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Review

Pulsar's Application in Energy Systems: Review of Current Status, Challenges, and Opportunities

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Abstract: To accelerate progress toward the realization of advanced energy systems, this review explores the potential of pulsar technology to create a more stable, economical, and environmentally friendly energy infrastructure. Pulsars, with their precise and reliable timing characteristics, have emerged as a promising tool for enhancing energy systems. This review begins by examining the development history of pulsar technology, shedding light on its evolution and the milestones achieved. It then provides a comprehensive summary of the current state of research, highlighting recent advancements and breakthroughs in this field. It also explores transformative pulsar applications in energy systems, including improved grid stability, advanced energy synchronization, and efficient energy storage management. However, implementing pulsar-related technologies presents significant technical, economic, and operational challenges. This review examines these hurdles and proposes strategies to overcome them, emphasizing the need for innovation, interdisciplinary collaboration, and supportive policies to fully integrate pulsar technologies into sustainable energy systems.

Keywords: pulsar; energy system; timing source; framework; application

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Academic Editor: Ahmed Abu-Siada

Received: 15 December 2024
Revised: 2 February 2025
Accepted: 6 February 2025
Published: 11 February 2025

Citation: Zhang, Y.; Wu, Y.; Liu, Y.; Sun, B.; Yang, J.; Thotakura, N.L.; Ahmed, K.I.; Liu, Q.; Shen, C.; Liu, Y. Pulsar's Application in Energy Systems: Review of Current Status, Challenges, and Opportunities. *Energies* **2025**, *18*, 828. https://doi.org/10.3390/en18040828

1. Introduction

With the increasing scale of power grids and the growing integration of distributed renewable energy sources, maintaining system stability has become a significant challenge [1,2]. The Global Positioning System (GPS) is extensively used as a synchronization and positioning source in various energy applications; however, its signals are inherently vulnerable [3,4]. These vulnerabilities include susceptibility to disruptions from system failures, space weather fluctuations, and deliberate interference such as jamming. Furthermore, cyberattacks like GPS spoofing pose severe threats, potentially jeopardizing the accuracy, reliability, and safety of grid operations. Consequently, developing alternative sources to support existing equipment within the energy system has emerged as a critical mitigation strategy [5–8].

Fortunately, discoveries from space [9–11] may provide new inspirations during this process. To build a safer, greener, and more economical energy system [12,13], it will be necessary to ensure precise timing. The pulsar, which is considered a natural cosmic clock with long-term stability [5,14], has attracted the attention of scholars and stimulated their imagination. We could not ignore the issues that may be faced in other time synchronization approaches. Making the most use of the characteristics of pulsars may bring us more tools, which will provide us with backups to deal with different situations. For example, capturing stable signals from pulsars can serve as a stable and reliable clock source for energy systems to function in the event of a GPS failure [11].

Although there have been some attempts to make contributions regarding the applications of pulsars in the energy system [1–8], many research gaps still exist considering the huge potential of pulsars. Furthermore, due to the interdisciplinary nature and practical difficulties involved, there are still certain technical issues that need to be addressed. For now, dealing with the large amount of pulsar data is a time-consuming task. Therefore, the performance of pulsar applications is related to data processing efficiency. Data compression may become a research point. Another challenge may come from accuracy. Unlike research only focused on pulsars, there is a high requirement for long-term accuracy due to the stability limits of the energy system when we use pulsars in the application of energy systems. For example, the influence of red noise [15] may influence the long-term accuracy of pulsar-based timing sources. Maintaining synchronization continuity is crucial for grid measurement [7]. So, this places high demands on pulsar-based timing sources. We may also face difficulties caused by the characteristics of pulsars and the limitations of existing equipment. Because there is no relationship between the white noise at the previous time point and the white noise at the next time point, we can add white noise to the pulsar circuit by repeating the signal with white noise. When we tried to add the red noise to the pulsar circuit, the time-related characteristics of red noise made errors in the process of repeating the signal with the signal generator.

The contributions of this review are summarized:

- Historical and current research overview: the review provides a detailed examination of the field's history and current research status, offering a foundation for understanding progress and challenges.
- Resource organization for accessibility: existing online resources are systematically organized to aid new researchers in efficiently entering the field.
- Opportunities from new perspectives: potential opportunities are identified by exploring emerging technologies and novel scenarios, departing from traditional research approaches.
- Comprehensive analysis of challenges: challenges are discussed in terms of technological complexity, environmental interference, economic costs, and the popularization of technology, guiding future research directions.
- Proposed response strategies: strategies to address identified challenges are presented across three dimensions: technical advancements, interdisciplinary cooperation, and the development of robust support mechanisms.

2. Development History and Current Status

2.1. History and Basic Knowledge

A literature review and analysis were conducted to examine the historical development of pulsar technology and its application in energy systems. Figure 1 shows the key milestones in the development history of pulsar detection and integration of pulsars into energy systems. Although over 50 years have passed since the first pulsar was discovered, significant progress in utilizing pulsar characteristics for energy system applications has only been made in recent years.

