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A perspective on hydrogen production via high temperature steam electrolysis

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High temperature (700–900 °C) steam electrolysis (HTSE) based on solid oxide electrolysis cells (SOECs) has been valued as an efficient and clean path for large scale hydrogen production with nearly zero carbon emissions, compared with the traditional paths of steam methane reforming or coal gasification. The main advantage of HTSE is that energy demand for electrolysis reaction of H_2O at gaseous state is less than that for liquid state. Thermodynamically, the electricity for water splitting is reduced by 15%–25% at elevated high temperature. HTSE also serves as a solution to the energy storage problems associated with non-electric application of nuclear power and the supply-and-demand conflictions of renewable energy like wind, hydro and solar power (Figure 1) [1]. A total thermal efficiency above 50% was calculated for large scale HTSE system for hydrogen production using the heat from nuclear reactors or solar. Table 1 compares the features of different hydrogen production paths by electrolysis [2,3].

SOECs, in principle, are reversely operated SOFCs (solid oxide fuel cells), sharing similar material libraries and stack configurations [4,5]. The overall electrolysis reaction is expressed in Eq. (1). The concept was first proposed by Donitz and Erdle [6] in the 1980s as part of the “HotElly” project. However, it did not receive enough attention until 2004, when the energy crisis exacerbated and oil price increased significantly. Hydrogen production based on HTSE has been acknowledged as an important function of GEN IV nuclear reactors by the US Department of Energy (DOE). Many research institutes, universities and companies across the world, such as the Idaho National lab (INL), Technical University of Denmark (DTU), Haldor Topsoe, Sunfire GmbH, Tsinghua University and Shanghai Institute of Applied Physics (SINAP), are engaged in the development of HTSE technology.

$$H_2O + \text{electricity} + \text{heat} \rightarrow \frac{1}{2}O_2 + H_2 \quad (1)$$

INL acted as a leading lab in the development of HTSE technology under the DOE Nuclear Hydrogen Initiative (NHI). In 2008, a 15 kW-HTSE system was operated for 45 d with a peak hydrogen production rate of 5700 Nl/h at INL. However, it experienced severe degradations after 700 h of continuous operation with the initial area specific resistance increasing by five times [7]. In 2015, O’Brien *et al*. [8] at INL reported a 4 kW-HTSE unit with a degradation rate of 3.1%/1000 h during 830 h operation under a current density of 0.41 A/cm^2. Shanghai Institute of Applied Physics started the research on HTSE system in 2011 within the project of the Thorium Molten Salt Reactor Nuclear Energy System, under the support of Chinese Academy of Sciences. In 2013, a 1 kW-HTSE system was established and operated at 800 °C for 500 h with a hydrogen production rate of 170 Nl/h and a degradation rate of 3.25%/100 h. In 2015, a 5 kW-HTSE system was established and operated at 750 °C for 1000 h with a hydrogen production rate of 1.37 Nm^3/h and

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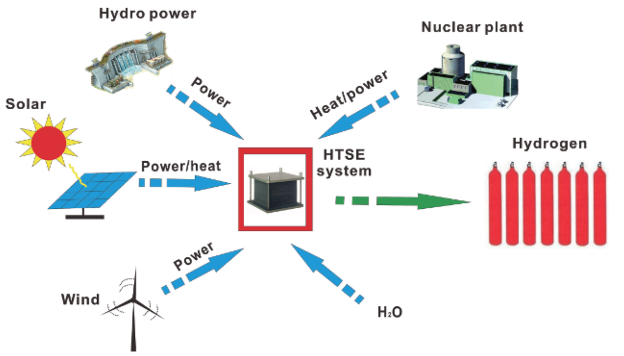

Figure 1 HTSE system coupled with clean energies for energy storage and hydrogen production (color online).

Table 1 Features of hydrogen production paths by electrolysis [2,3]

Technology	T (°C)	η_e (%) a)	η_t (%) b)
AEC	70–90	51–62	20–31
PEMEC	<100	74–79	28–45
SOEC	600–1000	90–100	53–59

a) η_e: electrolysis efficiency, the efficiency of converting electricity into chemical energy stored in fuels without considering the electricity generation efficiency; b) η_t: overall thermal efficiency by taking into account the electricity generation efficiency of power plants.

