INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 30470–30492

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

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ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form
29 September 2017
Accepted 9 October 2017
Available online 22 November 2017

Keywords:
Water electrolysis
Energy storage
Expert elicitation
Capital cost
Lifetime
Innovation

ABSTRACT

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 (PEMEC) 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 PEMEC 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.

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

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https://doi.org/10.1016/j.ijhydene.2017.10.045

0360-3199/

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 [32–34]. 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 ($CO + H_2$) from water steam (H_2O)

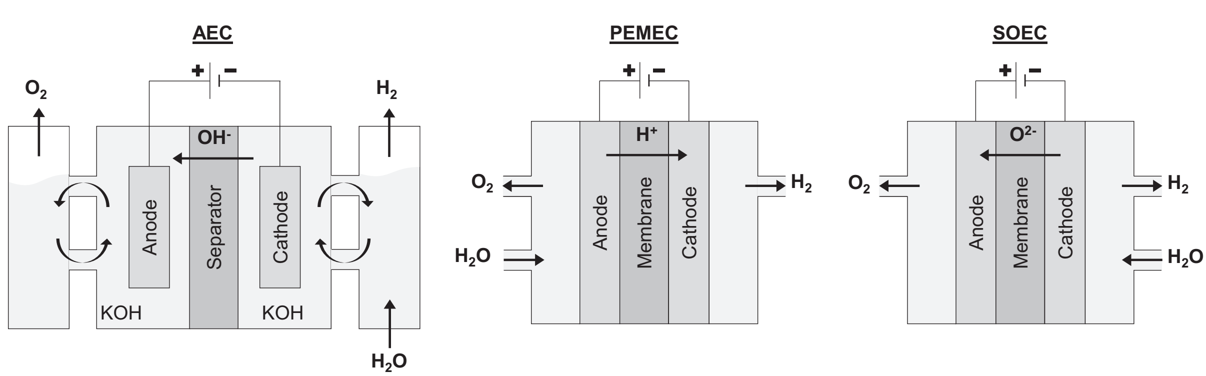

Fig. 1 – Conceptual set-up of three electrolysis cell technologies [9].

Table 1 – Main characteristics of AEC, PEMEC and SOEC systems.

	AEC	PEMEC	SOEC
Electrolyte	Aq. potassium hydroxide (20–40 wt% KOH) [9,32,33]	Polymer membrane (e.g. Nafion) [33,34]	Yttria stabilised Zirconia (YSZ) [37,38]
Cathode	Ni, Ni-Mo alloys [9,32,33]	Pt, Pt-Pd [34]	Ni/YSZ [37,38]
Anode	Ni, Ni-Co alloys [9,32,33]	RuO_2, IrO_2 [34]	LSM[b]/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 (m^2)	<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[c] (m^3_{H2} h^{-1})	<760 [33]	<40 [33]	<40 [33]
Stack energy[c] (kWh_{el} m^{-3}_{H2})	4.2–5.9 [34]	4.2–5.5 [34]	>3.2 [33]
System energy[c] (kWh_{el} m^{-3}_{H2})	4.5–6.6 [16]	4.2–6.6 [16]	>3.7 $(>4.7)_{kWh\_energy}$[a]
Gas purity (%)	>99.5 [32]	99.99 [33]	99.9[a]
Lower dynamic range[d] (%)	10 – 40 [33,34]	0 – 10 [34]	>30[a]
System Response	Seconds [33]	Milliseconds [33]	Seconds[a]
Cold-start time (min.)	<60 [16]	<20 [16]	<60[a]
Stack Lifetime (h)	60,000–90,000 [16]	20,000–60,000 [16]	<10,000[a]
Maturity	Mature	Commercial	Demonstration[a]
Capital Cost (€ kW_{el}^{-1})	1000–1200 [16]	1860–2320 [16]	>2000 [16]

[a] Where no reference is provided, data were derived during expert elicitations.
[b] Perovskite-type lanthanum strontium manganese ($La_{0.8}Sr_{0.2}MnO_3$).
[c] Refers to norm cubic meter of hydrogen (at standard conditions) and respective electrical energy consumption (kWh_{el}) if applicable.
[d] Minimum operable hydrogen production rate relative to maximum specified production rate.

and carbon dioxide (CO_2) [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_{el}^{-1} and 2000 € kW_{el}^{-1} for AEC and PEMEC systems (1 MW_{el}) respectively [9,16] (kW_{el} or MW_{el} refer to the electrical power consumption). SOEC systems are not yet widely commercially available and cost estimates lie above 2000 € kW_{el}^{-1} [16]. Studies comparing the capital cost of AEC systems to steam methane reformers (SMR), the incumbent technology for hydrogen production, report AEC costs to be around two to three times more expensive [39]. SMRs, however, are based on methane gas reformation, thereby rely on natural gas and cannot store intermittent renewable electricity or transfer it into other energy sectors.

The requirements for electrolysers to operate with intermittent power sources are: fast response of system components enabling dynamic operation; operation at lower dynamic range (see Table 1) without negative impacts on gas purity; and short cold-start times or energy efficient stand-by operation [35]. While PEMEC electrolysers appear to be best-suited to meet 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 2 – Elicitation procedure.

