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Empirical survey among experts on the relevance of various criteria for optimizing modular electrolysis systems

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ABSTRACT

Electrolysis systems must be constructed from multiple stack units. This modular system of stack units (modular electrolysis system) requires systematic optimization of its composition. This optimization depends on numerous, and sometimes conflicting, criteria. While such criteria have already been evaluated for modular plants in the process industry, they must be re-assessed in the context of modular electrolysis systems. To address this challenge, an expert survey was conducted within two research networks (H_2Giga and DECHEMA e.V. Research Network) and the VDMA P2X4A.The evaluation followed the two-stage process: After ranking the categories *costs, flexibility*, *process engineering* and *time-to-process* according to their overall importance a ranking of individual criteria within each category was conducted. The survey reveals a clear prioritisation: costs are in first place with 35.9%, followed by flexibility (25.4%), process technology (23.2%) time to process (15.4%). This ranking provides a structured overview of the most important factors guiding the optimisation of modular electrolysis systems. Another finding of the survey is how electrolysis systems should be operated in the future. Here, the focus was primarily on electrolysis systems related to fluctuating renewable energies, with a top-2-box result of 81% in each case. Based on this prioritisation, weightings for possible application in multi-criteria optimisation can now be derived. This makes it possible to determine suitable compositions of electrolysis stack unit systems when scaling systems and to refine optimisation efforts. The expert survey thus contributes to the optimised design of electrolysis systems and thereby supports the ramp-up of hydrogen production.

Keywords: modular electrolysis, modularization, requirements prioritization, expert survey, process equipment assemblies

INTRODUCTION

Electrolysis-based green hydrogen is widely regarded as a key enabler for decarbonizing energy-intensive industries because it provides a low-carbon feedstock and energy carrier that can substitute fossil-derived hydrogen and support new synthesis routes. Industrial deployment, however, requires electrolysis plants in the multi-hundred-megawatt to gigawatt range, which cannot be realized as a single stack and therefore relies on number-up of stacks and balance-of-plant subsystems [1–3]. As plant capacity increases, the overall system complexity rises disproportionately due to replicated auxiliaries and control layers, which makes engineering and integration a dominant cost and schedule driver.

Modularization has the potential to mitigate this complexity by structuring the plant into repeatable process units with defined interfaces, similar to the Process Equipment Assembly (PEA) concept that is established in modular process engineering [4, 5]. Despite the strong interest in modular electrolysis, requirements for electrolysis systems are often specified implicitly or inconsistently, and optimization targets for module boundaries remain unclear, which hampers the systematic development of modular architectures.

METHODOLOGY

This work applies a requirements-driven evaluation approach by repeating an expert survey that was originally developed for Process Equipment Assembly (PEA) selection in the process industry and transferring it to the German electrolysis sector. PEAs in modular plants can be easily adapted to changing boundary conditions. A PEA is a modular process unit that is mostly self-sufficient in terms of automation and provides a process engineering step [1]. The survey retained the same four high-level evaluation categories, namely ‘cost’, ‘flexibility’, ‘process engineering’, and ‘time-to-process’, while individual criteria were adapted where necessary to reflect electrolysis-specific characteristics and terminology [6]. Data collection was performed as a nationwide expert survey in Germany, with participation from 63 professionals/experts working in Research and Development (R&D) or engineering, sales, and project management and representing plant manufacturers, plant operators, component manufacturers, and research institutions within the Power-to-X for Applications of VDMA e.V. (VDMA P2X4A) network and the DECHEMA/H_2Giga project environment [7]. Figure 1 shows the distribution of experts across industries, and Figure 2 shows the distribution of experts within the field of work along the electrolysis value chain. Experts ranked the categories and criteria by relative importance using a rank-based point allocation comparable to the Simos approach [8], and the resulting point sums were normalized to obtain weights that can be interpreted as relative priorities for system optimization. With the completion of the expert survey, a rank could be determined for each category and criterion. To determine the rank, points are assigned for each rank. The points per rank are derived from the number of categories and are assigned in descending order. Subsequently, the weighting of the category or criterion is calculated according to formula (1) [6, 8]:

$$w_a\,[\%]=\frac{\sum_{i=1}^{n} p_{a,i}}{\sum_{i=1}^{n}(p_{a,i}+p_{b,i}+p_{c,i}+p_{d,i})} \qquad (1)$$

RESULTS

Ranking of optimisation criteria

The distribution of functional roles indicates a strongly engineering-oriented sample, as 62% of the participants work in R&D or engineering, while 11% work in sales, 8% in project management, and 19% in other roles. This composition is consistent with the current technology ramp-up phase, in which architectural and integration decisions are predominantly shaped by development and engineering organizations. With respect to organizational background, component manufacturers form the largest group with 46%, followed by plant manufacturers with 18%, research institutions with 12%, plant operators with 11%, and other organizations with 13%, which reflects the current industrial focus on stack and balance-of-plant scaling.

