

Powering the Future: IoT-Enabled Smart Grids for Sustainable Energy Systems



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Abstract The increasing demand for sustainable, reliable, and efficient energy systems necessitates innovative solutions. Internet of Things (IoT) technology has emerged as a promising tool, particularly in the context of Smart Grids, enabling enhanced control, efficiency, and sustainability. This paper aims to delve into the potential of IoT in revolutionizing power systems, with a focus on IoT-enabled Smart Grids as a pathway towards sustainable energy systems. We explore various IoT technologies applicable to power systems, discuss their roles in enhancing the functionality of Smart Grids, and provide tangible examples through case studies of successful implementations. Furthermore, we address the challenges involved in integrating IoT into power systems and propose potential solutions. Ultimately, we aim to provide a comprehensive overview of the transformative potential of IoT in power systems, emphasizing its critical role in steering the future of sustainable energy. The findings from this paper are expected to provide valuable insights for policymakers, energy providers, and researchers in their pursuit of sustainable energy solutions.

Keywords Internet of Things · Smart grids · Sustainable energy · Renewable energy technologies · Innovative digital technologies

1 Introduction

The world's power systems are currently at an inflection point. Traditional energy infrastructures, primarily built around fossil fuels, have served us for many decades. However, they're increasingly proving to be unsustainable due to their significant contribution to greenhouse gas emissions and the resulting climate change. Moreover, these conventional power systems often suffer from inefficiencies and vulnerabilities, leading to wastage of resources and occasional disruptions in energy supply

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[1]. Table 1 depicts the basic differences between the traditional grid and the IoT-enabled smart grid [2]. In recent years, the impacts of climate change have become more apparent and alarming, underlining the urgency to transition towards more sustainable energy systems [3]. Sustainability in this context doesn't only mean reducing carbon emissions but also improving energy efficiency and ensuring reliable and equitable access to energy for all. There's a growing recognition that our future energy systems need to be flexible, resilient, and able to accommodate diverse, often decentralized, energy sources [4]. Renewable energy technologies, such as wind, solar, and hydropower are expected to play a crucial role in this transition [5]. However, integrating these variable energy sources into the grid in a reliable and efficient manner poses significant challenges [6].

In this transformative scenario, innovative digital technologies, like the Internet of Things (IoT) have emerged as potential game-changers. By connecting and automating diverse elements in the power system, from generation and transmission to distribution and consumption, IoT offers promising avenues to improve system efficiency, resilience, and adaptability.

The IoT is a revolutionary concept that has permeated almost every sector of our lives, and the power industry is no exception. At its core, IoT is about connecting devices over the Internet, enabling them to collect, send, and receive data [7]. This seamless interconnectivity allows for unprecedented levels of automation and efficiency, making IoT a significant driver in the digital transformation wave. IoT in power systems refers to a network of interconnected devices, sensors, and systems across the entire energy value chain, from generation and transmission to distribution and end-use. These IoT devices gather real-time data, communicate with each other, and can automate decision-making processes, thereby enhancing efficiency,

Table 1 Traditional versus IoT-enabled smart grid

	Traditional grid	IoT-enabled Smart Grids
Metering	Electromechanical, solid state	Digital/Microprocessor
Communication	One-way and local two-way	Global/Integrated two-way
Customer interaction	Limited	Extensive
Generation	Centralized	Centralized and distributed
Power flow control	Limited protection, monitoring and control systems	Wide area monitoring protection and control, adaptive protection
Monitoring	'Blind'	Self-monitoring
Restoration	Manual	Automated, 'self-healing'
Operation and maintenance	Check equipment manually	Monitor equipment remotely
Control	Limited control system contingencies	Pervasive control systems
Reliability	Estimated: Prone to failures and cascading outages	Predictive: Pro-active real-time protective and islanding
Topology	Radial	Network

reliability, and flexibility in power systems. For instance, IoT can aid in real-time monitoring and management of power generation from various sources, including renewables, to optimally match supply with demand. In [8], the authors highlight the essential function of IoT in the monitoring and management of solar photovoltaic power production. IoT is depicted as a tool for enhancing the operational efficiency, surveillance, and maintenance of solar energy stations, largely due to its capability to enable remote control and observation via online platforms. This becomes increasingly useful for solar facilities in hard-to-reach areas where traditional monitoring is challenging.

