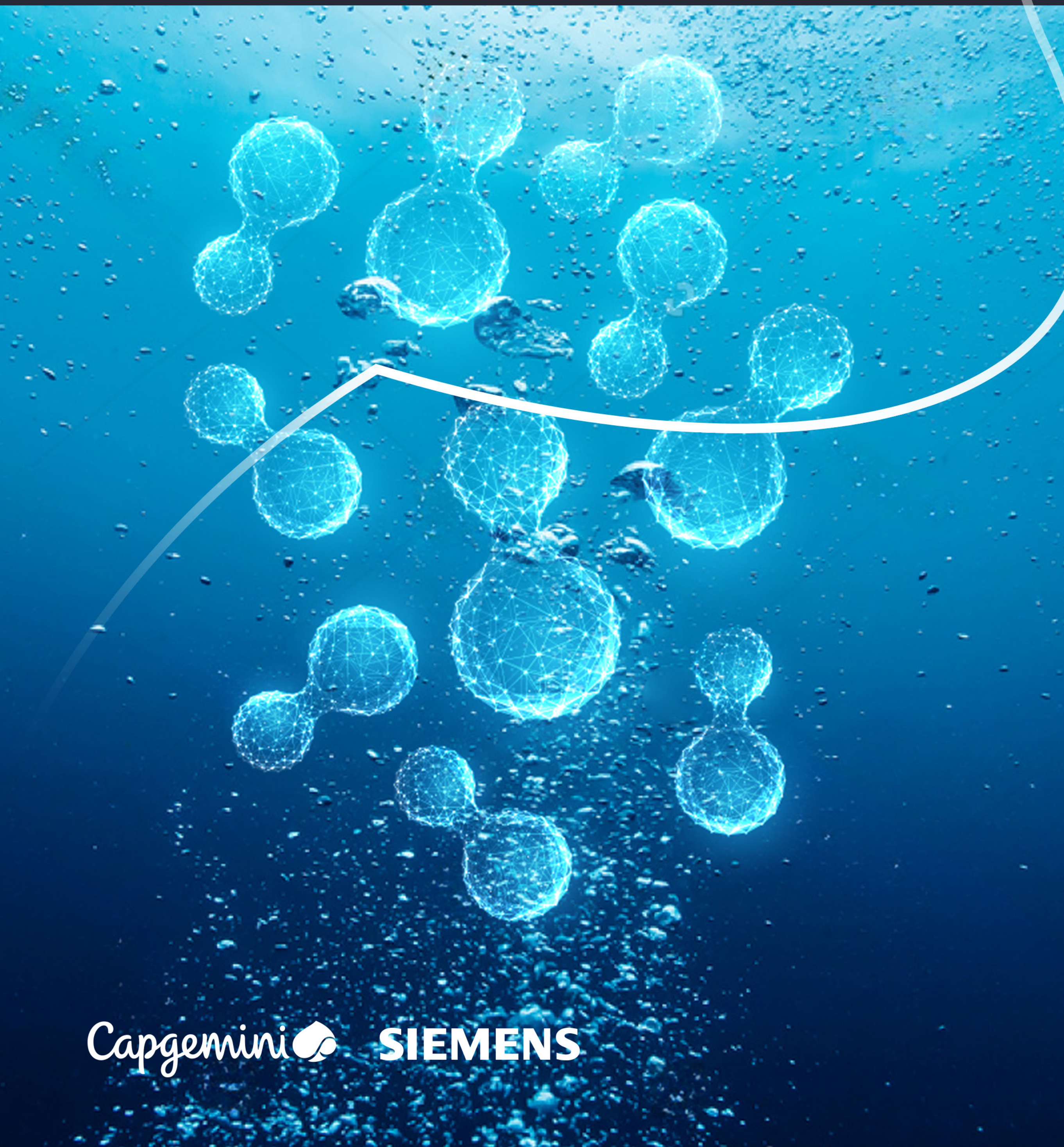
Accelerating *low-carbon hydrogen* and cutting costs with digital technology



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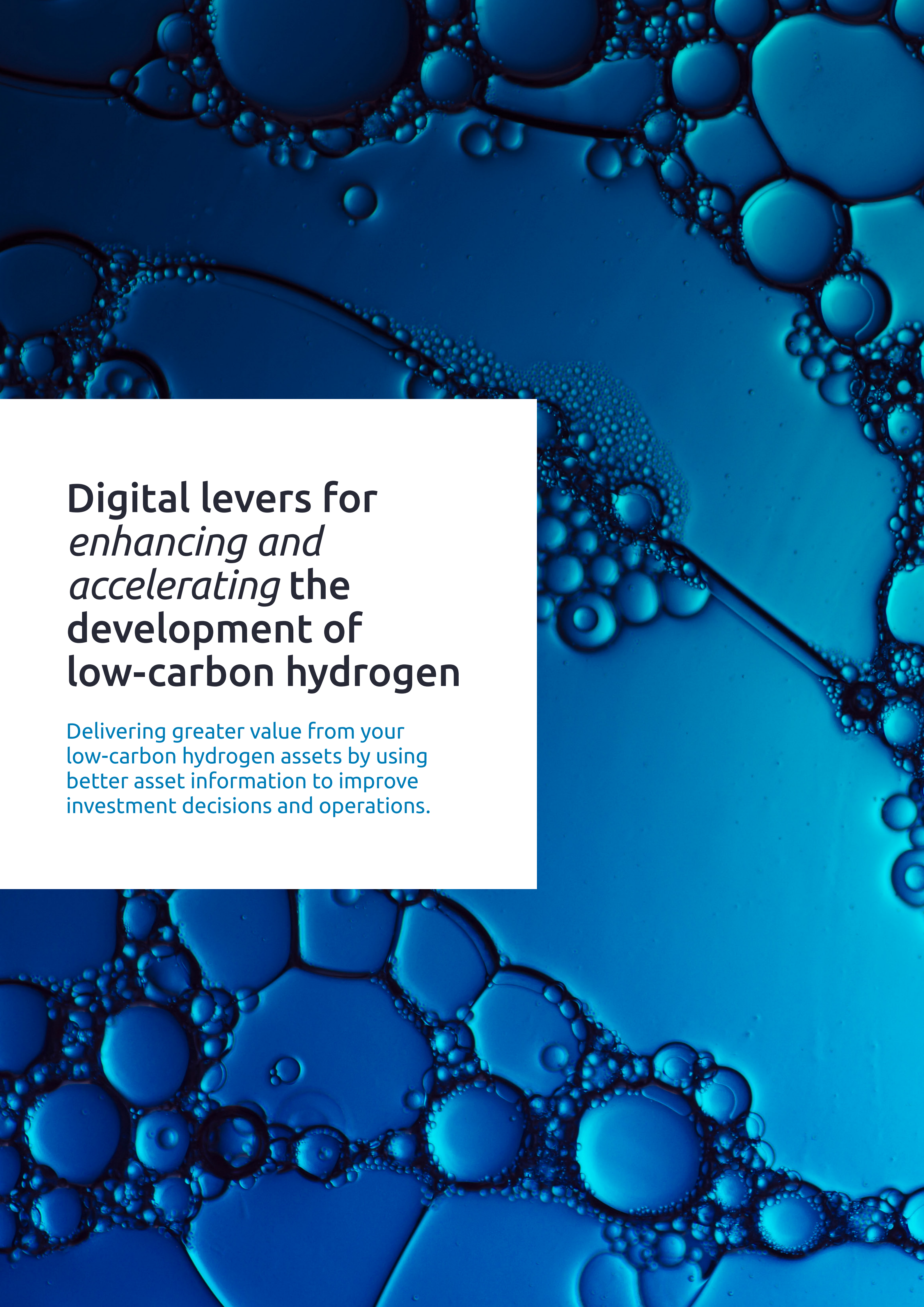
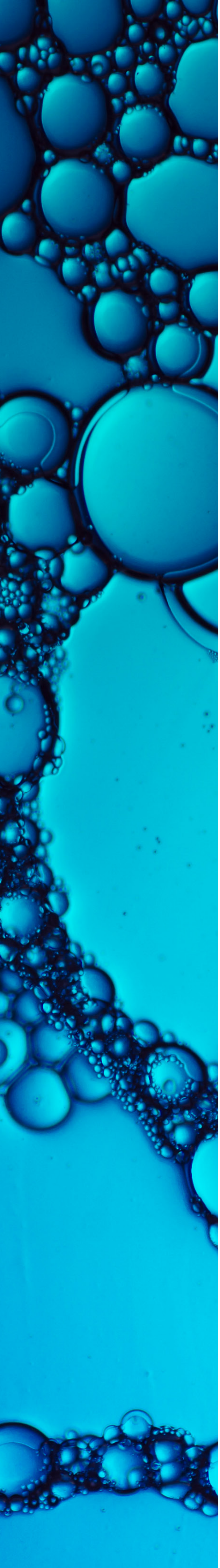


Digital levers for *enhancing and accelerating* the development of low-carbon hydrogen

Delivering greater value from your low-carbon hydrogen assets by using better asset information to improve investment decisions and operations.



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Executive Summary

Despite a dynamic trend, the hydrogen market does not progress as fast as expected

The decarbonization potential of low-carbon hydrogen in hard-to-abate sectors, coupled with its capacity to facilitate energy transport to resource-constrained regions at scale, has generated significant enthusiasm within the hydrogen sector in recent years. However, despite growing announcements of new low-carbon hydrogen projects – potentially reaching 38 Mt by 2030, if all announced projects materialize- only 4% of projects have reached the final investment decision (FID) or construction phase, as reported by the International Energy Agency (IEA). Clearly, we have not yet met our objectives.

Low-carbon hydrogen still struggles to become competitive

Low-carbon hydrogen remains too expensive and lacks competitiveness compared to carbon-based hydrogen.[1] The cost ranges from 6-9€/kg[2] for low-carbon hydrogen versus 1.5-3€/kg for hydrogen produced from natural gas reforming (before subsidies). This cost disparity arises from various factors related to production, infrastructure, and technological requirements. Transitioning to hydrogen from renewables is particularly costly due to expensive production processes and the advanced end-use technologies involved. Establishing the necessary infrastructure for hydrogen production, storage, and distribution requires substantial capital investment, including the construction of renewable energy plants, electrolyzers, storage facilities, and transportation networks.

Currently the low-carbon Levelized Cost of Hydrogen (LCOH) produced via electrolysis primarily comprises power costs (representing 40% to 60% of the total), equipment, engineering and construction costs (20% to 35%) and operational costs of (5% to 15%).[3] The LCOH is highly influenced by the load factor (including availability) which impacts production volume, power consumption, and capital expenditures (CAPEX) amortization.

The hydrogen sector is actively seeking levers to mitigate costs

As projects developers advance into early engineering and design stages, asset developers are actively seeking ways to mitigate costs and extensive literature outlines strategies to drive down costs and position hydrogen as an effective energy transition vector. While some levers have already been employed to reduce investment costs in low-carbon hydrogen, additional opportunities remain for players across the value chains, especially equipment manufacturers and asset developers (see figure 1).

Digital levers impact CAPEX, electricity costs and other OPEX as well as the volume of production

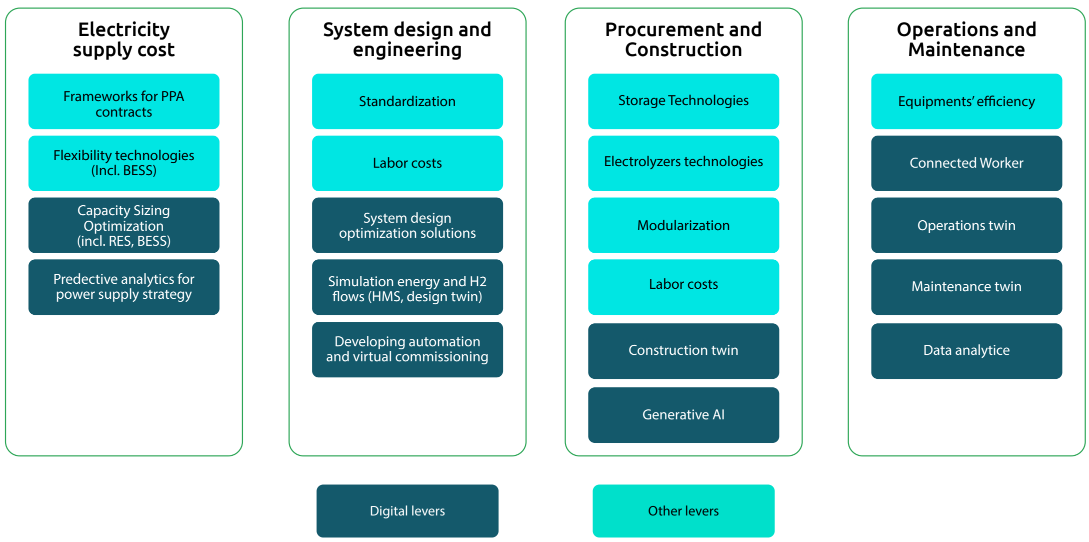


Figure 1 - LCOH reduction levers[4]

Why digitalization will play a pivotal role

As asset managers embrace the digital age, creating "digital native" assets becomes crucial. This approach ensures the comprehensive availability of operational and asset data for informed decision making through Digital Asset Management. By strategically focusing on key decisions within asset processes and transforming data into actionable insights, asset managers can deliver significant business value.

Digitalization will play a pivotal role in enhancing the investment case for low-carbon hydrogen projects by optimizing the design, operations and management of production assets[5], as per the following key facts:

- **Greenfield assets:** given that the low-carbon hydrogen sector is still in its early stages, greenfield projects offer a significant opportunity to develop digital native production assets and leverage digitalization even prior to the commencement of construction. Plants are being built for the first time and a digital twin of the plant is generated as a by-product of the engineering process without additional effort.
- **Innovative first of a kind plants:** being able to simulate before investing in the final construction brings a huge advantage.
- **New players and maturity of the market players' roles:** similarly, a digital plant can help overcome lack of experience from new incumbents.
- **Many similar but complex package units and components**, where digital tools facilitate the comprehensive integration of a modular set up.
- **Scale-up:** most of the plants and assets can act as a blueprint to be replicated later.
- **Securing financing:** a digital twin capable to demonstrate the validity of the engineering, which can also predict the effectiveness of the running plant enable the successful closing of fundraising activity.
- **Respecting project timeline:** the simulation opportunities offered by digital tools enable to anticipate, avoid errors that would occur in a first-of-a-kind project, and prepare for the start of operations at an early stage, - even to train operators, via virtual trainings.

1. For hydrogen production to be considered low-carbon, it must come under the EU's proposed emissions threshold of 3.38 kg CO_2e/kgH2, which is 70% lower than that of the predefined fossil fuel comparator, including transport and other nonproduction emissions. In the US, the corresponding carbon intensity value to qualify for hydrogen production tax credits under the IRA is 4.0 kg CO_2e/kgH2.

2. Low-carbon hydrogen produced with electrolysis.

3. These figures vary according to projects'configuration, but they represent the order of magnitude.

4. PPA: Power Purchase Agreement; RES: Renewable Energy Storage; BESS: Battery Energy Storage System

5. The hydrogen production asset is defined by the electrolysis unit and everything that surrounds it, to enable the ultimate production of low-carbon hydrogen.

Key economic benefits from digital tools over the LCOH

Digital tools can bring a significant impact in reducing the LCOH through reducing the development costs of a project, through more effective engineering and easier replicability of similar processes and components, and the operating costs through the optimized design and close control of running parameters interfaced with the digital twin data.

Our analysis shows with a concrete example a reduction between 9% and 12% of the LCOH overall, applying the different digital levers on a reference scenario.

