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# OPTIMISING BOP FOR GREEN HYDROGEN PRODUCTION IN PEM ELECTROLYSIS

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The study investigates the optimisation of Balance of Plant (BOP) subsystems in Proton Exchange Membrane (PEM) electrolyser systems for green hydrogen production. The research highlights that BOP is not a secondary support unit, but a core contributor to overall efficiency, reliability, safety, and cost performance. Literature-based evidence indicates that 40–60 % of the total installed PEM electrolyser CAPEX is linked to BOP components rather than the stack itself. BOP inefficiencies can reduce net system efficiency by up to 10 percentage points, suggesting that high stack performance may still lead to weak plant-level results. Key BOP subsystems assessed include water purification, thermal management, power electronics, gas handling and purification, compression and storage, and control/safety systems. PEM electrolysis requires ultrapure water with conductivity below 0.1 µS/cm and stable operating temperatures typically between 50 and 80 °C. A quantitative case study of a 10 MW PEM plant is used to illustrate subsystem-level impacts on cost and energy consumption. In this case study, BOP energy consumption is approximately 6–10 kWh/kg $H_2$, with major losses from power electronics (3–4 kWh/kg) and compression/storage (2–4 kWh/kg). Total electricity use is assumed at 55 kWh/kg $H_2$, including BOP losses. With 6,000 operating hours/year, the plant produces about 1.09 million kg $H_2$/year (≈1,091 t/year). Under a base electricity price of 50 EUR/MWh, annual electricity cost reaches ~3.0 million EUR/year. Total CAPEX is assumed at 900 EUR/kW, resulting in 9.0 million EUR investment for the 10 MW plant. Using a 20-year lifetime and 8 % discount rate, the calculated LCOH is approximately 3.8 EUR/kg $H_2$. The results confirm that BOP optimisation is essential for reducing parasitic losses, improving net efficiency, and lowering the levelized cost of hydrogen.

***Keywords:*** *BOP, energy losses, green hydrogen, LCOH, PEM electrolysis.*

## 1. INTRODUCTION

The European energy sector is undergoing a profound transformation driven by the twin imperatives of decarbonisation and energy security [1]. Among the technological pathways that support this transition, hydrogen has emerged as a key vector for energy storage, sectoral integration, and industrial decarbonisation [2]. Proton Exchange Membrane (PEM) electrolysers are the central element of this development due to their compatibility with intermittent renewable electricity, high current densities, and capability to deliver hydrogen of very high purity [3], [4]. However, the overall viability of PEM electrolysers depends not only on the electrochemical stack itself but also on the broader auxiliary systems collectively referred to as the Balance of Plant (BOP) [5].

BOP subsystems encompass water purification and distribution, thermal management, electrical power conditioning, gas handling and purification, compression and storage, as well as control, safety, and monitoring infrastructure. These elements account for a substantial proportion of both capital expenditures (CAPEX) and operational expenditures (OPEX). It is estimated that between 40 % and 60 % of the total installed cost of PEM electrolysers arises from BOP components, and that inefficiencies within BOP subsystems can lower net system efficiency by up to 10 percentage points. Therefore, studying into BOP is not peripheral but central to the optimisation of hydrogen production technologies [6], [7].

The scientific challenges are linked to the fact that BOP systems are designed, integrated, and operated in ways that maximise efficiency, reliability, and sustainability. Poorly optimised BOP components can reduce hydrogen purity, increase parasitic energy consumption, shorten stack lifetime, and elevate operational risks. Conversely, well-designed BOP subsystems can lower lifecycle costs, enable effective coupling with renewable energy, and improve system resilience. From a sustainability perspective, BOP design determines water consumption, energy efficiency, and opportunities for circular resource recovery.

The goal of the study is to analyse and

optimise BOP in PEM electrolyser systems to improve overall system efficiency, sustainability, reliability, and cost-effectiveness, with specific attention to how BOP influences energy losses, CAPEX/OPEX distribution, and the levelized cost of hydrogen (LCOH).

The study is based on the hypothesis that optimising key BOP subsystems, particularly power electronics, compression and storage, water purification, and thermal management, can significantly reduce parasitic energy consumption and total system costs, thereby improving net system efficiency and lowering LCOH in PEM-based green hydrogen production.

The study is guided by the following research questions:

- What are the main BOP subsystems in PEM electrolysis, and what roles do they play in system operation and performance?
- Which BOP subsystems contribute most significantly to parasitic energy losses and overall efficiency reduction in PEM hydrogen production systems?
- How does BOP design influence the economic performance of PEM electrolysers, particularly in terms of CAPEX, OPEX, and LCOH?
- Which BOP design configurations (centralised, modular containerised, hybrid renewable-integrated, high-purity, and heat/water recovery-focused) are most suitable for different deployment contexts and application needs?
- How do supply chain vulnerabilities and industrial dependencies affect the scalability, resilience, and strategic deployment of BOP components in PEM electrolyser systems?

The research limitations include the study's reliance on secondary data and its primary reliance on literature, meaning results depend on the availability and quality of published sources rather than direct operational measurements. The cost and performance values used for subsystem comparisons and the 10-megawatt (MW) plant example are indicative estimates and may differ depending on technology provider, plant design, geographic conditions, and market pricing. In addition, the LCOH evaluation is simplified and does not fully capture all real-world variables such as long-term degradation behaviour, component replacement schedules, detailed financing structures, or dynamic electricity pricing. The study also does not include experimental validation or pilot-scale testing of specific optimisation measures, which limits the ability to confirm performance improvements under real operating conditions. Also, some assumptions are based on typical European industrial conditions, which may reduce the direct transferability of results to other regions with different regulatory frameworks, energy markets, or infrastructure constraints.

## 2. MATERIALS AND METHODS

This study employed a structured methodological approach to analyse and optimise BOP in PEM electrolyser systems, focusing on sustainability, efficiency, cost, and supply chain resilience. The methodology was designed to move beyond a stack-centric perspective and instead evaluate PEM electrolysers as integrated industrial systems where auxiliary subsystems strongly influence overall performance [8]. As shown in Fig. 1, the study strategy combines literature-based technical assessment, industry mapping, comparative evaluation of design configurations, and supply chain analysis to build a comprehensive understanding of BOP functions and optimisation pathways.

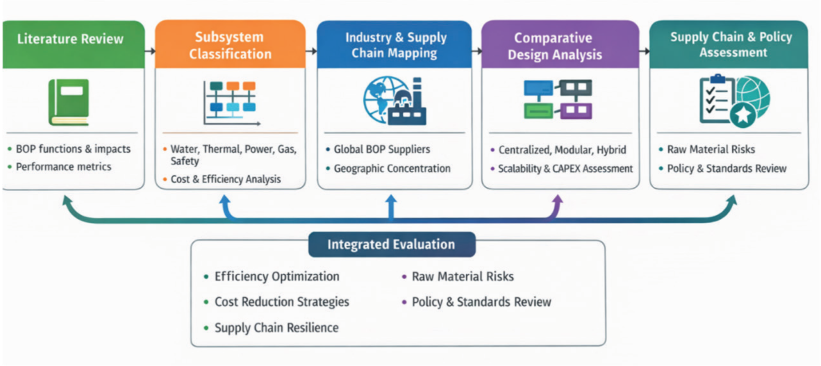

*Fig. 1.* Research design framework for BOP optimisation in PEM electrolysers.

The first methodological stage of the study consisted of a systematic literature review. Peer-reviewed journal articles, conference papers, and technical reports were screened to identify the main BOP subsystems used in PEM electrolysis and to establish their operational roles. This step ensured that the analysis was grounded in scientific evidence regarding water purification requirements, thermal management needs, power electronics efficiency, gas purification methods, and compression energy demand. The review also enabled the identification of common BOP performance indicators such as parasitic energy losses, net system efficiency, hydrogen purity specifications, and operational reliability metrics.

The second stage focused on data extraction and classification of BOP subsystems. Information from the literature was organised into categories, including water management, thermal management, power electronics, gas handling and purification, compression and storage, and control and safety systems. Each subsystem was assessed according to its functional contribution, energy consumption impact, and relevance to CAPEX and OPEX. This classification allowed the study to compare subsystems using a uniform framework and to identify which elements contribute most significantly to efficiency losses and cost escalation in PEM hydrogen plants.

