

Assessing emerging energy-efficient technologies for industry – application of the EDUAR&D methodology for the case of high temperature electrolysers

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Abstract

Research and Development (R&D) for energy efficient solutions is not an objective for itself, but it must serve society by reducing energy costs and avoiding GHG emissions. Public R&D funds should be efficiently allocated as far as possible by addressing substantial energy efficiency potentials, by identifying bottlenecks and detectable risks, and by supporting the stakeholder dialogue with comprehensive information.

These objectives can be supported by applying a methodology that has been developed by an interdisciplinary group of energy technologists, economists, and innovation researchers, called the Energy Data and Analysis of Research & Development – EDUAR&D; (Jochem et al. 2009). The methodology has been successfully applied to several energy technologies, such as passive houses, industrial furnaces, the PEM fuel cell, and carbon capture and storage.

The paper at hand gives summarised results from an analysis of solid oxide high temperature electrolysers as an innovative and energy efficient means to produce green hydrogen, e.g. for utilization in future primary steelmaking. Where applicable, e.g. for the innovation system, regional specifics for the case of Germany were assessed.

The analysis presented shows a promising energy efficient electrolyser technology for basic industries, in a low-to-medium stage of its technological development, with a considerable increase of R&D and patent activities (but still on a rather low absolute level), low market activities and a very clear need

for policies supporting further R&D as well as market entry through industrial scale demonstration plants.

Introduction – the EDUAR&D methodology

Researchers often focus intensively on particular activities. However, public funding of research and development assessing the chances and risks of supporting selected technologies must take a broader view. Supporting institutions must know about technical bottlenecks and the cost perspectives of the funded technology, as well as about the technical and economic performance and future perspectives of competing technologies. They need to get an idea on future societal impact of the funded technology such as reduced energy demand and costs or avoided greenhouse gas emissions. The EDUAR&D methodology described hereafter strives to deliver answers to these (and further) questions of the innovation process. The results of the assessment lead to R&D and innovation policy recommendations, targeted at overcoming identified bottlenecks and to support (or withdraw from) the development – and/or market entrance and diffusion – of the technology considered. The methodology may assist to avoid or terminate technological R&D lock-in situations by revealing the critical points in good time; the later this information is available, the more difficult it becomes to find a way out of the lock-in situation.

In this paper, we will report on a promising technology which could enhance energy efficiency of electrochemical hydrogen winning, the solid-oxide electrolyser (often also called high-temperature electrolyser), which could also be mutually beneficial with market entry of a new low-emission process to produce primary steel. As far as country-specific analyses have

been conducted (e.g. for the innovation system), this has been done for the case of Germany. The analysis was commenced by the German federal ministry for economics and energy.

Having decided on the technology, the analysis relies mostly on three different perspectives:

- An energy technology and energy economic analysis lays out how the technology may deliver energy savings in a form of a technical potential for a given country, what its environmental impacts could be with a time horizon of 20 to 30 years, and whether it improves security of energy supply. Assuming these potentials could be realised, a potential of economies of scale of the new technology may be estimated (e.g. from experience curves of related types of technologies). The analysis also considers traditional technologies or new technology rivals, as they set technical and cost benchmarks which the new energy technology must match. If this appears difficult to achieve, the methodology suggests making an intensive search for the bottlenecks determining the competition. The analysis should also consider assumptions of future energy prices.
- The technology life cycle approach investigates in which phase the new energy efficient technology is presently in. This step is underlaid by patent analysis and bibliometric essential information, which are necessary learn about technical details and cost aspects for further expert discussions and to tailor the intervention and policy measures to the specific requirements of the technology's phase. Where many candidates of efficiency technologies are being considered for public funding and policy intervention, this step can identify promising technologies based on the technology cycle assessment as a side effect.
- The innovation system approach, finally, is based on the insight that innovations are mostly generated and spread by the complex interaction of many actors in the policy system, the related research institutions, the manufacturers, the intermediates (e.g. financial institutions, or standardisation organisations), and finally the demand of the technology users. The relative appearance of stakeholders in this analysis can also provide further hints, or validation, regarding the technology cycle phase.

In the case at hand, patent and bibliometric analysis as well as two expert interviews were used besides comprehensive desktop research to gain information. The expert interviews as well as desktop research informed all the analytical steps, while patent and bibliometric analysis was used to deduce the position in the technology life cycle. Three different expert interviews have been conducted, with three different stakeholder groups (technology provider, technology user, independent researcher).

Description of the Analysed Technology

Water electrolysis is the electrochemical splitting of water into hydrogen and oxygen with the aid of electric current, i.e. a redox reaction forced by current flow. The increasing demand for climate-neutral reduction gas, syngas and (chemical) energy storage brings this technology more and more into focus. Especially, primary steel producers are dependent on competitive and emission-neutral process alternatives to the blast furnace

route for a relevant reduction of their own emissions. The process of direct reduction of iron ore and subsequent processing of the resulting direct reduced iron (DRI) to crude steel in the electric arc furnace ("direct reduction route") offers the possibility of using hydrogen as a reducing agent and substituting coal and coke (Lösch et al. 2018).

The water electrolysis is carried out using electrolyzers. The functional core of each electrolyzer is the electrochemical cell (or in practice a series of connected cells, called stacks). An electrochemical cell consists of four central functional components: an anode, at which oxidation takes place, a cathode, at or which reduction takes place, an electrolyte, which conducts the ions, and a voltage source, which provides the electrical energy needed. At present, three different technological approaches to water electrolysis can be distinguished: alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEM) and solid oxide electrolysis (SOE), the latter often being referred to as high-temperature electrolysis (HTE).