Phase	Interactions with expert	Timeline/Duration
Before interview	1. Making initial contact	–
	2. Sending elicitation protocol (background material, questionnaire)	2 weeks before interview
During 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

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

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)

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

Power Source	Intermittent Renewables
System Size	10 MW_{el}
H_2 output pressure	20–30 bar
H_2 application	Injection into natural gas grid

- 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 (R&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

- System: Balance-of-Plant, Operation, New set-up/ chemistry, Multiple
- Manufacturing: Automation, Design, Experience, Method, Scale
- Supply Chain: Volume, Competition

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).

The three experts favouring SOEC in 2030 highlighted superior efficiency when co-located with industrial processes, operational flexibility (co-electrolysis or reverse operation as fuel cell) and potentially low capital costs due to low cost materials.

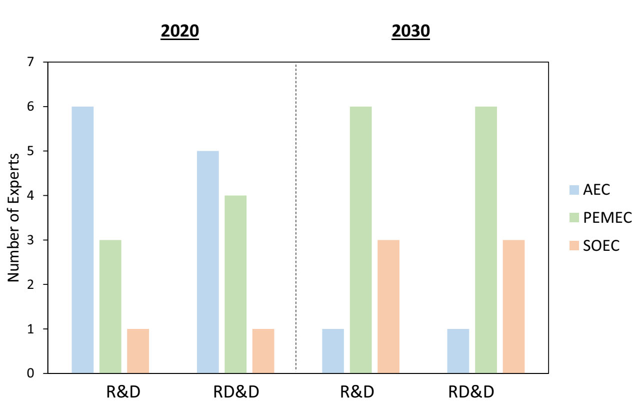

Fig. 2 – Expert's choice of technology with best suitability for given case study (R&D – no production scale-up, RD&D – production scale-up).

Capital costs

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 (◆ R&D, 1x) lie between 800 and 1300 € kW_{el}^{-1} (all 50th percentile estimates), but could range from 700 (lowest 10th) to 1400 € kW_{el}^{-1} (highest 90th). For PEMEC the respective range is 1000–1950 € kW_{el}^{-1} (all 50th) and 800–2200 € kW_{el}^{-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_{el}^{-1} (all 50th) with a significantly higher uncertainty range of 2500–8000 € kW_{el}^{-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 (◆ R&D, 1x) are estimated slightly lower than in 2020 at 750 € kW_{el}^{-1} (50th), potentially ranging from 700 to 1000 € kW_{el}^{-1} (10th, 90th). Similarly, the respective PEMEC estimates are slightly below 2020 figures, ranging from 850 to 1650 € kW_{el}^{-1} (all 50th) or 700–1980 € kW_{el}^{-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_{el}^{-1} (all 50th), however still highly uncertain with 750–6800 € kW_{el}^{-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 (● RD&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 (RD&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].

