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The role of fuel cells and electrolysers in future efficient energy systems

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Working principle

A fuel cell is an electrochemical cell that converts the chemical energy in a fuel to electricity and heat. The electrical efficiency of the conversion is not limited by the Carnot efficiency and hence may be very high compared to power production based on combustion processes.

Fuel cells possess a number of other characteristics which make them relevant to many different applications in the future energy system. They are by nature modular and may thus be used at a wide variety of scales: from battery replacements (0.1–1 kW), through combined heat and power (CHP) for single houses (1–10 kW) and decentralised units (100 kW–5 MW), to large centralised power and CHP plants (100–500 MW). Fuel cells may also be operated in reverse mode, as electrolysers, to convert electrical energy to chemical energy. An example is the reduction of steam to hydrogen and CO_2 to CO; using well-known catalytic routes the resulting gases can be further converted to a range of hydrocarbons which may be used as transport fuels, such as methanol, DME and even synthetic diesel [124].

Several different types of fuel cells exist. They can be classified by the type of electrolyte used (Table 6). All have their advantages and disadvantages, but none has to date matured to a level where fuel cells are in widespread commercial use or play a significant role in the energy system.

Alkaline fuel cells have been used for space and military applications but are expensive and challenging to use in other applications. Phosphoric acid (PAFC), molten carbonate (MCFC) and alkaline (AFC) fuel cells have historically attracted a lot of R&D, but still face a number of challenges for commercial use. Low- and high-temperature PEM and solid oxide (SOFC) fuel cells are currently attracting the largest development efforts for CHP and transport applications. Domestic CHP units based on both PEMFCs and SOFCs have recently been launched by industrial suppliers [125, 126] as have larger units for distributed generation [127].

Fuel cells and electrolysis cells are still to enter a wide spread use, but the technologies have great potential in a future more efficient and more sustainable energy system.

Fuel cells in a more efficient and sustainable future energy system

Fuel cells can save energy thanks to their high electrical efficiency. Whenever electricity is generated from fossil resources and the accompanying heat is not used, the electrical efficiency of the process determines the energy input required to meet the power demand. Most centralised fossil power plants worldwide operate with no or limited use of their waste heat. The electrical efficiency of a high-temperature fuel cell plant may be as high as 60% and if the fuel

Table 6
Characteristics of the main five different types of fuel cells.

Acronym	AFC	PEMFC	PAFC	MCFC	SOFC
Fuel cell type, electrolyte	Alkaline, Potassium hydroxide	Polymer membrane	Phosphoric acid	Molten carbonate	Solid oxide
Catalyst	Nickel	Platinum	Platinum	Nickel	Perovskites/Ni
Operating temperature	40-100°C	60-200°C	180-220°C	550-700°C	500-1,000°C
Fuel(s)	Pure H_2	Pure H_2 or CH_3OH	Pure H_2	H_2, CO, NH_3, hydrocarbons, alcohols	$H_2$2, CO, NH_3, hydrocarbons, alcohols
Intolerant to	CO, CO_2	CO, S, NH_3	CO, S, NH_3	S	S
Potential electric efficiency [1)]	~45%	~45%	~45%	~60%	~60%
Potential applications	Mobile units, space, military	Mobile units, micro-CHP	Smaller CHP units	Larger CHP units	CHP from micro- to large-scale

[1)] The achievable electrical efficiencies depend on stack load. The numbers in the table are indicative. Under special conditions higher electrical efficiencies may be achievable. For high-temperature PEMFCs a 55% net system efficiency has been achieved. The higher efficiencies quoted for the high temperature technologies (MCFC, SOFC) lie primarily in their suitability for using hydrocarbon fuels. MCFCs and SOFCs can achieve electrical efficiencies of 70-75% when combined with gas turbines or steam turbines. Total efficiency may be more than 90%, but depends on the cooling system and the operating temperature.

cell is combined with a steam cycle the overall efficiency may be as high as 70–75% [128]. This is higher than that of advanced condensing power plants and gas turbines, so the use of fuel cells may save energy by reducing losses during electricity production.

Making use of the heat produced during electricity generation turns power plants into CHP plants (combined heat and power). In Denmark there is a long tradition of using CHP to heat houses via district heating networks. In 2010, 61% of all the electricity produced in Danish thermal plants was accompanied by use of the waste heat. In a future energy system incorporating fuel cells, the use of heat from power plants will remain important.