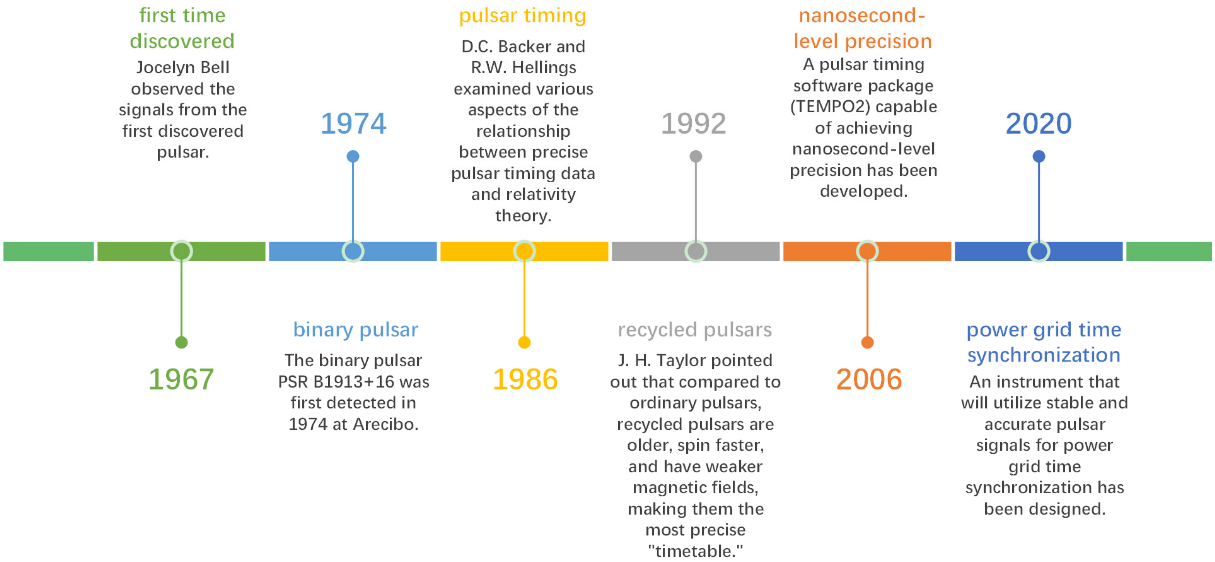

Figure 1. Review of Key Historical Nodes in pulsar's Detection and Applications in Energy Systems.

To help readers better understand the background [2,3,5–8,10,11,16] of pulsars, Figure 2 has been drawn. Figure 2 shows the classical profile characteristic [10,11,16] of the pulsar signal. Detailly, because of the relative positions of the pulsar, there are different and corresponding intensities. For example, if the orientations of the radio light of the pulsar are as shown in Figure 2a,c, the intensities are low. When the pulsar's radio light faces the observation equipment, as shown in Figure 2b, we can obtain the high intensity. We can obtain the pulsar period based on the interval between two adjacent highest-intensity points. Figure 2a–c present three typical statuses of pulsar signals. It should be noticed that due to the pulsar's periodic rotation, its signal intensities exhibit a periodic pattern. So, the repetition and fluctuation become the important factors of the pulsar profile data. These characteristics could be the fundamental reference for the following pulsar signal analysis and process.

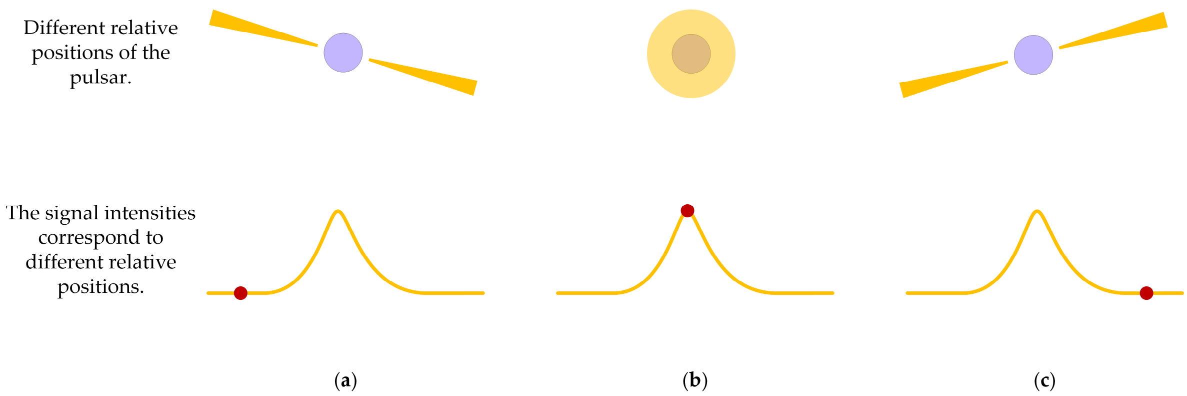

Figure 2. The pulsar signal illustration diagram. (**a**) Before pulsar signal irradiation (**b**) During pulsar signal irradiation (**c**) After pulsar signal irradiation.

2.2. Existing Resources

Thanks to the efforts of numerous scholars and engineers, subsequent researchers have benefited from a wealth of open-source resources for further study.

Below are the collected and organized online resources related to pulsar, as shown in Table 1. In Table 1, all databases are accessible on 10 December 2024 and the software listed are updated online. The combination of these tools and databases enables researchers to build a complete research chain from data collection to analysis, providing important support for pulsar research and other fields such as navigation and clock reference. Researchers can use them for pulsar signal processing, noise reduction, and modeling to optimize observation efficiency.

Table 1. Online resources for pulsar.

Purpose/Function/Contents	Online Resource	Type
Pulsar profiles provided by many authors	https://psrweb.jb.man.ac.uk/epndb/	Database
The comprehensive database of all published pulsars.	https://www.atnf.csiro.au/research/pulsar/psrcat/	Database
Pulsar observation data collected by the Murriyang Parkes radio telescope	https://data.csiro.au/domain/atnf/	Database
The complete library of published astronomical catalogs	https://vizier.cds.unistra.fr/	Database
The pulsar profiles obtained by the Five-hundred-meter Aperture Spherical Radio Telescope	http://zmtt.bao.ac.cn/psr-fast/	Database
An open-source C++ library for pulsar time-series digital signal processing	https://dspsr.sourceforge.net/	Software
An open-source C++ development library for pulsar astronomical data analysis	https://psrchive.sourceforge.net/	Software
A Python package for simulating pulsar signals and educating users	https://psrsigsim.readthedocs.io/en/latest/	Software
A C/Fortran toolkit for statistical analysis of pulsar data	https://www.jb.man.ac.uk/research/pulsar/Resources/psrsalsa.html	Software
A toolkit for pulsar data reduction, used to search for and visualize pulsed signals in noisy radio astronomy data	https://sourceforge.net/projects/sigproc/	Software

2.3. Recent Studies on Utilizing Pulsars in Energy Systems

The databases that provide the selected scientific papers include Google Scholar, IEEE Xplore, and Web of Science. The selected scientific papers can be divided into two parts. The first part is related to using the characteristics of pulsars in energy systems. The second part is other related papers like introductions to pulsars and new technologies. For the first part, the total number of scientific papers on using pulsar characteristics in energy systems is 11, up to the end date of the literature review. They are all listed in Table 2. For the second part, the classical or highly cited papers for background knowledge are selected. The advanced papers for innovations are selected.