The central characteristic of the SOE regarding potential industrial applications is its ability to operate at high temperatures. Thus, steam instead of liquid water is split at the reactive interface between cathode and electrolyte, opening up possibilities to use waste heat from the existing production processes to produce steam for the SOE. Moreover, heat can also be recuperated from product gases.

The electrolyte of an SOE is a highly porous, dense solid oxide, usually YSZ (yttrium stabilized zirconium oxide), through which the O_2 ions can diffuse. However, the electrolyte must not be electrically conductive in order to avoid short circuits, and furthermore it must only be permeable for ions. Together with other material requirements (chemical, mechanical, and thermal stability) this explains the complex search for optimized electrolyte materials (Meng et al. 2008) and their optimized application. The cathode is often made of nickel-doped YSZ and the anode of LSCF (a ceramic consisting of oxides of lanthanum, strontium, cobalt and iron) (Schroeder et al. 2015).

Additionally, it is also possible to operate the SOE in a co-electrolysis mode for H_2O and CO_2 . The product is a gas mixture consisting of CO and H_2 determined by a set of parameters. This approach is of potential interest particularly for direct-reduction steelmaking, if both natural gas and hydrogen are used as feedstocks. It would allow carbon to be (at least partially) recycled in the production system (Lösch et al. 2020 unpublished). This is a distinguishing characteristic for the SOE, as co-electrolysis is not feasible with AEL or PEM systems.

Energy Technology and Economic Assessment

SOME FUNDAMENTAL RELATIONSHIPS

The thermodynamic relationship between electrical and thermal energy demand can be described as follows:

$$\Delta G = \Delta H - T\Delta S \quad (1)$$

ΔH designates the reaction enthalpy, i.e. the total energy requirement for the reaction which is the difference between the enthalpies of formation of the species. Gibbs' free enthalpy, designated ΔG , designates the electrical energy requirement. The thermal energy requirement is given by $T\Delta S$, where ΔS denotes

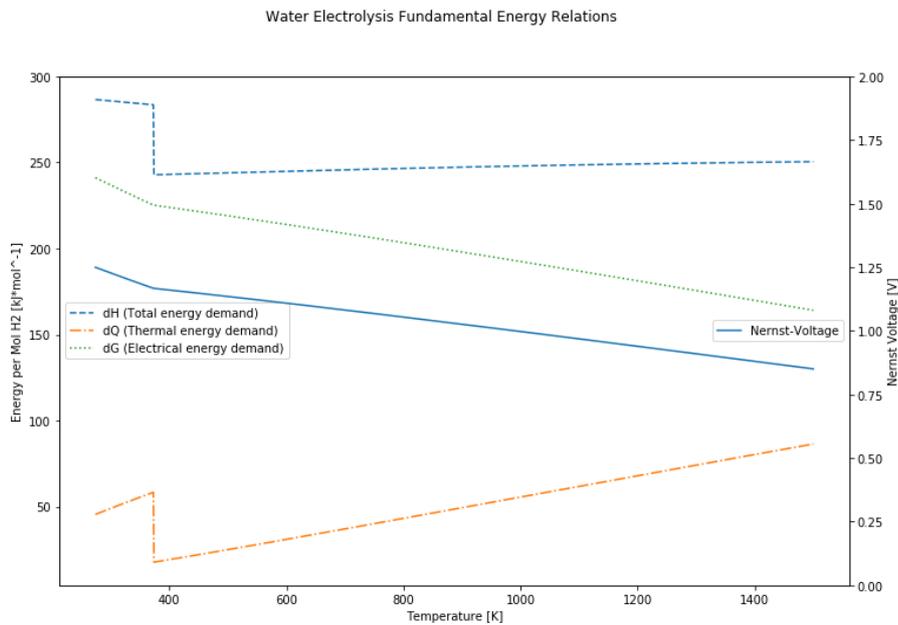


Figure 1. Fundamental Thermodynamic Energy Relations of Water Electrolysis.

the temperature-specific entropy difference of the reaction. The thermodynamic state variables mentioned are temperature- and pressure-dependent. As can be seen from Figure 1, the reaction enthalpy $\Delta H(T)$ is nearly constant in the temperature range under consideration, while the thermal energy requirement increases, and the electrical energy requirement decreases. From this fundamental thermodynamic relationship, the decisive characteristic of high-temperature electrolysis for application in industries with relevant waste heat sources and high hydrogen demand can already be deduced: a significant increase in (electrical) energy efficiency through a partial substitution of electrical energy demand by waste heat. The Nernst potential ΔE corresponds to the theoretical minimum voltage (Nernst voltage or decomposition voltage) required for the reaction to take place:

$$U = -\Delta E(T) = \frac{\Delta G(T)}{nF} \quad (2)$$

F is Faraday's constant and n (here: 2) the number of migrating electrons in moles per mole of water.

However, the reaction is kinetically slowed down by various factors (Kurzweil 2018). Additional energy must be introduced into the system by an overpotential above Nernst-voltage. This results in the practical decomposition voltage. The overpotential is determined by various processes, which take place particularly at the reactive interfaces, slowing down reaction kinetics. In addition, ohmic resistances of the electrolyte cause an increased decomposition voltage. The overpotentials can be roughly differentiated as follows: on the one hand, activation overpotentials to compensate for the inhibited passage of charge carriers, and on the other hand diffusion overpotentials which represent the delayed mass transport between electrolyte and reactive interface (Stempien et al. 2012; Kurzweil 2018). These effects at the interfaces are also called polarization resistances. Those lead to loss currents, with the slowest step determining the speed of the entire reaction (Kurzweil 2018).

