Technical University of Denmark

Storing electricity and CO2 as synthetic hydrocarbon fuels by high temperature electrolysis

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Publication date:
2014

DTU Energy Conversion
Department of Energy Conversion and Storage

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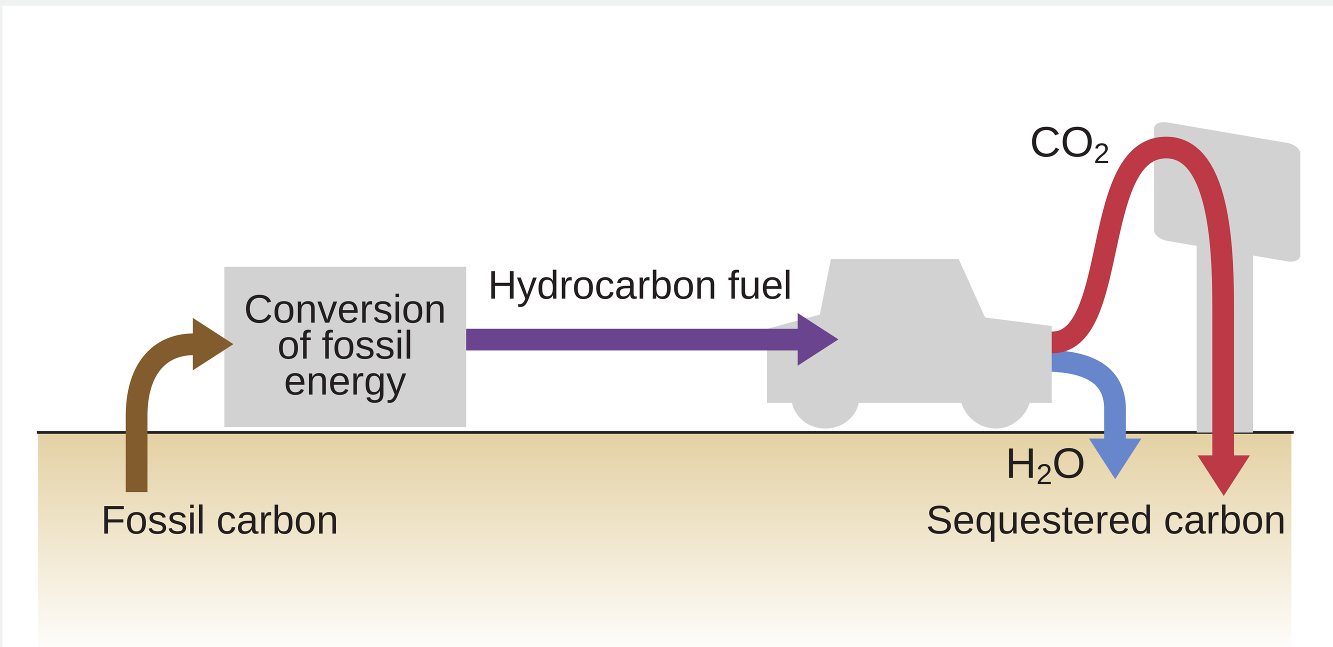
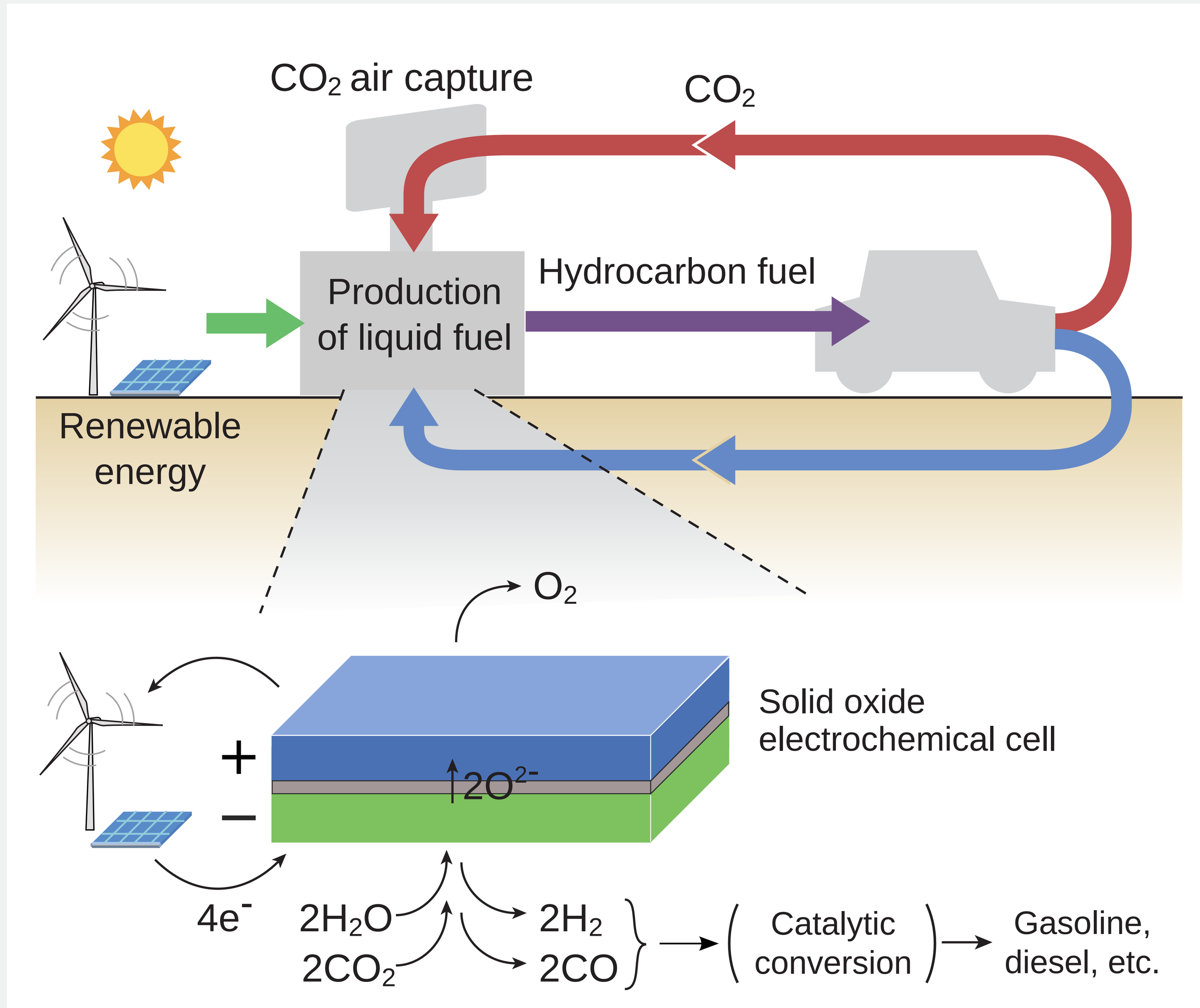
Carbon capture & storage (CCS)