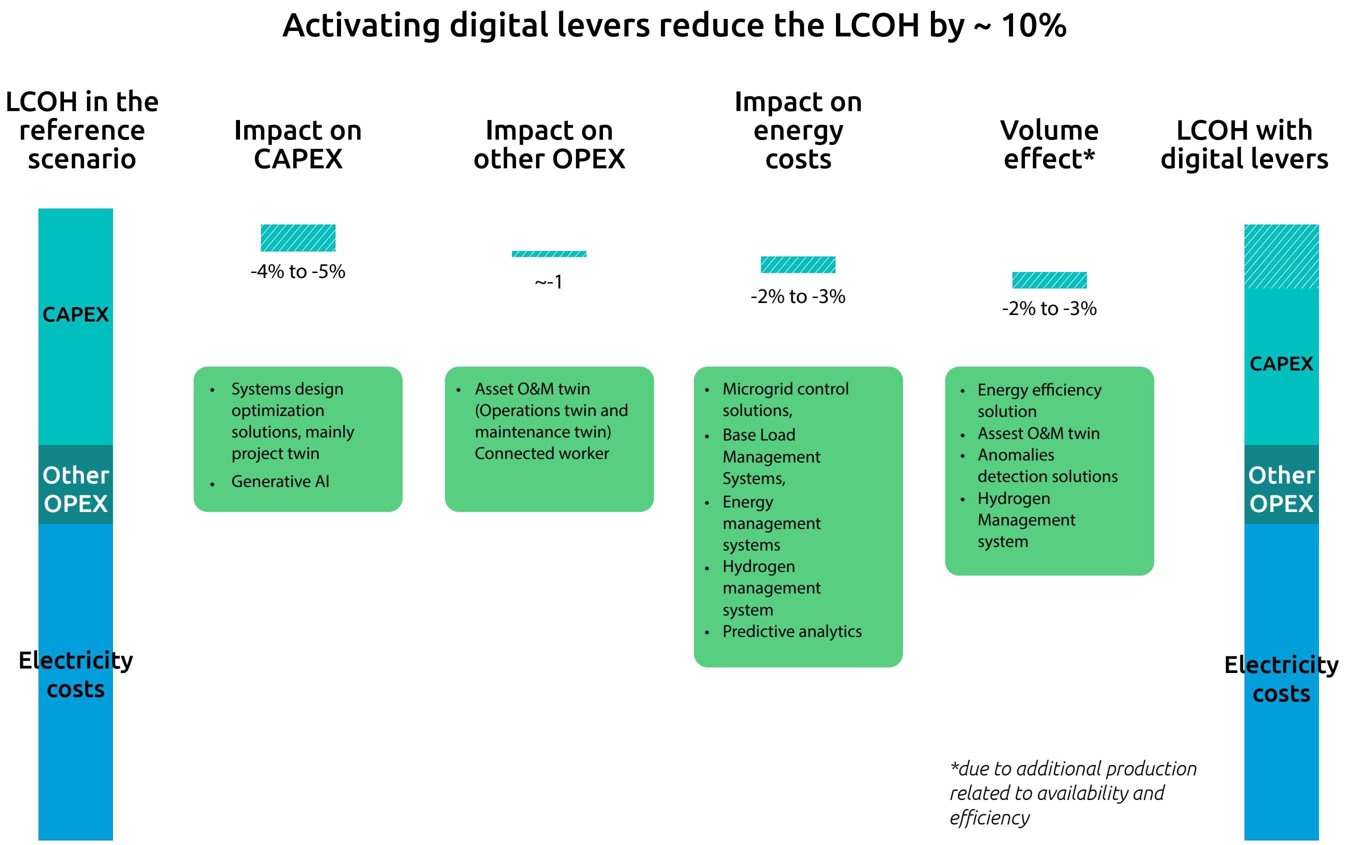


Figure 2 - Share of OPEX and CAPEX costs in the LCOH of a 100MW alkaline electrolysis installation and potential reduction through digital solutions.

Especially, this 100 MW electrolyzer plant, running 8000 hours a year, can reduce the yearly energy bill by 500 k€ or more per each percent of optimization provided by the digital twin. The amount of potential cumulated savings along the plant lifetime should justify having digital twin as a tier1 priority in any project in this domain.

You will find assumptions, further details and examples of Siemens digital tools related to these LCOH optimization in section 3.

We analyzed the role that digitalization can play throughout the value chain

Siemens and Capgemini have analyzed a range of digital solutions and identified specific levers that can reduce the Levelized Cost of Hydrogen (LCOH), enabling customers effective and fast adoption of a tailored digital toolset specifically designed to make their project competitive and future-proof. The following levers are designed to assist project developers, operators, and asset managers in addressing various challenges and refer to all phases of a Hydrogen Project.

1. **The design, engineering and construction phase – for project developers and asset owners**

- **Design effectively** through proper input requirements provided as per Owner-Operator mandates and Regulatory requirements. Optimizing asset design and engineering **through simulations** helps avoiding rework by enabling clash detections, accessibility concerns, etc. thereby reducing costs and time to construct.

- **Build faster** and reduce time to operations, throughout a data-centric approach - especially 3D Computer Aided Design (CAD) - accelerating collaborative interactions between different engineering disciplines involved and stakeholders especially between Engineering Procurement Construction (EPC), Original Equipment Manufacturers (OEM) and Asset Owners Operators (AOO) in compliance with industry process and safety standards using a pre-defined toolset to ensure all engineering data is at the end consistent and available for further use in operation.

- **Capitalize, replicate and scale faster at lower costs,** leveraging on the knowledgebase and lessons learnt from one project to another enabled by digital twin blueprints.

2. **The operations and maintenance phase – for asset owners and operators**

- **Handover the physical asset from project to operations, with all the digital information,** documents, procedures, manuals (operating and maintenance), 3D models of the equipment and instrumentations deployed in the asset along with Safety and Regulatory clearances.

- **Operate efficiently from day 1,** through accessible and activable data, optimizing process parameters by balancing productivity, improving quality and maintaining effective energy consumption across the various parts of the plant. This information/data digitally recorded and logged helps future fleet of assets, both:
  - in the control room, to monitor the production, orchestrate production process while maximizing the value, based on markets prices, contractual commitments and plannings (incl. maintenance)
  - on the shop floor, to automate production processes and provide the workers with relevant information (e.g. using a digital twin for maintenance)

- **Improve production continuity,** avoid unexpected production stops and maximize availability. The key role of maintenance teams is not only to maintain production continuity but also to maximize asset life through effective preventive maintenance programs, leverage predictive maintenance digital twins and plan for spare parts well in advance to ensure long-term reliability of the assets.

3. **Traceability – for the entire ecosystem:** ensure traceability, especially carbon content tracking to comply with clients' specifications or regulatory needs.

4. **The assets portfolio management – for asset owners**

- Optimize assets planning.
- Integrate new assets with existing legacy assets like O&G or Renewables. This will also define new future asset investment business models and organizational strategies which needs to be thought through and optimized.

Capgemini and Siemens stand ready to support the transition towards a low-carbon economy.

Any initiative targeting to deliver value and a timely achievement of project's milestones to its investors, shall put the creation of its own digital roadmap among first priorities since the beginning of the project development. Siemens and Capgemini can effectively support together these customers with a combined approach of broad consulting services, best-of-the-class digital tools, experienced and trained engineering resources. Through their innovative solutions and strategic collaborations, Capgemini and Siemens stand ready to support the transition towards a low-carbon economy.

This paper will then give important insights on how Capgemini and Siemens can consult and support owners, operators, EPC companies in achieving their goals and overcoming the challenges related to scaling up and industrializing low-carbon market technologies.

Scope of this paper

This paper delves into the digital levers that can reduce the LCOH while introducing the joint value proposition of Capgemini and Siemens, showing how the Digital Hydrogen plant with a holistic digital twin concept is key to reducing the LCOH. It covers costs in all phases of a hydrogen project, from Investment Decisions, Basic Engineering, Plant Engineering and construction up to operations.

Figure 3 - Project stages

The focus of this paper centers on hydrogen production, particularly in a context of electrolysis, but it represents only a fraction of the broader scope that Siemens and Capgemini can collectively address within the hydrogen domain. Their technological expertise and industry acumen extend to distribution, derivatives production, the utilization of hydrogen to decarbonizing industry, transportation and the energy sector. As a complementary asset in hard-to-abate sectors where electrification faces economic or technological challenges, hydrogen can have a pivotal role.

For example, sustainable aviation fuel, methanol, and ammonia production can leverage low-carbon hydrogen with advanced digital solutions optimizing conversion processes to enhance efficiency, sustainability, and mitigate financial and technical risks.

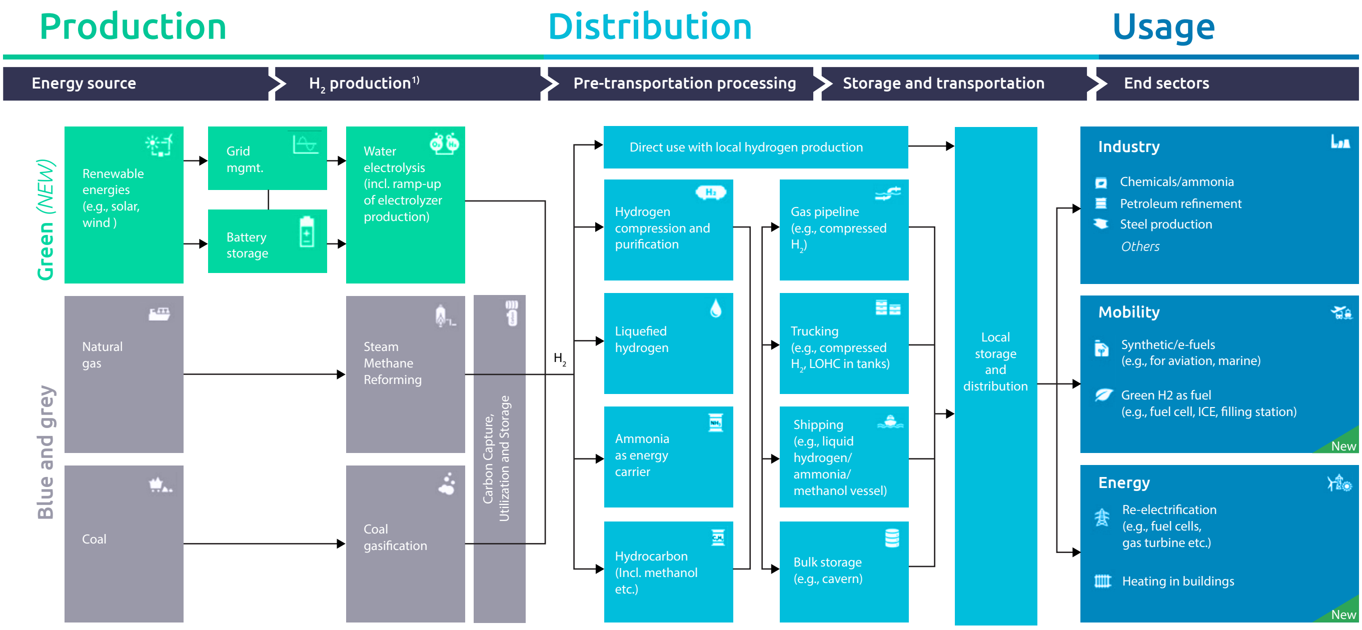


Figure 4 - Hydrogen supply chain: from energy source to hydrogen usage

1.

Siemens and Capgemini joint approach for low-carbon hydrogen assets

1.1 Our value proposition

Combining deep knowledge and experience in the **hydrogen industry, technical excellence** and **end-to-end industrial asset digitalization**, we at Capgemini and Siemens extend our historic collaboration to the hydrogen field.

Whether you are a plant owner, an EPC or a plant operator, Capgemini and Siemens can support you in meeting your key challenges:

We manage complexity to de-risk your investment

- We leverage **advanced simulation tools** to help you navigate uncertainty, envision multiple complex scenarios, and mitigate financial, regulatory, and operational risks all at once.
- We capitalize on our **extensive cross industry experience** to project your industrial asset future performance and make the best investment decisions.

We deliver investment and operational cost reduction to close the competitiveness gap

- We employ our **design, engineering, and simulation solutions** in early phases to build a plant that closely meets your current and future needs while optimizing CAPEX and OPEX throughout the entire project lifecycle.
- We align your **industrial strategy** and production setup with tailored **energy procurement strategies** to optimize the price of low-carbon energy, which remains a major driver of the LCOH. We supply and integrate **energy management and flexibility solutions** to enable those strategies.
- We assist you in identifying **process optimization** opportunities, reducing energy and water consumption.

We connect and digitalize the entire hydrogen ecosystem to accelerate the adoption of low-carbon solutions

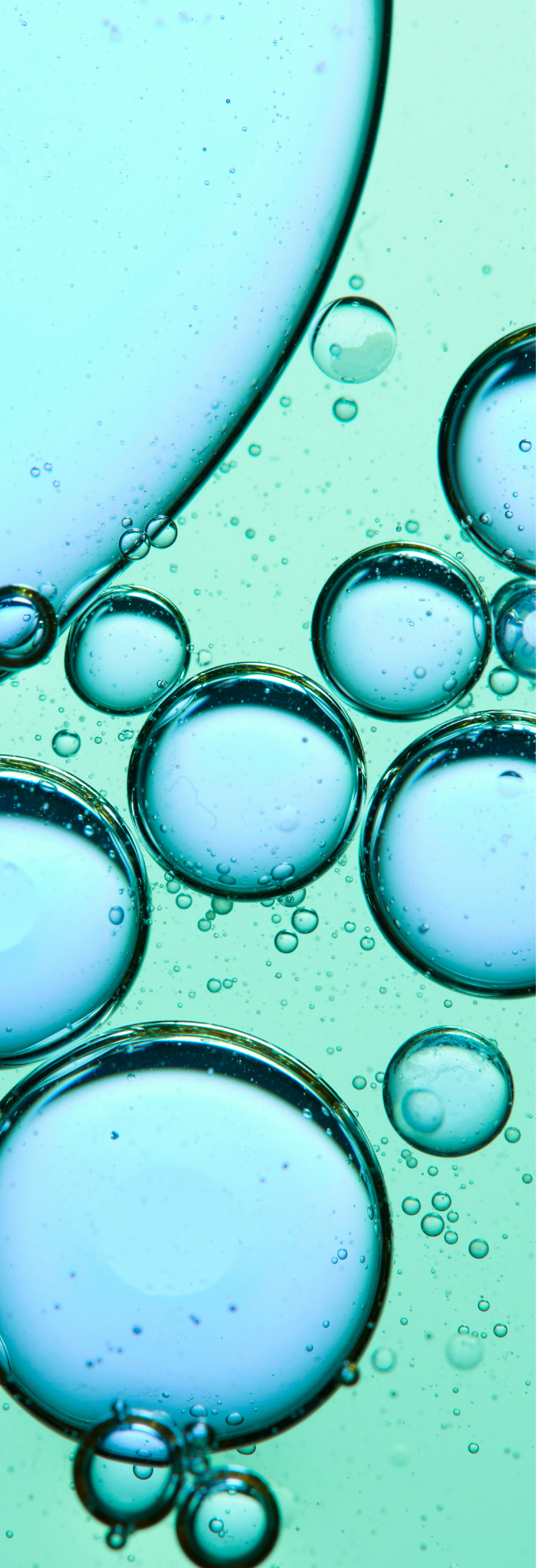
- Our expertise in the hydrogen industry allows us to know **established data standards** and the most effective methods for structuring and sharing information. By adopting a data-centric approach and creating a single source of truth, we facilitate collaboration across the value chain and help you accelerate your **go-to-market strategy.**
- We deploy **end-to-end traceability solutions** that are recognized by end users and public authorities to certify the carbon intensity of the hydrogen you produce, ensuring its **marketability and profitability.**
- We create digital twins that accumulate knowledge throughout the project lifecycle. These digital replicas function at different stages—'as-designed,' 'as-built,' and 'as-operated'—serving as blueprints for future hydrogen projects.

We help you develop future-proof, robust industrial assets from day 1

- We assist you in building **digital-native assets** with a tech stack architecture enabling digital continuity. You will be ready to capture the value that digital technologies offer today and tomorrow.
- With our advanced design and engineering solutions, you are ideally positioned to **scale up**, using standardized production elements, optimizing their compatibility, and simulating the expansion or replication of your plants in the future.
- We ensure the integrity of your industrial assets with **best-in-class cybersecurity solutions.**

We empower operation teams to make data-informed optimization decisions that lead to profitable results

- We promote and enable a **holistic decision-making approach**, combining real time process monitoring data and long-term CAPEX considerations to **secure your target levelized cost of hydrogen and your profit margin.**
- To achieve this, we implement a comprehensive portfolio of solutions for on-site measurement, data analytics, and real-time monitoring.
- We translate control room decisions into action by offering automation and connectivity solutions for field workers, while also conducting change to effectively harness the full potential of digital tools.



1.2 Siemens and Capgemini, a relevant partnership for the digitalization of the hydrogen industry

Siemens and Capgemini collaborate as complementary partners to fully leverage digital transformation throughout the low-carbon hydrogen value chain. Siemens, with its expertise in energy and chemicals sectors, offers advanced digitalization and automation solutions. Meanwhile, Capgemini, a trusted business and technological transformation partner for global industrial leaders, identifies high-value use cases, defines digital transformation roadmaps aligned with industrial strategies, implements technological solutions, and drives change.

2.

Setting up the scene – definitions, frameworks and prerequisites

2.1 Introducing the digital twin for asset intensive industries

The digital twin is a virtual representation of the current and almost future physical reality , e.g., of a product, a production process, a plant having multiple critical assets (pumps, motors and respective pipeline valves, etc.), including their behavior and health status. It brings together data from all lifecycle phases and from all functions and levels, helping to understand, manage and predict the performance of the corresponding process or plant and thereby laying the groundwork for informed data driven decisions through data centric approach.

