Review Article

Current status of stationary fuel cells for coal power generation

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Abstract

Fuel cells electrochemically convert chemical energy in fuels into electrical energy (and heat) and so can produce power efficiently with low environmental impact. Applications of fuel cells include stationary power generation, distributed combined heat and power (CHP) and portable power. Recently, research has been conducted on direct carbon fuel cell (DCFC) technology that converts the chemical energy in solid carbon directly into electricity. This article discusses these technologies and their development status. For small- to medium-sized stationary power systems and CHP, the USA ranks first for fuel cell capacity and Japan leads for delivery systems. South Korea is home to the world’s largest fuel cell power plant: the 59-MW Gyeonggi Green Energy park in Hwasung City. Deployment of fuel cell systems is driven by support from governments in the form of tax credits and other incentives. For large stationary power generation, current interest is in integrating a coal gasification process with high-temperature fuel cells (IGFC) to create ultra-high-efficiency, low-emissions power generation systems. The first IGFC demonstration plant with CCS may be in Japan in 2021 as a result of the CoolGen project. DCFC is still in its infancy and far from demonstration. The overall challenges for stationary fuel cells are cost and cell durability. Experience gained from research, designing, building and operating commercially available systems and the IGFC demonstration plant should lead to further development of the technologies and reduced costs, making them a realistic option for power generation.

Key words: stationary fuel cells; power generation; efficiency; carbon capture and storage; IGCC; IGFC; DCFC; coal

Introduction

The Paris Agreement of 2015 represents an historic milestone for the energy sector and confirmed the near globally agreed target of limiting future temperature increases to well below 2°C, as well as pursuing efforts toward 1.5°C. In the International Energy Agency (IEA) scenario to limit temperature increase to 2°C, carbon capture and storage (CCS) delivers 94 gigatonnes (Gt) of CO₂ emission reductions in the period to 2050. This amounts to 12% of the cumulative emission reduction required in the energy sector. Around 56% or 52 Gt of total CO₂ captured is from the power sector, predominantly from coal-fired power generation (80%) [1]. Achieving these ambitions will require a fast and extensive transformation of the energy sector. Some countries plan to phase out traditional coal-fired power generation unless facilities with carbon capture technology are installed. Another scenario is that critical infrastructure providers and some businesses with sensitive applications have a growing interest in becoming more independent from the grid, to reduce the risk of a failure of electricity supply. Achieving higher efficiency, lower emissions, CO₂...
capture-ready, flexible power generation is the challenge for the coal-fired power sector.

Fuel cells are electrochemical devices that convert the chemical energy of the reactants directly into electricity and heat with high efficiency. Fuel cells generate electricity continuously, provided that there is a source of fuel. The one-step nature of this process has several advantages over conventional power generation methods, which have multiple steps from chemical to thermal to mechanical to electrical energy. The potential advantages include high efficiency with combined heat, cooling and power (electrical efficiency of up to 60%, combined efficiency in cogeneration of more than 90%), high power density, small carbon footprint, low emissions, low noise and good quality power. Fuel cells integrated with coal-fired power plants could produce concentrated CO₂, ready for capture. Fuel cells are modular in nature and can be easily scaled down to a small size without large energy penalties. Due to these advantages, stationary fuel cell technology is considered as one of the most promising energy generation systems to meet the above challenges and has attracted considerable interest from the power generation sector in recent years.

The most important factors for the introduction of fuel cells to the market are:

- reducing the cost to make fuel cells competitive with other power generation technologies;
- selecting the type of fuel to be used and providing a suitable fuel supply infrastructure; and
- demonstrating sufficient durability.

Reducing the cost and increasing the durability of fuel cells is the focus of much research on fuel cell materials. As a fuel of choice, coal can play an important role. For example, syngas and hydrogen from coal gasification can supply the fuel cells. There is also work to develop fuel cells that will directly accept solid carbon as fuel.

This article assesses the current status of the various fuel cell technologies. With the focus on coal-related stationary fuel cell applications, the article begins with a brief introduction to the basic fundamentals of fuel cells followed by a review of recent developments of small- to medium-sized stationary fuel cells. It investigates the larger systems using gas derived from coal gasification for power generation. Converting solid carbon, including coal, directly into electricity in a highly efficient manner has attracted considerable attention. The latest research in this area is also reviewed.

1 An overview of fundamentals

The basic physical structure of a fuel cell consists of an electrolyte layer in contact with two porous electrodes, both containing catalysts to speed the electrochemical processes. One electrode, the anode, is negatively charged, and the other, the cathode, is positively charged (see Fig. 1). Electrochemical reactions take place at the electrodes to produce an electric current [2, 3].