Since applying the characteristics of pulsars to energy systems is a relatively new research area, the first attempt to utilize pulsars in energy systems occurred in 2020, as indicated by the Key Historical Nodes in Pulsar Detection and Applications in Energy Systems shown in Figure 1. Prior to 2020, studies on pulsars did not focus on energy systems. To provide a comprehensive overview, we conducted a thorough search and compiled all relevant papers to the best of our knowledge. Consequently, the papers listed in Table 2 cover only the period from 2020 to 2024, where PBTI is the pulsar-based timing instrument.

Table 2. Recent research on the application of pulsars in energy systems.

Featured Objective(s)	Contributions	Year	Ref.
The hardware and software architectures of the PBTI	The possibility of pulsars as alternative time sources for power systems is explored.	2020	[1]
A precise timing method based on pulsar observation data	Incoherent de-dispersion techniques are used to mitigate the dispersion effect of the interstellar medium to improve the accuracy of pulsar-based timing signals.	2021	[2]
The field-programmable gate array	The factors that affect the accuracy of the generated pulsar timing pulses are discussed.	2021	[3]
The novel pulsar-calibrated timing source	The characteristic that stable pulsars and superimposing longer-term pulse data can be used to obtain higher accuracy is described.	2021	[4]
The possibility of the use of a millisecond-rotation pulsar as a timing source	Implementing millisecond-rotation pulsar signal technology and deploying related equipment in the substation to see whether they can meet the size range requirements is attempted.	2021	[5]
Artificial pulse generation and analog front-end circuit	Designed a pulsar signal acquisition front-end circuit that can effectively generate analog pulses and is convenient and flexible.	2022	[6]
A simple analog front-end circuit and superheterodyne analog front-end circuit	The signal-to-noise ratio characteristics and robustness of the analog front-end circuit, which generates analog pulsars, were analyzed through experiments.	2023	[7]
Hardware and software frameworks for high-density pulsar data transmission and processing	Multiple-threading technology is applied to receive, parse, and splice pulsar data in order to address the high-frequency data rate issues encountered during the real-time transmission and processing of pulsar data.	2024	[8]
A digital phase-locked loop	An algorithm based on a digital phase-locked loop is proposed to control the atomic clock ensemble using the ensemble pulsar time, in order to calibrate the long-term frequency drift of atomic clocks and improve the long-term stability of atomic time.	2024	[9]
A pulsar signal simulator	A pulse profile extraction method based on the average pulse profile and cross-correlation is proposed, which is more efficient due to its independence from dispersion measures.	2024	[10]
The residual between the crystal oscillator and pulsar time	A method for calculating the residual between the integrated pulse profile and the standard pulse profile was proposed to address residual calibration for pulsar-based pulse-per-second systems.	2024	[11]

This table clearly demonstrates the research of applications of pulsars in energy systems, mainly focusing on areas such as timing synchronization, signal processing, and hardware development. These studies are of great significance for improving the accuracy, stability, and real-time response capability of energy systems, and also reflect the rapid development of this field. The research involves astronomy, engineering technology (hardware development, signal processing), and data science (algorithms and data analysis), reflecting the interdisciplinary application of pulsar technology. In terms of time frame, the study extends from 2020 to 2024, indicating that research in this field is still ongoing. In terms of trend, in recent years, the research focus has gradually shifted towards more efficient signal processing, hardware optimization, and integration with real-world scenarios, such as high-frequency data transmission and real-time processing.

The application of pulsars as alternative time sources in energy systems has been a growing area of research. Table 2 summarizes recent advancements in this domain. While these studies have made notable contributions, critical gaps and limitations persist.

Limitations of current studies are listed as follows:

- Scalability and real-world validation: Many studies focus on theoretical designs or simulations but lack field validation in large-scale power systems. This raises concerns about practical feasibility and implementation challenges.
- Signal robustness and noise mitigation: Some research investigates pulsar signal calibration but does not address signal degradation in high-noise environments. Similarly, another attempt analyzes analog front-end circuits but overlooks robustness under varying operational conditions.
- Integration with energy systems: although there has been a study proposing hardware solutions for analog pulse generation, it does not explore their integration with dynamic, distributed energy systems, leaving questions about interoperability.

Despite progress, unresolved challenges remain:

- Long-term stability and accuracy under diverse environmental conditions require further exploration [2,7].
- Real-time processing of high-density pulsar data with minimal latency has yet to be adequately addressed [8].
- The interdisciplinary potential of pulsar technology, particularly in data science and machine learning applications, remains largely untapped [11].

Given that pulsars are primarily used as a timing source in energy systems, Figure 3 summarizes the foundational structure needed for implementing pulsar-based timing applications, where PMUs represent phasor measurement units, and PPS refers to pulse-per-second.

