Agora Industry

Agora Energiewende

Levelised cost of hydrogen

Making the application of the LCOH concept more consistent and more useful

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WRITTEN BY

Agora Industry
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin
T +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-industry.org
info@agora-industrie.de

PROJECT MANAGEMENT

Matthias Deutsch
matthias.deutsch@agora-energiewende.de
Mauricio Belaunde
mauricio.belaunde@agora-energiewende.de

AUTHORS

Florian Nigbur,
Martin Robinius,
Patrick Wienert
(all Umlaut);
Matthias Deutsch
(Agora Energiewende)

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Preface

Dear reader,

The EU is raising its ambition for renewables-based hydrogen, and the regulatory framework required is taking shape. A long pipeline of green hydrogen projects awaiting final investment decisions can finally be opened. Meanwhile, China keeps increasing its cost advantage in electrolyser manufacturing, and the US Inflation Reduction Act, which includes a highly competitive package of incentives for hydrogen production in North America, has significantly increased the pressure on the EU. Against this background, the EU is intensifying efforts to develop production support schemes for renewables-based hydrogen in the context of the new Hydrogen Bank it has announced.

Numerous studies are now published every month containing estimates for the levelised cost of hydrogen (LCOH) production. They provide policymakers with the techno-economic basis on which to make their decisions and to design appropriate support schemes. But are the costs calculated consistently across these studies? How are system boundaries drawn? Which cost drivers are important, and which can be omitted? We address these questions in this study, commissioned by Agora Industry and conducted by Umlaut.

The study sheds light on why the LCOH differs both between individual studies and between studies and real-world projects and provides recommendations for improving the application of the concept based on sensible simplifications that enable LCOH comparisons. We hope that our report can in this way enhance future studies. Before delving into the technical considerations, we assess the need for public support for renewables-based hydrogen in the first place, highlighting important considerations regarding the integration of renewables-based hydrogen production into the energy system.

Yours, Frank Peter
Director, Agora Industry

Key conclusions:

1 **Renewables-based hydrogen produced via electrolysis will be crucial in making several no-regret applications climate-neutral.** As long as green hydrogen requires public support to be economically competitive, policymakers need transparent estimates of the levelised cost of hydrogen to guide them in designing support schemes. Key drivers are the assumed electricity costs, the number of full-load hours, the cost of capital and the investment costs for electrolysers.

2 **Optimal energy system integration leads to fewer full-load hours, increasing the proportion of capital expenditure in the overall cost of green hydrogen production.** For example, most widely-cited German energy scenarios expect electrolysers to run ~3 000 full-load hours in 2030, corresponding to a ~34 percent utilisation rate, which is expected to gradually increase up to 2045. The lower the number of full-load hours, the greater the proportional significance of electrolysis investment costs becomes.

3 **High-level guidance for policymakers based on simplified levelised cost calculations tends to underestimate real-world project implementation costs and needs to be clear about these limitations.** The price for electrolyser systems in the EU today is still generally high (significantly above 1 000 Euro/kW), although it is projected to fall considerably in the future.

4 **A pragmatic approach to cost calculations should focus on detailed fundamental cost drivers within generalised system boundaries while leaving out project- and site-specific considerations.** Other potentially important but non-fundamental cost drivers, such as project financing or tax credits, should generally not be factored in unless explicitly included. While simplified cost estimates are appropriate for high-level studies, their practicality depends on a sufficient degree of consistency and transparency regarding system boundaries and cost drivers.

Contents

Conclusions by Agora Industry

1. Making no-regret applications climate-neutral with renewable hydrogen

Climate neutrality can be achieved via direct electrification in most cases, but some applications require molecules rather than electrons due to their specific chemical properties, energy density or storability. Examples of such applications include industrial non-energy use of hydrogen in steelmaking and for chemicals, as well as long-haul aviation and shipping. Additionally, renewable hydrogen will have a role backing up renewable energy in the power and district heating sectors. These *no-regret* priority applications feature in global and European energy system scenarios.[1]

Producing green hydrogen using electrolysis as the most widespread core technology will require many new electrolysers and significant amounts of renewable electricity.[2] This is confirmed by a range of recent publications that have provided estimates of the levelised cost of hydrogen (LCOH) based on electrolysis technology. The levelised cost of hydrogen strongly depends on the assumed electricity costs, the number of full-load hours (FLHs), the cost of capital and the investment costs for electrolysers. As long as renewable hydrogen requires policy support to become economically competitive, policymakers will need transparent LCOH estimates in order to design appropriate support schemes.

1 Agora Energiewende, Agora Industry (2021): 12 Insights on Hydrogen, https://www.agora-energiewende.de/en/publications/12-insights-on-hydrogen-publication/

2 Electrolysis is at the centre of the discussion. Technically, other options are also conceivable for the future, but they still have lower technology readiness. (PTJ 2021: Expertenempfehlung Forschungsnetzwerk Wasserstoff)

2. Integrating electrolysers into energy systems with fewer full-load hours

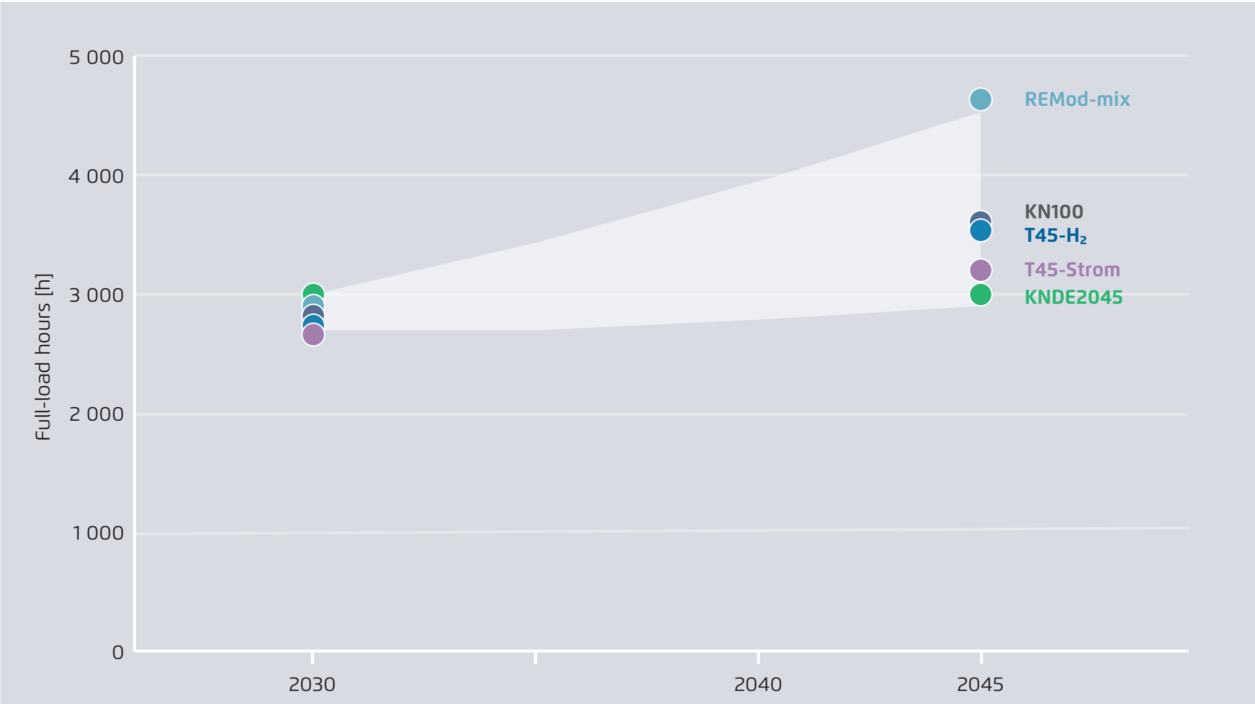
From a project development perspective, the basic economics would suggest that an electrolyser should run a sufficiently high number of hours at sufficiently low electricity prices to produce hydrogen competitively.[3] The distribution of hours with low electricity prices over a year will determine when it makes economic sense not to increase the number of operating hours because electricity prices are too high.

From an energy system perspective, electrolysers should contribute to power system flexibility. With increasing feed-in from variable renewable energy and a decline in conventional power plant capacity, new flexibility options are required to ensure a balance between supply and demand. On the demand side, electromobility, heat generators and electrolysers can and must be operated in a manner that supports the integration of wind and solar power into the overall system. The electrolysers therefore need to produce hydrogen during periods of high renewable generation when electricity cannot be used or transported elsewhere.[4] Depending on the availability and portfolio of renewable PPAs procured to cover the electrolyser's power demand, the achievable number of FLHs for grid-connected electrolysers complying with the (European) regulations governing renewable power procurement may also be limited.