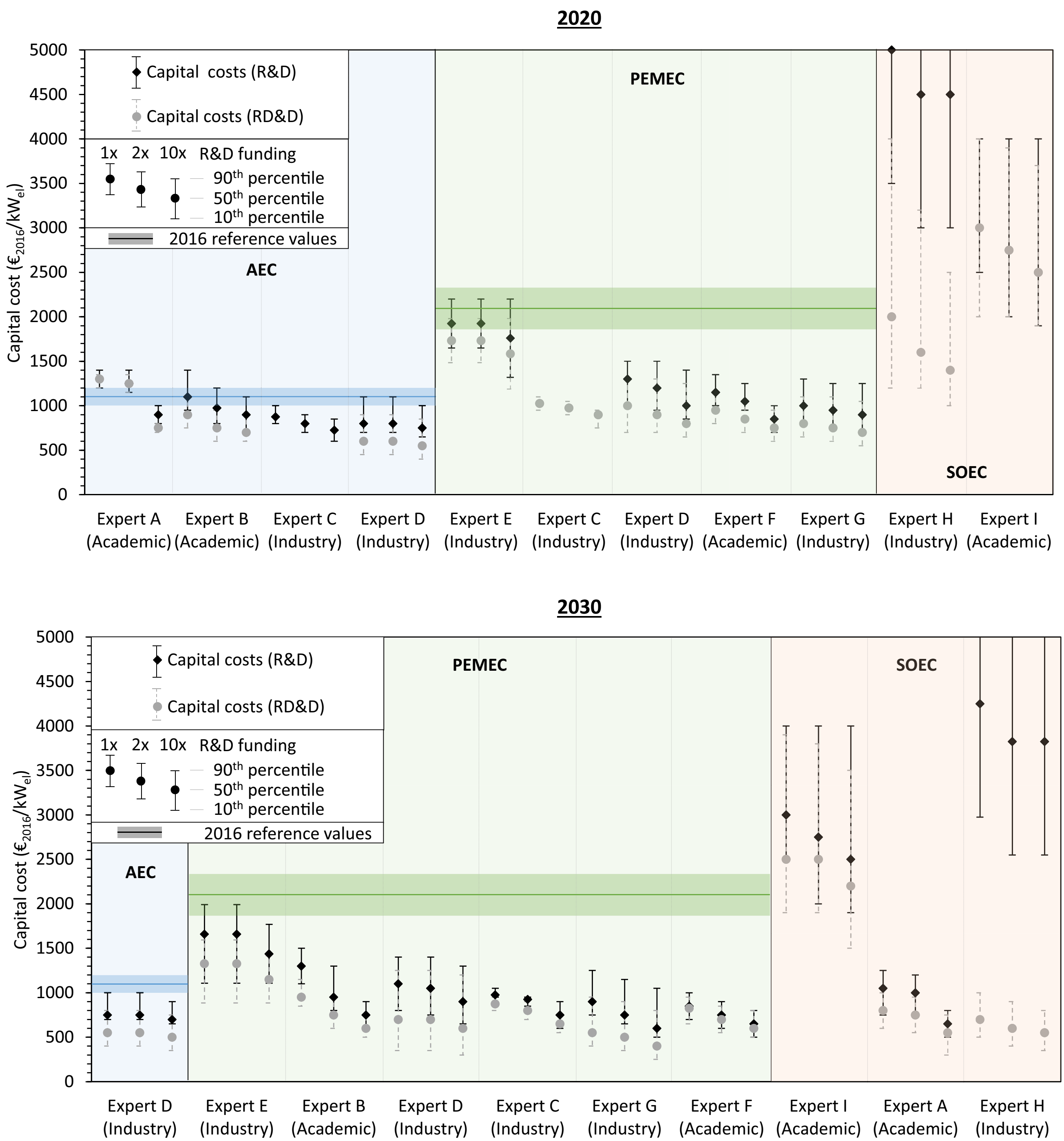

Fig. 3 – Elicited expert estimates for 2020 and 2030 capital costs without (◆ R&D) and with production scale-up (● RD&D) as a function of R&D funding (1x, 2x, 10x). Data points indicate 50th, uncertainty bars 90th and 10th percentile estimates. Expert C made 2020 estimates for AEC (R&D) or PEMEC (RD&D). Expert D made all estimates for AEC and PEMEC. Results are sorted by technology and in descending order for 50th percentiles without production scale-up (◆ R&D). 2016 reference values based on Table 1. No 2016 reference vales for SOEC as this technology is not yet widely commercialised.

