Scientific Developments for Natural and Engineering Sciences

CHAPTER 16

Solid Oxide Fuel Cells: Towards a Sustainable Energy Future (Rahmiye Zerrin Yarbay Şahin, Burçin Atılgan Türkmen)

Solid Oxide Fuel Cells: Towards a Sustainable Energy Future

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1. Introduction

Energy is the main component of nature-society relations and is known to be a critical resource for sustainable development. Energy sources are required to meet human needs, enhance life quality and empower technological, social, and economic growth. Nevertheless, the current ways that we have energy are utilized is widely regarded as unsustainable [1].

Continuing the use of fossil fuels faces problems such as the depletion of fossil fuel supplies, environmental issues, and a large rise in fuel prices. Energy supply contributes not only to problems related to climate change but also to environmental concerns like air, water, and soil pollution, loss of ozone, acid rain, deforestation, and release of toxic and radioactive substances [2]. Due to the increasing need for sustainable energy supply, a range of possible solutions have emerged, bearing energy conservation through increased power production, a decline in the use of fossil fuels, and an increase in the availability of environmentally friendly resources, such as fuel cells and renewable and sustainable energy sources [1, 2].

Implementation of sustainable issues in the planning, design, and manufacturing of energy systems is an important topic, in addition to the regular economic, environmental and social framework conditions. Interest in fuel cells is growing exponentially as an attempt to improve energy security while achieving the other sustainability objectives. Fuel cells are projected to provide potentially high electrical efficiency and have a high potential for environmental advantage as possible energy storage devices. Among various fuel cells, solid oxide fuel cell (SOFC) is accepted being one of the essential technologies for the sustainable power production of hydrogen-rich fuels with a high energy conversion efficiency [3].

The main aim of this chapter is to explain the sustainability of SOFCs systems by considering the environmental, economic, and social dimensions of sustainability. The inspiration for this work is the necessity to highlight the importance of sustainable production of alternative energy resources and carriers, besides the role SOFC technology is supposed to act in sustainable energy systems. As part of the sustainability topic, this research addresses many aspects of the sustainability impacts of SOFCs technology: the enhancement of improved energy efficiency and emissions, energy security, component material selection, combining with other systems, on the one hand, and the possible effect of materials used in the production cell.

2. Background Information

2.1 Fuel Cells

A fuel cell (FC), as one of the advanced technologies, transforms the chemical energy of a fuel directly into electricity, with the added benefit of high electrical performance and low environmental impact. Fuel cells are categorized in the literature based on the electrolyte and fuel used. Proton exchange membrane fuel cells, phosphoric acid fuel cells, alkaline fuel cells, molten carbonate fuel cells, and solid oxide fuel cells are the most common types [4]. Table 1 lists the characteristics of these different types of fuel cells.

Table 1. Major types of fuel cells [4]

Properties	Proton Exchange Membrane Fuel Cell	Phosphoric Acid Fuel Cell	Alkaline Fuel Cell	Molten Carbonate Fuel Cell	Solid Oxide Fuel Cell
Operando Temperature (°C)	60-200	200	60-220	~ 650	600-1000
Charge Carrier	H^+	H^+	OH^-	CO_3^{2-}	O^{2-}
Electrolyte	Polymer membrane	Liquid H_3PO_4	Liquid KOH	Molten Carbonate	Ceramic
Catalyst	Pt	Pt	Pt	Ni	Ni/YSZ
Fuel	H_2, CH_3OH	H_2	H_2	H_2, CH_4	H_2, CH_4, CO
Interconnects	Carbon based	Carbon based	Carbon based	Stainless steel	Ceramic based
Efficiency (%)	30-60	30-40	50-60	55-60	50-70
Lifetime	5000	30000-60000	5000-8000	20000-40000	Up to 90000