ENERGY DEMAND OF WATER ELECTROLYSIS AND EFFICIENCY GAINS BY HIGH-TEMPERATURE ELECTROLYSIS

The theoretical thermodynamic decomposition voltage for water at standard conditions ($T=25\text{ }^{\circ}\text{C}$ and pressure= 101.325 kPa) is 1.23 V (Kurzweil 2018), from which the theoretical minimum electrical energy requirement (ΔG) can be calculated to be 237.1 kJ/mol H_2 (or $2.94\text{ kWh/m}^3\text{ H}_2$), as can be seen in Figure 1.

In practice, due to overpotentials and ohmic losses, the necessary energy demand is significantly higher. (Wang et al. 2008) give a typical range for a required cell voltage of $1.65\text{--}1.7\text{ V}$ at standard conditions to form hydrogen and oxygen gas. For industrial electrolyser plants, typical cell voltages of $1.8\text{--}2.6\text{ V}$ are seen. The energy efficiency can then be calculated as the ratio between the energy usage and the thermodynamic minimum for the redox reaction. For example, assuming a practical cell voltage of 2 V and thus a resulting electrical requirement of $4.78\text{ kWh/m}^3\text{ H}_2$:

$$\begin{aligned} \eta(T) &= \frac{U_0}{U(I)} = \frac{\Delta G(T)}{W_{el}} \\ &= \frac{2.94 \frac{\text{kWh}}{\text{m}^3}}{4.78 \frac{\text{kWh}}{\text{m}^3}} = 61.5\% \end{aligned} \quad (3)$$

This is an indicator for useful energy efficiency, the conversion efficiency from primary to final energy is not considered. The useful energy is given by the chemically stored energy of the reaction products, i.e., the lower heating value of hydrogen. The so-called voltage efficiency is used as an indicator here. Further indicators can be defined to determine the efficiency of the electrolysis process, for the electrical energy consumption in relation to the lower heating value per product unit. The latter is often used and referred to as system efficiency.

At higher temperatures $\Delta G(T)$ changes, as shown in Figure 1. For example, at a temperature of $900\text{ }^{\circ}\text{C}$, which corresponds

well to the typical operating temperature of a shaft furnace during direct reduction of iron ore (Vogl et al. 2018), the Nernst voltage is reduced to 0.95 V, resulting in $\Delta G(T) = 2.27 \text{ kWh/m}^3 \text{ H}_2$. If only the electrical energy input is considered, this corresponds to a considerable theoretical efficiency gain of 22.8 % compared to the thermodynamic energy requirement at standard conditions. Furthermore, it was shown by (Heddrich and Riedel 2018) that the total resistance decreases considerably with increasing temperature. For example, when the temperature rises from 1,023 K (750 °C) to 1,123 K (850 °C), current density increases from below 0.15 A/cm² to approx. 0.35 A/cm². Further dependencies of the total resistance and the current density can be seen for operating pressure, steam fraction of the gas supplied, and the steam conversion rate (fraction of H₂O converted to H₂). Thus, two independent effects can be identified, both leading to a higher electrical energy efficiency of high temperature electrolysis compared to low temperature systems.

COMPARING ENERGY EFFICIENCIES OF DIFFERENT ELECTROLYSER TECHNOLOGIES IN PRACTICE

German technology provider Sunfire states the system efficiency of its Hylink module, under standard test conditions and at the beginning of its lifetime, to be $\eta = 82 \%_{\text{-LHV}}$ (Sunfire n.d.). This results in a specific electrical energy requirement of 40.6 kWh/kg_{-H₂}. For alkaline electrolysers, various specifications can be found in the literature and from manufacturers, also depending on system configurations. In (SZMF 2019), a typical electrical energy requirement of 51 kWh/kg_{-H₂} is specified for low temperature electrolysers, corresponding to $\eta = 65 \%_{\text{-LHV}}$. An exemplary selection of low-temperature systems available on the market confirms this value approximately, with a tendency towards slightly higher efficiencies. If the degradation problem is disregarded, the above-mentioned efficiency advantage of HTE is thus also confirmed in practice: if one assumes a value of $\eta = 65 \%_{\text{-LHV}}$ as a basis, SOE systems would currently be approximately 26 % more efficient. Assuming a higher value for the alkaline systems of $\eta = 70 \%_{\text{-LHV}}$, the efficiency advantage is still 18.5 %. System efficiencies of PEM modules on the market are currently still a bit below the AEL.

ENERGY ECONOMIC ASSESSMENT

In literature, a value of €7.6/kg_{-H₂} is found for the total H₂ production costs, referring to AEL, at electricity costs of €35/MWh (Machhammer et al. 2015). This is significantly higher than the typical production costs of steam reforming of natural gas of €1.9/kg_{-H₂}. The production costs of hydrogen via electrolysis will depend on the system configuration and on operation factors (e.g. full load hours). Moreover, electricity prices will obviously play an important role for production costs, generalizing statements are therefore difficult to make. The CAPEX of HTE is currently still significantly higher than for the AEL and PEM systems. A stakeholder assessment by (Smolinka et al. 2018) indicates a range of €1,350 to €3,250 per kW nominal capacity for 2017, with a central value of €2,300. The manufacturer interviewed for this analysis (Wolf et al. 2020) states the status quo at €2,500 per kW rated output. For the future development perspective of the CAPEX see below.