To support quantitative interpretation, the study incorporated indicative performance and cost breakdowns from representative plant scales such as 10 MW PEM electrolyser systems. Subsystem-level estimates for energy consumption per kilogram of hydrogen were used to identify major parasitic loads. Similarly, CAPEX share ranges for each subsystem were applied to highlight the economic weight of BOP relative to total system cost. This step provided a basis for linking technical subsystem performance to economic outcomes, which was necessary for sustainability-driven optimisation.

Next methodological element consisted of supply chain analysis. It traced the upstream dependencies of BOP components on raw materials, manufacturing capacity, and specialised industrial capabilities. Attention was given to vulnerabilities linked to semiconductors for power electronics, specialty alloys for compressors, and water treatment materials such as membranes and resins. The analysis also examined the risks of regional concentration and the implications of disruptions in logistics, trade policy, or industrial capacity constraints. This supply chain perspective strengthened the study by connecting engineering design decisions with industrial resilience and strategic competitiveness.

Also, the methodology integrated an assessment of policy and standardisation influences. Industrial policy measures, local content requirements, and international standards were considered as external drivers shaping BOP technology adoption and market evolution. This step was necessary because PEM electrolyser deployment was strongly affected by regulatory frameworks, hydrogen quality requirements, and safety certification procedures. The methodology, therefore, accounted for the fact that BOP development was not only technical but also institutional and market-driven.

The study also applied a multi-disciplinary evaluation logic that combined engineering, economics, and industrial organisation perspectives. Engineering analysis was used to interpret subsystem efficiency impacts, reliability requirements, and operational constraints. Economic reasoning was used to link subsystem design choices to CAPEX and OPEX outcomes. Industrial organisation concepts were applied to interpret geographic specialisation, supplier concentration, and competitive positioning in global BOP markets. This integrated perspective provides a more complete understanding of PEM electrolyser systems than single-discipline approaches.

## 2. FUNCTIONS OF BOP IN PEM ELECTROLYSIS

The concept of BOP is fundamental in modern energy systems, industrial facilities, and large-scale process engineering. It refers to all supporting infrastructure, auxiliary systems, and components that are required to ensure the proper functioning of a main process unit or core technology [5]. While the main plant typically performs the primary energy conversion or chemical transformation, such as electricity generation in a turbine, hydrogen production in an electrolyser stack, or combustion in a boiler, the BOP represents the broader technical environment that enables continuous, efficient, and safe operation [9].

In scientific terms, BOP can be understood as a cascade of subsystems whose collective function is to provide inputs, regulate operating conditions, manage outputs, and guarantee system-level stability [10]. Without an optimised BOP, even the most advanced core unit cannot deliver its theoretical performance. This is especially evident in sectors such as green hydrogen production, wind power, and nuclear energy, where system efficiency and economics are strongly influenced by auxiliary equipment.

Water management is one of the most critical BOP functions in many processes. For example, PEM electrolysis requires ultrapure water with conductivity below 0.1 μS/cm [11] to avoid catalyst poisoning and membrane degradation. BOP, therefore, incorporates reverse osmosis systems, deionization units, circulation pumps, and storage tanks. Poor water quality or inadequate distribution directly reduces electrolyser lifetime and hydrogen purity [12]. Similarly, in thermal power plants, water treatment and steam cycle conditioning are central BOP elements that help prevent scaling, corrosion, and system inefficiencies.

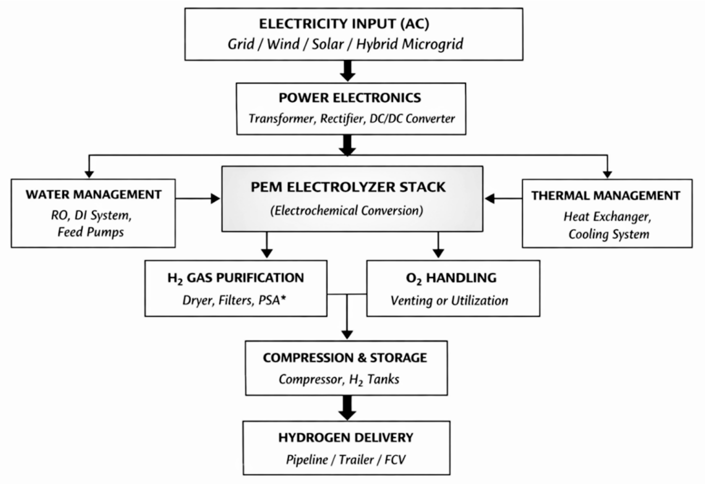

*Fig. 2.* BOP principal scheme for PEM electrolyser.

Thermal management represents another essential dimension of BOP. Almost all energy conversion processes generate heat, either as a useful by-product or as a loss that must be dissipated. BOP integrates chillers, heat exchangers, cooling towers, and pumps to maintain temperature within design limits. In the case of PEM electrolysis, the optimal temperature range is between 50 and 80 °C, and deviations may result in reduced efficiency or accelerated material degradation [13]. In other energy systems, such as combined-cycle power plants, heat recovery units form a key part of BOP, enhancing overall efficiency by capturing and reusing waste heat.

Power electronics and electrical conditioning subsystems form another large share of BOP, especially in renewable energy integration. Renewable sources such as wind and solar provide intermittent and fluctuating outputs, which must be converted into stable, stack-compatible current and voltage. Transformers, rectifiers, and DC/DC converters are, therefore, critical components of BOP. Their efficiency determines not only the parasitic losses but also the ability of the system to follow dynamic load changes.

Gas handling and purification are equally important to ensure that product streams meet the required quality standards. In hydrogen production, the gas leaving the electrolyser stack often contains water vapour and trace oxygen. BOP, therefore, integrates separators, dryers, and filters to deliver hydrogen of 99.999 % purity when destined for fuel cell applications. Oxygen handling also requires attention, since it may be vented, captured, or compressed depending on the industrial context [14]. Similarly, in natural gas processing or ammonia plants, the gas treatment BOP components guarantee compliance with safety regulations and product quality requirements [15].

Compression, storage, and transport infrastructure also fall under BOP [16]. In hydrogen production systems, compressors and high-pressure tanks represent both a technical challenge and a major share of cost. Hydrogen's small molecular size and tendency to cause embrittlement impose stringent requirements on materials, seals, and monitoring [17]. In wind or solar power plants, analogous BOP elements include grid connection systems, substations, and transmission lines, all of which enable integration of generated power into the wider energy network.

Control and safety systems represent the final category of BOP subsystems but are arguably the most important for operational reliability. These include sensors, programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA) platforms, fire suppression systems, and pressure relief valves. Their function is not limited to emergency response; they also enable predictive maintenance, real-time optimisation, and remote integration with smart grids or industrial process networks. Increasingly, BOP safety and control systems are linked to cybersecurity frameworks to protect the digitalised infrastructure.

Scientific analyses show that inefficiencies within BOP subsystems can undermine theoretical advantages of core technologies. For example, even if an electrolyser stack achieves 70 % efficiency, the parasitic loads of BOP subsystems can reduce system efficiency to 60–65 %. Similarly, in wind power plants, electrical losses in transmission and conversion significantly affect the net energy delivered to the grid [18]. Risk analysis further demonstrates that BOP reliability is a determining factor for system availability. Failures in pumps, compressors, or power electronics frequently cause unplanned downtime. As a result, predictive maintenance and redundancy strategies are increasingly implemented. Digital twin approaches are emerging as powerful tools for modelling BOP performance, predicting component degradation, and optimising lifecycle costs [19].

## 3. BOP OPTIMISATION FOR SYSTEM INTEGRITY

Research and innovation in BOP design focus on modularisation, standardisation, and hybrid integration. Modular BOP units can be mass-produced and easily scaled, reducing capital intensity. Hybrid systems allow waste heat from electrolysis or turbines to be used in district heating, while integrated purification reduces complexity by combining drying and separation in a single unit. Advanced materials research seeks to mitigate hydrogen embrittlement in compressors and improve efficiency in rectifiers [20].