2.2. Solid Oxide Fuel Cells

A solid oxide fuel cell (SOFC) generates electricity by the reaction of fuel with an oxidant in terms of oxide ion diffusion through an ion-conducting solid-electrolyte layer. In detail, a SOFC is made of three main layers including a dense electrolyte, anode, and cathode. The electrolyte plays an active role in order to make classifications upon electrolytes such as proton-conducting electrolyte and oxide-ion conducting electrolyte. While the proton (H^+) is achieved at the anode in the proton-conducting SOFC (H^+-SOFC), water vapor is obtained at the anode in the oxide-ion conducting-one [5]. Figure 1 demonstrates the working principle diagram. Molecular O_2 is reduced to oxygen anions for the first time with the help of the talented electrons obtained externally in the cathode which is denoted as the air electrode in the electrode. In a SOFC, the cathode needs to not only be high in electronic and ionic conductivities but also the O_2 dissociate ability.

Another challenging component is the electrolyte. An effective electrolyte should meet some criteria including being dense enough to distinguish the air and fuel components while showing high ionic conductivity to favour easy migration of oxygen anions and being an electronic insulator. Besides, the electrolyte is required to maintain these requirements over a broad range of oxygen partial pressures. The operando temperature should be determined to attain higher ionic conductivity in the electrolyte [6].

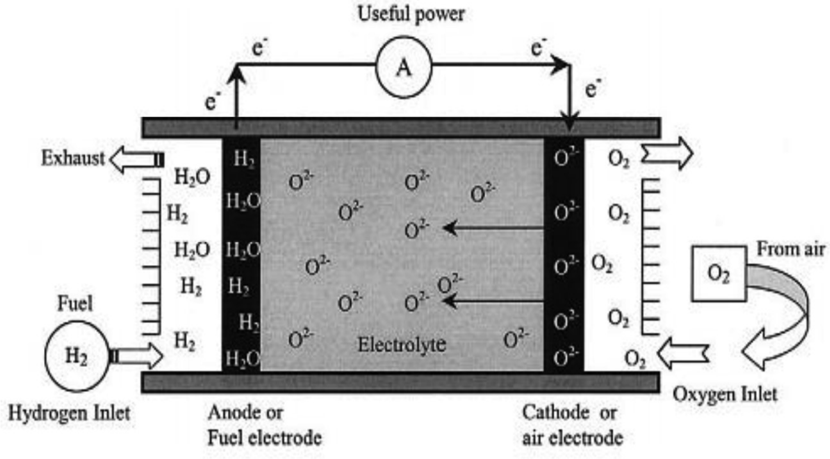

Figure 1. SOFC working principle diagram [2]

Implementation of SOFC systems in daily life has not been actualized yet because of the high cost of cell components, high operando temperatures, safety restrictions related to the handling of gases, and routine maintenance. Operando temperatures which generally fall in the range of 800-1000°C are recorded as one of the main drawbacks in many publications [7, 8]. This drawback may cause catalytic poisoning, electrode sintering, thermal instability, interfacial diffusion between electrolyte and electrode materials, and thermal or mechanical stress associated with different thermal expansion coefficients of the cellular components [5]. As a result, there is a great deal of reduction in SOFC operating temperatures in recent years.

2.3 Sustainability

At the beginning of the 21st century, sustainable development became an important issue, described as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [9]. This definition is widely recognized by all stakeholders as a guiding principle. The concept is gradually becoming more important for different stakeholders around the world.

Sustainability is based on three dimensions: environmental, economic, and social. It is generally recognized and acknowledged that sustainable development can be accomplished by balancing and integrating environmental, economic, and social assessments [10].

The first dimension of sustainability is environmental sustainability. This is concerned with how the natural resources for future generations can be preserved and retained. Environmental sustainability includes the protection of natural habitats, the conserving of scarce resources, the manufacture of environmentally friendly products, ensuring the quality of water, soil, and air for now and future generations, and reducing waste and pollution [11]. Examples of indicators cover environmental sustainability of energy systems: greenhouse gas emissions, pollution, resource depletion, acidification, solid waste, radioactivity, land-use transition, and eutrophication [12].