Further, in energy systems, IoT has also been deployed for predictive maintenance of power equipment, reducing outages and extending equipment life. Researchers in [9] have proposed a self-sustaining IoT solution for live tracking of various parameters in a high-voltage substation connector, termed as the Smart Connector. This innovative connector variant includes a thermal energy harvesting system, which powers a microcontroller that operates a transmitter and an array of electronic sensors. These sensors assess the temperature, current, and voltage drop across the connector, enabling the calculation of the connector's electrical contact resistance (ECR). The captured data are wirelessly transmitted to a nearby gateway via a Bluetooth 5 module. The gateway then relays this information to a database server for storage, in-depth analysis, and display. This IoT solution eases predictive maintenance in substations.

In addition to this, IoT supports advanced metering infrastructure (AMI), providing utilities and consumers with granular energy usage data, facilitating demand response programmes and energy efficiency. AMI, a vital part of modern grid systems, has seen substantial growth and now extends to almost half of all meters across the United States, as reported in [10]. The AMI enables bidirectional communication for the exchange of information such as energy use, power outages, and electricity tariffs between smart meters and utility companies. Research is also very active in the protection of AMI data. A thorough review of privacy-related research within the Internet of Everything, a larger version of IoT (IoE)-enabled smart grid environment has been provided in [11]. The analysis of privacy issues and their corresponding solutions within the AMI framework has been formulated.

Moreover, on the consumer side, IoT enables smart homes and buildings where appliances can respond to price signals or operational conditions of the grid, further contributing to system efficiency and flexibility. The authors of [12] have developed an energy management strategy using a price-based demand response (DR) programme for IoT-enabled residential buildings. This strategy involves a wind-driven bacterial foraging algorithm (WBFA). The proposed WBFA-based strategy manages power usage in IoT-enabled residential buildings by systematically scheduling the operation of smart appliances. This approach aims to reduce the peak-to-average ratio (PAR), decrease electricity costs, and enhance user comfort. As a result, energy utilization is more effective, improving the sustainability of IoT-enabled residences in smart cities.

2 Aim and Objectives

The aim of this study is to showcase the transformative potential of the IoT in advancing power systems towards a more sustainable future. Our main objectives include the investigation of specific applications of IoT technologies in different sectors of power systems, the identification of the challenges and barriers in implementing IoT in power systems, and the exploration of the future trajectory of IoT in power systems.

3 Background

In the realm of power systems, the concept of Smart Grids represents a significant leap forward from the traditional electric grid. While the conventional grid has served us well for over a century, it's been increasingly challenged by the modern demands of efficiency, reliability, and sustainability. Smart Grids, enriched by modern digital technologies like the Internet of Things (IoT), are poised to meet these challenges and revolutionize the way we generate, distribute, and consume electricity. At its core, a Smart Grid is an electricity network that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users [13]. It integrates multiple functionalities and advancements over the traditional grid, making it more intelligent, flexible, and resilient. One of the defining characteristics of Smart Grids is their two-way flow of electricity and information. Unlike the traditional one-way flow from generation to consumption, Smart Grids enable real-time interaction between utilities and consumers, improving demand response and allowing for decentralized energy production. Another key aspect is the incorporation of advanced metering infrastructure (AMI), which facilitates real-time monitoring and management of energy usage at the consumer level [14]. This not only empowers consumers to manage their energy consumption more efficiently but also provides utilities with valuable data for load forecasting and grid management. Smart Grids also support the integration of renewable energy sources and electric vehicles, enhancing the grid's sustainability and reducing its carbon footprint [15]. Furthermore, with the help of IoT, Smart Grids can leverage predictive analytics for preventive maintenance and swift fault detection, enhancing grid reliability and reducing outage times. However, the transition to Smart Grids is not without its challenges. Issues related to data privacy, security, interoperability, and regulatory frameworks need to be addressed as we move towards this promising future. Figure 1 depicts the main components of IoT-enabled smart grids.

