Stationary Fuel Cell System

Subjects: Energy & Fuels | Engineering, Environmental

Submitted by: Matteo Genovese

(This entry belongs to Entry Collection "Environmental Sciences")

Definition

Fuel cell technologies have several applications in stationary power production, such as units for primary power generation, grid stabilization, systems adopted to generate backup power, and combined-heat-and-power configurations (CHP). The main sectors where stationary fuel cells have been employed are (a) micro-CHP, (b) large stationary applications, (c) UPS, and IPS. The fuel cell size for stationary applications is strongly related to the power needed from the load. Since this sector ranges from simple backup systems to large facilities, the stationary fuel cell market includes few kWs and less (micro-generation) to larger sizes of MWs. The design parameters for the stationary fuel cell system differ for fuel cell technology (PEM, AFC, PAFC, MCFC, and SOFC), as well as the fuel type and supply.

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1. Introduction

Among the several options that the scientific community is recognizing as key elements to address climate changes [1] and fossil fuel dependence [2], fuel cell (FC) technologies are worldwide recognized as the best options to decarbonize the stationary power production sectors [3], including primary power generation units, backup power systems, and combined-heat-and-power configurations (CHP) [4].

Fuel cell technologies are capable of providing very high efficiency, minimum pollution, and high reliability [5][6]. The technology is applied in industries ranging from a distributed generation for power companies [7][8][9], to residential and industrial co-generation [10], portable generation [11], and vehicles [12]. The fuel cells are receiving considerable attention as they constitute, thanks to their ability to optimally use hydrogen [13], the key technology for the development of this energy carrier [14][15]. The design parameters for the stationary fuel cell system differ for fuel cell technology (PEM, AFC, PAFC, MCFC, and SOFC), as well as the fuel choice and supply [16].

The main sectors where stationary fuel cells have been employed are (a) micro-CHP, (b) large stationary applications, (c) uninterruptible power supply (UPS), and integrated power supply (IPS). The fuel cell size for stationary applications is strongly related to the power needed from the load. Since this sector ranges from simple backup systems to large facilities, the stationary fuel cell market includes few kWs and even fewer (micro-generation) and larger sizes of MWs.

2. The Key Role of Fuel Cell Technology

Hydrogen, intended as an energy carrier, can provide and release energy via different methods and through several systems:

- Hydrogen injection and burned via direct combustion;
- Hydrogen oxidation via catalytic combustion, with no-flame production;
- Production of water as steam, when pure hydrogen is combined with oxygen at high temperature;
- Hydrogen as reactant gas in a fuel cell operation.

In terms of flexibility of applications, potentials, and integration with several energy systems, hydrogen adopted as reactant and reductant gas in fuel-cell-based energy systems is generally the most efficient and cleanest technology for releasing energy from hydrogen [17]. In a fuel cell, gaseous hydrogen and gaseous oxygen are combined in a catalyzed electrochemical reaction, producing electricity, water, and heat. This process can achieve higher efficiencies, both electrical and thermal, than those of internal combustion engines while being pollution-free [18].

In more detail, a fuel cell is an electrochemical device that uses hydrogen as chemical input and reductant, reacting with an oxidant to produce electrons, protons, heat, and water [19]. Fuel cell operation is based upon the redox reaction, shown in Equation (1), where both reduction (at the cathode) and oxidation (at the anode) takes place, producing an ideal electromagnetic force, in standard condition, of 1.229 V [20].

The system provides then electricity via an electrical circuit with a DC load. Problems arise when fuel cells are manufactured. More in detail, the electrochemical reaction needs a consistent area of contact, while normally fuel cells have a very small area of contact between the electrolyte, the sites of the electrode, and the flows of reactant gases [21][22]. Moreover, the geometric distances between the electrodes introduce resistances in the fuel cell operation, reducing the production of electricity. Therefore, to address these problems, fuel cells have been manufactured with improved design and new approaches to tackle these issues [23][24][25]. Among the common solutions, there is the adoption of porous electrodes and a thin electrolyte, to reduce the electrical resistances [26]. The porous structure allows interaction among gas, ions, and electrolyte molecules to occur more effectively, improving the electrochemistry of the cell [27]. In this way, the contact area is maximized, guaranteeing better performance, efficiency, and current production [28].