3 Agora Energiewende and Guidehouse (2021): Making renewable hydrogen cost-competitive: Policy instruments for supporting green H_2, https://www.agora-energiewende.de/en/publications/making-renewable-hydrogen-cost-competitive/

4 See e.g. Agora Energiewende (2022): Climate-neutral power system 2035. How the German power sector can become climate-neutral by 2035, https://www.agora-energiewende.de/en/publications/climate-neutral-power-system-2035/

Full-load hours of domestic electrolysis in energy system scenarios for Germany — Figure A



Agora Energiewende (2023). Scenarios: KNDE2045 (Agora Energiewende, SKN 2021); KN100 (dena 2021); REMod-mix (Ariadne 2021); T45 (BMWK 2022), see footnote 5 for references

For example, most widely-cited German energy system scenarios[5] predict around 3000 FLHs for 2030, gradually increasing up to 2045 (see Figure A). 3000 FLHs corresponds to a utilisation rate of around 34 percent.

Unrelated to the issue of energy system integration, there is a different potential application involving directly connected electrolysers powered by solar PV only, which would also yield a relatively low number of FLHs, at least in Europe.[6]

Both cases mentioned above have similar implications for electrolysis project economics: the lower the number of FLHs, the greater the proportional significance of electrolysis investment costs.

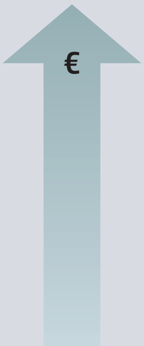
3. A tendency to underestimate real-world project implementation costs

High-level guidance for policymakers is typically based on simplified levelised cost estimates, which have their limitations. Anecdotal evidence suggests

5 Agora/Stiftung Klima (2021): Towards a Climate-Neutral Germany by 2045, https://www.agora-energiewende.de/en/publications/towards-a-climate-neutral-germany-2045-executive-summary/ ; Ariadne (2021): REMod-mix. https://ariadneprojekt.de/ and personal communication with Fraunhofer-ISE; BMWK (2022): Long-term Scenarios for the Transformation of the Energy System in Germany (Long-term Scenarios III), T45 scenarios, https://www.langfristszenarien.de/ ; dena (2021): Aufbruch Klimaneutralität, https://www.dena.de/newsroom/publikationsdetailansicht/pub/abschlussbericht-dena-leitstudie-aufbruch-klimaneutralitaet/

6 Even after oversizing the PV system relative to the electrolyser. See e.g. Vartiainen et al (2021): True Cost of Solar Hydrogen. https://onlinelibrary.wiley.com/doi/10.1002/solr.202100487.

From simple levelised cost of hydrogen to hydrogen prices — Figure B



Metric	Users	Use	Data sources
Hydrogen price	Sellers and buyers	Market transactions	Commercial
Realised project cost*	Project developers, investors	Making site-specific projects within regional context bankable**	Commercial, confidential
Simple levelised cost of hydrogen	Policy makers	High-level analyses at pre-feasibility level	Publicly accessible, traceable

Agora Industry (2023). *Final electrolysis system CAPEX can be 20–50% higher, according to anecdotal evidence. **Including further cost determinants such as construction duration, financing structure, taxes, royalties, concession payments, supply chain risks, local content requirements. Actual projects will also consider income streams such as sales of by-products (electricity, oxygen, heat) and policy support instruments for CAPEX/OPEX.

that electrolyser *prices* actually paid by project developers at the time of this publication in early 2023 are still generally high, at significantly above 1000 Euro/kW, and considerably higher than *cost* values found in the literature.

Any public discussion on electrolysis should therefore be conscious of different levels of cost abstraction, as illustrated in Figure B:

→ Estimates of the **simple levelised cost of hydrogen** abound, presented in multiple high-level studies, and are important for enabling a public, high-level policy discussion. Such high-level guidance tends to underestimate real-world project implementation costs, and should be clear about its limitations.
→ The **realised project costs** rely on commercial data and may include a range of further cost components typically not covered in the simple estimates, such as project-specific infrastructure requirements, taxes, royalties, concession payments and local content requirements. Consequently, they tend to be higher than simple, high-level LCOH estimates.
→ **Hydrogen prices**, finally, include profit margins, and will depend on supply and demand dynamics and the emergence of future hydrogen market segments and will likely be higher than realised project costs.[7]

4. Focusing on fundamental cost drivers and leaving out project- and site-specific factors

A simple pragmatic approach to cost calculations should focus on fundamental cost drivers within generalised system boundaries. The analysis below separates such drivers from project- and site-specific considerations and other minor factors and estimates their impact on the overall LCOH, providing recommendations for how best to include them in the

7 See e.g. Fh-ISI et al (2021): Importing hydrogen and hydrogen derivatives: from costs to prices, HYPAT Working Paper, https://hypat.de/hypat-wAssets/docs/new/publications/HyPAT-Working-Paper-01-2021-ENG-final.pdf

calculation of the LCOH. Bearing in mind the necessary simplifications required for a simple, high-level LCOH calculation, such an approach would benefit from an increased level of consistency and transparency with regard to system boundaries and the cost drivers considered. This is particularly important in view of the expected competition with regions currently benefitting from high production subsidies, or the competition between electrolysers from OECD countries and those from other countries with potentially lower costs, in particular China.[8]

While there is evidence that Chinese electrolysers are generally much cheaper, there seems to be less agreement on whether those cost estimates include all the major cost drivers needed to make a meaningful comparison, for example, the cost of inverters or of Engineering, Procurement and Construction (EPC).[9]

8 Agora Energiewende (2019): EU-wide innovation support is key to the success of electrolysis manufacturing in Europe. https://www.agora-energiewende.de/en/blog/eu-wide-innovation-support-is-key-to-the-success-of-electrolysis-manufacturing-in-europe/; Bloomberg (2022): China Leading Race to Make Technology Vital for Green Hydrogen. https://www.bloomberg.com/news/articles/2022-09-21/china-leading-race-to-make-technology-vital-for-green-hydrogen

9 IEA (2021): Global hydrogen review 2021. https://iea.blob.core.windows.net/assets/3a2ed84c-9ea0-458c-9421-d166a9510bc0/GlobalHydrogenReview2021.pdf#page=120

Executive summary

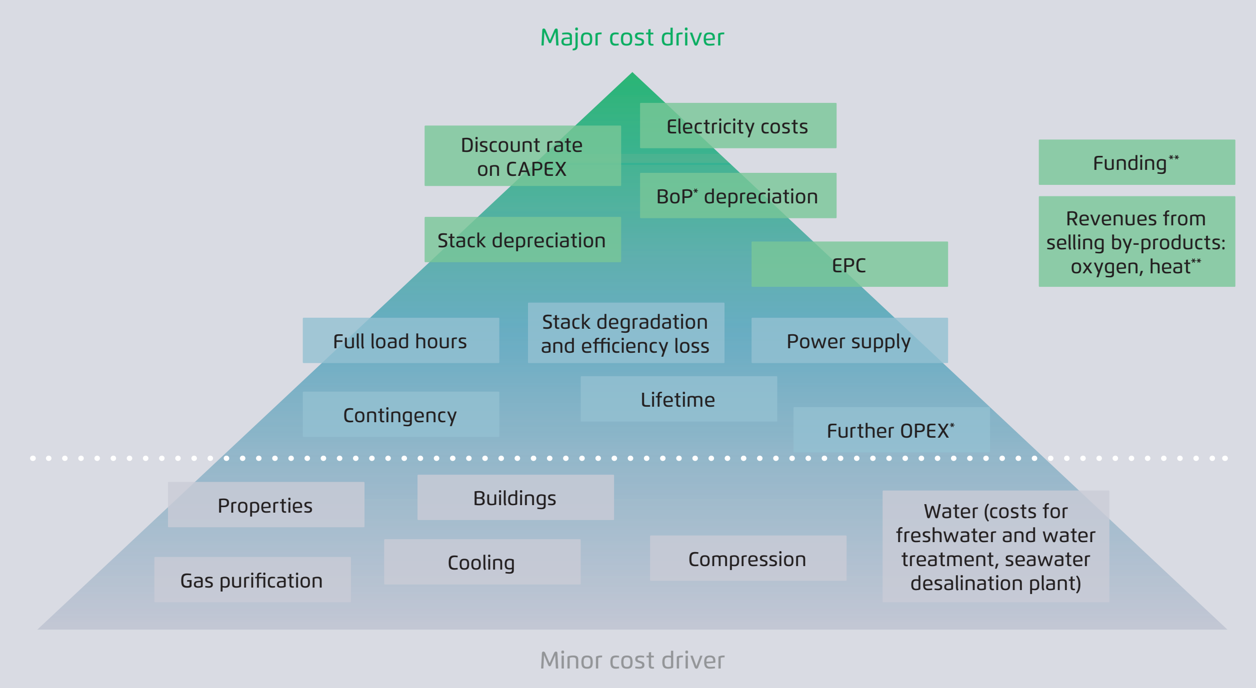
High-level studies of the hydrogen sector can have a significant influence on decision makers, who obtain some of their information from them. This applies not only to decision makers in companies, which in many cases perform their own calculations or seek external advice, but also and in particular to policymakers, whose decisions are especially important for the urgently needed ramp-up of the hydrogen economy. The so-called levelised cost of hydrogen (LCOH) is an important measure often used by decision-makers to assess the economic viability of hydrogen in Power-to-X-projects.