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

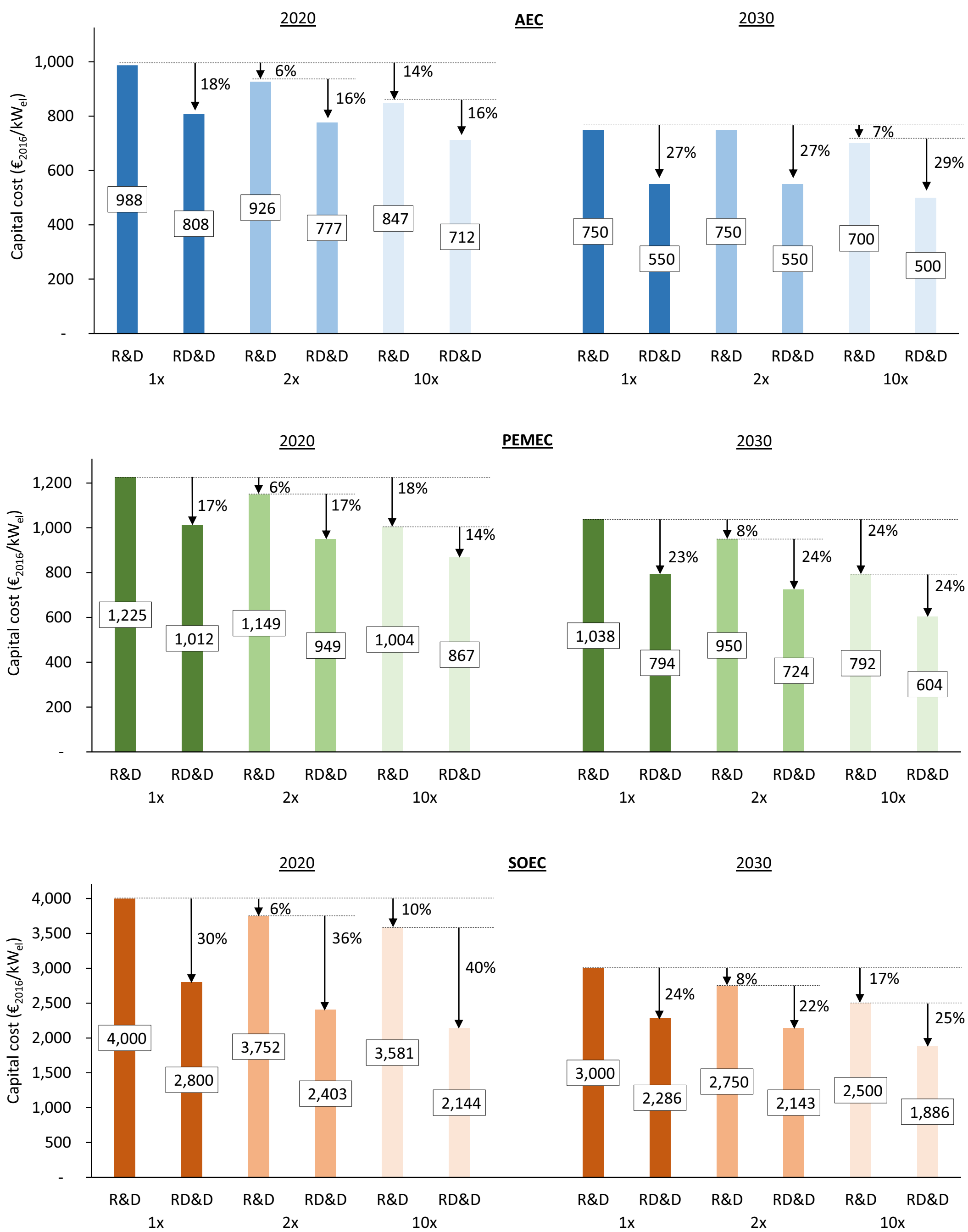

Fig. 4 – Relative impact of R&D funding (1x, 2x, 10x) and production scale-up (R&D, RD&D) on capital costs. Expert responses: AEC, 2020 = 4 (R&D) and 3 (RD&D); AEC, 2030 = 1; PEM, 2020 = 3 (R&D) and 4 (RD&D), PEM, 2030 = 6; SOEC, 2020 = 2; SOEC, 2030 = 3. First bar in 2020 and 2030 represents median of experts' 50th percentile cost estimates. All other capital cost figures are based on median percentage reduction of experts' 50th percentile estimates (percentage numbers).

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

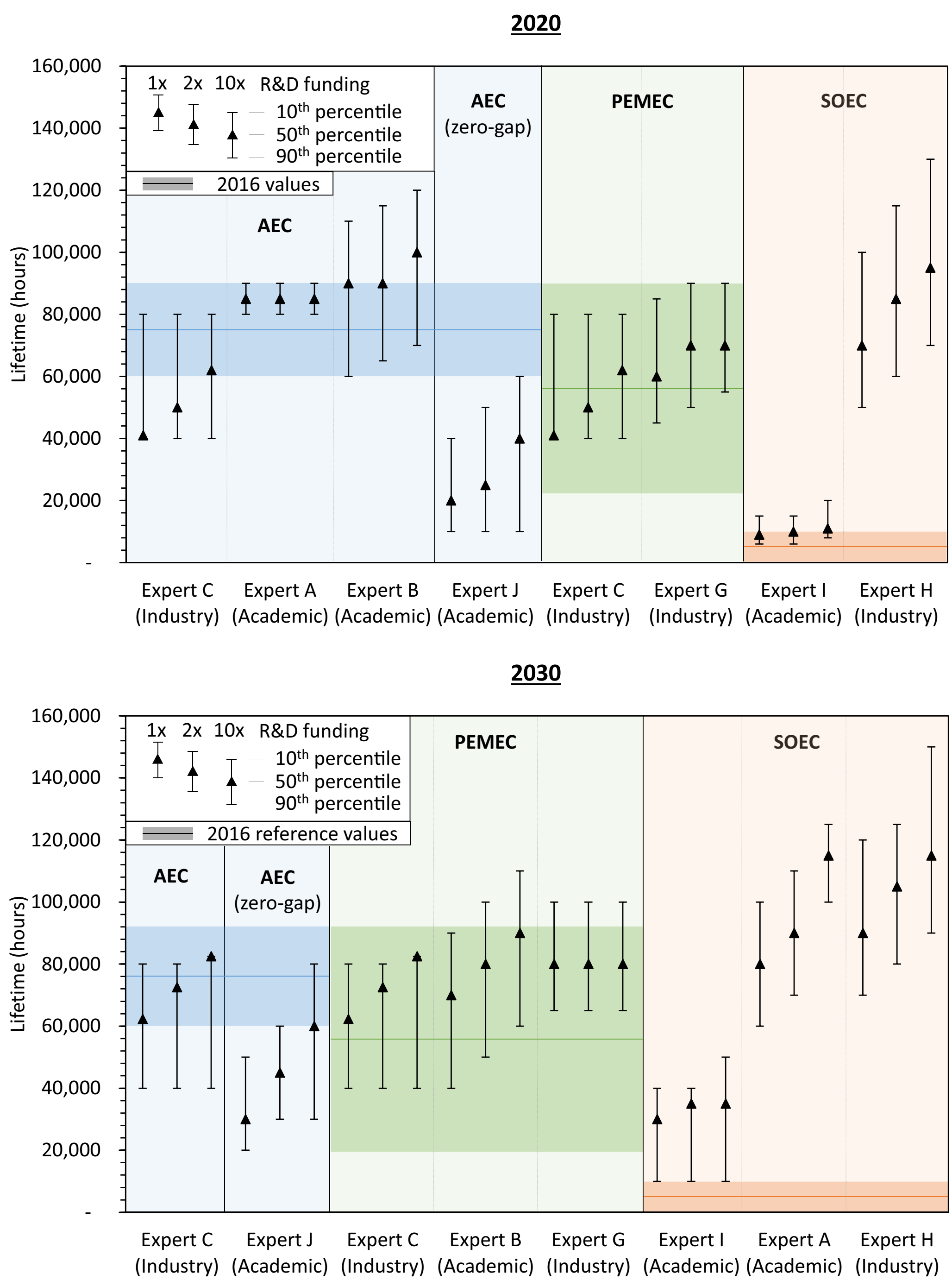

Fig. 5 – Elicited expert estimates for 2020 and 2030 lifetime (in hours) as a function of R&D funding (1x, 2x, 10x). Data points indicate 50th, uncertainty bars 90th and 10th percentile estimates. Expert C made estimates for AEC and PEMEC. Expert J made estimates for AEC zero gap configurations. Results 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: 90,000 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 (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 (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

