Future cost and performance of water electrolysis: An expert elicitation study

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The need for energy storage to balance intermittent and inflexible electricity supply with demand is driving interest in conversion of renewable electricity via electrolysis into a storable gas. But, high capital cost and uncertainty regarding future cost and performance improvements are barriers to investment in water electrolysis. Expert elicitations can support decision-making when data are sparse and their future development uncertain. Therefore, this study presents expert views on future capital cost, lifetime and efficiency for three electrolysis technologies: alkaline (AEC), proton exchange membrane (PEM) and solid oxide electrolysis cell (SOEC). Experts estimate that increased R&D funding can reduce capital costs by 0–24%, while production scale-up alone has an impact of 17–30%. System lifetimes may converge at around 60,000–90,000 h and efficiency improvements will be negligible. In addition to innovations on the cell-level, experts highlight improved production methods to automate manufacturing and produce higher quality components. Research into SOECs with lower electrode polarisation resistance or zero-gap AECs could undermine the projected dominance of PEM systems. This study thereby reduces barriers to investment in water electrolysis and shows how expert elicitations can help guide near-term investment, policy and research efforts to support the development of electrolysis for low-carbon energy systems.

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Introduction

Energy storage could play a pivotal role in future low-carbon energy systems, balancing inflexible or intermittent supply with demand. Storage of renewable energy in chemical bonds, in particular hydrogen, is attractive due to high energy density, elemental abundance, long-term storability, potentially low costs and the ability to transfer renewable electricity into other energy sectors [1–6]. Recent years have seen rising interest in this idea of converting intermittent renewable electricity via electrolysis into a storable gas, also termed Power-to-Gas [7–10]. The concept was first formulated as Renewable Power Methane in a patent filed in 2009 [11] and is...
regarded as the most cost-efficient solution for inter-seasonal energy storage [12]. It also allows linking electricity and gas networks and diffusing renewable energy to the heat and transport sector, and the chemical industry [13–15]. Water electrolysis is the key enabling technology. However, significant barriers to commercialisation remain; notably high capital costs of electrolysers and uncertainty about their future development [16,17].

Expert elicitations use structured discussions with experts to obtain estimates for uncertain parameters. They are a valuable tool to support investment and policy decision-making in conditions of uncertainty and limited data availability [18,19]. Accordingly, both the US National Research Council and the 2010 Inter Academy Council review of the IPCC climate change assessment recommend the use of expert elicitations to inform funding decisions in the energy field [20,21]. As a result, this method has been used to investigate the impact of research, development and deployment (RD&D) funding on cost reductions for low-carbon generation technologies [22–28] and electric vehicle batteries [29,30]. These studies also compare the impact of additional funding between technologies [23,24,30] or funding type [28], and identify the underlying technical innovations [22,28] or possible deployment scenarios [25,26].

This article explores cost and performance improvement potentials for water electrolysis through expert elicitations and therefore adds to this growing body of research in two dimensions: at the content level, a stationary energy storage technology is investigated; at the methodology level, cost as well as performance parameters are analysed, under extreme research and development (R&D) funding scenarios, while separating the impact of R&D funding alone and R&D funding combined with production scale-up.

The following section describes the three electrolysis technologies considered. Section Elicitation process then outlines the elicitation process and Section Results and Discussion presents and discusses the results. Section Conclusion concludes.

**Water electrolysis**

Three water electrolysis technologies are investigated: Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cells (PEMEC) and Solid Oxide Electrolysis Cells (SOEC). Fig. 1 depicts the technology set-up and Table 1 summarises component materials as well as performance and cost parameters.

AEC is the incumbent water electrolysis technology and widely used for large-scale industrial applications since 1920 [31]. AEC systems are readily available, durable and exhibit relatively low capital cost due to the avoidance of noble metals and relatively mature stack components [22–34]. However, low current density and operating pressure negatively impact system size and hydrogen production costs. Also, dynamic operation (frequent start-ups and varying power input) is limited and can negatively affect system efficiency and gas purity [33]. Therefore, development is focussed on increasing current density and operating pressure, as well as system design for dynamic operation [32,34], to allow operation with intermittent renewable sources, for example. Previous analyses suggest that future cost reductions are most likely driven by economies of scale [9,16,33].

PEMEC systems are based on the solid polymer electrolyte (SPE) concept for water electrolysis that was first introduced in the 1960s by General Electric to overcome the drawbacks of AECs [31]. The technology is therefore less mature than AEC and mostly used for small-scale applications [33]. Key advantages are high power density and cell efficiency, provision of highly compressed and pure hydrogen, and flexible operation [33–35]. Disadvantages include expensive platinum catalyst and fluorinated membrane materials, high system complexity due to high pressure operation and water purity requirements, and shorter lifetime than AEC at present. Current development efforts are therefore targeted at reducing system complexity to enable system scale-up and reducing capital costs through less expensive materials and more sophisticated stack manufacturing processes [9,33,34].

SOEC is the least developed electrolysis technology. It is not yet widely commercialised, but systems have been developed and demonstrated on laboratory scale [31] and individual companies are currently aiming to bring this technology to market [36]. SOECs use solid ion-conducting ceramics as the electrolyte, enabling operation at significantly higher temperatures. Potential advantages include high electrical efficiency, low material cost and the options to operate in reverse mode as a fuel cell or in co-electrolysis mode producing syngas (CO + H₂) from water steam (H₂O).
and carbon dioxide (CO₂) [33,37]. A key challenge is severe material degradation as a result of the high operating temperatures. Thus, current research is focussed on stabilising existing component materials, developing new materials and lowering the operation temperature to 500–700 °C (from 650 to 1000 °C) to enable the commercialisation of this technology [33,38].

Current capital costs are reported at around 1000 € kW⁻¹ and 2000 € kW⁻¹ for AEC and PEMEC systems (1 MWₐ) respectively [9,16] (kWₐ or MWₐ refer to the electrical power consumption). SOEC systems are not yet widely commercially available and cost estimates lie above 2000 € kW⁻¹ [16]. Studies comparing the capital cost of AEC systems to steam methane reformers (SMR), the incumbent technology for methane gas reformation, thereby rely on natural gas and carbon dioxide (CO₂) [33,37]. A key challenge is severe material degradation as a result of the high operating temperatures. Thus, current research is focussed on stabilising existing component materials, developing new materials and lowering the operation temperature to 500–700 °C (from 650 to 1000 °C) to enable the commercialisation of this technology [33,38].

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The requirements for electrolysers to operate with intermittent power sources are: fast response of system components enabling dynamic operation; operation at lower temperatures; operation with intermittent power sources; and ability to operate at lower pressures than SMRs. PEMEC systems are most suitable for these requirements with lifetime potentially benefitting from intermittent operation [40]. AEC and SOEC are also suitable and their system components can be successfully engineered to operate with an intermittent power supply [16,41].