Economic sustainability promotes long-term economic prosperity without damaging the social and environmental aspects of society. Overall, cost, the efficiency of energy conversion, energy use per unit of GDP, capital costs, and payback period are commonly used indicators for assessing the economic sustainability of energy technologies [12, 13].

A country's ability to function indefinitely at a defined level of social wellbeing is referred to as social sustainability. Examples of social sustainability indicators for energy systems include job creation, public acceptability, fatality rate, risk of accidents, and human rights [12].

Energy is one of the essential areas for development as sustainable indicting primary utilities such as transportation, heating, cooling, and cooking. Three aspects of sustainability are linked to the importance of energy in sustainable development. First, a reliable supply of energy is considered to be one of the essential requirements for economic growth. Second, the numerous natural and human disasters of recent decades have a strong connection with the energy supply. Lastly, it also illustrates the need for fairness in the energy sector, which can be converted into universal access to electricity [14].

Sustainable development of energy generation technologies involves the consideration of three dimensions of sustainability. Full development of sustainability in terms of the production, distribution, and usage of energy services is required to decide which technologies work better according to their economic, environmental, and social sustainability.

In this study, SOFC technology is discussed in the light of sustainability components. The design and operation of SOFC subject to restrictions based on requirements for materials and fuel specifications are considered as key factors affecting sustainability.

2.4 Literature Survey

Various studies have been undertaken in order to determine the sustainability of SOFCs. Among them, some studies highlighting the environmental, economic, and social sustainability of SOFC systems are selected from the literature and given in this subsection.

Wincewicz and Cooper [15] presented a comprehensive review of the production materials and systems used in SOFC technology as an initial part of the environmental sustainability assessment. Mehmeti, McPhail [16] studied life cycle assessment (LCA) of SOFCs. Their investigation highlighted that when SOFCs were utilized in power generation, a north worthy contribution was figured out to the aspired-to a future of sustainable power. Their empirical results showed that economic performance was the most effective criterion in the decision-making step. Stambouli and Traversa [2] dealt with SOFC as an environmentally friendly and effective energy source. Their outcomes have shown that greenhouse gas stabilization can be achieved as an early investment in emerging technology emerges. They also argued that global warming could be reduced without damaging the economy. Birnbaum [3] discusses the environmental effect of the technology of SOFC to give information about environmental sustainability in detail. They investigated stated materials used in the cell, emission balance, efficiency, end-of-life considerations were the key issues for their environmental sustainability evaluations. They underlined that having complex material systems and taking advantage of combining powerful systems such as combined heat and power (CHP) units proceed the outcomes/findings unpredictable.

Strazza, Del Borghi [13] combined the life cycle environmental assessment and life cycle costing tools to assess both environmental impacts and operating costs of SOFC systems for comparison with traditional systems Micro Gas Turbine (MGT) for distributed power generation systems. Natural gas was used as a reference fuel in their study, while biogas was chosen as an alternative biofuel option for the SOFC system. Global warming potential, acidification potential, eutrophication potential, depletion of abiotic resources, ozone depletion potential, summer smog, and life cycle costs have been evaluated as sustainability indicators. The natural gas-fuelled SOFC system showed that a large portion of the environmental impact was responsible for the fuel supply. The same system fed with biogas demonstrated environmental benefits depending on the combination of energy used during the digestion process. The analysis of SOFC and MGT systems has shown that the SOFC method provides environmental and economic advantages [17].

Chen and Ni [17] studied an economic evaluation of a SOFC cogeneration/trigeneration technology for a hotel located in Hong Kong. Their research was aimed to assess the economic evaluation of a SOFC-absorption cooling cogeneration/trigeneration mechanism for residences. Existing products of SOFC server and absorption chiller were considered for configuration. The results of this paper showed that the payback period of the three-generation scheme amounted to less than 6 years, with the government grant accounting for 50% of the entire system.

3. Sustainability of SOFCs

Sustainability impacts are related to energy-resource use and a low-cost and reliable supply of energy is important for economic development, human well-being, and quality of life. Consequently, sustainable development is necessary to address the existing environmental, economic, and social challenges.