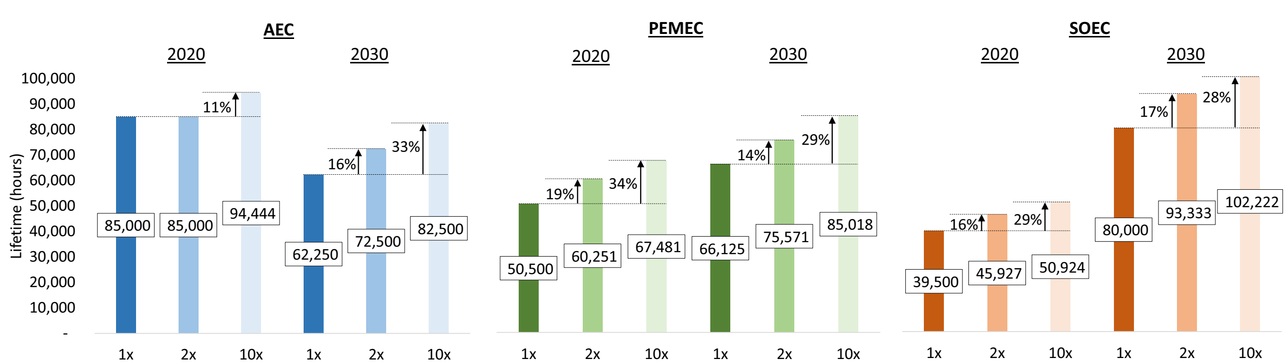

Fig. 6 – Relative impact of R&D funding (1x, 2x, 10x) on lifetime. Expert responses: AEC, 2020 = 3; AEC, 2030 = 1; PEM, 2020 = 2, PEM, 2030 = 3; SOEC, 2020 = 2; SOEC, 2030 = 3. First bar in 2020 and 2030 estimates shows median of experts' 50th percentile estimates. All other lifetime numbers are based on median percentage reduction of experts' 50th percentile estimates (percentage numbers). Responses for AEC zero gap technology are not displayed. Apparent reduction of AEC lifetime from 2020 to 2030 is result of reduced number of expert responses.

cell-level. Improvements are focussed 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

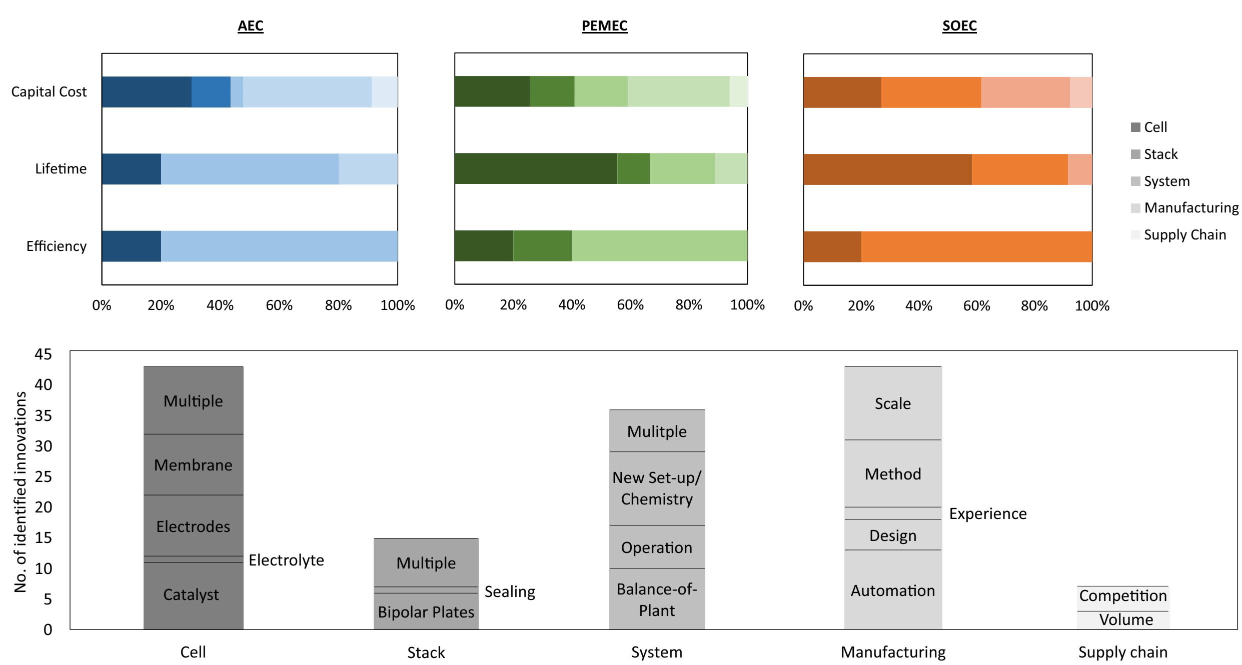

Fig. 7 – Top: Relative share of identified innovations along technology (AEC, PEMEC, SOEC), impact (Capital Cost, Lifetime, Efficiency) and innovation area (From darkest to lightest: Cell, Stack, System, Manufacturing, Supply Chain). No innovation mentioned on stack-level for SOEC. Bottom: Absolute number 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.