It is therefore particularly important to ensure that calculations of the levelised cost of hydrogen (LCOH) are performed consistently, i.e. using the same system boundaries and cost drivers. If the selection of system boundaries is unclear in different studies, policymakers may draw the wrong conclusions. For this reason, Agora Industry commissioned umlaut to investigate the system boundaries and cost drivers used in high-level studies in calculating the levelised cost of hydrogen.

One of the findings was that the way in which system boundaries are dealt with in high-level studies varies, and that consequently a sufficiently transparent description of the LCOH calculation in terms of system boundaries and cost drivers is not given. In addition, there is often no or very little information on the factors investigated, such as on-site storage, pressure, water, or purity. The non-inclusion of these

Result of meta-study on LCOH: Classification of cost drivers

Figure 1



Umlaut (2023). * Generic term. BoP: There is no standard definition of BoP, but it typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers. ** Despite their importance in real projects, the revenues from the sale of oxygen and heat as well as funding are not included in the consideration as they are not cost components.

factors is not necessarily a sign of poor-quality research. Some cost drivers have a negligible impact on LCOH and can therefore readily be omitted, while others are very significant and must be taken into account. Further investigations were therefore carried out in which cost drivers were classified according to their importance. While the discount rate, electricity costs, the costs for engineering, procurement, and construction (EPC), the costs of the stack, the expected lifetime and the balance of plant (BoP) are among the major cost drivers, the costs of cooling, gas purification and water treatment are classified as minor cost drivers. The classification of cost drivers is shown in Figure 1.

In order to ensure consistent LCOH calculation in future studies, recommendations are made here for a pragmatic approach to calculation which can provide orientation in the preparation of studies. These recommendations were validated by external experts in three workshops. The pragmatic calculation approach is aimed at researchers who, in contrast to project developers, can afford to make some simplifications. The recommendations include that revenues that can be recovered from the sale of the by-products oxygen and waste-heat should be excluded from the LCOH, as should funding, since both are strongly contingent on individual project setups. For the calculation of the LCOH, the total energy demand of the electrolyser – including auxiliary power – should be considered. The costs for buildings and foundations must also be included in the calculation. However, the costs for land should not be considered. It should be assumed that the necessary connections to the electrical and water grids are already in place, and that the electrolyser can be connected directly. Infrastructure for the transport of hydrogen as well as for storage should not be considered. The hydrogen is assumed to be produced with a quality of 5.0 and available at a reference pressure of 30 bar. In case of lower pressures, conversion to the reference pressure is recommended. The costs for stack replacement should be considered as part of the capital expenditures (CAPEX). Stack degradation should also be taken into account, e.g. by assuming an average specific energy requirement over a single-period calculation. The rationale for inclusion of all influencing factors on the LCOH is described in detail in this report and also in summary in Table 1. A calculation tool is also included enabling simple calculations and providing a clear illustration of the influence of different cost drivers.

Summary of the recommendations for a pragmatic approach to calculating LCOH — Table 1

Parameter	Notes
Electrolyser CAPEX	Account for CAPEX scaling influence.
Discount rate	Also known as Weighted Average Cost of Capital (WACC).
Electricity price	Should include all charges.
Electrolyser efficiency	Specific energy consumption including auxiliary power [kWh/kgH_2].
Electrolyser system lifetime	Major cost driver due to distribution of CAPEX.
Stack lifetime & replacement	Costs for stack replacement to be included in the CAPEX.
Stack degradation	Considered through average specific energy consumption.
Engineering, Procurement, Construction	Contains usually detailed planning and control, purchasing, execution of construction, installation work, and commissioning.
Buildings	Reflect cost difference between greenfield / brownfield.
Balance of Plant (BoP)	BoP typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers.
OPEX	Typically in the range of 1.5%–5% of CAPEX.
Compression	Consider compression costs for system output below reference pressure.
Hydrogen quality	Identified as a minor cost driver. Nevertheless, it is recommended to calculate with a 5.0 quality to ensure that there are no technical issues.
Water supply	Costs are to be considered if a seawater desalination plant is required.
Electrical grid	Assumption of an existing grid.
Contingency	Not taken into account in most studies.
Funding	Funding programmes strongly influenced by political conditions and vary over time.
Properties	Vary significantly between countries as well as urban and rural areas.
Hydrogen transport & storage	Multiplicity of further possible applications.
By-product revenues	Omit revenues from by-products (waste-heat, oxygen).

to be considered — individual decision — not to be considered

Umlaut (2023)

Introduction

An enormous expansion of hydrogen production capacities, especially for green hydrogen, is required if the ambitious national, European, and international targets for climate protection are to be met. In order to produce hydrogen while emitting almost no greenhouse gases, electrolysers powered by renewable electric energy are needed. While alkaline and polymer electrolyte membrane (PEM) electrolysers have already been successfully tested under operational conditions in high numbers, solid oxide electrolysers are as yet at lower technology readiness levels.

The steep ramp-up of hydrogen production required is dependent on political support and on supportive framework conditions. Political decision makers can influence the hydrogen ramp-up through legislation and associated funding programmes. High-level studies often serve as a source of information and orientation. These studies investigate and forecast the levelised cost of hydrogen (LCOH), often breaking this down for different regions and sources of hydrogen (renewable, fossil-based with and without carbon capture etc.). Decision makers use the LCOH calculated in such studies as a basis for their decisions.

However, the term 'levelised cost of hydrogen' is not always used consistently, resulting in differences between the analyses made in different studies. Cost components that can account for a significant share of the LCOH are sometimes not consistently included, and information on the calculation process is sometimes not presented transparently. One example of a cost component not consistently included among published LCOH studies is engineering, procurement, and construction (EPC) costs. Inconsistent use of the term LCOH, or inconsistent system boundaries, can lead to policy decisions being made based on incorrect assumptions.

The aim of this report is therefore to show how differences can arise in the calculation of LCOH and to raise awareness of which cost components are of greater and which are of lesser importance, and to show why the LCOH achieved in real-world projects can differ significantly from that estimated in high-level studies. For this purpose, a number of high-level reports were first analysed in a meta-study with respect to cost drivers, system boundaries and underlying assumptions. Subsequently, a pragmatic and standardised approach was developed along with recommendations for the calculation of LCOH. These can serve to guide and support the authors of future studies. The pragmatic approach was discussed, modified, and validated in three workshops conducted with external experts in the field. The first workshop involved researchers;, the second, experts from international energy organisations; and the third, electrolyser manufacturers and operators. In addition, an Excel-based calculation tool was created, which can be downloaded in addition to this report. It enables simple LCOH calculations as well as an analysis of the impact of some of the cost components, depicted in diagrams.

1 Meta-study focusing on system boundaries and cost drivers with respect to LCOH

The following studies were examined to acquire an understanding of the system boundaries and cost drivers underlying the LCOH calculations: IEA (2021), IRENA (2020), BNEF (2022), GFC (2021), Prognos (2020), ISPT (2022), and DNV (2022). The results are presented here firstly for the different system boundaries. This is followed by a classification of cost drivers, for which further literature has also been reviewed.