### Elicitation process

We followed best-practice recommendations from the literature to obtain representative results and minimise cognitive heuristics and bias (see below and Appendix A) [18,42]. Table 2 outlines the elicitation procedure and Table 3 lists the ten experts that were interviewed. While ten is a common number of experts to interview [43], there is no one rule for the correct number of interviewees required. However, it is important to select a set of experts who adequately represent the diversity of expert opinion in the area [19,44]. As such, we selected five from academia and five from industry, including

| Table 1 – Main characteristics of AEC, PEMEC and SOEC systems. |
|-------------------|-------------------|-------------------|
| **AEC**           | **PEMEC**         | **SOEC**         |
| Electrolyte       | Aq. potassium hydroxide | Polymer membrane | Yttria stabilised Zirconia |
| (20–40 wt% KOH)   | (e.g. Nafion) [33,34] | (YSZ) [37,38]    |
| Cathode Ni, Ni-Mo alloys [39,32,33] | Pt, Pt-Pd [34] | Ni/YSZ [37,38] |
| Anode Ni, Ni-Co alloys [39,32,33] | RuO₂, IrO₂ [34] | LSM⁵/YSZ [37,38] |
| Current density (A cm⁻²) | 0.2–0.4 [34] | 0.6–2.0 [34] | 0.3–2.0 [9,38] |
| Cell voltage (V)   | 1.8–2.4 [34] | 1.8–2.2 [34] | 0.7–1.5 [38] |
| Voltage efficiency (%HHV) | 62–82 [34] | 67–82 [34] | <110 [33] |
| Cell area (m²)     | <4 [33] | <0.3 [33] | <0.01 [33] |
| Operating Temp. (°C) | 60–80 [34] | 50–80 [34] | 650–1000 [37,38] |
| Operating Pressure (bar) | <30 [33] | <200 [33] | <25 [33] |
| Production Rate (m³/Hz h⁻¹) | <760 [33] | <400 [33] | <40 [33] |
| Stack energy (kWₐh m⁻²) | 4.2–5.9 [34] | 4.2–5.5 [34] | >3.2 [33] |
| System energy (kWₐh m⁻²) | 4.5–6.6 [16] | 4.2–6.6 [16] | >3.7 (>4.7)kWh_energy a |
| Gas purity (%)     | >99.5 [32] | 99.9 [33] | 99.9 a |
| Lower dynamic range (%) | 10 – 40 [33,34] | 10 – 10 [34] | >30 [34] |
| System Response   | Seconds [33] | Milliseconds [33] | Seconds a |
| Cold-start time (min.) | <60 [16] | <20 [16] | <60 [38] |
| Stack Lifetime (h) | 60,000–90,000 [16] | 20,000–60,000 [16] | <10,000 [37,38] |
| Maturity           | Mature | Commercial | Demonstration a |
| Capital Cost (€ kW⁻¹) | 1000–1200 [16] | 1860–2320 [16] | >2000 [16] |

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**Table 2 – Elicitation procedure.**

| Phase              | Interactions with expert | Timeline/Duration |
|--------------------|--------------------------|-------------------|
| Before interview   | 1. Making initial contact | –                 |
| During interview   | 2. Sending elicitation protocol (background material, questionnaire) | 2 weeks before interview |
|                    | 3. Discussing background material | 1 h during interview |
|                    | 4. Eliciting values of interest with questionnaire | 1 h during interview |
| After interview    | 5. Sending elicited values and possible implications for final approval | 1 week after interview |
experts on AEC, PEMEC and SOEC, from the UK, Denmark, Germany and Belgium. The interviews lasted for 2 h and were conducted face-to-face (6), via Skype (3) or by phone (1) to ensure attentiveness, enable the interviewees to fully convey their expertise, and to allow for spontaneous interviewer questions to fully capture that expertise [18,19]. They took place between February and June 2016.

Before the interview, potential experts were contacted and, upon agreement of participation, an elicitation protocol was sent two weeks before the interview [44]. The elicitation protocol outlines the motivation for the study, compiles background material on technological and economic aspects of electrolysis, describes the expert elicitation technique, and contains the elicitation questionnaire (see Supplementary Material). By iterating this protocol with electrolysis experts of Imperial College, we captured the latest available and relevant information, phrased unambiguous questions, and identified the academic and industry experts in the field [18].

During the interview, the first hour was spent discussing the background material to minimise any availability bias [18]. The second hour was spent introducing the case study (see Table 4) and eliciting the values of interest:

- Dominant electrolysis technology for this application for 2020 and 2030
- Capital cost estimates for 2020 and 2030 under three R&D funding scenarios (1x, 2x, 10x current) in situations without (R&D) and with production scale-up (RD&D) due to increased deployment
- Lifetime estimates for 2020 and 2030 under the three scenarios (1x, 2x, 10x current R&D)
- Efficiency estimates for 2020 and 2030 under the three scenarios (1x, 2x, 10x current R&D)

- Environmental impact of electrolysis manufacturing and operation
- Technical and value chain innovations driving these cost or performance improvements

We asked for 10th, 50th and 90th percentile estimates with extreme values being identified first to minimise any anchoring bias [18]. Using probing questions, we supported the expert in critically assessing, refining and verifying the given values. By eliciting distinct parameters (e.g. capital costs), instead of aggregate parameters that require implicit calculations (e.g. levelised cost of produced hydrogen), we further minimised uncertainty [18,23]. Audio recordings were made with the experts’ permission to ensure all responses were captured correctly.

After the interview, we transcribed responses into a spreadsheet and derived potential implications based on the elicited values in a separate document. Both were sent to the expert to allow for adjustments, point out potential inconsistencies, ask for additional comments and receive final approval of the elicited values.

These elicited values are anonymised and reported and discussed in Section Results and Discussion. To analyse the relative impact of increased R&D funding and production scale-up, we take the median 50th percentile estimate at current R&D funding scenario (1x) without production scale-up (RD&D) for 2020 and 2030 and deduct the median percentage reduction of experts’ estimates based on these drivers. Recent work highlights the suitability of the median as aggregation method for relatively small sample sizes [19,45]. However, it should be noted that any single measure must be treated with caution when aggregating elicitation results [46]. Previous studies also used the arithmetic mean to analyse results [27–30,47].

