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Article

HyPLANT100: Industrialization from Assembly to the Construction Site for Gigawatt Electrolysis

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Abstract: The global push for sustainable energy has heightened the demand for green hydrogen, which is crucial for decarbonizing heavy industry. However, current electrolysis plant capacities are insufficient. This research addresses the challenge through optimizing large-scale electrolysis construction via standardization, modularization, process optimization, and automation. This paper introduces H_2Giga, a project for mass-producing electrolyzers, and HyPLANT100, investigating large-scale electrolysis plant structure and construction processes. Modularizing electrolyzers enhances production efficiency and scalability. The integration of AutomationML facilitates seamless information exchange. A digital twin concept enables simulations, optimizations, and error identification before assembly. While construction site automation provides advantages, tasks like connection technologies and handling cables, tubes, and hoses require pre-assembly. This study identifies key tasks suitable for automation and estimating required components. The Enapter Multicore electrolyzer serves as a case study, showcasing robotic technology for tube fittings. In conclusion, this research underscores the significance of standardization, modularization, and automation in boosting the electrolysis production capacity for green hydrogen, contributing to ongoing efforts in decarbonizing the industrial sector and advancing the global energy transition.

Keywords: electrolysis plant; green hydrogen; modularization; electrolyzer production; automation; digitalization

Citation: Büsch, L.; Jakschik, M.; Syniawa, D.; Masuhr, C.; Christ, L.; Schachtsiek, J.; Haalck, K.; Nerlich, L.; Frömsdorf, E.; Schirmack, N.; et al. HyPLANT100: Industrialization from Assembly to the Construction Site for Gigawatt Electrolysis. *Hydrogen* **2024**, *5*, 185–208. https://doi.org/10.3390/hydrogen5020012

Received: 25 March 2024
Revised: 19 April 2024
Accepted: 22 April 2024
Published: 28 April 2024

1. Introduction

For the future, Europe wants to become less dependent on fossil fuels and associated critical global supply chains. Furthermore, in the European strategy "Fit for 55: shifting from fossil gas to renewable and low-carbon gases", the European Commission aims to change the gas market in Europe to prevent climate change and a rise in temperature over 1.5 °C [1].

Hydrogen, as a versatile energy carrier, plays an essential role in this transition. Global energy demands and the need for decarbonization spotlight hydrogen across various sectors [2]. However, the efficient use of its potential is not without challenges. The challenges include the cost of hydrogen production, particularly in comparison to the currently very cost-efficient methods such as methane steam reforming, which rely on fossil fuels [3]. Transitioning to low-carbon or green hydrogen demands substantial investments in infrastructure and technology. Green hydrogen, produced via electrolysis using renewable energy, requires significant investment in renewable capacity to become a major player in hydrogen production that does not emit CO_2 [4]. Different studies have assumed a European hydrogen demand of up to 2000 TWh/a in 2050 [5,6]. These immense demands arise primarily in the industry, transport, and building sectors [5]. A change in hydrogen production is required to meet these massively growing demands while facing climate issues. For this reason, a paradigm shift from small-scale electrolyzers to large-scale electrolyzers and the interconnection of several electrolyzers to large-scale electrolysis plants is expedient to exploit economies of scale. At the same time, the production capacities of individual electrolysis components, such as, e.g., water or gas purification, called Balance of Plant (BoP) or electrolysis stacks, have not yet been industrialized to such an extent that they are available to the market in sufficient quantities and at adequate prices. Simultaneously, potential areas where electricity and water resources are available in adequate quantities for constructing large-scale electrolysis systems compete with further applications, such as other industrial plants, agriculture, and housing. At this point, the hydrogen lead project H_2Giga [7] and the associated HyPLANT100 [8] project have started to face these problems.

HyPLANT100 tries to bridge the gap between developing and manufacturing electrolysis basic units as fundamental subsystems toward the final operational large-scale electrolyzer system—up to the gigawatt scale—at the installation site. Recommendations for standardization will be developed to accelerate and rationalize the efficient planning, assembly, and installation of large electrolysis systems. To this end, in addition to digitalization, the concept of modularization is used to improve efficiency in the engineering, installation, and operation of large electrolysis systems. The modularization of electrolyzer systems for green hydrogen production has the potential to reduce both Capital Expenditures (CapEx) and Operational Expenditures (OpEx). In breaking down the system into standardized modules, manufacturing costs can be lowered, installation can be streamlined, and scalability can be enhanced, thereby reducing Capex. Additionally, standardized modules enable easier maintenance, improve system reliability, and allow for better adaptation to changing energy demands, all of which contribute to lower Opex over the system's life cycle. However, detailed cost analyses for these large-scale facilities still in development are currently challenging and are not addressed within the scope of this work [9–11]. A schematic of such a large-scale hydrogen plant is depicted in Figure 1.

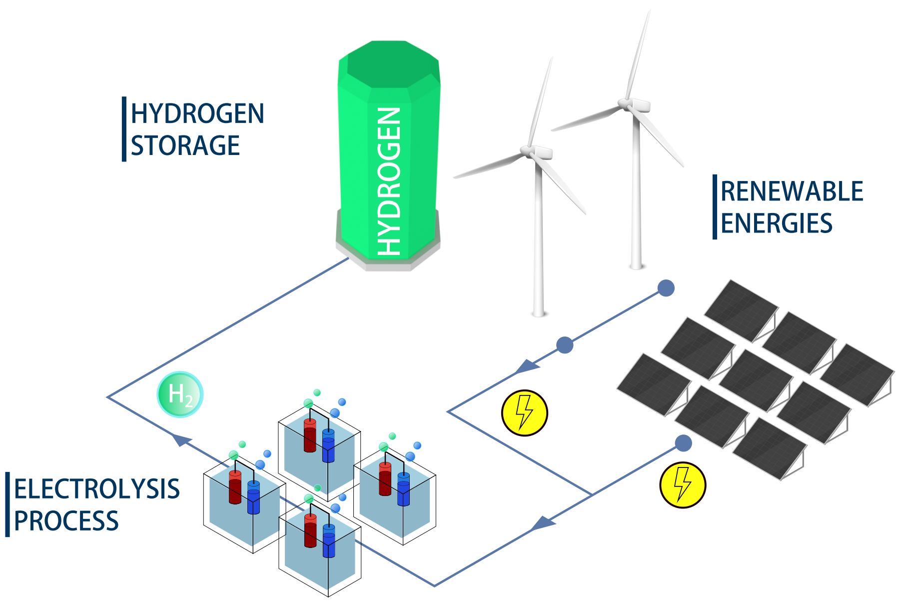


Figure 1. Schematic of an electrolysis plant in an energy grid.

Through a sensible combination of electrolyzers of different process technologies with standardized interfaces and the corresponding BoP, the utilization of individual systems and the space requirements of large plants can be optimized, as will be discussed in Section 3. In addition, standardized interfaces play a decisive role in successful (partial) automation. HyPLANT100 therefore analyzes and investigates the mechanical interfaces of the electrolysis technologies for the development of uniform standards. By defining standards, the creation of various connections between the modules is repetitive and highly suitable for automation. Furthermore, the corresponding structuring of pre-assembled modules, as well as research into intelligent assembly and installation methods for electrolyzers to form a large-scale electrolyzer system was conducted. In summary, there were three core topics for this research project:

1. The development and design of suitable modules;
2. The identification and development of (partial) automation;
3. Increasing efficiency through digitalization with the help of standardized data modeling.

These core and additional topics of the HyPLANT100 research project and their correlations are depicted in Figure 2.

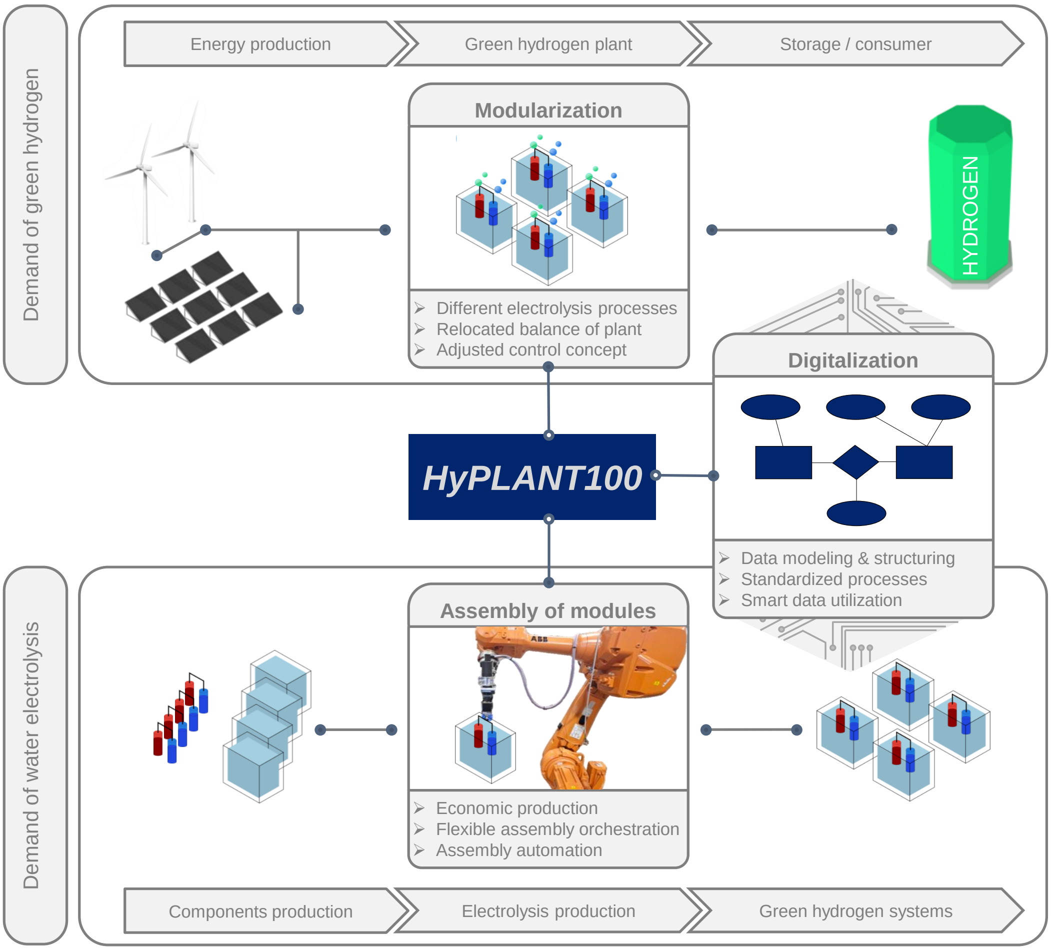


Figure 2. The focus of the research project HyPLANT100.

2. Related Work

Asalready motivated, an upscaling of electrolysis capacities is necessary to achieve the ambitious goals for decarbonizing. To this end, various comparable approaches are presented below, which are being investigated and developed in other research and industrial projects that are running in parallel or have already been completed.