The major disadvantage of the fuel cell is that the technology currently presents a more expensive capital expenditure than other forms of power conversion [29][30]. Once this barrier is overcome [31][32], thanks to the economy of scale and the adoption of cost-reduction actions, it is worldwide recognized that fuel cells will eventually become a dominant and efficient solution for energy conversion. Indeed, these technologies have an efficient operation, almost zero acoustic emissions and, if powered with green hydrogen, and zero polluting emissions [18]. Sound pollution is extremely important in on-site applications [33] and mobility [34][35]. By considering the current state of the art, fuel cells operate with an electric efficiency of about 40–50% and overall efficiency in cogeneration assets (production of combined heat and power) of more than 80% [36][37]. Their performance is indeed higher if compared to CHP internal combustion engines. Fuel cells have no moving parts, such as pistons, and for specific fuel cell types, most of the components are entirely made of solids, which simplifies the manufacturing process. Depending on the fuel cell type and the supplied fuel, the emissions can vary, but falling below the existing standards of emissions. Generally, a fuel cell system emits “<1 ppm of NO_x, 4 ppm of CO, and <1 ppm of reactive organic gases” [38]. All of these features make fuel cell technology an attractive and efficient solution in different energy sectors [39].

There are several types of fuel cells, according to the technology adopted and on the operating parameters, as shown in **Figure 1**, and the final application depends on the fuel cell chosen type and configuration [40].

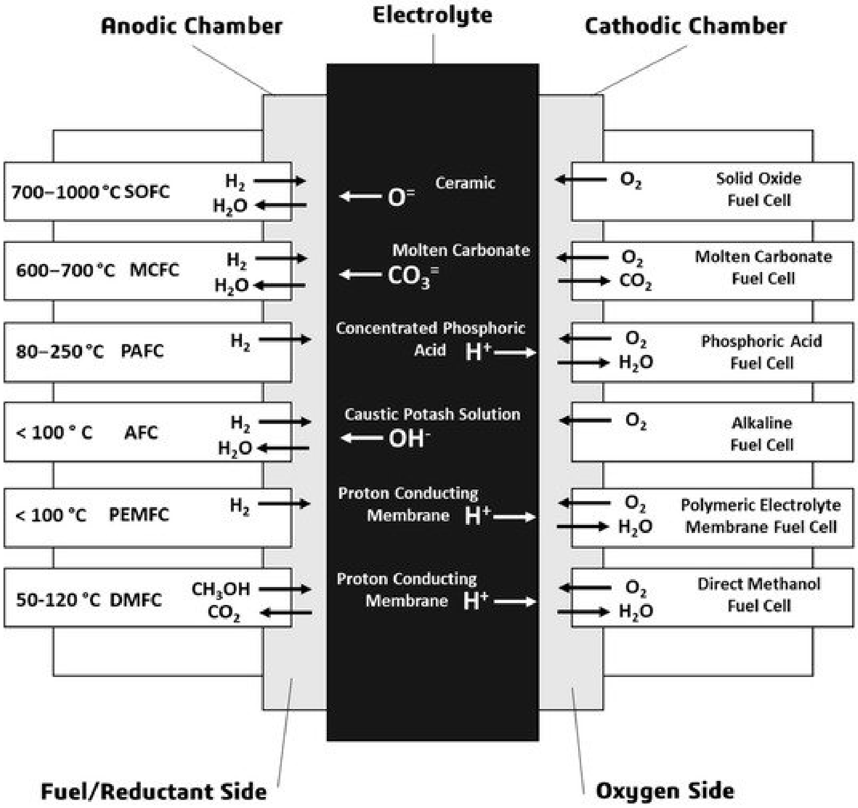

Figure 1. Fuel cell technology overview.