The identified innovations are categorised along three dimensions:

- Technology: AEC, PEMEC, SOEC
- Impact: Reduced capital cost, longer lifetime, higher efficiency
- Innovation area:
  - Cell: Catalyst, Electrolyte, Electrodes, Membrane, Multiple
  - Stack: Bipolar Plates, Sealing, Multiple

Table 3 – Experts interviewed for this study (ordered alphabetically and by category).

| Name                  | Institution                  | Role                                      | Category       |
|-----------------------|------------------------------|-------------------------------------------|----------------|
| Dan Brett             | University College London    | Professor, Electrochemical Engineering    | Academic       |
| Jens Oluf Jensen      | Technical University Denmark | Professor, Energy Conversion and Storage  | Academic       |
| Mogens Bjerg Mogensen | Technical University Denmark | Professor, Energy Conversion and Storage  | Academic       |
| Tom Smolinka          | Fraunhofer Institute - ISE   | Head, Chemical Energy Storage Department  | Academic       |
| Stephen Skinner       | Imperial College London      | Professor, Materials Chemistry            | Academic       |
| Franz Lehner          | E4Tech Ltd                   | Senior Consultant                         | Industry       |
| Ben Madden            | Element Energy Ltd           | Director                                  | Industry       |
| Marcus Newborough     | ITM Power Ltd                | Development Director                      | Industry       |
| Christian von Olshausen| SunFire GmbH                 | Chief Technology Officer                  | Industry       |
| Filip Smeets          | Hydrogenics Europe N.V.      | General Manager On-site Generation        | Industry       |

Table 4 – Electrolysis case study for energy storage and renewable energy transfer to other energy sectors.

| Power Source   | Intermittent Renewables |
|----------------|-------------------------|
| System Size    | 10 MW<sub>e</sub>       |
| H₂ output pressure | 20–30 bar             |
| H₂ application | Injection into natural gas grid |
We report the number of experts that mention innovations along each dimension and analyse how often innovations within each sub-category are mentioned overall. Finally, we compare the capital cost estimates for 2020 and 2030 to projections based on previously identified experience curves for electrolysis [39] and fuel cells [48,49](see Appendix B).

**Results and discussion**

Experts first indicated the technology they believe to be dominant in the given case study and then estimated capital cost, lifetime and efficiency parameters for the technology of their expertise. Many experts chose to make these estimates for the technology they believe to be dominant in case multiple technologies are within their area of expertise. Out of the ten experts, one did not make capital cost estimates, one made them for AEC and PEMEC and one partly for AEC and partly for PEMEC. Three experts did not make lifetime estimates and six did not estimate efficiency.

**Technology dominance**

The majority of experts identified AEC in 2020 and PEMEC in 2030 as most suitable for the given electrolysis case study (see Fig. 2). One expert argued that AEC would be more suitable in 2020 at current production levels, but this would change in favour of PEMEC with production scale-up. PEMEC exhibits superior characteristics for intermittent operation in the case study application (see Table 4); however, more manufacturing and operating experience is required before these characteristics lead to a commercial advantage. This argument also explains the overall shift in expert preference from AEC to PEMEC from 2020 to 2030. Only one expert considered AEC to be superior in 2030 as a result of substantive innovation in system configuration (see Section Drivers of cost and performance improvements). The trend of increasing preference for PEMEC compared to AEC in Power-to-Gas applications can be observed since 2011 with the amount of cumulative installed PEMEC systems set to overtake AEC [50] (see Appendix C).

Fig. 3 shows cost estimates across all experts for all three electrolyser types in 2020 and 2030. Capital costs for AEC systems by 2020 at current R&D funding and without production scale-up (\(\bullet\) R&D, 1x) lie between 800 and 1300 € kW\(^{-1}\) (all 50th percentile estimates), but could range from 700 (lowest 10th) to 1400 € kW\(^{-1}\) (highest 90th). For PEMEC the respective range is 1000–1950 € kW\(^{-1}\) (all 50th) and 800–2200 € kW\(^{-1}\) (lowest 10th, highest 90th), representing a strong improvement compared to the 2016 reference value and reduction of the gap to AEC system costs. SOEC electrolysers are estimated to be most expensive at 3000–5000 € kW\(^{-1}\) (all 50th) with a significantly higher uncertainty range of 2500–8000 € kW\(^{-1}\) (lowest 10th, highest 90th) (see Appendix Table D1 for all cost ranges in tabular form).

For 2030, most estimates were given for PEMEC and SOEC, because the majority of experts believe these technologies will be dominant by 2030. Costs for AEC electrolysers at current funding and without production scale-up (\(\bullet\) R&D, 1x) are estimated slightly lower than in 2020 at 750 € kW\(^{-1}\) (50th), potentially ranging from 700 to 1000 € kW\(^{-1}\) (10th, 90th). Similarly, the respective PEMEC estimates are slightly below 2020 figures, ranging from 850 to 1650 € kW\(^{-1}\) (all 50th) or 700–1980 € kW\(^{-1}\) (lowest 10th, highest 90th). SOEC systems could experience the strongest relative cost reduction by 2030 in this scenario with cost ranges of 1050–4250 € kW\(^{-1}\) (all 50th), however still highly uncertain with 750–6800 € kW\(^{-1}\) (lowest 10th, highest 90th). Nonetheless, experts A and H suggest SOEC capital costs similar to AEC and PEMEC by 2030 with production scale-up (\(\bullet\) R&D).

Fig. 4 explicitly depicts the relative impacts of increased R&D funding and production scale-up based on the median percentage reductions of the experts’ 50th percentile estimates. The cost impact of production scale-up at current funding (R&D, 1x) ranges from 17 to 30% by 2020 and 23–27% by 2030 across the three electrolysis technologies and is higher than increasing R&D funding only (R&D, 2x and 10x): 6–18% by 2020 and 0–24% by 2030. This aligns with previous studies which find that cost reductions for solar PV modules should mainly be attributed to economies of scale as opposed to technology advances [23]. Other studies, however, discuss the importance of R&D funding and production scale-up at different development stages and find that R&D funding has a stronger cost reducing impact in all of them when comparing a two-fold increase in cumulative R&D spending to a two-fold increase in cumulative production [51].
The particularly high cost reduction potentials for SOEC systems of 30–40% by 2020 (RD&D) in our study indicate that production scale-up is most significant for technologies that are not yet commercialised. It would mean that learning in production in the early development stage of SOEC has a larger marginal effect on cost reduction than for the commercial AEC and PEMEC systems, for which improvements in production have been partially exploited already. This argument would follow the learning curve theory [52], where each doubling of cumulative produced
capacity leads to a constant relative cost reduction. The same absolute increase in production then leads to higher cost reductions for early stage technologies than for mature ones. In terms of the other technologies, higher cost reduction potentials are expected for PEMEC by 2030 than for AEC based on increased R&D funding alone (8–24% vs. 0–7%). This could reflect the lower technological maturity of PEMEC, where more potential for innovation from R&D remains unexploited.

The figures also show the diminishing returns of increased R&D funding as observed in previous studies [23]. While a doubling of R&D funding in the absence of production scale-
up leads to 6–8% cost reduction, a tenfold increase has an impact of 7–24% across all technologies. Thus, the 3-fold additional cost reduction potential (8%–24%) is lower than the 5-fold funding increase (2x to 10x).

Compared to other energy technologies, the cost reducing impact of doubling R&D funding by 2020 without production scale-up for AEC (0–7%) is comparable to other mature (e.g. supercritical coal: 6.03% [51], hydropower: 2.63% [51]; data from POLES energy systems model [51]), and for PEMEC and SOEC (6–8%) just above other emerging technologies (e.g. offshore wind: 4.9% [51], solar thermal: 5.3% [51]).