MACROECONOMIC POTENTIALS

The macroeconomic potentials for energy saving and GHG emission avoidance are currently hardly plausible to assess, which can be explained by several factors that lead to considerable uncertainties:

- The current hydrogen demand is already subject to considerable uncertainties (at least for the case of Germany), both in terms of production capacities and production quantities
- The estimates for future hydrogen demand and necessary electrolysis capacities in scenario studies show a very broad bandwidth. In 50 scenarios analysed by (Smolinka et al. 2018), this ranges from 0 to approx. 120 GW installed electrolysis capacity in 2030 and from 0 to approx. 270 GW in 2050.
- Which of the electrolysis technologies (AEL, PEM or SOE) will prevail in the market and to what relative extent, and accordingly how high the diffusion share of SOE will be with corresponding efficiency advantages compared to the other two technologies, can hardly be seriously estimated at present.
- The further development perspective of the performance parameters of the electrolysis technologies, e.g. system efficiency and thus the electricity demand of the SOE systems, is also subject to uncertainties, although there are at least plausible estimates from stakeholders, as shown below.

Some of these uncertainties partly result from unclear framework conditions or a lack of political specifications for a concrete market ramp-up (see also below). Therefore, only an exemplary consideration will be given here to illustrate the possible magnitude of future energy savings by SOE systems compared to AEL/PEM systems. For this purpose, the case of direct reduction steelmaking is used. Assuming that approx. 50 % of today's German primary steel production, i.e. 15 million tonnes of crude steel per year, would be replaced by a completely hydrogen-based direct reduction, a typical system efficiency of AEL would result in an electricity demand of approx. 60 TWh (Lösch et al. 2020 unpublished). The efficiency advantage of SOE systems can be conservatively estimated at 20 %, as described above. This would result in considerable energy savings of 12 TWh or 43.2 PJ per year for this application (if the required waste heat is available and not already used). This is however a theoretical maximum value, as it assumes a 100 % market share for SOE, which will not be a real-world case.

Classification with the Technology Life Cycle

USING PATENT AND PUBLICATION ANALYSIS TO ASSESS TECHNOLOGY LIFE CYCLE PHASE

In order to analyse the development of R&D activities in the field of SOE, a patent and a publication analysis were carried out. The same search terms were used for both analyses:

S ((Solid oxide electrolys? OR High Temperature Electrolys? OR SOEC) AND (Hydrogen OR Water))

Patent analysis

The analysis was carried out with the World Patents Index (WPI) database, which is particularly efficient for keyword searches. It covers patent applications at about 50 patent offices worldwide. The analysis of transnational patent applications, i.e. patent that are filed in several countries, from WPI has proven to be an effective means of avoiding double counting. The filing costs are high, and the international filing strategy is expected to yield particularly high returns. These are thus particularly valuable patents and the statistics make countries comparable with each other. Due to the legal regulations on the publication of patent applications, analyses can currently be carried out until 2017. A country ranking was determined for the period 2000–2017 (Table 1).

A look at the course of applications since 2000 (Figure 2) shows a moderate increase from 2004 and a strong increase from 2015, but at a low absolute level. It is of interest whether the patent applications are basic or application patents and whether the course of the patent applications shows a recognizable trend. In this case, a classification of patent applicants into research institutions (tending to conduct basic research) and enterprises (tending to register application patents) shows a balanced picture. Of a total of 87 patent applications in the period 2000–2017, 30 applications can be assigned to research institutions and 57 to enterprises. This shows, also in connection with the clear trend of patent applications over time, a generally high level of interest also in industry.

Publication analysis (bibliometric analysis)

The research was conducted with the database Web of Science, resulting in 3,006 hits for 1976–2019. The time series is shown in Figure 3. Early publications date back to 1976, but a steep rise can only be observed from 2002 onwards. Looking at the country participation for the last year covered, 2019, a ranking according to Table 2 emerges, with China's position being striking. This is a strong indication that China will also play a major technical role in approx. 5 years (Schmoch et al. 2017). A com-

Table 1. Country ranking of SOE/HTE patents 2000–2017.

France	21
USA	13
Denmark	12
Germany	12
UK	4
Japan	4
Norway	1
Sweden	5
Finland	1
Austria	1
Belgium	1
Switzerland	1
China	1
Italy	1
Russia	1

parison with 2010 shows that publication activities of Chinese institutions have increased significantly, but this also applies to German institutions, as shown in Table 2.

It is also possible to assess the most active institutions regarding these publications. For the case of Germany and in 2019, these were the Helmholtz Association (with various institutes) with 15 publications, Forschungszentrum Jülich with 9, RWTH Aachen University with 6, DLR (Stuttgart) with 5, and Sunfire GmbH with 4 publications.

Overall, the publication analysis, like the patent analysis, shows an increasing interest in SOE/HTE technology among the R&D-stakeholders involved, which is reflected in a sharp rise in the number of publications. Transnational patent applications are also rising clearly, albeit at a much lower absolute level than publications, which indicates the still low level of transfer or implementation of research results in technological practice.