PEM electrolysers have become critical technology for green hydrogen production, especially in contexts where high current density, fast load response, and compatibility with intermittent renewable power sources are required [21]. While the electrolyser stack itself represents the core of the hydrogen production unit, the overall system performance, efficiency, safety, and cost-effectiveness are strongly determined by BOP. The BOP encompasses all auxiliary equipment and subsystems required to enable, control, and optimise the electrolysis process beyond the stack. This includes fluid handling, thermal management, electrical conversion, gas purification, compression, and safety infrastructure. A scientific understanding of BOP is fundamental in assessing technical feasibility, economic competitiveness, and scalability of PEM-based hydrogen production plants.

The role of the BOP can be divided into four key functions:

- supplying necessary inputs to the stack (water, electricity, and cooling);
- ensuring proper operational environment (temperature, pressure, and purity);
- handling and conditioning the output gases (hydrogen and oxygen);
- providing system-level services such as control, monitoring, safety, and integration with external infrastructure [22].

A weakness or inefficiency in any of these subsystems has direct consequences on hydrogen quality, energy consumption, capital cost, and system reliability.

The water management subsystem is particularly crucial. PEM electrolysis requires high-purity deionized water, typically with conductivity below 0.1 µS/cm, to avoid contamination of the proton-conducting membrane. Therefore, BOP incorporates deionization units, reverse osmosis systems, and circulation pumps. Water distribution must be carefully regulated to maintain stack hydration, prevent membrane dry-out, and avoid flooding. Inefficient water management can accelerate membrane degradation, reduce efficiency, and increase operating costs. Furthermore, oxygen produced on the anode side is typically vented or captured for industrial use, which requires separation units, piping, and venting infrastructure.

Thermal management is another critical component of BOP. The electrolysis reaction is endothermic, and the system also generates resistive heat under high current density operation. For PEM systems operating at 50–80 °C, precise temperature control is required to optimise kinetics while avoiding thermal stresses. Heat exchangers, pumps, chillers, and thermostatic valves are implemented in the BOP [23]. Proper heat integration with external processes can improve overall plant efficiency, for example, by using waste heat in district heating or industrial applications.

Electrical power conditioning represents one of the largest contributors to overall system losses. Renewable energy sources such as solar photovoltaic or wind turbines generate fluctuating DC or AC power, which must be converted to stable DC current at the required voltage for the electrolyser stack. BOP, therefore, includes transformers, rectifiers, DC/DC converters, and power distribution systems. The efficiency of these subsystems directly affects the overall energy consumption of hydrogen production, typically expressed as kilowatt-hours per kilogram (kWh/kg) of hydrogen.

Gas handling and purification are another dimensions of BOP. Hydrogen leaving the cathode side contains water vapour, oxygen, and potential contaminants. Dryers, demisters, and gas–liquid separators are included to ensure hydrogen meets purity specifications, often 99.999 % for fuel cell applications. Similarly, oxygen streams must be safely vented, collected, or compressed, depending on use cases [24]. Gas compression is often integrated downstream, enabling storage at 30–700 bar. Compressors, storage vessels, and safety valves form a critical part of the BOP. These subsystems must be designed to handle hydrogen's unique properties, such as high diffusivity and material embrittlement risks.

Table 1 summarises the main BOP components in PEM hydrogen production systems and their technical functions.

BOP in PEM electrolyser-based green hydrogen production is a multifaceted system integrating water, heat, power, gas, and control subsystems. Its role is not auxiliary in the trivial sense but rather integral to system efficiency, safety, and economic viability. The scientific challenge is to optimise BOP design to reduce capital intensity, minimise parasitic loads, and enhance reliability while maintaining compatibility with renewable energy sources. Future directions include digitalisation, hybridisation with other industrial processes, and standardisation of BOP modules to accelerate scale-up. Achieving breakthroughs in BOP technology will be as decisive for the hydrogen economy as improvements in electrolyser stack materials.

**Table 1.** The Main BOP Components for PEM Electrolysers

| Subsystem | Component | Function |
|---|---|---|
| Water Management | RO units, deionizers, pumps, tanks | Ensure ultrapure water supply and distribution to the stack |
| Thermal Management | Heat exchangers, chillers, and circulation pumps | Maintain optimal stack temperature (50–80 °C) and remove waste heat |
| Power Electronics | Transformers, rectifiers, DC/DC converters | Convert renewable AC/DC to stable DC for stack operation |
| Gas Handling | Separators, dryers, demisters, filters | Purify hydrogen and oxygen streams from water vapour and contaminants |
| Compression and Storage | Compressors, tanks, piping, valves | Enable hydrogen storage and delivery at required pressures |
| Control and Safety | Sensors, PLCs, SCADA, safety valves | Monitor operation, control processes, and prevent hazardous conditions |

## 4. OPTIMAL BOP DESIGN VARIATIONS FOR PEM ELECTROLYSERS

The design of BOP for PEM electrolysers determines the system's overall efficiency, reliability, cost, and scalability [5]. While the electrolyser stack is the technological core, the BOP dictates the ability of the system to integrate with renewable energy sources, produce hydrogen at high purity, and operate under dynamic conditions. Scientific research and industrial practice have identified several distinct BOP design variations, each optimised for specific applications such as large-scale industrial hydrogen production, integration with wind and solar farms, or distributed on-site hydrogen generation. The universal design example of BOP for PEM electrolyser is shown in Fig. 3.

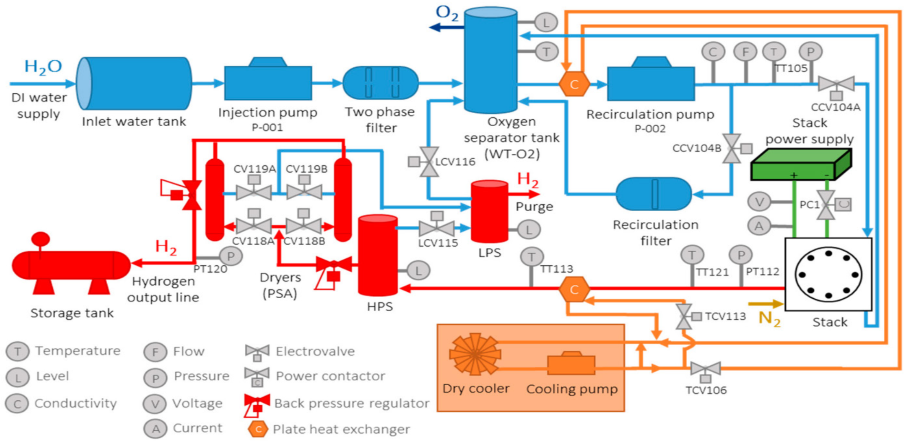

**Figure 4.** Balance of plant (BOP) of the developed PEM electrolyzer.

*Fig. 3.* The technical design example of BOP for PEM electrolyser.

## 4.1. Centralised Industrial BOP Design

The centralized industrial BOP design for a PEM electrolyser is a concept in which the auxiliary systems required for the operation of the electrolysis stack are concentrated in a single, integrated infrastructure [5]. In this configuration, the electrolyser stacks themselves remain relatively simple devices, while all the supporting subsystems for water purification, gas management, power electronics, cooling, and compression are centralised in a larger plant facility. This approach is generally applied in large-scale hydrogen production projects, where economies of scale justify a unified system rather than multiple smaller and distributed BOP units [25].

In a centralised system, water treatment is the first critical component. Since PEM electrolysers require ultrapure deionized water to prevent membrane contamination and catalyst degradation, a central purification unit is installed to treat large volumes of feed water. This unit typically consists of reverse osmosis, deionization resins, and polishing filters, ensuring stable water quality across all connected stacks. The purified water is then distributed to multiple electrolyser modules, reducing redundancy in treatment equipment.

Power electronics form another essential part of the centralised BOP. A single large rectifier and transformer system is used to convert AC from the grid or a renewable energy source into DC required for the PEM electrolyser stacks. This central arrangement lowers capital costs compared to multiple small converters and allows for optimisation of power quality and distribution [26]. Power electronics are also equipped with control mechanisms to regulate load-following capabilities, enabling efficient response to fluctuations from intermittent renewable energy sources such as wind or solar.

