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European Commission

SCIENCE FOR POLICY BRIEF

*Hydrogen brief*

# Energy efficiency of water electrolysers for hydrogen production

## HIGHLIGHTS

→ Improving the energy efficiency of electrolysers is a key enabler of the REPowerEU aspirational objectives for renewable hydrogen.

→ Energy efficiency definitions differ among manufacturers depending on industrial practices. Information about the measurement and testing protocols is required to compare characteristics across systems. Energy efficiency can be measured based on the electrical input or the energy content of the produced hydrogen at cell, stack or full electrolyser system levels.

→ The efficiency of electrolysers can be improved at cell level with the development of innovative materials and fabrication methods that would reduce impurities, chemical heterogeneity and energy losses.

→ At stack level, the development of better design of components including gas diffusion layers, or bipolar plates could reduce thermal and mechanical energy losses.

→ Innovative full electrolyser systems that synergize better within industrial configurations could increase the overall system efficiency. Electrolysers (especially high-temperature technologies) could be integrated to use high-grade heat that would otherwise be wasted for example.

→ Using more efficient systems does not necessarily translate into a lower levelised cost of hydrogen, because of the strong dependency of such cost on the cost of electricity, the capital expenditures and the operating conditions of the electrolysers.

## INTRODUCTION

Industrialised societies extensively rely on machines designed to convert energy from one form into another (e.g. bikes, cars, fridges, lightbulbs, or power plants). Just as light bulbs convert electric energy into thermal energy (heat) and radiant energy (light), electrolysis systems (hereafter referred as "electrolysers") convert heat and electrical energy into chemical energy (hydrogen and oxygen). Electrolysers consume electricity to break the chemical bonds between hydrogen and oxygen atoms in water ($H_2O$) molecules and rearrange these atoms as separate molecules using bipolar membranes, semi-permeable separators, or sufficient electrode gaps [1]. The consumed energy is stored chemically in the bonds of the newly formed molecules, dihydrogen ($H_2$) and dioxygen ($O_2$). The produced hydrogen molecule contains energy that can be reconverted into electricity and heat when recombined via the reverse electrochemical reaction with oxygen to form water, via combustion or a fuel cell. The hydrogen molecule can also be used as chemical feedstock or as reaction agent.

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The energy efficiency of any system refers to its ability to produce a specific amount of useful output, such as providing heat, mobility, lighting, and other energy services, from a given amount of energy input. However, information on electrolysers energy efficiency is not provided in a consistent way by manufacturers or project developers. Different metrics and electrochemical concepts are used, which reduces the understanding by non-experts.

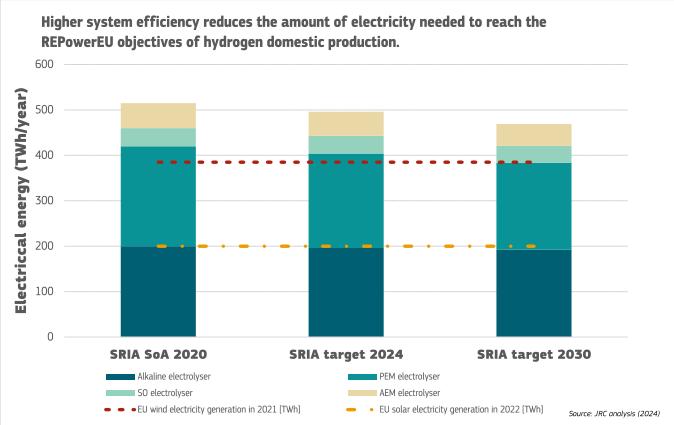
This Science for Policy brief attempts to shed lights on the different concepts used by manufacturers and to provide an overview of the interconnectedness of electrolyser efficiency with other techno-economic aspects, such as the Levelised Cost of Hydrogen (LCoH) or the operation of a full electrolyser system under variable load. This brief also provides data on commercial systems as reported by manufacturers.