**Lifetime**

Fig. 5 shows that at current R&D funding (1x), AEC lifetime by 2020 is estimated to be likely within the range of 41,000 to

![Fig. 5](image-url)

Fig. 5 — Elicited expert estimates for 2020 and 2030 lifetime (in hours) as a function of R&D funding (1x, 2x, 10x). Data points indicate 50th, uncertainty bars 90th and 10th percentile estimates. Expert C made estimates for AEC and PEMEC. Expert J made estimates for AEC zero gap configurations. Results are sorted by technology and in ascending order for 50th percentile estimates. 2016 reference values based on Table 1.
90,000 h (all 50th). When accounting for uncertainty, the range expands slightly to 40,000–110,000 h (lowest 10th, highest 90th) (Appendix Table D2 shows all estimates in tabular form). The uncertainty ranges of experts A and C remain constant across the funding scenarios (2x, 10x), following the rationale that currently achievable lifetimes of up to 90,000 h are sufficient for the given case study (intermittent operation: 30,000 h means about 20 years) and technological advances are more likely to be directed towards capital cost reductions. Expert C specifically referred to warranted lifetimes of commercial products, acknowledging that actual lifetimes can be higher.

The respective lifetime ranges for PEMEC systems are 41,000–60,000 h (all 50th) and 40,000–85,000 h (lowest 10th, highest 90th), which is slightly lower than for AEC. The estimates of expert C show that from a commercial perspective lifetime warranties for PEMEC are equal to AEC systems.

For SOEC systems, there is a significant difference in academic and industry perspective for 2020 lifetime estimates. The academic expert suggests a range of 6000–15,000 h (10th, 90th), while the industry experts deems 50,000–100,000 h possible (10th, 90th). This is indicative of the current research efforts to increase SOEC lifetime and the varying views regarding its success.

Expert J made estimates for a potential development of AECs, a zero gap configuration where porous electrodes are directly attached to the membrane, similar to PEMEC and SOEC (compare Fig. 1), thereby reducing the inter-electrode gap to minimise internal resistance and increase cell efficiency [53,54]. The lifetime of such systems is estimated at 10,000–40,000 h (10th, 90th), below traditional AEC systems, however with potential for improvement due to increased R&D funding.

By 2030 little improvement is expected for traditional AEC systems, based on the belief that longer lifetime is not required, while zero gap AEC and PEMEC systems could match the lifetime of AEC systems, the former in particular with increased R&D funding. The lifetime of SOEC systems is expected to match that of AEC and PEMEC systems, even with the potential to surpass it under increased R&D funding. For context, PEM and solid oxide fuel cell lifetimes have increased 10-fold since the early 2000s to around 40,000–80,000 h for residential systems [55]. But, there remains strong disagreement whether these improvement potentials for SOEC systems can be realised, with 50th percentile estimates ranging from 30,000 up to 90,000 h.

The impact of increased R&D funding (2x, 10x) appears to have a smaller effect on traditional AEC (0–33%) compared to PEMEC (14–34%) and SOEC (16–29%) lifetime, reflecting their relative immaturity (see Fig. 6). Again, the diminishing returns of increased R&D funding can be observed. At most, the additional improvement potential by a 5-fold increase in additional funding (2x to 10x) is only 2-fold. The current SOEC research focus on lifetime is reflected in the expected two-fold increase from 2020 to 2030.

**Efficiency and environmental impact**

Six of the ten interviewees indicated that improvements in efficiency are possible but not prioritised for two reasons. First, relatively low electricity cost and non-continuous operation in the given case study mean that operating costs are small, so that reduction of capital costs has priority. Second, efficiencies are maximised at low current density, but to reduce capital costs, however, research is focussed on increasing current density. Experts also highlight that system efficiency alone is not the most important factor, but rather the efficiency including hydrogen purification and pressurisation for its final application [56].

Four experts, however, indicated which efficiency improvements are conceivable for AEC, zero gap AEC and PEMEC (see Appendix E). For AEC, current R&D funding could improve system efficiencies beyond the boundaries given in Table 1 by 2020, while for PEMEC this would only be the case by 2030. By 2030, zero gap AEC systems could become more efficient than AEC or PEMEC. For SOEC systems, experts highlight that feasible thermodynamic limits can already be achieved at the
cell-level. Improvements are focused on fully translating these efficiencies to the system-level.

Environmental impact was not a core knowledge area for many of the experts, in particular with respect to lifecycle carbon dioxide emissions. Three main themes emerged when discussing the environmental impact of electrolysis coupled with renewable generators:

1. When low-carbon generators provide the power input, carbon dioxide emissions are insignificant compared to alternative hydrogen production technologies (e.g. steam methane reformation) [57,58]. More significantly, several experts believe that the potential to store renewable electricity or decarbonise other energy sectors like heat or transport outweighs any emissions or toxicity impact associated with electrolyser manufacturing.

2. Experts believe it is likely that electrolysis based energy storage would outperform other electrochemical energy storage technologies in terms of lifecycle carbon dioxide emissions if the natural gas network is used as an existing storage facility, or if composite storage tanks are developed.

3. The majority of experts mentioned catalyst mining as the key source of environmental impact in electrolysis manufacturing. In addition to the associated energy consumption, health and contamination issues related to Nickel and Platinum usage were highlighted. PEMEC is most prone to these issues, also due to the use of fluorinated membrane materials, and AEC to a limited extent due to the use of Nickel. This shows a potential environmental advantage for SOEC since none of these materials are used.

These views closely mirror the findings from life cycle assessments for the analogous fuel cell types [59–61].

Drivers of cost and performance improvements

When eliciting cost and performance estimates, experts also noted the particular technical and value chain innovations upon which their estimates are based. Fig. 7 depicts the relative share of identified innovations along the dimensions: technology, impact and innovation area; as well as the absolute count of innovations mentioned by experts along the innovation areas and their sub-groups (see Appendix Table G1 to G6 for detailed breakdown of innovations per technology).

Regardless of technology, the key areas for innovation are catalysts, electrodes and membranes on the cell-level, optimised system set-up and balance-of-plant components on the system-level and automation, methods and scale effects in manufacturing. Supply chain improvements refer to increased bargaining power due to higher purchase volumes and more supplier competition, and were only mentioned by industry experts (see Appendix F).