3.1 Environmental sustainability of SOFCs

Fuel cell technology has been described as a means of producing electricity that is clean and efficient and would be an appealing alternative to traditional technologies. This picture emerges mainly from the concept that hydrogen gas can power fuel cells. Among the most appealing technologies of all kinds of fuel cells is the SOFCs which could directly transform fuel chemical energy into electricity [18]. Efficiency and ecology converge issues maintain attention as alive to the SOFCs considering for electricity generation in the utility industries, especially in cogeneration of heat and power.

The environmental influence of SOFC usage mainly changes with the fuel used. If the fuel is only pure H_2, all FCs do not emit any emissions except occurring water and releasing heat. Besides, the SOFC systems are considered very flexible among other fuel cells in terms of fuels [19].

Pure hydrogen as fuel lays out some problems related to storage and transportation. But the researchers offer new ideas to overcome this obstacle such as the development of a solar hydrogen economy in which photovoltaic cells are predicted to transform sunlight into electricity. On the other hand, the high efficiency of SOFC outcomes in less fuel being spent for the production of a given amount of electricity. This condition is addressed by lower CO_2 emissions. If we consider natural gas for hydrogen source fuel, SOFCs do not lay net emissions of CO_2. This can be explained with photosynthetic plants which favour uptake carbon released. As a result, CO_2 emissions can be declined by more than 2 million kg/year. Indeed, emissions from SOFC systems will be very low with near-zero levels of NOx, SOx, and other contaminants in the atmosphere, removing 20,000 kg of acid rain and smog-causing pollutants [3].

Another important issue to take into account is that the components of SOFC are produced from materials that are not widely faced in traditional energy equipment [3]. Although a SOFC is made of three major layers, five elements including electrolyte, cathode, anode, interconnect, the cell-to-cell connector should be considered to understand the environmental sustainability in detail [20]. This requirement is related to the environmental performance of the SOFC production step which greatly relates to the amount of metal mainly steel used and the energy resource [16]. While these materials are made of either ceramics or metals, they are mostly mixtures and not pure elements so extracting or manufacturing from relevant raw materials should be carried [20]. Excepting the steel parts made of iron ore and chromite, particularly rare earth, nickel ore, and alkaline minerals are essential sources of raw materials. Mining and processing chains are also important for environmental sustainability in detail [3]. Although many elements including strontium, titanium, manganese, nickel, cobalt, fluorine are used in many components and interconnect, it is useful to start the material investigation from zirconium, yttrium, and lanthanum which are used commonly. Zirconium which is commonly produced from zircon is known as being one of the major constituents of SOFC, especially YSZ (yttrium stabilized zirconia) electrolytes recently. Yttrium, a rare earth element that presents in almost all rare earth minerals, is used to stabilize zirconia lattice in electrolyte materials within a range of 3–10 mol% (such as 3YSZ, 8YSZ, 10YSZ). Lanthanum, one of the rare earth metals with the highest reactivity, is a key component of SOFCs, appearing not only in cathodes but also in ceramic interconnects, electrolytes, and contact pastes. An extra amount should be charged to prevent direct reactions to elemental carbon, sulphur, nitrogen, silicon, phosphorus, boron, selenium, and halogens and to oxidize quickly when exposed to air [3].

Although the importance of cell manufacturing is evident, there is only one comprehensive study dealing with this important topic. Hart et al. compared the environmental influence of six fabrication techniques including electrochemical and physical vapor deposition, screen printing, slurry spraying, tape casting, and calendaring on the SOFC manufacturing process. While five of the manufacturing techniques laid superior material use, the electrochemical vapor deposition (EVD) method resulted in the utilization of a poor material during manufacture. Besides, an analysis of the energy required to produce the anode, electrolyte, and cathode layers for a 200 kW SOFC CHP device revealed that when the unit's consumption mode is compared to conventional, the environmental burden associated with the manufacture can be repaid within 3 days of operation [21].