## ENERGY EFFICIENCY AS A KEY ENABLER OF THE EUROPEAN GREEN DEAL

The European Union considers renewable and low carbon hydrogen as a key enabler for reaching the objective of a climate-neutral Europe by 2050. The REPowerEU plan of May 2022 aims at the development of a hydrogen economy in the European Union with an aspirational target of 20 million tons of renewable hydrogen by 2030. The Net Zero Industry Act (NZIA) supports the deployment of European manufacturing capacities for electrolysers by f.ex. accelerating permitting procedures, the public procurement rules or creation of the Net Zero Acceleration Valleys [2]. Renewable hydrogen production will benefit from public funding granted through several auctions of the European Hydrogen Bank [3] and an ongoing support of the Clean Hydrogen Joint Undertaking, an EU body in the field of research and innovation.

**Figure 1** illustrates the differences in electricity consumption required to reach the REPowerEU objective if energy efficiency targets set in the Strategic Research and Innovation Agenda (SRIA) of the Clean Hydrogen Joint Undertaking [4] are met . This shows the magnitude of electricity savings that a small improvement in energy efficiency can yield if extrapolated at a whole energy system level. This is given only for illustration purposes and is not the result of any modelling activity. As shown below, up to 515 TWh of electricity would be required if the electrolysis capacity deployed has the performance of the 2020 state-of-art efficiencies. If electrolysers perform according to the 2030 energy efficiency targets, 469 TWh of electricity is necessary. This represents an 8.9% reduction in electricity consumption.

**Figure 1** – A marginal increase of energy efficiency of electrolysers could save terawatt-hours of electricity to reach the REPowerEU aspirational objectives.




*Source:* Joint Research Centre (2024). The shares of each electrolyser technology in Europe are arbitrarily assumed to be as follows: alkaline (40%), proton-exchange membrane (PEM) (40%), solid-oxide (SO) (10%), and anion-exchange membrane (AEM) (10%). This does not reflect any forecast or modelling activities.

More efficient electrolysers also mean that fewer resources are required to produce a said volume of hydrogen. In addition to electricity, this includes raw materials as well as freshwater resources[1].

## ENERGY EFFICIENCY AND THE LEVELISED COST OF HYDROGEN

Energy efficiency directly impacts the levelised cost of hydrogen (LCoH) that project developers aim to minimize over the asset lifetime.

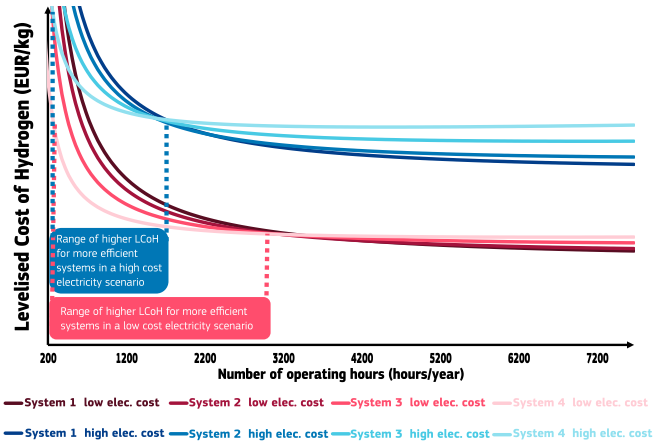
The LCoH depends on many factors including the system capital expenditure (CAPEX), the number of hours the electrolyser is running per year, the degradation rate of the stack, the electricity price, as well as other costs such as the grid fees, the electricity taxes or the cost of maintenance. This means that systems of higher efficiency do not necessarily lead to a lower LCoH, especially in the lower range of operating hours per year. Although they will consume less electricity to produce a given amount of hydrogen, they usually are more expensive than less efficient systems. This can be due to the

[1] IRENA estimates a 2% reduction of freshwater consumption per percentage point of energy efficiency, mainly due to less thermal losses to be dissipated by the water cooling system [5].

use of more costly catalytic materials (e.g. platinum or iridium) or more technology advanced electrolytes.

This is illustrated in **Figure 2** where the levelised cost of hydrogen is calculated depending on the number of operating hours for 4 theoretical systems from the most efficient (System 1) to the least efficient (System 4). The two sets of lines show the same 4 systems under different electricity cost assumptions (scenario with low electricity cost in shades of reds and high electricity cost in shades of blues).

**Figure 2** - Theoretical illustration of the levelised cost of hydrogen versus the number of operating hours for different systems.