Manufacturing automation, new electrode coating methods and increased production rates are perceived as key drivers for AEC cost reductions. On the cell-level, experts envision increased current densities up to 0.6 A cm⁻² through

![Fig. 7 – Top: Relative share of identified innovations along technology (AEC, PEMEC, SOEC), impact (Capital Cost, Lifetime, Efficiency) and innovation area (From darkest to lightest: Cell, Stack, System, Manufacturing, Supply Chain). No innovation mentioned on stack-level for SOEC. Bottom: Absolute number of mentions of innovations along innovation areas and sub-groups. Includes double-counting of same innovation if mentioned by different experts. Refer to Appendix Table G1 to G6 for detailed breakdown of innovations per technology.](image-url)
Fig. 8 – Comparison of median expert estimates on capital costs to capital cost projections based on experience rates for AEC, PEMEC and SOEC at current R&D funding (1x) without (left) and with production scale-up (right). Left: Constant production capacity from 2015 onwards based on continued historic deployment rates; annual market 0.36 GWel. Right: Production scale-up from 2015 onwards as a result of increased deployment, annual market of 1 GWel by 2020 and 2.5 GWel by 2030 [16] (see Appendix B). Error bars represent range of reference values or median 90th (upper) and 10th (lower) percentile of expert estimates. AEC experience rate is based on capital cost development and capacity deployment between 1956 and 2002 [39]. Experience rate capital cost projections for PEMEC and SOEC are speculative, based on proxy experience rates from fuel cell technologies [48,49] and assumptions on global cumulative capacity for PEMEC and SOEC in 2015 (see Appendix B).
better mixed metal oxide catalysts and more stable electrodes and electrolytes for potential high temperature operation by 2030 [62,63], and perhaps, more radically, a move to zero gap configurations [53,54].

For PEMEC, a significant capital cost reduction driver seems to be component standardisation, which, combined with production scale-up, enables the shift to high volume production methods like laser cutting, plastic injection moulding or 3D-printing [17]. In addition, further increased current density (>3A cm$^{-2}$) is investigated through better electrode design, catalyst coatings and thinner membranes [64]. In parallel, the reduction of catalyst loading and replacement of titanium in bipolar plates with high-conductivity coatings on low-cost substrates like steel would reduce capital costs [65,66]. Finally, more operational experience would enable the de-risking of system design to optimise and combine system components for better system integration and operation at optimised set points.

For SOEC systems, capital cost reductions would be based on reducing the electrode polarisation resistance to enable lower operating temperatures (~450 °C) that then allow the employment of lower cost component materials like stainless steel [67]. Similar to PEMEC, increased field experience could allow leaner system engineering and improved system integration. The mentioned manufacturing (high volume methods, reduced overhead costs) and supply chain improvements (higher volumes, more suppliers) apply to SOEC systems as well.

Increasing lifetime is at the heart of current research efforts for SOECs. High operating temperatures lead to fast degradation of active materials and balance-of-system components. Therefore, the reduction in operating temperature was mentioned in parallel with more robust materials [68,69]. For PEMEC, membranes with higher impurity tolerances are a key area of innovation alongside structural improvements of electrode and catalyst coatings to reduce the movement or deactivation of active catalyst particles [70].

For all three technologies, efficiency improvements can be achieved through innovations on the system-level like feed-water and hydrogen gas purification as well as optimised system integration due to increased operational experience. On the cell-level, zero gap design for AECs [53,54] or thinner membranes for PEMECs [71] could improve efficiency, while the focus for SOECs appears to be on improved material-microstructure integration for better oxygen conductivity [37].

This explicit account of innovations underlying the elicited cost and performance improvements adds a qualitative dimension to the quantitative results and enables targeted investment and policy recommendations [22,27,44]. It reveals that strongest improvement potentials can be realised through investments in production methods and product standardisation to automate manufacturing and produce higher quality components (e.g. electrode and bipolar plate coatings). The operation of pilot plants is key to gain operational experience and optimise system design. Laboratory research should be focussed on reducing the operating temperature for SOECs and developing new system designs like zero gap AECs or PEMEC stacks for higher pressure or differential pressure operation.

**Comparison to experience rate cost projections**

We compare the elicited capital cost estimates to projections based on experience rates (Fig. 8). For AEC systems an experience rate of 18 ± 13% has been identified [39] as the rate at which AEC system capital costs have reduced between 1956 and 2002 relative to increased cumulative produced capacity. Due to the lack of published experience rates for PEMEC and SOEC systems, we use the rates of the related fuel cell technologies as a proxy. These were identified as 18 ± 2% for PEMFC [48] and 28 ± 16% for SOFC systems [49] (see Appendix B). This comparison enables the analysis of expert estimates in context of historic cost developments and in relation to a fundamentally different method for projecting future costs [23].

When projecting the experience curve forwards from 2002 for AEC systems, while accounting for the associated uncertainty of ±13%, we find that capital cost development by 2005 [35] and 2015 [9] was in line with the high experience rate of 18 ± 13%. When projecting the experience curve beyond 2015, we also account for production scale-up uncertainty. While a constant annual electrolysis market means no production scale-up (R&D), annual market growth by a factor of 3 by 2020 and 7 by 2030 [16] (see Appendix B) translates into the respective production scale-up (RD&D). In both cases, experts estimate future capital costs below the range given by the high experience rate projection. This means, experts expect stronger cost reductions for AEC systems in the future than observations from the past indicate.

Regarding PEMEC, experts are more optimistic in their cost estimates for 2020 than an experience rate of 18 ± 2% would suggest given the underlying capacity additions. While this is also true for the 2030 estimate in the R&D only scenario, elicited estimates and experience rate projection match in the RD&D scenario with increased market growth by 2030. This could suggest that experts tend to underestimate the detrimental impact of limited market size on technology cost reductions.

In line with these findings, a study based on stakeholder expectations rather than analyses of historic cost reductions also found cost ranges for 2020 and 2030 below the range given by the experience rate [16]. Similarly, a recent expert elicitation study on future wind energy costs found that expert estimates were more optimistic than preceding cost developments indicated [22]. This could show that expert elicitation tends to yield overly optimistic projections due to the limited ability of experts to take into account historic trends and the possible relation to cumulative produced capacity. On the other hand, it could show that experts can factor-in potential step-change innovations, which cannot be captured by experience curves. Here, a retrospective analysis could reveal the applicability of each hypothesis.
For SOEC, 2020 estimates are broadly in line with an experience rate of 28%. 2030 estimates are above or below this rate in the no production scale-up (R&D) and production scale-up (RD&D) scenario respectively, however still within the $28 \pm 16\%$ uncertainty range.

Conclusion

We conduct expert elicitations to determine the potential future capital cost, lifetime and efficiency of three water electrolysis technologies that can be used for utility-scale energy storage and to transfer renewable electricity to other energy sectors.

The majority of experts believes in a shift from incumbent AEC to PEMEC systems from 2020 to 2030 as the preferred technology for electrolysis coupled to renewable generators. Although the difference in capital cost is already significantly reduced by 2020, it is only by 2030 that PEMEC costs paired with the higher operational flexibility translate into a commercial advantage. Those experts indicating SOEC systems could be favoured by 2030 expect this technology to reach the cost and lifetime regime of AEC and PEMEC systems, albeit associated with high uncertainty.

Quantitative estimates indicate that production scale-up is perceived as more impactful on capital cost reduction for the observed technologies than increased R&D funding. This is mostly driven by improved manufacturing methods and automation as well as increased operational experience leading to optimised system designs. The impact of increased R&D funding is also significant for cost and performance improvements, but shows diminishing returns. Unequivocally, lowest cost and highest performance estimates are made in conditions of combined R&D funding and production increase.