In [12], the cost development for the construction of a large-scale electrolysis plant in the gigawatt range was investigated. For this purpose, diverse plant visualizations were also crafted to depict how they would appear within the five major industrial clusters in The Netherlands. Scaling was achieved by connecting existing plants in parallel. The modularization of the electrolysis process technologies was not taken into account. In another approach from a different domain of application, the idea of modularization was applied in the field of computer science. In the context of server architecture, the development of an exa-scale performance class supercomputer was implemented using container-based modules. The server racks of a supercomputer are comparable to the electrolysis stacks of an electrolyzer plant. These are easily scalable due to modularization and can be expanded into complete computers with predefined supply units. This approach enables short assembly times, good adaption to external requirements, and scalability [13].

Furthermore, industrial large-scale hydrogen projects are gaining momentum worldwide, showcasing the potential of green hydrogen as a clean energy solution. In Spain, the Puertollano Green Hydrogen Plant stands out with its 20 MW electrolyzer, powered by a 100 MW solar plant, already operational and producing hydrogen [14]. Meanwhile, in Germany, innovative projects like the Hamburg Green Hydrogen Hub [15] and the Northern German Living Lab [16] are making significant strides toward implementation. The Hamburg Green Hydrogen Hub aims to repurpose an old power plant for a 100 MW electrolysis capacity, while the Northern German Living Lab plans to deploy eight electrolyzers with a combined capacity of 40 MW, leveraging waste heat utilization of 700 GWh per year, marking a significant step forward in sustainable energy production once realized. Such projects highlight the critical need for ongoing research into large-scale hydrogen plants to meet global energy demands and combat climate change effectively.

3. Modularization of Electrolysis Systems

Electrolysis systems that are currently available on the market have capacities of up to 1 MW per unit [17] and are gradually being developed into larger configurations of 2 to 5 MW [18]. However, for extensive systems with an electrolysis capacity of 1 to 2 GW, it is essential to systematically interconnect these units at defined nodes. The modularization pursued here involved the integration of electrolysis technologies from different manufacturers, e.g., Proton Exchange Membrane (PEM) or Anion Exchange Membrane (AEM), depending on availability and the required performance criteria at specific hydrogen plants. The efficient combination of these units in a large-scale electrolysis plant is challenging [19]. However, this challenge can be addressed with the development of guidelines for standardization and modularization. These guidelines are also necessary due to the desired scalability of large-scale electrolysis plants, as not every site offers the same conditions, e.g., in terms of space or water availability. For this purpose, the various electrolysis processes were divided into functional modules. The first step of the investigation dealt with the isolation of the electrolysis technology. Here, the electrolysis reaction occurs in the main component, the "electrolyzer stack" and its nearest periphery form the electrolysis module, which is the starting point for the modularization concept development. Subsequently, further common functional modules are identified and analyzed to check whether they can be outsourced from the electrolysis process and used centrally across electrolysis technologies. Standardized interfaces are defined once the functional units have been outsourced to ensure scalability and flexibility. This modularization concept is illustrated in Figure 3.

In the following, a brief overview of the most relevant water electrolyzer (WE) technologies as well as the basic BoP systems are provided. Furthermore, the modular approach for upscaling electrolyzer capacity is presented.

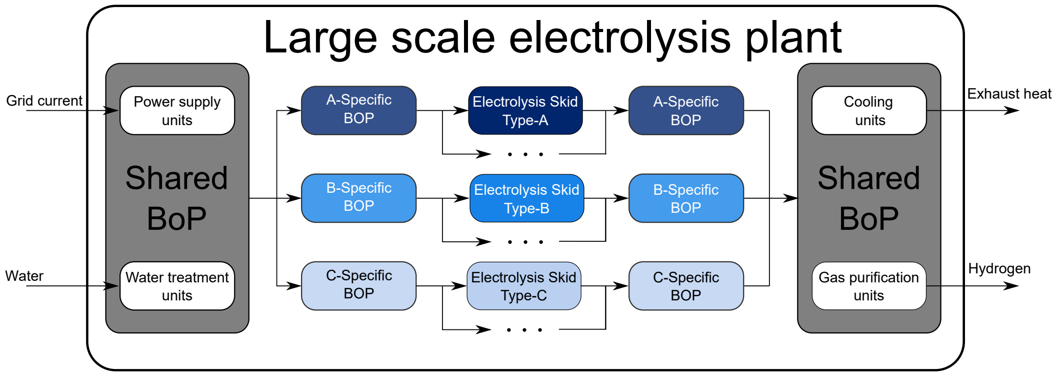


Figure 3. Modularization concept for large-scale electrolysis plants with varying electrolysis technologies.

3.1. Electrolysis Technologies and Their Respective Balance of Plant

Over the years, various WEs have been developed. The common factor is the overall cell reaction. Apart from that, they differ regarding the half-cell reactions, process conditions, materials, and properties. The different technologies with their corresponding half-cell reactions at the anode (oxidation) and the cathode (reduction) are given in Table 1. In addition to the technologies already mentioned, AEM and PEM, alkaline water electrolysis (AWE), and solid oxide water electrolysis (SOWE) complete the content of the table.

Table 1. Comparison of major electrolyzer technologies based on [20,21].

Electrolyzer Type	Half Cell Reactions	Process Conditions	Electrode, Electrolyte, and Separator Materials
AWE	Ox: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$ Red: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	pH: 13–14 T: 60–80 °C p_{H_2} : 0.5 barg/30 barg	*Ni*. aqu. *KOH*-solution, -
PEM	Ox: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ Red: $4H^+ + 4e^- \rightarrow 2H_2$	pH: acidic T: 50–80 °C p_{H_2}: 40 barg	*Pt*,*C* and *Ir* oxides, Nafion membrane, -
AEM	Ox: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$ Red: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	pH: basic T: 50–80 °C p_{H_2}: 35 barg	*Ni*, aqu. *KOH*-solution, AEM membrane
SOWE	Ox: $O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$ Red: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$	T: 700–850 °C p_{H_2}: 0 barg	Ceramic materials; Zirconium-based solid electrolyte,

In general, all electrolysis stacks, regardless of the specific technology, require similar BoP systems in the upstream and downstream processes to perform the entire electrolysis process. The BoP ensures that the stack receives the educts, pure water, and electricity, and that the products, gaseous hydrogen and oxygen, are safely and efficiently managed. Further, the BoP includes utilities such as compressed air and a heat exchanger network. Thus, proper BoP design and maintenance are essential for any electrolysis project's long-term success. Whether for small-scale applications or large industrial setups, the principles governing the operation of the stack remain consistent, with the primary differences lying in design specifics and materials used. The BoP systems of an electrolyzer mainly include the following:

- **Water Purification System:** Furnish the electrolyzer with ultrapure water. Components include *deionization units, filters, reverse osmosis units, and storage tanks*
- **Gas Purification System:** Purify and analyze hydrogen and oxygen gases produced during the electrolysis process. Components include *separators, reactors, dryers, and gas analyzer systems*
- **Heat Exchanger Network:** Ensure optimal temperature range. Components include *heat exchangers, pumps, and temperature sensors*.
- **Power Supply and Conversion:** Channel the requisite electrical power to the electrolyzer. Components include *rectifiers, transformers, and power factor correction*.
- **Utilities:** Supply compressed air and nitrogen. Components include *compressors, air separators, and a nitrogen trailer station*.
- **Control and Monitoring:** Evaluate and control the electrolyzer operation. Components include *sensors and programmable logic controllers*.

If all WEs require the same BoP, an increase in efficiency could result by building a large-scale plant with several WE technologies and a common BoP. Those plants achieve maximum independence from WE suppliers and resilience regarding the uncertainties of these new technologies and vulnerable supply chains. To realize this general concept, several additional aspects need to be considered. Not every WE is suitable for collaborative operation in a large-scale electrolysis plant. This applies to the SOWE since it is only beneficial if certain location economies are given, which are continuous load situations and the availability of high-temperature waste heat. The waste heat from other electrolysis technologies can only be used if they produce under continuous load and the SOWE also operates under continuous load. It is currently not feasible to operate a production plant dependent on renewable energy sources at a constant load in the gigawatt range. A closer look at the process conditions in Table 1 reveals that not all WEs can share exactly the same BoP components. SOWEs and AWEs operate with the same pressure at both electrodes, which is typically under near-atmospheric conditions. Even though certain AWE designs work with higher pressures of up to 30 barg, the pressure still builds up on both electrode sites. In contrast, the dense membrane in PEMs and AEMs enables operation with different pressures on the anode and cathode sites. This results in near-atmospheric pressures at the anode and elevated pressures of up to 40 barg at the cathode. Pressure conditions thus exclude the AWE due to its vulnerable porous half-cell separator. As a result, only PEMs and AEMs are currently suitable for coupling in a joint large-scale electrolysis plant.

PEMs, along with AWEs, are one of the most mature technologies. In comparison to the AWE electrolysis, the PEM technology has a higher efficiency, has a more compact design, due to its higher current density, and has a rapid response time [22]. PEM electrolyzers can therefore quickly adjust to changing input power levels, making them ideal for integration in a sensitive power grid dependent on renewable energy sources that have variable power outputs. The AEM technology does not require noble metals and still offers similar advantages to PEM technology due to the comparable cell design. But AEM technology is still under development and is, therefore, not as mature [23].

AEM and PEM systems, despite using different electrolytes, can utilize the same process water and operate in the same temperature range. Both technologies can synergistically complement each other. PEM demands a high degree of water purity and is extremely sensitive to impurities due to the precious metals involved. In contrast, AEM, which does not rely on noble metals, is more resilient to impurities, offering both better abundance and cost-effectiveness regarding the catalyst material. When it comes to operational power requirements, a typical 5 MW PEM system needs a minimum of 500 kW, whereas AEM systems can operate with as little as 70 kW. This difference highlights the flexibility and scalability of AEM technology. In terms of durability, PEM stacks boast a longer lifetime of 70,000 h compared to AEM's 35,000 h. However, AEM compensates for this with its rapid stack replacement capability, taking mere minutes, while PEM replacements can span days.

The collaborative use of these technologies can lead to the abovementioned increased resilience, flexibility in supplier choices, and independence due to the diversified abundance of raw materials. This combination also aids in risk mitigation, given the nascent stage of empirical data for prolonged electrolysis operations, and compensates for individual weaknesses, such as PEM's need for high water purity. Furthermore, a combined approach can reduce the overall footprint by sharing the BoP components and serve as a tangible proof of concept for the integration of diverse electrolysis technologies. PEM and AEM systems may not be the sole technologies that can be synergistically combined for enhanced performance. However, their integration is a key component of this approach, which envisions the fusion of multiple electrolysis technologies. If identical electrolysis technologies from different manufacturers differ significantly in their interfaces with the upstream and downstream balance of plant (BoP), they may be treated as different technologies in terms of concept.