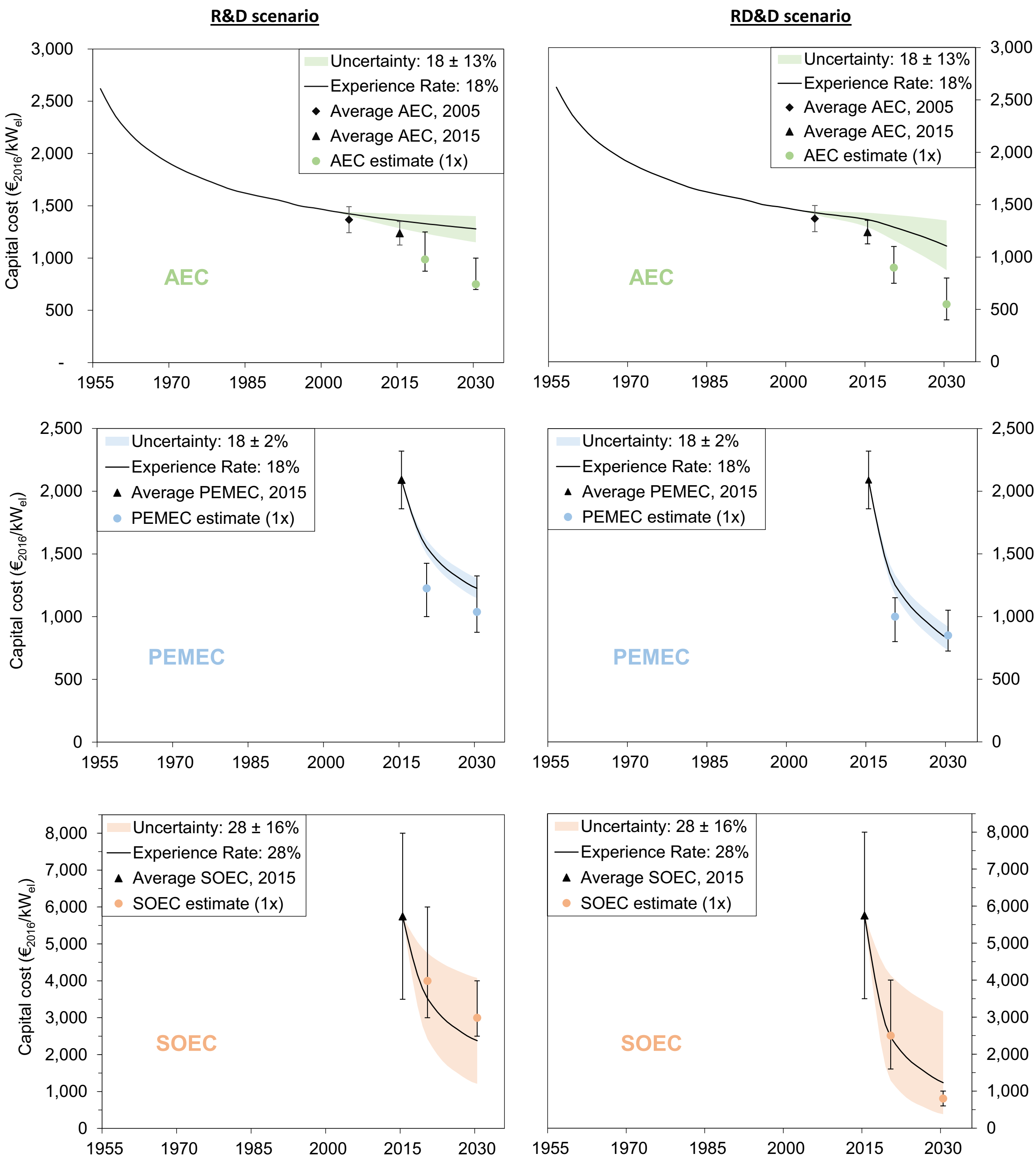

Fig. 8 – Comparison of median expert estimates on capital costs to capital cost projections based on experience rates for AEC, PEMEC and SOEC at current R&D funding (1x) without (left) and with production scale-up (right). Left: Constant production capacity from 2015 onwards based on continued historic deployment rates; annual market 0.36 GW_{el}. Right: Production scale-up from 2015 onwards as a result of increased deployment, annual market of 1 GW_{el} by 2020 and 2.5GW_{el} 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 elicitations tend 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 ± 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.

Acknowledgements

We would like to thank all participating experts for sharing their expertise for these elicitations. Also, we would like to acknowledge Prof Nigel Brandon and Dr Gregory Offer for their valuable feedback on the design of this study. In addition, Oliver Schmidt would like to acknowledge support from the Imperial College Grantham Institute for his PhD research. This work was enabled through the EPSRC and ESRC Imperial College London Impact Acceleration Accounts EP/K503733/1 and ES/M500562/1.

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 information (the "anchor"), and adjust relatively conservatively 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.	Informing interviewee about heuristic. 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.
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 %.

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

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])

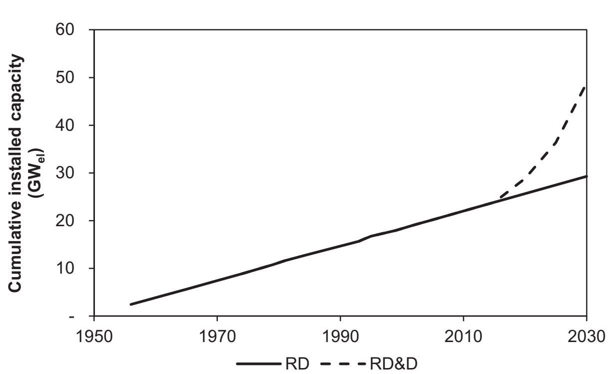

Fig. B.1 – Cumulative installed water electrolysis capacity based on data from 1956 to 2002 [39] projected forwards to 2030 (RD scenario, black). Increased annual market modelled from 2015 to 2030 (RD&D scenario, grey).