By replicating real-world plant operations in virtual simulations, engineers and operators can fine-tune designs, identify potential issues early on, and streamline their processes. This not only reduces commissioning times but also slashes costs, making hydrogen production more economically viable. This enables the reduction in commissioning times from a regulatory and auditory perspective, enhances information handover to Owner Operators teams thereby slashing related costs, faster go to market in terms of production output making it more economically viable.

But what exactly are digital twins?

A digital twin is a virtual replica of a physical asset, such as a production plant, that consolidates data from all lifecycle phases. By harnessing the power of simulation models and process engineering software, engineers can design and optimize plant layouts, create detailed process flow diagrams, and plan automation systems with precision. It also enables best in class construction practices by simulating clash detections, construction worker safety and accessibility scenarios and future O&M activities for the AOO.

Digital twins enable seamless integration into existing energy systems, allowing operators to better manage fluctuating energy supplies from renewable sources. By accurately simulating plant operations, operators can optimize energy usage, minimize costs, and maximize overall system flexibility.

Another crucial aspect of digital twins is the potential for scalability and innovation. With the ability to copy (by numbering up per "drag-and-Drop") and rebuild entire hydrogen plants virtually, engineers can explore new design concepts, using the digital twin of the plant as a blueprint, to experiment with different configurations, and scale up production seamlessly. It is also thinkable that an electrolyzer Manufacturer could use that to make a world-wide fleet management of any of their delivered electrolyzers to further optimize or provide service and support. This not only accelerates time-to-market but also lays the groundwork for the widespread adoption of green hydrogen production

Capgemini and Siemens see a special momentum for adoption of a holistic digital twins in Green H2 Production landscape that will maintain information continuity through the asset lifecycle.

2.2 Integrated engineering

The above-mentioned steps can be realized using integrated engineering to integrated operation. The digital twin is a secondary result of the integrated engineering process.

Integrated engineering actually refers to an approach of augmented engineering with automation and simulation. This requires using a defined all-embracing tool set for simulation and engineering, to make sure all engineering data is consistent and accessible in one platform.

6. The representations are probabilistic and approximate and depends on accuracy of historical and real-time data and any unknown phenomenon can alter future reality even if all historical information is correct. In that sense, digital twin is not a true – even if virtual – representation of a "future physical reality".

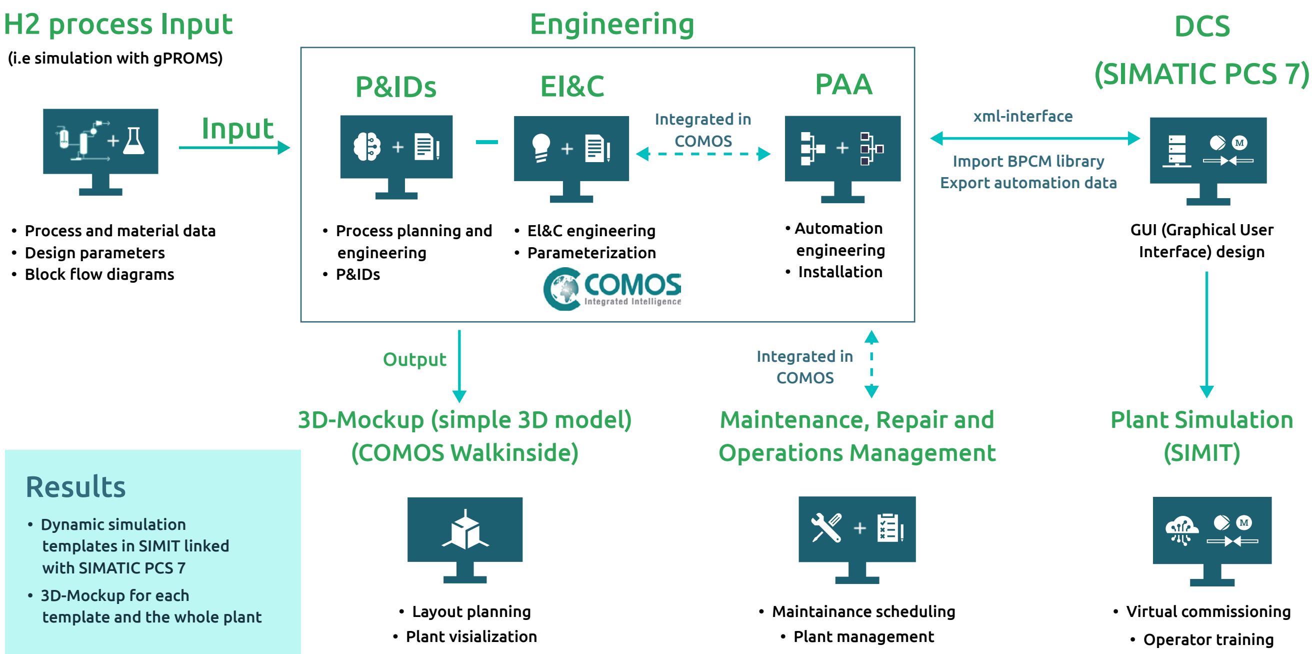


Figure 5 - Integrated approach with Siemens solutions for holistic data exchange between modeling, process engineering, simulation and automation

Integrated engineering phase involves complex tasks to ensure smooth hydrogen production design implementation:

- Ensuring data consistency across disciplines is a primary challenge, as inconsistent data can cause errors, delays, and increased costs.
- Thorough testing and training are essential to reduce startup time and costs. Virtual commissioning and operator trainings prevent operational inefficiencies and safety incidents.

A unified database for seamless data flow improves decision-making and reduces engineering cycle times.

This makes it possible to use the digital twin in the operation phase to optimize the operations of the plant. There is also the option to bring together all data of the digital twin (operation digital twin, maintenance twin), the simulation model and the operational data to enable learning the best performance and most material friendly operation of the plant.

The digital twin concept from integrated engineering to integrated operations and the "Hydrogen Performance Suite" as described in section 3.2 builds a comprehensive basis to realize this approach in a Digital Hydrogen Plant.

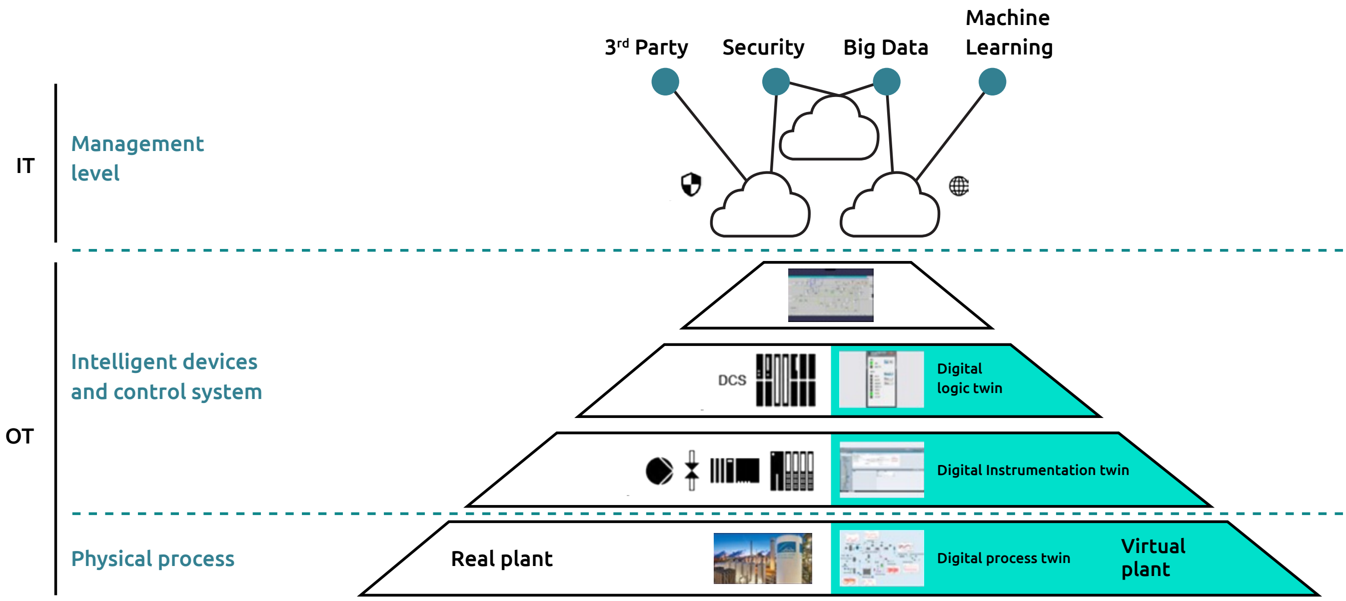


Figure 6 - The digital hydrogen plant, from integrated engineering to operation

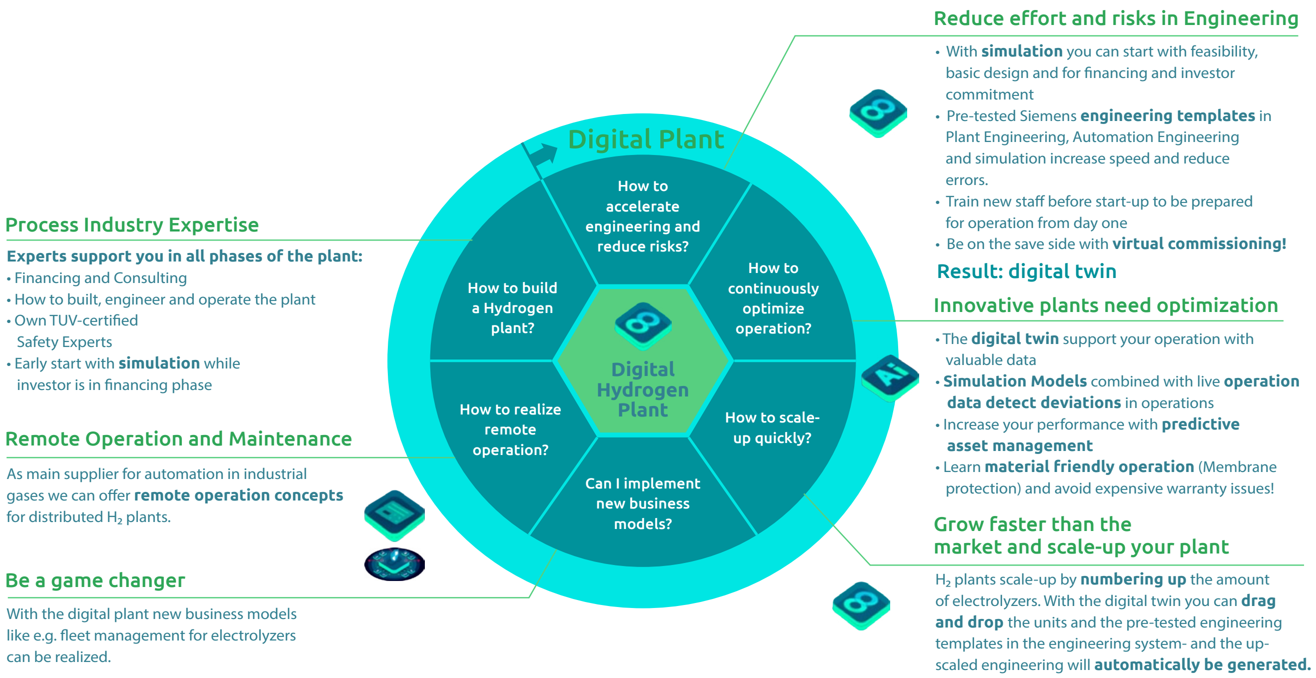


Figure 7 - The Digital hydrogen plant benefits

2.3 Prerequisites to unleash digital potential

Asset managers often struggle with fragmented information scattered across disparate software systems. This challenge impacts decisions related to safety, regulatory compliance, production efficiency, budget constraints, and market pressures. The consequences? Poor choices, delays, and ineffective outcomes resulting in costly project setbacks, industrial incidents, or penalties. To mitigate risks and reduce costs, asset decisions must rely on a foundation of trusted information. When digitalized and standardized, this information creates a true digital identity for industrial assets.

For greenfield assets, building these foundations from the beginning allows digital continuity to emerge, particularly through a comprehensive system of five digital twins: “as required”, “as designed”, “as built”, “as operated” and “as maintained”.

First what we need is a **shareable data platform** on which the developers along with owner operators and maintenance personnel can work together through the Requirements and Design, Engineering and Simulations. This then leads to **establishing a common communication language using 3D models** for visual understanding between different disciplines and to adhere to a sequential approach in construction. It ensures broad collaboration among stakeholders including EPC teams, operators, maintenance personnel and asset managers. Developers, owners, and operators should account for various information scopes related to industrial processes across different asset lifecycle stages—from construction to operation. Efficiently structuring, classifying, and storing this information is critical. **Given multiple stakeholders’ involvement throughout the lifecycle, relying on a single source of truth for communication is essential** (see figure

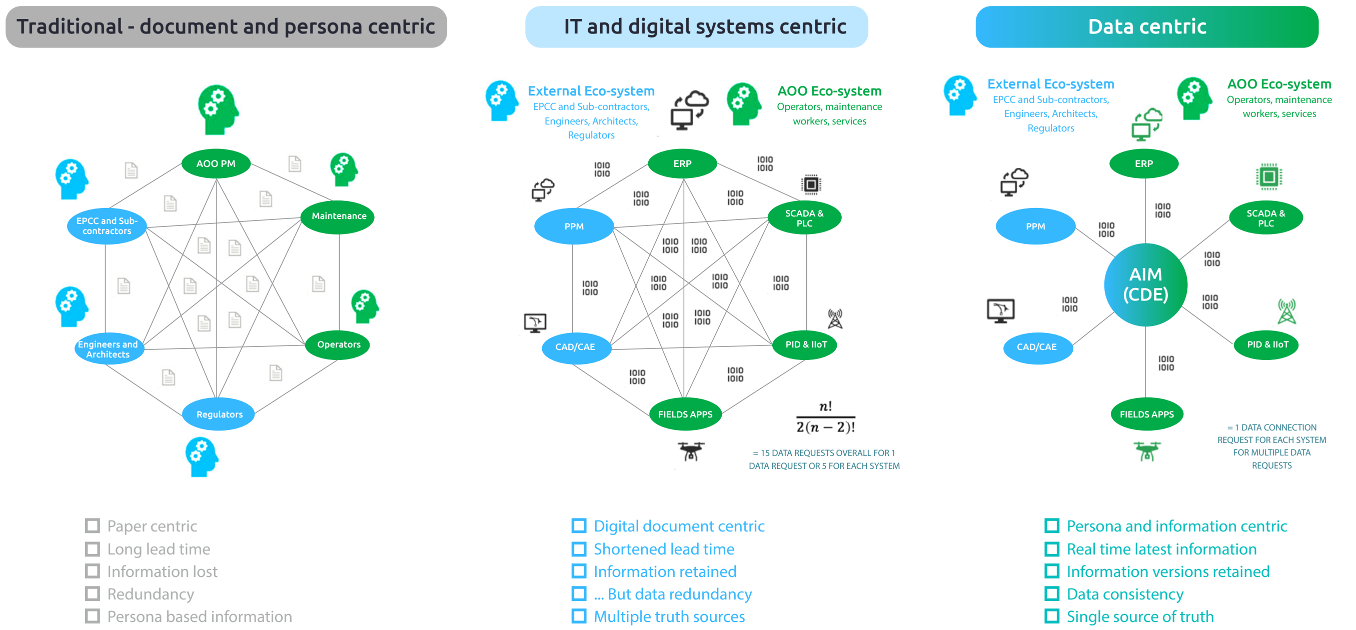


Figure 8 - From “document and persona centric” to “data centric” for a single source of truth

below).

Note: The figure above explained

- *On the left: Traditional paper and document approach. Most legacy brownfield projects are structured in this way, with low or no Digital Maturity.*
- *In the middle: Many companies have adopted IT and Digital Systems but still facing challenges from an ecosystem perspective in managing the data overload throughout the lifecycle.*
- *On the right: What Capgemini proposes for a best-in-class approach for AOO is AIM (Common Data Environment) approach for single source of truth maintaining digital continuity in ecosystem enabled by 5 digital twins)*

The asset information management system acts as a foundational collaborative repository, facilitating data exchange and updates within an **industry-defined ecosystem.** When digitalizing asset information, standardized data is crucial for interoperability, although specific standards may vary across domains and industrial processes.

Developers, owners, and operators dealing with complex infrastructure assets should recognize that a universal standard covering all their business and asset needs does not yet exist. To achieve best-in-class results, leveraging knowledge from different industries is essential.

At Capgemini, we **define data ontology and governance** to facilitate information exchange across business participants and systems throughout the asset lifecycle.