3.2. Modularization of Water Electrolysis

In chemical industry, the usual approach to designing a process plant is to specify each component for the total mass flow of educt or product. Exceptions to this are critical components, which are designed redundantly, and technological limitations, which are overcome by connecting multiple units in parallel. In addition to this need for modularization, there are further advantages to this alternative concept from a process engineering perspective. It reduces individual planning for each site, as it enables simpler and standardized planning, resulting in shorter planning times, faster implementation, and lower specific costs. Further, the load range of the plant system is wider, which increases the adaptability of the operating mode to the educt availability (water, electricity) and the product demand. Finally, there is no total downtime for service work, as the modules can be serviced individually. This greatly increases availability, as conventional chemical parks must contend with turnaround periods lasting months.

However, modularization, or more specifically the number of modules, increases the complexity of the process plant. It is therefore advisable to analyze each BoP system individually and assess whether the modularization is mandatory, possible, and reasonable, and what module size should be aimed for. Regarding the systems described previously, modularization is mandatory for electrolyzer stacks, their power supply, and conversion systems. For them, the current state-of-the-art methods determine the module sizes. No matter what design approach is chosen, the number of modules will always correlate with the plant's dimension. Since modularization is not required for all BoP systems, there is a certain degree of freedom when dimensioning the modules. It is recommended to select the largest possible module size that still guarantees redundancy, a wide load range, and the expandability of the overall plant. However, pre-assembly and transportability must also be taken into account when dimensioning the modules.

To ensure adaptability and future scalability, the integration of PEM and AEM technology within the HyPLANT100 framework is designed to be modular. This modular approach not only facilitates seamless integration, but also paves the way for incorporating additional technologies in the future, further emphasizing the project's forward-thinking vision. Therefore, in the pursuit of creating an efficient hydrogen production plant that integrates both PEM and AEM electrolyzers, a modular approach is paramount. The planning of modules should commence from the central components of the plant, which are the electrolysis stacks, and then proceed outward.

The criteria for selecting peripheral components in the stack module are multifaceted. They must be necessary for the functionality of the system, such as pumps and heat exchangers. Energy efficiency is crucial, particularly in components like vessels in water circulation systems. Safety measures, such as hydrogen-in-oxygen measurements, must be integrated to ensure a secure operation. The standardization of hydrogen output stream characteristics and quality analyses are vital for consistency. Additionally, the design should aim to simplify the piping between modules and ensure product quality control through hydrogen analyses and flow measurements.

The sizes of the modules are proportional to the overall size of the plant, adhering to the "economy of quantity" principle. However, it is important to note that while there is significant automation potential in the modular design of the stacks and their peripherals, this is not the case for water and gas treatment or the heat transfer network. For these components, fewer modules with the largest possible dimensions are preferred, following the "economy of scale" principle. This approach not only benefits expandability and redundancy, but also contributes to the overall efficiency and effectiveness of the hydrogen production plant.

The integration of AEM and PEM technology is examined by comparing the interfaces to determine whether the BoP could be shared. This facilitates identifying comparable/similar media and electrical requirements of electrolyzers. The alignment and modification of technologies (PEM and AEM) become key to sharing standard interfaces. At the interfaces, process monitoring for the process parameters may need to be installed to monitor the quality of the media required for the AEM and PEM systems. Here, the interface definition provides design requirements for up- and downstream modules to embed the electrolyzers in shared infrastructures.

3.3. Operation of Modularized Electrolyzers

Running a modular electrolyzer plant involves a systematic approach, where operations are streamlined through detailed standard operating procedures and training manuals tailored to each module. Control is achieved through sophisticated systems like Distributed Control Systems (DCSs) and Programmable Logic Controllers (PLCs), with centralized monitoring via integration software. Maintenance hinges on proactive schedules and comprehensive manuals, supported by a Computerized Maintenance Management System (CMMS) for efficient tracking. The documentation is meticulous, encompassing operation logs, performance reports, and regulatory compliance records.

Compared to a standard plant, a modular plant offers greater flexibility and scalability. Each module can be operated independently, which simplifies expansion and allows for redundancy, minimizing downtime during maintenance or technical issues. In a standard plant, operations are more interdependent, and scaling up often requires significant reconfiguration of the existing setup. Modular plants can adapt more quickly to changes in demand or technology, while standard plants may have longer lead times due to their integrated nature. Additionally, the modules can be easily replaced or upgraded since the modular approach enables their mass production.

3.4. Investigation of the Degree of Modularization

In the following, different degrees of modularization of the electrolysis plant are examined. The different degrees of modularization are considered based on total system capacities of 30 to 2000 MW.

In the simplest scenario (S1), standalone systems available on the market with system capacities of 2–5 MW, such as those from Enapter [24] or FEST [18], are considered. The total system capacity of the electrolysis plant is scaled by the number of standalone electrolyzers. As the electrolyzers in this scenario can be operated alone, the S1 scenario is characterized by a high level of redundancy and no shared BoP. Therefore, this scenario is characterized by high flexibility and good expandability. This scenario is shown in Figure 4, on the left-hand side.

Furthermore, a scenario (S2) with 100 MW clusters is considered. In this scenario, an electrolysis capacity of 100 MW, as described in Sections 3.2 and 3.3, is realized in a modular plant with a shared BoP. The total system capacity is then scaled based on the number of 100 MW clusters. The S2 scenario is shown in the middle of Figure 4.

The last scenario considered (S3) describes a fully modular approach. The design methods used for the 100 MW plant are also applied here, but now for each total system capacity to be examined. This scenario lags behind the S1 scenario without further optimizations in terms of flexibility and expandability. Optimizations in this regard can be digitalization, as discussed in Section 5, and standardization, as discussed in Section 3.2. The S3 scenario is shown in Figure 4, on the right-hand side.

The degree of modularization thus increases steadily from scenarios S1 to S2 to S3. This is intended to compare the extrema and a solution in between, as depicted in Figure 4. For a comparison of the scenarios, the site requirements for a large-scale electrolysis plant are discussed subsequently.

Figure 4. Scenarios with varying degrees of modularization required to achieve different total system capacities.

In addition to the economic framework parameters, which are indispensable for investment decisions, the technical conditions are crucial for location determination. The key aspects, briefly elucidated below, include the following:

- Water availability;
- Availability of space and topology;
- Availability of renewable energy.

Water availability: The electrolysis plant must be designed according to the existing environmental parameters regarding water availability and supply [25]. A limiting factor is the year-round availability of water. In the future, the groundwater supply in most regions of Germany, especially in drier summer months, may not be sufficient for a gigawatt-scale electrolysis plant [26]. Therefore, alternative water sources must be considered. Various sources can be utilized, but the water treatment process must always be adapted to the available water quality. Besides groundwater, rivers and seas serve as natural sources. Rainwater can also be collected in retention basins and then utilized. Another source can be water from the final treatment stage of a wastewater treatment plant. When selecting the available water source, reference should be made to the requirements of the various process technologies described in Section 3.1. Although modularization does not mean that less water can be used than with a standalone solution, utilizing the water treatment system and the ratio of the water requirement to the water to be treated can be optimized by combining different process technologies.

Availability of space and topology: Under German law, an electrolyzer may only be erected in designated areas. The decision as to which areas are selected for the construction of electrolyzers lies with the respective municipality. The municipality must carry out the planning procedure and draw up a development plan for the project. Either it has already designated areas for such projects, or it designates a location for a specific project. The approach presented here aims to minimize the amount of space required to reduce sealing and competition for space with other projects. This can be achieved through a modular construction method with several levels, as seen in scenarios S2 and S3 in Figure 4.

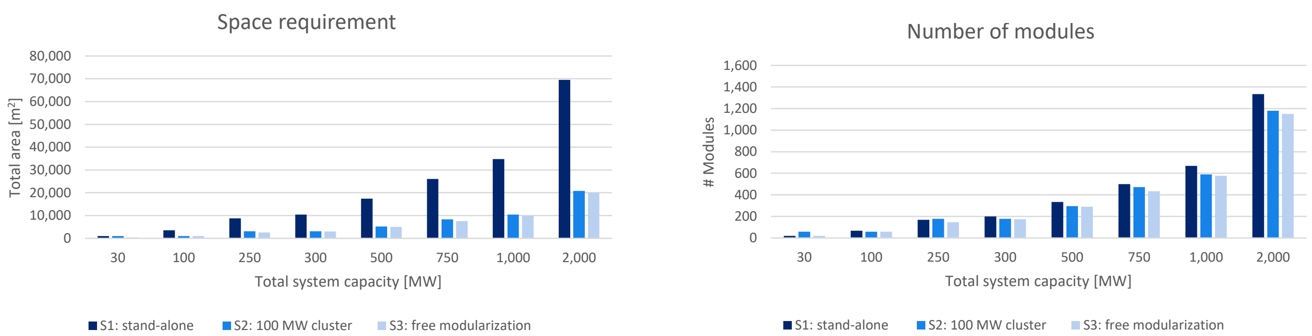
Availability of renewable energy: Power supply with renewable is a complex task [27], and it must be assessed individually for each location. This must also consider at which voltage level the system can be integrated into the existing power grid depending on the individual performance requirements of the designed plant. However, due to the high load and the associated cable cross-sections, a short distance from the grid to the transformer station is recommended to minimize costs. In addition to the output of the electrolyzer, auxiliary systems such as pumps, water treatment systems, and compressors must also be supplied with energy. A general statement about the energy supply is, therefore, not possible and must be examined individually for each plant.

As the location criteria for water and electricity supply are highly location dependent, as described above, and a general comparison of defined scenarios S1 to S3 is to be conducted in the following, the availability of space was selected as a comparison criterion. It is generally applicable that a reduction in the area required for an electrolysis plant facilitates site selection and reduces the cost of acquiring land. The number of modules and, consequently, containers required is used as a further criterion for comparison. The reduction in the number of modules required for a defined total system capacity corresponds to a reduction in investment costs. Therefore, the space requirements and the required number of modules for the total system power to be investigated are subsequently examined, as shown in Figure 5.

The basis for calculating the number of modules and the space requirements of the individual scenarios is described herein. The system boundary was selected to exclude the connection to the electricity grid, which is only dependent on the overall system capacity and the site conditions and not on the degree of modularization from the calculation. The same applies to the connection to the local water supply.

For scenario S1, 3 MW per the standalone solution was assumed. According to [18] and conducted expert interviews, this requires two modules, each with an area of 52 m^2 including a safety distance. For scenarios S2 and S3, a toolbox was developed to determine and visualize the space requirements and the number of modules required for the desired overall system capacity. For this purpose, the required media flows were analyzed from a process engineering perspective, and the BoP and electrolysis modules were designed. The number of electrolysis modules required and the required BoP modules could then be calculated based on the desired electrolysis output. Based on the number and size of the individual modules, conclusions could then be drawn about the area required. Furthermore, the toolbox enables the stacking of three layers of modules through the sophisticated space organization and spatial separation of critical modules. The 100 MW cluster (S2) was designed using this toolbox. In the S3 scenario, this toolbox was used to design the plant for any required electrolysis capacity flexibly.