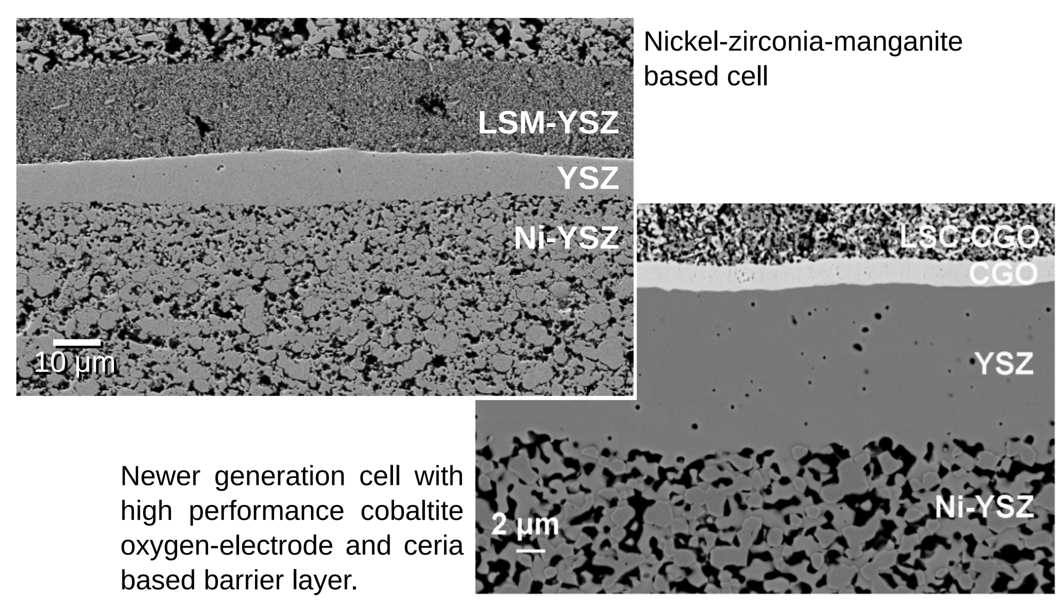
Carbon capture & recycling (CCR)