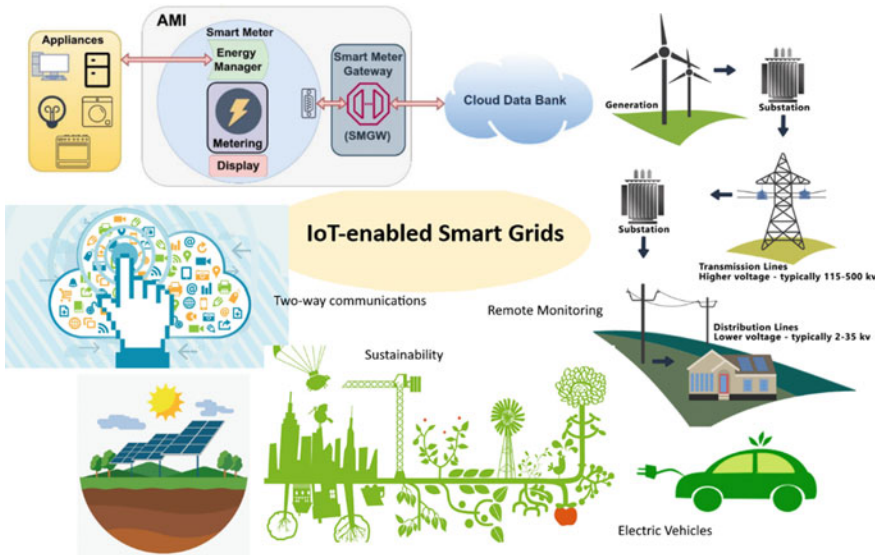


Fig. 1 Main components of IoT-enabled smart grids

4 Case Studies

The following case studies collectively illustrate the potential of IoT-enabled Smart Grids in revolutionizing the energy landscape. Whether it is in urban areas, individual households, or remote communities, IoT technologies provide the tools to optimize energy management, integrate renewable sources, improve grid reliability, and empower consumers. As these technologies continue to evolve, they present exciting opportunities for sustainable energy systems and pave the way for a smarter, greener, and more resilient energy future.

4.1 Case Study 1: Smart Grid Implementation in Austin, Texas

In Austin, a successful implementation of an IoT-enabled Smart Grid has revolutionized the power system infrastructure. In 2019, Austin Energy’s Smart Grid included 437 square mile service area, more than 500,000 residential and commercial meters, 11,651 miles of transmission and distribution line, and 74 substations [16]. Through the deployment of advanced IoT technologies, the local utility has significantly improved operational efficiency, reliability, and sustainability. One key aspect of this implementation is the integration of smart meters and IoT-enabled sensors throughout the grid. Smart meters provide real-time data on energy consumption,

enabling consumers to monitor and manage their usage effectively. This empowers them to make informed decisions, optimize energy consumption, and participate in demand response programmes, resulting in reduced peak demand and improved overall system efficiency.

IoT sensors deployed across the grid continuously collect data on various parameters such as voltage, current, and power quality. This real-time monitoring allows for the detection of anomalies and potential faults, enabling prompt response and preventive maintenance. By proactively addressing issues, the utility has significantly improved grid reliability, minimizing downtime and enhancing the overall resilience of the power system. Another notable feature of this implementation is the incorporation of renewable energy sources, such as solar and wind power, into the grid. IoT technologies facilitate the monitoring and control of these distributed energy resources, optimizing their utilization based on real-time data. This seamless integration of renewable energy sources into the Smart Grid has enabled the utility to reduce reliance on traditional fossil fuel-based generation, contributing to a greener and more sustainable energy system. Furthermore, the implementation of IoT-enabled asset management systems has played a crucial role in this case study. IoT sensors installed on critical infrastructure, such as transformers and distribution lines provide real-time data on asset health and performance. This data enables predictive maintenance, allowing for proactive repairs and replacements before failures occur. As a result, asset lifespan is extended, maintenance costs are minimized, and the overall reliability of the grid is enhanced.

Overall, this case study demonstrates the successful implementation of an IoT-enabled Smart Grid in Austin. By integrating smart meters, IoT sensors, renewable energy sources, and advanced asset management systems, the local utility has achieved significant improvements in operational efficiency, grid reliability, and sustainability. This case serves as an inspiration and blueprint for other regions aiming to leverage IoT technologies for smarter and more resilient power systems.