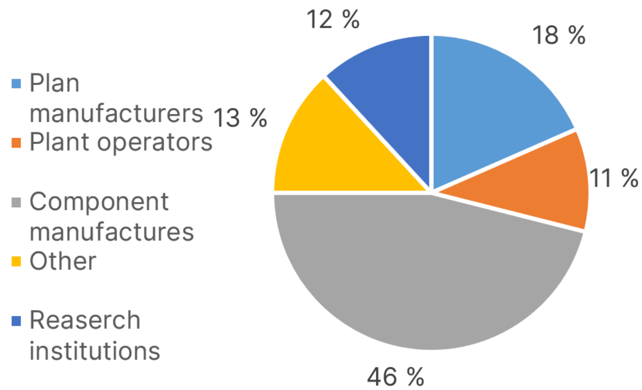

Figure 1. Branch of participating industry experts

The category weighting reveals that cost is the dominant requirement group with an overall share of 35.9%, whereas flexibility reaches 25.4%, process engineering reaches 23.2%, and time-to-process reaches 15.4%, which jointly define a quantitative priority profile for modular electrolysis optimization. Figure 3 shows the entire distribution of categories with their criteria in a sunburst diagram.

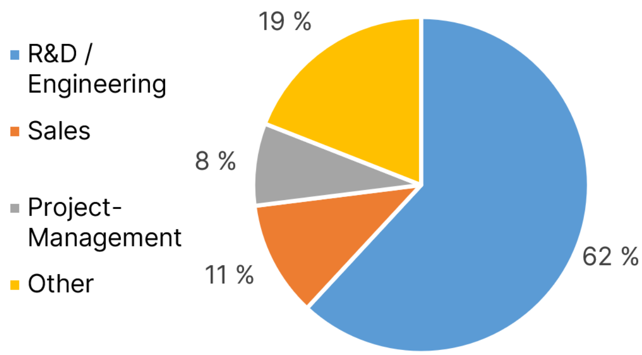

Figure 2. Work field of participating industry experts

Within the cost category, operating and maintenance costs contribute 19.08% to the overall weighting, corresponding to 53.1% of the cost category, while investment costs contribute 16.85% and therefore account for 46.9% of the cost category, which indicates that both CAPEX and OPEX reduction are considered nearly equally important.

Flexibility is primarily driven by capacity flexibility with 8.72% and dynamic operation capability with 8.28%, while location flexibility reaches 4.66% and product specification flexibility reaches 3.77%, which confirms