*Source:* Joint Research Centre (2024). Assuming constant load operation for the indicated number of hours. Note: The darker lines represent the most efficient systems. No absolute LCoH values are provided because of the simplified model used for illustration purposes.

As illustrated above, the economic gains resulting from using a more efficient electrolyser system will only appear from a certain level of operating hours. The choice between systems depends on the business case and the expected number of hours when the system will operate, which can be adjusted to comply with regulations.

## ENERGY EFFICIENCY METRICS AND UNITS

Numerous efforts have been made to harmonise the definitions and standardise testing protocols to measure the efficiency of systems [6], [7], [8], [9]. However, recent reports raised awareness about the gap that can reach up to 20% between the efficiency measured by manufacturers and the actual system performance measured by project developers [10]. Discrepancies in performance were also noticed in a recent coordinated laboratory testing campaign where 11 institutions tested benchmarked cells materials following the same protocols [11]. This proves that comparing systems always involve the consideration of contextual information about how the measurement has been performed and which technical assumptions were made. This requires the understanding of key technical concepts that this section will try to clarify.

### No universal definition of energy efficiency of electrolysers

Different energy efficiency metrics and units are used depending on industrial practices.

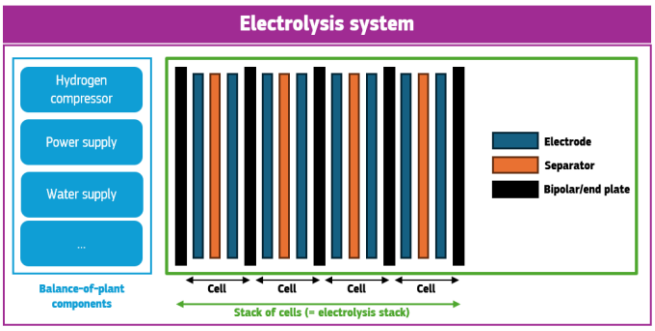
One commonly used metric is the ratio (expressed in percentage (%)) of useful energy output which can be exploited to provide energy services -also known as exergy- to the total energy input. Accordingly, manufacturers also use power efficiency (%), which is not strictly equivalent[2]. Another commonly used metric is the energy consumption to produce one unit of hydrogen, expressed either by mass in kilogram (kg) or volume in cubic meters ($m^3$). Following practices from the gas industry, the use of the Normal cubic meter ($Nm^3$) is widespread although not officially recognised by the International System of Units (SI) unit. Normal cubic meter embeds information not only on the volume (cubic meter), but also on the temperature and pressure of the considered gas (usually 0°C and with a pressure of 1 atm[3], where standard ambient temperature and pressure refers to a gas at 25°C and 1 atm).

Finally, manufacturers do not consistently report on the efficiency testing and measurement scope. Indeed, the efficiency can usually be expressed at cell, stack or system level as illustrated in **Figure 3**. Efficiency at cell or stack level is often directly measured by manufacturers. Efficiency at system level will depend on the efficiency of auxiliary components such as the power supply or hydrogen compressors and will be measured by system integrators or project developers.

[2] As power efficiency is an instantaneous value and can be provided at a specific point in time, where energy efficiency can be performed over a complete operating window as a ratio of what energy has been consumed against the total production of hydrogen.

[3] Note that the ISO 13443 standard reference conditions for natural gas and similar fluids are 288.15 K (15.00 °C) and 101 325 kPa (1 atm).

**Figure 3** - Overview of an electrolysis system

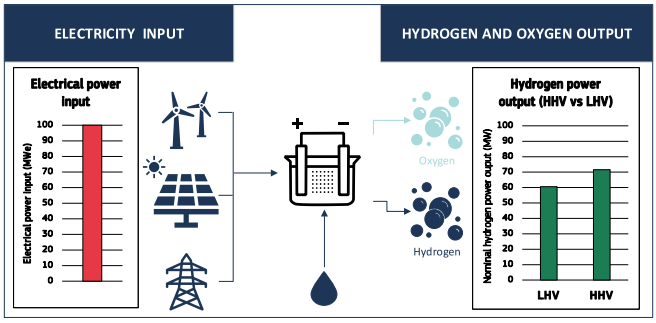



*Source:* Joint Research Centre (2024)

Finally, some manufacturers provide efficiency-related information using either the *input* (electric power) or the *output* (the chemical power contained in the hydrogen produced at a given output rate) of the system. This is a common source of confusion. For example, an electrolyser having a 100 $MW_e$ nominal electrical power input consuming 55 kWh of electricity to produce one kilogram of hydrogen can also be described as a 71.7 MW electrolyser expressed in power output based on hydrogen's higher heating value (HHV).