4.2 Case Study 2: Smart Home Energy Management System

In this case study, residents have access to a user-friendly interface that provides real-time energy consumption data for different appliances within their homes. IoT-enabled smart plugs and sensors are installed to monitor the energy usage of individual devices, providing consumers with detailed insights into their energy consumption patterns. Through the smart home energy management system, consumers can set energy usage preferences and receive real-time alerts and recommendations for optimizing their energy consumption. For example, the system can suggest adjusting thermostat settings during peak demand hours or switching to energy-efficient modes for appliances. By actively managing their energy consumption based on these recommendations, consumers can reduce their energy bills and contribute to overall energy efficiency.

Moreover, the system integrates with the utility's demand response programmes, allowing consumers to participate in load management initiatives. During periods of high demand, the utility can remotely control certain appliances, such as water heaters or air conditioning units, to reduce electricity consumption. This demand response capability not only helps balance the grid but also provides financial incentives to consumers who participate. Through this IoT-enabled smart home energy management system, consumers have greater control over their energy usage, leading to reduced wastage and improved energy efficiency. The system's integration with the utility's demand response programmes contributes to grid stability and reduces the need for additional power generation during peak periods. This case study showcases the successful implementation of IoT technologies at the consumer level, highlighting the potential of IoT-enabled Smart Grids to transform individual energy behaviours and empower consumers to actively participate in the energy transition.

4.3 Case Study 3: Microgrid Management with IoT Integration

This case study focuses on a small-scale microgrid that integrates various distributed energy resources, including solar panels, wind turbines, and energy storage systems. IoT technologies play a crucial role in the monitoring and control of these resources, optimizing their utilization and ensuring grid stability.

Through IoT-enabled sensors and control systems, real-time data on energy generation, consumption, and storage are collected and analyzed. This data enables advanced control strategies that manage the power flow, balance energy supply and demand, and ensure efficient operation of the microgrid. With IoT, the microgrid can seamlessly adapt to fluctuations in energy availability and demand, effectively integrating renewable energy sources into the grid. Moreover, IoT facilitates energy management at the individual consumer level within the microgrid. Smart meters and IoT-enabled devices provide consumers with insights into their energy usage, allowing them to track and manage their consumption. This empowers consumers to make informed decisions about their energy usage patterns and optimize their consumption based on real-time data, resulting in reduced energy waste and increased energy efficiency. Additionally, the IoT-enabled microgrid management system incorporates predictive maintenance capabilities. IoT sensors monitor the health and performance of critical components such as inverters, batteries, and transmission lines. By continuously collecting data on their condition, the system can identify potential issues before they escalate, enabling proactive maintenance and minimizing downtime. Overall, this case study demonstrates the successful implementation of IoT technologies in microgrid management, showcasing the ability to optimize energy utilization, enhance reliability, and empower consumers. Through

real-time data monitoring, predictive maintenance, and consumer engagement, IoT-enabled microgrids offer a viable solution for remote communities and areas with limited access to the main power grid.

4.4 Analysis of the Impact of These Implementations on Sustainability

The implementations of IoT-enabled Smart Grids have a profound impact on sustainability across multiple dimensions, driving significant progress towards a more environmentally responsible and socially equitable energy system.

One of the primary impacts of these implementations is the reduction of greenhouse gas emissions. By integrating renewable energy sources and optimizing their utilization through real-time data monitoring and control, IoT-enabled Smart Grids contribute to a significant decrease in the reliance on fossil fuels. This shift towards cleaner energy sources helps mitigate climate change and improves air quality, resulting in a more sustainable and healthier environment for both present and future generations.

Moreover, IoT-enabled Smart Grids promote energy efficiency, a key pillar of sustainability. The real-time data provided by IoT devices allows utilities and consumers to identify energy wastage and implement targeted energy-saving measures. Through demand response programmes, IoT-enabled Smart Grids incentivize consumers to reduce electricity consumption during peak periods, resulting in a more balanced and efficient grid operation. These efficiency gains not only reduce overall energy consumption but also optimize the use of resources, leading to cost savings and a lower environmental footprint.

Furthermore, the integration of IoT in Smart Grids enables better load management and grid optimization. By monitoring and analyzing real-time data on energy generation, consumption, and grid performance, utilities can optimize the distribution of electricity and balance supply and demand more effectively. This minimizes the need for excess generation capacity, reduces transmission losses, and ensures a more stable and reliable power supply. By maximizing the utilization of existing infrastructure and minimizing energy losses, IoT-enabled Smart Grids contribute to resource conservation and enhance the overall efficiency of the energy system.