Fuel cells can be categorized into different types based on the reactant type, electrolyte type and operating temperature. Commonly, there are five types of fuel cell, distinguished by their electrolyte, which are being considered for power generation:

- solid oxide fuel cell (SOFC)
- molten carbonate fuel cell (MCFC)
- alkaline fuel cell (AFC)
- phosphoric acid fuel cell (PAFC)
- polymer electrolyte membrane fuel cell or proton exchange membrane fuel cell (PEMFC).

Of these, the SOFC and MCFC are considered as high-temperature fuel cells, whereas AFC, PAFC and PEMFC are low-temperature fuel cells. The main characteristics of these fuel cells are listed in Table 1.

A power system based on fuel cells requires many other components in addition to the cell itself. These include a fuel processing facility, a power conversion unit to convert

![Fig. 1 Schematic of the basic structure of a fuel cell [2]](https://academic.oup.com/ce/advance-article-abstract/doi/10.1093/ce/zky012/5055431/2)
the DC power produced by the fuel cell to AC power for
supply to the electricity grid and waste heat utilization
equipment (see Fig. 2).

Various fuels have been suggested for fuel cells including
hydrogen, ethanol, methanol, natural gas, liquefied
petroleum gas, diesel, biomass and coal. Despite this
range, essentially all commercial or near commercial fuel
cells operate on pure hydrogen or a mixture of pure hydro-
gen and CO at the cell level, with the exception of direct
alcohol and direct borohydride fuel cells [5]. The hydrogen
and CO gases are produced via external reforming, internal
reforming within the cell or partial oxidation of the fuel.
Hydrogen can be obtained from coal by gasification. In an
integrated gasification fuel cell cycle, the chemical energy
of the fuel gas is directly converted to electricity by the
fuel cell, which is a more efficient conversion process than
combustion with expansion of a working fluid. All fuel cells
are somewhat sensitive to sulphur and CO (see Table 1).

The three main markets for fuel cell technology are sta-
tionary power, portable power and transportation. Small- to
medium-sized stationary power includes any application in
which the fuel cells operate at a fixed location for primary
power, backup power, remote power, supplemental power,
distributed power or combined heat and power (CHP). For
large stationary power generation, integration of coal gas-
sification with high-temperature fuel cells has been investi-
gated. Recently, progress has been made in the use of solid
carbon fuel, such as coal, to convert the chemical energy in
carbon directly into electricity without the need for com-
bustion or gasification. Recent developments in small- and
medium-sized stationary fuel cell power systems, coupling
IGCC with fuel cell systems for power generation, and direct
carbon fuel cell technology are reviewed below.

2 Recent market developments on
small- and medium-scale stationary
fuel cells

Due to their high efficiency, development and deployment of
small- and medium-sized fuel cell systems are moving
fast. All stationary fuel cell applications on the market to date are fuelled by natural gas or hydrogen. Therefore, the details of the system itself and its development are not discussed here. However, the development of technologies to convert coal into hydrogen and syngas may make it possible to utilize cheap coal for fuel cell systems. It is useful to assess the technology and market readiness of fuel cell systems. Europe, North America and Southeast Asia are the three main regions active in fuel cell development, and the countries taken as examples are the USA, Japan, Germany and South Korea.

As a world leader in the fuel cell industry, the US Department of Energy (DOE) is a major funder of hydrogen and fuel cell projects, contributing approximately US$150 million in 2015 [10]. Research and development activities in the USA include developing lower cost, better performing plant components such as air compressors, fuel processors and sensors and water and heat management systems. Some research is focused on catalysts as they are a major driver of costs. Materials’ chemical and mechanical durability, conductivity and cost are also crucial. In September 2017, the US DOE Office of Fossil Energy awarded funds of US$10.2 million to 16 projects to advance SOFC technology. The projects address the technical issues facing the cost and reliability of SOFC technology and include field tests of an integrated prototype system project intended to validate the solutions found. The projects fall under two distinct topic areas: SOFC prototype system testing and core technology development.