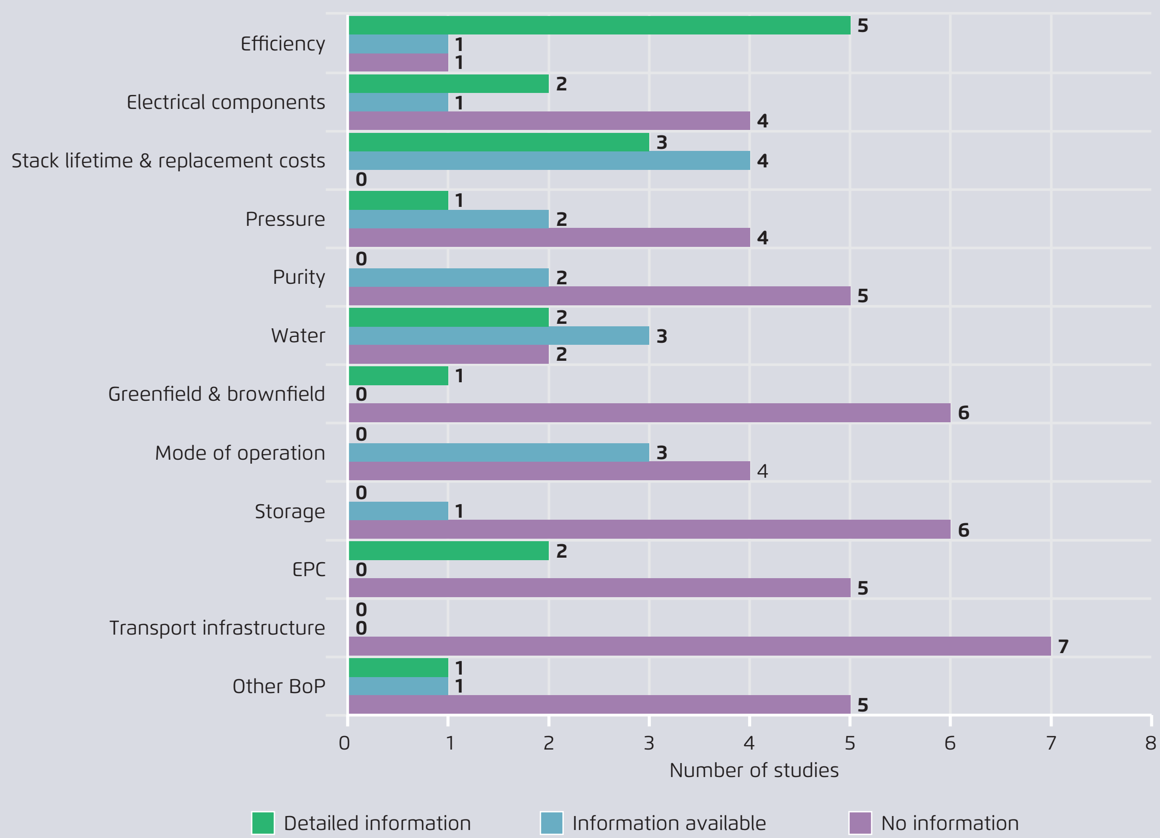
1.1 System boundaries and cost drivers

In analysing the studies, the first step was to examine which system boundaries were drawn. The choice of system boundaries significantly determines the LCOH. For example, the calculation of the LCOH may or may not include costs for land, buildings, and EPC. The approach may vary from study to study, and often the selection of system boundaries or the exclusion of cost drivers is not transparently presented. In the bulk of the literature, no relationship is drawn between the application of a system boundary and costs. Figure 2 shows the results of the evaluation. The factors briefly described below are included in the evaluation.

1. **Efficiency:** Is the efficiency or the specific energy demand of the system given, and is its influence on the LCOH described properly? For example, is the total auxiliary consumption taken into account in the specific energy demand, and are reference points specified (lower heating value and higher heating value)?
2. **Electrical components:** Are power electronics (especially transformers and rectifiers) completely or partially included?
3. **Stack lifetime and replacement costs:** Is the lifetime mentioned? Is stack degradation considered, and are costs for stack replacement given?
4. **Pressure:** Is the pressure in the electrolyser and at the hydrogen outlet specified? Is a distinction made between internal and external pressure, and is the influence on the LCOH analysed?
5. **Purity:** Is the hydrogen gas quality specified and is its influence on costs given?
6. **Water:** Is the type of water supply and any necessary water treatment specified (seawater, freshwater)?
7. **Greenfield or brownfield:** Has a distinction been made between new facilities on previously undeveloped land and projects on land with existing facilities? The brownfield approach can result in lower costs due to the use of existing infrastructure, but can also result in higher costs if commissioning is done in parallel with plant operation.
8. **Mode of operation:** Is any information given on whether the electrolyser is operated at nominal or partial load, whether it is an island network, and whether it is operated flexibly?
9. **Storage:** Is on-site storage considered, and if so, what is the storage capacity taken into account?
10. **Engineering, procurement, and construction:** Is EPC included in the LCOH? And if so, what value is assumed?
11. **Transport infrastructure:** Are costs for on-site transport infrastructure considered, or are connections already available at the electrolyser?
12. **Other Balance of Plant (BoP):** Are costs for other balance of plant components or contingencies specified? BoP typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers. Hence, other BoP means everything that is not already included in 2. electrical components (above).

Figure 2 shows the results of the literature evaluation with respect to the factors mentioned above. This shows that studies differ regarding the LCOH evaluation criteria they apply, but also that some criteria are dealt with in detail, while others are not dealt with or are not presented transparently. Sufficient information is provided in almost every study on efficiency or specific energy requirements, while electrical components, such as power electronics, are generally not discussed in detail. Information is often given on stack lifetimes; however, whether degradation of the stack was considered in the LCOH calculation, or how high the costs for a stack replacement are, is less frequently reported. Pressure, and especially any correlation between pressure and cost, is rarely reported on. The same applies to hydrogen quality and to the distinction between salt water and fresh water and corresponding water treatment. The term greenfield is used from time to time in the literature analysed. However, none of the studies makes a distinction between the greenfield and brownfield approaches, and thus potential differences in costs are not addressed. Almost all the literature reviewed fails to address on-site storage and its costs in relation to the LCOH calculation. With respect to EPC, there is often no detailed information given. However, in some cases, such as ISPT (2022), it is discussed in detail. The on-site transport structure and

Comparison of system boundaries and other cost drivers in high-level studies on LCOH* — Figure 2



Agora Energiewende (2023). * The evaluation is based on the following studies: IEA 2021, IRENA 2020, BNEF 2022, GFC 2021, Prognos 2020, ISPT 2022, and DNV 2022 its influence on costs is not discussed in the studies examined. In some cases, other BoP elements and their associated costs were discussed.

In general, the way high-level studies deal with system boundaries varies considerably, and a transparent description of the role of system boundaries and cost factors in the calculation of the LCOH is often not given. In addition, there is often no or very little information provided on the factors taken into account, such as on-site storage, pressure, water, or purity. The non-inclusion of these factors is not necessarily a sign of poor-quality research. It is quite possible that some factors have a large impact while that of others is relatively small. This will be clarified in the analysis of cost drivers that follows, which distinguishes between major and minor cost drivers.

1.2 Classification of cost drivers

In addition to the studies mentioned above, Hydrogen Europe (2021), NREL (2019), Saba, S.M. (2021) and Bertuccioli, L. et al. were all reviewed in respect of the cost drivers they included. In all of these studies, the cost drivers included were identified and then classified. The studies quantify both the cost drivers and/or their shares in the total costs. When comparing them, it is noticeable that different terms are used to describe the cost structure and that it is not always obvious precisely which costs are included. An important example is the term BoP. There is no precise definition of what exactly is meant by this or of what should always be included in the term and what should not. Tsotridis, G., Pilenga, A. (2018) provides a clear definition of terminology for water electrolysis. However, BoP is not defined there either. An illustration of the differing application of the term is provided by comparing the studies IRENA (2020) and ISPT (2022). IRENA (2020) first roughly describes the cost structure of an electrolysis system and divides it into "stack" and "balance of plant". Subsequently, the costs for the BoP are subdivided in more detail into "power supply", "deionised water circulation", "hydrogen processing", and "cooling". In ISPT (2022), on the other hand, the so-called "direct costs" are divided into "balance of plants", "civil, structural, and architectural works", "utilities and process automation", "power supply and electronics", and "stacks". In this second case, then, the power supply is not assumed to be part of the BoP. In most of the studies, what exactly is included in the BoP is not specified. Similarly differing and inconsistent applications of terminology can be demonstrated for a number of other cost drivers, which makes a precise evaluation of cost drivers difficult.

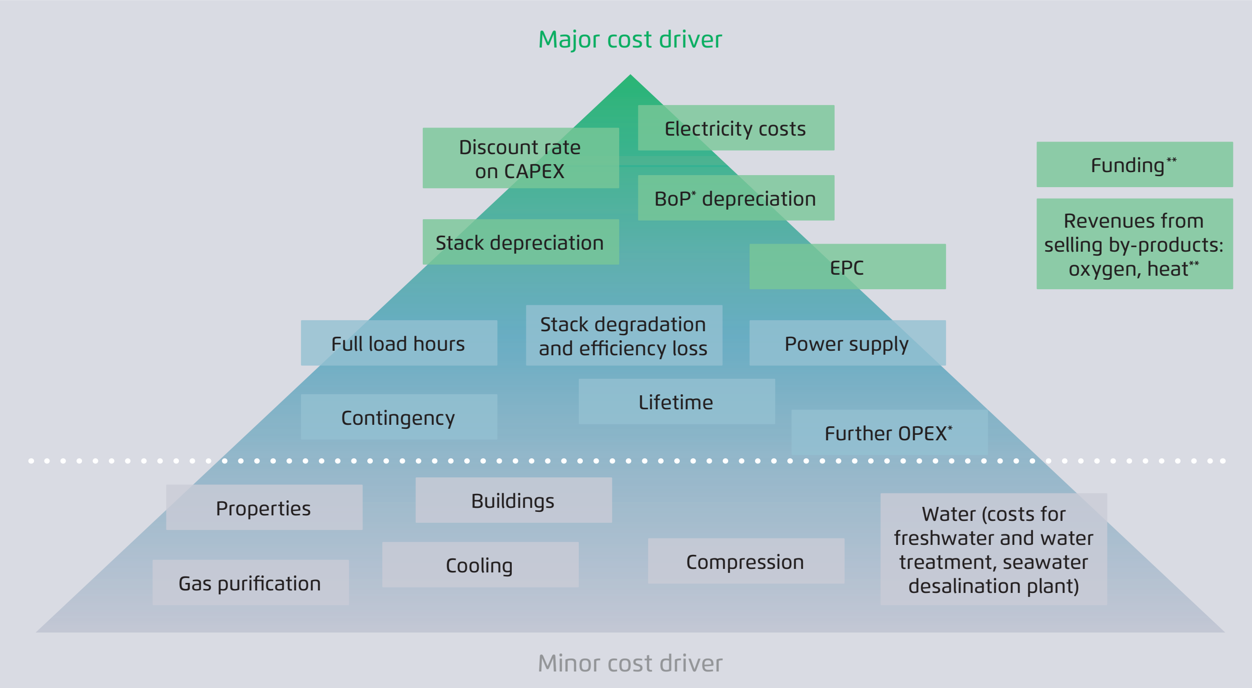
Figure 3 shows the classification of cost drivers derived from the meta-study. The identified cost drivers are plotted on a triangle, where the height at which the respective cost driver is positioned in the triangle reflects their impact. Cost drivers in the upper part of the triangle are referred to as major cost drivers and those in the lower part of the triangle are minor cost drivers. Cost reducing factors such as public funding and potential by-product revenues are shown outside the cost driver pyramid. In the triangle, the areas are separated by a dashed line to indicate a rough division of the cost drivers into minor and major. An exact arrangement or order of the cost drivers cannot be created, as the studies show too much variation. Moreover, a great deal depends on the choice of parameters. For example, in a scenario with a high electricity price, the costs for the stack or for power supply are less significant, and vice versa. However, the classification presented here is a qualitative presentation of results which provides useful information for the development of a pragmatic approach for calculating LCOH and can partly explain the choice of system boundaries in the studies. In what follows, the various cost drivers mentioned in the triangle are described briefly. A more detailed discussion follows in the next section, where a pragmatic and standardised approach for LCOH calculation is developed.