A **digital twin architecture** helps deliver the digital twin initiatives in a smooth manner. Figure 9 below shows a high-level architecture with three major technology foundations required for delivery, along with the services that a digital twin enables. **This may vary in functionality across the 5 twins but the concept remains the same.**

DESIGN AND IMPLEMENT A DIGITAL TWIN ARCHITECTURE

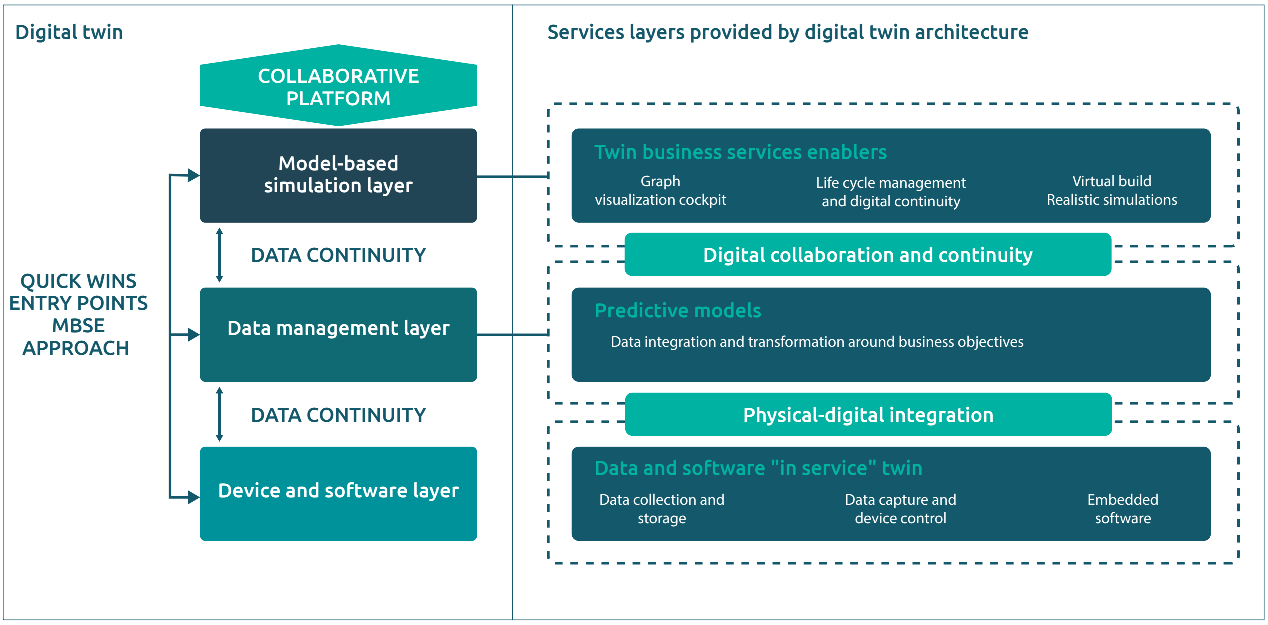


Figure 9 - A high level digital twin architecture

- A data management layer allows access and storage of data coming from the various sources and throughout the asset lifecycle (such as in Siemens COMOS system and the "Hydrogen Performance Suite)
- A device and software layer makes it possible for employees and teams to interact with the twin and allows monitoring and automation for better decision making such as digital worker concept
- A model-based simulation layer, which should be flexible and able to offer advanced data services, such as modeling and simulation, intuitive visualization, analytics and AI/ML, and event-orchestration, to manage predictive/ preventive alerts and real-time incidents efficiently as realized in Siemens Hydrogen Performance Suite (see section 3.2.2)

For simple use cases or quick wins, all these three layers can be addressed separately or through systems engineering. Through a flexible modular approach of Data Exchange and Interoperability Frameworks - the architecture suits best for an Owner Operator business model.

The figure also shows the service layers that the digital twin architecture provides:

It allows **physical-digital integration** by means of **data collection and storage, data capture and device control**, and through **embedded software.** Data collection should build a single and up-todate source of truth federating "cold" (historical system specifications and models etc.,) and "hot" (IOT, OT, real-time events) data, as well as "descriptive" (GIS, BIM, CAD/CAM, etc.) and "transactional" (PLM, ERP, MES etc.) data. However, a single source of truth does not necessarily mean that all data sources and computing activities need to be centralized in one place; data consistency and performance would not be manageable in such a scenario. Therefore, striking the right balance in terms of data-sizing, synchronization, and computing is critical to scaling up.

Further, **digital collaboration and continuity** is enabled through data integration and transformation around business objectives. It can leverage and replicate the knowledge and lessons learnt from one unit of assets and transferred to another unit thereby reducing time to market for operations and production across portfolio of assets.

In order to realize all these successfully, organizations should focus on **lifecycle management, digital continuity, realistic simulations, and cockpit and dashboard services.**

For further details, read Capgemini Research Institute's publication digital twins: adding reality to the real world

Zoom: the role of automation systems for the Digital Hydrogen Plant

A well-designed automation system architecture is crucial to make use of the digital twin in operation, as the data from the plant is needed to use the digital twin to increase performance or to use it for asset optimization, condition-based maintenance, and maintenance execution. Through this integration the digital twin is used in daily plant operation and maintenance and consequently always stays up to date ("evergreen digital twin-concept").

An in-depth process understanding and the holistic view on the typical components of a hydrogen plant builds the foundation of the provided automation concept. From green energy source transforming water into Hydrogen via distribution to final usage in different end sectors (see figure 10).

Typical component structure of a hydrogen plant

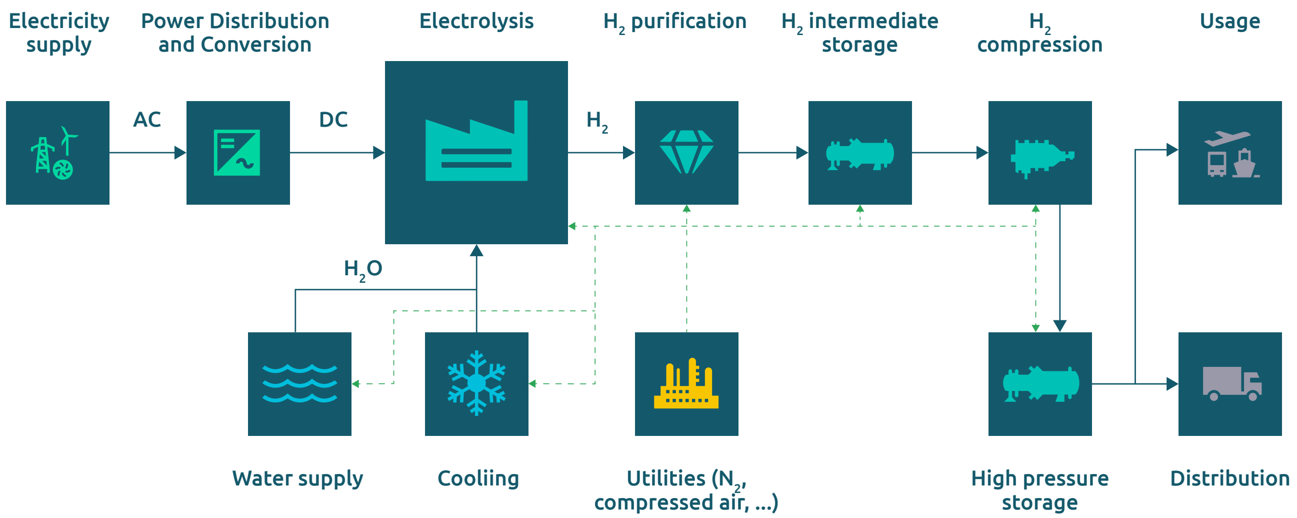


Figure 10 - Simplified view of typical subsystems and components constituting the hydrogen production system to final usage

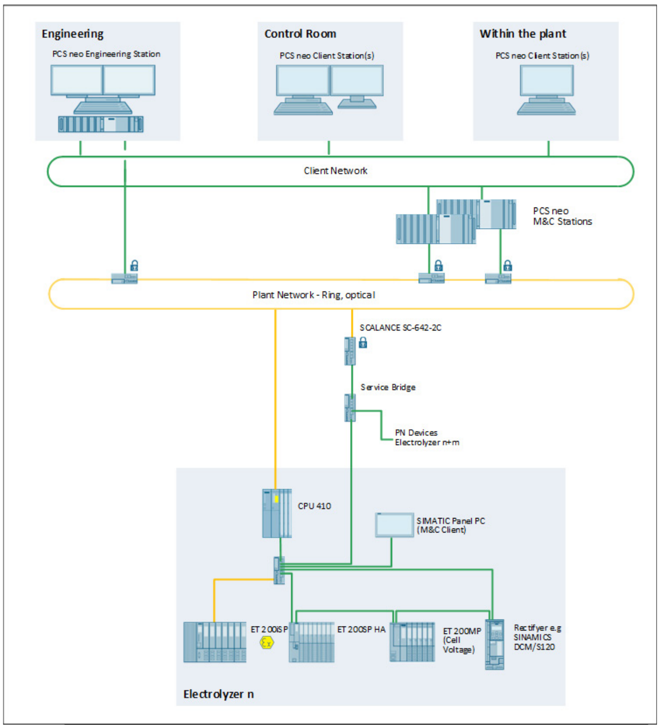
In summary the automation system and in particular the system architecture are of crucial importance for the digital plant and the digital twin. It is important that owner operators are aware for this and specify suitable requirements to make sure the plant operation and maintenance over the lifecycle is providing all necessary pre-conditions.

This needs to be done at a early stage of the project, before package unit suppliers specifications are submitted.

Siemens can realize any automation system architecture and can consult owner operators, EPC companies, Solution Providers and Package Unit Suppliers.

Various automation architectures based on the plant automation with the DCS Systems SIMATIC PCS 7 or SIMATIC PCS neo are available for green hydrogen plants which however have dedicated advantages, strengths and weaknesses. Some allow the highest level of integration and therefore provide the most comprehensive pre-conditions to use data within the digital twin. Others pronounce the most flexibility for electrolyzer manufacturers so that they can produce, sell and automate their electrolyzer units like lego pieces but with tremendous disadvantages in regard to integration and use of data, central updates etc. Also fleet management and remote access concepts for electrolyzer manufacturers are available. Siemens has prepared all relevant automation architectures for hydrogen.

Exemplary two typical architectures amongst many other are shown in the following:



Full integrated solution with DCS for each PU

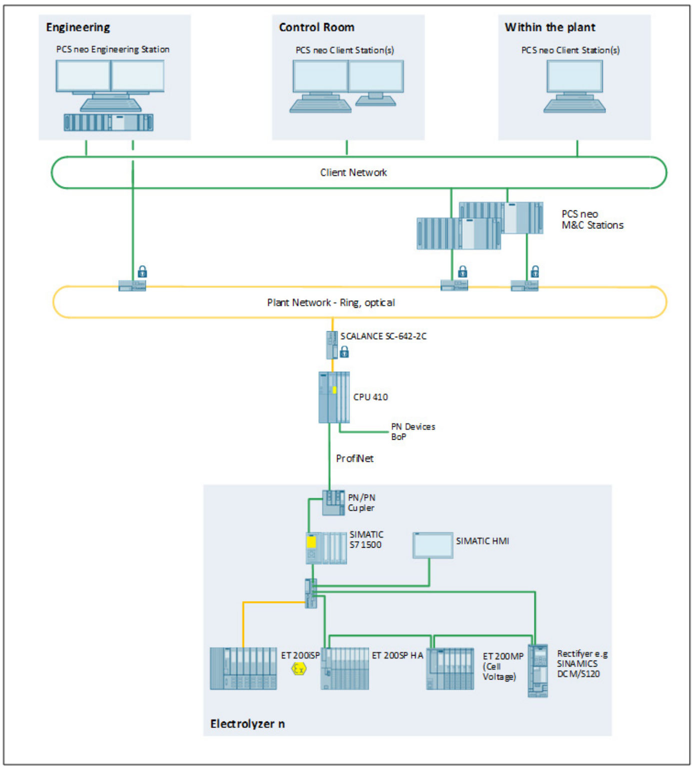
Overview

- PU CPU is part of a PCS 7/PCS neo project
- Standardized operation and monitoring through system wide standard Control Modules
- Unified engineering and maintainence
- High availability by redundant system components
- Centralized update and upgrade functionality

Figure 11 - Variant: Full integrated solution with DCS for each Package Unit (PU)

Automation System Architecture based on the Process Control Systems (DCS) Simatic PCS 7 or Simatic PCS neo with full integration of complex package units like electrolyzers into the Process Control System. As only one controller is needed for many package units with just one remote I/O unit per package unit a redundant system for highest availability can be realized at low additional costs.

7. PU: package unit ; CPU: central processing unit ; DCS : Distributed Control Systems. A DCS System uses Controller to integrated a larger Process Plant for central automation



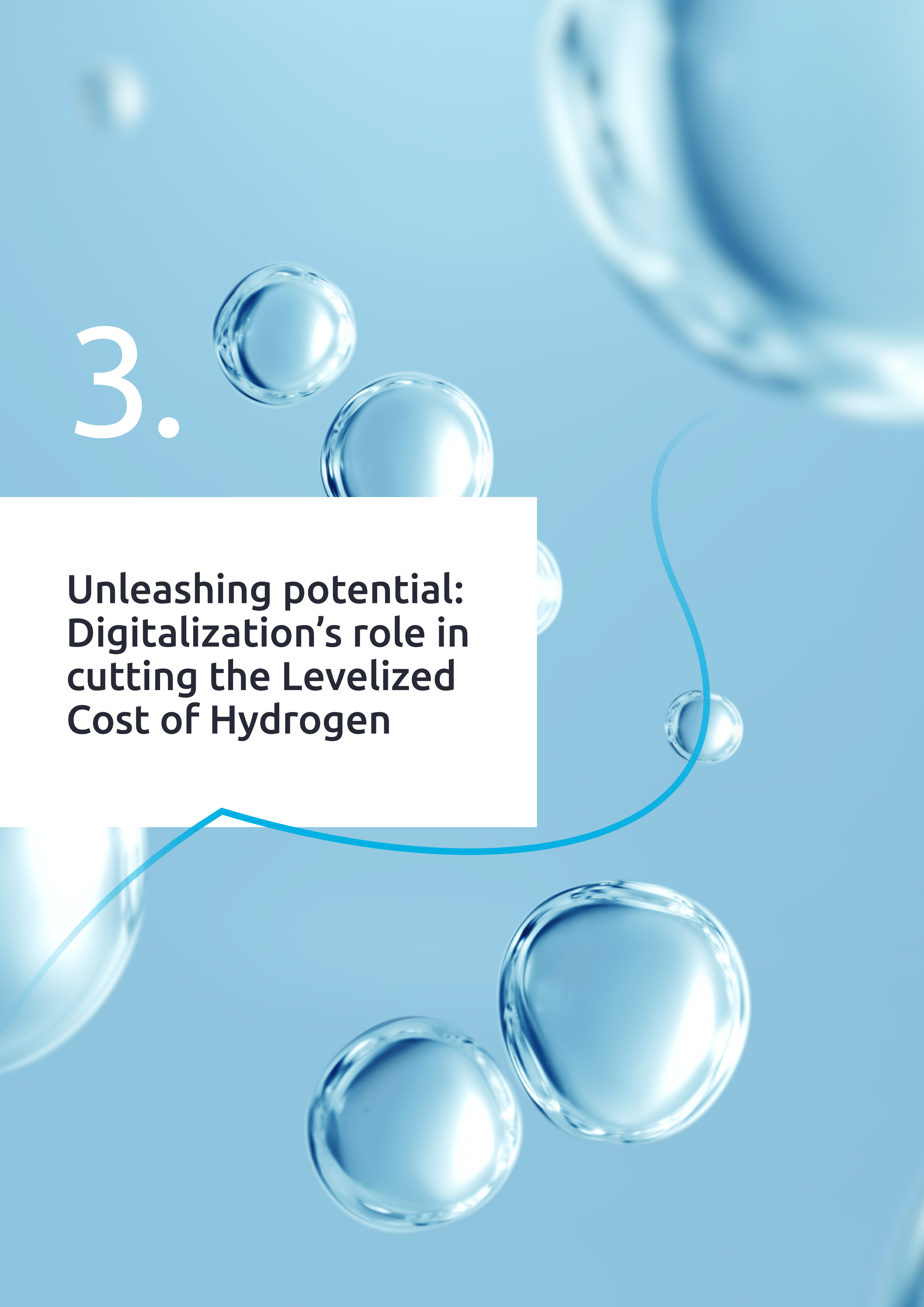
- PU CPU is part of Electrolyzer OEM incl. Application Software
- Defined interface for hardware, application software and responsibility
- High-performance data exchange via ProfiNet
- Limited use of the standardized DCS control modules

Figure 12 - Variant: integration through fieldbus coupling

Automation System Architecture using Simatic PCS 7 or Simatic PCS neo as Process Control System (DCS) for plant automation, but electrolyzer Package units are equipped with an own controller each. This version integrates the electrolyzers as package units with stand-alone automation systems with a Simatic S7-1500 controller engineered with TIA portal for each single electrolyzer unit. This “hybrid architecture” version allows maximum flexibilty for electrolyzer manufacturers but limited integration for the owner operator in regard to integrated safety, usage of data like diagnostic data, central updates etc.