Stationary fuel cell installations in the USA are dominated by three world-leading manufacturers: FuelCell Energy (FCE) Inc., Doosan Fuel Cell America and Bloom Energy. Units from these developers range in size from 100 kW to several MW. FuelCell Energy, based in Danbury, Connecticut, has won orders for its Direct FuelCell® MCFC technology. Its orders in 2016 included a 1.4-MW unit for the Pepperidge Farm Company in Bloomfield, Connecticut, which will be installed adjacent to the existing fuel cell plant; together they will meet approximately the entire energy needs of the facility, with an on-site solar array supporting peak power needs for the farm. A 5.6-MW project for two units for Pfizer Inc. in Groton, Connecticut, has been confirmed. Long Island Power Authority will install 39.8 MW of FCE units at three locations and Connecticut Municipal Electric Energy Cooperative in Groton will install 7.4 MW to supply power and heat to the US Navy’s submarine base.

Doosan Fuel Cell America was established in 2014 with PAFC systems in South Windsor, Connecticut. They installed three 400-kW fuel cell systems for the Becker + Becker company in Hartford and New Haven, Connecticut, and Roosevelt Island, New York City. The same model was installed for the CT Transit depot at Hamden, Connecticut [11–13].

Bloom Energy leads the field in installation of SOFC systems in the USA. It has supplied fuel cell power generation systems for 44 Walmart stores, and various size units for companies including Constellation, a subsidiary of Exelon Corporation, Apple, IKEA, Johnson & Johnson, Disney Pixar Animation Studios, Equinix, Maxim Integrated, AT&T and Morgan Stanley.

Japan is the leader in stationary fuel cell applications with its Ene-Farm project. In 2009, a consortium of major Japanese energy suppliers and fuel cell manufacturers—including Panasonic, Toshiba, Eneos and Aisin Seiki Co., Ltd—began marketing fuel cell micro-cogeneration units under the common commercial name of Ene-Farm. Panasonic launched its new hydrogen fuel cell system that has a lifetime of 70,000 hours in April 2015. Toshiba offered its H2One™, a hydrogen-based autonomous energy supply system that combines a battery, an electrolyzer, a hydrogen storage tank and a fuel cell. Since its launch, H2One™ units have become operational at the Kawasaki Marien public facility and Higashi-Ogishima-Naka Park in the Kawasaki Port area in June 2015, and in the Phase-2 building of the Henn na Hotel at the Huis Ten Bosch theme park in Nagasaki, Kyushu, in March 2016. The system was also installed in April 2016 at the Yokohama Cargo Center on Daikoku Futo, an artificial island and pier in the Port of Yokohama, as an emergency power supply and load management system [10, 14, 15]. The commercialization
of Ene-Farm systems has proceeded swiftly with sales increasing each year. The accumulated sales were 138,000 units in 2014, 150,000 units in 2015, 200,000 units in 2016 and 223,000 units by October 2017 [13, 16]. Since 2009, the government subsidy has fallen gradually, and now stands at ¥300 K per unit. In the meantime, Japan aims to install 1.4 million residential micro-CHP fuel cell units by 2020 and 5.3 million units by 2030. These targets could only be achieved with dramatic sales growth, which is largely reliant on stronger government subsidies [16, 17]. Eneos, Aisin and Kyocera are engaged in demonstration of a SOFC-based CHP system under the project name Ene-Farm S. Kyocera and Eneos have also started installations of SOFC-based CHP; approximately 300 units were pre-ordered by March 2012 [18]. FCO Power Inc. announced the advance of its next-generation SOFC stack, the Printed Fuel Cell™, for residential fuel cell systems in 2015 [10]. The Japanese branch of Bloom Energy announced the installation of the Bloom Energy Server, a 1.2-MW SOFC generating system, at the Osaka Prefectural Central Wholesale Market in Ibaraki City, Osaka Prefecture, in March 2015. The system supplies 50% of the overall electricity to the building [19].

South Korea is advancing its ambitions for slightly larger scale systems, notably MCFC, although other technologies are also in development. The South Korean government identified the importance of fuel cell technology and allocated a budget of US$11.8 billion for its development in the period 2003–12. According to the roadmap, trials continued through 2014, and then commercial sales expand rapidly from 2015 onward. The government subsidizes 80% of the purchase price, plus there is up to 10% in additional subsidy from local government. As a result of strong governmental supporting policies and substantial investment by South Korean companies, the country now has the world’s largest fleet (by MW) of stationary fuel cell systems, including the 59-MW Gyeonggi Green Energy park (see Fig. 3) in Hwasung City, South Korea [13, 18]. POSCO Energy (http://eng.poscoenergy.com) is South Korea’s largest fuel cell system supplier with a total of 154.2 MW of stationary fuel cell capacity in operation at over 20 locations. Doosan Fuel Cell (http://www.doosanfuelcell.com) reported that it had 129 fuel cell plants totalling 50 MW in November 2015. Doosan’s latest activities are the Busan Green Energy project containing 70 PAFC units totalling 30.8 MW, and the Korea Western Power 5-MW plant of 11 PAFC units in Incheon. Doosan is also involved in the 50-MW Daesen Fuel Cell plant, using hydrogen from Hanwha Total Petrochemical [10, 13, 16, 20].