As a result, deployment policies for all water electrolysis technologies to encourage investments in production methods and product standardisation can be recommended. In parallel, research should be focussed on SOEC systems as well as novel AEC and PEMEC system designs. This study thereby shows that expert elicitations can be a useful tool to quantify the impact of R&D funding and production scale-up on technology cost and performance and associate these with qualitative innovations to derive targeted investment and policy recommendations. This should be a core element of future elicitation studies, which should expand these elicitations of expert views to additional stationary energy storage technologies to further improve the understanding of their future cost and performance improvement potentials.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ijhydene.2017.10.045.

Appendix

A. Best-practice recommendations to obtain representative results in expert elicitations

| Table A.1 – Cognitive heuristics and bias and recommended countermeasures [18,42]. |
|---------------------------------------------------------------|
| **Description**                                                                 | **Countermeasure**                                                                 |
| Anchoring Tendency to rely too heavily on a first piece of     | Informing interviewee about heuristic.                                             |
| information (the “anchor”), and adjust relatively conservatively| Asking for extreme estimates first (90th, 10th percentiles), then for median estimate (50th percentile). Asking for reasons for estimates to lie outside of indicated range. |
| from this when making probabilistic decisions, rather than fully considering factors which may influence a quantity of interest, leading to overconfident estimates, i.e. too narrow ranges. |                                                                                   |
| Availability Heuristic procedure of making a decision according to the ease with which one can imagine an event occurring, which may for example bias judgements towards recent trends or events. | Informing interviewee about heuristic. Providing background material to compile latest data and research insights from multiple sources. Asking for reasons for estimates to lie outside of indicated range. |
| Representativeness Heuristic procedure to evaluate the probability that an object/event (A) belongs to a class/process (B) by the degree to which A is representative of B, that is, the similarity between A and B. | Not applicable to this study. |
B. Method for comparison of expert estimates to experience rate based projections

Experience rates track the cost reduction of a technology as a function of cumulative production and allow the future projection of capital costs by forecasting the identified historic trend.

We use Wright's formula \([52]\) to project future capital cost based on the identified experience rates and future capacity additions, where \(P(x)\) is the price at the cumulative produced electrolyser capacity \(X\). The normalisation factor \(A\) and experience rate \(b\) are obtained with a regression analysis of the logarithms of the historic price and capacity data. ER refers to the experience rate in %.

\[
P(x) = A*(X)^{-b} \quad \text{ER} = 1 - 2^{-b}
\]

There are two scenarios for future capacity additions that we investigate, in line with the scenarios used for the expert elicitations:

- R&D: continued average annual market size of 0.36 GW\(_{el}\) [39]
- RD&D: annual market grows to 1 GW\(_{el}\) by 2020 and 2.5 GW\(_{el}\) by 2030 [16].

The R&D scenario is based on the average annual market size of 0.36 GW\(_{el}\) between 1956 and 2002 [39]. The RD&D scenario is based on stakeholder assessment for the EU and the assumption that the EU electrolysis market comprises 20% of the global market (EU share in global GDP [72]).

The experience rate for AEC systems is 18 ± 13% based on capital cost data from 1956 to 2002 [39]. We project the experience curve forwards to 2015 and include average AEC price data from 2005 [35] and 2015 [9] to assess the performance of the experience curve in the past 15 years. Global cumulative produced AEC capacity is around 24 GW\(_{el}\) in 2015 [39]. We then project the experience curve forwards to 2030 using the two market growth scenarios.

For PEMEC, the experience rate is based on capital cost development and cumulative production of PEM fuel cells between 2004 and 2015. The identified rates are 19.1–21.4% [73], 16% [74], 18% [75] and 18 ± 2% [48], of which we use the latter one. Experience curve starting point is set at 2015 with respective capital cost [16] and assumption of 1 GW\(_{el}\) cumulative produced PEMEC capacity.

The SOEC experience rate is based on capital cost development and capacity production of solid oxide fuel cells between 1996 and 2008, ranging between 12% and 44% [49]. Experience curve starting point is set at 2015 with respective capital cost (Expert H estimate for 1x R&D scenario in 2020, based on expert’s estimation rationale) and assumption of 0.1 GW\(_{el}\) SOEC capacity in 2015.

To convert expert estimates from € to US$, we use the average 2016 exchange rate of €1 = $1.10 [76].

C. Historic deployment of AEC and PEMEC systems in Power-to-Gas applications

The cumulative installed capacities of AEC and PEMEC systems in Power-to-gas applications (data taken from Ref. [50]).

Fig. B.1 – Cumulative installed water electrolysis capacity based on data from 1956 to 2002 [39] projected forwards to 2030 (RD scenario, black). Increased annual market modelled from 2015 to 2030 (RD&D scenario, grey).
Table D.2 – Median expert estimates for lifetime.

| Technology/Percentile | 2020 Lifetime (hours) | 2030 Lifetime (hours) |
|-----------------------|-----------------------|-----------------------|
|                       | 1x 2x 10x             | 1x 2x 10x             |
| AEC                   |                       |                       |
| 10th                  | Max                    | 110,000 115,000 120,000 | 80,000 80,000 82,500 |
|                       | Min                    | 80,000 80,000 80,000   | 80,000 80,000 82,500 |
| 50th                  | Max                    | 90,000 90,000 100,000  | 62,250 72,500 82,500 |
|                       | Min                    | 41,000 50,000 62,000   | 62,250 72,500 82,500 |
| 90th                  | Max                    | 80,000 80,000 80,000   | 40,000 40,000 40,000 |
|                       | Min                    | 40,000 40,000 40,000   | 40,000 40,000 40,000 |
| PEMEC                 |                       |                       |
| 10th                  | Max                    | 85,000 90,000 90,000   | 100,000 100,000 110,000 |
|                       | Min                    | 80,000 80,000 80,000   | 80,000 80,000 82,500 |
| 50th                  | Max                    | 41,000 50,000 62,000   | 62,250 72,500 82,500 |
|                       | Min                    | 45,000 50,000 55,000   | 65,000 65,000 65,000 |
| 90th                  | Max                    | 40,000 40,000 40,000   | 40,000 40,000 40,000 |
|                       | Min                    | 6000 6000 8000         | 10,000 10,000 10,000 |
| SOEC                  |                       |                       |
| 10th                  | Max                    | 100,000 115,000 130,000 | 120,000 125,000 150,000 |
|                       | Min                    | 15,000 15,000 20,000   | 40,000 40,000 50,000 |
| 50th                  | Max                    | 70,000 85,000 95,000   | 90,000 105,000 115,000 |
|                       | Min                    | 9000 10,000 11,000     | 30,000 35,000 35,000 |
| 90th                  | Max                    | 50,000 60,000 70,000   | 70,000 80,000 100,000 |
|                       | Min                    | 6000 6000 8000         | 10,000 10,000 10,000 |