Thermal management is achieved through a centralised cooling loop, typically water-based, which extracts waste heat from the electrolyser stacks and supporting equipment. The cooling system includes pumps, heat exchangers, and cooling towers or chillers, depending on the site conditions. By concentrating thermal management in a single system, efficiency is improved, and operational costs are lowered. Additionally, waste heat can be recovered and redirected for secondary uses, such as district heating or industrial processes, enhancing the overall energy efficiency of the hydrogen production facility.

Gas handling and separation systems are also centralised. The hydrogen and oxygen streams generated in the electrolysers require drying, purification, and sometimes compression before further use or storage. In a centralised BOP, large-scale purification units, such as pressure swing adsorption (PSA) or membrane-based dryers, ensure that hydrogen reaches fuel-cell-grade purity. Similarly, oxygen can be collected for industrial applications or safely vented. Centralising these processes ensures consistency in product quality while minimising equipment duplication.

Another essential element of the centralised BOP is the compression and storage infrastructure. Instead of integrating small compressors with each electrolyser stack, a larger central compression station is used, feeding hydrogen into storage tanks or pipelines. This reduces operational complexity and maintenance requirements while enabling the handling of high throughput volumes more efficiently.

Process utilities and control systems are integrated into the centralised design. Instrumentation for pressure, temperature, and gas quality monitoring is consolidated into a single SCADA system. This allows plant operators to monitor and control all auxiliary processes in real time, improving safety, reliability, and automation. Centralised control also simplifies maintenance planning and predictive diagnostics, since all critical BOP subsystems are networked into one data architecture [27].

From an economic standpoint, centralised BOP design significantly reduces the per-unit cost of equipment due to economies of scale, but it also introduces challenges. The high degree of interdependence between electrolyser stacks and centralised infrastructure means that failures in one BOP subsystem, such as the cooling system or power electronics, can impact the operation of the entire facility. This creates potential bottlenecks and increases the importance of redundancy in critical subsystems. Therefore, large-scale hydrogen plants often incorporate backup pumps, secondary cooling loops, or dual power supplies to ensure operational continuity.

The scientific and engineering advantages of centralised BOP include improved efficiency, reduced redundancy, better integration with external networks, and cost competitiveness in large-scale deployment. However, the disadvantages involve reduced modularity, higher vulnerability to single-point failures, and limited flexibility for scaling down operations. Despite these drawbacks, centralised designs remain the dominant choice for gigawatt-scale PEM electrolyser projects, where the centralisation of auxiliary systems ensures lower total costs, optimised resource usage, and simplified system integration into industrial hydrogen hubs.

The centralised industrial BOP design for PEM electrolysers represents a highly integrated and cost-effective solution for large hydrogen production facilities, combining centralised water treatment, power conversion, thermal regulation, gas handling, compression, and control into a unified plant structure that maximises efficiency and lowers operational costs, while at the same time requiring careful attention to redundancy and reliability to avoid systemic failures.

### 4.2. Modular Containerised BOP Design

The modular containerised BOP design for a PEM electrolyser is an engineering approach where each electrolyser unit is packaged with its own supporting auxiliary systems inside a standardised container [28]. Instead of relying on a single centralised infrastructure for water purification, thermal regulation, power electronics, gas handling, and compression, each module includes its own dedicated BOP subsystems. This containerised format makes the electrolyser a self-contained and easily deployable hydrogen production unit, providing flexibility, redundancy, and scalability that is especially suited for distributed or rapidly deployable hydrogen projects.

In this design, water treatment is integrated within each container. Small-scale reverse osmosis and deionization systems ensure that ultrapure water is supplied directly to the electrolyser stack inside the same module. Unlike centralised designs, where one large water treatment system serves many stacks, the modular system duplicates water treatment across containers. This duplication increases the cost per unit of hydrogen but provides independence and allows each container to operate autonomously.

Power electronics are also embedded within each module. Dedicated rectifiers and transformers convert incoming alternating current into direct current, tailored to the specific needs of the electrolyser stack within that container. This modularity makes it easier to connect containerised electrolysers directly to renewable energy sources, as each unit can independently regulate its power load and respond to variations in supply. The presence of multiple independent converters also increases resilience, since failure in one unit does not affect the operation of others.

Thermal management in modular BOP design is localised, with cooling systems installed in each container. These typically include small-scale water-cooling loops with pumps, heat exchangers, and compact chillers or air-cooled radiators. This arrangement enables flexible deployment in diverse climates and simplifies installation, as each unit is pre-engineered for thermal regulation. However, it also means that thermal integration between modules is limited, and opportunities for large-scale waste heat recovery are reduced compared to centralised designs.

Gas handling and purification are performed at the module level. Each container is equipped with drying and purification units to ensure hydrogen meets the necessary purity standards. This often includes desiccant dryers, membrane separators, or compact PSA units. The advantage is that each module guarantees consistent hydrogen quality regardless of external connections, while the drawback is the higher capital cost associated with duplicating purification systems across multiple modules.

In terms of compression and storage, modular designs can include small compressors inside each container or rely on external shared compressors. In many cases, the modular units are designed to produce hydrogen at ambient pressure, while compression and storage are handled externally to optimise cost. When included inside the container, compression capacity is usually limited, making this option best suited for small-to-medium hydrogen demands rather than large-scale industrial supply.

Controlling and automation systems in containerised BOP designs are built for independence. Each container has its own control panel, instrumentation, and sensors to monitor temperature, pressure, purity, and power consumption. The automation can function locally, allowing the unit to operate in isolation, or be networked into a central supervisory control system for coordinated management of multiple containers. This makes the system highly adaptable to both stand-alone installations and larger modular arrays.

The key economic advantage of the modular containerised BOP design is rapid deployment. The units are preassembled, factory-tested, and shipped as turnkey systems, drastically reducing installation time and costs at the deployment site. They are particularly attractive for hydrogen fuelling stations, pilot projects, and off-grid applications where scalability and flexibility are more important than maximum efficiency. However, the duplication of subsystems across containers leads to higher overall capital and operational costs compared to centralised designs, especially in very large installations.

From a resilience perspective, modular systems offer strong reliability. If one container fails or requires maintenance, the others can continue operating without interruption. This redundancy reduces downtime and makes the system inherently more robust in distributed environments. The modularity also allows incremental scaling of hydrogen production, where additional containers can be added as demand grows, avoiding the large upfront investment required for centralised plants.

Comparative analysis of centralised and modular containerised BOP designs is shown in Table 2 and Fig. 4.

**Table 2.** Comparative Analysis of Centralised and Modular Containerised BOP Designs

| **Parameter** | **Centralised Industrial BOP** | **Modular Containerised BOP** |
|---|---|---|
| System Efficiency (% LHV) | 63–67 % (optimised through large-scale integration of cooling, power, and water systems) | 60–65 % (lower due to duplicated subsystems and limited heat/water recovery) |
| CAPEX (per kW installed) | Lower per unit at scale due to economies of scale; typical share of BOP ~40–45 % of CAPEX | Higher per unit due to equipment duplication; typical share of BOP ~50–55 % of CAPEX |
| OPEX Impact | Medium; centralised systems easier to maintain but can be costly if a failure affects all units | Higher; more maintenance due to many small subsystems, though failures are isolated |
| Reliability | Depending on redundancy in centralised subsystems; single-point failures can affect full plant | High resilience; failure in one container does not affect others |
| Scalability | High for large-scale plants (>100 MW), but scaling requires significant upfront investment | Flexible and incremental scaling; containers can be added gradually as demand increases |
| Deployment Time | Longer, requires significant site engineering, permitting, and integration | Shorter; containerised units are factory-tested and delivered as turnkey solutions |
| Hydrogen Purity | Consistent; purification centralised with large PSA or membrane units | Consistent; each container integrates compact purification, ensuring independence |
| Heat and Water Recovery | High potential: centralised loops allow industrial integration of waste heat and water reuse | Low potential; each unit self-contained, limiting resource integration opportunities |
| Best Applications | Large industrial hydrogen clusters, refineries, steelmaking, chemical industries | Distributed generation, hydrogen refuelling stations, off-grid projects, renewable integration |
| Economic Risk | High exposure to system downtime if central BOP fails | Lower systemic risk; distributed redundancy across containers |