Industrial waste production and resource exploitation have a huge effect on sustainability due to the effects they can have on the ecosystem. Regarding the stages such as disposal of the SOFCs, investment and operating costs, recovery efficiency, energy demands, hazard/toxicity, and other environmental impacts can be classified as key parameters for the recovery of valuable materials and components from a cell. So, for further investigations such as LCA, these parameters should be involved [22].

Worldwide, central electricity generation is calculated considering resources like coal, nuclear, released into the atmosphere and accepted as waste heat. As a result, high-efficiency electricity-generating equipment is of interest in reducing electric power production's environmental impact and ensuring the long-term viability of relevant primary energy resources. SOFC technology is specifically helpful with its high efficiency in such a transition phase since it can use both fossil and renewable energy sources [3]. SOFCs have been accepted as the cleanest and most efficient devices available when combined with a waste heat engine. Without harming the environment, SOFC can produce high-quality waste heat that can be used to heat the home or provide refrigeration and air conditioning [3].

3.2 Economic sustainability of SOFCs

SOFCs generally run at extremely high temperatures (500-1000°C). At these temperatures, SOFCs do not need expensive catalysts such as platinum which makes these systems more favourable.

SOFC systems can be competitive if used for cogeneration, with high electrical efficiency. Cogeneration is defined by the World Alliance for Decentralized Energy as “the process of producing both electricity and usable thermal energy (heating or cooling) at high efficiency and close to the point of use” [17]. The percentage of the input fuel that can be used as power or heat determines a cogeneration system's efficiency. The trigeneration system is thought to be the next step in the evolution of the cogeneration system. It also recovers waste energy, which is commonly used to heat water [13].

Performance comparisons among cogeneration systems based on different conversion techniques indicate that the main benefits of fuel cells are their high performance and low emissions. In comparison, conventional heat engines require a range of energy conversion steps, including combustion transforming the fuel's chemical energy into thermal energy, which is then used to turn the turbines for production using a generator, while fuel cell-based cogeneration/trigeneration generates electricity directly from electrochemical reactions. This study's findings come in low maintenance and operating costs. Furthermore, the fuel cell system generates power quietly and reduces noise levels [13].

3.3 Social sustainability of SOFCs

SOFC systems are still at a design stage where they can be sold to customers. Potential applications of the SOFCs range from single homes and apartment buildings to industrial and public buildings, as well as small and medium-sized businesses. The decline requirement in operando temperature is vital in commercialization especially in mobile services and laptop direct use.

Today, energy security is one of the major global issues. As fossil fuels are depleting and becoming more difficult to supply energy from fossil fuels, fuel cells can improve energy security and increase reliability by enabling a wider range of fuels to be used, and by making existing fuels more efficient [23]. Highly efficient SOFC technology is critical for the security of the energy supply.

Public acceptance of new energy sources is one of the key points to further increase their share of the total energy supply. Public opposition to energy technologies poses a significant risk to the implementation and management of energy policies. Public preferences and views on various energy choices vary significantly. The public is concerned with appearance, health and safety issues, property values, construction and decommissioning-related impacts, and the noise level of the new technologies. SOFCs' quiet, vibration-free operation often reduces noise produced by traditional power generation technologies. The public generally expresses a positive attitude towards the installation of SOFC systems [24].

4. Conclusions

In the last 20-40 years, SOFCs have been subject to comprehensive research providing many advantages over traditional methods of electricity generation. in terms of not only higher efficiencies but also lower emissions and high fuel versatility. SOFCs systems can help to achieve sustainability by using hydrogen generated from renewable energy resources. While it is acknowledged that achieving a competitive balance of cost, performance, and durability is a major challenge, sustainability has gained new perspectives from the point of view of environmental, social, and economic issues. The outcomes highlighted in this work are that the manufacturers, investigators, scientists, and end-users should not only deal with the reaction mechanisms and materials involved but also need to consider the environmental, economic, and social sustainability of SOFCs to contribute to a sustainable world where borders are removed especially in the last decades.

5. References

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