The modular character of the technology and the fact that CHP units may be made as small as 1–10 kW to several 100 MW allows both local and decentralised power generation based on fuel cells. This provides another way to save energy, since local generation reduces transmission losses for both power and heat. Losses in the electrical grid depend on the transmission voltage and distance; at ~400 kV the losses are in the range from 4% - 9%/1000km [129, 130]. In Denmark the total loss associated with electricity transmission is estimated to be 6% [131]. Heat losses depend on system size; as an example, in a 20 MW system supplying around 6,000 houses, around 20% of the heat is lost in transmission [132]. Local production in CHP units eliminates these losses. Whether the energy saving economically will warrant the extra investments depends on assumed future energy and technology costs. System simulations [133] (see further below) show that despite the potential for reduced transmission losses with local fuel cell CHPs introduction in larger units (0,5-5MW) is more favourable from a system perspective.

Increased amounts of fluctuating power production on the grid from solar and wind will further increase the need for both load balancing and backup generating capacity. It is crucial that this capacity is flexible and can start up quickly [133]. Future energy systems may need several types of fuel cells within both the heat and power sector and the transport sector. To identify feasible applications for fuel cells it is important to see them as part of the entire energy system, and not just the isolated role they play in supplying consumers directly with power and heat.

Integration studies of fuel cells in the Danish energy system

A recent study examined the use of fuel cells and electrolysis in future energy systems, with a focus on Denmark [133]. For isolated houses domestic fuel cells units (1–10 kW) based on natural gas is an option that does expand the amount of CHP in the system and increases the efficiency compared to boilers. However, the analysis points out that the best way to expand CHP based on fuel cells is through use in de-central plants (>0.5 MW) [133]. These plants are more efficient than the local ones and allows for more extensive use of heat pumps locally where district heating grids are not feasible. The latter is beneficial as the heat pumps via their high efficiencies ("heat out"/"electricity in") exceeding one allows the heat-demand to be covered using less fossil resources and a larger share of intermittent power production (wind, solar) in the system. Fuel cells in decentralised CHP plants give higher fuel savings when used in integrated energy systems with large shares of intermittent renewable energy, compared to conventional energy systems. The reason is that the high electrical efficiency of fuel cells reduces the amount of heat produced by CHP plants. In conventional energy systems this means that more heat would have to be produced by boilers, whereas in integrated systems incorporating wind power the extra heat demand can be met by large heat pumps for district heating, increasing the overall fuel efficiency of the system.

From an energy efficiency perspective, combining fuel cells with heat pumps and heat storage creates synergy with intermittent production based on renewable resources. In decentralised CHP plants with district heating grids, fuel cells are especially promising as replacements for conventional simple cycle gas turbines. Fuel cells have higher efficiencies, even at part load, and like gas turbines they can be combined with heat pumps and heat storage. It is harder for fuel cells to compete with combined cycle gas turbines. Fuel cells can become important in the move towards future 100% renewable energy systems, because in such integrated energy systems they are able to reduce our dependence on fossil fuels to a greater extent than combustion technologies. It should be noted that above conclusions on where fuel cells may be best placed from an energy system perspective depends on a number of assumptions regarding technology availability and importantly on expected costs and efficiencies of the applied technologies.

Fuel cells in the transport sector

Fuel cells may also improve energy efficiency in services other than power production. A particularly important example is transport. Transport accounts for around 33% of the total annual energy consumption in Denmark [134] and there is a huge potential to save energy in this sector, as discussed in Chapter 9. One route is via fuel cell cars.

The efficiency of a fuel cell is roughly double of that of a combustion engine. Subtracting the energy losses associated with producing the fuel (hydrogen or methanol), the overall well-to-wheel energy saving is reduced to around 15–25% (for hydrogen from natural gas) [135]. For hydrogen derived from biomass there is no efficiency gain compared to diesel, but of course there is a dramatic benefit in terms of emissions [136, 137, 128, 138].

Several car manufacturers including Honda, Hyundai, Daimler and Ford have development programmes on fuel cell cars, though commercial fuel cell cars are not yet available. Small demonstration fleets exist in several places in the world, including buses [139] as well as cars [140]. Development has proved to be much slower than expected a decade ago, but several developers have announced that they expect market introduction around 2015 [141].