The DCS-based engineering templates had already been introduced in the engineering chapter of this document. Also for package units automated with a machine-like automations system based on Simatic S7-1500 and TIA Portal Siemens has prepared the system for hydrogen.

7. PLC: Programmable Logic Controller. That is a part of a SCADA system (Supervisory Control and Data Acquisition) for smaller automation tasks e.g. within a smaller package unit



3.

Unleashing potential: Digitalization's role in cutting the Levelized Cost of Hydrogen

Lower risks and costs can be achieved when decisions are based on trusted asset information. When digitalized and standardized, this information establishes a true digital identity of industrial assets. It empowers asset managers to enhance operational efficiency, comply with the most stringent safety, health, and environmental regulatory frameworks, and improve returns on asset investments.

For asset owners with substantial investments in low-carbon hydrogen projects, a robust digital platform to record, organize, validate, and apply asset and process information offers a competitive edge. This platform eases the day-to-day decision-making process of asset managers, reduces risks and costs, and prepares an industrial footprint to brace for natural calamities, seasonal production spikes, and planned maintenance shutdowns (see section 3.2 – on Hydrogen Performance Suite). By avoiding the common pitfalls of dispersed and inconsistent data, such a platform also serves as an advanced training tool for new entrants in industrial ecosystems – from trainee engineers to Chiefs Of Operations (COOs) - e.g. Operator Training Systems or AI-based Piping and Instrumentation Diagrams (P&ID).

EPC companies will play an increasingly important role in green hydrogen plant construction as plant sizes will get bigger than the small and laboratory-like installations of the past years. Additionally, a 'digital by design' approach enables owner-operators and EPC partners to seamlessly handover digital assets, while retaining their integrity during transitions. A predefined technology stack that is available for green hydrogen plants helps EPCs to implement the owner operator's requirements of a digital plant into the specifications of their suppliers and to integrate into a holistic digital engineering process and prepare the end customer's plant for a digitalized operations concept.

As EPC companies have not necessarily been involved in the laboratory-like installations of the recent past and therefore many of them do not yet have a blueprint for hydrogen. For those is now the momentum to start right away with the digital hydrogen plant as they can major benefit by enabling their customers with the digital twin and re-use the digital plant by re-using the digital twin as a blueprint for every of their future projects as Hydrogen Projects are in spite of their individual frame conditions more similar to each other than plants of other industries. Furthermore, pre-engineered templates support the industry in Engineering and operational concepts.

Correctly implemented digitalization can reduce the Levelized Cost of Hydrogen (LCOH) at several steps during the lifecycle, from design to operation.

3.1 Unlocking efficiency: Digital levers for efficient design and engineering, faster construction, and asset replication

During the early phases of a project, design choices significantly influence the final project costs. As the project progresses, this influence decreases while the cumulative expenses rise, especially when procurement and construction start. Design changes at later stages can thus have a substantial impact on both time and budget, leading to increased costs and delays. Understanding these dynamics is crucial for effective project management and cost control.

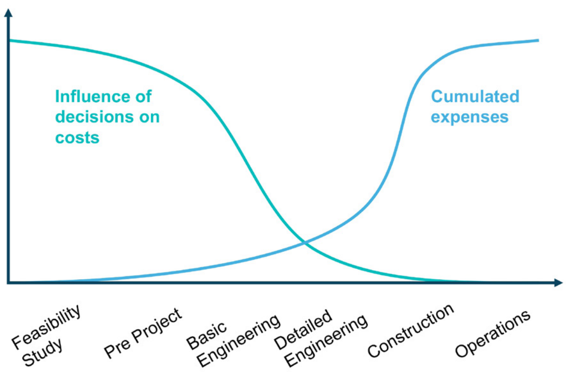


Figure 13 - Upstream phases of a low-carbon hydrogen production project are critical for managing overall costs

Capgemini and Siemens can support owner operators and investors with holistic concepts to take the right decisions right from the start. Asking owner operators about their attitudes shows that also herein the market is not yet that mature like e.g. the chemical industry where Lifecycle Cost analysis is an important part of the investment decisions. Many companies – partly under restrictions of their financial investors' limitations – still focus mainly on the initial erection costs of the first plant while at the same time targeting at plant lifecycles of 30 years and more.

Capgemini and Siemens are following the approach to reduce the LCOH as a whole – considering all phases of the project and plant.

The "better design" is enabled throughout **design optimization solutions and simulation** tools. They enable engineers to create cost-effective hydrogen production systems. These tools consider variables such as energy and water supply strategies, regulatory requirements, equipment costs, stack technology, system capacity, and storage options. By predicting future plant performance, developers can **efficiently allocate engineering resources, optimize investment costs**, and **secure business case.** A low-carbon hydrogen production system comprises five main subsystems from energy production down to clean hydrogen storage and usage, each with its own equipment (e.g., compressors, pumps, heat exchangers, electrolyzers). Balancing system availability and invested capital is crucial for financial performance. Techno-economic data, including acquisition costs, operating costs, mean time to failure, mean time to repair, process efficiencies, and production rates, are essential for project bankability. Given the complexity of technology choices and trade-offs, digital simulation becomes invaluable for low-carbon project developers.

Benefits of these solutions are estimated between 5% to 15% of OPEX and CAPEX can decrease by 10% to 15%.

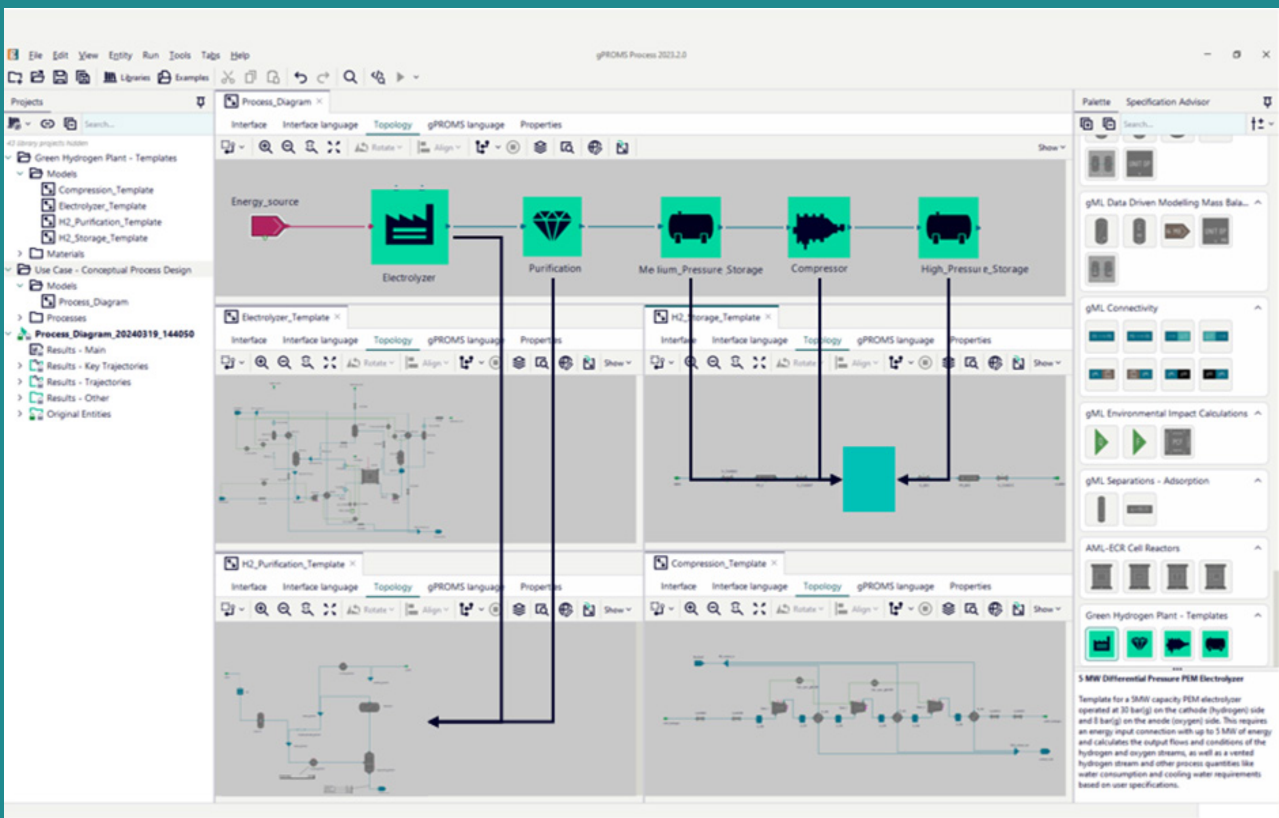
Integrating the above-mentioned subsystems into a coherent system is complex. Poor integration can lead to inefficiencies, increased costs, and safety hazards. Additionally, reliance on variable renewable energy sources like solar and wind can cause inconsistent hydrogen production and higher operational costs.

Determining optimal equipment design and sizing is another challenge. Improper sizing can increase capital costs and maintenance expenses. Ensuring economic viability while managing risks associated with new technologies is critical. Poor economic planning can result in unprofitable operations and difficulty securing investments.

gPROMS by Siemens – Digital process design software

Siemens' gPROMS software addresses equipment design, sizing and integration challenges by enabling detailed modeling and simulation of the entire hydrogen production process. It helps optimize process parameters and reduce design time, while dynamic simulation capabilities allow for assessing system performance under various scenarios. gPROMS aids in accurate equipment sizing, minimizing inefficiencies and maintenance costs. gPROMS includes economic analysis and risk management tools to evaluate design options and support informed decision-making. Implementing gPROMS in the conceptual design phase improves operational efficiency, reduces physical testing, and optimizes energy use. Similar projects have achieved efficiency gains 5 to 10 %. Additionally, gPROMS enhances safety, compliance, scalability, and adaptability to changing market conditions. Comprehensive economic evaluations ensure financial soundness and investor appeal, boosting overall project viability.

For green Hydrogen a complete simulation model and library is existing and ready to use. One of the key characteristic of the gPROMS philosophy is that it is also used in the operation phase. The system can interpret deviations between simulated values and process values from the automation system in order to enhance plant performance, find material-friendly production, optimize the energy mix or to estimate the degradation of the membrane. gPROMS is part of the holistic approach of the Hydrogen Performance Suite.



Digital twins[9] **lay a crucial role in optimizing the design of hydrogen units and plants** through simulation. Additionally, they facilitate **faster construction** by ensuring:

- consistency and continuity of digital twins from the “as required” to the “as designed” and the final “as built” state;
- enhanced collaboration among project’s stakeholders by providing a single source of real time information, including Engineering, Procurement, and Construction (EPC);
- asset replication, streamlining the delivery of multiple projects within a portfolio.

Assets replication and streamlined engineering: asset replication, a key aspect of scalability, is facilitated through digital twins and comprehensive blueprints. These blueprints serve as standard models and templates, expediting engineering processes and minimizing errors. They encompass system architecture, safety standards, industrial security, analytics, automated engineering templates and libraries, including testing and simulation workflows.

By adopting this streamlined approach, projects not only develop faster, reducing time to operations, but also maintain consistency and efficiency across multiple deployments. Estimate suggest that replicating an asset reduces development costs from 5% to 3% of EPC expenses.

In green hydrogen production, this aspect has a significant impact because many identical package units are used in the plant. This is due to the need to scale up plant capacities by increasing the number of electrolyzers.

Standardization for design optimization: Design optimization tools incorporate standardized elements evaluating their benefits throughout a project’s lifecycle.

These technologies provide modular, scalable solutions that adapt to changing market conditions and varying production capacities. **Similar processes have improved productivity by 10%, significantly reducing downtime and enhancing overall management.**

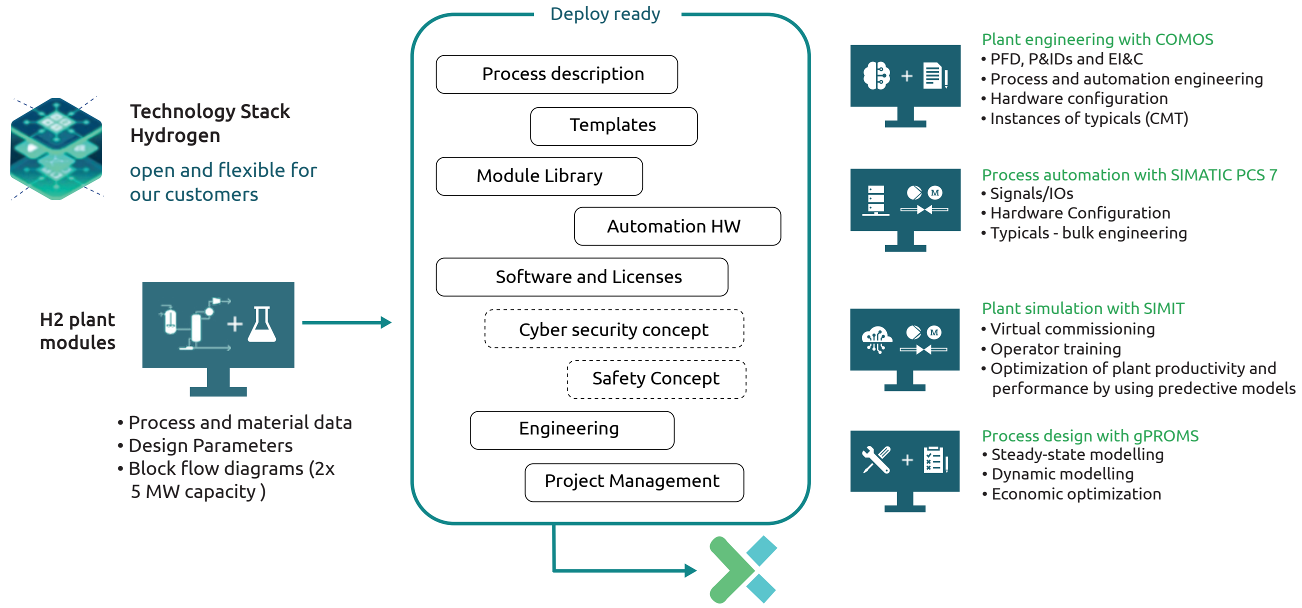


Figure 14 - Standardized industry solution combining process design, automation engineering enabling the digital twin

9. In that particular phase, project’s twins are leveraged, starting from the “requirements twin” to the “design twin” up to the “construction twin”

Using Siemens' technologies, such as COMOS, SIMIT, and SIMATIC PCS 7 or SIMATIC PCS neo, in the integrated engineering phase improves efficiency, reduces costs, and ensures safety and compliance.

Although hydrogen plants are unique, Siemens has prepared a collection of pre-engineered, ready-to-use templates and libraries for all necessary systems to implement a digital plant. Users can be Package Unit suppliers, EPC companies as well as Owner Operators. The idea is to make the integrated engineering process as easy as possible while using Siemens tools like gPROMS for simulation, COMOS for Plant Engineering, SIMATIC PCS 7 / SIMATIC PCS neo/ SIMATIC TIA portal for automation you do not need to start from scratch. Users can take the pre-configured engineering and just adopt it to their individual situation – and at the end to reach a holistic digital twin of the plant.

Owner Operators and EPC companies can use these contents to create suitable specifications of the plant. Furthermore it can help to create the framework how an EPC Company does create a digital twin during their engineering process and how an Owner Operator can get the relevant parts of that digital twin to make use of the according benefits in operation (see section 3.2).

The developed technology stack for hydrogen provides templates for Process Flow Diagram (PFD), Piping and Instrumentation Diagrams (P&ID), and Engineering instruction and Control (EI&C), as well as process and automation engineering. It includes hardware configurations and predefined simulation models to shorten the development of green hydrogen projects. Therein Siemens has invested significantly to support users and industry partners alike to realize their hydrogen projects utilizing the existing in-depth understanding of the hydrogen production process and the typical components of a hydrogen plant (see figure 10).

The digital twin is developed with the creation of template library with each Hydrogen component with an integrated engineering workflow using COMOS for P&ID, EI&C and DCS configurations. Creating engineering templates in COMOS, PCS 7 and SIMIT and exchanging the data between them allows for a fast and parallel engineering workflow. The digital twin is realized in simulation and visualization with the integrated engineering workflow with bi-direction import/export of COMOS data into PCS 7 (Graphical User Interface) and SIMIT (Plant simulation). Integrated Engineering Workflow - Integration of simulation and visualization packages. The digital twin benefits you in reducing planning efforts with template libraries for Hydrogen, engineering efficiencies in standardized and reproducible processes and lastly, time and cost savings.