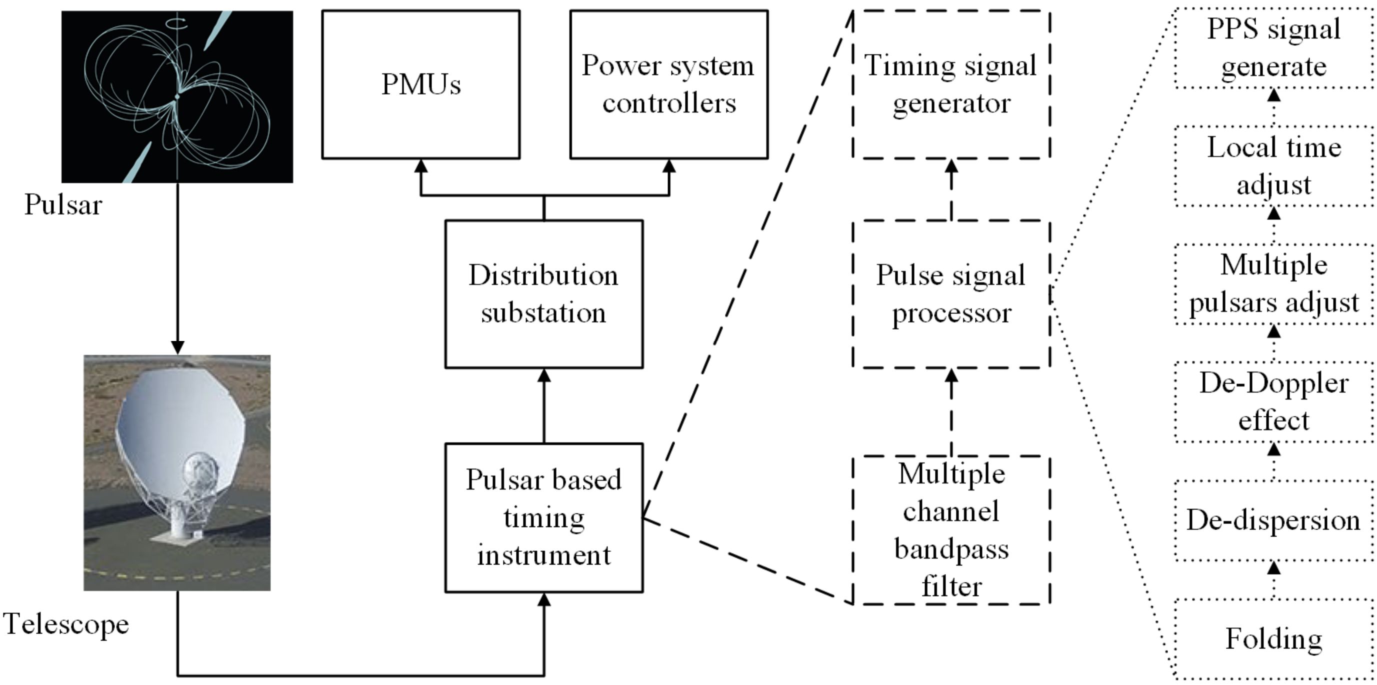

Figure 3. The general framework for a pulsar timing application.

The pulsar's signals were received by the telescope; then, they were sent to the pulsar-based timing instrument. The pulsar-based timing instrument consists of the multiple-channel bandpass filter, pulse signal processor, and timing signal generator. For the multiple-channel bandpass filter, it was utilized to optimize the signal isolation and process. In the multiple-channel bandpass filter, the sampled radio frequency signals were separated into digital signals in the bandwidth we wanted. The pulse signal processor, which was made of 6 subfunction blocks (folding, de-dispersion, de-Doppler effect, multiple pulsars adjust, local time adjust, and PPS signal generate), was an important part of generating an accurate pulse signal. The timing signal generator includes a digital-to-analog converter (DAC) and translates digital pulse signals into pulsar-per-second signals.

3. Opportunities

3.1. Possible Applications of Pulsars in Energy Systems

Pulsar-based technologies offer transformative potential for modern energy systems, inspired by their unique characteristics and well-established applications in astrophysics. Several promising areas for leveraging pulsars in energy systems are outlined in Figure 4.

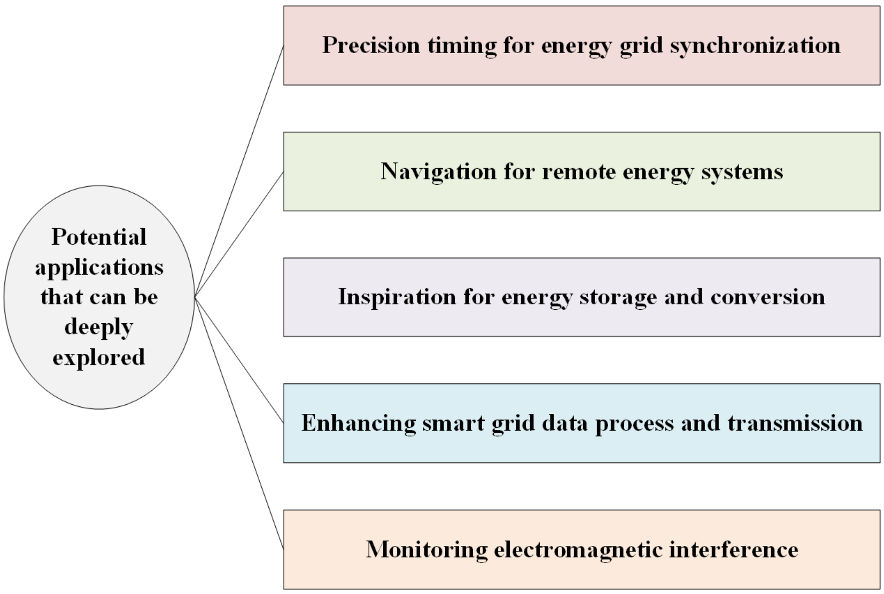

Figure 4. Potential applications of pulsar in energy systems.

In terms of precision timing for energy grid synchronization, pulsars can be the natural clock, which provides accurate time references for energy grid synchronization. The reliability of the natural clock will improve the stability and efficiency of energy system networks, especially in interconnection networks with fluctuations in renewable energy.