For transport with improved environmental performance, fuel cell vehicles are in strong competition with battery-based electric vehicles. Whereas fuel cell vehicles provide longer drive ranges – around 500 km – than battery EVs [142], the latter are technically more mature and nearer commercial availability. At the current state of development, battery EVs are also more fuel-efficient and cheaper than fuel cell vehicles. Due to their limited range, battery EVs may be best suited to covering only certain parts of the transport demand. For long journeys a hybrid solution may be the best option, combining the high fuel efficiency of battery EVs with efficient fuel cells to increase the range. In this case fuel cells would compete with the small combustion engines used in current hybrid vehicles [133].

Large-scale introduction of both technologies is hampered by the higher cost of the vehicles as well as the large investments needed for new infrastructure (hydrogen fuelling stations and charging/battery replacement stations, respectively). From an emission reduction perspective an interesting alternative is to run conventional combustion engines on synthetic fuels produced by electrolysis (see below) [143].

Besides their use for power production in CHP plants and transport, as discussed above, fuel cells may reduce energy losses by replacing inefficient existing technologies in a number of specific niches. One example is the auxiliary power units which long-distance trucks use to generate electricity for cargo refrigeration and driver comfort. Conventional auxiliary power units based on generators driven by the main engine are very inefficient (<15%), so fuel cells could be an attractive alternative.

Electrolysis in the future energy system

In the specific context of saving energy by replacing fossil fuels, fuel cells may have even greater potential when used in reverse, for electrolysis. Electrolysis converts electrical energy to chemical energy, so for instance water may be split electrochemically into hydrogen and oxygen.

Electrolysis may act as an "enabling technology" facilitating substitution of fossil energy by alternatives in several different ways. These include storing energy from intermittent renewable sources such as wind and solar power, and producing synthetic fuels for transport. The latter will be important in a future sustainable system where biomass resources will be scarce [144].

The energy efficiency of electrolysis can be very high, at around 90–95% (based on higher heating value) [143, 145]. The exact value of the efficiency depends on temperature, current loading, and the chosen electrolysis cell technology (Table 6).

Energy storage

An increasing share of power production that relies on fluctuating sources like solar and wind places increasing demands on load balancing on the electricity grid. This is true both at short timescales, to keep the frequency constant, and for longer-term storage of surplus electricity so that the system can cover periods when consumption exceeds production. Both objectives can be met by electrolysis, with storage of the gases produced and conversion back to electricity as required. For ease of storage and reuse it may be best to produce either methane or liquid fuels. Methane can be produced in two steps. Syngas (a CO/H_2 mixture) is first produced either via co-electrolysis of CO_2 and H_2O or by reacting CO_2 with hydrogen from steam electrolysis [146], and then catalytically converted to methane. Both routes to syngas have been demonstrated [145,146] and the conversion of syngas to methane is well established in the chemical industry.

From a number of detailed analyses of how to realise a totally fossil-free Danish energy system by 2050, transmission grid manager Energinet.dk has assessed the amount of extra wind power capacity needed (among other renewable sources) as well as the required storage capacity [147]. Energinet.dk concluded that an extra 17 GW of installed wind capacity is needed, plus around 3.5 TWh of storage. (Interestingly, the capacity of the existing Danish natural gas grid, including two storage sites, is about 11 TWh.) Energy storage in batteries on board a fleet of EVs is another option, though of rather low capacity. Around 1.5

million EVs would be able to store on the order of 50 GWh, which could match hour-to-hour fluctuations but would not be enough to cover weeks of low wind generation.

Electrolysers can thus become important in the transition to renewable energy. In this transition it is very important to integrate the electricity sector with the heating sector and the transport sector as will be discussed further below

Transport fuels

Extensive use of electrolysis may also play a role in reducing consumption of fossil energy and emissions from the transport sector.

Hydrogen for fuel cell vehicles may be produced by steam electrolysis using power from renewable sources like wind and solar. An alternative which also avoids the problems associated with hydrogen storage is to produce synthetic fuels – methanol, DME or synthetic diesel – via Fischer-Tropsch processes. These liquid fuels can be produced from syngas, which in turn is made via electrolysis powered by renewables.

The synthetic fuels route has the disadvantage that it does not bring the efficiency improvements possible by replacing combustion engines with fuel cells. However, it has several advantages: the existing liquid fuel infrastructure can still be used, and future sustainable non-fossil energy systems will still need liquid fuels, for example for aviation and shipping. A detailed techno-economic analysis shows that this route can produce synthetic fuels at an energy efficiency of around 70% (electricity to liquid fuel). Assuming an electricity price of $0.04–0.05 /kWh, which is close to the average wholesale electricity price in the USA, the process would break even at a fuel price of $3 /gallon (DKK 4.25 /l) [143].