To encourage fuel cell development, in May 2014 the Council of the European Union refreshed the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) programme (http://www.fch.europa.eu) under the EU Horizon 2020 Framework with a budget of €1.33 billion. Pathway to Competitive European micro-CHP Market (PACE), a €90 million project, received €34 million from FCH 2 JU. The project was announced in 2015, began in June 2016 and runs to February 2021. It aims to support the deployment of 2650 micro-CHP units of around 1-kW power output from four European producers: SOLIDpower, Bosch, Vaillant and Viessmann. Prior to PACE, FCH JU supported the ene. field project (http://enefield.eu) with €26 million. The ene. field (echoing the Japanese programme Ene Farm) was a European-wide micro-CHP field demonstration scheme, launched in 2013 with the similar aim of installing around 1000 fuel cell micro-CHP systems across 12 EU member states by 2017. This project involved manufacturers, including Baxi, Bosch, Ceres, Hexion, SOFCpower and Vaillant, and intended to demonstrate novel intermediate-temperature SOFC and high-temperature PEM technologies as well as the more established stack technologies. It supported 1046 PEM and SOFC micro-CHP units from 300 W to 5 kW, of which only 200 units had been installed by the end of 2015. However, more than 300 were installed in the final 12 months. The project ended in August 2017 [13, 16, 22].

The German government, along with the science and industry sectors, supports the development of fuel cell and hydrogen technologies in Germany in the form of a strategic alliance known as the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). NIP I ran from 2007 to 2016 with a budget of €700 million for R&D activities and demonstration projects. By 2016 it had achieved industrial applications with a stack durability of 40,000 hours and the installation of 3000 domestic fuel cell units for household energy supply [23]. By 2015, over 500 units had been installed across the country under the Callux programme, mainly carried out by three major German manufacturers, Hexion and Vaillant (both SOFC) and Baxi Innotech (PEMFC), which positioned Germany third in the world for the installation of FC CHP. The programme aims to install 72,000 units by 2020 with a target cost of 1700 €/kW. Further to the Callux programme, more units were installed in Germany since the launch of Ene Field consortium in 2012 [17, 18, 22, 24]. NIP II was approved and started in 2016 with funding of approximately €1.4 billion over 10 years. This second phase will focus on helping the technologies enter the market. It is intended to support deployment of fuel cell and hydrogen technology in large numbers with more funds than the European FCH 2 JU programme. The focus will be on cost reduction and large demonstrations [13].

In order to compete with established technologies in the marketplace, fuel cells must provide advantages over the incumbent technology such as increased efficiency and lower emissions at similar cost and durability. The wide-scale commercialization of stationary fuel cell systems depends on many factors such as system reliability and durability, but ultimately on economics. The high upfront capital cost remains a major hurdle. While cost reductions will largely come from improvements in the technologies themselves and from industry achieving economies of scale, it is likely that advanced techniques and processes will be required to enable manufacturing at competitive costs. The main measures for future cost reduction at all scales are [24]:
• reducing system complexity through design optimization;
• eliminating major system components;
• cell-level design improvements such as reducing catalyst content and increasing power density;
• greater collaboration between manufacturers to standardize minor components and overcome research challenges more effectively; and
• further expansion of manufacturing volumes and mass production techniques.

Using cheaper fuels will obviously help to reduce the cost of fuel cell systems. The breakthrough here may come from the development of hydrogen from coal technology.

3 IGFC

Coal gasification can produce a wide variety of products including natural gas and hydrogen, which can be used as a fuel for fuel cells. There are already over 400 coal gasifiers around the world, some of which are large IGCC plants, for example, the 800-MW Edwardsport plant in the USA, the 250-MW Nakoso and 166-MW Osaki CoolGen in Japan and the 400-MW GreenGen in Tianjin, China [25]. Due to the advantages of fuel cell power systems, especially their high efficiency (above 50% HHV), coupling a coal gasification plant with a fuel cell system for stationary power generation or CO₂ capture has become an active topic.