3. Fuel Cell Installations

Figure 2 summarizes the shipments per fuel cell type [41]. While PEMFC seems to have a steady decreasing trend until 2018, in 2019 and 2020, PEMFC installations increased, thanks also to a new demand required by the mobility sector. The market is showing how big efforts are ongoing to strengthen the market for SOFC, since their performance is better and they possess high modularity and flexibility, leading to a wide range of applications. DMFCs are used for mobile and stationary applications, while AFC and MCFC had very few installations. However, their resulting size was bigger (MWs), as highlighted in **Figure 3**. MCFC had a high level of research interest until 2014 [42][43][44][45], but the trend is now decreasing. MCFC installations in 2018 [46] were slightly more than 25 MWs, while in 2020, they decreased down to 8.8 MWs. Even if PEMFC installations decreased until 2018, their size installation presents an increasing trend, a signal of their technology maturity. AFC installations are infrequent, while Korea has the leadership on PAFC installations. The PEM fuel cell is indeed used in several applications (both stationary and mobile applications), and it contributes to the highest number of installations. SOFCs (more shipments at lower size) and PAFCs (low shipments at higher size) had a slow implementation in 2014, but their trend is increasing.

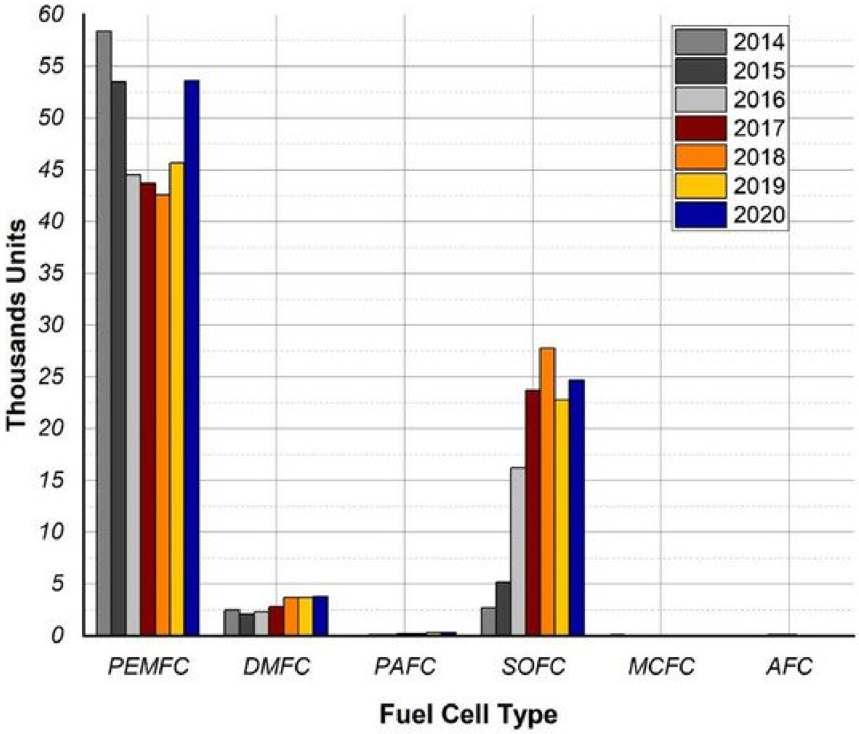

Figure 2. Fuel cell shipments.