In terms of navigation for remote energy systems, similar technologies like X-ray pulsar-based navigation (XNAV) [17–19] could be applied to manage and monitor the energy infrastructures in remote areas such as offshore wind farms, unmanned solar power stations, and energy equipment in the deep sea. They could be the backup or substitute for a global positioning system (GPS) to reduce the amount of external infrastructure.

In terms of inspiration for energy storage and conversion, the energy release mechanism of pulsars can inspire the next generation energy system's energy storage and conversion. For example, we can find solutions for high-density energy storage [20–24] based on the extreme environment of pulsars.

In terms of enhancing smart grid data processing and transmission, the principles of pulsar data processing and transmission could be applied to improve the speed and reliability of data processing and transmission in energy systems, especially for long-distance situations.

In terms of monitoring electromagnetic interference, pulsar signals can be used to detect the interference factors [25–27] in energy systems by using signal comparisons with ideal or templated pulsar signals. Researchers can identify and reduce the interference sources that affect the performance of sensitive energy equipment by investigating the interactions between the observed pulsar signals and local environments.

Taking the energy system types as the classification index may help us realize the application potential of pulsars in energy systems.

- Distributed energy systems: pulsars' precision timing capabilities can be applied to synchronize distributed energy systems, such as interconnected renewable energy networks, ensuring stability and efficiency, particularly in regions with high fluctuations in energy output.
- Remote energy infrastructures: Technologies like X-ray pulsar-based navigation (XNAV) can be used to monitor and manage energy infrastructures in remote areas, including offshore wind farms, unmanned solar power plants, and deep-sea energy facilities. Pulsars serve as a reliable backup or substitute for GPS, reducing reliance on external infrastructure.
- High-density energy storage systems: The energy release mechanisms of pulsars inspire advancements in next-generation energy storage and conversion technologies. For example, pulsar-inspired systems can address challenges in high-density energy storage for extreme environments.
- Smart grid systems: pulsar data processing and transmission principles can enhance smart grids by improving the speed and reliability of data transfer, particularly over long distances or in scenarios with fluctuating grid demands.
- Electromagnetic-sensitive energy systems: By comparing pulsar signals with ideal templates, researchers can detect and mitigate electromagnetic interference in sensitive energy equipment. This application ensures the reliable performance of energy systems exposed to high electromagnetic disturbances.

3.2. The New Scenario in the Energy System: Pulsar-Based Location of Mobile Storage for Energy Systems

Detailly, Figure 5 shows the pulsar-based location for energy systems' mobile storage. The radio telescope is used to capture the pulsar signals, and pulsar-based location technology (the communication position unit) [28,29] is responsible for providing the position information of the corresponding mobile storage. These energy storage units transfer energy between different locations, and they are dynamically scheduled according to the demands and energy prices of different locations of the energy system [30]. During this process, the pulsar-based location technology gives the location information of the corresponding mobile storage, which is the important variable of the optimal model for improving economic benefits. Pulsar-based navigation determines position by recording pulsar signal arrival times, correcting for motion, and comparing with predicted values. Discrepancies adjust position and velocity iteratively until accurate. Three pulsars enable 3D positioning; more improve time precision.

Considering the size of the radio telescope, initial implementations of mobile storage units can use a combination group. In this approach, a specialized vehicle carries the radio telescope, while additional vehicles transport the energy storage units. These vehicles move in close proximity to share a common location reference. As pulsar-related technologies evolve, more compact radio telescopes are expected, potentially solving space-time optimization challenges in dynamic energy systems [31]. Future advancements could expand the role of pulsars, enabling them to act not only as timing sources but also as positioning guides for next-generation energy systems.

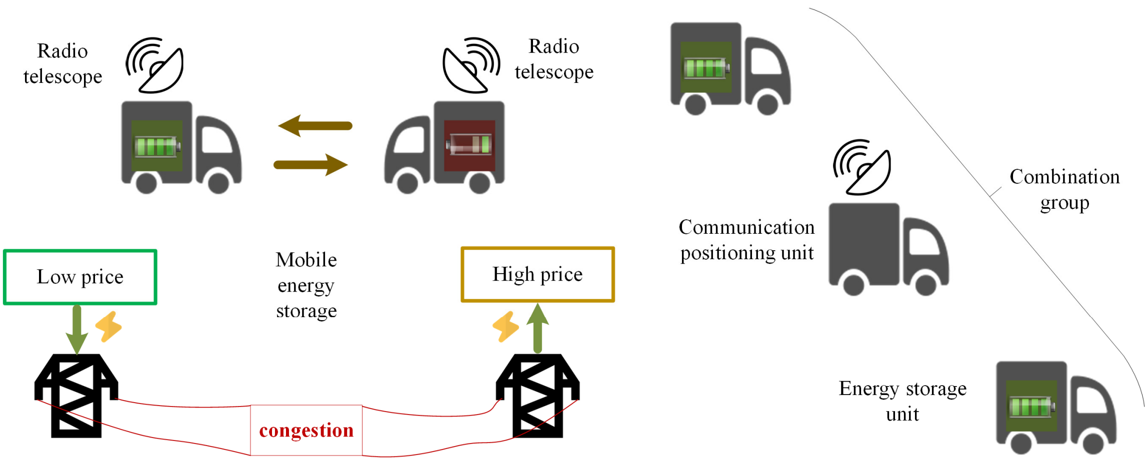

Figure 5. Pulsar-based location of mobile storage for energy systems.

3.3. The New Opportunity Brought by the New Technology: Data Sonification of Pulsar Data

Because of the complexity of the pulsar-related research issues, there are great demands for concept explanations, the presentation of relationships, and mechanism investigations. Therefore, it will be very helpful if there are tools that help people to better understand and explore the influences of pulsar's different types, parameters, and dynamic processes on the performance of its applications.

Fortunately, related areas' views, thoughts, tools, devices, and technologies—such as artificial intelligence [32–37]: computer vision [32], graph generative models [33], convolutional neural networks [34], artificial intelligence safety [35], back propagation neural networks [36], and Bayesian models [37]; data presentation: data visualization [38], data sonification [39], cluster sampling [40], digital twin [41]; and human–machine interactions: human feedback system [42], human–robot interaction [43], and environment simulators [44]—may open up a new way to accelerate the process of developing convenient pulsar research tools.