A simple IGFC system is similar to an IGCC system, but the gas turbine (GT) power island is replaced by an FC island. Some system configurations still have a gas or steam turbine to utilize the extra heat. In recent years, most of the systems have also included a CCS process (see Figs 2 and 4). SOFC and MCFC are more fuel flexible and are not poisoned by carbon monoxide and carbon dioxide. They can operate at high temperature, making them good candidates for IGFC systems.

Processing coal to supply a fuel cell is through coal gasification and gas processing. As with a conventional IGCC, the coal is converted to syngas, which is then cleaned to a level that the fuel cells can tolerate. Fuel cell power systems require gas of high purity to avoid poisoning the electrodes or fuel-reforming catalysts. The tolerance of the systems to contaminants is much lower than that of gas turbines. Therefore, more stringent cleanup of the fuel gas is necessary. The syngas produced from coal gasification is a mixture of H₂, CO, CO₂, H₂O, N₂, HCl, H₂S, COS, NH₃, Ar and Hg. The gasification processes operate at high temperatures. Simple thermodynamic analysis reveals that gas cleaning at high temperature incurs less of an energy penalty in terms of the overall cycle efficiency than low-temperature cleanup. However, low-temperature cleaning technology is more mature. The syngas needs to cool through a series of heat exchangers before entering the FC system. The recovered heat is sent to a heat recovery steam generator (HRSG) for superheating or reheating to...
create steam in most of the IGFC configurations. Gas cleaning can be arranged after the cooling process [27].

The first stage of gas cleaning for all types of fuel cells involves the removal of particulates from the syngas by filtration. Ceramic filters are commonly used in IGCC in the temperature range 250–450°C. The syngas is then quenched to capture acid gases. After going through a series of cleaning devices, such as a water scrubbing system, carbonyl sulphide hydrolysis unit, low-temperature syngas cooling system, trace element removal system, Selexeol single-stage acid gas removal process, syngas reheat unit and ZnO fixed-bed sulphur-polishing unit, the syngas is cleaned [26, 28]. In some systems, hydrogen is separated from the syngas. Part of the CO₂ can also be captured here. The cleaned syngas may need the pressure to be reduced before entering the FC island to generate power.

Due to the large costs of the prototypes, even at a laboratory scale, no experimental test for an IGFC system has been performed to date. Research efforts and published papers are mainly on the design and optimization of the IGFC systems. However, two small projects are planned in the USA and one large one in Japan.

The first IGFC plant is planned for operation in Japan in 2021 as a result of the Osaki CoolGen project (http://osaki-coolgen.jp). Launched in April 2012, the project is subsidized by the New Energy and Industrial Technology Development Organization (NEDO) and run by Osaki CoolGen Corporation, a joint venture of J-POWER and the Chugoku Electric Power Co. Using knowledge obtained from the EAGLE (coal Energy Application for Gas, Liquid and Electricity) project, Osaki CoolGen seeks to demonstrate IGFC with CO₂ separation and capture technology in three stages. In the first stage, an oxygen-blown single chamber, two-stage swirl-flow entrained-bed gasifier was constructed at Chugoku Electric Power’s Osaki Power Station. The coal feed rate is 1180 t/d, and combined cycle output is 166 MW. Both the gasifier and gas turbine were supplied by Mitsubishi Hitachi Power Systems Ltd. Construction is finished and the IGCC plant started operation in June 2016. A photograph taken in March 2016 shows the basic layout of the project (see Fig. 5). This phase of the demonstration is to verify the scaled-up EAGLE gasification technology and gain operational and control experience with the IGCC system. The second stage will involve adding CO₂ capture equipment to the IGCC system. In the third stage, a fuel cell system will be incorporated to demonstrate IGFC with CO₂ capture. The goal is for the IGFC system to achieve an efficiency of 55% [29–32].

The US DOE has actively promoted R&D on IGCC systems since 2000 through research programmes such as Vision 21 and on IGFC systems through the Solid State Energy Conversion Alliance (SECA). Currently, SECA is focused on the development of low-cost, modular and fuel-flexible SOFC technology suitable for a variety of power generation applications. The Office of Fossil Energy’s National Energy Technology Laboratory (NETL) also founded projects on advancing the reliability and endurance of low-cost SOFC for use in large-scale stationary electrical power generation. One project is to reduce the degradation rate of an SOFC stack and to verify the production cost of the stacks. The other project is to advance the readiness of the SOFC system for deployment into field testing, by qualifying an advanced stack design that will reduce costs and increase system robustness and reliability for entry-into-service field test units. The Office of Fossil Energy also supports a Solid Oxide Fuel Cell Program (https://www.netl.doe.gov/research/coal/energy-systems/fuel-cells). This combination of work

![Flowsheet of power generation process of IGFC system with CCS](https://academic.oup.com/ce/advance-article-abstract/doi/10.1093/ce/zky012/5055431)
will provide foundational fuel cell technologies for coal-based fuel cell power systems. Based on these results, NETL aims to demonstrate a 10-MW IGFC system by 2020 and a 50-MW IGFC system by 2025 [33].