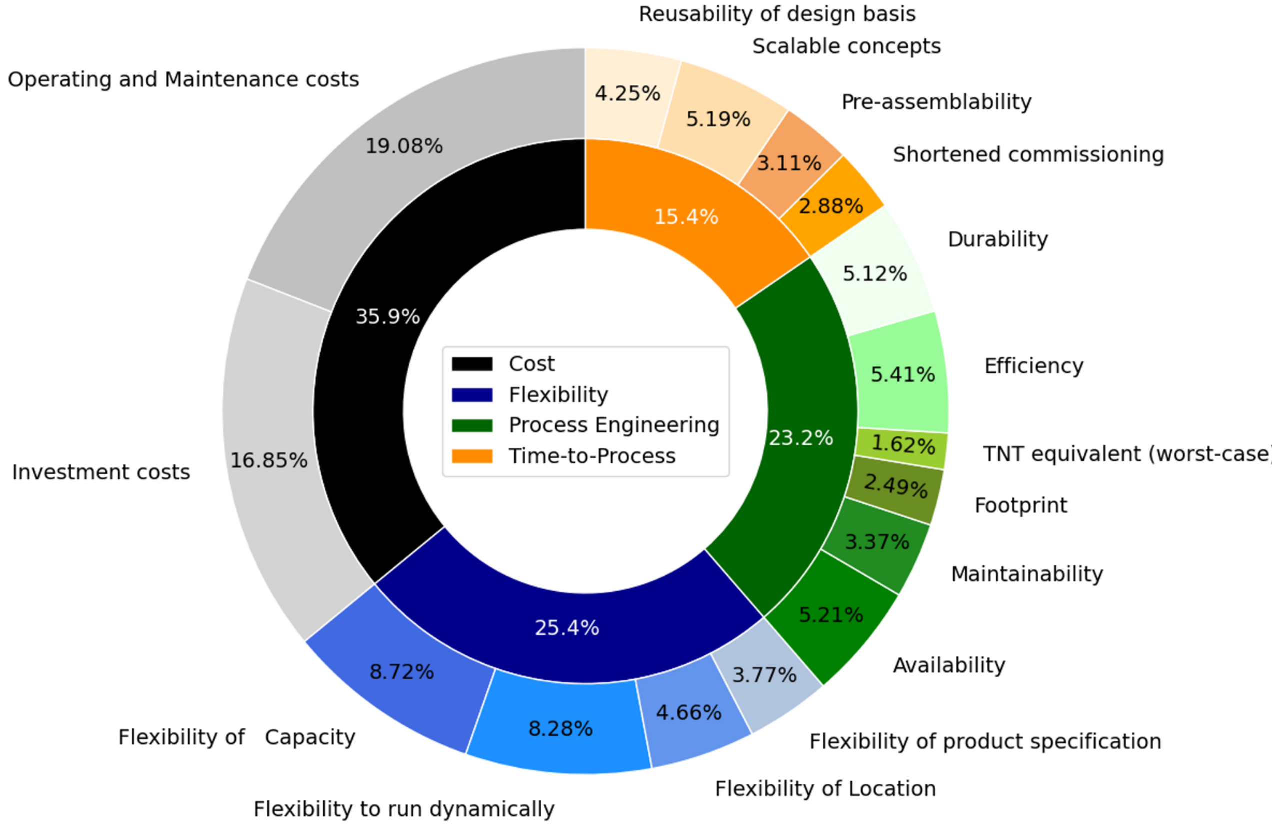

Figure 3. Sunburst diagram: Categories are shown in the inner circle. These are identical to the categories from the process industry. The criteria for later optimization of electrolysis systems are in the outer circle.

that electrolysis plants are expected to provide both scalable capacity and load-following behavior in volatile electricity systems.

Process engineering requirements are dominated by efficiency with 5.41%, availability with 5.21%, and durability with 5.12%, whereas maintainability reaches 3.37%, footprint reaches 2.49%, and the TNT-equivalent worst-case safety indicator reaches 1.62%, which highlights the importance of robust long-term operation and energy conversion performance.

Time-to-process is led by scalable concepts with 5.19% and reusability of the design basis with 4.25%, while pre-assemblability reaches 3.11% and shortened commissioning reaches 2.88%, which suggests that the main schedule benefits are expected from reuse and scaling strategies rather than from commissioning acceleration alone.

A comparison with the original process-industry survey shows that cost remains the most important category in both sectors, yet electrolysis assigns substantially higher relevance to flexibility and correspondingly lower relevance to time-to-process. In the process-industry results, cost accounts for 31%, time-to-process for 27%, process engineering for 25%, and flexibility for 17%, whereas the electrolysis survey shifts flexibility to the second rank and places time-to-process last. This shift can be attributed to the system role of electrolysis as a Power-to-X converter that must operate efficiently under fluctuating renewable power availability, which makes operational flexibility a first-order design driver rather than a secondary feature. Both the process industry and the electrolysis sector place a significant focus on flexible production volumes. However, in the process industry, flexibility is equated with the reconfiguration of production plants and varying product specifications that can be manufactured within a single plant [9]. In contrast, flexibility in the electrolysis sector is understood as the ability to respond to fluctuating power inputs while maintaining constant product specifications [10]. Figure 5 shows a summary comparison of the categories from [6] from the process industry compared with the results of the survey from this study for the electrolysis industry.

Expert assessment of grid connection concepts for electrolysers

This section summarizes expert ratings on the relevance of four electrical grid connection and operation concepts for electrolyzer systems. Respondents