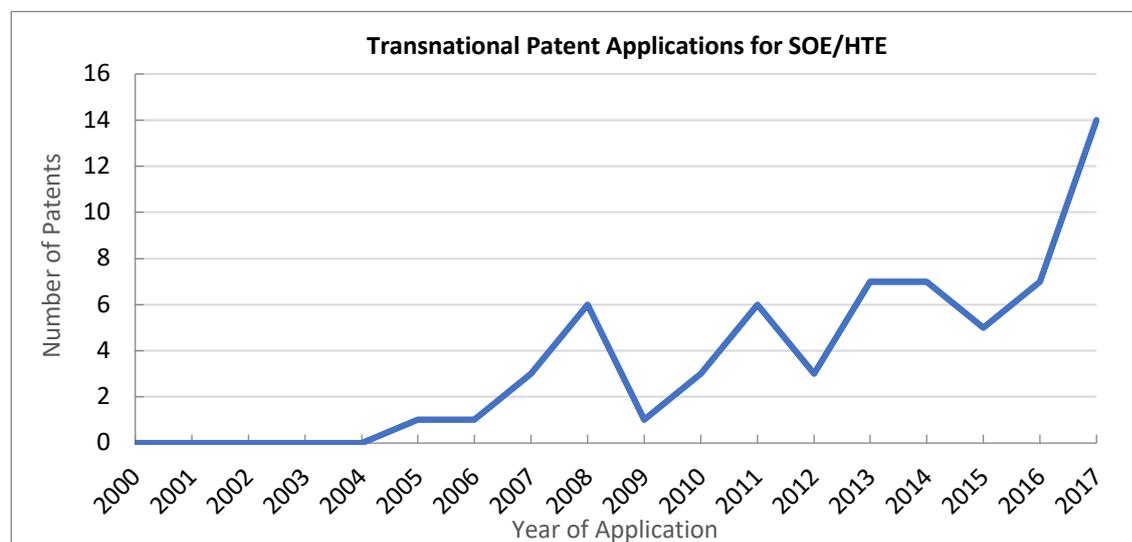


Figure 2. Transnational Patent Applications for SOE/HTE 2000–2017.

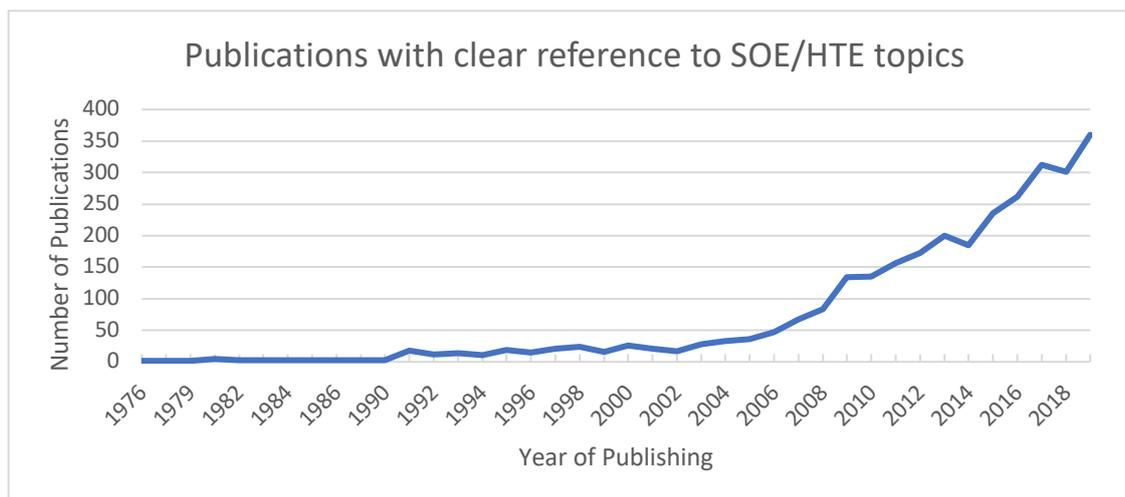


Figure 3. Publications with clear reference to HTE/SOE topics.

Table 2. Country ranking of SOE/HTE publications in 2019.

Countries/Regions	Count
PEOPLES R CHINA	107
USA	57
GERMANY	33
ITALY	25
SOUTH KOREA	25
DENMARK	16
FRANCE	15
JAPAN	15
SPAIN	15
SWITZERLAND	14
ENGLAND	13
CANADA	10
IRAN	10
NETHERLANDS	10

Table 3. Country ranking of SOE/HTE publications in 2010.

Countries/Regions	Count
USA	31
PEOPLES R CHINA	17
JAPAN	14
FRANCE	10
DENMARK	9
ENGLAND	9
ITALY	8
TURKEY	8
CANADA	6
INDIA	6
SOUTH KOREA	6
BRAZIL	5
GERMANY	4
GREECE	4

ASSESSING AND COMPARING COMPETITIVE TECHNOLOGIES & SPECIFIC ADVANTAGES OF SOE/HTE

Process alternatives for water electrolysis to SOE/HTE are the already mentioned alkaline electrolysis (AEL), and proton exchange membrane electrolysis (PEM).

Water electrolysis by means of an alkaline electrolyser (AEL) is already technically advanced due to the widespread use of chlor-alkali electrolysis in the basic chemistry. The electrodes are immersed in water made ionically conductive by adding acids, bases or salt solutions. In this process, 30 % potassium hydroxide solution (KOH) is the best conductor of electrical current (Kurzweil 2018). Most hydrogen production by alkaline electrolysis is a by-product of chlorine production in the chemical industry. For example, the maximum production capacity for chlorine using this process in the EU was 9.4 million

tonnes in 2019, from which stoichiometrically a production capacity for 0.25 million tonnes of hydrogen as a by-product can be deduced (Eurochlor 2020).