In comparison with the demonstration projects, theoretical research on IGFC is more active. Economic analysis of IGFC systems has been carried out from technology, exergy and thermodynamic perspectives. The most comprehensive techno-economic analysis was carried out by NETL [28, 34]. NETL proposed four different IGFC system configurations: two parallel pathways of conventional coal gasification and catalytic gasification with the systems working either under atmospheric or pressurized conditions in each pathway. The study assumes that all four IGFC plants use advanced planar SOFC featuring separated anode and cathode off-gas streams with anode off-gas oxy-combustion for cases with carbon capture. The power plant cost and performance are estimated based not only on the current state of SOFC development but also on a projected pathway of advances in SOFC technology development and expected improvement in plant availability and capacity. The results conclude that IGFC plants have significant environmental advantages over all other fossil fuel power plants and consume 50% less raw water than even the water economical natural gas combined-cycle system (NGCC) with CCS. The cost of electricity with the IGFC system is projected to be significantly lower than IGCC and pulverized coal system with CCS, while being competitive with NGCC systems with CCS. The study also indicates that a significant reduction of the rate of degradation of SOFC performance is required for the IGFC system to be economically competitive with other technologies, in addition to enhancing SOFC electrical performance.

Developments are also required for the catalytic gasifier, the SOFC stack unit reliability when operating on high methane syngas and the oxy-combustion technology. Exergy-economic analyses [35] and thermodynamic-economic analysis [36, 37] also confirm that IGFC systems are economically viable compared to IGCC-CCS and PC-CCS plants, as the high capital cost of the SOFC power island is offset by its high power conversion efficiency and low cost of postcombustion CO₂ capture.

Conceptual designs for different SOFC hybrid systems have been proposed to assess the efficiency of the IGFC systems. The latest one is the advanced IGCC/IGFC system proposed by Japanese researchers, which is based on the theory of exergy recuperation [38]. The system (see Fig. 6) uses a steam-reforming gasifier, which operates at a low temperature (≤900°C) using steam or low oxygen-to-steam ratios, to replace the high-temperature gasifier. The proposed high-density triple-bed circulating fluidized bed gasifier system comprises a pyrolyzer, a bubbling fluidized bed gasifier and a riser combustor. The coal is pyrolyzed and then the pyrolysis tar and gas are separated from the char by a fast gas-solid separator. Finally, the char is gasified in the gasifier using the steam from the gas/steam turbine and/or SOFCs. The unreacted char is moved to the combustor, where it is partially or completely combusted to generate heat. A large amount of inert solids are used as the heat carrier circulating in the three beds to provide heat efficiently from the combustor to the pyrolyzer and char gasifier. Early laboratory-scale experiment results show that the amount of oxygen supplied to the gasifier can be reduced, which increases the thermal efficiency of the IGCC system by approximately 10%. Recently, a super-IGFC concept, with power generation efficiency...
as high as 89%, was proposed in Japan [39]. The system is
mainly composed of a steam gasifier and a SOFC, in
which the heat and steam generated in the SOFC are fed
directly to the steam gasifier. Other hybrid power genera-
tion systems, such as integrating catalytic gasification,
SOFC, oxygen transfer membrane (OTM) and gas turbine
[40] or integrating coal gasification, SOFC, and chemical
looping combustion (CLC) processes [41], also achieved
high energy efficiency. Retrofitting existing IGCC power
plants with SOFC and CO₂ capture has been simulated and
results indicate significant thermodynamic advantages in
terms of boosting electrical and exergy efficiencies [42].

There is also research on integrating an IGCC or PC coal-
fired power plant with an MCFC for CO₂ capture, where
two fuel sources are arranged, coal for the gasifier or com-
bustor and methane for the MCFC [43, 44].