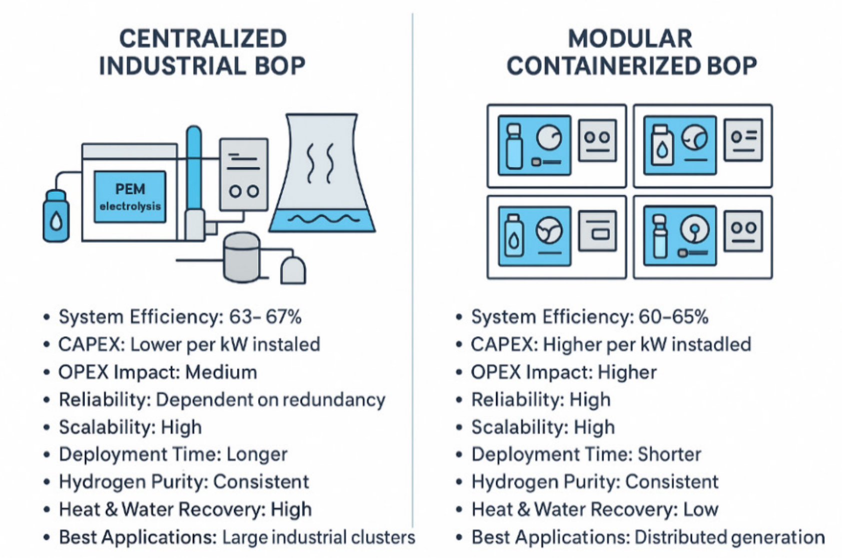

*Fig. 4.* Comparative categories of centralised and modular containerised BOP designs.

In terms of scientific and engineering implications, the modular containerised BOP design emphasises flexibility, portability, and adaptability. It is particularly suited to early-stage hydrogen markets, remote regions, and renewable energy integration projects that require distributed generation. While less efficient in terms of resource utilisation and cost per unit hydrogen compared to centralised systems, it provides a practical, scalable, and resilient pathway for deploying PEM electrolyser technology in diverse contexts.

The modular containerised BOP design for PEM electrolysers represents a decentralised, scalable, and redundant solution for hydrogen production. Each containerised module includes its own water treatment, power electronics, cooling, gas purification, and control systems, enabling flexible deployment and incremental growth [29]. Though it introduces higher costs due to duplication of equipment, it offers unmatched portability, rapid deployment, and resilience, making it an optimal design for distributed hydrogen generation, renewable integration, and early-market adoption scenarios.

## 4.3. Hybrid Renewable-Integrated BOP Design

The hybrid renewable-integrated BOP design for PEM electrolysers is an advanced architecture specifically developed to manage the challenges associated with coupling hydrogen production directly to intermittent renewable energy sources such as wind and solar [30]. Unlike traditional centralised or modular designs, this approach integrates energy conversion, storage, and regulation components into the BOP to ensure stable and efficient operation under highly dynamic input conditions. Its primary function is to transform fluctuating renewable energy into a stable supply of power and auxiliary resources that allow the electrolyser stack to operate safely, efficiently, and with minimal degradation.

At the core of this BOP design are advanced power electronics, which convert variable renewable electricity into the direct current required for PEM operation. These units incorporate rectifiers, converters, and inverters capable of handling rapid load fluctuations. High frequency switching devices, coupled with digital control algorithms, allow fast ramping up and down of electrolysis activity without damaging the membrane electrode assembly. This feature is crucial, as direct connection to solar and wind farms exposes the electrolyser to sharp variations in power availability, which could otherwise reduce efficiency and shorten system lifetime.

Another defining component of this hybrid BOP design is the inclusion of buffer energy storage systems, such as lithium-ion batteries, flow batteries, or supercapacitors. These buffers store excess renewable electricity during peaks and release it during low production periods, smoothing out short-term fluctuations. By doing so, they reduce stress on the electrolyser stack, improve hydrogen production stability, and allow the plant to maintain predictable output even under intermittency. The integration of these storage systems represents one of the most significant differentiators of this architecture compared to conventional designs.

Water and thermal management systems are also optimised for flexibility. Water purification and circulation must respond dynamically to variable electrolyser loads, ensuring that ultrapure water is always available without excessive wastage. Thermal management systems, such as chillers and heat exchangers, must rapidly adjust to varying heat loads, preventing temperature spikes when the electrolyser ramps up quickly or maintaining stability during partial load operation. The BOP, therefore, requires highly responsive pumps, variable-speed drives, and control loops.

On the gas-handling side, the hybrid renewable-integrated design includes dynamic purification and drying units that operate efficiently under fluctuating hydrogen and oxygen output rates. Compact membrane dryers or modular PSA systems are typically used to adapt to variable flows, ensuring that hydrogen purity remains constant even when stack operation changes rapidly. Some systems also integrate intermediate storage buffers for hydrogen, which act as shock absorbers between the electrolyser and the downstream compression or distribution infrastructure.

System control and automation play a central role in this design. The BOP incorporates advanced monitoring, predictive control, and machine-learning-based optimisation to balance renewable supply, electrolyser demand, and storage system state-of-charge. Supervisory control systems analyse weather forecasts, grid signals, and real-time renewable generation data to plan electrolyser operation, ensuring maximum efficiency while protecting the stack from excessive cycling.

As for economics, the hybrid renewable-integrated BOP design incurs higher capital and operational costs than conventional systems because of the need for advanced electronics, storage units, and dynamic control infrastructure. However, these costs are justified in projects where grid independence or renewable coupling is essential. By enabling efficient direct use of intermittent energy, this design avoids the need for intermediate grid stabilisation or curtailment, making renewable hydrogen production economically viable [31].

In terms of performance benefits, the hybrid BOP significantly reduces degradation of the PEM stack by moderating the effects of power cycling, thereby extending operational lifetime. It also ensures that hydrogen output remains continuous and predictable, an important factor for downstream consumers. Additionally, the incorporation of energy buffers can provide ancillary grid services such as frequency regulation or reserve capacity, offering additional revenue streams.

From a systems engineering perspective again, the hybrid design is highly flexible. It can be deployed in remote renewable sources for off-grid hydrogen production or in grid-connected applications where electrolysers act as a flexible load to stabilise networks with high renewable penetration. This makes the architecture attractive both for distributed green hydrogen projects and for integration into large renewable energy hubs [32].

Hybrid renewable-integrated BOP design for PEM electrolysers is characterised by advanced power electronics, integrated energy storage, flexible thermal and water systems, dynamic gas purification, and intelligent control. It enables efficient, stable, and durable hydrogen production directly from intermittent renewable sources, balancing technical complexity and cost with the strategic advantage of decarbonised energy integration. This design is, therefore, central to the future of renewable hydrogen, bridging the gap between variable energy generation and reliable hydrogen supply.

**Table 3.** Key Elements of Hybrid Renewable-Integrated BOP for PEM Electrolysers

| Subsystem | Main Components | Primary Functions | Advantages | Challenges |
|---|---|---|---|---|
| Power Conversion and Control | Rectifiers, DC/DC converters, inverters, grid interface, high-frequency switches | Convert variable renewable AC/DC into stable DC for PEM; manage fast load variations | High efficiency; enable direct renewable coupling; protect PEM stack | Expensive; complex control algorithms; sensitive to high-frequency harmonics |
| Energy Storage (Buffering) | Lithium-ion batteries, flow batteries, supercapacitors | Absorb excess energy; release energy during low renewable generation; smooth fluctuations | Stabilise electrolyser load; prolongs stack lifetime; enables steady hydrogen output | Add cost; require maintenance; limited storage capacity |
| Water Supply and Purification | Water softeners, reverse osmosis, deionizers, pumps, circulation systems | Provide ultrapure water dynamically in line with varying electrolyser loads | Ensure high purity feed water; avoid stack contamination; flexible response | High operating cost; energy-intensive purification; risk of scaling/fouling |
| Thermal Management | Heat exchangers, chillers, pumps, variable-speed drives | Control stack temperature under fluctuating load; recover waste heat where possible | Protect membrane and catalysts; potential for district heating integration | Require rapid responsiveness; costly under variable operations |
| Gas Handling and Purification | Hydrogen dryers (membrane, PSA), oxygen separation units, gas storage buffers | Purify and condition hydrogen/oxygen at variable flow rates; stabilise output quality | Ensure constant hydrogen purity; enable storage between renewable fluctuations | Efficiency loss under variable load; add equipment duplication |
| Automation and Control Systems | SCADA, predictive algorithms, weather-linked forecasting tools | Coordinate renewables, electrolyser stacks, storage, and gas handling; optimise efficiency | Enable predictive load following; increase operational stability; reduce downtime | Complex integration; cybersecurity risks; high software development costs |
| Grid Interaction (optional) | Smart inverters, demand response systems | Allow electrolyser to operate as grid-stabilizing load; export/import power as needed | Additional revenue from grid services; enhance renewable penetration | Require regulatory approval; add complexity in hybrid operation |
| Hydrogen Storage and Compression | Low-pressure tanks, high-pressure compressors, storage vessels | Store hydrogen for continuous supply even under intermittent input | Decouple production from delivery; enable flexible use | Compression losses; added CAPEX and footprint |
| Integration with Renewables | Direct coupling to solar PV, wind turbines, hybrid microgrid | Source electricity from variable renewable generation | Decarbonised hydrogen production; avoid curtailment of renewable energy | Strongly dependent on weather patterns; require large land/ space |