The following content is a sample based on a new approach to contribute to pulsar search tools that are used for familiarization with pulsars' undiscovered characteristics. Data sonification [39] technology is used to translate pulsar profile data into the sounds. Taking the J1939+2134 (B1937+21), for example, data can be collected from the online resources shown in Table 1; the related parameters of different conditions are shown in Table 3. In Table 3, "poln" means polarization, which is often used to describe the polarization status information of observed pulsars [45–47]. "DM" means the dispersion measure, which is the important parameter used to describe the dispersion effect [48–50]. "RM" means rotation measure [51–53], which is the parameter that measures the degree of Faraday rotation undergone by a polarized signal as it travels through the magnetized interstellar medium (ISM). The "receiver" and "back-end" are essential components of the radio telescope system, and they are responsible for the front-end and back-end jobs, respectively. The former is used to receive and amplify the pulsar signal so as to provide a high-quality signal input, and the latter is used to extract scientific information such as the pulsar period [54–57].

Then, according to the reflection rules [39], the pulsar's data can be translated into sounds or music. The corresponding data sonification results are shown in Figure 6. In Figure 6, the pulse profile intensities are mapped to musical pitches, which provides a novel way to analyze pulsar data. We can distinguish the classical profile shown in Figure 2 from that in Figure 6. In terms of "music", people use it to discover the hidden patterns that may be ignored by our eyes [58].

Table 3. Related parameters of data on J1939+2134 (B1937+21).

Condition	1	2	3	4	5	6	7
site	lovell	parkes	parkes	lovell	effelsberg	effelsberg	parkes
freq (MHz)	610	728	1369	1410	1579	1610	3100
poln	stokes	stokes	stokes	stokes	intensity	intensity	stokes
DM ($cm^{-3}pc$)	71.04	71.02	71.02	71.04	71.04	71.04	71.02
RM ($radm^{-2}$)	−10	6.7	6.7	−10	0	−10	6.7
T_{obs} (s)	~0	~95,392	~177,949	~0	~0	~0	~165,639
receiver	undefined	1050 cm	multi	undefined	undefined	undefined	1050 cm
back-end	undefined	caspsr	Pdfb3	undefined	undefined	undefined	pdfb3

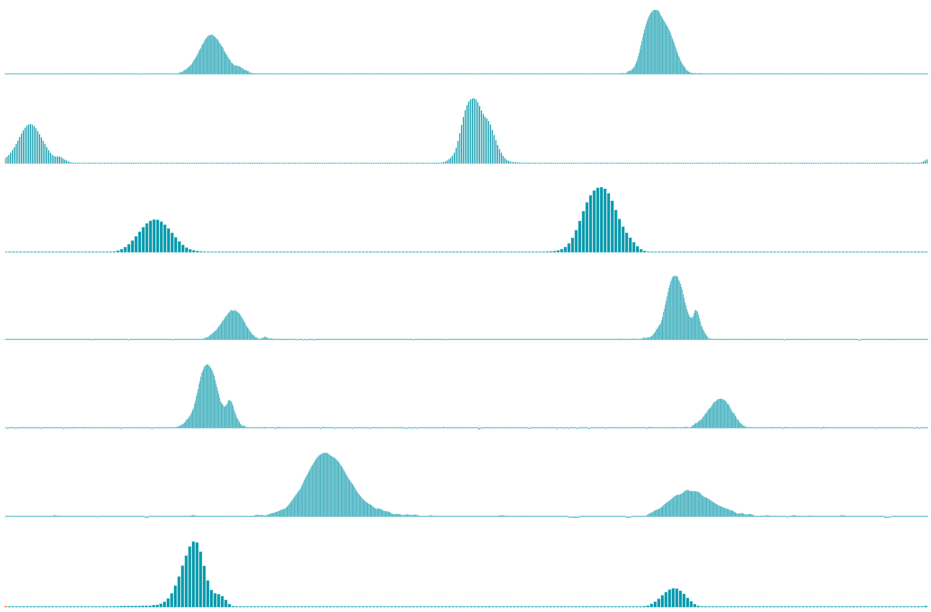

Figure 6. Data sonification results (musical scale) of profile data of pulsar J1939+2134 (B1937+21): (**a**) Condition 1; (**b**) Condition 2; (**c**) Condition 3; (**d**) Condition 4; (**e**) Condition 5; (**f**) Condition 6; (**g**) Condition 7.

On the astrophysics side, sound is favored for discovering more patterns [59]. A research result shows that real-time auditory feedback has the potential to improve operator accuracy, although achieving acceptance remains a challenge [60]. So, adding training for the pulsar sound analyzers makes sense. By doing this, pulsar sound analyzers may improve the ability to obtain information from the sounds by training. It should be noted that the sounds we generate based on pulsar data are not only heard by humans but also "heard" by the machine or robots [61]. Considering the noise in pulsar data [62–64], comparing ideal noiseless pulsar signals with noisy data through sound and waveform analysis offers a unique opportunity to identify interesting patterns. These insights could enhance pulsar signal analysis and improve practical applications. This process can be implemented in hardware devices integrated into pulsar-based energy systems.

To address the complexity of pulsar-related research and its potential applications in energy systems, we explore how pulsar characteristics can directly benefit energy system performance.

Pulsar characteristics and their roles:

- Polarization (“poln”): Describes the polarization status of pulsar signals, which is essential for minimizing signal interference. In energy systems, this characteristic can improve the reliability of communication channels in noisy environments.
- Dispersion Measure (“DM”): Represents the dispersion effect caused by the interstellar medium, critical for ensuring signal accuracy over long distances. For energy systems, accurate “DM” calibration can optimize data transmission across distributed grids.
- Rotation Measure (“RM”): Measures the effect of magnetic fields on pulsar signals. In energy systems, “RM” can be utilized to monitor and detect anomalies in electromagnetic environments, such as power grids with fluctuating magnetic fields.