4 DCFC

A direct carbon fuel cell (DCFC) is a device that generates
electricity through the direct electrochemical oxidation of
solid carbon to CO₂ (see Fig. 7). A DCFC has a single process
chamber for solid fuel conversion contacting the anode.
Attempts to use solid carbon to generate electricity date
back more than a century to the demonstration of the first
molten hydroxide DCFC proposed by William Jacques in
1896. Useful reviews of devices tested in the early years
of development were conducted by Howard in 1945 and
Liebhafsky and others in 1968. However, it was the DCFC
demonstration at Stanford Research Institute in the 1970s
that renewed interest in the direct electrochemical oxida-
tion of solid carbon [5, 45].

In theory, DCFC technology can offer high electrical effi-
ciency (~70%) among various power generation technolo-
gies, and combined heat and power efficiency of ~90%. The
by-product is highly concentrated CO₂ requiring no gas
separation that can be directly stored, avoiding cost and
efficiency penalties. Fuel utilization can be almost 100% as
the fuel feed and product gases are distinct phases and
thus can be easily separated. There is no need for water
usage in the process, an advantage over the IGFC concept.

Despite the advantages, the development of DCFC tech-
nology is still in its infancy. Carbon derived from cheap
sources, like coal, can have a high electrical conductivity
and when pressed directly onto the solid electrolyte offers
the shortest distance possible for mass transport from the
anode to the electrolyte. However, refuelling the anode still
has technical issues and only conductive forms of carbon
can be used, which excludes raw coal. Coal processing can
add cost. DCFC technology also has to overcome other chal-
enges before becoming commercially viable, such as poor
power density, high degradation rates, fuel feed system,
scaling up the technology and fuel processing procedures.
Current efforts are broadly focused on material selection
for critical fuel cell components and understanding reac-
tion mechanisms for carbon oxidation. Research relevant
to coal includes the effect of coal properties and pretreat-
ment on DCFC performance and some DCFC operational
tests with coal as the fuel, which are described below.

Almost all types of coal have been tested in DCFCs. The
effects of the physical and chemical properties of coal,
and the coal preparation methods on DCFC performance,
have been studied. The results revealed that the
DCFC performance is affected by coal properties, such as

Fig. 6 Schematic diagram of A-IGCC/IGFC system [38]
volatile matter, oxygen content and structure disorder. High coal reactivity enhances cell performance whereas high ash and sulphur content reduces it. The best DCFC performance was obtained with bituminous coal, due to its high volatile matter and low sulphur content. Many coals are treated to remove impurities and to recover volatiles before use in fuel cells, which have improved the cell performance [47–55].

Performance of DCFC with different electrolytes has been studied. Scientific Applications and Research Associates (SARA) Inc. in the USA has been the main developer in direct carbon molten hydroxide fuel cells (DC-AFC) and has developed successive generations of prototypes. Coal-derived carbon anode, iron–titanium alloy cathode and humidified air as the oxidant are used for DCFC. Power densities of 33 and 84 mW/cm² were achieved from a coal-derived rod (active surface area ~65 cm²) and graphite rod (active surface area ~51 cm²) at 630°C, respectively, although these power densities are too low for commercial purposes [5, 56].

For direct carbon molten carbonate fuel cells (DC-MCFCs), solid carbon fuel is directly fed into the anode chamber where it is oxidized. Cooper and co-workers at Lawrence Livermore National Laboratory (LLNL) in the USA have been the main developers of this technology. Power densities up to 100 mW/cm² and 80% efficiency have been routinely achieved by LLNL with several types of carbon fuels, one of which is a self-feeding cell that was refuelled pneumatically and incorporated internal pyrolysis of the coal. However, the technology was licensed to Contained Energy, and no further progress is reported [57].

Fig. 7 Schematic of a coal-fuelled DCFC power generation system [46]

An integrated external (to the fuel cell stack) gasifier and fuel cell system, which operates on gas derived from coal, cannot be strictly described as a direct carbon fuel cell. However, due to the close proximity of the gasifier and fuel cell, which leads to both thermal and gas phase coupling, this design is still considered as DCFC. This approach differs from an IGFC system as it electrochemically converts coal to electricity based on dry gasification using anode recycle of the product gas CO₂ (see Fig. 9). IGFC employs steam gasification of coal to deliver the carbon in the form of a gaseous fuel to the anode surface of SOFC. Gür and team at Stanford University lead the research in this field. They have reported a system with a tubular SOFC operated on CO generated from an external Boudouard gasifier using low-sulphur Alaskan coal as fuel. The highest power density, 450 mW/cm², was achieved at 0.64 V and commercial interest in the further development of this technology [5, 56].