Table D.1 – Median expert estimates for capital costs.

| Technology/Percentile | 2020 capital cost range (€/kW_el) | 2030 capital cost range (€/kW_el) |
|-----------------------|-----------------------------------|-----------------------------------|
|                       | R&D                               | RD&D                              | R&D                               | RD&D                              |
|                       | 1x 2x 10x                         | 1x 2x 10x                         | 1x 2x 10x                         | 1x 2x 10x                         |
| AEC                   | Max                                | 1400 1400 1100 1350 1350 900      | 1000 1000 900 800 800 750          |
|                       | Min                                | 1000 900 850 900 900 800          | 1000 1000 900 800 800 750          |
| 50th                  | Max                                | 1300 1250 900 1300 1250 750       | 750 750 700 550 550 500            |
|                       | Min                                | 800 800 725 600 600 550           | 750 750 700 550 550 500            |
| 10th                  | Max                                | 1200 1150 800 1200 1150 700       | 700 700 650 400 400 350            |
|                       | Min                                | 700 700 600 450 450 400           | 700 700 650 400 400 350            |
| PEMEC                 | Max                                | 2200 2200 2200 1980 1980 1980     | 1980 1980 1760 1584 1584 1408      |
|                       | Min                                | 1300 1250 1000 1100 1050 950      | 1000 900 800 950 850 750           |
| 50th                  | Max                                | 1925 1925 1760 1733 1733 1584     | 1650 1650 1430 1320 1320 1144      |
|                       | Min                                | 1000 950 850 800 750 700          | 850 750 600 550 500 400            |
| 10th                  | Max                                | 1650 1650 1320 1485 1485 1188     | 1100 1100 1100 880 880 880         |
|                       | Min                                | 800 750 700 650 600 550           | 700 600 500 350 350 250            |
| SOEC                  | Max                                | 8000 8000 8000 4000 3900 3700      | 6800 6800 6800 3900 3800 3500       |
|                       | Min                                | 4000 4000 4000 4000 3200 2500      | 1250 1200 800 1000 900 750         |
| 50th                  | Max                                | 5000 4500 4500 3000 2750 2500      | 4250 3825 3825 2500 2500 2200       |
|                       | Min                                | 3000 2750 2500 2000 1600 1400      | 1050 1000 650 700 600 550           |
| 10th                  | Max                                | 3500 3000 3000 2000 2000 1900      | 2975 2550 2550 1900 1900 1500       |
|                       | Min                                | 2500 2000 1900 1200 1200 1000      | 750 750 500 500 400 300            |
E. Quantitative expert estimates for system efficiency

Fig. E.1 – Elicited expert estimates for 2020 and 2030 electrolysis system energy requirements (in kWh_{el}/m^3 H_2 – refers to norm cubic meter of hydrogen at standard conditions). Data points indicate 50th, uncertainty bars 90th and 10th percentile estimates. Secondary y-axis shows thermodynamic system efficiency relative to the higher heating value of hydrogen (HHV). Expert C made estimates for AEC and PEMEC. Expert J made estimates for AEC zero gap configuration. Results are sorted by technology and in ascending order for 50th percentiles. 2016 reference values based on Table 1.

F. Number of experts naming innovations by 2020 or 2030 per innovation area

Fig. F.1 – Number of experts naming innovations by 2020 or 2030 per innovation area.
G. Detailed breakdown of innovations for AEC, PEMEC and SOEC technology

| Impact Area | Component | Innovation | Comment |
|-------------|-----------|------------|---------|
| Reduced capital cost | Cells | Increased current density | Up to 0.5 or 0.6 A/cm² by 2020 |
| | Catalysts | Better materials | Mixed metal oxides, e.g. RuOx, IrOx; leads to increased current density due to higher reaction rates |
| | Electrodes | More stable electrode materials | |
| | Electrolyte | Electrolytes for high temperature operation | e.g. molten salts; by 2030 |
| | Separator | New membrane | e.g. ion-solvating; ion-exchange; effect is higher current density (due to lower internal resistance) |
| | Stack | High pressure operation | Effect is higher current density; by 2020 |
| | System Balance-of-Plant | Aq. KOH lye circulation loop | - improved system dynamics |
| | | Thermal management | - lower cost |
| | | Water purification | |
| | New set-up/chemistries | Zero-gap configuration | i.e. non-porous membrane, porous electrodes; effect is increased current density (due to lower internal resistance) |
| Longer lifetime | Cells | More stable electrodes | e.g. better materials, design, catalyst coating |
| | System | Incremental improvements | |
| | Balance-of-Plant | Improved water purification | Effect is less impurities (e.g. trace metals) in feed-water that plate onto electrodes and deactivate them |
| | New set-up/chemistries | Higher durability materials for zero-gap cells | |
| | | New system configurations | Avoidance of impurity penetration (e.g. valves set-up) |
| Higher efficiency | Cells | Electrode | Improved design |
| | | Ion Exchange Membrane | e.g. Alkaline PEM |
| | System Balance-of-plant | Thermal management | |
| | | Water purification | e.g. 3–5% system efficiency; |
| | | Hydrogen drying | |
| | | Rectification | e.g. 2–3% system efficiency with more expensive diodes |
| | Operation | Start/Stop procedure | Optimised depending on operation strategy |
| | New set-up/chemistries | Higher operating temperature | e.g. 200 °C, by 2030 |
| | | Zero-gap configuration with state-of-the-art membrane/diaphragm | By 2030 |
### Table G.2 – AEC system innovations due to production scale-up (innovations in bold were mentioned by multiple experts).

| Impact Area | Category | Innovation | Comment |
|-------------|----------|------------|---------|
| Manufacturing | Automation | Reduced capital cost | From batch to roll-to-roll production |
| | | Method | Electrode coating process |
| | | Scale | Increased production rates |
| | | Experience | Learning in manufacturing |
| | | Supply chain | Volume purchasing agreements |
| | | Longer lifetime | Manufacturing |

| Impact Area | Component | Innovation | Comment |
|-------------|-----------|------------|---------|
| Manufacturing | Method | Manufacturing in clean rooms | Avoid impurity penetration |

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### Table G.3 – PEMEC system innovations as a result of R&D (innovations in bold were mentioned by multiple experts).