The results of the analysis of space utilization are visualized in Figure 5a, the results of the analysis of the required modules are shown in Figure 5b, and these are discussed subsequently.



(**a**) (**b**)

Figure 5. Evaluation of the degree of modularization for varying total system capacities. (**a**) Required space of the individual scenarios. (**b**) Required modules of the individual scenarios.

Both the area requirement and the number of modules increase with an increasing total system capacity for all scenarios. The numbers for the S1 and S3 scenarios increase steadily and for the S2 scenario by leaps and bounds with integer multiples of 100 MW, as was to be expected. Nevertheless, S2's and S3's numbers lie close to each other, so S1 is compared against both scenarios, S2 and S3, in the following.

For scenario S1, the space requirement is 3.4 times greater on average across all system capacities than for the S2 and S3 scenarios. The average number of modules in S1 is 1.1 times greater. Since the toolbox allows the three-layer stacking of modules due to optimized safety zones in scenarios S2 and S3, this explains factor three in the space requirement. The 3.4 times higher space requirement and the 1.1 times higher number of modules required indicate a more efficient utilization of the divided BoP in scenarios S2 and S3.

Scenarios S2 and S3 are the same for a system capacity of 100 MW, as they are based on the same calculation. For non-integer multiples of 100 MW, S2 performs significantly worse than S3, as an oversized and unsuitable system layout must then be selected. In addition, S2 generally performs slightly worse for total system capacities above 100 MW, as the BoP modules can be better adapted to the requirements of the electrolysis modules for larger system capacities.

In conclusion, scenario S1 should not be favored for system capacities larger than 30 MW, as it requires a significantly larger area and a higher number of modules than the other scenarios considered due to the high redundancy and poor space utilization. Scenario S2, conversely, performs similarly well to scenario S3 for integer multiples of the system capacity of 100 MW but does not have to be redesigned for each capacity class. As a result, the planning effort in scenario S2 is significantly lower than in scenario S3. In comparison, scenario S3 has the best performance in terms of space requirements and number of modules. However, this requires significantly higher design and dimensioning efforts, as the toolbox does not provide a fully engineered system but only a rough dimensioning.

In addition to the advantages in terms of the basic layout requirements, there are many other positive effects of modularization compared to non-modularized large-scale plants. A hydrogen plant engineered in modules is much more resilient in its process than an individual plant. So, in the case of maintenance, it is not necessary to shut down the entire system, only the modules requiring maintenance. Furthermore, maintenance is much more efficient if the systems are standardized and modularized so that the modules can be replaced during the maintenance period. Additionally, as described above, these systems are significantly more powerful than individually planned systems in terms of their expandability.

4. Production

To meet the tremendously growing demand for electrolyzers, a successful ramp-up of production capacities for scalable electrolysis plants is essential. Based on the modular design of the electrolysis plant, the underlying production processes are described, and optimization options are examined. The processes are categorized according to the working environment into processes on the shop floor and the construction site [28]. In providing an efficient and ergonomic assembly environment, the individual modules are primarily pre-assembled on the shop floor (Figure 6 on the left-hand side) and subsequently installed on the construction site (Figure 6 on the right-hand side).

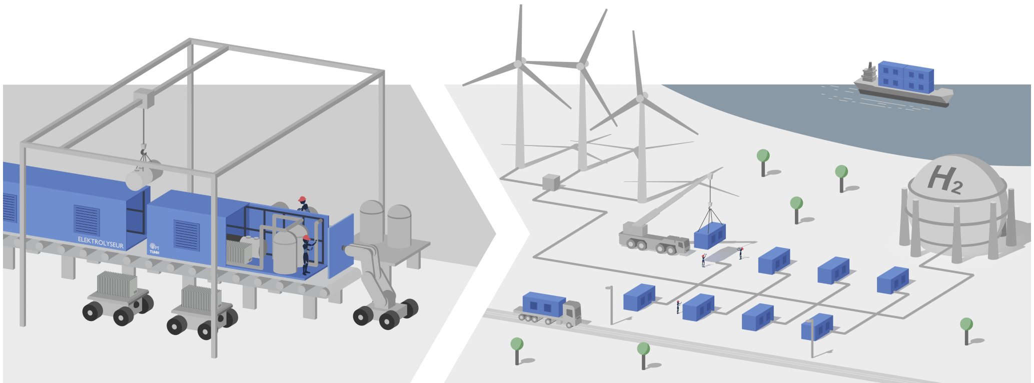


Figure 6. Modular assembly concept for large-scale electrolysis plants [29].

4.1. Pre-Assembly on the Shop Floor

In this section, options for improving the processes in the pre-assembly of the electrolysis and BoP modules are examined. In the following, automation options are investigated using the example of the tubing of the electrolysis stacks. Furthermore, the implementation of a production control system in the assembly, which is characterized by manual processes, is considered.

As described in Section 3.2, standardized interfaces play a decisive role in successful (partial) automation. The upscaling of the electrolyzers has also resulted in a significant increase in the number of interfaces. Different electrolysis methods share the same interfaces, so this connection technology remains consistent and has historically relied exclusively on manual assembly. This connection technology involves cables, hoses, and tubes, with the first two posing challenges due to their pliable nature. For example, the Enapter AEM NEXUS consists of 420 Stack modules, each connected via two hoses and one tube, totaling at least 840 hoses and 420 tubes for a one-megawatt capacity [24]. Furthermore, a process model was developed as part of the project, which is based on an MTM-1 analysis and evaluation of the required processes in terms of their suitability for automation and collaboration between humans and robots. The assessment also revealed that the tubing process has a high potential for automation, meaning that the tube fastening process should be investigated using a robot-assisted approach.

To compensate for the sensory capabilities of human workers, a combination of sensor technology, data analysis, and quality assurance protocols is indispensable. The system is complex, involving mechanical, electrical, and information-processing components that require a precisely defined sequence of operations. The development process involves creating an end-effector for an industrial robot that aligns with VDI 2221 [30,31] and VDI 2206 [32] while incorporating principles from VDI 3633 [33]. Figure 7 depicts the developed end effector, which is mounted on an ABB IRB4600 with a handling weight of 60 kg to ensure the necessary working space and stability. The end effector consists of several modules, including a motor-gear unit, a clamping device realized by a two-jaw gripper, and quality assurance through the integration of different sensors, some of which are concentric to the tool center point of the robot. The robot controller integrates the motor controller, and an external six-axis force/torque sensor is used to validate the robot's process [34,35].

The processes for manufacturing the modules on the shop floor are characterized by manual tasks and constant changes due to product adaptation and variance [28]. To increase efficiency, production capacities as well as supply and logistics must be controlled. The variance in the product and the required flexibility pose challenges for a production control system. To develop such a control system for the mentioned application, the requirements must be derived based on a detailed process analysis. The individual components of such a control system can then be identified and developed. Production control is therefore concerned with capacity control, material supply, sequencing, and task authorization and is based on detailed progress recognition and process and product knowledge. In addition, requirements for quality assurance and material requirements planning can also be mapped. A detailed conceptual design of such a production control system based on a process analysis in the manufacturing of large-scale electrolyzers is currently under investigation.

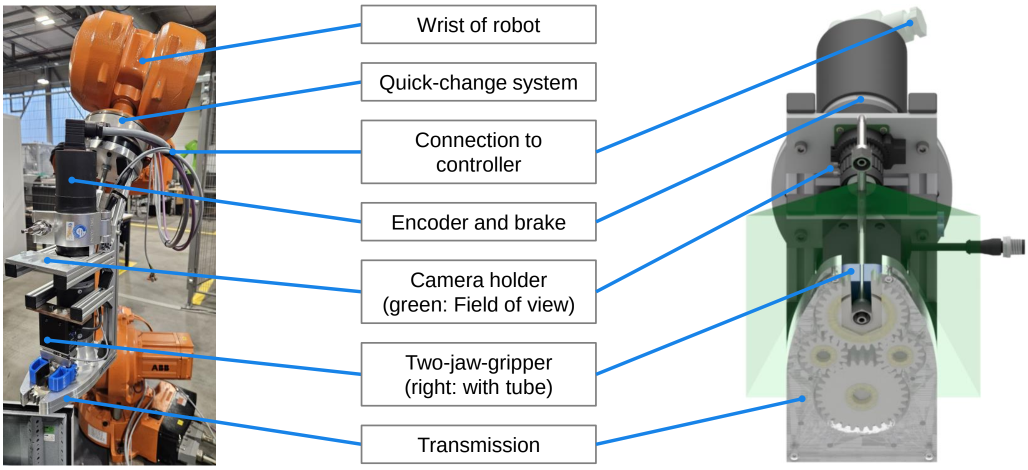
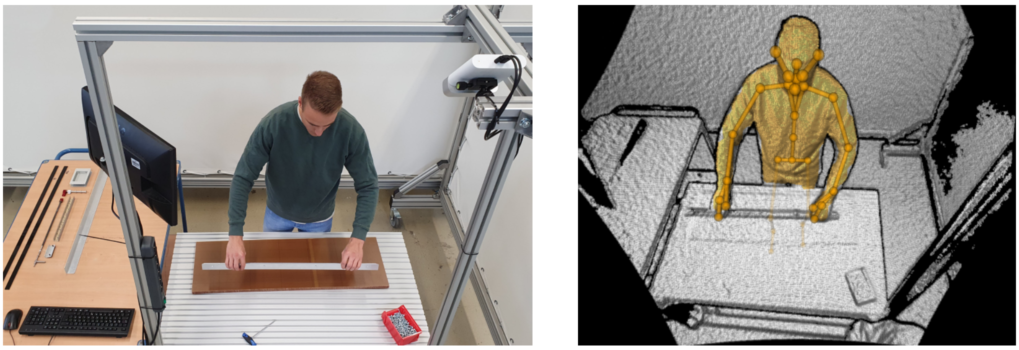


Figure 7. Robotic endeffector for the assembly of hydrogen tube fittings.

Being an important part of the orchestration system, progress detection consists of three steps: data acquisition, data preparation, and data evaluation [36]. A system for automatic progress detection in manual multi-variant assembly processes is being developed [37,38] to be integrated as a module in the aforementioned production control system. This system leverages an Artificial Intelligence (AI)-based detection of the assembly steps and tools in use to track the assembly progress automatically and without additional manual effort. The corresponding test setup is depicted in Figure 8.



(**a**) (**b**)

Figure 8. Human action recognition demonstrator [37]. (**a**) Workstation equipped with Azure Kinect. (**b**) View of Azure Kinect.

4.2. Quality Assurance

A fully automated assembly process, detailed in Section 4.1, includes a crucial final quality check to prevent pressurized hydrogen leaks and potential accidents. Hydrogen's small molecular size allows it to penetrate even tiny spaces and cracks [39], posing explosion risks due to its odorless nature and low ignition energy. Given hydrogen's nearly invisible flames, leakage prevention is paramount in hydrogen electrolyzer assembly, ensuring both safety and an optimal electrolyzer performance.

