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Intelligent Communication and Advanced Technologies for Smart Hydrogen Energy Networks: A Brief Review

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Abstract. Hydrogen is being recognized as pivotal to clean and sustainable energy systems around the world. Nevertheless, in practice it has been challenging to successfully combine techniques for hydrogen production, storage and utilization due to the complexity of systems involved, which are very dynamic depending on operating conditions. This article reviews the most recent advance in artificial intelligence (AI) and communications technology for managing hydrogen energy. AI techniques (e.g. machine learning, predictive control) will advance the optimisation of systems, fault prediction and energy performance. Meanwhile, communication networks and IoT platforms enable the real-time control, data sharing and orchestration across the entire hydrogen value chain. The combination of intelligent sensors and an smart communication system increases the confidence, scalability, and operational sophistication of a Siemens IoT sensor. The study further highlights current research gaps, including data management, connectivity, and security, as well as future opportunities for research, such as on digital twins, edge computing, and IoT communication technologies. In practice, AI and communication technologies are one important direction towards smart and sustainable hydrogen energy systems.

1. Introduction

The shift toward low carbon energy systems is progressing global and hydrogen appears to be an important option for achieving ambitious decarbonization pathways as well as enabling long-term environmental friendly energy solutions. As an energy containing medium, hydrogen is quite adaptable to multiple usage, like the integration of renewable energies, large scale storage of electricity and transport and industry decarbonization [1]-[3]. Although, as the saying goes, Fast growing hydrogen economy ushers in flexible and robust energy but on the one hand raises new questions of how to handle production/storage/distribution/usage in large scale while its system grows inevitable complex along with variable operation condition changes. In order to control and optimize HESs effectively, we argue such smart computation-based real-time monitoring and predictive control, as well as cross-system coordination have to be supported by reliable communication infrastructures [4], [5], [6]. H 2 OPT Artificial Intelligence (AI) and high-performance data-driven computing are increasingly necessary for optimization of hydrogen systems [7]. AI methods, such as ML, DL and RL have been well studied and implemented in the policy of electrolyzer control [8], [9], renewable power prediction, fault diagnosis, and energy optimization. They enable us to take data-driven decisions and thereby drive results, increase risks

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and install confidence through the entire hydrogen value chain. On the other hand, comms and IoT frameworks create the links that connect sensors, actuators, and controllers across different places in distributed hydrogen infrastructures [11]. The latest technologies in mobile communications (e.g., 5G, Low-Power Wide-Area Networks, OPC-UA) represent key components in real-time data collection and failure detection systems for IoT architectures, contributing to the overall automation of processes [16]. Computing at the edge and in the Cloud might also provide support for big data processing for training models, identifying anomalies, and optimising systems [12].

Leveraging AI and IoT to create intelligent hydrogen energy production networks (SIHENs) smart, highly interconnected ecosystems that learn, adjust, and change [13]. Through the combination of machine learning power and IoT-based telecommunication infrastructure, SHRs could enable advanced features such as predictive maintenance, adaptive consumption control, and systemic optimization of hydrogen production and demand [8]. In this way, the integration of data and telecommunication represents a crucial developmental progression towards a more sustainable and autonomous hydrogen infrastructure.

This review attempts to summarize recent development of AI and communication technologies for hydrogen energy networks. The paper explores:

(i) AI-supported calculation for optimization level and fault detection of Hydrogen System,
(ii) communications and IoT platforms for real-time control,
(iii) integrated design of intelligent hydrogen networks,
(iv) limitations and open issues, such as cyber security, interoperability and data.

The rest of this paper is organized as follows: in section 2, an overview of the existing works and the main relevant topics. Section 3 introduces the concept and digitalization of hydrogen energy networks. Section 4 is devoted to the main advanced communication technologies within hydrogen energy systems. It deals the role of IoT in hydrogen energy control and monitoring, the communication technologies, and the intelligent integration for smart hydrogen networks. Section 5 concludes the work.

2. Related works

Smart hydrogen energy systems include both end-use technology and hydrogen production processes. These systems combine a variety of technologies to create, store, and use hydrogen for a range of uses. In order to increase the sustainability and efficiency of smart hydrogen energy systems, numerous methods and strategies have recently been created. According to the literature review, the primary areas of concentration are control and monitoring systems, IoT, IIoT technologies, data analysis, and AI tools.

The integration of digitalization and smart technologies into hydrogen energy systems has attracted considerable research attention in recent years. Several studies have explored different aspects of this emerging field, which can be categorized into four main research directions. The following table summarizes the existing works including the main topics and their techniques and concepts.