3.4. The New Tool: AI-Driven Pulsar Signal Recognition

The integration of machine learning into pulsar signal recognition has greatly enhanced efficiency and accuracy. A bispectrum-based pulsar identification method [65] employs high-order spectrum analysis and deep convolutional neural networks (GoogLeNet) for improved noise suppression and feature extraction. Validated with Rossi X-ray Timing Explorer (RXTE) data, this approach has demonstrated high performance in X-ray pulsar signal identification for deep-space exploration. Commonly used algorithms in this field include Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), Decision Trees, and Ensemble Learning techniques [66], which are also adaptable for radio signals in pulsar searching and timing applications.

Considering there are many concepts in this review, further discussion about the use of pulsar technology in renewable energy systems can be found in Appendix A.

4. Challenges

The potential applications of pulsars in energy systems offer promising opportunities, but understanding the challenges is essential for assessing current limitations and guiding future efforts.

4.1. The Complexity of the Technology

It is obvious that we face the requirement of high accuracy in pulsar’s application, considering that there exist mature competitors such as global positioning system (GPS) [67] with excellent performance. This also raises stringent requirements for the front-end and back-end equipment of pulsar signals. Another complex problem may from the weak intensity of pulsar signals. So, there is a need for highly sensitive equipment to capture the weak pulsar signals. The pulsar signal process is related to complex calculation and modeling; therefore, the real-time process ability to deal with the pulsar signals is critical because of the real-time response and adjustment of the energy system. It will call for progress in big data process methods and advanced calculated algorithms. Otherwise, delays will happen, which influences and has effects for application.

4.2. The Interference of the Environment

It cannot be ignored that there is electromagnetic noise exists in the energy system, especially in the high-voltage transmission lines [68–70], equipment [71,72], and electric load [73]. Hence, we have to develop a specific anti-electromagnetic interference device for the pulsar’s application in the energy system. Other challenges may arise from the weather and geographical environment of the pulsar implementation site. Unfortunately, the existing layout of the energy system may not consider the new pulsar application’s join. Certain geographic regions, such as cities and abnormal humidity and temperature areas, may pose challenges to signal reception.

4.3. The System Integration

Integrating pulsar-related technologies into the existing energy system requires the design of a new interface and protocol [74,75], which may cause a large number of reconstructions of infrastructure. The energy storage equipment and other loads may have a dynamic status; how to coordinate them with the pulsar's application is another challenge that we do not have sufficient experience with. The conflict and resolution between pulsar applications and existing applications in energy systems are also thought-provoking issues. Considering how it is an emerging technology, there is also a lack of cross-departmental cooperation and international standards. Furthermore, we are in situations without corresponding policy support and regulatory framework. In addition, like in other new applications before integration into the energy system, it is very important to conduct safety and reliability checks. Therefore, strict tests and identification are necessary to ensure the safe and stable operation of the energy system with the pulsar's application.

4.4. The Economic Cost

Considering that the status of the pulsar's application in the energy system is still in the initial stage, there is a lack of a clear business model to assess the return on investment. The costs of constructing and adjusting the pulsar's application-related equipment are hard to neglect [76,77]. We can look forward to cost reduction in the future due to technological advancements. However, this is an important issue concerning whether pulsar technology and its applications can gradually develop in the energy system. In the beginning, more meaningful and forward-looking research can be conducted to enhance the value and credibility of the pulsar's application in energy projects. Additionally, it is worth exploring recycling and reduction technologies to lower potential costs, thereby further alleviating investors' concerns about waste.

4.5. Technology Popularization

The pulsar's application in the energy system involves knowledge from different subjects, such as electrical engineering [78], communication engineering [76], astrophysics [79], and data science [80]. This requires researchers and engineers equipped with interdisciplinary thinking and a comprehensive knowledge system, and the number of talented individuals who can go through such strict screening is currently insufficient. On the other hand, the acceptance level and trust level of the decision-makers and operators from the energy industry on pulsar's application in the energy system may affect the technology's popularization. Because there is a lack of a successful project about pulsar's application in the energy system, it will take a certain amount time to build a mature environment and system of trust.

5. Response Strategies

In response to the aforementioned challenges, corresponding response strategies are provided here to provide a reference for future research.

5.1. Technical Aspects

Considering the complexity of the technology, existing pulsar signal processing algorithms should be optimized to handle large-scale data more efficiently and reduce computation time, in order to meet the real-time requirements of energy systems. This can be achieved by introducing artificial intelligence and machine learning technologies, such as designing adaptive signal filters, optimizing model parameters, and improving computational efficiency. In addition, developing distributed computing architectures [81] can enhance computational capacity while reducing costs.

Considering the environmental interference, the ability to capture weak pulsar signals can be enhanced by developing more sensitive receivers and antennas. At the same time, devices should be designed with stronger anti-interference capabilities to effectively reduce the impact of electromagnetic noise from energy systems and external environmental interference. This may involve innovative integration of materials science [82], electronic engineering [83], and signal enhancement technologies [84].

Considering the dynamic characteristics of the energy system [85,86], an adaptive pulsar signal optimization system [87] should be designed to ensure stability and accuracy of the application in complex environments.

5.2. Disciplinary Cooperation

Taking this interdisciplinary research topic into consideration, it will be helpful to facilitate deep collaboration among astronomy, energy engineering, and computer science to integrate the strengths of different fields. For example, astronomers can provide expertise in pulsar signal analysis, energy engineers can address system integration challenges, and computer scientists can develop efficient algorithms and computing platforms.

In terms of institutes, setting up dedicated and interdisciplinary research centers or laboratories to concentrate resources on solving key challenges in pulsar technology, while also cultivating versatile talents capable of meeting the demands of multiple disciplines, should take place.