Checking the manufactured connections for leaks is one of the most critical quality checks for electrolyzers. In addition to the immediate detection of leaks, it is also important to reduce the probability of their occurrence in the future. To ensure this, the quality of newly manufactured connections must be checked and monitored over the product's life cycle. An expert survey and literature review have revealed that leaks are mainly caused by improper installation and human errors [40]. The quality inspection of the assembly starts from pre-assembly in a factory environment up to the final commissioning on a construction site. Standardized quality parameters for machines and systems as well as used materials and sealings must be fulfilled, which are not specific to hydrogen electrolyzers [41]. Compliance with tolerances and the use of tested materials, components, and modules (e.g., stacks and BoP) contribute to a safe product. The following discussion focuses on quality control, with a particular emphasis on detecting leaks during the assembly process.

Leakage testing occurs during pre-assembly, system commissioning, and maintenance. Helium and hydrogen are commonly used as a tracer gas for leak testing procedures. Techniques such as bubble soap tests and hydrogen sniffers are employed for detection as depicted in Figure 9. Despite ongoing research, there is currently no cost-effective alternative to these methods [42]. A promising approach, however, is Background-Oriented Schlieren technology (BOS). BOS technology utilizes optical principles to detect gas flows, offering leak localization capabilities using standard camera sensors [43]. While BOS technology can achieve rapid turnaround times with moderate detection limits, it is unlikely to fully replace sniffer procedures [42]. Its accuracy depends on factors like distance, background optimization, and lighting conditions.

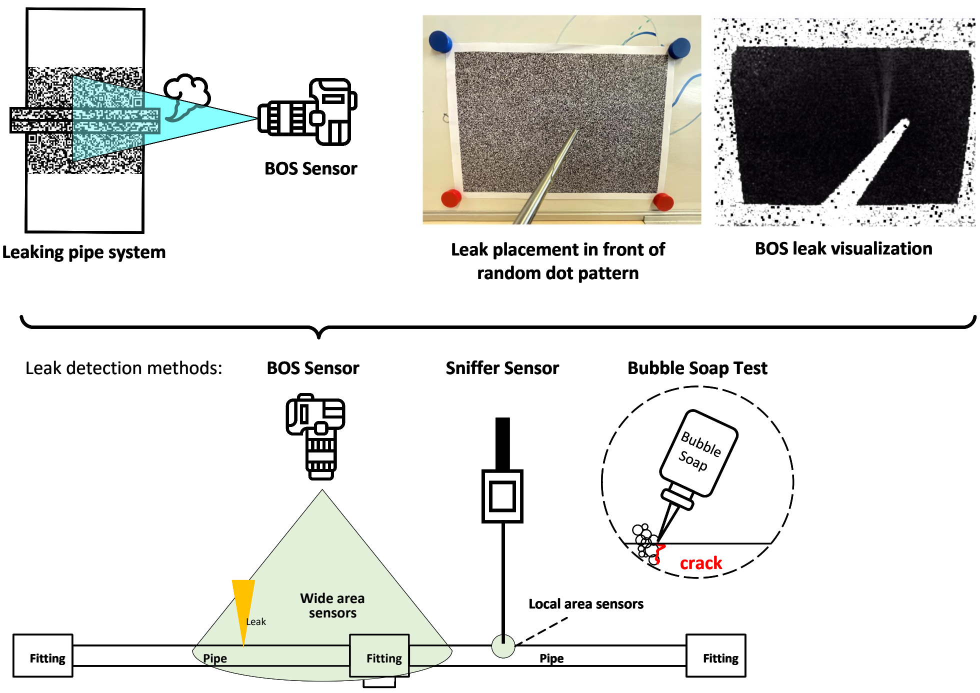


Figure 9. Hydrogen leak testing procedures based on different sensor technologies.

Manual leakage inspection can be enhanced with assistance systems to reduce human errors associated with hydrogen sniffer technology. Providing feedback on sensor guidance improves measurement accuracy, making Augmented Reality (AR) glasses a viable solution (see Figure 10). AR applications offer real-time feedback on process execution, aiding in monitoring measurement trajectories and sensor speed. The digital data obtained can reliably document compliance with test plans using generic models, facilitating automated documentation and consistent electrolyzer descriptions. Leveraging and refining such models enable additional services like assembly and layout planning [44].

Figure 10. Augmented reality assistance for leak inspection of instrument panel.

The leak test outcome also implies a proper installation of mechanical connections as a secondary derived test feature. A final completeness test of the installed components is also important and is carried out in end-of-line tests. Camera-based solutions can provide further automation in this step, with the help of optical image processing. On-site inspection usually takes place after installation and is carried out by qualified personnel. The electrolyte, gas flow, and conductivity are tested here. The correct wiring of the process logic controller is checked again as well. Proper integration with the control and monitoring systems is crucial for efficient operation, allowing for real-time adjustments and troubleshooting.

4.3. Assembly at the Construction Site

Once the modules have been assembled on the shop floor as described in Section 4.1, they are transported to the construction site where they are joined to form a complete hydrogen production plant.

Construction site processes can be categorized into two main groups [28]. The first is site preparation and building construction, which encompasses civil engineering tasks like water retention, deep foundation work, and concrete and steel construction, along with activities such as measuring, inspection, formwork manufacturing, and transportation. The second category involves module assembly, including equipment and pipeline assembly, pressure and leak testing, electrical wiring, corrosion protection, and insulation, along with tasks like alignment, bolting, welding, grinding, painting, and rinsing.

The efficient assembly of modular electrolysis plants demands streamlined processes and automation [28,45]. To achieve this, an automated system is essential for coordinating personnel, machines, and logistics. Manual methods fall short as processes grow in complexity and involve more actors. Automated progress detection is thus necessary for both pre-assembly and on-site construction, especially considering the significant cost implications. Streamlining construction processes through automation promises time and cost savings, highlighting the importance of investigating automated progress detection methods for large-scale hydrogen plant construction sites. A concept for such a system was developed in [28] and is based on collaborative data acquisition conducted by humans, and ground- and air-bound robots equipped with various sensor systems. The sensor selection is depicted in Figure 11.

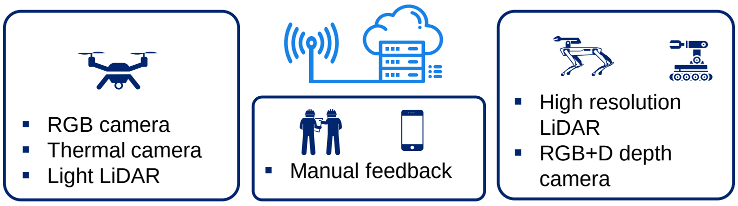


Figure 11. Selected subsystems for data acquisition in [28].

4.4. Further Automation Potential

The utilization of tube connections, as described in Section 4.1, results from the special challenges involved in transporting hydrogen. In addition to hydrogen, other media such as water or oxygen need to be transported for the electrolysis process. Their molecule sizes differ significantly from that of the hydrogen molecules, which makes them much easier to handle. Hoses are sufficient as connecting components for these media. These connection types are usually assembled by hand, which makes this process time and cost consuming. Reasons for the predominantly manual assembly of hoses are the challenges associated with the handling of deformable materials by robots. The precise handling of linear deformable objects is a common technical problem [46]. Path planning for the handling of dimensionally unstable components is confronted with a variety of uncertainties [47]. Another factor is the pressure-sensitive assembly of the hose connection, where the hose is inserted into the connection, and the retaining element is pushed back. There is a clamping sleeve at the end of the connection that unlocks when it is pushed back. Preliminary work has already been carried out to handle the several challenges of an automated assembly, through developing functions, and the assignment to their function holder as shown in Figure 12. Based on this, a suitable end effector at the maturity stage of a prototype is to be developed and researched as part of this project.

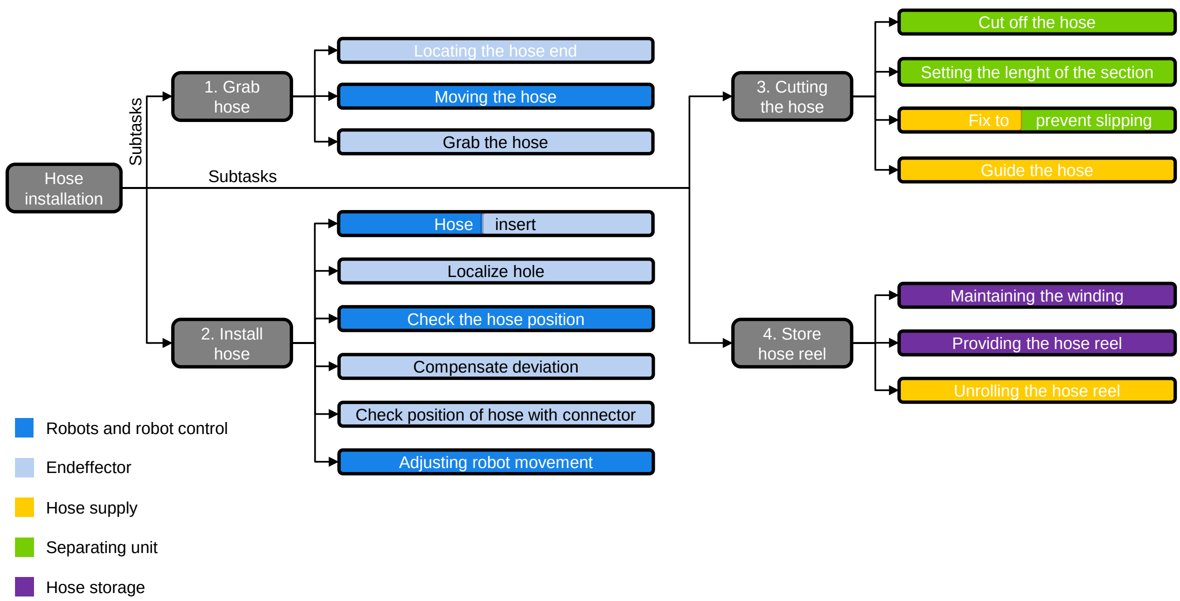
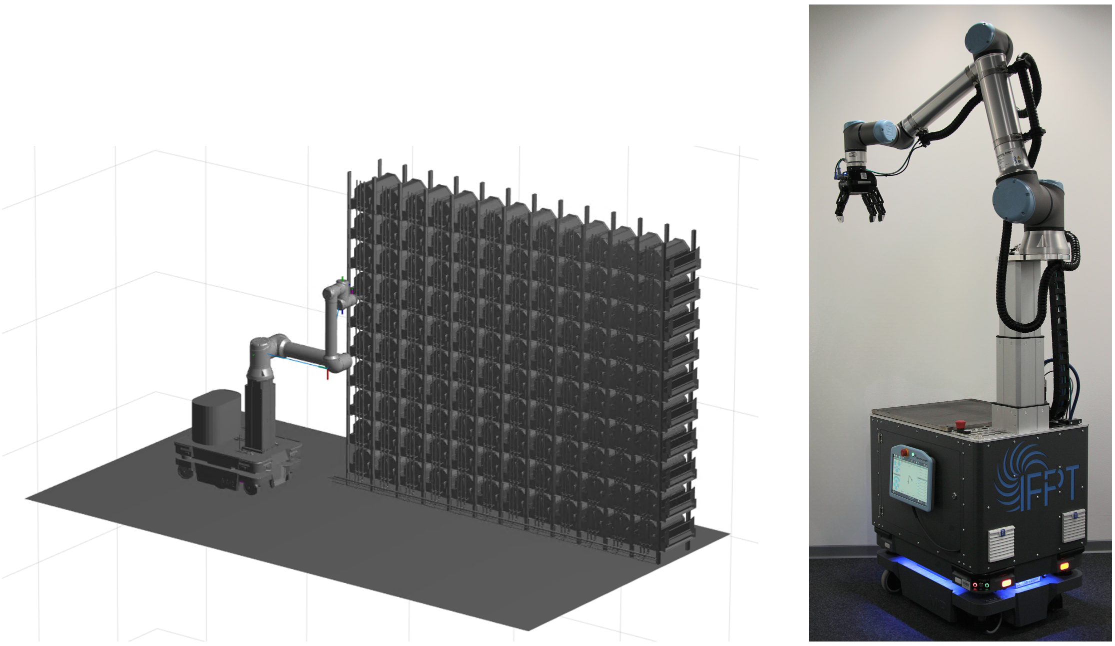


Figure 12. Assignment of subfunctions to function holders.