Carbon sources and biomass upgrades

The synfuels discussed above need a source of carbon. An appealing option from a sustainability point of view is to use biomass as the carbon source. However, biomass is scarce and is estimated to cover only around 20% of total energy requirements [148], so it is important to use this resource efficiently. Furthermore, one should be careful In replacing food production with energy crops.

An interesting option in this context is "carbon capture and reuse", where one first burns the biomass to produce electricity and heat, and then uses the resulting CO_2 to produce synfuels via electrolysis. This is a way to produce transport fuels from biomass efficiently in terms of both energy and carbon yield [149,143]. Effectively it uses the CO_2 to carry electricity from wind, solar or hydro to the transport sector in the form of synfuels.

In the short term, sources of CO_2 apart from biomass could include industrial point sources such as cement plants, which contribute 5% of total global anthropogenic CO_2 emissions. In the longer term it might be possible to capture CO_2 from air [150].

Electrolysis in the Danish energy system

Detailed systems analyses of fossil-free future Danish energy systems [133,144] have also pointed out the potential of electrolysis to balance fluctuating power production and to provide a route to synthetic fuels for heavy transport, shipping and aviation. In the long term some applications of electrolysis are more suitable than others, and other energy storage technologies – such as large heat pumps in combination with heat storages in CHP plants and battery electric vehicles – may well precede large-scale electrolysis because of high efficiency and lower cost at the present stage of development [144].

Fuel from electrolysers combined with fuel cells in CHP plants can supplement other fuels, such as biogas or syngas, in energy systems with high shares of intermittent renewable energy. When the share of renewable electricity from wind or PV exceeds 50% of the supply, the advantage of electrolysers for hydrogen and synthetic fuel production improves significantly. If electrolysis is introduced to a system with a smaller share of fluctuating renewable electricity there is a risk that conventional power plants would sometimes have to supply electricity for electrolysis which is undesirable as it reduces overall efficiency of the system [133].

The Danish government aims for 50% of the electricity demand coming from wind power by 2020. Although electrolysis is not the only balancing or storage option for the Danish system, it has the potential to become important because of its ability to supply transport fuels and to sidestep the biomass resource limit outlined above.

Technology status

All the fuel cell types listed in Table 6 have similar (or even identical) counterparts in electrolysers.

Alkaline electrolysis systems have been commercially available for many decades from a number of suppliers. Megawatt-scale plants are in operation, typically for on-site use in industrial processes where scale or transport costs make conventional hydrogen processes more expensive. By far the largest share of global hydrogen production comes from fossil fuels, however.

Recently PEM electrolysis systems have also become available from industrial suppliers, though so far only a few plants exist.

As yet there are no commercial suppliers of solid oxide electrolysis (SOEC) plants, but standard SOFCs have been shown to work well for electrolysis at modest current densities [151]. The development and marketing of SOECs can therefore be expected to follow a few years behind that of SOFCs, with the same industrial players involved. Though it has only been demonstrated at a scale of 15 kW this technology has great potential to become cost-competitive; the high operating temperatures allow the use of expensive noble metals to be avoided, and high volumetric production can be achieved without compromising efficiency [143,145].

Both fuel cells and electrolysis cells can play important roles in the future energy system, where the focus is on saving energy and replacing fossil resources. Which of the technologies mentioned will be developed and used on a global scale depends eventually on their availability on the right scale at the right time, and most importantly on their costs compared with competing technologies. In our view the most promising systems, which are also the ones currently attracting most of the development funding, are:

- alkaline electrolysis;
- low- and high-temperature PEMFCs and PEMECs; and
- SOFCs/SOECs.

Denmark's transition to a smart energy system

This section presents the results of systems analyses of a future Danish energy system based on 100% renewable energy by 2050. The analysis balances supply and demand under a range of assumptions about future trends in consumption and availability and the estimated costs of supply technologies. The work was carried out under the CEESA (Coherent Energy and Environmental System Analyses) project funded by the Strategic Research Council [144]. In the analyses the energy system analyses model EnergyPLAN has been used. EnergyPLAN [152] is a deterministic simulation model ensuring that the system balances from hour to hour throughout the year.