Siemens generic solutions for hydrogen are available to support a standardization of automation concepts reducing efforts in engineering. It provides worldwide standards with:

- Scalable and customizable engineering using Modular Type Packages (MTP) and modular libraries (e.g., ready to use libraries and templates available in software tools such as TIA Portal, TIA Project, TIA Selection Tool, SIMIT) or dedicated hardware bill of materials.
- Guidelines for engineering and parametrization
- Compatible and easy to integrate solutions that are intrinsically safe with one software tool.

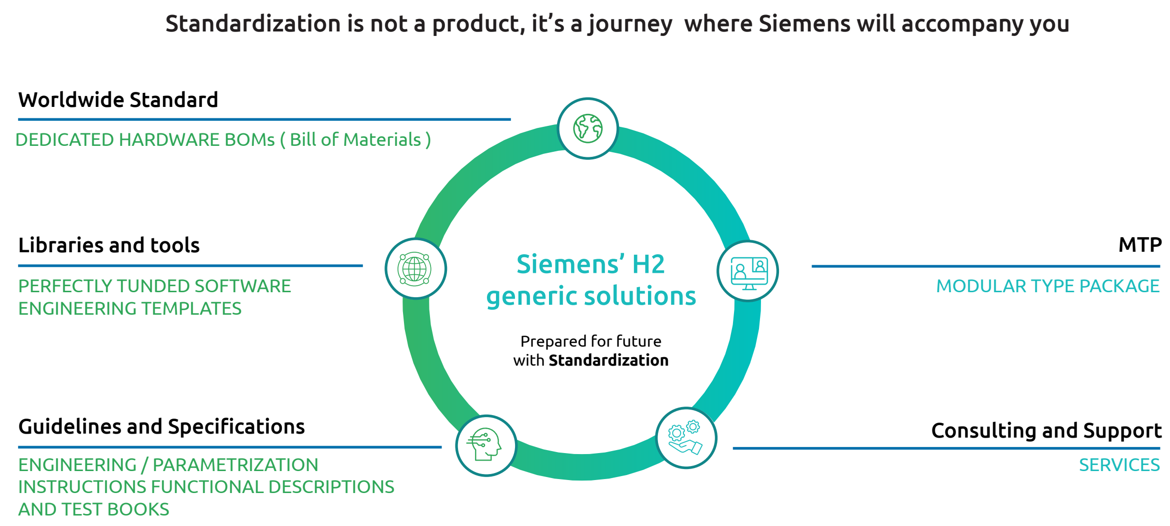


Figure 15 - The standardization journey with Siemens' H2 generic solutions

Finally, generative AI (GenAI) is emerging as a promising solution, with proven relevance in various use cases, such as

- **GenAI-Driven 3D Simulation Scenarios:** Within a Unity-based simulation framework, GenAI crafts detailed 3D simulation scenarios. These scenarios simulate diverse weather conditions and model the behaviors of entities within a 3D environment. Notably, GenAI can also generate 3D point clouds from monocular video footage, particularly valuable in medical applications. Previous projects have explored creating 3D point clouds from single 2D images, showcasing GenAI's potential. Ongoing research investigates advanced techniques like Neural Radiance Fields (NERFs) and Gaussian Splatting to reconstruct 3D models from a limited set of 2D images.
- **Augmented System Engineering with enhanced technical documentation analysis:** In this use case, we aim to augment the analysis of technical engineering documentation. We achieve this by creating a conversational agent that assists engineers in swiftly locating specific requirements and providing comprehensive responses from various sources for product design inquiries. By enhancing access to and compilation of technical data, we streamline engineering operations.
- **Contract and documentation management to accelerate EPC process:** Our focus in EPC-related use cases is to expedite the EPC process through the following strategies:
  - rapid access to comprehensive knowledge related to design requirements,
  - efficient navigation through all EPC documentation,
  - facilitating internal referential interactions,
  - strengthening relationships with EPC partners (e.g., verifying claims or preventing costly change orders).
  - GenAI support creation of P&ID using pre-defined templates

In addition GenAI is going to increasingly revolutionize the way, users can interact with engineering and operations software which is in particular interesting in the hydrogen industry.

3.2 Optimizing production: enhancing efficiency from energy supply to operation and maintenance

It is of major importance that the digital twin as described in the previous chapters is used also during the operation phase. This may require suitable contractual alignments and specifications between Owner Operators/ Investors and EPC companies and electrolyzer OEMs. Capgemini and Siemens can support and consult the players on this.

As part of operating expenses, the electricity costs must be considered on their own, being the main LCOH component.

3.2.1 Energy supply operations

During the design phase, the power sourcing strategy is primarily defined. However, during operations, two key levers can be combined to minimize electricity cost in hydrogen production:

- **Reducing electricity consumption:**
  - Energy efficiency solutions play a crucial role in identifying optimization opportunities within production settings. Operation digital twins simulate and pinpoint areas for improvement, enhancing overall efficiency.
  - Monitoring teams translate these optimization margins into actionable steps, which can be executed more efficiently through automation at equipment level or digitally guided augmented workers.
- **Lowering average price of electricity:**
  - Renewable integration solutions, such as SICAM Microgrid Control, helps structure and control the energy mix by configuring actuators based on consumer, producer, and storage priorities, and generation assets, the grid remains stable dealing effectively harness the intermittent nature of these renewable sources. The Microgrid Control ensures an efficient utilization of renewable energy and guarantees the required power flow.

    However, a complete Energy Management Systems is not only able facilitate seamless transition between different energy sources, maximizing the effectiveness of the electricity purchase strategy. But also aligning maintenance operations with production periods for further enhanced availability. Such system considers 2 layers:
  - The planning layer where the optimization happens on power procurement where forecasting renewable energy generation is crucial, as well as demand-side management.
  - The monitor and control layer, which controls the renewable generation assets, grid operation and the process control for electrolysis operations (described in detail in the following chapter), hydrogen storage, and distribution.
    (Note: Refer to Figure 23 on page 38.)

The estimated benefits from implementing these solutions range from 2% to 7% reduction in electricity expenses.

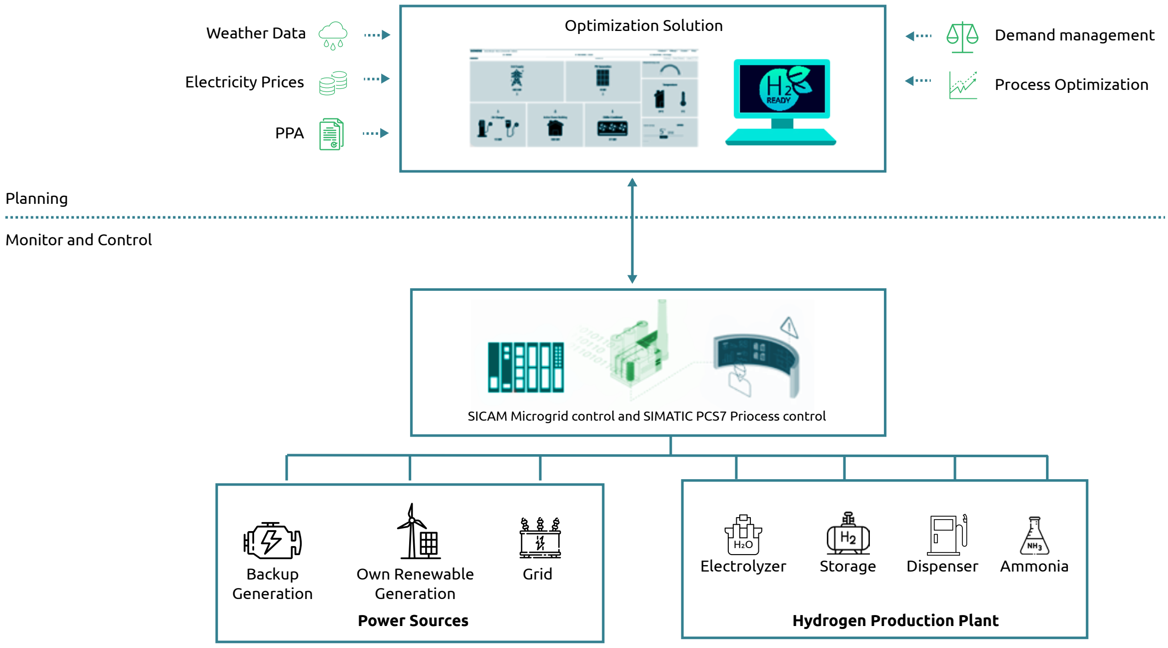


Figure 16 - Energy Management Systems concept

3.2.2 Production processes

In the production process, a critical economic challenge lies in optimizing the load factor of the electrolyzer. While some of this work occurs during the design phase, additional levers can be activated during operations. The delicate balance involves considering the following factors:

- Production volume to "amortize" CAPEX: achieving an optimal production volume helps offset capital expenditures (CAPEX). Balancing output with cost considerations is essential.
- Electrolyzer's use profile: preventing stack degradation is crucial for maintaining energy efficiency. Deterioration of stacks leads to additional CAPEX for replacements and necessitates maintenance stops, reducing overall availability.
- Strategic production timeslots: selecting the best timeslots for production involves analyzing electricity prices and consumption profile. Efficient scheduling aligns with cost-effective energy usage.

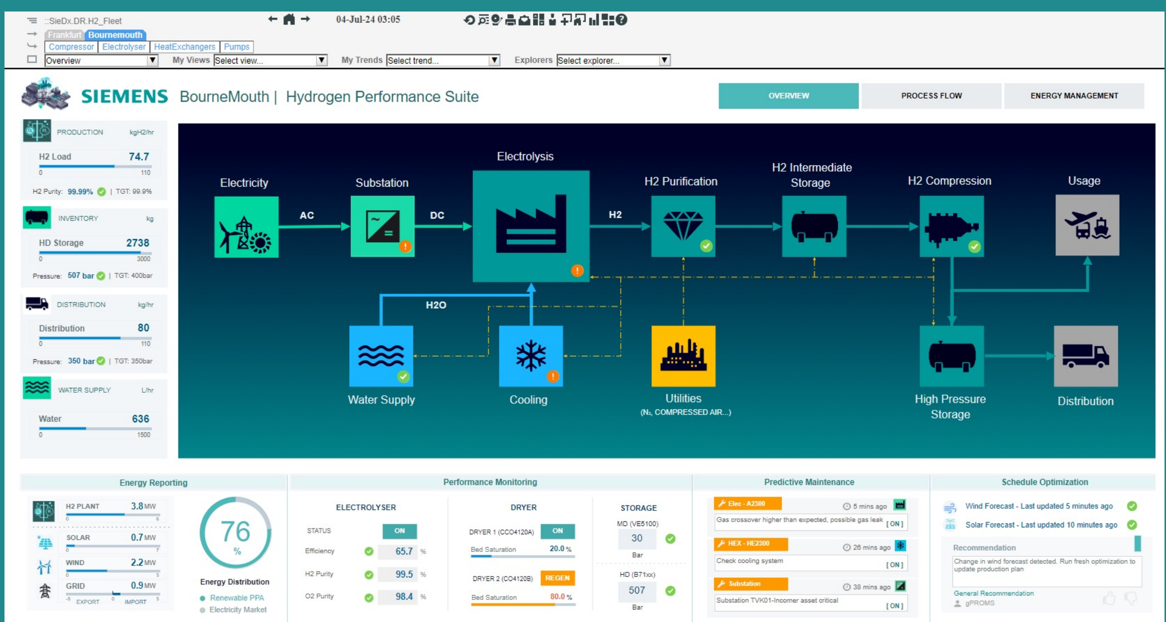
At this stage, leveraging **operations digital twins and Hydrogen Management Systems (HMS)** becomes imperative. These solutions simulate, monitor, and make real-time decisions to optimize production parameters while considering economic indicators. Whether in the short or long run, they ensure efficiency, operational longevity, and minize the need for additional CAPEX.

Production Optimization with the Hydrogen Performance Suite

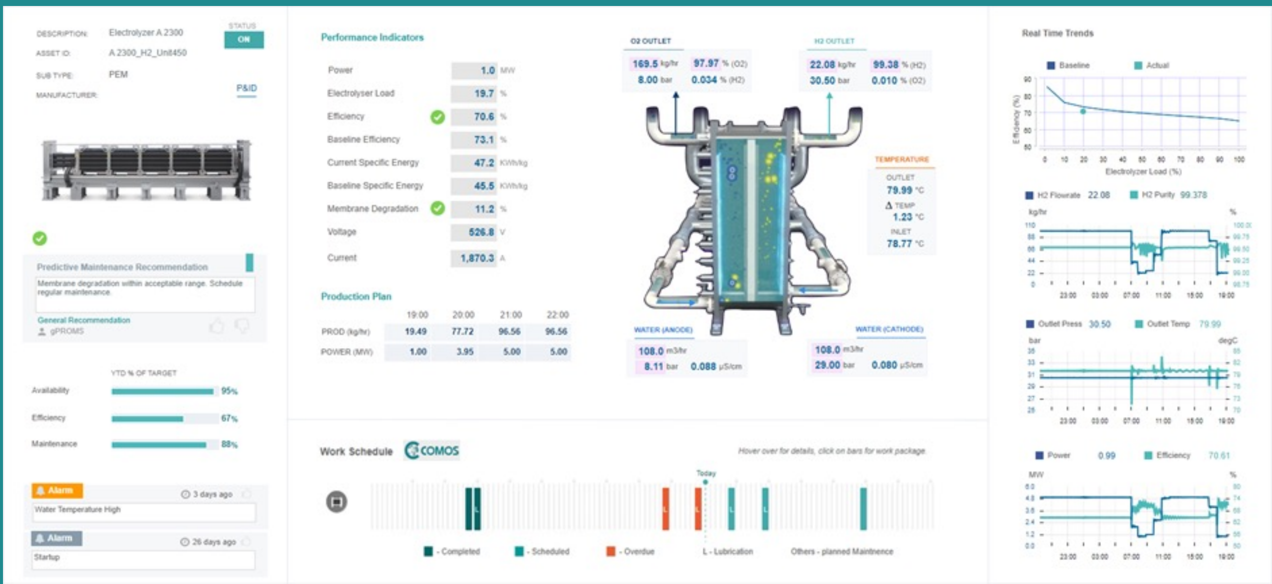
As described above for operation of a hydrogen plant, a Hydrogen Management System is necessary. Siemens offers the "Hydrogen Performance Suite".

The operational and maintenance phase of hydrogen production facilities presents critical challenges. Accurate data acquisition and real-time monitoring are essential for effective control and identifying issues, preventing inefficiencies, and safety risks. Managing multiple production units requires efficient integration to minimize downtime and maintenance costs. Ensuring energy efficiency and optimizing processes are crucial to reduce costs and environmental impact. Predictive maintenance is vital to prevent unplanned downtimes and extend equipment lifespan.

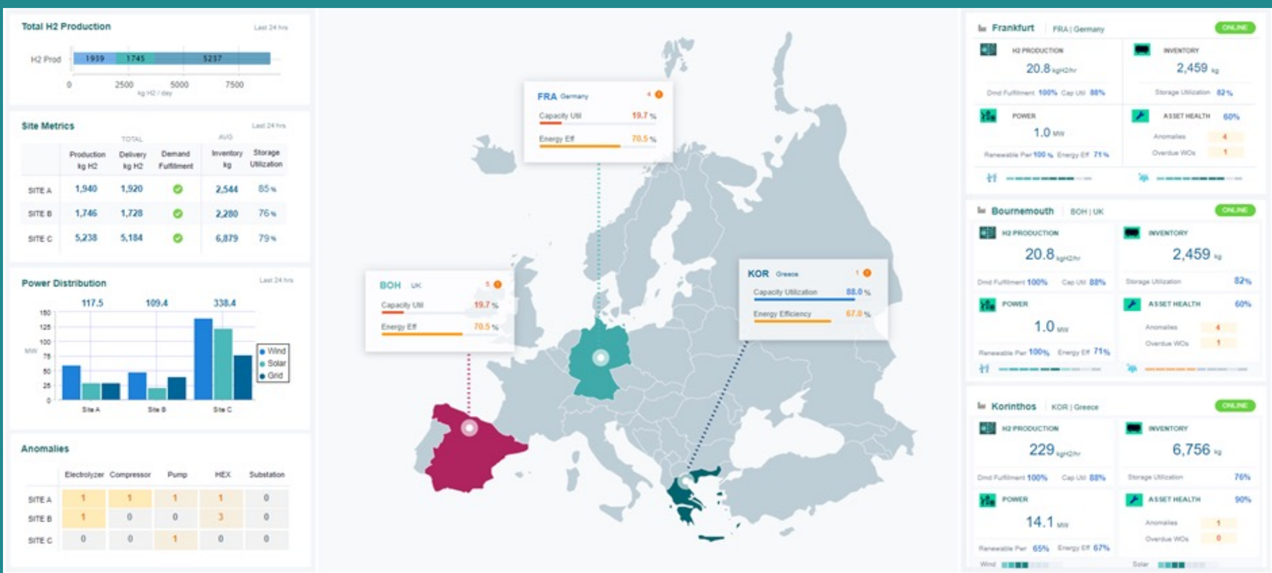
Siemens' Hydrogen Performance Suite addresses these challenges effectively and provides all relevant information on the hydrogen plant in one cockpit. It integrates the information gained through the digital twins, the simulation models and the process automation system.