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

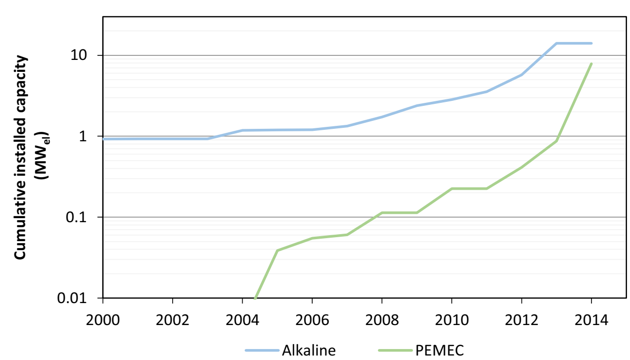

Fig. C.1 – Cumulative installed capacities of AEC and PEMEC systems in Power-to-gas applications (data taken from Ref. [50]).

D. Median expert estimates in tabular form

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	90th	*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	90th	*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	90th	*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

Table D.2 – Median expert estimates for lifetime.

Technology/Percentile			Lifetime (hours)					
			2020			2030		
			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*	60,000	70,000	70,000	80,000	80,000	90,000
		Min	41,000	50,000	62,000	62,250	72,500	80,000
	90th	*Max*	45,000	50,000	55,000	65,000	65,000	65,000
		Min	40,000	40,000	40,000	40,000	40,000	40,000
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

E. Quantitative expert estimates for system efficiency

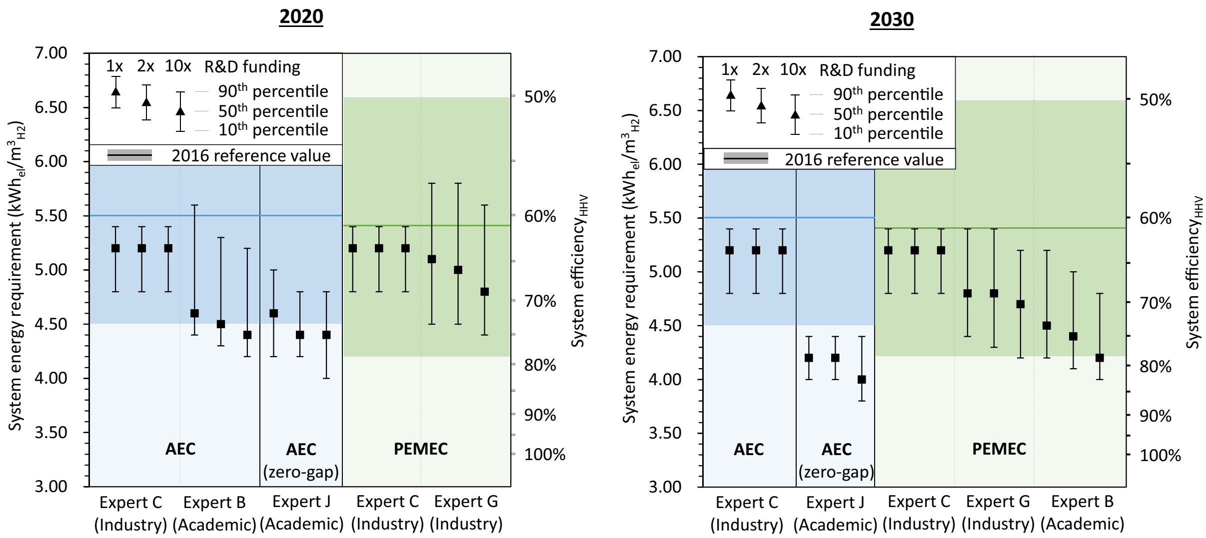

Fig. E.1 – Elicited expert estimates for 2020 and 2030 electrolysis system energy requirements (in $kWh_{el}/m^3{}_{H2}$ – refers to norm cubic meter of hydrogen at standard conditions). Data points indicate 50th, uncertainty bars 90th and 10th percentile estimates. Secondary y-axis shows thermodynamic 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