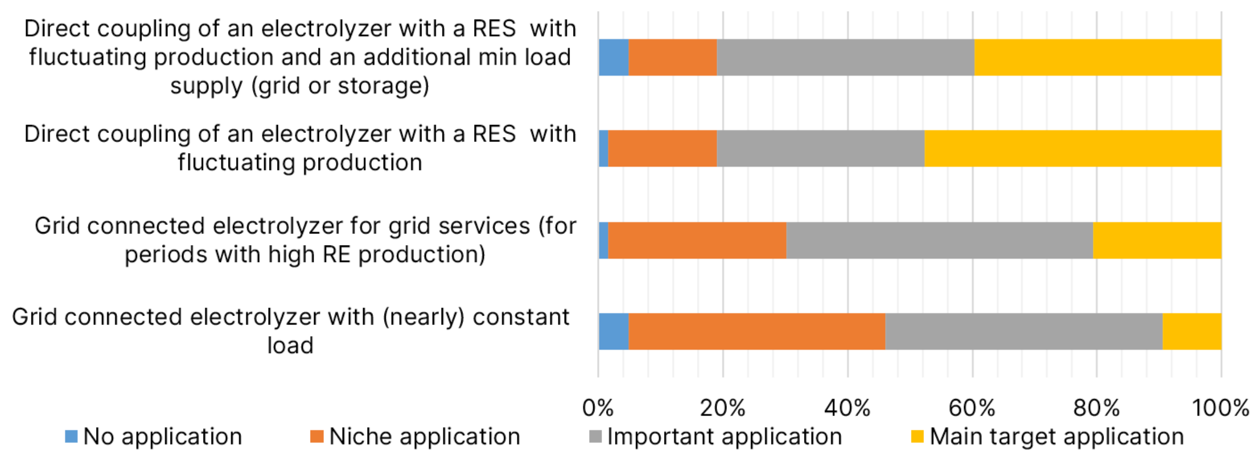

Figure 5. Evaluation of the expert survey on the future electrical connection and grid integration of electrolysis systems

classified each concept on an ordinal four-level scale ("No application", "Niche application", "Important application", "Main target application"). The provided dataset contains normalized response shares per concept (each row sums to 1.0), corresponding to 63 expert responses. For comparative interpretation, an additional mean relevance score was computed by mapping the four levels to 0–3 (0 = No application, 3 = Main target application).

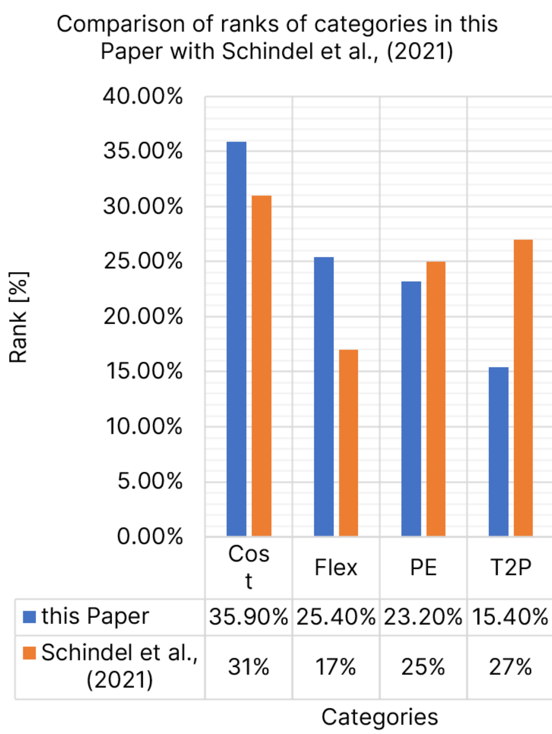

Figure 4. Comparison of categories with [6]. Abbreviations: Flexibility (Flex), Process Engineering (PE), Time-to-Process (T2P)

Results and ranking

Across all concepts, experts clearly prioritized configurations that enable direct integration with renewable energy sources (RES). The concept "direct coupling with fluctuating RES production" achieved the highest share of "Main target application" (47.6%) and the highest mean relevance score (2.27/3). A closely related hybrid concept—direct coupling with fluctuating RES production plus an additional minimum-load supply via grid or storage—was rated almost equally relevant (39.7% "Main target", mean score 2.16/3). Both direct-coupling options reach an identical top-2-box share of 81.0%, indicating broad consensus that these concepts should be treated as important-to-primary use cases rather than edge scenarios. The top 2 box share is the proportion of respondents who scored one of the two highest answer categories on an ordinal scale - e.g. Select "Main target application" and "Important application". It is therefore an aggregated agreement/positivity figure in percent that compresses the "high" rating of a statement. The higher the top-2-box share, the higher the consensus strength in the upper valuation range.

Grid-connected operation aimed at grid services (operation in periods with high renewable generation) occupies an intermediate position (mean score 1.89/3, Top-2 box 69.8%). While only 20.6% selected it as the main target, nearly half of respondents (49.2%) still considered it an important application, suggesting that flexibility-oriented grid-connected operation is widely valued but not universally seen as the dominant design point.