This is illustrated in **Figure 4** below and further explanations on the higher and lower heating values of hydrogen (HHV vs LHV) are provided in the next sub-section.

**Figure 4** - Illustration of the difference between power expressed as electrical power input or hydrogen power output (Low Heating Value and High Heating Value) of a 100-MWe class electrolyser with a system energy consumption of 55 kWh/kg($H_2$).



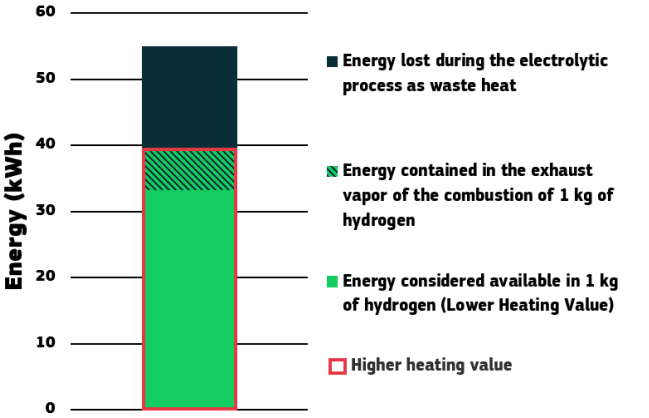

*Source:* Joint Research Centre (2024)

## Higher and lower heating values

The higher or lower heating values of hydrogen are commonly used in electrolyser specifications. The Higher Heating Value (HHV) is the total amount of thermal energy produced by complete combustion of a unit of hydrogen **including the energy of condensation of produced vapors**. The Lower Heating Value (LHV) refers to the energy produced by combustion of **hydrogen without considering the energy contained in the vapor** (e.g. the heat contained in the exhaust gases of an internal combustion engine released into the atmosphere).

The relation between HHV and LHV for a water electrolyser is illustrated in **Figure 5**. For hydrogen, the Lower Heating Value is 33.3 kWh/kg, and its Higher Heating Value is 39.4 kWh/kg.

**Figure 5** - Illustration of energy content of 1 kilogram of hydrogen considering High Heating Value and Low Heating Value produced by electrolysis.




*Source:* Joint Research Centre (2024)

## ENERGY EFFICIENCY OF COMMERCIAL SYSTEMS - DATA REPORTED BY MANUFACTUERS

The reporting of energy efficiency differs among electrolyser manufacturers who use different metrics and/or measurements protocols following conventional industrial practices. The same electrolyser system[4] can be described using different efficiency values. The following table shows efficiency-related specifications directly extracted from various manufacturers specifications and illustrates the variety of units, metrics and information provided.

[4] System here can either refer to a single electrolysis stack or a electrolysis stack and balance-of-plant components.

**Table 1 - Raw extraction on reported efficiency related parameters of commercially available systems from 6 manufacturers (anonymised)**

| Manufacturer | Efficiency-related information provided by the manufacturer |
|---|---|
| **1** | — Nominal power consumption (system level): 17 MW<br>— Hourly hydrogen production: 335 kg<br>— Plant efficiency: 75.5% |
| **2** | — Power consumption (at stack): 3.8 – 4.4 kWh/Nm3 |
| **3** | — Efficiency (DC – at stack level): 82% HHV<br>Power consumption (DC – at stack level): max. 4.3 kWh/$Nm^3$ |
| **4** | — Total stack power consumption: 100 MW<br>— Specific power consumption, stack level: 3.1 kWh/Nm<br>— Specific power consumption, plant level : Depending on heat integration and H2 pressure |
| **5** | — Nominal power consumption: 4.8 kWh/$Nm^3$, beginning of life |
| **6** | — Claims of a electricity consumption reduction of 14% without baseline quantity |

*Source:* Manufacturer websites (collected by the Joint Research Centre in April 2024)

