineering* 2, no. 1 (2023): 13.
- [5] Sperling, Marvin, and Tommi Kivelä. "Concept of a dual energy storage system for sustainable energy supply of automated guided vehicles." *Energies* 15, no. 2 (2022): 479.
- [6] Kim, Dongjun, Minho Choi, and Jумыng Um. "Digital twin for autonomous collaborative robot by using synthetic data and reinforcement learning." *Robotics and Computer-Integrated Manufacturing* 85 (2024): 102632.
- [7] Miranda, Sofia, Carlos Renato Vázquez, and Manuel Navarro-Gutiérrez. "Energy consumption analysis and optimization in collaborative robots." *Frontiers in Robotics and AI* 12 (2025): 1671336.
- [8] De Laet, Robbe, Nick Van Oosterwyck, Lorenzo Scalera, Annie Cuyt, Alessandro Gasparetto, and Stijn Derammelaere. "Energy-efficient motion planning for robotic systems using polynomials in the Chebyshev basis." *Robotics and Autonomous Systems* (2025): 105051.

- [9] Miranda, Sofia, and Carlos Renato Vázquez. "Analysis and Prediction of Energy Consumption in a Collaborative Robot." *IFAC-PapersOnLine* 56, no. 2 (2023): 3710-3715.
- [10] Nonoyama, Kazuki, Ziang Liu, Tomofumi Fujiwara, Md Moktadir Alam, and Tatsushi Nishi. "Energy-efficient robot configuration and motion planning using genetic algorithm and particle swarm optimization." *Energies* 15, no. 6 (2022): 2074.
- [11] Jiang, Pei, Zuoxue Wang, Xiaobin Li, Xi Vincent Wang, Bodong Yang, and Jiajun Zheng. "Energy consumption prediction and optimization of industrial robots based on LSTM." *Journal of Manufacturing Systems* 70 (2023): 137-148.
- [12] Cai, Zhengying, Xiangyu Du, Tianhao Huang, Tianrui Lv, Zhiheng Cai, and Guoqiang Gong. "Robotic Edge Intelligence for Energy-Efficient Human–Robot Collaboration." *Sustainability* (2071-1050) 16, no. 22 (2024).
- [13] Taraglio, Sergio, Stefano Chiesa, Saverio De Vito, Marco Paoloni, Gabriele Piantadosi, Andrea Zanela, and Girolamo Di Francia. "Robots for the Energy Transition: A Review." *Processes* 12, no. 9 (2024): 1982.
- [14] Farooq, Muhammad Umar, Amre Eizad, and Hyun-Ki Bae. "Power solutions for autonomous mobile robots: A survey." *Robotics and Autonomous Systems* 159 (2023): 104285.
- [15] Choi, Minje, Seongjin Park, Ryujeong Lee, Sion Kim, Juhyeon Kwak, and Seungjae Lee. "Energy efficient robot operations by adaptive control schemes." *Oxford Open Energy* 3 (2024): oiae012.
- [16] Forootan, Mohammad Mahdi, Iman Larki, Rahim Zahedi, and Abolfazl Ahmadi. "Machine learning and deep learning in energy systems: A review." *Sustainability* 14, no. 8 (2022): 4832.
- [17] Khalili, Siavash, and Christian Breyer. "Review on 100% renewable energy system analyses—A bibliometric perspective." *IEEE access* 10 (2022): 125792-125834.
- [18] Bhardwaj, Hitesh, Nabil Shaukat, Andrew Barber, Andy Blight, George Jackson-Mills, Andrew Pickering, Manman Yang et al. "Autonomous, Collaborative, and Confined

Infrastructure Assessment with Purpose-Built Mega-Joey Robots." *Robotics* 14, no. 6 (2025): 80.

[19] Muqheet, Hafiz Abdul, Rehan Liaqat, Mohsin Jamil, and Asharf Ali Khan. "A state-of-the-art review of smart energy systems and their management in a smart grid environment." *Energies* 16, no. 1 (2023): 472.

[20] Soori, Mohsen, Behrooz Arezoo, and Roza Dastres. "Optimization of energy consumption in industrial robots, a review." *Cognitive Robotics* 3 (2023): 142-157.

[21] Prina, Matteo Giacomo, Benedetto Nastasi, Daniele Groppi, Steffi Misconel, Davide Astiaso Garcia, and Wolfram Sparber. "Comparison methods of energy system frameworks, models and scenario results." *Renewable and Sustainable Energy Reviews* 167 (2022): 112719