The importance of international collaboration [88,89] on pulsar's application in the energy system cannot be denied. The following strategies may improve our ability to deal with the problems we face in pulsar's application in the energy system: collaborate with international academic institutions, energy companies, and technology development teams to share research findings and practical experiences, jointly advancing technological progress.

5.3. Support Mechanisms

The start can take place in the manner of a pilot project [90]. With the demonstration of the application effects, not only can it verify the feasibility of the technology, but it can also reduce initial costs through economies of scale and accumulate experience for subsequent promotion.

Another effort that can be made is to explore the commercial integration [91] of pulsar technology and energy management, such as deep integration with smart grids, energy storage optimization, and power trading platforms. Through commercial operation, we can gradually achieve the recovery of technology costs and sustainable development.

Other possible help may come from policy and regulation; for example, encouraging the energy industry to prioritize the adoption of high-tech solutions and establish technical standards for the development and application of pulsar technology.

On the enterprise side, providing tax exemptions, funding subsidies, or research and development incentives to enterprises or projects that adopt pulsar technology, and motivate industry participants to accelerate the implementation and application of related technologies, can be enacted. At the same time, policies will guide the energy industry to actively explore new models that combine with pulsar technology.

It is essential to establish regulatory and evaluation mechanisms [92,93] to support development. Standardizing and regulating the use of pulsar technology in the energy sector will ensure safety and effectiveness. Furthermore, establishing a scientific technology evaluation system will provide critical data for continuous optimization.

6. Conclusions

The application of pulsar technology in energy systems presents a transformative opportunity to enhance precision, reliability, and resilience. This review highlights the potential of pulsars, as natural cosmic clocks, to address critical challenges in synchronization, navigation, and interference monitoring within energy infrastructures.

The integration of pulsar-based timing systems, as demonstrated in recent studies, offers a robust alternative to conventional timekeeping systems like GPS [1,2]. These systems can ensure stability and accuracy in grid synchronization and facilitate dynamic energy distribution even under challenging conditions. The novel applications of pulsar signals, such as mobile energy storage positioning and data sonification, further underscore the adaptability and versatility of pulsar technology in diverse energy scenarios.

However, significant challenges remain. Technical complexities, including weak signal reception and high accuracy requirements, necessitate advancements in signal processing and hardware development. Environmental interference, system integration issues, and high economic costs also pose substantial hurdles to widespread adoption. Moreover, the interdisciplinary nature of this field highlights the need for cross-sector collaboration and skill development.

In response to these challenges, this review proposes strategic solutions spanning technical optimization, interdisciplinary collaboration, and policy support. Enhancing computational efficiency, fostering collaboration among astronomy, engineering, and data science, and implementing pilot projects with supportive regulatory frameworks are critical for accelerating the adoption of pulsar technology in energy systems.

Despite these challenges, the potential benefits of pulsar technology—ranging from improving grid stability to enhancing the economic efficiency of the energy system—make it a promising frontier for future energy systems. With ongoing research and innovation, pulsar technology could play a pivotal role in shaping a sustainable, efficient, and resilient energy landscape.

Author Contributions: Conceptualization, Y.Z., Y.W., Y.L. (Yu Liu) and Y.L. (Yilu Liu); methodology, B.S., J.Y., N.L.T., K.I.A. and Y.L. (Yilu Liu); investigation, Y.Z., Y.W., Y.L. (Yu Liu), Q.L. and C.S.; writing—original, Y.Z., Y.W., Y.L. (Yu Liu) and Y.L. (Yilu Liu); draft preparation, Y.Z., Y.W., Y.L. (Yu Liu), Y.L. (Yilu Liu), B.S. and J.Y.; supervision, Y.L. (Yilu Liu). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Science Foundation under NSF Award Number EEC-1920025.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

DAC	digital-to-analog converter
DM	dispersion measure
GPS	global positioning system
ISM	interstellar medium
PBTI	pulsar-based timing instrument
PMU	phasor measurement unit
PPS	pulse per second
RM	rotation measure
XNAV	X-ray pulsar-based navigation

Appendix A. A Discussion About the Use of Pulsar Technology in Renewable Energy Systems

On the use of pulsar technology in renewable energy systems: Pulsars are highly regular astronomical sources that emit electromagnetic radiation with remarkably stable periodicity. This unique property allows pulsars to be used as highly accurate timing sources, generating precise time signals, such as Pulse Per Second (PPS) signals. These can serve as a backup to GPS timing, which is critical for maintaining the synchronization accuracy of Phasor Measurement Units (PMUs). PMUs play a vital role in monitoring and controlling power systems, including those incorporating renewable energy. They are used to measure electrical waveforms in real time, providing crucial data on voltage and current phase angles. Since renewable energy sources often exhibit rapid dynamic behavior due to their intermittent and variable nature, PMUs enable the monitoring of these dynamics and facilitate the secure and economic operation of the power grid. While the application of pulsar technology directly to renewable energy systems has not been reported in the literature to date, its use as a timing source for PMUs demonstrates its indirect relevance to renewable energy system operation. With advancements in this field, we believe pulsar technology could be applied directly in renewable energy systems, especially when current bottlenecks—such as the deployment cost, technological readiness, and integration challenges—are overcome.

On detailing minimal requirements for implementing pulsar technology in renewable energy systems: At present, no concrete implementation of pulsar technology directly within renewable energy systems has been documented. However, for such integration to be feasible, several minimal requirements would need to be satisfied:

- High stability and reliability: the timing system must be robust to environmental disturbances, providing synchronization accuracy comparable to or better than GPS.
- Cost-effectiveness: the technology must demonstrate economic advantages over existing timing solutions, particularly in large-scale renewable energy applications.
- Interoperability: the timing signals generated by pulsars must seamlessly integrate with existing power system monitoring and control infrastructure.

A case study demonstrating the use of pulsar-based timing in a PMU network monitoring a renewable energy system is indeed an exciting avenue for future work.

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