To facilitate partial automation using mobile robotics, a test stand is established. This platform is intended for conducting experiments regarding human–robot collaboration in the manufacturing of electrolysis modules on the shop floor, as described in previous research [37]. Furthermore, experiments involving data acquisition for progress determination on the construction site [28], as well as automated leakage testing, can be conducted [42].

For the automation research, a mobile robotic system was designed to achieve high flexibility in confined environments. This system combines a Cobot (UR10e) with an attached three-finger gripper, mounted on a Liftkit affixed to an autonomous platform. The system is depicted in Figure 13, with the robotic system shown in Figure 13b and a simulation of automated leakage testing based on a digital twin approach presented in Figure 13a.



(**a**) (**b**)

Figure 13. Part of the automation demonstrator in HyPLANT100. (**a**) Simulated automated leakage inspection. (**b**) Mobile robotic system.

5. Digitalization

The planning and development of the electrolysis plants described in this work are carried out by interdisciplinary teams, and there are various approaches to increasing the efficiency of the overall production process. The frequent data exchange between all domains involved and the specific tools used lead to high import and export efforts, which is time consuming and, in the worst case, can lead to the loss of information when interpreting different data formats. As with modularization and production automation, standardization can especially tackle the mentioned challenges. The agreements on such planning details are based on data that can be described in a variety of ways, but a standardized description in a neutral data format is advantageous. This can reduce the need for individual importers and exporters for the tools described and avoid possible conversion losses. Various approaches have been established for standardized description based on a neutral data format. In [48], interoperability using the Asset Administration Shell (AAS), Open Platform Communications Unified Architecture (OPC UA), and Automation Markup Language (AutomationML) was discussed between the associations, organizations, and participating companies and served as a basis for decision making in this article. This approach is used to complement each system solution and to describe recommendations for actions for developers and users. To this end, the authors refer to the RAMI4.0 [49] reference architecture model, which serves as a platform and orientation framework for digitalization. Based on RAMI4.0, AutomationML is recommended for use in the asset development life cycle and for planning the productive use of an asset, including all content, and for communication in all networks [48]. Therefore, the approach presented uses AutomationML to digitally describe the system in the planning process through to the implementation at the construction site. As described above in the context of modularization, the HyPLANT100 data framework is also modular. In addition to data exchange, this approach also facilitates the derivation of initial solution approaches in the various engineering processes. In the following, the advantages of the usage of a standardized neutral data format are described.

5.1. Layout Planning in the Context of Modularization

The developed data structure can be divided into three stages. Stage one describes the defined modules needed for an electrolyzer system shown in Section 3. The defined modules of a large-scale electrolyzer plant are summarized in functional units and are implemented in libraries. Figure 14 depicts an example of an Entity relation diagram (ERD) of the water supply unit, which is further specified using various attributes. Furthermore, every element is more detailed through its specific interfaces for its media supply and one non-physical interface where all external interfaces are clustered. These are the references to the geometry models and the XML document about the location parameters of the physical interfaces. In addition, the documents of the previously described quality assurance of the interfaces are attached, depending on the tested connections. A more in-depth description of the data structure in connection with the superstructure and the increase in engineering efficiency is presented in [50,51].

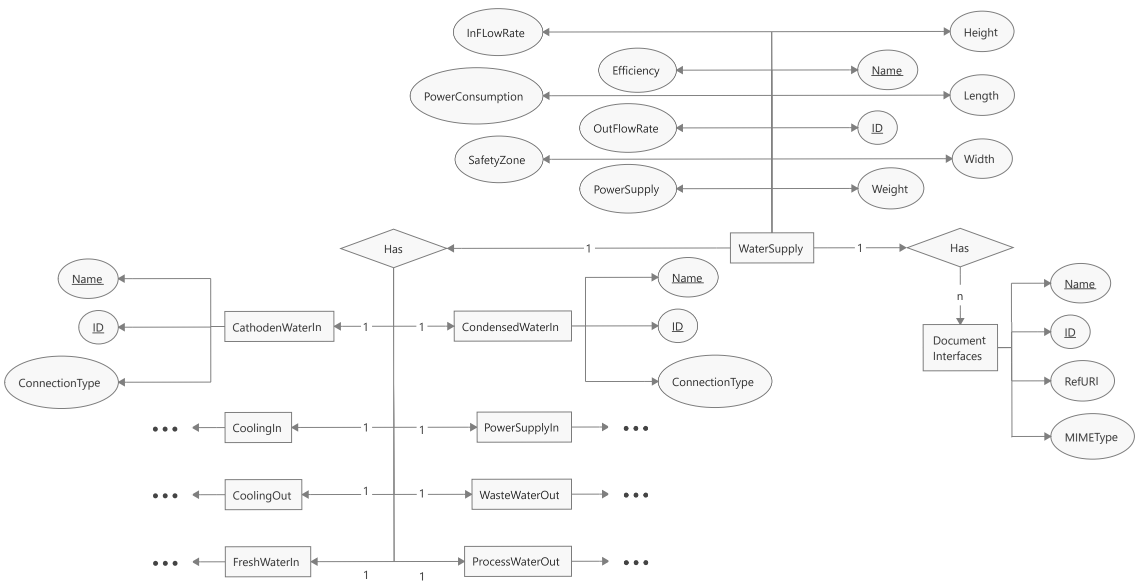


Figure 14. Entity-relation diagram of the water supply module.

With the help of this data description, a tool is to be developed for the approach described here that automatically generates layouts based on the previously defined requirements for the installation site. It can be used for initial estimates and a prototype-like visualization, but it primarily demonstrates the advantages of consistent data management, as these currently still very complex planning processes can thus be made leaner and more efficient. In addition to the layout planning, the data structure and, thus, the information about the specific products can also be used to increase efficiency in the planning processes of production automation.

5.2. Derived Simulation for Production Automation

In addition to the aspects already presented, the simulation setup for robot-assisted production systems in the context of electrolyzer production can also be accelerated using suitable data structuring and descriptions in AutomationML. For this purpose, standardized data models are initially used, which summarize information on the production resources of the overall production system, products to be processed, and the processes to be carried out. This modeling can be performed with the Product–Process–Resource (PPR) model [52]. This model obtains the pure semantic description of the essential components and considers the interaction of the individual group's products, processes, and resources. In the context of AutomationML, these interactions can be realized using specific PPR connectors and internal links. Resources and product objects are described in the simulation context by their geometric shape as well as spatial relationship to each other and by object-specific parameters relevant to the overall process. The data models used for simulation derivation describe geometric shapes using referenced 3D CAD models. These can be available in various formats. However, exclusively manufacturer-neutral formats, such as STEP and COLLADA, are employed here. The spatial relationship of the physical objects in a simulation is represented by corresponding information on positions and orientations with regard to an absolute reference. Specifically for AutomationML, the so-called frame attribute can be used in this context, which provides these components as the standard. Object parameters relevant to the process, such as positions of assembly points, necessary assembly methods, or characteristics of robotic systems (handling weight, range, etc.), are realized as attribute descriptions in the overall data model. A method described in [53] was used to realize the process simulation. Thus, based on program templates and process descriptions in AutomationML, and in following the ideas in [54], comprehensive robot programming was derived and integrated into the simulation environment. The derived simulation based on the described data structure is depicted in Figure 15.

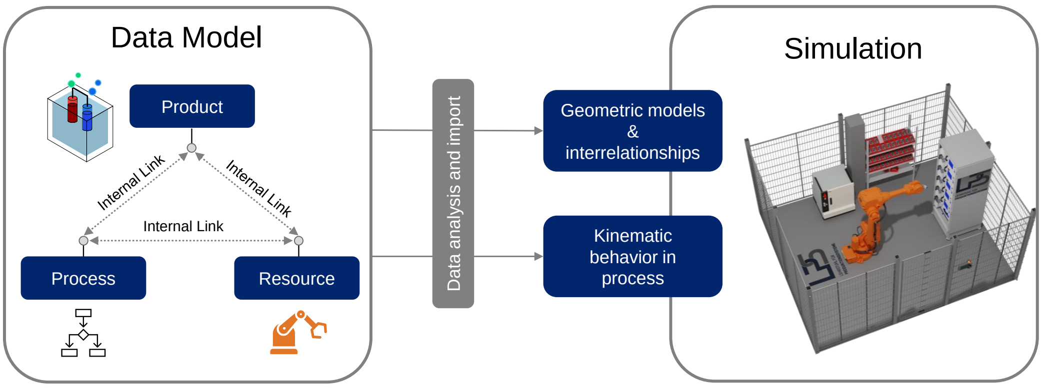


Figure 15. Derived simulation based on described data structure.

5.3. AI-Based Error Compensation

The assembly process of double ferrule connections has high-accuracy requirements. To fulfill them, it is necessary to compensate for process-related deviation using an additional algorithm. In the context of this project, an AI-based algorithm was developed for this purpose, and accordingly, it must be trained using data that are acquired in the real world or synthetic data that are generated virtually. To make this process as efficient as possible, a digital twin can be implemented to make the training data generation possible even before the physical production system is available so that the training can be carried out in parallel with the development of the production system. After implementing the physical production system, it is possible to supplement the training with data acquired in the physical system to maximize performance [55].