Today's major sustainable energy efforts are (i) reduction of CO_2 emissions and (ii) increasing the share of renewable energy. One way of CO_2 emissions reduction is CO_2 sequestration, which can be pursued independently of renewable energy. Another way is CO_2 utilization, which at large scale means conversion of CO_2 into synthetic hydrocarbon fuels for use in existing infrastructure. This conversion must be driven by energy sources that do not produce CO_2 emissions, e.g. renewable or nuclear energy sources. Advantageously, using renewable energy to convert CO_2 to fuels also helps increase the share of renewable energy because the most abundant renewable sources, solar and wind, provide fluctuating energy supplies which must be stored. Synthetic hydrocarbon fuels are excellent energy storage media. Solar energy can be used to convert CO_2 and H_2O into fuels in a variety of ways. The most common way is by growing biomass, but also many artificial energy conversion processes are actively researched, including photoelectrochemical, photovoltaic+electrolytic, solar thermochemical, solar thermolytic, and solar thermoelectric+electrolytic conversions. Wind energy, on the other hand, is collected exclusively as electricity, and therefore electrolysis is the most appropriate and direct type of conversion.

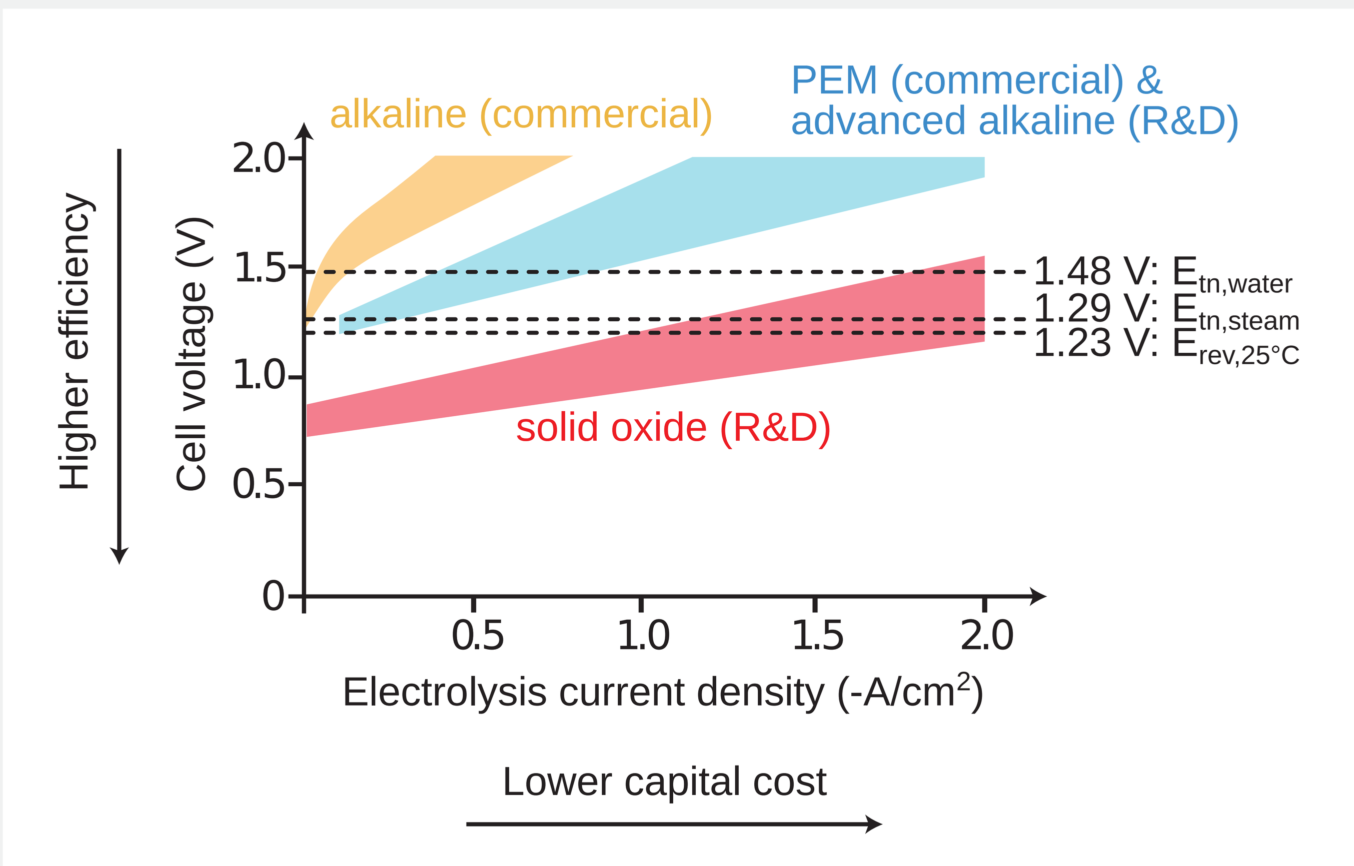
Our group at the Technical University of Denmark (formerly Risø National Lab) has been researching high temperature electrolysis of CO_2 and H_2O using solid oxide electrolysis cells (SOECs) for more than 10 years. The ceramic cell technology that was developed most actively for fuel cell application (solid oxide fuel cells) can be simply run in the reverse by applying electrical energy. Besides using the cells optimized for fuel-cell mode operation, new types of cells optimized for electrolysis mode operation are also under development.

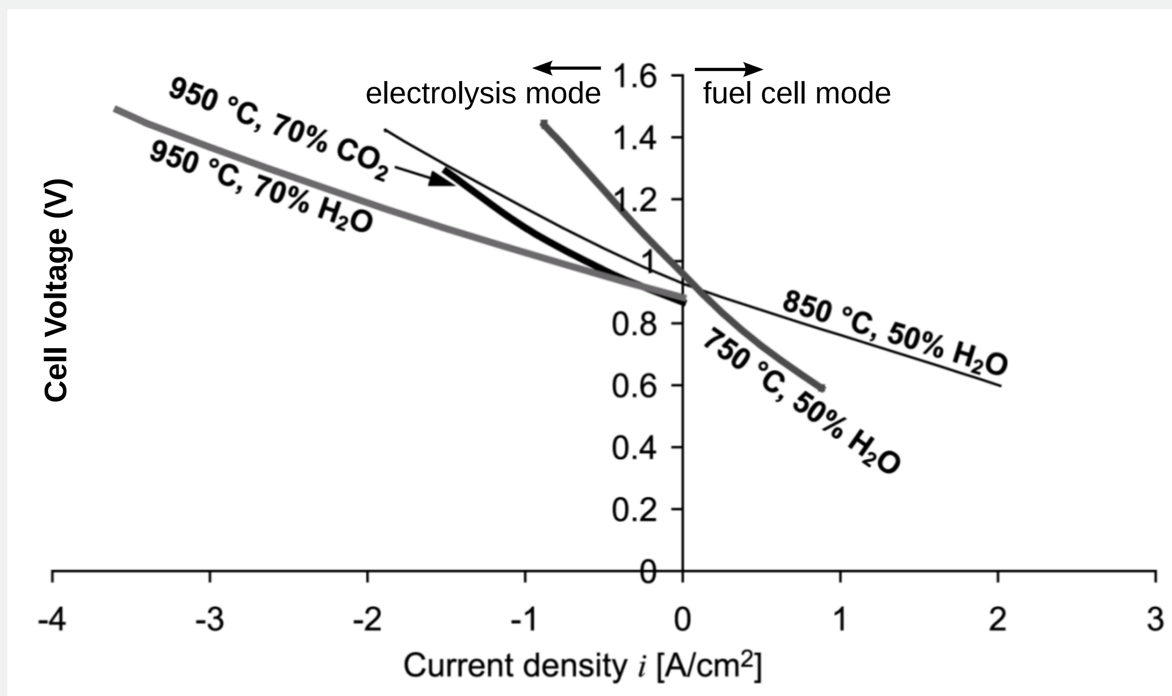
SEM micrographs of fuel-electrode-supported solid oxide electrolysis cells