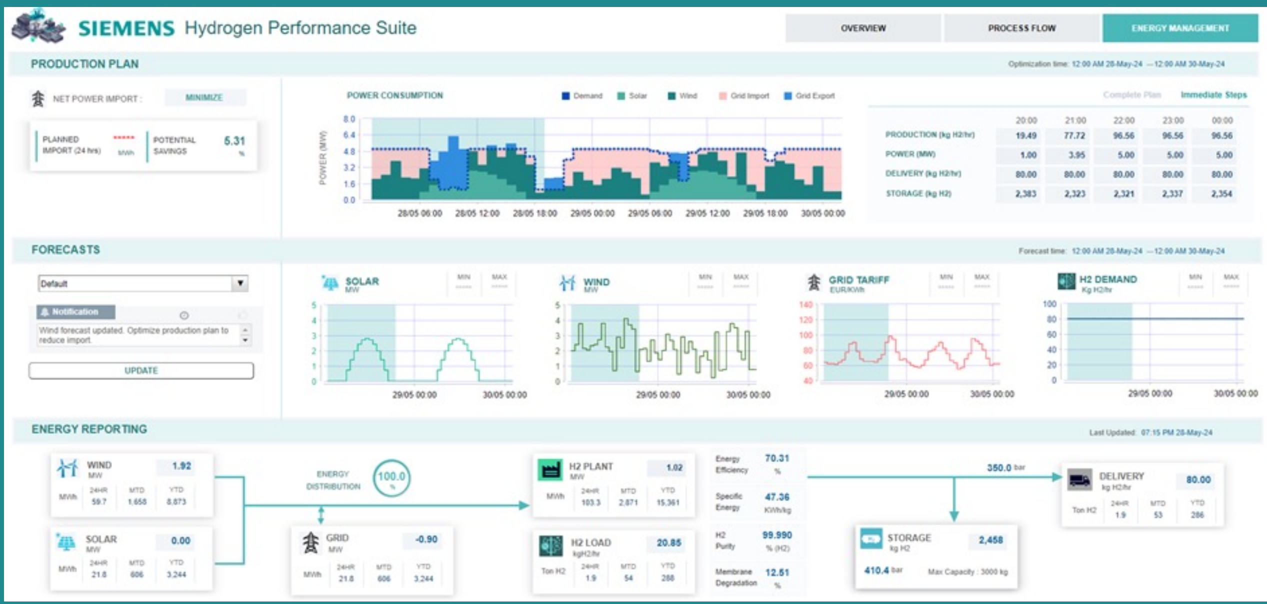
Soft sensing provides accurate real-time data using virtual sensors and connects to the digital twin to plan and execute maintenance. Operational programs, performance curves etc. are available to get full transparency. This view can be used by owner operators, but also electrolyzer manufacturers could use this for fleet management or maintenance/ performance services.



Fleet Management integrates multiple units for optimal performance management.



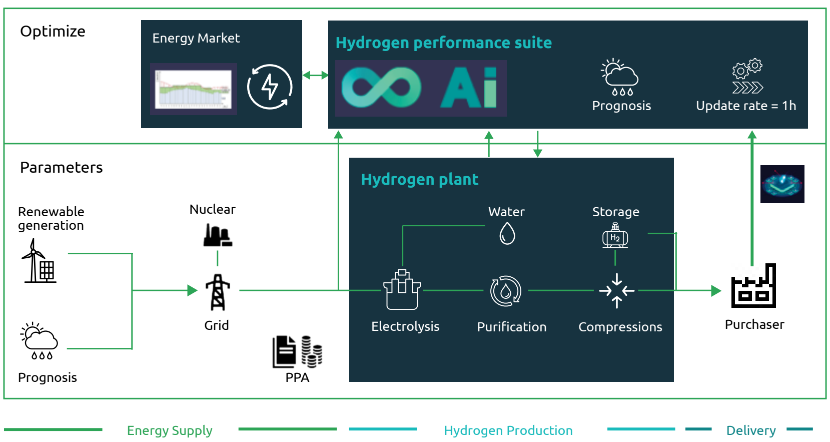
Energy and Process Optimization enhances efficiency and reduces operational costs. Predictive Maintenance uses analytics to foresee equipment failures, scheduling proactive maintenance.



Implementing Siemens' Hydrogen Performance Suite in this phase brings substantial benefits. Improved energy efficiency reduces costs and environmental impact. Predictive maintenance lowers repair costs and extends equipment lifespan. Enhanced safety and compliance reduce accident risks and ensure regulatory adherence. Overall, the suite improves economic viability by optimizing processes, reducing costs, and mitigating operational risks. In similar fields, these combined technologies have demonstrated up to 12% improvements.

Hydrogen performance suite
Balancing consumption, cost,and climate goals

Future production plan	Setpoints	Production	Storage	Delivery	Electricity
	Time n	1,375 kg/h	50 kg	1,325 kg/h	50 MWh
	Time n+1	1,200 kg/h	20 kg	1,880 kg/h	20 MWh



Benefits

Energy is major operational cost driver

- **Cost reduction**
  Lower operational expenses by optimizing energy usage
- **Energy efficiency**
  Minimize energy waste and improve consumption efficiency
- **Revenue opportunities**
  Generate income by trading excess energy in the market
- **Compliance strategy**
  Manage CO_2 certificates to offset carbon emissions and meet regulations and off-taker requirements
- **Real-time management**
  Immediate insights and control over energy use
- **Sustainability**
  Reduced carbon footprint and promotion of environmental initiatives
- **Risk mitigation**
  Protect against energy price volatility and supply disruptions

Figure. 17 - Hydrogen performance suite: balancing consumption, cost, and climate goals

The Hydrogen Performance Suite enables Energy and Process Optimization based on simulation models and forecast data.

The role of automation systems for the Digital Hydrogen Plant

In the prerequisites, it was highlighted that a robust automation system architecture is essential for leveraging a digital twin in plant operations. It ensures that real-time data from the plant is utilized to enhance performance, optimize assets, and execute condition-based maintenance. This integration keeps the digital twin continuously updated, embodying the "evergreen digital twin" concept.

It was previously described how the Automation Engineering is made easier in a Digital Plant as there is an interface between plant engineering Software and Automation Engineering. However, also in Operation there is a bi-directional interface between the Plant digital twin in COMOS, the Simulation in gPROMS and the Process values in the Automation Systems.

Safety, security and operations continuity

During operations, maximizing equipment availability is critical for uninterrupted production. Beyond routine maintenance (as outlined in section 3.3), production continuity can be secured through the following measures:

- **Hardware redundancy:** Implementing reliable, digitally enabled power distribution ensure robustness. This redundancy allows for changes and operational adjustments while maintaining uptime (see more details in Chapter 1.2.3 on automation architectures).

- **IT systems integrity and cybersecurity:** Industrial next-generation firewalls, VPNs, and network segmentation protect against cyber threats. Compliance with standards and country-specific regulations is essential. Understanding both IT and cybersecurity in OT environments promotes transparency and safeguards the plant. An effective multi-layered Industrial Cybersecurity concept, based on the Defense-in-Depth principle, provides robust protection. IT security is even more important when plants are operated remotely or need a connection to external parties and service providers.

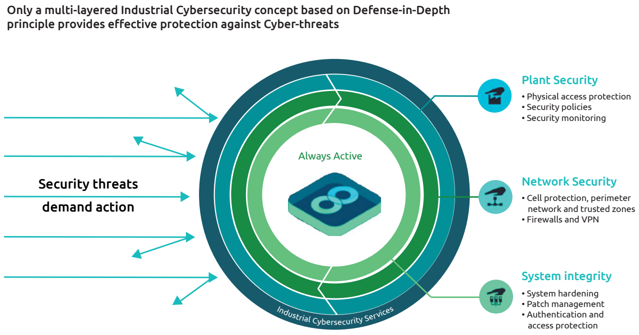


Figure 18 - Multi-layered Industrial Cybersecurity concept based on Defense-in-Depth

Siemens provides not only automation systems and Software, but has also in-house Hardware Components and Software for Cybersecurity, which are perfectly suitable to the requirements in production plants. Also consulting and services for cybersecurity is available from one source.

For green Hydrogen plants Siemens has prepared various Cybersecurity Blueprints for any plant architecture.

- **Process safety** is of crucial importance in a hydrogen plant. The plant automation needs to comply with IEC 61511. The functionalities of a Process Safety system with also called Saftey Matrix fits perfectly to configure all emergency shut-down events and procedures of the whole plant.

With an Integrated Control and Safety System (ICSS), the quality and efficiency in execution to meet project schedule requirements can be guaranteed through the following:

- Hardware design based on hydrogen blueprints.
- Optimized panel layouts.
- Virtual validation of program with digital twin model in Factory Acceptance Test (FAT).
- Integration testing of third-party OEM packages.
- Virtual operator training prior to plant startup.

A common peripheral, network and IT portfolio reduces integration complexity, enhance compatibility, and ensure interoperability. This standardization minimizes maintenance complexity (resulting in fewer spare parts) while simultaneously boosting scalability, efficiency and productivity, requiring fewer engineering efforts.

3.2.3 Maintenance

In the realm of operations, the synergy between digital twins and **anomaly detection** solutions proves invaluable. By harnessing real-time data from field sensors, these systems continuously monitor performance parameters. Their ability to swiftly identify deviations from the norm prevents over 80% of potential shutdowns.

Key benefits include:

- Essential components, such as electrolysis stacks, benefit significantly. By minimizing downtime, we reduce capital expenditures (CAPEX).
- The electrolysis stack, comprising multiple cells, plays a pivotal role. To assess cell degradation, we employ a voltage measurement module.
- This module provides granular insights into individual cell conditions, detects gas crossover, and identifies potential leaks.

In summary, this proactive approach ensures operational efficiency while optimizing CAPEX utilization.

Siemens' Hydrogen Performance Suite realizes the described approach to use e.g. anomaly detection and uses the digital twin of the plant or asset to do condition-based and predictive maintenance.

Figure 19 - Predictive maintenance recommendations: understand that your heat exchanger lost efficiency

Example how the Operational digital twins for Plant- and Maintenance Data in Siemens' Software are used in Operation and in this case used within Siemens' Hydrogen Management System – the "Hydrogen Performance Suite"

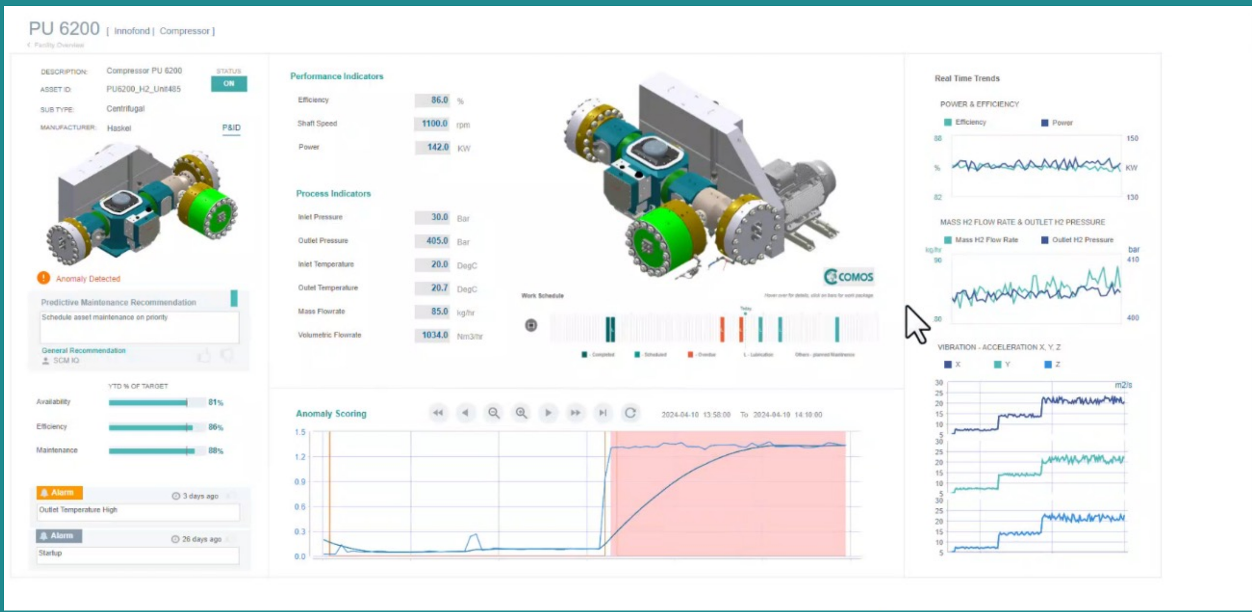
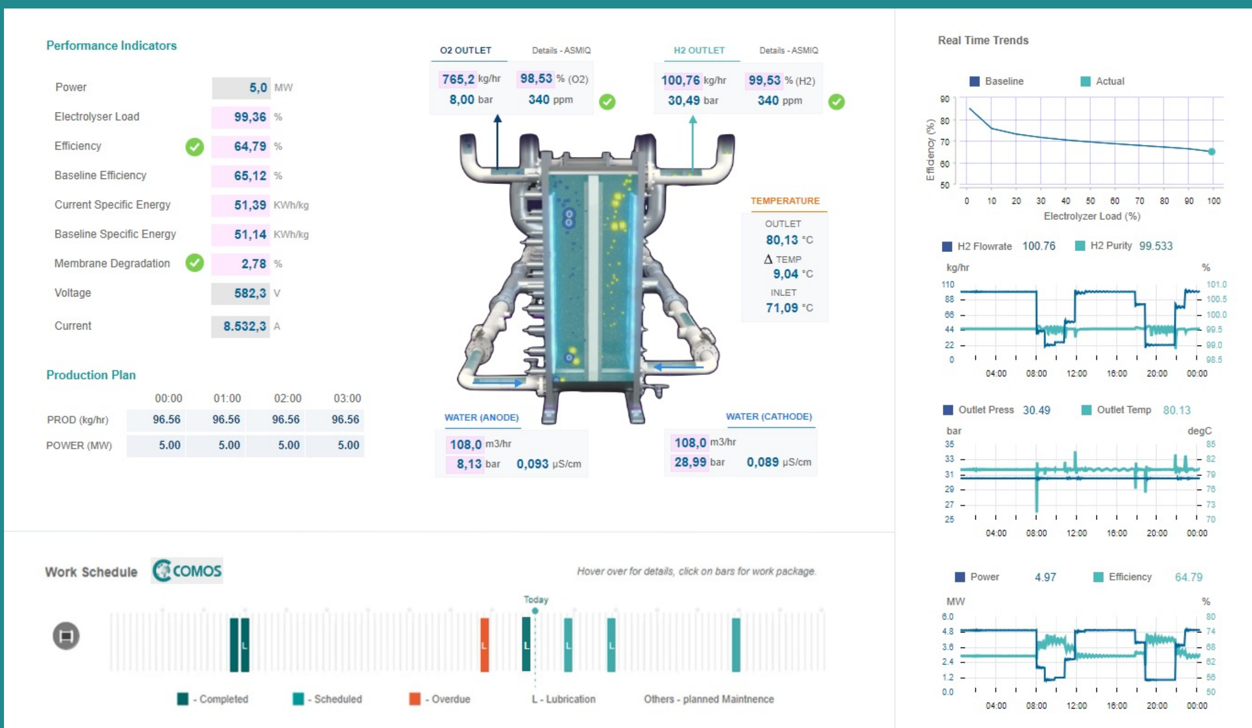


Figure 20 - Detailed information of the compressor: users can deep dive into vibration, temperature and AI KPIs

For electrolyzers all relevant information can be captured in one dashboard up to information on performance curves, production programs and predictive maintenance information such as the membrane degradation.



As soon as a maintenance task is necessarily to be done, the digital twin is used again to support – possibly unskilled workers – to carry out the task. The maintenance staff gets all relevant data on a mobile device and is supported – if necessary even step-by-step – by the system to fulfill the task. At the same time the digital twin is kept up-to-date automatically ("evergreen digital twin"). If necessary he/she could also connect remotely to a specialist from far away – e.g. from the electrolyzer manufacturer.

Figure 21 - How a maintenance worker can utilize augmented reality in the digital worker functionality to do their maintenance task.