This heterogeneity prevents an informed comparison between systems. First, because the intrinsic system performances are quantified using different metrics and units. Second, because the scope used to evaluate efficiency is not consistent. Finally, since electrolyser degrade over time, efficiency diminishes and changes over the electrolyser lifetime. Beginning-of-life (BoL) efficiency will be higher than end-of-life (EoL) efficiency. However, not all manufacturers will specify both the value at BoL and EoL, nor the degradation rate that would allow project developers to calculate the EoL efficiency. To illustrate the relationships between these values, the **Table 2** below provides a complete technical description of a hypothetic 100-MWe electrolyser using different metrics, units and scopes.

**Table 2 – Description of a hypothetical 100-MWe electrolyser system**

| | |
|---|---|
| **Power class of the electrolyser** | |
| Nominal electrical power input | 100 $MW_e$ |
| Power expressed in hydrogen output (higher heating value at 25°C and 1 atm) | 71.7 $MW_{H2\text{-}HHV}$ |
| Power expressed in hydrogen output (lower heating value at 25°C and 1 atm) | 60.5 $MW_{H2\text{-}LHV}$ |
| Hydrogen production rate at nominal power | 21 700 $Nm^3/h$ or 1 820 kg/h |
| **Electric energy consumption at system level** | |
| Electric energy consumption per unit of mass (kg of hydrogen) | 55 $kWh_{system}/kg$ |
| Electric energy consumption per unit of volume ($m^3$ of hydrogen at 0°C and 1 atm[5])[6] | 4.61 $kWh_{system}/Nm^3$ |
| Electric energy consumption per unit of volume ($m^3$ of hydrogen at 0°C and 100 000 kPa) | 4.88 $kWh_{system}/m^3$ |
| **Electric energy consumption at stack level** | |
| Electric energy consumption per unit of mass (kg of hydrogen) | 49 $kWh_{stack}/kg$ |
| Electric energy consumption per unit of volume ($m^3$ of hydrogen at 0°C and 1 atm) | 3.98 $kWh_{stack}/Nm^3$ |
| Electric energy consumption per unit of volume ($m^3$ of hydrogen at 0°C and 1 atm) | 4.35 $kWh_{stack}/m^3$ |
| **Energy efficiency at system level** | |
| Energy efficiency at system level expressed in percentage based on the higher heating value of hydrogen | 71.7 $\%_{HHV}$ |
| Energy efficiency at system level expressed in percentage based on the lower heating value of hydrogen | 60.5 $\%_{LHV}$ |
| **Energy efficiency at stack level** | |
| Energy efficiency at stack level expressed in percentage based on the higher heating value of hydrogen | 80.4 $\%_{HHV}$ |
| Energy efficiency at stack level expressed in percentage based on the lower heating value of hydrogen | 68 $\%_{LHV}$ |

*Source:* Joint Research Centre (2024). Note: the density of hydrogen is considered 0.08871 kg/$m^3$ at 0°C and 0.1 MPa.

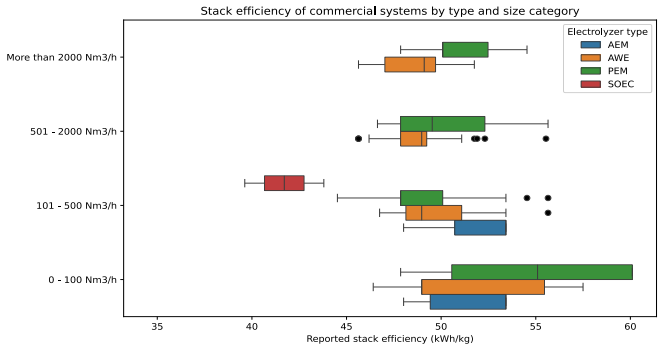
[5] 1 atm = 101 325 kPa.

[6] These conditions (0°C and 1 atm) refers to the conditions used as reference for the non-SI unit "Normal cubic meters (Nm3)" which is commonly used in the compressed gas industry.

## Reported energy efficiency of commercial systems

**Figure 6** provides a statistical overview of electrolyser stacks efficiency as provided by manufacturers. Large uncertainty remains since manufacturers do not provide sufficient information about the measurement and testing conditions.