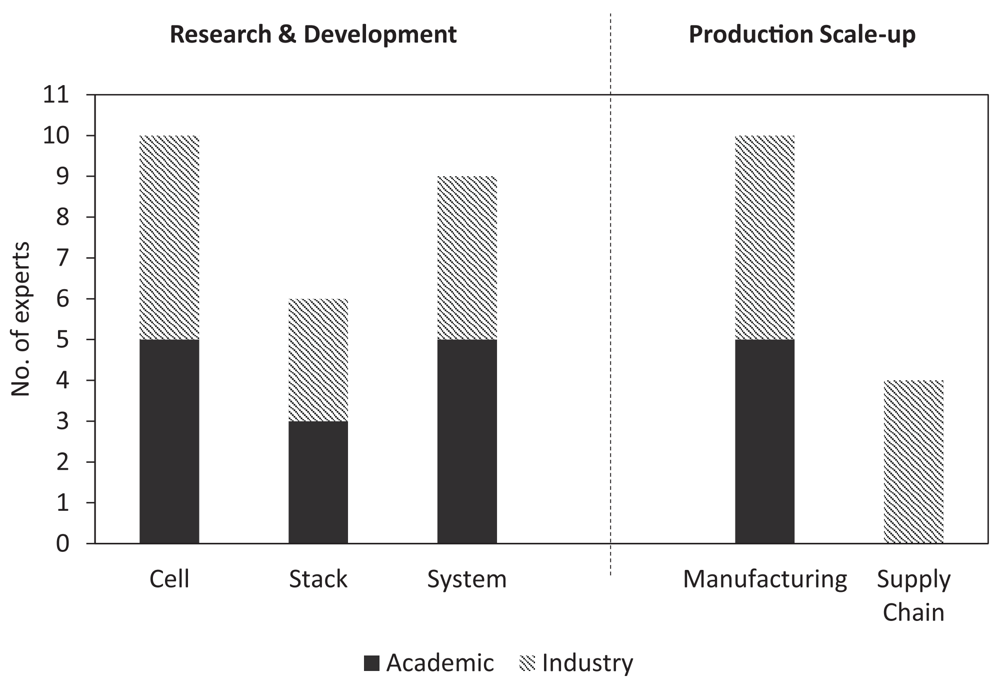

Fig. F.1 – Number of experts naming innovations by 2020 or 2030 per innovation area.

G. Detailed breakdown of innovations for AEC, PEMEC and SOEC technology

Table G.1 – AEC system innovations as a result of R&D (innovations in bold were mentioned by multiple experts).

Impact	Area	Component	Innovation	Comment
Reduced capital cost	Cells		Increased current density	Up to 0.5 or 0.6 A/cm^2 by 2020
		Catalysts	**Better materials**	Mixed metal oxides,e.g. RuOx, IrOx; leads o 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
			Larger stack sizes	e.g. 200kW; by 2020
	System	Balance-of-Plant	Aq. KOH lye circulation loop Thermal management	- improved system dynamics - 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	Electrodes	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	optimise transport processes (e.g. electrons, ions, water, bubbles)
		Separator	Ion Exchange Membrane	e.g. Alkaline PEM
	System	Balance-of-plant	Lye circulation	
			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
Reduced capital cost	Manufacturing	Automation	From batch to roll-to-roll production	
			Robot assembly	
		Method	**Electrode coating process**	e.g. plasma method
		Scale	**Increased production rates**	Economies of scale with reduced overhead costs
			Larger unit sizes	less engineering work per kW and BoP scale effects
			Larger plant sizes	Reduced overhead costs
		Experience	Learning in manufacturing	Incremental improvements
	Supply chain	Volume	Volume purchasing agreements	e.g. materials, components, balance-of-plant
Longer lifetime	Manufacturing	Method	Manufacturing in clean rooms	Avoid impurity penetration

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/cm^2 by 2020
			Size scale up	scale effects in cell, stack and system components
		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)
			New/Improved catalysts	e.g. Telluride, nano-catalysts
		Electrode	Structural improvements Improved coating	Incremental up to 2030, enabling more efficient use of catalyst particles
		Membrane	Thinner	Incremental up to 2030
			Novel Chemistries	e.g. non-fluorinated/organic alternatives to Nafion
	Stack		Electrochemical pressurisation	Up to 100 bar by 2030
			Differential pressure operation	
			Increased stack size	Reduces overall system footprint and costs
		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
			Optimised diffusor set-up	To enable mass transport at increased current densities
	System		**Combination and scale-up of system components due to operational de-risking/increased operational confidence**	Safe operation with >200 cells, e.g. combined and scaled cooling and water circulation
		Balance-of-Plant	More efficient water purification	
			Improved component integration	"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
			Design for high pressure operation	new stack concepts
Longer lifetime	Cell	Catalyst	Improved durability	
		Electrode	Structural improvements	Electrode design and/or coating reduces movement/ deactivation of active catalyst particles
		Membrane	**Higher physical stability** **Higher impurity tolerance**	Incremental
	Stack	Bipolar Plates	Slower H2 embrittlement through more suitable coating	
	System	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	
	Stack		Higher operating temperatures	~120 °C in pressurised systems leading to 15–20% increase in stack efficiency and increase in cooling efficiency
	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	Learning in manufacturing	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

Table G.5 – SOEC 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		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 optimise oxygen transport
			Size scale-up	Larger cell area
		Catalyst	Alternatives for Nickel and Cobalt	
		Electrodes	Reduce polarisation resistance Replace Ni-YSZ with stainless steel	Enable lower operating temperatures (~450 °C); positive effects on lifetime
		Membrane	Proton conducting materials	
	System		**Leaner system engineering** **Improved system integration**	Result of field experience
			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 optimise oxygen transport
		Electrodes	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 optimise oxygen transport
	System		Pressurised system	e.g. up to 40 bar
			Leaner system engineering	Result of field experience
			Improved system integration	
		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	From batch to roll-to-roll production	
		Method	Vapour deposition Laser printing	High investment manufacturing technologies for low cost production (i.e. additive manufacturing)
			Typecasting	
			Screen printing	
			3D-printing	
			Thin-film technologies	
		Scale	**Increased production rates**	Economies of scale with reduced overhead costs
			Mass produced balance-of-system components	
	Supply chain	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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