| Impact Area | Component | Innovation | Comment |
|-------------|-----------|------------|---------|
| Reduced capital cost | Cell | Increased current density | Up to 3 A/cm² by 2020 |
| Catalyst | Lower loading of Platinum-group metal catalysts | Incremental reduction, up to –50% by 2020, e.g. due to more stable support (Ir/Ru not as blacks) |
| Electrode | Structural improvements | Incremental up to 2030, enabling more efficient use of catalyst particles |
| Membrane | Thinner | Incremental up to 2030 |
| Stack | Electrochemical pressurisation | Up to 100 bar by 2030 |
| Bipolar Plates | Reduction of titanium use | High conductivity coating on low-cost substrate e.g. steel instead of titanium; 10–20% cost reduction by 2020, up to 100% by 2030 |
| System | Combination and scale-up of system components due to operational de-risking/increased operational confidence | To enable mass transport at increased current densities |
| Balance-of-Plant | More efficient water purification | “good engineering”, e.g. pumps, cooling |
| Operation | Optimised operation set points | |
| New set-up/chemistries | Alkaline Polymer Systems | Novel stack designs e.g. rotating systems |
| | Novel stack designs | |
| Longer lifetime | Cell | Improved durability | |
| Catalyst | Structural improvements | Electrode design and/or coating reduces movement/deactivation of active catalyst particles |
| Electrode | Higher physical stability | Incremental |
| Membrane | Higher impurity tolerance | |
| Stack | Slower H2 embrittlement through more suitable coating | |
| System | Improved water purification | |
| Balance-of-Plant | Improved water purification | |
| New set-up/chemistries | Avoidance of impurity penetration e.g. valves set-up | |

(continued on next page)
Table G.3 – (continued)

| Impact              | Area      | Component | Innovation                          | Comment                                                                 |
|---------------------|-----------|-----------|-------------------------------------|-------------------------------------------------------------------------|
| Higher efficiency   | Cell      | Membrane  | Thinner                             | -120 °C in pressurised systems leading to 15–20% increase in stack efficiency and increase in cooling efficiency |
| Stack               |           |           | Higher operating temperatures       |                                                                         |
| System              | Balance-of-Plant |         | More efficient rectification through more expensive diodes | e.g. 2–3% increase                                                                 |
|                     |           |           | More efficient hydrogen purification | e.g. 3–5% increase                                                                 |

Table G.4 – PEMEC system innovations due to production scale-up (innovations in bold were mentioned by multiple experts).

| Impact                  | Area     | Category     | Innovation                               | Comment                                                                 |
|-------------------------|----------|--------------|------------------------------------------|-------------------------------------------------------------------------|
| Reduced capital cost    | Manufacturing | Automation  | From batch to roll-to-roll production   | e.g. membrane electrode assembly (MEA)                                   |
|                         |          |              | Improved process integration            |                                                                         |
|                         |          |              | Robot assembly                           |                                                                         |
|                         |          |              | Method                                   |                                                                         |
|                         |          |              | Water/laser cutting                      | e.g. sheets                                                             |
|                         |          |              | Stamping                                 | e.g. bipolar plates                                                     |
|                         |          |              | Hydroforming                             | e.g. bipolar plates                                                     |
|                         |          |              | Layer-by-layer wielding                  | e.g. stack                                                              |
|                         |          |              | Plastic injection moulding               |                                                                         |
|                         |          |              | Scale                                    |                                                                         |
|                         |          |              | Increased production rates               | Economies of scale with reduced overhead costs, in particular effect for MEA |
|                         |          |              | Larger unit sizes                        | less engineering work per kW and BoP scale effects                     |
|                         |          |              | Larger plant sizes                       | Reduced overhead costs                                                  |
|                         |          |              | Design                                   |                                                                         |
|                         |          |              | Design for manufacture and low costs     |                                                                         |
|                         |          |              | Bespoke BoP components                    |                                                                         |
|                         |          |              | Component standardisation                | Standards/codes between suppliers                                       |
|                         |          |              | Experience                               | Incremental improvements                                                |
|                         |          |              | Supply chain                             |                                                                         |
|                         |          |              | Volume                                   |                                                                         |
|                         |          |              | Volume purchasing agreements             |                                                                         |
|                         |          |              | Competition                              | Stronger supplier competition                                           |
|                         |          |              |                                          | e.g. membrane electrode assembly (MEA)                                  |
|                         |          |              | Longer lifetime                          |                                                                         |
|                         |          |              | Manufacturing                            |                                                                         |
|                         |          |              | Method                                   | Manufacturing in clean rooms                                            |
|                         |          |              |                                          | Avoid impurity penetration                                              |
| Impact Area | Component | Innovation | Comment |
|-------------|-----------|------------|---------|
| Reduced capital cost | Cell | Higher power density | Due to thinner materials as result of better material processing methods (e.g. vapour deposition) |
| | | Material-Microstructure combination/integration | optimise triple phase boundary network |
| | | Size scale-up | optimise oxygen transport |
| | Catalyst | Alternatives for Nickel and Cobalt | |
| | Electrodes | Reduce polarisation resistance | Enable lower operating temperatures (~450 °C); positive effects on lifetime |
| | | Replace Ni-YSZ with stainless steel | |
| | Membrane | Proton conducting materials | |
| | System | Leaner system engineering | Result of field experience |
| | | Improved system integration | |
| | | Pressurised system | e.g. up to 40 bar |
| | Balance-of-Plant | Optimised components and system integration | Result of lower operating temperature |
| | New set-up/chemistries | Proton conducting cell design | to produce dry H2 at high operating temperatures |
| | | Reversible systems (electrolysis, fuel cell operation) | |
| Longer lifetime | Cell | More robust materials | As result of better material processing methods (e.g. vapour deposition) |
| | | Material-Microstructure combination/integration | optimise triple phase boundary network |
| | | Electrodes | optimise oxygen transport |
| | | Reduce polarisation resistance | Enable lower operating temperatures (~450 °C); positive effects on lifetime |
| | System | Operation | Optimised operation scheme |
| | | Methods for accelerated testing | Methods for in-situ monitoring |
| | Higher efficiency | Cell | Material-Microstructure combination/integration | optimise triple phase boundary network |
| | | System | optimise oxygen transport | |
| | | Balance-of-Plant | Optimised components and system integration | Result of lower operating temperature |
Table G.6 – SOEC system innovations due to production scale-up (innovations in bold were mentioned by multiple experts).

| Impact            | Area          | Category           | Innovation                                                                 | Comment                                                                 |
|-------------------|---------------|--------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Reduced capital cost | Manufacturing | Automation Method  | From batch to roll-to-roll production                                        | High investment manufacturing technologies for low cost production (i.e. additive manufacturing) |
|                   |               |                    | Vapour deposition                                                           |                                                                         |
|                   |               |                    | Laser printing                                                              |                                                                         |
|                   |               |                    | Typecasting                                                                 |                                                                         |
|                   |               |                    | Screen printing                                                             |                                                                         |
|                   |               |                    | 3D-printing                                                                 |                                                                         |
|                   |               |                    | Thin-film technologies                                                      |                                                                         |
|                   |               | Scale              | Increased production rates                                                  | Economies of scale with reduced overhead costs                          |
|                   | Supply chain  |                    | Mass produced balance-of-system components                                 |                                                                         |
|                   | Volume        |                    | Volume purchasing agreements                                               | e.g. materials, components, balance-of-plant                            |
|                   | Competition   | More suppliers      |                                                                             |                                                                         |
| Longer lifetime   | Manufacturing | Method             | Improved material processing (e.g. vapour deposition)                      |                                                                         |

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