IoT technologies also enable greater consumer engagement and empowerment, which is vital for fostering a sustainable energy culture. Through IoT-enabled devices, consumers have access to real-time energy data, enabling them to make informed decisions about their energy usage patterns. This heightened awareness empowers consumers to adopt energy-saving behaviours, adjust their consumption habits, and actively participate in the transition to a sustainable energy future. In turn, this consumer engagement drives a collective shift towards sustainable energy practices and a more sustainable society at large.

Essentially, the analysis of the impact of IoT-enabled Smart Grid implementations reveals significant contributions to sustainability. These implementations lead to reduced greenhouse gas emissions, improved energy efficiency, optimized grid operations, and enhanced consumer engagement. By promoting cleaner energy sources, optimizing energy consumption, and empowering individuals, IoT-enabled Smart Grids play a pivotal role in creating a more sustainable energy system that addresses the challenges of climate change, resource scarcity, and environmental degradation.

5 Challenges and Solutions

The implementation of IoT in power systems brings forth a set of challenges that must be addressed to fully harness its potential and realize the benefits it offers.

5.1 Challenges

One significant challenge is ensuring data security and privacy. IoT-enabled power systems involve the collection, transmission, and storage of vast amounts of sensitive data.

Protecting this data from unauthorized access, manipulation, or breaches is crucial. Robust cybersecurity measures, such as encryption, access controls, and secure communication protocols must be implemented to safeguard data integrity and maintain consumer trust in the system [17].

Interoperability poses another challenge in implementing IoT in power systems. IoT devices and systems are often developed by different manufacturers and utilize various communication protocols, making seamless integration and communication between devices complex. Establishing interoperability standards and protocols is essential to ensure compatibility and enable seamless data exchange and cooperation between different devices and systems within the power ecosystem [18].

The scalability and complexity of IoT deployments in power systems can also be challenging. As the number of IoT devices and sensors increases, the management, maintenance, and scalability of the infrastructure become more intricate. Establishing robust network architectures, scalable data storage solutions, and effective device management protocols are crucial to handle the growing volume of IoT devices and ensure the seamless operation of the system [19].

The regulatory and policy framework is another challenge in implementing IoT in power systems. The evolving nature of IoT technologies often outpaces the development of regulations and policies that govern their implementation. Ensuring appropriate regulatory frameworks that address data privacy, cybersecurity, interoperability, and other key aspects is essential to foster trust, encourage investment, and enable the widespread deployment of IoT technologies in power systems [20].

Finally, there is the challenge of managing the transition from legacy systems to IoT-enabled infrastructure. Many existing power systems have been in operation for decades and may not have been designed with IoT integration in mind. Retrofitting existing infrastructure to accommodate IoT technologies requires careful planning, coordination, and investment. Ensuring a smooth and cost-effective transition while minimizing disruptions to the existing system poses a significant challenge.

5.2 Solutions

Addressing the challenges associated with implementing IoT in power systems requires proactive solutions and collaborative efforts from various stakeholders. Here are some proposed solutions to overcome these challenges:

Data Security and Privacy: Implement robust cybersecurity measures to safeguard data integrity and privacy. This includes encryption, secure communication protocols, access controls, and regular security audits. Establish comprehensive data governance policies and compliance frameworks to ensure data protection and privacy rights are upheld.

Interoperability: Develop and adopt common standards and protocols to enable seamless integration and interoperability among different IoT devices and systems. Collaboration between manufacturers, industry alliances, and standardization bodies is crucial to establish open and interoperable frameworks.

Scalability and Complexity: Design scalable network architectures and data storage solutions to handle the growing volume of IoT devices and data. Implement efficient device management protocols to streamline operations, such as automated provisioning, firmware updates, and remote diagnostics. Embrace cloud computing and edge computing technologies to distribute processing capabilities and manage the complexity effectively.

Energy Consumption: Develop energy-efficient IoT devices and promote energy-saving practices in their design. Explore energy harvesting technologies, such as solar or kinetic energy, to power IoT devices. Optimize communication protocols to minimize energy consumption and implement intelligent power management strategies to ensure devices operate efficiently.