As mentioned before, using a digital twin can contribute to a more efficient and smart production system for water electrolyzer production. The developed data structure can be a suitable basis for this but never a sole solution for the implementation of a digital twin. The digital twin concept is shown in Figure 16. As shown, a dynamic intersection exists between the virtual and the real world. AutomationML was not designed for such dynamic data exchange and storage activities. In [48], the use of OPC UA for operational data access is recommended as a course of action, whereas the AAS is intended for the storage of these data. The AAS acts as a product passport and holds information from the entire product life cycle and thus also the data generated from the engineering process, which is described based on AutomationML.

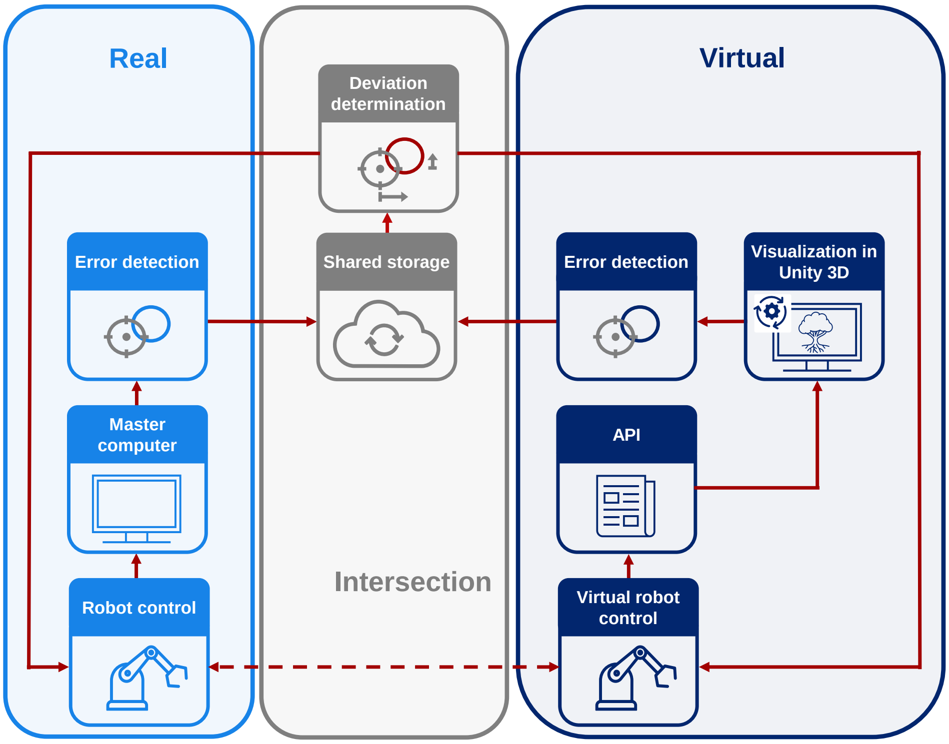


Figure 16. AI -based error compensation for the digital twin based on [55].

6. Conclusions and Outlook

In conclusion, this research underscores the crucial role of standardization, modularization, and automation in addressing the pressing need to enhance the electrolysis production capacity for green hydrogen. By focusing on the development of large-scale hydrogen plants, such as through the H_2Giga project and HyPLANT100, this study highlights the importance of scaling up electrolysis infrastructure to meet the demands of the energy transition. A modular design simplifies planning, reduces costs, and enhances flexibility and scalability. Introducing redundancy through modularization ensures continuous operation during maintenance or technical issues. The scenario analysis showed how fully modular approaches optimize space and resource utilization, though they require more planning efforts. In conclusion, modularization is a key strategy for optimizing hydrogen production plants, offering enhanced efficiency, flexibility, and resilience. Through the integration of AutomationML and the utilization of digital twin concepts, opportunities for improving production efficiency and error mitigation are illuminated. While construction site automation offers clear advantages, careful consideration of pre-assembly tasks is essential for ensuring seamless integration. The case study involving the Enapter Nexus electrolyzer demonstrates the practical application of automation technologies in streamlining plant construction processes. By identifying key tasks suitable for automation and estimating required components, this study lays a foundation for future advancements in large-scale hydrogen plant development. The findings contribute to the broader goal of advancing the global energy transition by facilitating the production of green hydrogen, which is crucial for decarbonizing heavy industry and accelerating the transition to sustainable energy sources.

Looking ahead, the potential of hydrogen for sector coupling offers a promising approach to integrating diverse economic sectors like transportation, industry, and heating. With faster ramp-up and more economical electrolysis plants, hydrogen becomes more abundant and affordable, serving as a versatile energy carrier. This aids the transition to renewable energy sources and significantly reduces carbon emissions while enhancing energy efficiency across sectors. Additionally, utilizing process heat from electrolysis plants enhances sustainability and efficiency. This byproduct can be utilized for heating applications, especially in housing projects. Integrating electrolysis plants with district heating systems or directly using process heat for space and water heating in residential buildings minimizes energy waste, reduces the environmental footprint, and can offer cost-effective heating solutions for communities. This further increases the efficiency of the electrolysis process. Flexible hydrogen plants can play a vital role in stabilizing volatile electricity grids shaped by renewable sources. With fluctuating wind and solar energy generation, the demand for flexible control energy increases to stabilize the grid. By balancing supply and demand through the fast and flexibly controllable power integration of modular electrolysis plants, grid fluctuations can be effectively mitigated. In summary, leveraging the potential of large-scale hydrogen plants through modularization and optimization of the assembly processes can accelerate the transition to a cleaner, more sustainable energy future.

Author Contributions: Conceptualization, L.B., M.J., D.S., C.M., L.C., J.S., K.H., L.N., E.F., N.S., B.E., C.K. and P.A.; methodology, L.B., M.J., D.S., C.M., L.C., J.S., K.H., L.N., E.F., N.S., B.E., C.K. and P.A.; software, L.B., M.J., D.S., C.M., L.C., J.S., K.H. and P.A.; validation, L.B., M.J., D.S., C.M., L.C., J.S. and P.A.; formal analysis, L.B., M.J., D.S., C.M., L.C., J.S., K.H., L.N., E.F., N.S. and P.A.; investigation, L.B., M.J., D.S., C.M., L.C., J.S., K.H., L.N., E.F., N.S., B.E., C.K. and P.A.; resources, K.H., B.E., P.A., T.S. and B.K.; data curation, L.B., M.J., D.S., C.M., L.C., J.S., K.H. and P.A.; writing—original draft preP.A.ration, L.B., M.J., D.S., C.M., L.C., J.S., K.H., L.N., E.F., N.S., B.E., C.K., P.A., T.S. and B.K.; writing—review and editing, L.B., M.J., D.S., P.A., T.S. and B.K.; visualization, L.B., M.J., D.S., C.M., L.C., J.S. and P.A.; supervision, L.B., P.A., T.S. and B.K.; project administration, L.B., C.M., K.H., N.S., B.E., P.A., T.S. and B.K.; funding acquisition, K.H., B.E., P.A., T.S. and B.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the German Federal Ministry of Education and Research (BMBF) under the grant number 03HY114 within the research project H_2Giga—HyPLANT100.

SPONSORED BY THE

Federal Ministry of Education and Research

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article

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

Abbreviations

The following abbreviations are used in this manuscript:

AAS	Asset Administration Shell;
AEM	Anion Exchange Membrane;
AI	Artificial Intelligence;
AR	Augmented Reality;
AutomationML	Automation Markup Language;
AWE	Alkaline Water Electrolysis;
BoP	Balance of Plant;
BOS	Background-Oriented Schlieren;
CapEx	Capital Expenditures;
CMMS	Computerized Maintenance Management System;
DCS	Distributed Control System;
ERD	Entity Relation Diagram;
MTM	Methods-Time Measurement;
OPC UA	Open Platform Communications Unified Architecture;
OpEx	Operational Expenditures;
PEM	Proton Exchange Membrane;
PLC	Programmable Logic Controllers;
PPR	Product–Process–Resource;
SOWE	Solid Oxide Water Electrolysis;
WE	Water Electrolyzer.

References

1. Fit for 55. Available online: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ (accessed on 8 February 2024).
2. Ishaq, H.; Dincer, I.; Crawford, C. A review on hydrogen production and utilization: Challenges and opportunities. *Int. J. Hydrogen Energy* **2022**, *47*, 26238–26264. [CrossRef]
3. Ueckerdt, F.; Verpoort, P.C.; Anantharaman, R.; Bauer, C.; Beck, F.; Longden, T.; Roussanaly, S. On the cost competitiveness of blue and green hydrogen. *Joule* **2024**, *8*, 104–128. [CrossRef]
4. Wappler, M.; Unguder, D.; Lu, X.; Ohlmeyer, H.; Teschke, H.; Lueke, W. Building the green hydrogen market—Current state and outlook on green hydrogen demand and electrolyzer manufacturing. *Int. J. Hydrogen Energy* **2022**, *47*, 33551–33570. [CrossRef]
5. Neugebauer, R. (Ed.) *Wasserstofftechnologien*; Springer eBook Collection; Springer: Berlin/Heidelberg, Germany , 2022. [CrossRef]
6. Fonseca, J.; Durdevic, D.; Muron, M.; Pawelec, G.; Yovchev, I.P.; Bellomo, N.; Muse, K.; Kuhn, M.; Fraile, D.; Waciega, K. Clean Hydrogen Monitor. **2023**. Available online: https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf (accessed on 14 February 2024)
7. H2Giga: Serial Production. Available online: https://www.wasserstoff-leitprojekte.de/leitprojekte/h2giga (accessed on 14 February 2024).
8. HyPLANT100. Available online: https://www.region-heide.de/projekte/hyplant100.html (accessed on 14 February 2024).
9. Yates, J.; Daiyan, R.; Patterson, R.; Egan, R.; Amal, R.; Ho-Baille, A.; Chang, N.L. Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. *Cell Rep. Phys. Sci.* **2020**, *1*, 100209. [CrossRef]
10. Reksten, A.H.; Thomassen, M.S.; Møller-Holst, S.; Sundseth, K. Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development. *Int. J. Hydrogen Energy* **2022**, *47*, 38106–38113. [CrossRef]
11. Ginsberg, M.J.; Venkatraman, M.; Esposito, D.V.; Fthenakis, V.M. Minimizing the cost of hydrogen production through dynamic polymer electrolyte membrane electrolyzer operation. *Cell Rep. Phys. Sci.* **2022**, *3*, 100935. [CrossRef]
12. Van 't Noordende, H.; Ripson, P. Baseline Design and Total Installed Costs of a GW Green Hydrogen Plant: State-of-the-Art Design and Total Installed Capital Costs. Available online: https://ispt.eu/media/ISPT-public-report-gigawatt-green-hydrogen-plant.pdf (accessed on 7 February 2024).
13. Exascale-Supercomputer Jupiter Entsteht Aus Containern. Available online: https://www.heise.de/news/Exascale-Supercomputer-Jupiter-entsteht-aus-Containern-9606417.html (accessed on 15 February 2024).
14. Iberdrola Commissions the Largest Green Hydrogen Plant for Industrial Use in Europe. Available online: https://www.iberdrola.com/about-us/what-we-do/green-hydrogen/puertollano-green-hydrogen-plant (accessed on 15 February 2024).
15. Hamburg Green Hydrogen Hub. Available online: https://www.hghh.eu/en (accessed on 15 February 2024).
16. Northern German Living Lab (NRL). Available online: https://en.norddeutsches-reallabor.de/ (accessed on 15 February 2024).
17. The AEM NEXUS 1000. Available online: https://www.h2coresystems.com/en/h2c_product/aem-nexus-1000/ (accessed on 8 February 2024).
18. Green Electrolyzer: The State-of-the-Art Integrated Electrolysis System for On-Site Production of Hydrogen. Available online: https://www.fest-group.de/en/hydrogen-technology/electrolysis-systems/ (accessed on 8 February 2024).
19. Lange, H.; Klose, A.; Beisswenger, L.; Erdmann, D.; Urbas, L. Modularization approach for large-scale electrolysis systems: A review. *Sustain. Energy Fuels* **2024**, *8*, 1208–1224. [CrossRef]
20. Pitschak, B.; Mergel, J.; Müller, M. Elektrolyse-Verfahren. In *Wasserstoff und Brennstoffzelle*; Töpler, J., Lehmann, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2017; pp. 207–227. [CrossRef]
21. Shiva Kumar, S.; Lim, H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep.* **2022**, *8*, 13793–13813. [CrossRef]
22. van Pham, C.; Escalera-López, D.; Mayrhofer, K.; Cherevko, S.; Thiele, S. Essentials of High Performance Water Electrolyzers—From Catalyst Layer Materials to Electrode Engineering. *Adv. Energy Mater.* **2021**, *11*, 2101998. [CrossRef]
23. Vincent, I.; Bessarabov, D. Low cost hydrogen production by anion exchange membrane electrolysis: A review. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1690–1704. [CrossRef]
24. The AEM Nexus: Produce Megawatt-Scale Green Hydrogen. Available online: https://www.enapter.com/de/aem-electrolysers/aem-nexus (accessed on 15 February 2024).
25. Simoes, S.G.; Catarino, J.; Picado, A.; Lopes, T.F.; Di Berardino, S.; Amorim, F.; Gírio, F.; Rangel, C.M.; Ponce de Leão, T. Water availability and water usage solutions for electrolysis in hydrogen production. *J. Clean. Prod.* **2021**, *315*, 128124. [CrossRef]
26. Birth, T.; Jentsch, S.; Hayen, S.; Scheffler, M. Water as a critical resource for hydrogen production. *gwf Wasser Abwasser* **2022**, *162*, 73–88. [CrossRef]
27. Hofrichter, A.; Rank, D.; Heberl, M.; Sterner, M. Determination of the optimal power ratio between electrolysis and renewable energy to investigate the effects on the hydrogen production costs. *Int. J. Hydrogen Energy* **2023**, *48*, 1651–1663. [CrossRef]
28. Büsch, L.; Koch, J.; Schüppstuhl, T. Development of a multi-sensor concept for progress detection in the site assembly of electrolysis units. *Procedia CIRP* **2023**, *120*, 1363–1368. [CrossRef]
29. Masuhr, C.; Büsch, L. Grünen Wasserstoff schnell produzieren. *Ind. Prod.* **2022**, *6*, 46–47.