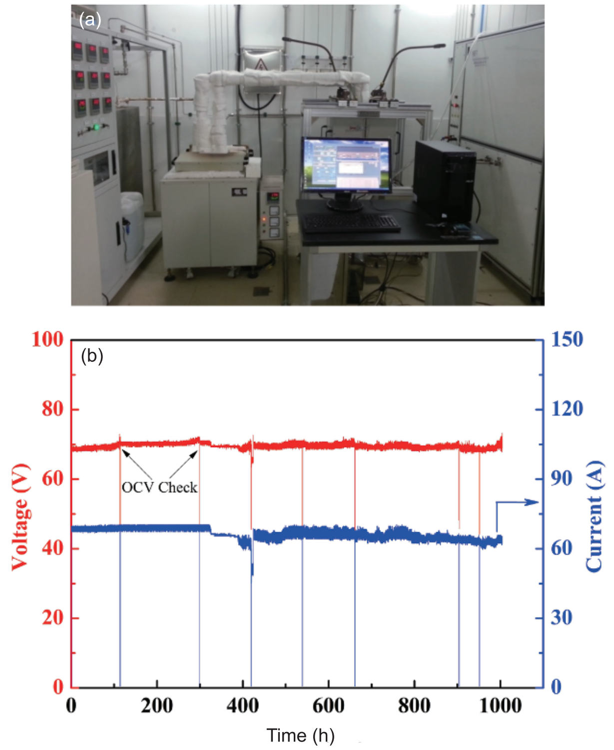

Figure 2 5 kW-HTSE system and operation at Shanghai Institute of Applied Physics. (a) Photo of the system; (b) long-term stability test of the system at 750 °C under a current density of 0.25 A/cm^2 (color online).

a degradation rate of 2.25%/1000 h (Figure 2). Besides, Tsinghua University also devoted to the development of HTSE system as a non-electric application of the high temperature gas cooled reactor (HTGR). Currently a 1 kW-HTSE system has been established and operated at Tsinghua University with a hydrogen production rate of 105 Nl/h. They plan to realize large scale hydrogen production coupled with nuclear reactors and construct the demonstration plant. Except for nuclear hydrogen application, HTSE research is also active in energy storage and conversion of renewable energy. Sunfire GmbH and Forschungszentrum Jülich are developing a power-to-liquid process for producing synthetic fuel based on HTSE technology, desiring to resolve the energy storage problems associated with the renewable energy. In 2016, Sunfire GmbH, in cooperation with Boeing, built the World's largest reversible electrolysis (RSOC) demonstration system, using hydrogen as storage medium to ensure the reliable supply of electricity originally generated from wind power or photovoltaic arrays and yielding 42 N m^3 hydrogen per hour in electrolysis mode [9]. Coupling HTSE technology with the clean energies, such as solar, wind and nuclear power, has become a trend for the further development of this technology.

Currently, the commercialization of HTSE technology for large scale hydrogen production still faces some technological challenges. First, one key limitation lies in the degradation of SOEC stack during long-term operation. For commercialization, a degradation rate below 1%/1000 h is desired for SOEC stacks to ensure a life of 3–5 years. Nevertheless, most reported degradation rate for SOEC stacks was above 2%/1000 h under low current densities (≤0.5 A/cm^2) in atmospheres with low steam concentration. Under harsher conditions, the degradation will be even faster. Some strategies have been advanced to improve the life of solid oxide cells, such as: (1) operating the solid oxide cells in a reversible mode between electrolysis and fuel cell; (2) replacing traditional Ni-YSZ (Y stabilized ZrO_2) hydrogen electrode with $La_{0.4}Sr_{0.4}M_xTi_{1-x}O_{3\pm\delta}$ (M=Fe^{3+}/Ni^{2+}, x=0.06) perovskite oxides; (3) optimizing the electrode microstructure [10–12]. But these results are limited to single cell test and needs further validation in large stacks. Another issue is the lack of mature integration technology for large-scale HTSE system, which bears great influence on the overall efficiency and stability of the system. The commercially available HTSE system to date is below 100 kW, far below the MW scale requirement for large scale hydrogen production coupled with nuclear energies or renewables [13]. One difficulty lies in the lack of suitable strategy for SOEC stack integration and the other one lies in how to integrate the system, including steam generator, heat exchanger, hot box, and SOEC stacks, efficiently to form a large HTSE system. In addition, the most feasible and efficient way for HTSE system with clean energies, a good match for hydrogen production and energy storage, is still yet to be well understood based on the limited facilities and results available. Recently, SOECs have also been applied for other purposes, such as syngas production by high temperature steam/CO_2 co-electrolysis, high purity CO production by CO_2 electrolysis and biogas upgradation by using hydrogen from SOECs [14].

HTSE technology has a great potential for large scale hydrogen production, which comprises an important part among the non-electric applications of advance nuclear energy. However, it still faces some technological challenges in materials, stack design and system integration. Large scale pilot demonstration helps to accelerate the commercialization of HTSE technology. HTSE will witness rapid development in the next 5–10 years with the rapid development in clean energies and exacerbating environmental concerns.

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Conflict of interest The authors declare that they have no conflict of interest.

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