Among the biggest cost drivers are the **electricity costs** and the **discount rate**, to which we will return later. The **stack** is a major cost driver as well. Some of the literature studied delivers detailed information on the cost structure of the stack, e.g. IRENA (2020). In this study, the stack costs are broken down into the components "bipolar plates", "porous transport layer", "small parts (sealing, frames)", "stack assembly and end plates", and "catalyst coated membrane", and the latter is further subdivided into "manufacturing", "PFSA membrane" (perfluorosulfonic acid membranes), "iridium" and "platinum" (for PEM-technology).

Even if cost information on the stack components is only partially available, the breakdown of stack costs is often not necessary for the calculation of LCOH. Studies can be divided into top-down and bottom-up studies. Bottom-up studies include the lower-level components of an electrolyser or stack. From these, the elements at a more aggregate level are then deduced. The procedure for top-down studies is the other way around. The potential operator, investor or project developer of an electrolyser will make a calculation based on the investment costs for the whole electrolysis system plus some additional costs for the turnkey construction of the system. They therefore do not need information on the cost structure of the stack. For the operator's purposes, the information source is usually system cost data from the manufacturer or from existing studies. For this reason, the stack is considered in this report exclusively as a complete unit and its costs are not further broken down.

The **BoP** is also a major cost driver, as shown in Figure 3, but BoP is a generic term, meaning it includes other cost drivers which are already included in the figure. There is no standard definition of BoP, but it typically includes power supply,

Result of meta-study on LCOH: Classification of cost drivers — Figure 3



Umlaut (2023). *Generic term. BoP: There is no standard definition of BoP, but it typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers. **Despite their importance in real projects, the revenues from the sale of oxygen and heat as well as funding are not included in the consideration as they are not cost components.

water conditioning and process utilities like pumps, process-value-measuring devices, and heat exchangers.

EPC is also a major cost driver. It includes all the work necessary to build the electrolyser on a turnkey basis (usually detailed planning and control, purchasing, execution of construction and installation work, and commissioning).

Another major cost driver is the **power supply**. According to Tsotridis, G., Pilenga, A. (2018), this includes the stack rectifier, the incoming power distribution, which consists of the grid connection and transformer, and the system control/safety system with the switchboard, the programmable logic controllers (PLCs), safety sensors, process parameter measuring devices, piping and valves, data input/output, and personal computer (PC).

The **lifetime of the electrolyser** system has a major influence, since a longer lifetime means a larger quantity of hydrogen is produced to which the CAPEX can be allocated. A similar calculation applies to the **full load hours**, and also, where applicable, to the size of any associated renewable generation plant such as photovoltaics. Thus, the assumed supply characteristics for the electrical energy consumed, e.g. whether island or grid operation of the electrolyser, with photovoltaics or wind, or both combined, all have an impact on the costs. While in the past electrolysers were usually operated at constant load, flexible operation now affects not only full load hours but also stack degradation.

The lifetime of the stack has also a major influence on the LCOH. The stack lifetime is shorter than the lifetime of the rest of the electrolysis system, which means that the stack degrades during its operation and has to be replaced after reaching its end of life. A stack that needs to be replaced more often means higher costs and also periodic non-availability of parts of the plant. **Stack degradation** and the associated **efficiency loss** should not be underestimated; it means a lower quantity of hydrogen is produced for the same amount of electricity. A stack replacement can also lead to an efficiency gain. In the calculations used in SRIA (2021), the stack lifetime is assumed to be over when there is a 10 percent increase in the energy required for hydrogen production. If the end of life is quantified differently, stack degradation and efficiency loss could be positioned elsewhere in the triangle.

Contingency costs are rarely considered in high-level studies, but they can also be regarded as major cost driver. Contingency refers to costs that are planned for uncertainties in a project. They can be estimated based on experience with similar projects in the past. For instance, in ISPT (2022), in a breakdown of total installed costs with PEM water electrolysis, contingency costs are estimated at 26 percent of the total, and for alkaline water electrolysis at 20 percent. The reason for this difference is the relative level of maturity, and therefore of the associated technology risks, of large-scale PEM versus alkaline water electrolysis.

Operational expenditures (OPEX) are also classified as a major cost driver. Electricity costs are generally considered part of the OPEX. However, since they are particularly significant, electricity costs are usually presented separately. In this report OPEX therefore does not include electricity costs, but it does include costs for water and for maintenance of the system.

Water costs and costs for water conditioning are classified as a minor cost driver. According to Tsotridis, G.; Pilenga, A. (2018), water conditioning consists of water storage, water feed pump, distilled deionised water production (DIW), ion exchanger, liquid separators, and demisters. Water costs are part of the OPEX.

Buildings and **properties** are also classified as minor cost drivers. These cost components are also not considered in most studies or are not presented transparently. Not only can their costs vary significantly between countries, but for properties, the differences between urban areas with high land prices and rural areas with lower property prices can also be significant for the competitiveness of the plant. In addition, the **costs for gas purification, cooling, compression, and water** are also classified as minor cost drivers. This is discussed in more detail in the following section.

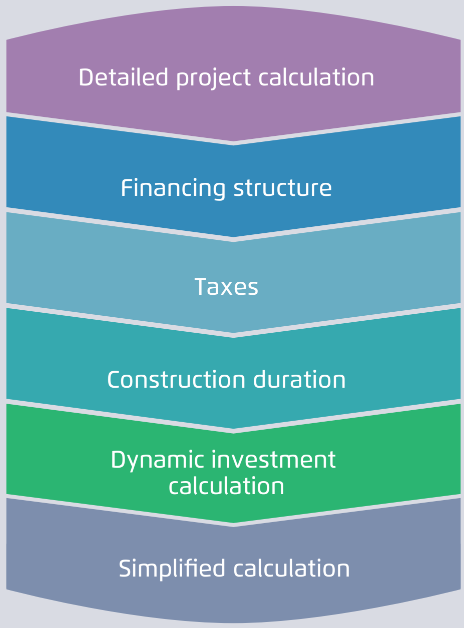
Public funding can compensate for a large part of the costs, but it varies between regions and countries and changes quickly over time. Losses in the conversion of electricity to hydrogen lead to (low temperature) waste heat being discharged. If a suitable heat sink or a consumer for process heat is available, the heat can be sold. Water electrolysis produces half a mole of oxygen for each mole of hydrogen. This can also be sold, though purification is sometimes required.

By classifying the cost drivers, we can see that some of them have a very large influence on the LCOH whereas others only affect it slightly. This also explains why certain factors are hardly addressed in studies, as the meta-analysis showed; for example the purity or the gas purification costs, which are minor cost drivers. Other major cost drivers, such as EPC, vary across a wide range, or are not considered at all in the high-level studies examined, such as contingency costs.

At this point it can be summarised that different system boundaries can result in significant differences in the LCOH. However, there is no right or wrong choice for system boundaries, only different requirements for the calculation methodology, depending on the purpose of the calculation. A high-level study may be more inclined to ignore certain costs such as contingency costs or taxes, and to pay little heed to minor cost drivers in general. In addition, project-specific cost components, such as on-site storage, are generally ignored. The perspective of investors, operators, or project developers may be very different. Understandably, they need to consider all cost components that are actually incurred up to the commissioning of an electrolyser. These comprehensive cost levels from the perspective of a project developer are shown in figure 4. They will be relevant for a project developer but not necessarily for a study author.

The most detailed cost level 'Financing structure' includes everything required for financing the project, such as raising capital or choosing an optimal ratio of equity and debt capital suited to the debt-to-equity ratio of the company. The second level takes taxation into account, the third level considers the construction phase. This means that the construction duration is also reflected in the LCOH calculation. And the fourth level is about dynamic investment calculation. In contrast to a single period calculation, a dynamic investment calculation considers the total lifetime of the electrolyser. All cash inflows and outflows are considered over time.