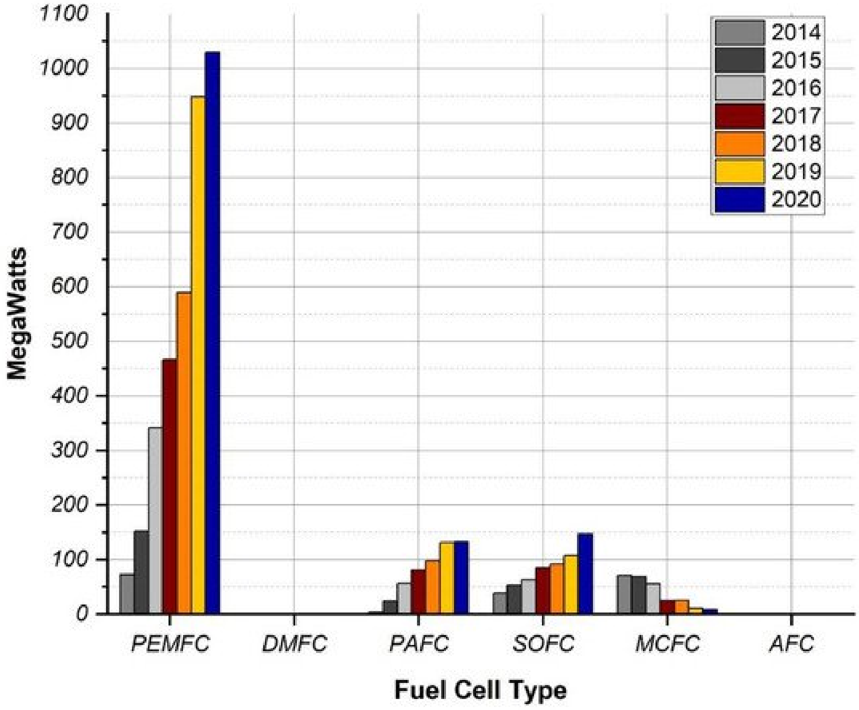

Figure 3. Fuel cell size installations.

4. Niche Applications

Other niche applications based on fuel cell technologies are BUP and UPS, as well as hydrogen boilers using catalytic burners/hydrogen gas turbines. For the latter, few references and available performances have been found, since the market is probably still too small.

Hydrogen Europe [47][48] has drafted a roadmap for new hydrogen technologies and R&D actions, since they could reveal themselves as the best options when CHP installations are not economically viable. For UPS, in the IEA Hydrogen and Fuel Cells roadmap [49], small uninterruptible power systems for backup power are considered key factors for autonomous power systems for either stationary or portable off-grid applications, but few commercial applications have been found.

The mobile telecommunication industry is an example of a sector that needs backup and off-grid power, with an estimated 7 million stations worldwide, increasing every year by 100,000. For these applications, fuel cells can offer more reliable and stable operations, given their resilience to harsh environmental conditions rather than batteries, without the need to add extreme cooling equipment and withstand severe environmental conditions without affecting their performance.

Recent research trends pursue the possibility of blending green hydrogen up to a volume of 20% into natural gas pipelines. Current levels are about 5%, assuring between 32 and 58 kg of avoided carbon dioxide emissions per year and per household.

5. Breakdown of the Current Costs

The main sectors where stationary fuel cells have been employed are micro-CHP and large stationary applications. With particular attention to the building sector, fuel cells were suitable for micro-cogeneration: these energy systems inherently produced both electricity and heat from only one source of fuel, which could be innovative and more efficient, even if more expensive, such as hydrogen, but these systems can also operate by adopting traditional fuels, such as biogas, methane and natural gas, after being properly reformed.

For building applications and micro-cogeneration, PEMFC systems are the most common fuel cell type used and installed, being more mature than other technologies, and guaranteeing high efficiency, covering the peak energy demand during the day, and also covering the energy needs at night. PEM fuel cell operation can benefit from its low-temperature requirement, a solid membrane electrolyte installation, which strongly reduces maintenance cost, degradation phenomena, and corrosion, and a quick start-up.