Regulatory and Policy Framework: Foster collaboration between policymakers, regulators, and industry stakeholders to develop agile and adaptive regulatory frameworks that keep pace with IoT advancements. Establish clear guidelines and standards for data privacy, security, interoperability, and consumer protection. Encourage information sharing and dialogue to facilitate a harmonized approach to regulation across different jurisdictions.

System Transition: Develop comprehensive transition plans that encompass legacy system upgrades and the integration of IoT technologies. This includes conducting thorough system assessments, identifying areas for IoT implementation, and

creating roadmaps for phased deployment. Provide financial incentives and regulatory support to facilitate the transition process and minimize disruptions to the existing infrastructure.

6 Conclusion and Future Perspectives

This paper has explored the theme of IoT in power systems and its implications for sustainable energy systems. It has provided insights into the concept of smart grids, the importance of IoT in their implementation, and the benefits and challenges associated with IoT-enabled smart grids. The findings highlight the significant role of IoT in optimizing energy management, enhancing grid reliability, and promoting sustainability in the power sector. By leveraging IoT technologies, we can pave the way for a greener, more efficient, and sustainable energy system for the future. In addition to this, the future of IoT-enabled Smart Grids holds immense potential for further advancements and transformative developments in the power sector. As technology continues to evolve and new possibilities emerge, several areas of future development can be anticipated:

1. **Advanced Energy Management Systems:** IoT-enabled Smart Grids will witness the emergence of more sophisticated energy management systems. These systems will leverage artificial intelligence, machine learning, and advanced analytics to provide real-time insights into energy usage patterns, predictive load forecasting, and optimized energy distribution. They will enable proactive energy management strategies, demand response programmes, and autonomous decision-making to enhance grid efficiency and reliability.
2. **Decentralized Energy Systems:** IoT technologies will play a crucial role in the proliferation of decentralized energy systems. As renewable energy sources like solar and wind become more widespread, IoT-enabled devices will facilitate their seamless integration into the grid. Peer-to-peer energy trading platforms, enabled by blockchain technology, may emerge, allowing consumers to directly exchange energy and enable a more decentralized and democratized energy ecosystem.
3. **Edge Computing and Distributed Intelligence:** The proliferation of IoT devices will lead to increased data volumes, necessitating efficient data processing capabilities. Edge computing, where data is processed at the edge of the network, closer to the source, will become more prevalent. This distributed intelligence will enable faster response times, reduced latency, and improved decision-making within the Smart Grid, enhancing grid reliability and enabling real-time grid management.
4. **Enhanced Grid Resilience:** IoT-enabled Smart Grids will continue to enhance grid resilience through advanced monitoring and control systems. IoT devices, sensors, and analytics will provide real-time data on grid conditions, asset health, and potential disruptions. Predictive maintenance and fault detection algorithms will enable utilities to proactively address issues and minimize downtime. The

integration of microgrids, energy storage systems, and smart grid islanding capabilities will further enhance grid resilience during natural disasters or other emergencies.

5. **Electrification of Transportation: IoT-enabled Smart Grids** will support the growing adoption of electric vehicles (EVs). Charging infrastructure will be integrated with the Smart Grid, allowing for dynamic charging optimization, load management, and vehicle-to-grid (V2G) capabilities. V2G technology will enable EVs to provide grid support services by feeding excess energy back into the grid during peak demand, further balancing the load and enhancing grid stability.
6. **Enhanced Consumer Engagement:** IoT technologies will empower consumers with more interactive and personalized energy experiences. Smart home devices and applications will offer consumers real-time energy data, personalized energy insights, and smart energy management features. Virtual assistants and voice-controlled devices will allow seamless control over energy usage, enabling consumers to optimize their consumption patterns and participate actively in demand response programmes.
7. **Integration with Smart Cities:** IoT-enabled Smart Grids will form an integral part of smart city initiatives. Integration with smart city infrastructure, such as intelligent street lighting, smart buildings, and urban mobility systems will enable holistic energy management and optimization at the city level. The integration of IoT technologies will enable cross-domain data sharing and coordination, leading to energy-efficient and sustainable urban ecosystems.

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