The most advanced direct carbon solid oxide fuel cell (DC-SOFC) technologies are through carbon placed within the anode chamber and use gasification. Akron University proposed a design using YSZ electrolyte button cells and coal as the fuel for stationary power generation (see Fig. 8). Raw or devolatilized coal is placed within the anode chamber in direct contact with the cell. Nickel, copper and gold-based materials and lanthanum strontium manganite (LSM) are used for anode and cathode catalysts, respectively. The cells are operated in the temperature range of 800–900°C. Power densities achieved over a short duration of a few hours were in the range 50–150 mW/cm². It has been claimed that a build-up of ash on the anode surface decreases the power density, but on removal of ash, the power density is restored to its previous values. It was found that the limited oxygen ion diffusion across the electrolyte membrane and the long-term activity of the anode catalyst are the main issues affecting performance [5].
720 mA/cm² current density at 850°C for a fixed flow rate corresponding to 60% CO utilization [59]. Different carbon fuels, such as coals, coal chars, graphite, activated carbons, biochar and commercial carbon blacks, were studied for in situ gasification and DCFC. So far, cells have operated for only up to 100 h [56] and more research is required on this technology.

Ong and Ghoniem [60] proposed a system that couples coal gasification to a SOFC. In this configuration (see Fig. 10), from the bottom, steam (pink arrows) passes through pulverized coal, releasing gaseous fuel (red arrows) made up of hydrogen and CO. The fuel goes into a SOFC (disc near top) in the same chamber, where it reacts with oxygen from the air (blue arrows) to produce electricity. A modelling study of SOFC coupled with steam and dry coal gasification indicated that the DC-SOFC system is capable of power densities >1.0 W/cm² with H₂O (steam) recycle, and power densities ranging from 0.2 to 0.4 W/cm² with CO₂ recycle. This result also suggests that the DC-SOFC system performs better with steam than with CO₂ gasification.

Hybrid direct carbon fuel cells (HDCFC) consist of a SOFC in which the anode is immersed in molten carbonate slurry and carbon fuel. The cell feeds carbon directly to the electrolyte surface using molten carbonate. The major developers of this technology have been SRI International and St Andrews University, UK. Deleebeeck and others [45, 48] at the Danish Technical University have joined the work on this topic recently. SRI International demonstrated a six-cell stack constructed from six YSZ tubular cells immersed in a single molten carbonate bath containing solid carbon fuel. This design was tested on biomass, coal, tar and mixed plastic waste as fuels, achieving power densities of 70, 110, 80, and 40 mW/cm², respectively. SRI International also operated a similar design cell in excess of 1200 h [5, 56]. Irvine and team at St Andrews University [47, 50] studied the effects of carbon properties on HDCFC performance with different kinds of coal, including anthracite, lignite and bituminous coal before and after demineralization, in a button cell with a NiO-YSZ anode, an YSZ electrolyte and a LSM-YSZ cathode. The cell with bituminous and anthracite
coal showed good durability over two hours of testing compared to the lignite coal. The cell was tested at the relatively low temperature of 700°C and the power output is comparable to that of the cell with binary carbonate operating at 750°C. They also compared anthracite coal with bituminous coal as a fuel for HDCFC in terms of maximum power density, short-term (24 h) and long-term durability (>100 h). The total power output from anthracite coal was higher than that from the bituminous coal. Deleebeeck’s team evaluated anode- and cathode-supported HDCFC performance for anthracite and bituminous coals as fuel, including several different pretreatment methods. They found that pyrolysis in air of demineralized anthracite coal samples and utilization of a cathode-supported SOFC architecture enhanced cell performance. Cathode-supported cells resulted in higher power densities than the carbon black-fuelled anode-supported counterpart [61–63].

Fig. 10 Possible configuration for the coal gasification and SOFC system [60]

IGFC technology. DCFC technology is still at the concept validation stage. Current efforts are focused on materials selection and understanding reaction mechanisms.

The overall challenges for stationary fuel cells are the cost and cell durability. For the IGFC system, the gas cleaning process adds another energy barrier to its power generation. For DCFCs, coal fuel contamination and low power density are the main issues to overcome. Until now, stationary fuel cells have been manufactured at very low volumes and further investment is required in the development of large scale manufacturing technology. Further development of electrode materials, catalysts, membranes and electrolytes are critical for improving cell performance and commercial viability. Reducing the cost of manufacture can benefit all aspects of fuel cell systems, including hydrogen production and storage systems, and hydrogen infrastructure. Support from governments is critical to progress stationary fuel cell applications until they are ready to enter the market.

Conflict of interest statement. None declared.

References