As a rising technology, SOFC systems are gaining more credit [50]. A SOFC fuel cell can operate at higher temperatures, reducing the catalyst’s strict requirements, allowing a greater carbon monoxide level to be tolerated, thus simplifying the system in terms of the needed purification system at the reformer level [51]. This fuel flexibility can surely represent a key driver to support the transition towards the hydrogen economy, also allowing greater levels of efficiency to be achieved.

It is indeed noticeable how these systems present potential solutions for cogeneration applications for buildings and districts. Currently, the units which have been installed in buildings provided for the energy needs of a small district system, composed of collective houses or apartments. In order to decrease the cost and to produce systems with lower power capacities, governments and states promoted financial programs to sustain the transition of these technologies, from research and development, towards early market adoption.

The balance of plant components, reformers, and stack were the key elements of potential failures and cost reduction.

References

1. Maroufmashat, A.; Fowler, M. Transition of future energy system infrastructure; through power-to-gas pathways. Energies 2017, 10, 1089.
2. Kilkiş, B.; Kilkiş, Ş. Hydrogen economy model for nearly net-zero cities with exergy rationale and energy-water nexus. Energies 2018, 11, 1226.
3. Wołowicz, M.; Kolasiński, P.; Badyda, K. Modern small and microcogeneration systems—A review. Energies 2021, 14, 785.
4. Sharaf, O.Z.; Orhan, M.F. An overview of fuel cell technology: Fundamentals and applications. Renew. Sustain. Energy Rev. 2014, 32, 810–853.
5. Alaswad, A.; Omran, A.; Sodre, J.R.; Wilberforce, T.; Pignatelli, G.; Dassisti, M.; Baroutaji, A.; Olabi, A.G. Technical and commercial challenges of proton-exchange membrane (Pem) fuel cells. Energies 2021, 14, 144.
6. Shigeta, N.; Hosseini, S.E. Sustainable development of the automobile industry in the united states, europe, and japan

with special focus on the vehicles' power sources. Energies 2021, 14, 78.