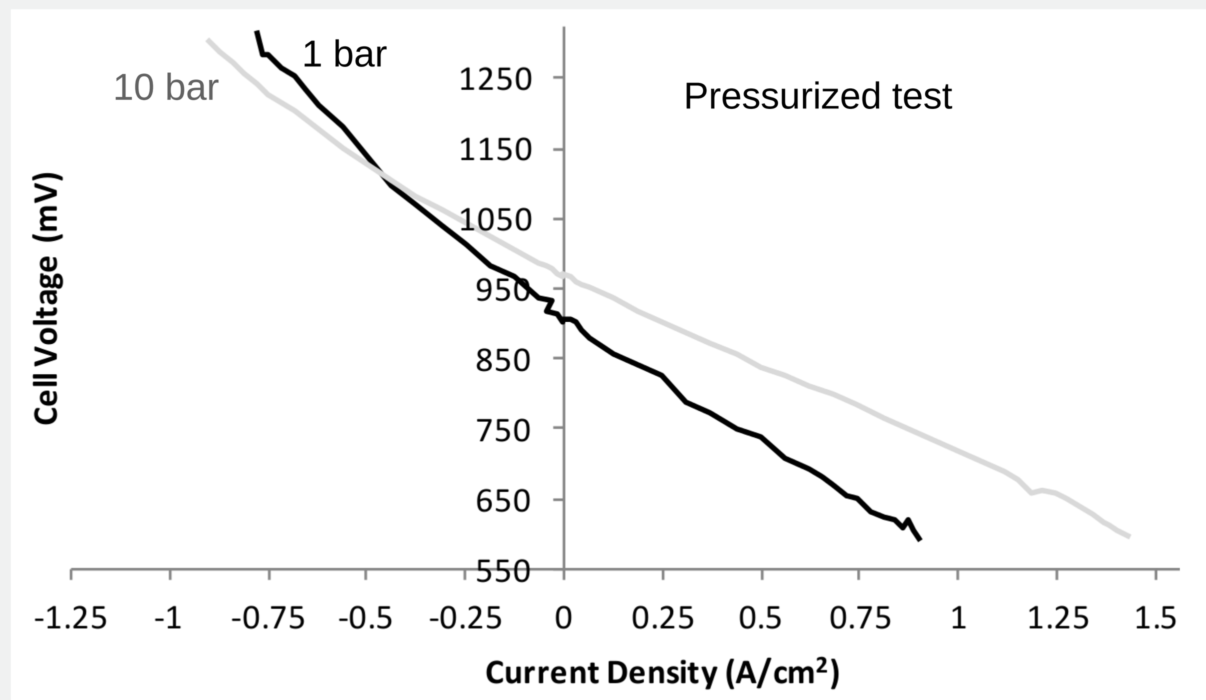


Cell performance

Compared with conventional low temperature electrolysis, operating at high temperature has several advantages that lead to higher efficiency as well as potentially lower capital cost. First, high reaction rates are achieved without expensive electrocatalysts such as platinum. Second, the electrolysis reaction becomes increasingly endothermic with increasing temperature and the inevitable resistive losses in the cell can be used as heat in driving the reaction. The combination of these two advantages enable operation at high throughput (>1 A/cm²) at the thermoneutral voltage (100% electrical-to-chemical energy conversion efficiency; in a real system, heat-exchanger losses will make the efficiency slightly lower). When operated at atmospheric pressure, high temperature electrolysis of CO_2 and H_2O yields CO and H_2 at the cathode and O_2 at the anode. The CO/H_2 mixture (syngas) is subsequently converted with well-known catalytic reactors used in the fossil fuel industry to produce liquid or gaseous hydrocarbons such as methane, methanol, gasoline and diesel. By pressurizing the SOEC device instead of only pressurizing the catalytic hydrocarbon synthesis reactor, it is possible to directly produce hydrocarbons like methane in the cathode chamber. Pressurized operation can therefore reduce the electrolysis system cost and increase the efficiency for production of synthetic fuels.