A proper predictive maintenance of the entire energy distribution of the plant is key to prevent unexpected shutdowns and this can be achieved with a detailed monitoring asset management using digital tools, such as Electrification X. It allows visualization and continuous monitoring of the electrical assets from one substation across different locations, provides operational data, health status and alarms with status and details, all available for risk assessment and determination of corrective actions.

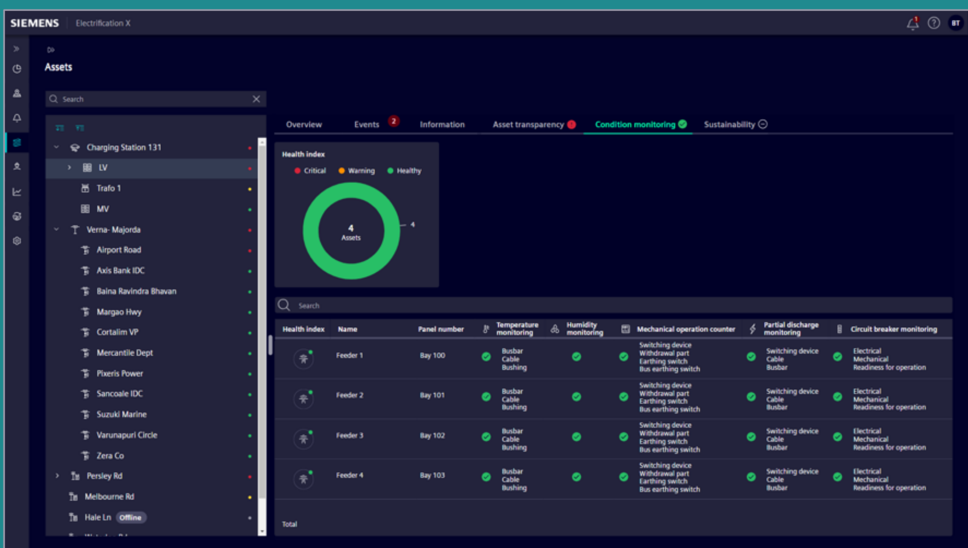


Figure 22 - Power Distribution System asset management with Electrification X

3.3 Enabling traceability, compliance targets, and carbon intensity

Digital solutions play a crucial role in enhancing real-time monitoring and data tracking for low-carbon hydrogen traceability across the entire value chain. **Comprehensive traceability is essential for market entry strategies and securing public subsidies.** It provides transparent and verifiable proof of the low-carbon nature of the hydrogen produced, ensuring compliance with regulation and meeting customers demand.

In both the EU and the US, specific thresholds define what qualifies as "clean" hydrogen: 3.38 kg CO_2e/kgH2 and 4.0 kg CO_2e/kgH2, respectively. These thresholds serve as minimum compliance targets, and the markets and some regulatory approaches provide incentives to do better. For instance, in the case of the US Inflation Reduction Act, Section 45V production tax credits have a maximum value of $3.00 per unit of hydrogen with a carbon intensity of 0.45 kg CO_2e/kgH2.

Rather than solely categorizing hydrogen based on its production pathway (e.g., green, blue, gray, or pink), establishing numeric targets for carbon intensity—certified independently—shifts the focus to rigorous life cycle assessments of associated emissions. This approach encourages the development of new, cleaner pathways and incentivizes existing pathways to reduce emissions.

Site-specific variables, such as plant design, operating conditions, feedstocks carbon intensity, and the carbon intensity of the electrical grid, influence hydrogen actual carbon intensity. In the EU, hydrogen can qualify as renewable fuel of non-biological origin (RFNBO) only if it satisfies three criteria: additionality, temporal correlation and geographic correlation.

The EU's Carbon Border Adjustment Mechanism (CBAM) levels international trade by addressing carbon-intensive imports. Initially targeting products like cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, CBAM requires importers to report on imports during the current transitional phase (2023–2025). Full implementation, including taxation, is scheduled for January 2026.

For hydrogen importers, CBAM involves calculating and reporting the carbon intensity of imported hydrogen using an EU-specified methodology. Importers will register with national authorities, purchase CBAM certificates based on the relevant weekly average auction price of EU ETS allowances (expressed in €/ton of CO2 emitted), declare embedded emissions and surrender corresponding certificates annually. If importers can demonstrate that a carbon price was already paid during the production of the imported goods, they can deduct the corresponding amount.

Digital solutions play a crucial role for traceability for clean hydrogen and derivative products, as there are many data requirements across the value chain, some of which includes high-frequency data at the points of production:

- Process control software and digital twins: These tools leverage data from on-site industrial sensors and control systems to provide visibility into the energy requirements and emissions associated with various operating conditions and plant configurations, and provide predictions on required maintenance. This detailed data also serves as the foundation for life cycle assessment and certification.
- Life Cycle Assessment (LCA tools): Ideally, these tools take the data directly from the data historians in the process control software and digital twins, rather than rely on intermediate processing through spreadsheets. They then analyze the greenhouse gas (GHG) emissions associated with hydrogen production, the feedstocks and utilities used, distribution and ultimate use. Some focus on the point of production ("well-to-gate") as that is the scope of some regulatory standards, while others go to end-use, particularly with transportation fuels ("well-to-wheels"), as that scope allows a more direct comparison of alternatives in end-use. Notable examples include the GREET model used in

US policy making, OpenLCA, the Open Hydrogen Initiative (OHI) toolkit, Umberto, and SiGREEN. Ultimately the best practice for LCA tools is to provide carbon intensity calculations across all relevant domestic and international standards, so that certification of regulatory requirements and end-user benefits can be certified as part of a single process by independent certification bodies.

- Distributed ledgers such as blockchain: Once the environmental attributes of hydrogen are independently certified, associating those attributes to specific products creates an immutable record of hydrogen production, transportation, and distribution. Each supply step can be securely documented, ensuring transparency and accountability. **Smart Contracts** automate transactions and compliance checks, verifying hydrogen's carbon content criteria before market entry. These tools are essential for understanding the sustainability and overall environmental footprint of hydrogen as an energy carrier, and also ensure that the environmental attributes are recognized, transferred, and retired once the hydrogen or derivative products is used.

Product Carbon Footprint (PCF):

SiGREEN is an emission management tool that uses block-chain technology to consolidate the data and calculate the PCF connecting companies with all their suppliers. Due to increasingly stringent regulatory requirements, industrial companies are faced with the major challenge of seamlessly tracing the entire Product Carbon Footprint (PCF). This can only be achieved through continuous data exchange along the entire value chain. This requires digital solutions that all connected companies can trust. With SiGREEN, you can rely on a scalable, accurate and secure tool for managing dynamic PCF data.

With SiGREEN, you can quantify emissions as they occur on-site and aggregate them along the entire value chain. The result is a dynamic PCF that helps you make data-driven decisions for impactful reduction measures

This is thanks to the automation system architecture described in the prerequisites (section 2.3) that allows the use of Energy Management up to SiGreen to create documentation that the produced hydrogen is really proven "Green Hydrogen".

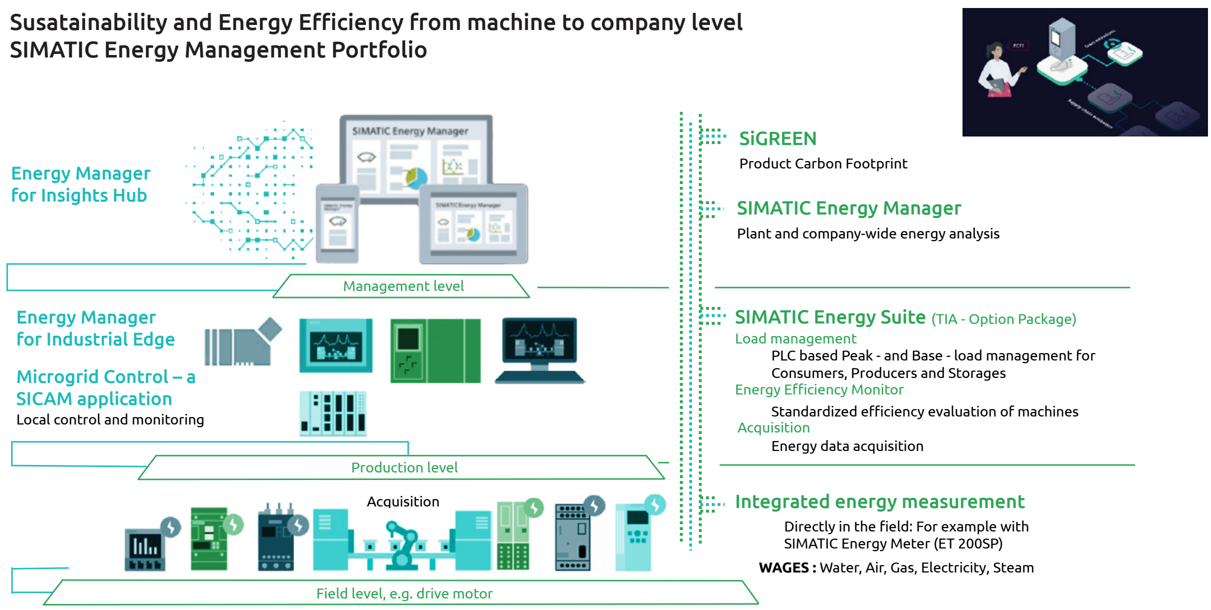


Figure 23 - Energy Efficiency from machine / package unit level to company level

3.4 Manage efficiently Assets portfolio

The digital solutions mentioned earlier not only benefit developers and operators at the plant level but also offer significant advantages to industrial asset managers at portfolio level. These solutions enable informed capital expenditures (CAPEX) investment decisions and strategic planning over time. For each asset, managers can simulate the impact of upgrades or expansions on future production costs and volumes and they can plan it over time.

Additionally, Advanced Analytics and Asset Investment Planning enable assets manager to leverage new data and information from different business functions and deploy best practices and sustainability roadmap at portfolio level. Asset investment planning that is typically done once a year or once every five years in an analog world, can become an integrated part of day-to-day business operations. This comprehensive approach ensures that investments are strategically targeted to maximize efficiency and profitability across the entire portfolio of low-carbon hydrogen production assets.

It is particularly relevant for asset owners with an existing legacy assets like O&G or Renewables. Investment strategies and organizations can be optimized with such approach and tools.

3.5 LCOH can be reduced by an estimated 9% to 12% activating digital levers and associated actions

Applying the different levers on a reference scenario, we reached a reduction of 9% to 12% of the LCOH overall. Assumptions were made according to benefits observed in implementing solutions in similar projects.[10]

The assumptions are the following:

- The reduction of CAPEX is impacted by a -13% reduction applied via a project twin (for system design optimization)
- Electricity costs are reduced by 5% through flexibility solutions (EMS), base load management systems and microgrid control solutions.
- Annual OPEX (operations and maintenance incl. labor costs, excl. electricity costs) are reduced by 10%, mainly due to operations twin and maintenance twin.
- The volume of production increases by 7% due to energy efficiency improvements (electricity consumption reduced by 5%) and availability (+2%) through maintenance solutions (incl.anomalies detection solutions).

Activating digital levers reduce the LCOH by ~ 10%

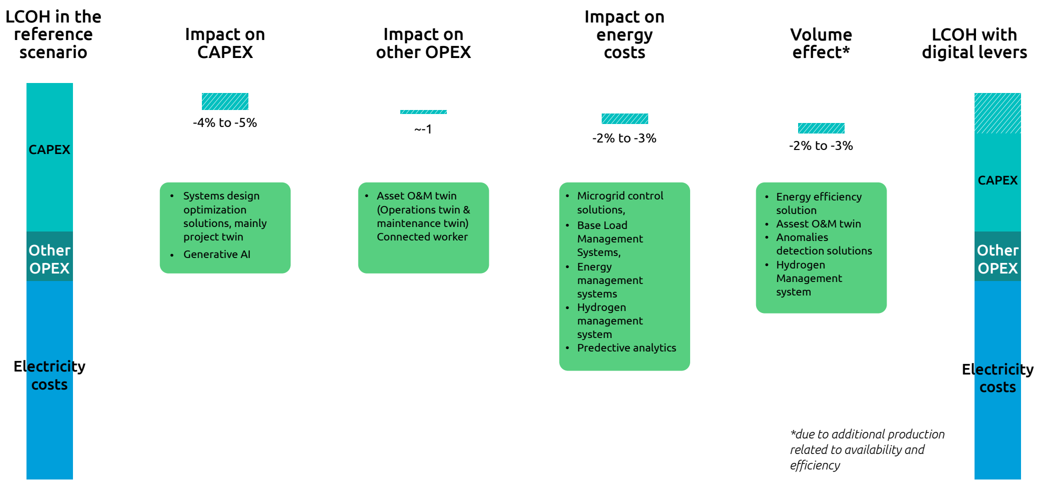


Figure 24 - Share of OPEX and CAPEX costs in the LCOH of a 100MW alkaline electrolysis installation and potential reduction through digital solutions.

10. Capgemini and Siemens references and Capgemini Research Institute (2022), Digital twins: adding intelligence to the real world

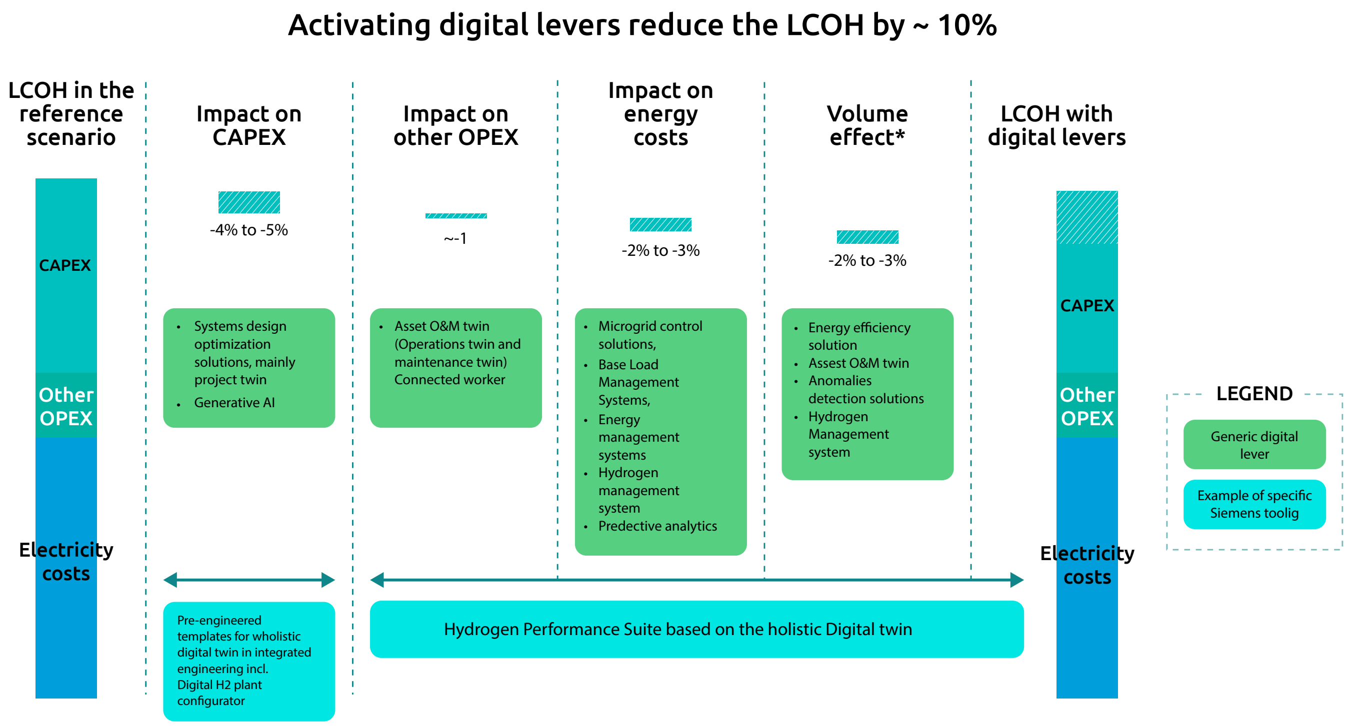


Figure 25 - Siemens solutions to reduce the LCOH.

In this figure you can see how Siemens can provide suitable systems and pre-defined engineering templates and libraries as well as a holistic suite for operation optimization realizing the defined LCOH savings:

- With the pre-engineered templates for the digital twin users can save ~ 10% of engineering time.
- As the Hydrogen Performance Suite is the umbrella of all digital twin functionality in the operation phase,owner operators may save ~10% of cost/ benefitting from a 10% performance increase (depending on the owner operators' business model) through energy and process optimization, purchasing of energy based on forecast data, optimized operation performance, material friendly operation maximizing asset lifetimes, optimized maintenance processes and support of their workforce/ labor.

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Further information is available on the Internet at www.siemens.com
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