## 4.4. High-Purity Hydrogen BOP Design

The high-purity hydrogen BOP design for PEM electrolysers is a specialised system configuration that prioritises the delivery of hydrogen with exceptionally high purity, typically at levels exceeding 99.999 % (5N) for critical applications such as fuel cells, semiconductor manufacturing, and advanced chemical processes [33]. Unlike general-purpose BOPs, which balance efficiency and cost, this design is engineered with additional subsystems for gas cleaning, drying, and compression to meet stringent quality requirements. It integrates tightly with the PEM electrolysers stack, ensuring that the hydrogen produced is not only generated efficiently but also refined to match demanding industrial standards.

At the core of this BOP architecture is the advanced hydrogen purification system, which includes PSA, palladium membrane purifiers, or advanced polymeric membrane separators [34]. These units remove residual water vapour, oxygen, nitrogen, and trace impurities that may escape from the electrolysers. Depending on the application, purification can be performed in multiple stages to ensure redundancy and minimise contamination risks. This additional equipment is critical for applications like hydrogen refuelling stations or electronics industries, where even trace impurities can severely damage downstream systems.

Drying units form another essential component of the high-purity hydrogen BOP. Since PEM electrolysers inherently produce humidified hydrogen due to water crossover through the PEM, drying technologies such as desiccant dryers, cold traps, or selective membrane dryers are integrated into the BOP. These systems ensure that residual water vapour is reduced to extremely low parts-per-million levels, safeguarding storage vessels and pipelines from corrosion and ensuring compatibility with sensitive end-use technologies.

The design also includes dedicated gas handling and compression systems optimised for purity retention. Compressors used in this setup are oil-free and fitted with contaminant-free seals to prevent hydrocarbon contamination of the hydrogen stream. Multi-stage compression may be employed, with intercooling and filtration between stages to preserve purity levels. The gas is typically stored in high-pressure cylinders or supplied to downstream users directly, with continuous monitoring to ensure the absence of impurities.

Water management systems are designed to supply the electrolysers with ultrapure feed water, as the quality of input water directly affects the purity of the output hydrogen. Reverse osmosis, deionization, and polishing filters are employed in multiple stages to eliminate trace of minerals and organics. Constant monitoring ensures that the resistivity of the water meets strict specifications, preventing contamination of the hydrogen stream with unwanted ions or particulates.

Thermal management systems are also adapted to the requirements of high-purity operation. Effective cooling of both the stack and purification units is essential to maintaining stable operation and preventing thermal degradation of purification membranes. Heat exchangers and chillers are typically constructed from stainless steel or inert materials to avoid leaching contaminants into the process stream, thereby maintaining the integrity of the hydrogen purity chain.

In addition to these technical elements, the BOP includes real-time monitoring and quality assurance systems. Online gas chromatographs, moisture analysers, and oxygen sensors are integrated to verify that hydrogen purity meets the desired standard continuously. Automated alarms and shutdown protocols are included to prevent the delivery of substandard hydrogen to end users, protecting critical applications from contamination.

The economic characteristics of this BOP design differ from those of standard systems. Capital costs are higher due to the addition of purification, drying, and monitoring equipment, and operational costs increase with energy requirements for purification and compression. However, these investments are justified in high-value industries where the cost of hydrogen impurities far outweighs the added system expense.

The advantages of the high-purity BOP design include compatibility with the strictest application requirements, extended durability of end-use equipment, and compliance with international hydrogen quality standards such as ISO 14687 [35]. The challenges are primarily economic and operational, with higher costs and increased system complexity. Maintenance must be more frequent and handled with specialised expertise to preserve performance over long-term operation.

The high-purity hydrogen BOP design for PEM electrolysers represents a highly engineered system that integrates advanced purification, drying, compression, water treatment, and monitoring into a seamless architecture. It is tailored to industries where hydrogen quality is non-negotiable, and where the value of guaranteed purity outweighs the higher CAPEX and OPEX. This design ensures that hydrogen produced through electrolysis is delivered at the required quality for the most demanding applications, thereby positioning PEM electrolysers as reliable suppliers of ultra-pure hydrogen in the global clean energy and advanced materials markets.

### 4.5. Integrated Heat and Water Recovery BOP Design

The integrated heat and water recovery BOP design for PEM electrolysers represents an advanced system architecture that focuses on maximising the overall efficiency of hydrogen production by capturing, reusing, and optimising both thermal and water resources generated during operation [36]. Unlike conventional BOP configurations, which primarily handle utilities and gas conditioning, this design integrates thermal energy recovery and water recycling systems directly into the hydrogen production process, reducing both energy consumption and water footprint. The approach is particularly relevant in industrial and renewable energy settings where sustainability and resource efficiency are of high priority.

At the core of this BOP design is a heat recovery loop that captures the waste heat generated by the PEM electrolyser stack, auxiliary equipment, and gas conditioning subsystems [37]. Electrolyser stacks typically operate at moderate temperatures (50–80 °C), and cooling is required to maintain stable membrane performance and prolong system durability. Instead of discarding this thermal energy, heat exchangers are installed to recover it from coolant circuits and gas streams. The recovered heat can be utilised for preheating the feed water before electrolysis, supplying low-temperature district heating, or even powering absorption chillers for cooling applications. By reducing the amount of additional heating energy required, the system achieves higher overall energy efficiency and lowers operational costs.

The water recovery subsystem forms another critical element of this BOP configuration. During hydrogen production, the PEM electrolyser consumes deionized water at the anode, and part of the process inherently results in water crossover through the membrane, leading to humidified hydrogen and oxygen streams. Instead of venting this water vapour into the environment, condensers and separation units are integrated to collect and recycle it back into the water treatment and feed circuits. Advanced polishing filters, ultraviolet sterilization, and ion-exchange beds ensure that the recovered water meets ultrapure specifications before it is reintroduced into the electrolyser. This recycling loop can reduce net water consumption by 30–50 %, which is a critical advantage in arid regions or large-scale deployments where water supply constraints may limit hydrogen production capacity.

The design also incorporates integrated thermal and water management controls, which dynamically balance heat and water recovery depending on load conditions and external demand. For instance, during high-load operation, greater amounts of heat are recovered and directed toward water preheating, while in partial-load operation, excess heat may be directed to external heating networks or stored in thermal buffers. Similarly, real-time sensors monitor the purity and quantity of recycled water to ensure compliance with system requirements and prevent any contamination that could damage the PEM stack. This dual integration of heat and water flows creates a synergistic system that optimises both electrolysis efficiency and resource utilisation.

The economic and environmental advantages of this design are significant. By reducing the reliance on external heating sources and freshwater input, OPEX are lowered, and the carbon footprint of hydrogen production is minimised. In industrial integration scenarios, the captured heat can be directly used for processes such as low-temperature steam generation or chemical preheating, further increasing system value. In addition, by lowering water consumption, this BOP configuration aligns with sustainability goals and regulatory frameworks aimed at reducing industrial water use and enhancing circular economy practices.