Cost levels — Figure 4



Umlaut (2023)

The inclusion or non-inclusion of the different cost levels and cost drivers, as well as differences in the system boundaries applied, inevitably lead to variations in the LCOH. Analysis of real-world projects in 2021 showed that in practice the CAPEX are often 20 percent to 50 percent higher than anticipated. Depending on the share of CAPEX in the total costs, this in turn influences the LCOH. It is therefore important not only to be aware of the possible reasons for this, but also to make precise calculations retrospectively using completed real-world projects and to include all costs incurred.

2 A pragmatic approach to calculating the LCOH

In this section, recommendations for an improved use of the LCOH concept, including sensible simplifications, are given. The aim of this approach is to provide guidance for future LCOH calculations. The target group is not project developers, investors in electrolysers, or project operators, but rather authors of high-level publications. The development of this approach was supported by three workshops held together with external experts from academia, from international energy organisations, and from relevant technology operators and manufacturers.

2.1 Proposal: Calculation methodology

For the calculation of LCOH, all cost components must be added together. The following formula shows the calculation of LCOH as given in Fraunhofer (2018).

Figure 5 shows the formula used there for the calculation of the LCOH. The formula contains four overarching elements: CAPEX, OPEX, annuity and electricity costs. The electricity costs are presented separately due to their significance. CAPEX is depreciated over the operating life of the plant. The calculation of the annuity includes the discount rate, or cost of capital.

Often in such formulas, as in the one presented here, the OPEX are given as a percentage of the CAPEX per year; corresponding (simplified) values can be found in the literature.

→ **Specific energy consumption:** The term lower heating value (LHV)/efficiency in front of the brackets relates the LCOH initially to the kWh, so that the result is available in Euro/kgH_2; at the same time, the influence of the system efficiency on the LCOH is shown. Since efficiency in the case of an electrolyser is defined as the ratio of the output of hydrogen, which is, for example, the product of the hydrogen mass flow and the lower heating value of the hydrogen, to the electrical power required for producing it, the term in front

LCOH calculation formula — Figure 5

$$LCOH = \underbrace{\frac{LHV}{\eta_{sys,LHV}}}_{\text{specific energy demand}} \left(\left(\underbrace{\frac{\frac{i}{100} \cdot \left(1+\frac{i}{100}\right)^n}{\left(1+\frac{i}{100}\right)^n - 1}}_{\text{annuity}} + \frac{OPEX}{100} \right) \frac{CAPEX}{\tau} + E \right)$$

LCOH	levelised cost of hydrogen [€/kgH_2]	$\eta_{sys,LHV}$	system efficiency related to the LHV
LHV	lower heating value [kWh/kgH_2]	τ	full load hours [h]
i	discount rate [%]	OPEX	operational expenditures [% CAPEX/a]
n	lifetime [a]	CAPEX	capital expenditures [€/kW]
E	electricity costs [€/kWh]		

Umlaut (2023) based on Fraunhofer (2018) of the brackets can also be directly replaced by the specific energy consumption of the electrolysis system. But this must include everything that the electrolyser system requires, meaning that the system's auxiliary consumption must also be considered. This includes rectifier or transformer losses.

- **Heating value:** Even though it is not necessary to specify the efficiency at this point and the specific energy input is sufficient to calculate the LCOH, it should be noted that the use of the LHV is recommended for calculations using efficiencies to ensure comparability and to avoid errors resulting from inconsistent use of higher heating value (HHV) and LHV. In the literature we examined, efficiency data were also almost exclusively based on the LHV. HHV values are about 10 percent higher than LHV values.

In addition to this simple formula, more complex methods can also be used for LCOH calculation. From a project developer's point of view, the cash flows are usually considered over the entire lifetime of a plant, including the construction period. This is another approach that can be used in the preparation of studies. The calculation of future cash flows is then discounted accordingly (discounted cash flow method). The formula shown here simplifies the calculation by relating all data to a single period.

- **By-products revenues & public funding:** Based on discussions in the expert workshops, we recommend excluding revenues generated by the sale of the by-products oxygen and waste heat as well as public funding in the calculation of the LCOH at the study level for the following reasons. Firstly, public funding is very much dependent on the country and the region in which the electrolyser is to be built. But the difficulty here is caused not so much by regional differences, but by the ongoing changes in such public funding programmes and the strong influence of political framework conditions on them. Secondly, the sale of by-products is highly project-specific, and if included in the calculation it would lead to a lack of comparability between projects. If public funding and/or the sale of by-products are nevertheless considered, it is recommended that there should be a secondary calculation of results including such revenues and using the initially calculated LCOH as a baseline. As with all recommendations given in this report, the transparent presentation of the calculation procedure is vitally important.

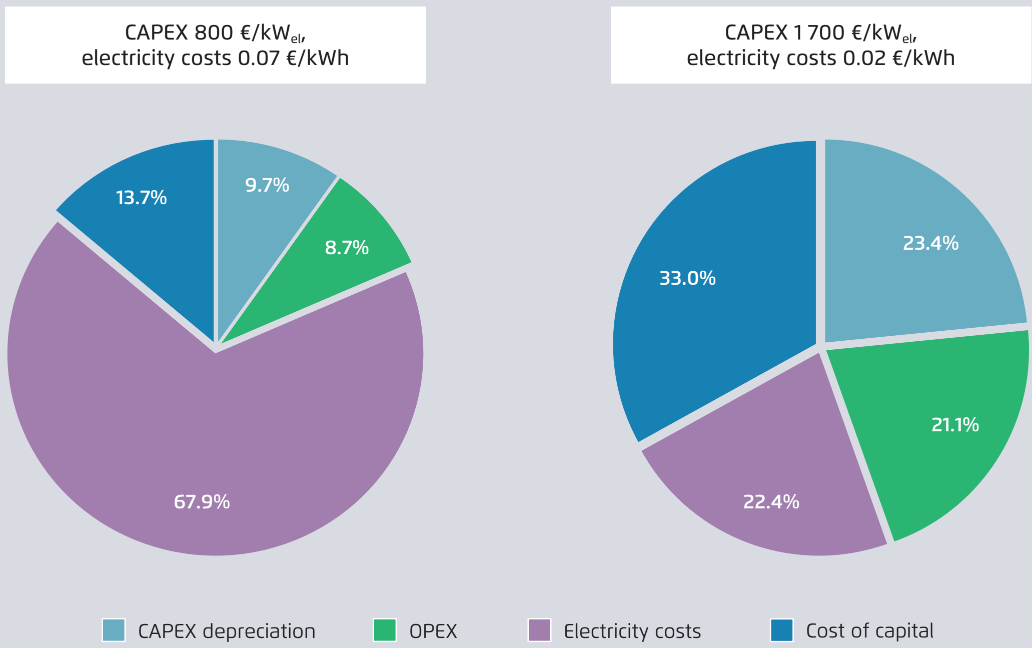
The application of this formula delivers the LCOH. In addition, the formula can be broken down into its components so that the four overarching cost drivers can be identified. This is shown in Figure 6. The diagram in the figure is also part of the dashboard of the downloadable tool.

2.2 Recommendations with regard to cost drivers

Figure 6 shows how the influence of overarching cost drivers can change. In the example on the right, a scenario with relatively high CAPEX (1.700 Euro/kWel) and low electricity costs (0.02 Euro/kWh) is shown. In the example on the left, relatively low CAPEX (800 €/kWel) and high electricity costs (0.07 Euro/kWh) are assumed. Otherwise, the same assumptions apply. It can be observed that the influence of the cost drivers can vary strongly. More interesting for the development of the pragmatic approach, however, is the discussion of the other more detailed cost drivers, which have already been addressed in the section above. Our recommendation is that everything that can reasonably be estimated for the turnkey construction of an electrolyser as well as for its operation should be included in the LCOH.

- **Influence of scaling on CAPEX:** CAPEX includes all components that are essential parts of a turnkey electrolyser. In addition, CAPEX is strongly dependent on the performance of the electrolysis system. IRENA (2020) summarises electrolyser investment costs as a function of module size using

Illustrative calculation of the four overarching cost drivers, and relevant assumptions — Figure 6



Umlaut (2023) based on provided tool. Note: General assumptions: specific energy demand: 55.5 kWh, 4 000 h/a, discount rate 7%, OPEX 3% of CAPEX, lifetime 30 a.

various sources[1]. Based on these data points, the following polynomial can be approximated:

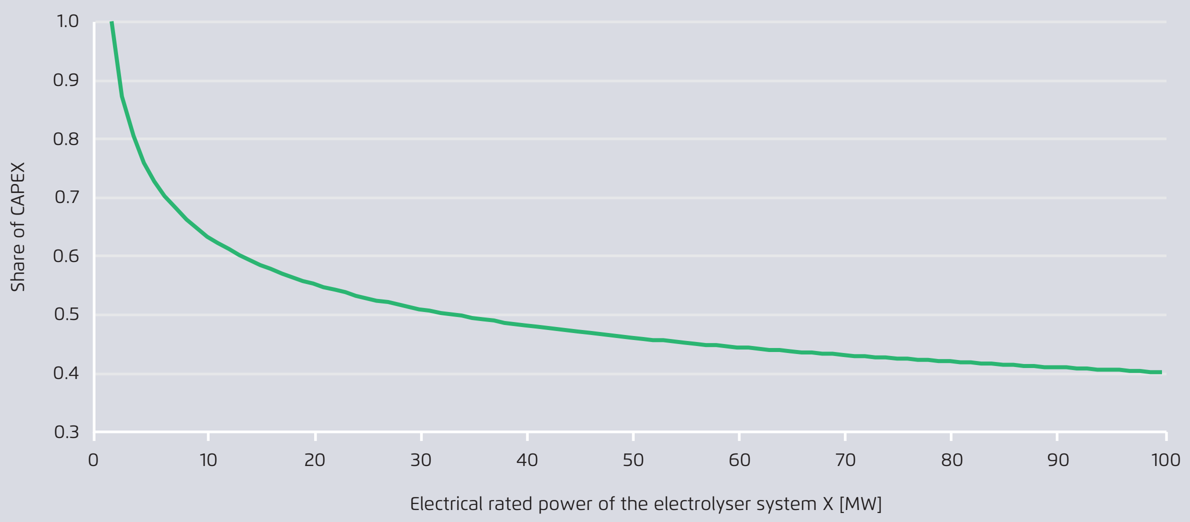
$$\text{CAPEX scaling factor} = X^{-0,1976}$$

X stands for the electrical rated power of the electrolyser system ($1 \leq X \leq 100$ MW) in the unit MW. With this scaling factor, CAPEX or the LCOH can be compared for electrolysers of different capacities. However, it should be noted that this is not an exact method and that the database underlying the polynomial requires continuous updating. The polynomial is plotted in Figure 7. It can be observed that the specific CAPEX for a 10 MW electrolyser system are only about 63 percent of the specific CAPEX of a 1 MW system. For a 100 MW electrolyser, the specific CAPEX decrease to about 40 percent.

→ **EPC:** It is recommended that costs for EPC are included in the LCOH. These costs can vary considerably depending on the project.
→ **Contingency costs:** It is recommended that contingency costs are not included in the LCOH.They are not usually considered in high-level studies, and can also vary considerably.
→ **Buildings, foundations, properties:** Buildings, including foundations and land, are essential for the construction of an electrolyser. In most studies, there is no information on the costs for land and buildings. With regard to properties, we recommend not including their costs in the calculation of the LCOH in high-level studies. Data gathering for this

1 IRENA own calculations for PEM and alkaline electrolysers, Saba et al. (2018) for alkaline electrolysers (1 atm), and Proost (2020) for alkaline electrolysers

Specific CAPEX as a function of electrical rated power of electrolyser systems | Figure 7



Umlaut (2023) based on data from IRENA (2020), Saba et al. (2018), and Proost (2020)

is challenging, especially when comparing properties in different countries and in rural as well as urban locations. This recommendation is also in line with the objective of our study to identify and provide reasonable simplifications for future cost comparisons of LCOH. With regard to the costs for buildings, we recommend including these in the LCOH. Although costs here also differ somewhat between regions and (sometimes significantly) between different countries, data gathering is less complex. The calculation tool already mentioned has the capacity to include the costs for land via an open input field.

→ **Greenfield or brownfield:** In the meta-study it was shown that the terms greenfield and brownfield are hardly mentioned in the studies examined. A definition of the terms is also given there. Although the term greenfield is used in three studies, none of the studies distinguishes the term and the associated costs from the brownfield approach. A precise delimitation seems difficult and project-specific circumstances would have to be included. This also means that a precise classification into greenfield or brownfield projects does not have to be made, but rather is given by the overarching context, i.e. how the costs for properties, buildings, foundations and connections to the water supply, electricity grid, and perhaps the natural gas or hydrogen grid or similar are treated. The connections, the system boundaries and the balance boundary of the electrolyser are therefore discussed below.

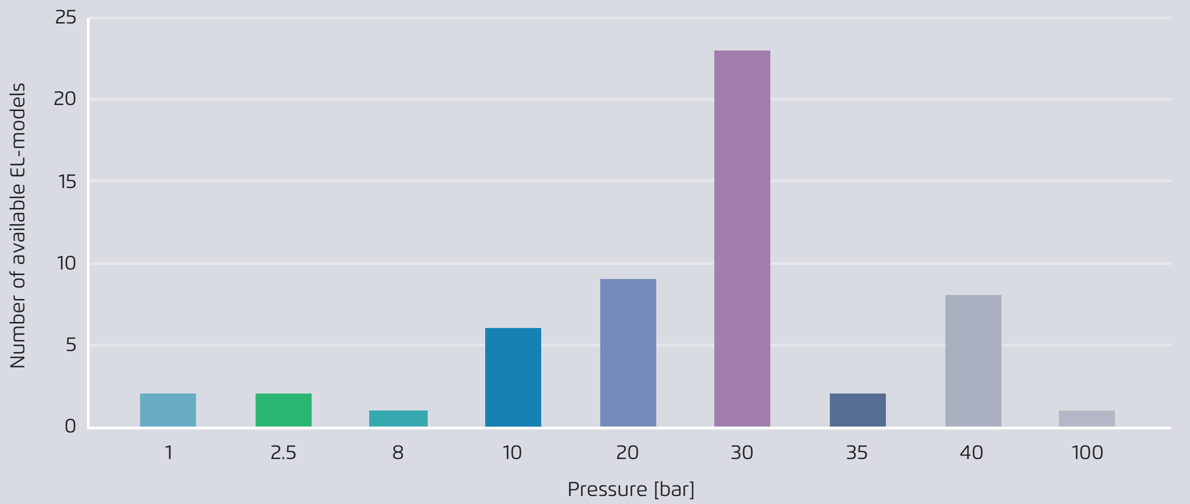
→ **Electrical grid:** With regard to the connection of the electrolyser plant to the electrical network, it is assumed that an existing network is available and that the electrolyser can be connected directly to it. Obviously, this assumption may not apply to large-scale projects in particular – for example, if an electrolysis plant is built in an area without a strong electrical grid and is to be connected to a renewable generation plant. Such so-called "off-grid" project-specific conditions would lead to an incomparability of the LCOH in studies. With regard to electricity costs, everything the operator of the electrolyser has to pay (taxes, duties, transmission costs) must also be included in the calculation of the LCOH. If the electrolyser is connected to a high-voltage grid, a high voltage substation including a transformer may also need to be included in the CAPEX. This must be taken into account for the specific energy consumption.

- **Water supply:** With regard to the water supply system, it is assumed that an existing network is available and that the electrolyser can be connected directly to it. If, however, a seawater desalination plant has to be built to supply the electrolyser with water, this should also be included in the costs. Although the costs for water treatment are very low e.g. for reverse osmosis 0.01-0.02 $/kgH$_2$ (IEA (2021)), this is nevertheless an aspect that should be given more attention in the future, since there is a risk of salinisation in certain marine regions if electrolysis capacities and any linked seawater desalination plants are massively expanded.
- **Transport & storage:** Due to the multiplicity of further potential applications, the costs for the subsequent use or transport of hydrogen cannot be easily taken into account, and are therefore omitted from the calculation in the pragmatic approach. Potential further direct use applications include storage, fuel stations, trailers, industrial plants, blending it into the natural gas network and feeding it into dedicated hydrogen gas pipelines for transportation over distance or in Power-to-X plants. For reasons of comparability, it is therefore recommended that the system boundary for the calculation of the LCOH is drawn directly at the hydrogen outlet of the electrolyser. (On-site) storage should also not be included in the calculation for the same reason. At this point, however, drawing a system boundary is not sufficient. The role played by the quality of the hydrogen produced and the pressure at which it comes out of the electrolyser can also be questioned.

But what role does the pressure play? The internal pressure in electrolysers varies significantly. Most of the analysed studies refer to the pressure of the electrolysers examined Figure 8 shows that pressures levels at which commercially available electrolysers

Product overview of electrolysers

Figure 8



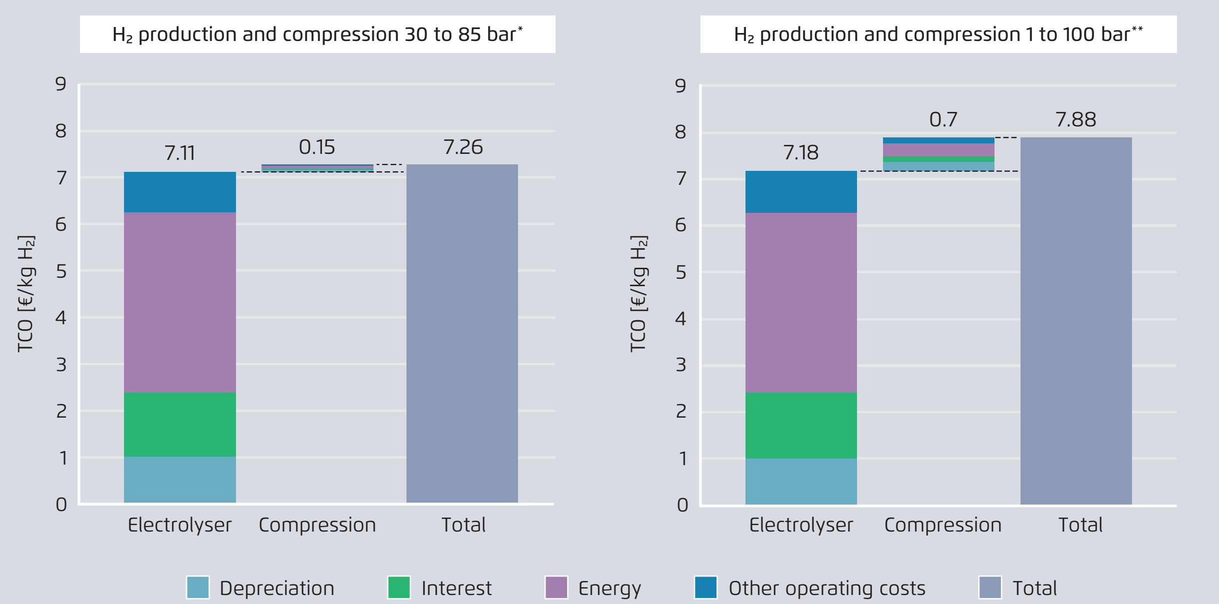
Umlaut (2023). Note: Manufacturers considered: Kumatec, elogen, Enapter, Hähn, HIAT, H-Tech Systems, Hydrogenics, ITM Power, McPhy Energy, Ostermeier, PlugPower, Sunfire.

operate typically lie in the range of 30 bar. It was created from data obtained from C.A.R.M.E.N (2021).