In proton exchange membrane electrolysis (PEM), the electrolyte is a proton-permeable polymer membrane. The electrodes are layered directly on the membrane and consist of platinum (cathode) and iridium or ruthenium (anode). The water flowing against the anode is catalytically decomposed at the precious metal electrode, producing electrons, elementary oxygen and hydrogen ions. These then migrate through the membrane to the cathode and react to form hydrogen by absorbing electrons. Although PEM electrolysis does not yet have the same level of technological maturity as alkaline electrolysis, more and more companies are opting for this technology, particularly because of the development potential that

can still be expected. For example, the Rhineland refinery is building a plant designed with a capacity of 10 MW to produce 1,300 tonnes of hydrogen per year (Shell 2018).

Keeping its relative technological immaturity in mind, the perspective competitive advantages of SOE/THE-systems compared to AEL and PEM for industrial applications are, however, manifold and obvious. Iron and steel production and the chemical industry could represent market entry niches for SOE/HTE as to their high demand of electricity for decarbonating production processes, making electricity efficiency an urgent matter, and as to the existing on high-temperature waste heat which could be used for steam. This assessment has been confirmed by both SOE/HTE producers and steel companies (Wolf et al. 2020; Kroop et al. 2020)

The availability of usable waste heat for SOE/HTE is given both in the steel industry and in the chemical industry. In DRI-steelmaking, the heat generated in the reduction shaft can be reused to generate steam for the SOE. In addition, waste heat from other processes, e.g. the electric arc furnace (EAF), can be used.

In the chemical industry, hydrogen can be used for diverse processes. However, regarding the chemical industry, it is important to consider HTE not only as a perspective hydrogen supplier. The fact that the SOE is the only electrolysis process where the oxygen ion migrates allows the use of a wide variety of gas compositions as feed, which is not possible with other electrolysis technologies. For example, syngas (CO and H₂) can be produced from CO₂ and H₂O in a single process step using co-electrolysis, which with low-temperature electrolysis is only possible with an additional reverse water gas shift reactor. In addition, a desired mixture of CO and H₂ can be individually adjusted during co-electrolysis, where feed-gas composition is the only parameter to vary.

CLASSIFICATION

Based on the pattern and the content of the patent and publication analyses and interviews with experts in this field it became evident that the SOE/HTE technology has not yet reached technological maturity and economic marketability. The technol-

ogy can be classified to be in phase 2 of the technology cycle (euphoria, when researchers believe that the new technology could be used in many applications), Figure 4. Whether the technology can overcome the “Valley of Death” between laboratory research and pilots on the one hand and market introduction and diffusion on the other, or whether the phase of re-orientation will be entered, depends in particular on political framework conditions, as discussed below. Due to the necessities of climate protection, it might well be that the phase of re-orientation will be successfully reached and passed, for the hydrogen demand of basic industries. In terms of the Technology Readiness Level (TRL) the technology seems to have reached TRL 5.

Innovation System Assessment

Innovation systems generate, disseminate and use innovations. They are composed of components and relations. Components are actors, technologies, and regulatory frameworks. Relations are the various formal and informal relationships between the components. Central actors in the technical innovation system of the SOE/THE-technology are currently, with regard to its location in the technology cycle, in particular the research institutes and researching companies, as well as in Germany the federal government’s energy research programme as a funding body. This is also shown by an analysis of the projects funded by that programme. The ENARGUS database (Enargus 2020) was searched for SOE/THE projects for the period 2000–2019. It was immediately apparent that not a single project was funded in the period 2000–2009. A supplementary search showed that the ENARGUS database lists a total of eight research projects from 1975 to 1987, but no further project was funded until 2010. For the period 2010 to 2019 (project start date), a total of 26 individual projects were identified that were supported by the federal government’s energy research programme. Figure 5 shows the distribution of projects and the funding over the years. It is noticeable that a whole series of new projects was launched in the last year (2019).

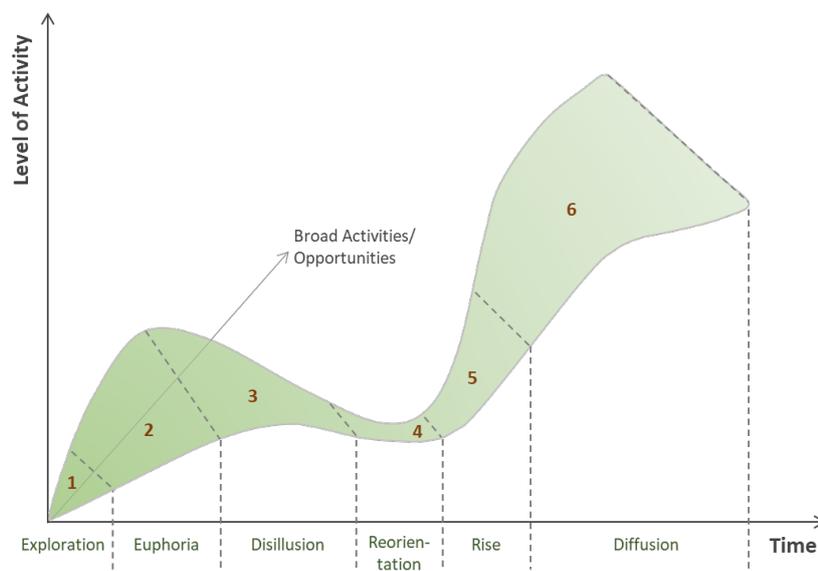


Figure 4. The typical Technology Life Cycle.