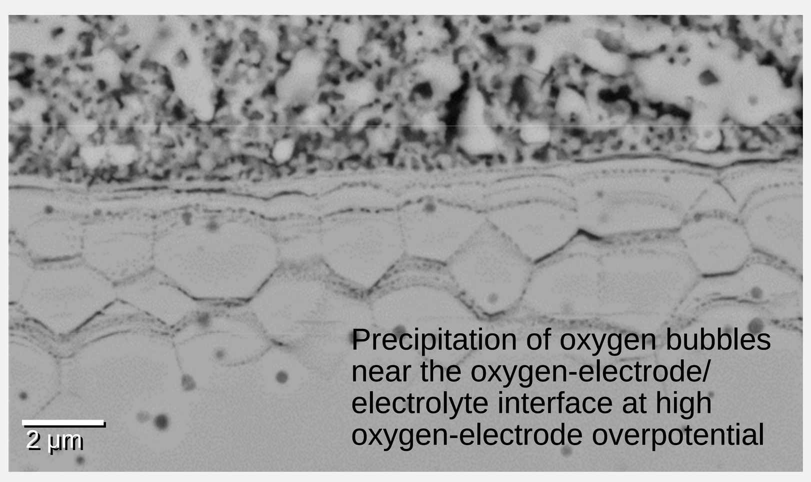


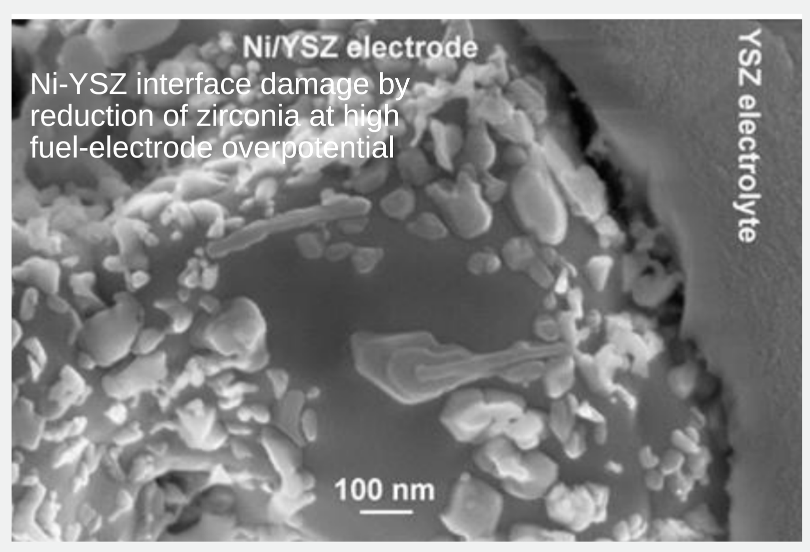


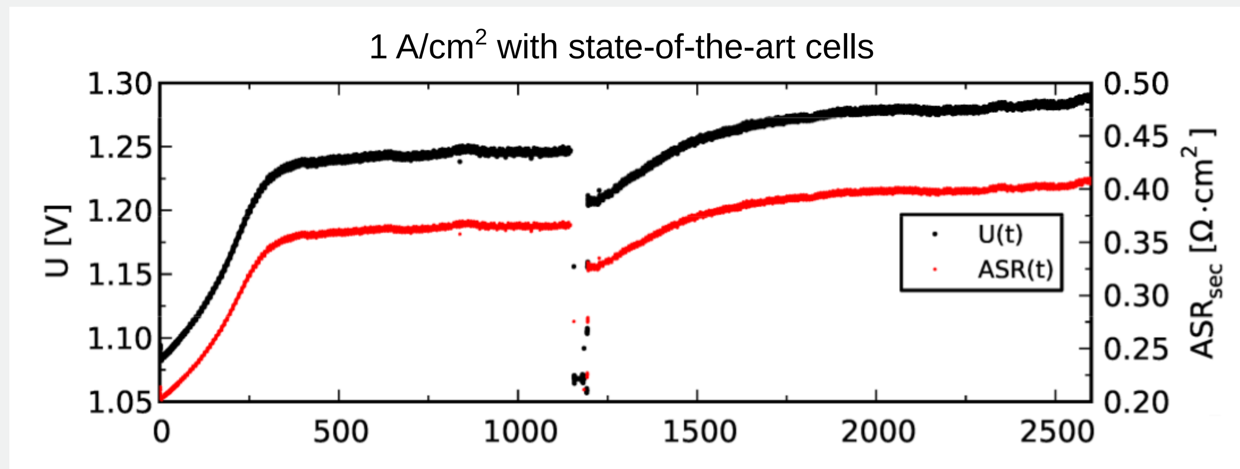


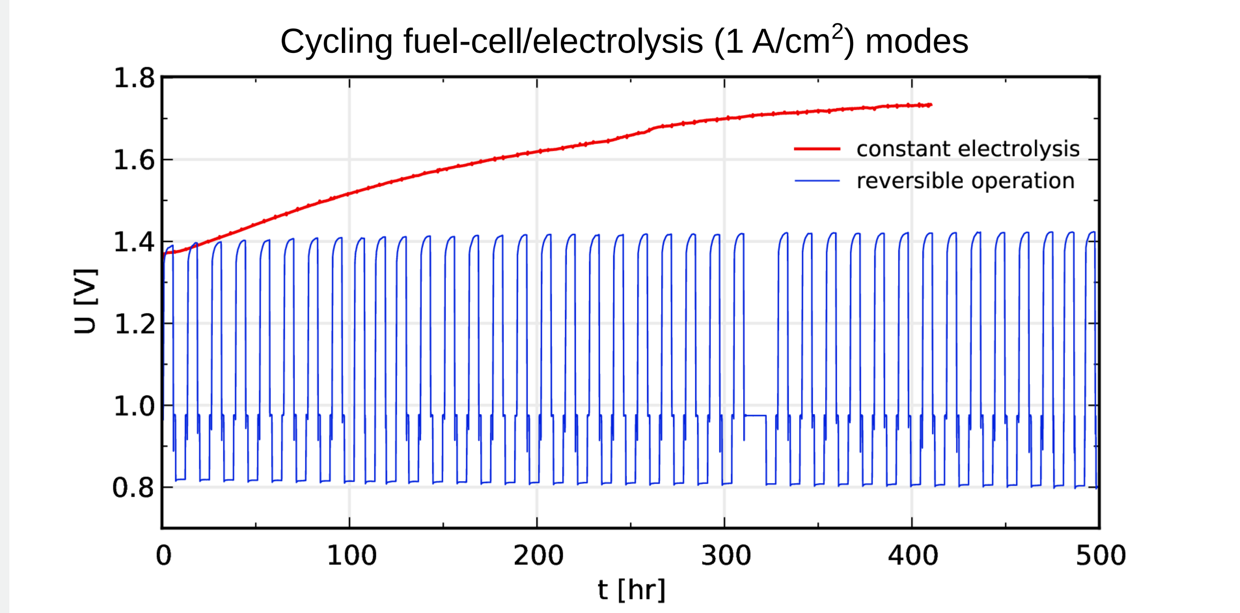
Long-term stability

However, the high temperature reactive environment also poses challenges for long-term stability: the fine porous microstructures of the electrodes can coarsen over time, the local gas composition and electrical potential can induce detrimental structural or phase changes, the component materials can react with each other, and operating errors can lead to sudden thermal transients or exposure of certain materials to oxidizing or reducing conditions which damages the material. Despite all the possible degradation mechanisms, the large effort in materials design that has been undertaken for many years has brought 5-10 year operating lifetimes with reach. SOEC research therefore entails a combination of fundamental studies of materials with long-term testing of pre-commercial devices for thousands of hours, as well as investigating integration into the larger energy system to test relevant intermittent operating profiles.