30. Ausg. Deutsch/Englisch. (Ed.) *VDI 2221 Blatt 1, Entwicklung Technischer Produkte und Systeme—Modell der Produktentwicklung: = Design of Technical Products and Systems—Model of Product Design*; VDI-Richtlinien; Beuth Verlag GmbH: Berlin, Germany, 2019.
31. Ausg. Deutsch/Englisch. (Ed.) *VDI 2221 Blatt 2, Entwicklung Technischer Produkte und Systeme—Gestaltung Individueller Produktentwicklungsprozesse: = Design of Technical Products and Systems—Configuration of Individual Product Design Processes*; VDI-Richtlinien; Beuth Verlag GmbH: Berlin, Germany, 2019.
32. Ausg. Deutsch/Englisch. (Ed.) *VDI/VDE 2206, Entwicklung Cyber-Physischer Mechatronischer Systeme (CPMS): = Development of Cyber-Physical Mechatronic Systems (CPMS)*; VDI/VDE-Richtlinien; Beuth Verlag GmbH: Berlin, Germany, 2021.
33. Ausg. Deutsch/Englisch. (Ed.) *VDI 3633 Blatt 1, Simulation von Logistik- Materialfluss- und Produktionssystemen—Grundlagen: = Simulation of Systems in Materials Handling, Logistics and Production—Fundamentals*; VDI-Richtlinien; Beuth Verlag GmbH: Berlin, Germany, 2014.
34. Adler, P.; Syniawa, D.; Christ, L.; Kuhlenkoetter, B. *Robot-Based Assembly of Hydrogen Tube Fittings for Large-Scale Electrolyzers*; Ruhr-University Bochum, Chair of Production Systems (LPS): Bochum, Germany, 2023. [CrossRef]
35. Adler, P.; Christ, L.; Weckendrup, C.; Kuhlenkötter, B. Smart production system for the process-reliable assembly of hydrogen tube fittings. *Procedia CIRP* **2023**, *120*, 440–444. [CrossRef]
36. Xue, J.; Hou, X.; Zeng, Y. Review of Image-Based 3D Reconstruction of Building for Automated Construction Progress Monitoring. *Appl. Sci.* **2021**, *11*, 7840. [CrossRef]
37. Koch, J.; Büsch, L.; Gomse, M.; Schüppstuhl, T. A Methods-Time-Measurement based Approach to enable Action Recognition for Multi-Variant Assembly in Human-Robot Collaboration. *Procedia CIRP* **2022**, *106*, 233–238. [CrossRef]
38. Büsch, L.; Koch, J.; Schoepflin, D.; Schulze, M.; Schüppstuhl, T. Towards Recognition of Human Actions in Collaborative Tasks with Robots: Extending Action Recognition with Tool Recognition Methods. *Sensors* **2023**, *23*, 5718. [CrossRef]
39. Rosen, P.A. Beitrag zur Optimierung von Wasserstoffdruckbehältern. PhD Thesis , Technische Universität Chemnitz, Chemnitz, Germany, 2018.
40. Mirza, N.R.; Degenkolbe, S.; Witt, W. Analysis of hydrogen incidents to support risk assessment. *Int. J. Hydrogen Energy* **2011**, *36*, 12068–12077. [CrossRef]
41. Bundesanstalt für Materialforschung und -Prüfung. *Wasserstoff: Unser Beitrag zur Sicherheit/Hydrogen: Our Contribution to Safety*; Bundesanstalt für Materialforschung und -Prüfung: Berlin, Germany, 2020 .
42. Masuhr, C.; Büsch, L.; Schüppstuhl, T. Leakage Inspection for the Scale-Up of Hydrogen Electrolyzers: A Case Study and Comparative Analysis of Technologies. In *International Conference on Flexible Automation and Intelligent Manufacturing*; Springer: Cham, Switzerland, 2023; pp. 496–508. [CrossRef]
43. Hayasaka, K.; Tagawa, Y. Mobile visualization of density fields using smartphone background-oriented schlieren. *Exp. Fluids* **2019**, *60*, 171. [CrossRef]
44. Kousi, N.; Gkournelos, C.; Aivaliotis, S.; Lotsaris, K.; Bavelos, A.C.; Baris, P.; Michalos, G.; Makris, S. Digital Twin for Designing and Reconfiguring Human–Robot Collaborative Assembly Lines. *Appl. Sci.* **2021**, *11*, 4620. [CrossRef]
45. Adler, P.; Syniawa, D.; Jakschik, M.; Christ, L.; Hypki, A.; Kuhlenkötter, B. Automatisierte Montage großskaliger Wasser-Elektrolyseure: Digitale Montageplanung für eine nachhaltige Wasserstoffwirtschaft auf Grundlage von Produkt, Prozess und Ressource. *Proz. Ressour. I40M* **2022**, *2022*, 12–16. [CrossRef]
46. Saadat, M.; Nan, P. Industrial applications of automatic manipulation of flexible materials. *Ind. Robot. Int. J.* **2002**, *29*, 434–442. [CrossRef]
47. Patil, S.; van den, J.; Alterovitz, B.R. Motion Planning Under Uncertainty in Highly Deformable Environments. In *Robotics Science and Systems: Online Proceedings*; University of North Carolina: Chapel Hill, NC, USA, 2011. [CrossRef]
48. Drath, R.; Mosch, C.; Hoppe, S.; Faath, A.; Barnstedt, E.; Fiebiger, B.; Schlögl, W. Diskussionspapier—Interoperabilität Mit der Verwaltungsschale, OPC UA und AutomationML: Zielbild und Handlungsempfehlungen für Industrielle Interoperabilität: Zielbild und Handlungsempfehlungen für Industrielle Interoperabilität. Available online: https://opcfoundation.org/wp-content/uploads/2023/04/Diskussionspapier-Zielbild-und-Handlungsempfehlungen-fur-industrielle-Interoperabilitat-5.3-protected.pdf (accessed on 15 February 2024).
49. *IEC/PAS 63088*CEI/PAS 63088*; Smart Manufacturing—Reference Architecture Model Industry 4.0 (RAMI4.0). IEC International Electrotechnical Commission: Geneva, Switzerland, 2017.
50. Syniawa, D.; Jakschik, M.; Hypki, A.; Kuhlenkötter, B. Automated data-driven dimensioning and planning of modular large-scale electrolysis plants. In Proceedings of the 17th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Ischia, Italy, 12–14 July 2023; Elsevier: Amsterdam, The Netherlands, 2023.
51. Jakschik, M.; Syniawa, D.; Hypki, A.; Kuhlenkötter, B. Automated pipe routing in context of large-scale electrolyzer plants. In Proceedings of the 17th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Ischia, Italy, 12–14 July 2023; Elsevier: Amsterdam, The Netherlands, 2023.
52. Schleipen, M.; Drath, R. Three-view-concept for modeling process or manufacturing plants with AutomationML. In Proceedings of the 2009 IEEE Conference on Emerging Technologies & Factory Automation, Palma de Mallorca, Spain, 22–25 September 2009; IEEE: Piscataway, NJ, USA, 2009; pp. 1–4. [CrossRef]
53. Jakschik, M.; Hypki, A.; Kuhlenkötter, B. Roboterprogrammierung mithilfe von AutomationML. *Atp Mag.* **2022**, *64*, 52–58. [CrossRef]

54. Lüder, A.; Hundt, L.; Keibel, A. Description of manufacturing processes using AutomationML. In Proceedings of the 2010 IEEE 15th Conference on Emerging Technologies & Factory Automation (ETFA 2010), Bilbao, Spain, 13–16 September 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 1–8. [CrossRef]
55. Christ, L.; Adler, P.; Schulte, L.; Kuhlenkötter, B. Synthetic data derived from a digital twin for an error compensation algorithm of hydrogen tube fitting assembly. *Procedia CIRP* **2023**, *120*, 445–450. [CrossRef]