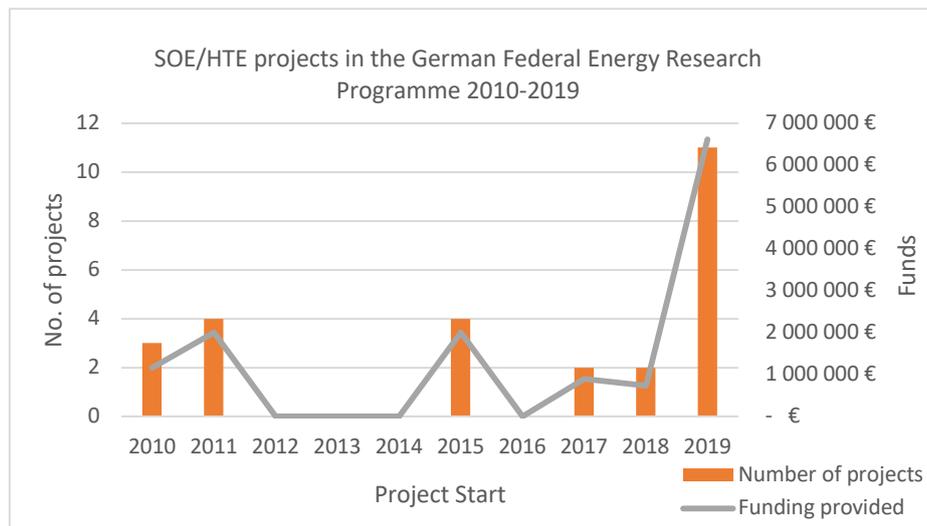


Figure 5. Funded R&D projects for SOE/HTE-technology in Germany.

Regarding the innovation system, the analysis of the groups of actors involved in the projects is of interest. It is worth noting that most of the projects identified (21 of 26) were or are being implemented within collaborative projects. From the actors in Germany since 2010, preliminary conclusions can be drawn about the innovation system. As to the groups of actors, it becomes apparent that a few researching technology suppliers – especially Sunfire GmbH as manufacturer of SOE/FC cells and stacks, but also KERAFOL GmbH & CO. KG as a manufacturer of ceramic electrolyte layers – cooperate with various research institutions. Sunfire has also installed the first SOE pilot plant in Germany at a steel plant. The participating research institutes also clearly show that the activities of this group of actors in Germany are limited to a few, but very active institutions. These include the Jülich Research Centre, the Institute of Technical Thermodynamics of DLR, and the European Institute for Energy Research (EIFER). Moreover, the innovators Sunfire GmbH, Siemens, Salzgitter AG as well as DLR and Forschungszentrum Jülich have also acted as patent applicants. It is quite clear that R&D activities in Germany are rising for the case of SOE/THE, and that a handful of research institution and researching technology suppliers are very active in this area. Funding has been playing an important role so far for technological advancement.

Derivation of Possible Development Targets

PRIMARY TECHNOLOGY RESEARCH TASKS

Currently, SOE/HTE system performance drops considerably during the demanding operation (high temperatures, ~850 °C) due to material problems, especially at higher current densities (Kurzweil 2018):

- The electrodes applied directly to the electrolyte become detached (delamination) and deactivated by migration of alloy/doping elements between the electrodes and the electrolyte.
- Nickel from the cathode diffuses into the electrolyte. In addition, nickel agglomerates in the cathode and thus reduces the reaction surface, which in turn leads to a higher overpotential

- The solid electrolyte changes its crystal structure and thus loses considerable on ionic conductivity.

The extent of degradation can be derived from different sources. (Kurzweil 2018) reports an increase in overvoltage (and thus a decrease in efficiency) of 0.36 V after 9,000 operating hours for an anode-supported single cell. Compared to a practical decomposition voltage of 1.2 V, this would correspond to a 30 % decrease in efficiency. (Schroeder et al. 2015) as well as (Fang et al. 2015) indicate a reduction of the efficiency by 3–5 % after 1,000 operating hours. Depending on the operation parameters (temperature, pressure, etc.), (Heddrich and Riedel 2018) report a degradation rate for Sunfire cells in the range of 0.7 to 2.6 % with respect to the cell voltage per 1,000 operating hours, with an accelerating trend. However, the interviewed experts from Sunfire (Wolf et al. 2020) are optimistic regarding that issue, stating that degradation rates are currently reduced considerably year-on-year, and in the medium-term could well fall to as low as 0.3 %/1,000 hours with respect to the cell voltage.

To further enhance its competitive advantage of the SOE due to its high electrical efficiency, system efficiency must be enhanced further. In the medium-term, according to (Wolf et al. 2020), it may be well possible to get from $\eta = 82 \%_{-LHV}$ up to $\eta = 86\text{--}87 \%_{-LHV}$ concerning pure H₂O electrolysis. For co-electrolysis of H₂O and CO₂, $\eta = 83 \%_{-LHV}$ is deemed feasible. Upscaling is not seen as a problem by experts, and for the case of SOE/HTE is done by combining more cells in one stack and more stacks in one module, while cell dimensions will not be changed (which is different from AEL/PEM-Systems, where the cell dimensions are also subject of R&D). While a SOE/HTE module produced by Sunfire today has a nominal power of 150 kW, upscaling to 1 MW modules is seen as unproblematic.

POSSIBLE DEVELOPMENT OF ECONOMIC INDICATORS

In (Smolinka et al. 2018), stakeholders were asked about possible development paths for the CAPEX of different electrolyser technologies. Table 4 shows that the three paths (progressive/central/conservative) differ strongly for both status quo and development perspective. As to be expected, the estimates for the SOE/HTE differ most strongly due to a lack of marketabil-

ity and information. However, the SOE also seems to offer the greatest CAPEX reduction potential through further development. According to this assessment, the SOE would already have the lowest CAPEX in all three development paths in 2030. However, of course these expert estimates are subject to considerable uncertainty. Nevertheless, this shows the high conceivable development potential of the technology.