Figure 8 provides a non-comprehensive overview of typical electrolyser pressure ratings. The evaluation of electrolyser models available on the market has shown that most electrolysers operate at a pressure of 30 bar. But there are also some with different internal pressures. If electrolysers operate at a relatively low pressure, but a uniformly higher pressure is chosen for a study, it is necessary to establish what external compression would cost. External compression means that a compressor is connected downstream from the electrolyser to adjust the pressure. In order to estimate these costs, the calculation shown in Figure 9 was carried out.

In Figure 9, the LCOH of an electrolyser is calculated and the costs of additional compression are then shown separately. The assumptions for the calculation were based on a MW-electrolyser in central Europe. In the left-hand diagram a downstream additional compression is shown which compresses the hydrogen from the 30 bar internal pressure of the electrolyser to 85 bar, for example in order to feed it into a transmission network. The diagram on the right shows a case in which an electrolyser is operated at a pressure of 1 bar and the hydrogen is compressed downstream externally to 100 bar. All other assumptions are the same in both diagrams (including specific energy demand and investment costs). The performance of a compressor depends largely on the pressure ratio, which is 2.83 in the diagram on the left and 100 in the diagram on the right. The cost of external compression from 30 bar to 85 bar is about 2.1 percent of the LCOH. For compression from 1 bar to 100 bar, the proportional cost of external compression in the total LCOH is 8.9 percent. When the location or the parameters and compression ratios are changed, the costs of external com-

Calculation of the LCOH for an electrolyser with downstream external compression — Figure 9



Umlaut (2023). *Planned pressure level for pipelines by company Neumann Esser. **Min. and max. pressure of available electrolysers.

pression vary accordingly. However, it is important to be able to roughly estimate the costs using this calculation. With the knowledge this provides, we recommend calculating LCOH for a reference pressure of 30 bar, as this is the pressure at which most electrolysers available on the market operate. SRIA (2021) also uses the same assumption when defining key performance indicators (KPIs).

- **Reference pressure:** If LCOH calculations are made using the reference pressure of 30 bar but the electrolysers investigated operate at lower internal pressures, , additional costs should be included in the LCOH via the entries for cost of the compressor, its efficiency and pressure ratio. The downloadable calculation tool has an input field for the internal electrolysis pressure and performs this calculation independently after the specific compressor costs and the compressor efficiency have been entered.
- **Hydrogen quality:** This section will deal with the role played by the purity of the hydrogen. A hydrogen quality of 3.0 has a purity of 99.9 percent, a quality of 3.5 has a purity of 99.95 percent and a quality of 5.0 has a purity of 99.999 percent. Information on the quality is frequently given in the studies examined. However, no correlation between quality and cost is provided. In the classification of cost drivers based on the meta-study, gas purification costs were identified as a minor cost driver. This was confirmed by our own calculations and in an interview with a gas purification equipment manufacturer. The costs are low, and ignoring them does not have a major impact on the LCOH. Nevertheless, we recommend calculating the LCOH assuming a hydrogen quality of 5.0. This allows the hydrogen produced to be used for the vast majority of applications, including fuel cell applications. In addition, this means there are usually no problems with damage to compressors or downstream infrastructure due to condensation. Furthermore, SRIA (2021) also uses the same assumption when defining the KPIs.
- **Operational expenditures (OPEX):** OPEX are usually reported in the literature as a percentage of CAPEX per year. In the literature examined, between 1.5-5.0 percent. The variation results from the different types of electrolysers, predicted price developments and different manufacturers in different countries. These figures include assumed costs for personnel, insurance, maintenance, servicing, water, and everything required to operate an electrolyser.
- **Lifetime of the stack, and stack replacement costs:** The lifetime of the stack is given in the literature and varies according to the type of electrolyser and the predicted start date. However, information on stack replacement costs is rarely given (25 percent of system CAPEX (BNEF (2022)), 35 percent of system CAPEX (Agora (2021)), constant even in future scenarios). We recommend including the stack replacement costs in the CAPEX. For this purpose, the actual lifetime of the stack has to be calculated from the lifetime specified by the manufacturer as well as from the full load hours of the electrolyser. A separate annuity is then calculated for the stack. The costs for the stacks required during the lifetime of the electrolysis system are included (proportionally) in the CAPEX. This procedure is also included in the calculation tool provided.
- **Stack degradation:** To take account of stack degradation, we recommend using an average specific energy requirement in the single-period calculation method shown. If the calculation is made using a discounted cash flow analysis, the degradation in the individual periods can be taken into account. Simply assuming that the ageing of the stack is approximately linear (while in fact it is not) results in there being no significant differences between the two methods.

All of the recommendations are summarised in Table 2. The recommendations for a more consistent use of the LCOH concept given above omit some cost components (such as costs for property acquisition or costs for on-site storage) or draw relatively strict system boundaries (as for example with the connection of the electrolyser to the water and electricity grids). Note also that we recommend disregarding public funding as well as revenues from the sale of the by-products waste heat and oxygen. However, there may be significant differences, especially between the simplified calculation method presented here and real-world project costs, as the latter may include project-specific costs such as costs for land, for connections to more distant grids, for infrastructure for site development, as well as different costs for EPC, etc..

However, the research informing this report and the resulting recommendations have also shown that simplifications are justifiable. This is because the influence of certain factors can be small, so that ignoring them causes only an insignificant change in the resulting LCOH while significantly reducing the effort required to prepare studies. Furthermore, the investigations have shown that it is difficult to make generalised recommendations for the calculation of the LCOH. Depending on the specific focus of a study, individual modifications in the LCOH concept can be sensible. In all cases, however, it is important to

Summary of the recommendations for a pragmatic approach to calculating LCOH — Table 2

Parameter	Notes
Electrolyser CAPEX	Account for CAPEX scaling influence.
Discount rate	Also known as Weighted Average Cost of Capital (WACC).
Electricity price	Should include all charges.
Electrolyser efficiency	Specific energy consumption including auxiliary power [kWh/kgH_2].
Electrolyser system lifetime	Major cost driver due to distribution of CAPEX.
Stack lifetime & replacement	Costs for stack replacement to be included in the CAPEX.
Stack degradation	Considered through average specific energy consumption.
Engineering, Procurement, Construction	Contains usually detailed planning and control, purchasing, execution of construction, installation work, and commissioning.
Buildings	Reflect cost difference between greenfield / brownfield.
Balance of Plant (BoP)	BoP typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers.
OPEX	Typically in the range of 1.5%–5% of CAPEX.
Compression	Consider compression costs for system output below reference pressure.
Hydrogen quality	Identified as a minor cost driver. Nevertheless, it is recommended to calculate with a 5.0 quality to ensure that there are no technical issues.
Water supply	Costs are to be considered if a seawater desalination plant is required.
Electrical grid	Assumption of an existing grid.
Contingency	Not taken into account in most studies.
Funding	Funding programmes strongly influenced by political conditions and vary over time.
Properties	Vary significantly between countries as well as urban and rural areas.
Hydrogen transport & storage	Multiplicity of further possible applications.
By-product revenues	Omit revenues from by-products (waste-heat, oxygen).

to be considered — individual decision — not to be considered

Umlaut (2023)

present calculation approaches and assumptions in a transparent manner. In this context, it should also be pointed out that some cost drivers such as stack degradation, stack replacement costs or costs for EPC can have a considerable influence on the LCOH and are often ignored or not presented transparently in publications. These cost drivers should be given more attention in future reports. The purpose of the simplified approach presented here is to provide guidance for the preparation of future studies and to explain how differences between published LCOH and LCOH estimates for projects can come about.

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Agora Industry

Agora Energiewende

Agora Industry
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin, Germany
P +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-industry.org
info@agora-industrie.de

Agora Energiewende
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin, Germany
P +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-energiewende.de
info@agora-energiewende.de