7. Ahmed, K.; Farrok, O.; Rahman, M.M.; Ali, M.S.; Haque, M.M.; Azad, A.K. Proton exchange membrane hydrogen fuel cell as the grid connected power generator. Energies 2020, 13, 6679.
8. Kang, H.S.; Kim, M.H.; Shin, Y.H. Thermodynamic modeling and performance analysis of a combined power generation system based on HT-PEMFC and ORC. Energies 2020, 13, 6163.
9. Popel', O.S.; Tarasenko, A.B.; Filippov, S.P. Fuel cell based power-generating installations: State of the art and future prospects. Therm. Eng. 2018, 65, 859–874.
10. Al-Bonsrulah, H.A.Z.; Alshukri, M.J.; Mikhaeel, L.M.; Al-Sawaf, N.N.; Nesrine, K.; Reddy, M.V.; Zaghib, K. Design and simulation studies of hybrid power systems based on photovoltaic, wind, electrolyzer, and pem fuel cells. Energies 2021, 14, 2643.
11. Chou, C.J.; Jiang, S.B.; Yeh, T.L.; Tsai, L.D.; Kang, K.Y.; Liu, C.J. A portable direct methanol fuel cell power station for long-term internet of things applications. Energies 2020, 13, 3547.
12. Un-Noor, F.; Padmanaban, S.; Mihet-Popa, L.; Mollah, M.N.; Hossain, E. A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development. Energies 2017, 10, 1217.
13. Valencia, G.; Benavides, A.; Cárdenas, Y. Economic and environmental multiobjective optimization of a wind-solar-fuel cell hybrid energy system in the Colombian Caribbean region. Energies 2019, 12, 2119.
14. Cerniauskas, S.; Grube, T.; Praktiknjo, A.; Stolten, D.; Robinius, M. Future hydrogen markets for transportation and industry: The impact of CO2 taxes. Energies 2019, 12, 4707.
15. Boait, P.J.; Greenough, R. Can fuel cell micro-CHP justify the hydrogen gas grid? Operating experience from a UK domestic retrofit. Energy Build. 2019, 194, 75–84.
16. Herrmann, A.; Mädlow, A.; Krause, H. Key performance indicators evaluation of a domestic hydrogen fuel cell CHP. Int. J. Hydrogen Energy 2019, 44, 19061–19066.
17. Ellamla, H.R.; Staffell, I.; Bujlo, P.; Pollet, B.G.; Pasupathi, S. Current status of fuel cell based combined heat and power systems for residential sector. J. Power Sources 2015, 293, 312–328.
18. Larminie, J.; Dicks, A. Fuel Cell Systems Explained, 2nd ed.; John Wiley: New York, NY, USA, 2013; ISBN 9781118878330.
19. Wang, Y.; Ruiz Diaz, D.F.; Chen, K.S.; Wang, Z.; Adroher, X.C. Materials, technological status, and fundamentals of PEM fuel cells—A review. Mater. Today 2020, 32, 178–203.
20. Jayakumar, A. A comprehensive assessment on the durability of gas diffusion electrode materials in PEM fuel cell stack. Front. Energy 2019, 13, 325–338.
21. Dwivedi, S. Solid oxide fuel cell: Materials for anode, cathode and electrolyte. Int. J. Hydrogen Energy 2020, 45, 23988–24013.
22. Hussain, S.; Yangping, L. Review of solid oxide fuel cell materials: Cathode, anode, and electrolyte. Energy Transit. 2020, 4, 113–126.
23. Wang, G.; Huang, F.; Yu, Y.; Wen, S.; Tu, Z. Degradation behavior of a proton exchange membrane fuel cell stack under dynamic cycles between idling and rated condition. Int. J. Hydrogen Energy 2018, 43, 4471–4481.
24. Cecen, A.; Wargo, E.A.; Hanna, A.C.; Turner, D.M.; Kalidindi, S.R.; Kumbur, E.C. Microstructure analysis tools for quantification of key structural properties of fuel cell materials. ECS Trans. 2019, 41, 679–687.
25. Su, H.; Hu, Y.H. Recent advances in graphene-based materials for fuel cell applications. Energy Sci. Eng. 2020, 9, 958–983.
26. Taherian, R. A review of composite and metallic bipolar plates in proton exchange membrane fuel cell: Materials, fabrication, and material selection. J. Power Sources 2014, 265, 370–390.
27. Dhand, A. Advances in materials for fuel cell technologies—A Review. Int. J. Res. Appl. Sci. Eng. Technol. 2017, 5, 1672–1682.
28. Sarfraz, A.; Raza, A.H.; Mirzaeian, M.; Abbas, Q.; Raza, R. Electrode materials for fuel cells. In Reference Module in Materials Science and Materials Engineering; Elsevier: Amsterdam, The Netherlands, 2020; ISBN 9780128035818.
29. Wang, J. Barriers of scaling-up fuel cells: Cost, durability and reliability. Energy 2015, 80, 509–521.
30. James, B. 2018 Cost projections of PEM fuel cell systems for automobiles and medium-duty vehicles. In Proceedings of the Fuel Cell Technologies Office, Department of Energy, USA, Online Webinar, 27 April 2018.
31. Wang, J.; Wang, H.; Fan, Y. Techno-economic challenges of fuel cell commercialization. Engineering 2018, 4, 352–360.
32. Whiston, M.M.; Azevedo, I.L.; Litster, S.; Whitefoot, K.S.; Samaras, C.; Whitacre, J.F. Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles. Proc. Natl. Acad. Sci. USA 2019, 116, 4899–4904.
33. Kwan, T.H.; Katsushi, F.; Shen, Y.; Yin, S.; Zhang, Y.; Kase, K.; Yao, Q. Comprehensive review of integrating fuel cells to other energy systems for enhanced performance and enabling polygeneration. Renew. Sustain. Energy Rev. 2020, 128, 109897.
34. Apostolou, D.; Casero, P.; Gil, V.; Xydis, G. Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market. Int. J. Hydrogen Energy 2021, 46, 5756–5762.
35. Tanç, B.; Arat, H.T.; Baltacıoğlu, E.; Aydın, K. Overview of the next quarter century vision of hydrogen fuel cell electric

vehicles. Int. J. Hydrogen Energy 2019, 44, 10120–10128.