Table 1: Review of the literature on smart hydrogen energy systems: key issues, methods, and concepts

Main topic	Main techniques/ concepts	References
Control and monitoring systems	SCADA-based techniques, predictive control, Rule-based energy management, diagnosis end fault detection,	[9], [14], [15], [16], [17]
Sensors IoT, and IIoT technologies	Sensor-based monitoring for hydrogen systems, data measurement, I-Energy, Information integration, Coordinated monitoring	[10], [11], [12] [18], [19]
Data analysis and AI tools	Predictive power management, Data-driven optimisation, AI-based diagnosis, AI-based prediction	[20], [21], [13], [22]
Network frameworks	Energy–information integration (HIES), forcasting, OPC UA and MQTT protocols, LPWAN, 5G	[22], [23], [24]

3. Hydrogen Energy Networks and Digitalization

Hydrogen energy systems comprise production, storage, transmission and application subsystems within an integrated infrastructure [9]. These networks enable hydrogen as an energy carrier for renewable integration and sector coupling. The infrastructure includes on-site production units, storage systems, distribution networks and end-use applications [24].

Successful energy management and control depend on the exchange of time-critical data and feedback signals. Digitalization, namely the convergence of data acquisition, smart communication, and computation, is necessary for large-scale hydrogen infrastructure management [25]. SHENs employ connected objects, cyber-physical systems, and intelligent sensors for the purpose of real-time surveillance and data-driven decision-making [26].

Information technology integration is used to conduct online pressure, thermal, velocity, and hydrogen quality measurements. IoT-SCADA systems make it easier to conduct predictive service, and optimize performance. The communication protocols allow for the smooth interoperability of devices and a transparent distributed control. In addition, cloud and edge computing enable large-scale data analysis and artificial intelligence-driven [14], [15].

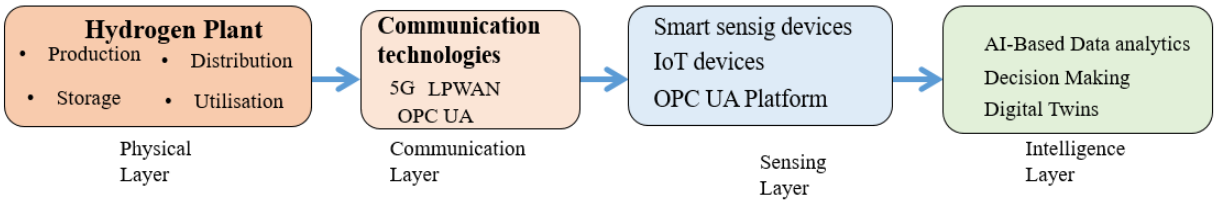


Figure 1: The general architecture of a smart hydrogen energy network

In this case, Figure 1 presents the general architecture of a smart hydrogen energy network that is composed by four layers:

- Physical Layer: this layer encompasses hydrogen generation, storage, delivery and utilization systems;
- The sensing layer: consists of intelligent sensors, IoT nodes and DAQ devices;
- Communication Layer: this layer aims to transmit securely information using wired and wireless communication links (5G, LPWAN, OPC-UA) for real-time connectivity;

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- Intelligence Layer : It focuses on critical AI, data analytics, digital twinning and decision-support solutions to optimize hydrogen plant operations.

The stacking of the layers is leading the situation where single hydrogen systems are developed to smart grids over which hydrogen also can be transported (and vice versa) automated. This transition offers increased reliability, energy flow optimization and supports 2050 net-zero and smart grid objectives [19],[20].

4. Hydrogen System Communication and IoT Technologies

New hydrogen energy networks are becoming larger and more complex; as such, robust, interoperable and intelligent communication infrastructures will be required. Such infrastructures (Figure 2) allow smooth transfer of data and control commands among production, storage, distribution and final usage sub-systems as per demand and support for real-time visualization and decision-making. In this regard, the Internet of Things (IoT) introduced as a key enabler consisting of sensors, controllers and mobile computing platforms, unified as cyber-physical system [15],[10].

4.1 IoT-Based Monitoring and Control

Neural networks are used in hydrogen systems to observe the status of the system and critical parameters like hydrogen flow, gas pressure, and temperature. Thanks to distributed sensor networks, IoT provides automated monitoring and condition-based maintenance for hydrogen filling stations [10]. While wireless standards such as ZigBee, LoRaWAN, and 5G offer scalable capabilities, other wireless networks are also available that can serve high-density, ultra-low-power devices.

Such IoT-enabled systems provide greater visibility into operations and increased flexibility in how hydrogen infrastructures respond to changing grid and demand conditions. For example, edge-computing gateways deployed close to electrolyzers or tanks can perform pre-processing of sensor data and transmit them to SCADA systems in the cloud.

4.2 Communication Architectures

Diverse communication similar to electrical networks, hydrogen networks must be diversified and accommodate a range of operational scales, from local plant operations to a nationwide hydrogen transmission network. Usually, the communication layer consists of:

- Near range protocols (ZigBee, Bluetooth, Wi-Fi) for connecting devices;
- Low-power WAN (LoRaWAN, NB-IoT and 5G) technologies for mobile transport;
- Control and interoperability Industrial protocols (OPC-UA, MQTT, Modbus) [12].

For example, to provide reliable and secure hydrogen services, the new hydrogen systems tend to use the SDN/NFV for dynamic routing and protection of data exchange [24]. These features make it possible to dynamically configure resources used in communication according to network load and requirements.