Increasing penetration of intermittent renewable resources in the electricity grid increases the demand for smart energy systems. In a smart energy system the focus is not only on the electricity grid and its balance of supply and demand, but also on sector integration through demand flexibility and various storage options:

- heat storage and district heating with CHP plants and large heat pumps;
- new electricity demands from large heat pumps, and electric vehicles for electricity storage;
- electrolysers and synthetic, liquid fuels for the transport sector, enabling energy storage in a dense liquid form;
- gas storage and gas grids for biogas and syngas/methane.

Smart energy systems enable flexible and efficient integration of large amounts of fluctuating electricity production from sources such as wind turbines. The whole idea of building wind turbines or PV systems is to cut use of fossil energy sources. The gas grid´s storage facilities and liquid fuels provide long-term storage, while electric vehicles and large heat pumps in combination with thermal heat storage contribute shorter-term storage and flexibility. If the large-scale integration of renewable energy is accompanied by the integration of sectors, the increased fuel efficiency can potentially decrease the costs of the total energy system.

The first and most important step is the integration between the heating and power sectors. This is already in place to some extent in Denmark, where approximately 60% of the electricity demand is met by CHP plants and more than 60% of heat demand is supplied by district heating. This integration requires thermal storage, which is currently installed in more than 500 small and medium-sized CHP plants to enable them to operate more flexibly (present thermal storage capacity in the Danish district heating system is estimated to be approx 50 GWh). This can reduce fuel consumption in the overall energy system by replacing condensing power plants and helping to integrate fluctuating wind power effectively. More important than the content of the storage is that the storage allows for flexible production and an unbundling of the heat demand and the electricity production.

20–25% of wind power on the grid can be integrated without significant changes to the energy system. With more than 20–25% of wind power, the analysis points to installation of large heat pumps in district heating plants in combination with the heat storages as the next needed step in integrating the heating and power systems. With wind power levels above 40–45% the transport sector also needs to be integrated with the electricity system [153]. Integration with the transport sector will be a significant challenge in the coming years. Electric vehicles can be important in this integration, as they provide flexibility on the demand side. Exceeding 50-60% fluctuation renewable energy in the system electrolysis becomes important as really large capacities have to be put in place to balance supply and demand [133,153]. This will introduce extra losses in the system, but has the advantages that larger shares of fluctuating production can be tolerated and biomass consumption is reduced.

A smart energy system strategy implies the development and integration of a wide range of supply and end-use technologies, markets and control systems, including electric boilers and heat pumps in distributed generation, electric vehicles, mechanical and electrochemical storage systems, flexible demand mechanisms, and more. Denmark and the Nord Pool already have systems in place to operate smart energy markets, specifically on electricity markets that also enable smaller technologies to participate. These can be further developed in the coming years to accommodate more and more integration technologies. A recent study has documented that systems with large amounts of renewable energy and flexible integration technologies will perform equally well or better (i.e. make more money) on the Nord POOL market than a reference system similar to the one we have today [154].

By 2050, when the Danish energy system is envisaged to be fossil-free, new technologies will be needed to make sure that renewable energy can meet all the demands placed on the system. Hence the CEESA 2050 analysis has a scenario where after 2030, electrolysers producing hydrogen for bio-DME or biomethanol are gradually increased in volume to provide large amounts of liquid fuels to the transport sector. At the same time, co-electrolysers begin to produce feedstocks for DME and methanol using carbon captured from power plants, CHP plants or other sources. Figure 47 shows the energy flows in a 100% fossil-free Danish energy system in 2050 according to the CEESA 2050 scenario [144]. In these scenarios methanol is used as an example of how it is possible to use electrolysers to make synthetic fuels; turning wind energy into liquid fuels. There are more technologies that enable this, however this principle will become increasingly important as other biofuels for transport put a larger strain on the limited biomass resource. In the specific scenario the electrolysers produce more than 20 TWh of hydrogen or more than 70 PJ. This amount of energy would have to be replaced by at least as mush biomass if we did not have the electrolyser technology in the system.

Figure 47
Energy flows in a 100% fossil-free Danish energy system in 2050, according to the CEESA 2050 scenario. The flows represent the annual aggregated values; however every single hour for all demands and production technologies is accounted for in energy system analyses.

Reference: Preliminary 2011 version of results presented in Mathiesen, B.V. et.al. "CEESA 100% Renewable Energy Scenarios towards 2050". Aalborg University, 2012 [144].