From a technical perspective, the system requires specialised equipment and materials to handle repeated cycles of heat and water recovery without compromising reliability. Stainless steel or corrosion-resistant alloys are used in piping and heat exchangers to prevent degradation, while redundancy in filtration and sterilization ensures consistently high water purity. Energy efficiency improvements are also implemented by optimising pump and compressor sizing to take advantage of preheated water and stabilised thermal loads.

The integrated heat and water recovery BOP design transforms the PEM electrolysers from a standalone hydrogen generator into a multifunctional resource-efficient system. By capturing waste heat for reuse and recycling process water back into the feed loop, it reduces both energy and water demands while improving overall sustainability. This configuration is especially attractive for large-scale hydrogen projects co-located with industrial plants or district heating systems, where recovered resources can be directly integrated into wider energy and water networks. Through this approach, the PEM electrolysers not only produce green hydrogen but also contribute to a more holistic model of energy efficiency and resource circularity in the clean energy transition.

## 5. THE BOP-FOCUSED ECONOMIC ANALYSIS

The economic performance of PEM electrolysers is strongly influenced by BOP subsystems, which represent a major share of total investment and operating expenditure. While the stack defines the electrochemical conversion efficiency, the BOP determines the real plant-level cost structure through power conditioning losses, compression energy demand, water treatment requirements, cooling loads, instrumentation, and safety systems. Therefore, as shown in Fig. 5, a complete economic assessment of PEM electrolysers must include subsystem-level CAPEX allocation, OPEX drivers, and their combined effect on LCOH.

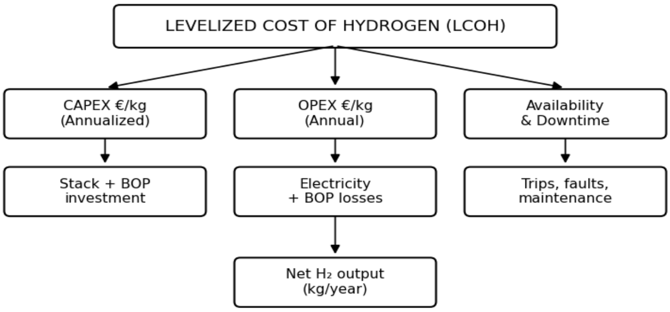

*Fig. 5.* Hydrogen cost formation structure of PEM electrolyser.

## 5.1. Economic Analysis Elements

A consistent economic analysis of BOP-enhanced PEM electrolysers requires the following elements:

- CAPEX structure. Total CAPEX includes the electrolyser stack, BOP equipment, installation, and indirect costs such as engineering and commissioning. BOP costs are commonly grouped into power electronics, thermal management, gas handling and purification, compression and storage, and control/safety systems. In large-scale projects, BOP can account for a comparable or even higher cost share than the stack due to high-pressure operation and grid connection requirements.
- OPEX drivers. OPEX is dominated by electricity cost, but BOP significantly contributes through parasitic energy consumption, scheduled maintenance, component replacement (e.g., compressors, filters, sensors), and water consumption. The BOP also influences stack lifetime through stable thermal control and smooth operation under variable loads, indirectly affecting replacement costs and downtime.
- Energy efficiency and parasitic losses. BOP parasitic loads reduce net hydrogen output per unit of electricity. Compression, cooling pumps, drying/purification, and DC power conversion losses are typical contributors. Even small improvements in BOP efficiency translate into measurable reductions in LCOH, particularly under high electricity prices.
- Scaling effects and modularity. Centralised systems benefit from economies of scale and lower cost per kW, while modular containerised systems offer faster deployment but increase duplication of equipment. These design choices affect both CAPEX intensity and maintenance costs.
- LCOH framework. A standard metric for economic comparison is LCOH, which expresses hydrogen cost as EUR/kg or USD/kg over the project lifetime. Economic performance depends on CAPEX, electricity price, efficiency, capacity factor, discount rate, and maintenance cost.

A simplified LCOH representation is as follows:

$$\mathrm{LCOH} \approx \frac{\text{Annualized CAPEX} + \text{Annual OPEX}}{\text{Annual H}_2\text{ production}} \quad ,$$

where annual hydrogen production depends on net system efficiency and operating hours, both strongly affected by BOP.

The conceptual economic structure of PEM electrolyser hydrogen cost highlights that LCOH is determined by the combined influence of CAPEX, OPEX and plant availability. The CAPEX component represents the upfront investment required for the stack and BOP equipment, which is converted into an annualised cost over the project lifetime. This means that higher initial investment directly increases the cost per kilogram of hydrogen unless compensated by high utilisation rates.

**Table 4.** CAPEX Distribution in PEM Electrolyser Systems (BOP-focused)

| **Cost element** | **Typical share of total CAPEX (%)** | **Economic implication** |
|---|---|---|
| Stack system | 40–60 | Core cost driver: improved stack durability reduces replacement cost |
| Power electronics (rectifier, transformer, controls) | 10–20 | Efficiency losses increase the electricity cost per kg $H_2$ |
| Thermal management (cooling loop, heat exchangers) | 5–10 | Stabilises performance and reduces degradation risk |
| Gas purification and drying | 5–15 | Higher purity targets increase CAPEX and maintenance |
| Compression and storage interface | 10–25 | Strongly impacts both CAPEX and parasitic energy |
| Instrumentation, safety, monitoring | 2–8 | Reduce risk and downtime; support compliance |
| Installation and indirect costs (EPC, commissioning) | 10–20 | Depend on project scale and site complexity |

The OPEX component is mainly driven by electricity consumption, which includes both the electrolysis power demand and additional parasitic losses from BOP systems such as power electronics, cooling, and compression. Since electricity cost is usually the largest contributor, small efficiency improvements can lead to significant reductions in total hydrogen cost.

**Table 5.** The Main OPEX Components and Their Drivers in PEM Electrolyser BOP

| OPEX component | BOP subsystem link | Primary cost driver | Impact on hydrogen cost |
|---|---|---|---|
| Electricity cost | Power electronics + auxiliaries | EUR/MWh and efficiency losses | Highest impact; dominates LCOH |
| Maintenance and service | Compressors, pumps, valves, sensors | Wear, vibration, spare parts | Medium–high; increase with pressure |
| Water treatment consumables | DI system, filters, resins | Water quality and replacement cycles | Medium; affect reliability |
| Cooling utilities | Pumps, fans, chillers | Ambient conditions and load factor | Low–medium; higher in warm climates |
| Downtime and availability losses | Control and safety systems | Faults, trips, maintenance | High indirect impact through lost production |
| Replacement of auxiliary equipment | Compression and purification | Lifetime of rotating machinery | Medium; affects long-term cost stability |

In addition, BOP-related energy losses reduce net hydrogen output, further increasing cost per unit produced. The third component, availability and downtime, reflects the operational reliability of the electrolyser system and its auxiliary units. Unplanned shutdowns, faults, and maintenance reduce annual hydrogen production, which increases LCOH even if CAPEX and OPEX remain unchanged.

Therefore, stable operation and preventive maintenance strategies play a critical economic role. The diagram also indicates that CAPEX and OPEX interact with net hydrogen output, meaning that production volume is the key denominator that determines overall cost. A system with high efficiency but low availability may still produce expensive hydrogen due to reduced output. Similarly, a highly available system with high parasitic losses may incur higher electricity costs and reduced competitiveness. Overall, the figure demonstrates that reducing LCOH requires a balanced strategy that improves efficiency, controls investment cost, and ensures high operational uptime.

## 5.2. 10 MW PEM Electrolyser

A 10 MW PEM electrolyser system is evaluated under typical European industrial conditions to estimate its LCOH. The LCOH is calculated by dividing annualised CAPEX and annual OPEX by the annual hydrogen production, ensuring that both investment and operating costs are reflected in the final cost per kilogram of hydrogen produced.

Table 6 provides a quantitative breakdown of BOP impact on system efficiency and costs in a 10-MW PEM hydrogen plant.

The technical assumptions include a rated electrolyser power of 10 MW, with 6,000 operating hours per year, corresponding to a capacity factor of 6,000 / 8,760 ≈ 0.685. The net specific electricity consumption, including BOP losses, is assumed to be 55 kWh/kg $H_2$, while the electricity price is taken as 50 EUR/MWh, which equals 0.05 EUR/kWh.