36. Isa, N.M.; Tan, C.W.; Yatim, A.H.M. A comprehensive review of cogeneration system in a microgrid: A perspective from architecture and operating system. Renew. Sustain. Energy Rev. 2018, 81, 2236–2263.
37. Fragiacomo, P.; De Lorenzo, G.; Corigliano, O. Performance analysis of an intermediate temperature solid oxide electrolyzer test bench under a CO2-H2O feed stream. Energies 2018, 11, 2276.
38. Department of Energy, USA. Fuel cell Handbook, 6th ed.; Online Version; 2002; EG&G Technical Services, Inc., Science Applications International Corporation Under Contract No. DE-AM26-99FT40575; Available online: http://courses.washington.edu/mengr430/au07/handouts/f_c_6.pdf (accessed on 10 August 2021).
39. Lyu, Y.; Xie, J.; Wang, D.; Wang, J. Review of cell performance in solid oxide fuel cells. J. Mater. Sci. 2020, 55, 7184–7207.
40. Wilberforce, T.; Alaswad, A.; Palumbo, A.; Dassisti, M.; Olabi, A.G. Advances in stationary and portable fuel cell applications. Int. J. Hydrogen Energy 2016, 41, 16509–16522.
41. E4tech. The Fuel Cell Industry Review 2020; E4tech: London, UK, 2021.
42. Bargigli, S.; Cigolotti, V.; Pierini, D.; Moreno, A.; Iacobone, F.; Ulgiati, S. Cogeneration of heat and electricity: A comparison of gas turbine, internal combustion engine, and MCFC/GT hybrid system alternatives. J. Fuel Cell Sci. Technol. 2010, 7, 011019.
43. Cigolotti, V.; McPhail, S.; Moreno, A. Nonconventional fuels for high-temperature fuel cells: Status and issues. J. Fuel Cell Sci. Technol. 2009, 6, 021311.
44. Cigolotti, V.; Massi, E.; Moreno, A.; Polettini, A.; Reale, F. Biofuels as opportunity for MCFC niche market application. Int. J. Hydrogen Energy 2008, 33, 2999–3003.
45. Di Giulio, N.; Bosio, B.; Cigolotti, V.; Nam, S.W. Experimental and theoretical analysis of H2S effects on MCFCs. Int. J. Hydrogen Energy 2012, 37, 19329–19336.
46. Hart, D.; Lehner, F.; Jones, S.; Lewis, J.; Klippenstein, M. The Fuel Cell Industry Review 2018; E4tech: London, UK, 2018.
47. Hydrogen Europe. Strategic Research & Innovation Agenda, Final Draft. 2020. Available online: https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/20201027-SRIA-CHE-final-draft.pdf (accessed on 1 May 2021).
48. Hydrogen Europe. Clean Hydrogen for Europe. Available online: https://hydrogeneurope.eu/clean-hydrogen-europe (accessed on 1 August 2020).
49. IEA. International Energy Agency Technology Roadmap Hydrogen and Fuel Cells; International Energy Agency: Paris, France, 2015.
50. Facci, A.L.; Cigolotti, V.; Jannelli, E.; Ubertini, S. Technical and economic assessment of a SOFC-based energy system for combined cooling, heating and power. Appl. Energy 2017, 192, 563–574.
51. McPhail, S.J.; Cigolotti, V.; Moreno, A. Fuel Cells in the Waste-to-Energy Chain; Springer: London, UK, 2012.

Keywords

fuel cell;market trends;energy performance;durability and cost breakdown