The expert interview with Sunfire confirms this optimistic outlook for the SOE/HTE CAPEX relative to the competing technologies, which can also be plausibly substantiated by the following (Wolf et al. 2020):

- PEM is, due to the iridium and platinum coating of the electrodes, the most expensive electrolysis technologies in terms of material costs, which will not change in the foreseeable future (materials to substitute these precious metals or PEM are not known yet). On the other hand, the systemic costs of PEM electrolysis are to be regarded as relatively low.
- Contrariwise, AEL has relatively high system costs. Among other things, the product must be purified, but the production and recycling of the electrolyte also require considerable effort.
- For SOE, neither materials (no precious metals) nor systems (no fluids, no moving parts, etc.) are cost intensive. What leads to the currently high CAPEX is its early stage of development, especially considering the yet missing automatization of production. Therefore, market entry and automatization of production can be expected to lead to considerable positive costs effects.

Policy Recommendations and Conclusions

RECOMMENDATIONS FOR RESEARCH FUNDING IN GERMANY

The analysis has shown that a significant increase in R&D activities can be observed for SOE/HTE topics. National research funding is available and is also being accepted, as can be clearly seen from Figure 1. The technology is ready to leave the laboratory so that testing the operational behaviour on industrial scale is becoming a priority. However, deficiencies related to the solid nature of the cells, as described above, are not yet resolved and need to be further addressed with material research and R&D funding for these purposes should continue to be available in the future.

While acknowledging the effectiveness of German research funding to be very high in principle, the experts surveyed emphasized that research funding should focus more on testing the operating behaviour on an industrial scale. At present, some of the researchers involved in national research funding projects feel compelled to scale down plant and component dimensions in order to be able to meet project budgets. However, the pilot operation of such scaled-down plants allows only limited conclusions to be drawn about the operating behaviour of future plants on an industrial scale. Therefore, there seems to be a need for increased funding of such demonstration projects in national programmes. For SOE/HTE systems, this would mean at least demo-plants in the range of a nominal power of 1 MW, operating over several years. Accordingly, it is recommended that the budgeting of projects should be reviewed and, if necessary, adjusted so that demonstration plants can be implemented on an industrial scale. Another point in this context is increased funding for dedicated SOE/HTE system components, such as compressors designed specifically for hydrogen.

RECOMMENDATIONS ON THE ENERGY AND CLIMATE POLICY FRAMEWORK

Investment security regarding the various actors in the value chain is indispensable for the market entry of new technologies. The system suppliers of SOE/HTE systems are thus dependent on a reliably foreseeable sales market, and as described above, iron and steel manufacturers and the chemical industry can act as relevant entry markets on the customer side. This assessment is shared by representatives of both system manufacturers and customers (steel industry) (Wolf et al. 2020; Kroop et al. 2020). Further downstream, too, the suppliers of the system manufacturers are in turn dependent on gaining certainty about the potential sales market, otherwise they will not invest. Conversely, this means that a possible promotion of large demonstration plants for primary steel production via the direct reduction route with SOE/HTE systems could also significantly accelerate their launch in other markets, for example in the chemical industry. In order to solve this typical “chicken-and-egg problem”, politics as the decisive actor is required to trigger expectations regarding market development through clear decisions (formulation of concrete strategies, roadmaps, and market introduction instruments).

In view of the now possibly imminent comprehensive state funding of the hydrogen economy in Germany, tendering models for the ramp-up of electrolyser capacity must be viewed critically regarding innovation funding. There is a risk of first-

Table 4. Stakeholder expectations for electrolyser CAPEX development, taken from (Smolinka et al. 2018).

CAPEX in [€/kW]	Values from Stakeholder Feedback		
	2017	2030	2050
<i>(Development paths)</i>			
PEM (progressive)	1,390	490	210
AEL (progressive)	620	410	250
HTEL (progressive)	1,350	310	160
PEM (central)	1,470	810	510
AEL (central)	920	690	500
HTEL (central)	2,300	460	280
PEM (conservative)	1,540	1,120	800
AEL (conservative)	1,220	970	750
HTEL (conservative)	3,250	610	400

mover-disadvantage on the part of investing companies (e.g. steel manufacturers) interested in deploying SOE. With a foreseeable steep technological learning curve, there is a danger of a wait-and-see attitude about innovative technologies such as SOE/HTE with considerable development potential, which could lead to a delay in market entry. A purely volume- or capacity-oriented funding mechanism for the rapid build-up of electrolysis capacities in Germany could lead to only AEL and PEM systems being built on a significant scale, as these are technologically more mature than SOE/HTE today. Therefore, within a funding mechanism for the construction of electrolysis capacities a technology funding component would be needed. This component could target the first-mover disadvantage mentioned, e.g. by granting an additional bonus or higher funding rates for the deployment of technologies with considerably higher CAPEX (due to e.g. relatively low production volumes).

To conclude, SOE/HTE electrolyzers are highly promising technology options, especially for the electrification of steelmaking and the chemical industry and can play an important role in a hydrogen economy. This is due to their favourable characteristics, utilizing waste heat to reduce electricity demand and potentially low system costs compared to other electrolyser technologies in the future. However, SOE/HTE technology is currently still immature. Material development and field testing of demonstration plants must be brought forward. Policies for market ramp-up of the hydrogen economy should consider these aspects, to not pass over this high-potential technology.

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