From an economic perspective, the total installed CAPEX is assumed to be 900 EUR/kW, resulting in a total investment cost of 10,000 kW × 900 EUR/kW = EUR 9,000,000. The project lifetime is set at 20 years, with a discount rate of 8 %, reflecting typical financing and investment conditions.

Fixed operation and maintenance costs are assumed at 2 % of CAPEX per year, covering routine servicing and system upkeep. In addition, costs for water and consumables are included as EUR 0.05/kg $H_2$, representing a typical placeholder value used in simplified hydrogen cost calculations.

**Table 6.** Quantitative Breakdown of BOP Impact on System Efficiency on 10 MW PEM Electrolyser

| **Subsystem** | **Energy Consumption (kWh/kg $H_2$)** | **CAPEX Share (%)** | **Notes** |
|---|---|---|---|
| Power Electronics | 3–4 | 20–25 | Losses in rectifiers, inverters, converters |
| Thermal Management | 0.5–1 | 5–10 | Cooling water, chillers, heat exchangers |
| Water Management | 0.2–0.5 | 5–7 | Ultrapure water preparation and circulation |
| Gas Handling | 0.2–0.4 | 8–12 | Hydrogen drying, separation, purification |
| Compression and Storage | 2–4 | 15–20 | Major OPEX driver due to compression energy demand |
| Control and Safety | <0.1 | 3–5 | Monitoring, control, redundancy, safety systems |
| Total BOP Impact | 6–10 | 40–60 | Accounts for a significant share of energy and costs |

The annual hydrogen production is estimated based on the total electricity supplied to the electrolyser during one year of operation. With a rated power of 10 MW and 6,000 operating hours per year, the total annual electricity input is calculated as $E_{\text{annual}}$ = 10 MW × 6,000 h = 60,000 MWh/year. Converting this value into kWh gives 60,000 MWh = 60,000,000 kWh/year, which represents the total usable electrical energy entering the system. Using the assumed net specific electricity consumption of 55 kWh per kg of $H_2$ (including BOP losses), the annual hydrogen output is obtained by dividing the annual electricity input by the energy required per kilogram of hydrogen. This results in annual hydrogen production of approximately 1.09 million kg/year, which is equivalent to about 1,091 tons per year, confirming the strong production potential of a 10 MW PEM electrolyser under high-utilisation industrial operating conditions.

LCOH for the 10 MW PEM electrolyser plant is calculated by dividing the total annualised cost of the system (annualised CAPEX plus annual OPEX) by the annual hydrogen production. First, the annual electricity input is determined from the rated power and operating hours: 10 MW × 6,000 h/year = 60,000 MWh/year, which corresponds to 60,000,000 kWh/year. Using the assumed net specific electricity consumption of 55 kWh/kg $H_2$ (including BOP losses), the annual hydrogen production is calculated as 60,000,000 / 55 ≈ 1,090,909 kg/year, which is approximately 1.09 million kg/year (≈ 1,091 t/year).

To annualise CAPEX, the total installed CAPEX is taken as EUR 9,000,000 (based on EUR 900/kW × 10,000 kW). With a project lifetime of 20 years and a discount rate of 8 %, the Capital Recovery Factor is applied, giving a value of approximately 0.1019. This results in an annualised CAPEX of 9,000,000 × 0.1019 ≈ EUR 917,100 /year, representing the yearly equivalent investment cost of the electrolyser system.

Annual operating costs are then calculated by summing up the main OPEX components. Electricity cost is the dominant term, equal to 60,000,000 kWh/year × EUR0.05 / kWh = EUR 3,000,000/year. Fixed operation and maintenance costs are assumed to be 2 % of CAPEX per year, which gives 0.02 × 9,000,000 = EUR 180,000/year. In addition, water and consumables are included at EUR 0.05/kg of hydrogen, resulting in 0.05 × 1,090,909 ≈ EUR 54,545/year. Therefore, total annual OPEX becomes 3,000,000 + 180,000 + 54,545 ≈ EUR 3,234,545/year. The total annual system cost is obtained by combining annualised CAPEX and annual OPEX, giving 917,100 + 3,234,545 ≈ EUR 4,151,645/year.

At the end of this evaluation, LCOH is calculated by dividing this total annual cost by annual hydrogen production: EUR 4,151,645/year ÷ 1,090,909 kg/year ≈ EUR 3.81/kg of hydrogen. Under the given base-case assumptions, the estimated LCOH for the 10 MW PEM electrolyser plant is, therefore, approximately EUR 3.8/kg of hydrogen, confirming that electricity price and BOP-included energy consumption are the most influential drivers of hydrogen cost in this scenario.

## 6. CONCLUSION

The findings of this study confirm that BOP is a decisive factor in the real-world performance, sustainability, and economic viability of PEM electrolysis systems, and it should be treated as a core part of electrolyser design rather than a secondary add-on. While the electrolyser stack is responsible for electrochemical hydrogen generation, the surrounding subsystems, including water purification, thermal management, power electronics, gas handling, compression, storage, and control systems, strongly influence net efficiency, operating stability, hydrogen purity, and overall plant lifetime.

- RQ1: Main BOP subsystems and their roles. The study concludes that the BOP is essential for ensuring stable, safe, and efficient PEM electrolyser operation and for translating stack-level performance into real plant-level output. The key BOP subsystems include water purification and circulation, thermal management, power electronics, gas handling and purification, compression and storage, and control and safety systems. Together, these components provide critical inputs, regulate operating conditions, manage product gas quality, and ensure system reliability. Therefore, BOP must be treated as a core part of PEM electrolyser system design rather than a secondary support structure.
- RQ2: Major contributors to parasitic losses and efficiency reduction. The study confirms that BOP subsystems contribute significantly to parasitic energy consumption, which can reduce net system efficiency even when the electrolyser stack performs well. The largest energy losses are associated with power electronics due to conversion inefficiencies and with compression and storage due to high-pressure hydrogen requirements. Thermal management systems also create continuous auxiliary electricity demand through pumps, chillers, and heat exchangers. In addition, gas drying and purification processes increase energy use, especially when high hydrogen purity is required. Overall, minimising these parasitic loads is a key pathway for improving efficiency and reducing energy consumption per kilogram of hydrogen.
- RQ3: Influence of BOP design on CAPEX, OPEX, and LCOH. The study concludes that BOP design has a strong influence on the economic performance

of PEM electrolyser systems because it affects both investment costs and operating expenses. BOP can represent a major share of total installed CAPEX, often comparable to the electrolyser stack itself. It also increases OPEX through additional electricity consumption, maintenance requirements, and replacement of auxiliary components such as compressors, pumps, and filters. Since electricity cost is the dominant contributor to hydrogen production cost, BOP-related inefficiencies directly increase LCOH. Therefore, improving BOP efficiency and reliability is essential for achieving cost-competitive green hydrogen production.
- RQ4: Most suitable BOP configurations for different applications. The study finds that there is no single optimal BOP configuration, as design suitability depends on plant scale, deployment context, and hydrogen end-use requirements. Centralised industrial BOP designs are most suitable for large-scale projects because they benefit from economies of scale and integrated resource management. Modular containerised designs are better for distributed applications and rapid deployment due to flexibility and redundancy, although they may increase costs due to subsystem duplication. Hybrid renewable-integrated BOP designs are most effective when coupling directly with intermittent renewable power sources, as they require advanced control and power conditioning. High-purity and recovery-focused designs are best suited for applications requiring strict hydrogen quality standards or improved resource efficiency through heat and water reuse.
- RQ5: Supply chain vulnerabilities and strategic deployment challenges. The study concludes that supply chain vulnerabilities and industrial dependencies can limit the scalability and resilience of BOP deployment in PEM hydrogen systems. Key risks arise from reliance on specialised manufacturing and globally concentrated supply chains for power electronics, compressors, valves, and water treatment materials. These constraints can increase costs, delay project timelines, and create strategic exposure to disruptions in logistics and industrial capacity. The study highlights that BOP optimisation should include not only technical performance improvements but also strategies for standardisation, modularisation, and diversified sourcing. Strengthening supply chain resilience is, therefore, necessary for large-scale, reliable expansion of green hydrogen production.

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