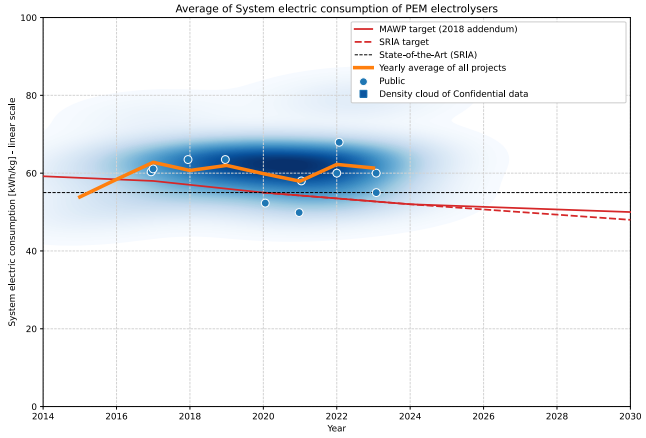
**Figure 6** - Reported stack efficiency of commercial systems expressed in kWh/kg of hydrogen by type of electrolysers (alkaline, anion-exchange membrane, proton exchange membrane, solid-oxide electrolysers) and size.




*Source:* Joint Research Centre analysis based on public system specifications collected by Rystad Energy (2024)..

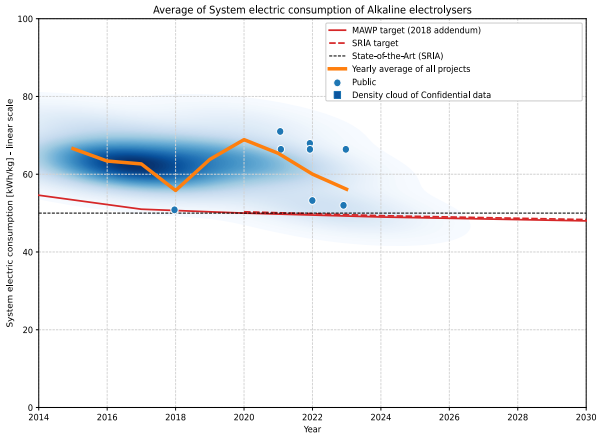
The two figures below show the **energy consumption** of electrolyser projects funded by the Clean Hydrogen Joint Undertaking from 2015 to 2023. **Figure 7** covers proton exchange membrane electrolysers and **Figure 8** covers alkaline electrolysers.

**Figure 7** – System level energy consumption of PEM electrolysers deployed by the Clean Hydrogen Joint Undertaking projects




*Source:* Joint Research Centre analysis based on data provided by the Clean Hydrogen Joint Undertaking (2024)

**Figure 8** - System level energy consumption of alkaline electrolysers in the projects of the Clean Hydrogen Joint Undertaking projects

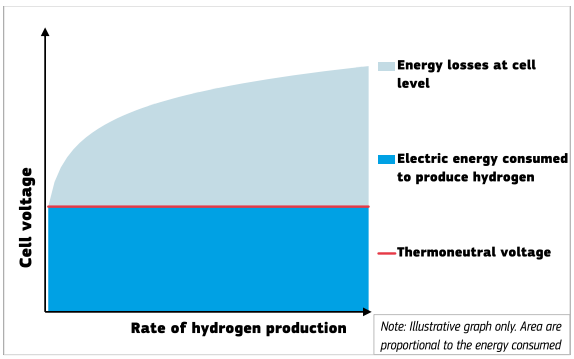



*Source:* Joint Research Centre analysis based on data provided by the Clean Hydrogen Joint Undertaking (2024)

## INFLUENCE OF VARIABLE LOAD ON ENERGY EFFICIENCY

At cell and stack level (see **Figure 3** for the breakdown), energy losses reach a minimum when the cell or stack operate at a specific voltage called the thermo-neutral voltage (around 1.48 V at 25°C and 100 kPa). This is the voltage where the exact quantity of energy required to split a molecule of liquid water is provided. At this operating voltage, the efficiency reaches a maximum, but the hydrogen production rate is also at its lowest. To increase the production rate of hydrogen, more electric power is needed. When increasing the operating voltage, the energy efficiency at cell level decreases as more energy is lost during the process as illustrated in **Figure 9**. This is a trade-off that project developers arbitrarily set based on the project use case to maximise the production of hydrogen at the lowest cost.