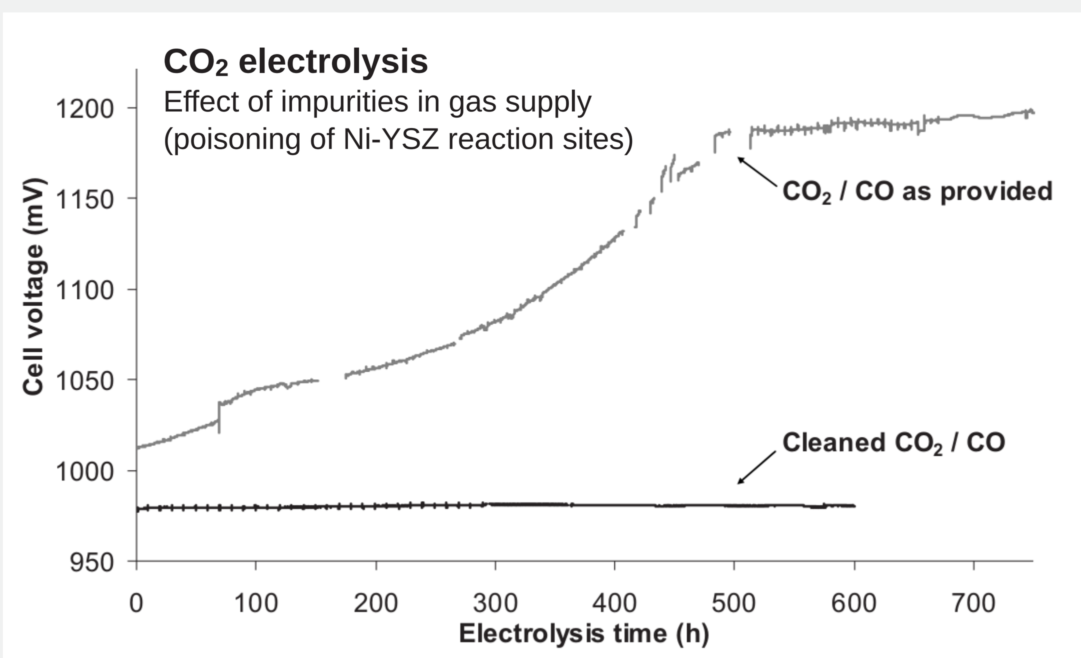






Outlook

Production of synthetic hydrocarbon fuels from CO_2 and renewable electricity using SOECs is feasible. State-of-the-art cells developed at our lab can now run with minimal degradation below 1 A/cm². Recent cell improvements and careful control of cell operation has led to nearly stable performance at 1 A/cm² at the thermo-neutral voltage. The achievable lifetime at this operating point suggests that the technology is approaching cost-competitiveness, based on SOEC system cost estimates for high volume mass production. We are continuing to improve the basis for safe operation and degradation minimization though further detailed measurements and modeling, and we anticipate significant improvements in reaction rates and robustness though further basic materials and electrochemical research, aiming towards further advances in electrodes, cell and stack design.



Poster prepared by Chris Graves <cgra@dtu.dk> for presentation on 14-16 April 2014 at the Columbia University (New York) workshop "Air Capture and its Applications in Closing the Carbon Cycle" and "Research Coordination Network (RCN) on Carbon Capture Utilization and Storage (CCUS) Annual Meeting", http://energy.columbia.edu/events/rcn-ccus-annual-meeting-agenda/. The figures are from: Graves et al (2011) doi:10.1016/j.rser.2010.07.014, Jensen et al (2007) doi: 10.1016/j.ijhydene.2007.04.042, Ebbesen and Mogensen (2010) doi:10.1149/1.3455882, Sun et al (2013) doi:10.1149/05701.3229ecst, Chen et al (2013) doi:10.1149/2.098308jes, Hjalmarsson et al (2014) 10.1016/j.jpowsour.2014.03.133, Graves et al (2013) doi:10.1149/05701.3127ecst.3) doi:10.1149/2.098308jes,