In contrast, a nearly constant-load, grid-connected electrolyzer is the least preferred concept (mean score 1.59/3) and is most frequently characterized as niche (41.3%). Only 9.5% rated constant-load operation as the main target application. This pattern indicates a shift away from a baseload-centric view toward operational regimes dominated by variability, flexibility, and power-system interaction. The results can be found in Figure 4.

Interpretation and implications for system requirements

The observed ranking strongly suggests that future electrolyzer system design—and, by extension, requirement prioritization—should be anchored in dynamic operating conditions rather than steady-state operation. High relevance assigned to direct RES coupling implies that experts expect electrolyzers to (i) tolerate strongly fluctuating power input, (ii) operate efficiently across a broad load range, and (iii) maintain performance and lifetime under frequent transients (start/stop cycles, ramping, and partial-load operation [10]). The comparable relevance of the "minimum-load supply" variant indicates that practitioners anticipate technical or economic constraints that motivate stabilizing measures (e.g., minimum turndown limits, stack protection strategies, or process integration requirements), achievable through either grid backup or buffering (electrical storage, hydrogen storage with operational control, or hybrid supply architectures).

The relatively high 'Important' share for grid-service operation highlights an additional requirement cluster: electrolyzer systems are expected to interact with the power system beyond simple consumption. This typically translates into needs for advanced control strategies capable of responding to market or grid signals (e.g., absorbing renewable peaks, participating in flexibility products, or managing curtailment). Even if not the dominant main-target case for all respondents, its broad 'important' rating suggests that 'grid-interactive' capability can be a meaningful differentiator in system architectures and should be considered in modular interface and control design.

Finally, the low prioritization of nearly constant-load operation implies that optimizing solely for steady-state efficiency at a single design point may not match the dominant deployment expectation in the surveyed expert community. Instead, robust performance across operating regimes - and the ability to integrate fluctuating RES supply - emerges as a central design intent. For a modularization-oriented development approach, these findings support emphasizing modules and interfaces that enable (i) flexible power conversion and grid/RES interfacing, (ii) transient-capable process control.

SURVEY LIMITATIONS

One limitation of the evaluation is that it only contains aggregated distributions at respondent level. Subgroup effects, such as the examination of connections between interest groups and the level of a rated category or criterion, have not yet been taken into account here. This means that statistical conclusions that go beyond a descriptive ranking cannot be evaluated here. Another limitation of the survey is the broad spectrum of perspectives. However, this is still focused on technology development and component supply, which is due to the expert networks of VDMA P2X4A and the DECHEMA network in the H2Giga lead project. This should be taken into account when interpreting the relative weighting of the technical criteria.

CONCLUSIONS

The transferred survey method provides an empirically grounded prioritisation of requirements for modular electrolysis systems in Germany and thereby clarifies optimisation targets for module decomposition. The optimisation criteria should focus on the efficiency, dynamic operation and levelized cost of hydrogen of the electrolysis system. The modular approach of small-scale electrolysis systems should be transferable to large-scale systems. In particular, electrolysis systems that can cope with fluctuating power inputs and operate efficiently over a wide 'Load Flexibility' range should be investigated.

The approaches to modularising process engineering systems pursue different goals in the process industry and in the electrolysis industry. Cost reduction remains the overarching objective, but the high weighting of flexibility and the strong process engineering emphasis on efficiency imply that modular concepts must simultaneously support dynamic operation, reliable performance and scalable concepts. In the process industry, the approach to standardised modules seems to be more about the rapid realisation of products in order to secure market share.

OUTLOOK

Future work should implement the derived weightings in the optimisation of electrolysis systems and evaluate the modular system approach for scaling under realistic fluctuating operating profiles. To support this, a standardised test signal/operating profile combined from different components (e.g. from a step, ramps, a pseudo-random binary sequence/'sawtooth function' and a synthetic solar profile) can be developed to optimise consistency across different electrolysis system sizes. In this way, modular heterogeneous electrolysis systems of different technologies and power ratings can be investigated in terms of system efficiency, operating flexibility and levelized cost of hydrogen. The consistent test signal allows investigation of whether the modular system approach represents a scalable concept.

Another field of research is the investigation of hybrid electrolysis systems with storage integrated into the process, consisting of a battery-electric and a hydrogen storage system. After all, the experts rated the 'grid-connected electrolyser for grid services (for periods with high RE production)' with a top-2-box value of 69.8%, which argues for a high storage share that can be divided among different technologies.

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