**Figure 9** - Simplified illustration of energy losses at cell level when the flow of produced hydrogen increases.

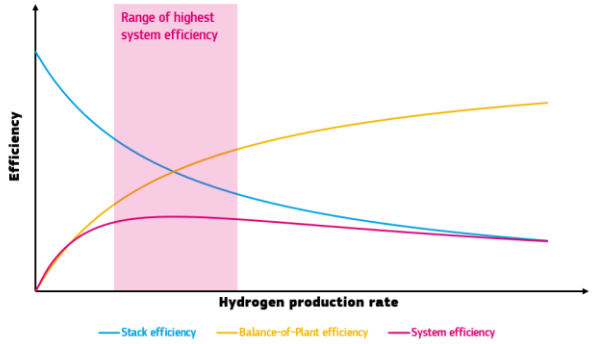



*Source*: Joint Research Centre (2024)

At system level, the efficiency also depends on the efficiency of the balance-of-plant components. They usually follow a positive correlation with the operating power and are usually more efficient when they operate at a higher hydrogen production rate.

The combination of the electrolyser stack and balance-of-plant component efficiencies gives a power range where the system reaches its highest efficiency point. This is illustrated in **Figure 10**. Project developers will consider this range and the overall impact on the LCoH as illustrated in **Figure 2**. This means that systems fed with variable electricity sources or that need to power a variable load will not necessarily be able to operate at their highest efficiency point. Compliance with the temporal correlation as in the *Delegated Act on a methodology for renewable fuels on non-biological origin* will influence the capacity of electrolysers to operate within power range that maximize the whole system efficiency.

**Figure 10** - Illustration of efficiencies variation depending on the production rate of hydrogen in a theoretical 100 MWe electrolyser system including the stacks and the balance of the plant efficiencies




*Source:* Joint Research Centre based on [12] (2024)

## IMPROVEMENT OF ENERGY EFFICIENCY AND REMAINING CHALLENGES

At cell and stack level, the development of more advanced materials (e.g. membranes, separators or catalytic materials) can reduce ohmic losses at higher current density ultimately reducing the amount of energy required to produce hydrogen. This also involves the development of innovative fabrication methods that reduce impurities and improve the homogeneity of catalytic ink when sprayed on the membrane, allowing for better electric conductivity [13], [14]. The use of more advanced –and potentially more costly materials can also increase the cost of the system, thus increasing the LCoH in specific operating conditions. Extensive research efforts are made to develop new fabrication methods to reduce the use of costly material while reaching the same performance. Research efforts focussing on better understanding nano-scale phenomenon such as the generation of micro and nano-bubbles would allow for the development of more efficient designs [15].

At system level, improving the integration between the stack and balance-of-plant components can directly impact the overall efficiency. Although according to some estimates, the balance-of-plant for large-scale systems only consumes around 2 % of the system power, this can amount to 10-20 % for smaller systems [16]. Additionally, better integration of an electrolyser within an industrial setting - such as its coupling with an external source of heat - can reduce the electric energy consumption to produce hydrogen. High-temperature electrolysers relying on solid-oxide or proton conducting ceramic technologies can be used in co-generation applications, where waste heat from another high-temperature process can be used to provide the energy required for the electrolysis process [17]. Finally, the use of multiple technologies in a same project can leverage technology specific advantages to improve the overall plant efficiency. For example, the reduction of the frequency of standby and shutdown events of a specific section of alkaline electrolysers ensuring the baseload hydrogen production while PEM systems ensure the peak loads can minimize operational losses [18].

## CONCLUSIONS

There is no universally accepted definition of energy efficiency and, because of the variety of industrial use-cases, it is unlikely to appear soon. To reduce ambiguity when providing information about efficiency, it is necessary to assess the boundary configurations and the metrics used, as well as the operating conditions under which the efficiency is measured. Developing and using better materials, components or system designs are a reliable way to improve efficiency. There are trade-offs on the cost of hydrogen production such as the number of operating hours of electrolysers and correlation with renewable power.

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Julien.Bolard@ec.europa.eu