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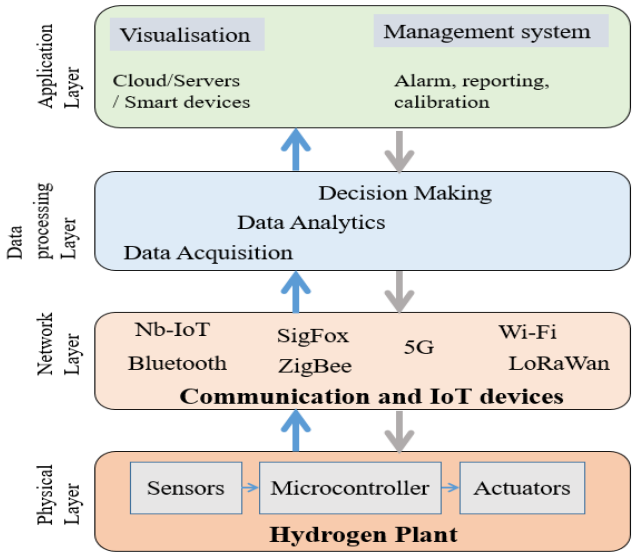


Figure 2: Advanced IoT technologies for a smart hydrogen energy network.

4.3 Digital Communication Ecosystem

Communication infrastructure is the backbone of SHENs, connecting IoT devices, digital twins and AI decision engines. Digitalization in the cloud Hydrogen assets can also be digitally represented in the form of digital twins hosted on cloud platforms, which will allow for model-based analytics and scenario simulations. The combined overall communication and IoT framework for hydrogen systems is depicted in Figure 3, which demonstrates the interfacing of physical elements through IoT gateways with cloud and edge computing layers that are utilized for data analytics along with decision-making.

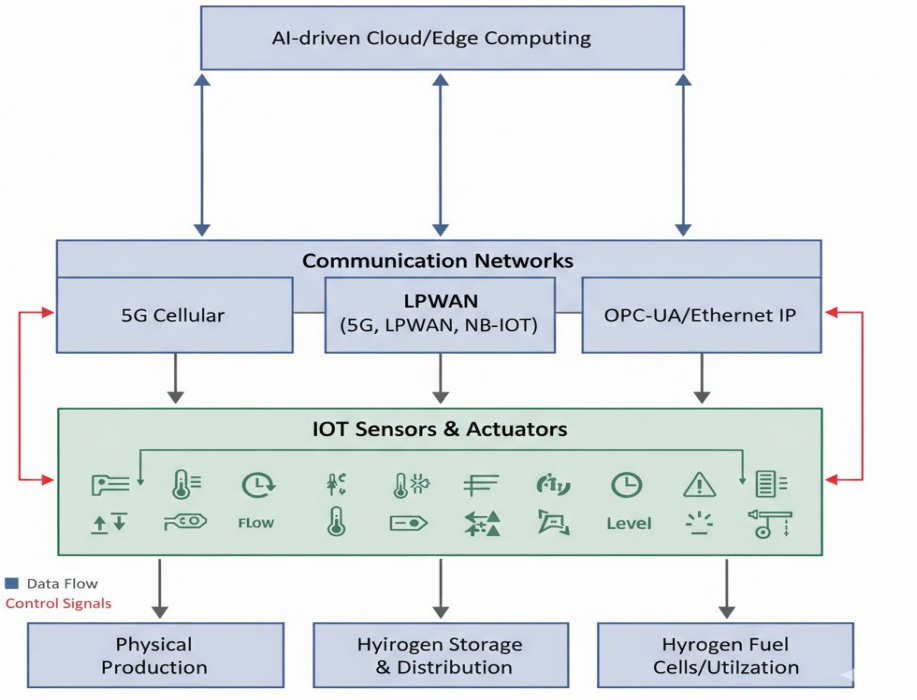


Figure 3. *Communication and IoT architecture for Smart Hydrogen Energy Systems, showing connections between physical hydrogen subsystems, IoT sensors, communication networks (5G, LPWAN, OPC-UA), and AI-driven cloud/edge computing layers.*

5. Conclusion

This paper reviewed the integration of artificial intelligence (AI) and communication technologies in smart hydrogen energy networks (SHENs). As hydrogen becomes critical for global decarbonization, smart computation and digital communication are essential for efficiency, reliability and sustainability across the hydrogen value chain.

AI approaches (specifically machine learning, deep learning and reinforcement learning) proven effective for electrolyzed optimization, production forecasting, fault diagnosis and predictive maintenance. Internet of Things devices, edge computing, cloud computing, and broadband protocols (including 5G, LPWAN, and OPC-UA) allow for real-time control, network interoperability, and localized management of hydrogen infrastructure.

The convergence and intersection of AI and telecommunications technologies can create autonomous and self-adaptive hydrogen systems promoting renewable energy incorporation and operational safety. However, significant challenges still exist in cybersecurity, the standardization of data, as well as the availability of datasets. To address these challenges, we need to conduct coordinated research, develop open data ecosystems, and apply responsible approaches to AI.

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