Journal of Power Sources 275 (2015) 322–335

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Environmental and economic assessment of a cracked ammonia fuelled alkaline fuel cell for off-grid power applications

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HIGHLIGHTS

- Detailed life cycle assessment of 3 kW alkaline fuel cell (AFC) with primary data.
- Fossil and renewable based ammonia production pathways analysed.
- Environmental impacts of AFC depend strongly on the fuel production pathway.
- AFC performance comparable to diesel generators when fuelled with fossil ammonia.
- AFC outperforms diesel generators when fuelled with biomass sourced ammonia.

ARTICLE INFO

Article history:
Received 22 July 2014
Received in revised form
14 October 2014
Accepted 5 November 2014
Available online 6 November 2014

Keywords:
Alkaline fuel cell
Ammonia
Off-grid power
Life cycle assessment
Environmental impacts
Levelised cost of electricity

ABSTRACT

Global mobile telecommunication is possible due to millions of Base Transceiver Stations (BTS). Nearly 1 million of these are operating off-grid, typically powered by diesel generators and therefore leading to significant CO_2 emissions and other environmental burdens. A novel type of Alkaline Fuel Cell (AFC) powered by cracked ammonia is being developed for replacement of these generators. This study compares the environmental and economic performance of the two systems by means of Life Cycle Assessment (LCA) and Levelised Cost of Electricity (LCOE), respectively.

Results show that the production of ammonia dominates the LCA results, and that renewable ammonia production pathways greatly improve environmental performance. Sensitivity analyses reveal that the fuel cell parameters that most affect system cost and environmental burdens are cell power density and lifetime and system efficiency. Recycling of anode catalyst and electrode substrate materials is found to have large impacts on environmental performance, though without large cost incentives. For a set of target parameter values and fossil sourced ammonia, the AFC is calculated to produce electricity with life cycle CO_2 eq emissions of 1.08 kg kWh^{-1}, which is 23% lower than a diesel generator with electricity costs that are 14% higher in the same application.

1. Introduction

In order to improve network coverage, telecommunication Base Transceiver Stations (BTS) are being built in ever more remote areas where connection to the electricity grid is not feasible. The global telecommunications network is very large in scale and approximately 900,000 BTS are currently operating off-grid; out of which over 90% are powered by a diesel generator, consuming 3–5 kW on average [1–3]. Diesel generators are not commonly available below 5 kW peak capacity and demonstrate poor fuel efficiency at part load, leading to even larger consumption of diesel fuel [4,5]. This results in significant greenhouse gas emissions and other environmental impacts. Furthermore, diesel generators require frequent, regular maintenance which can be difficult and expensive in remote locations. Fuel theft further exacerbates the difficulties associated with remote operation. There is currently much research ongoing to reduce the reliance on diesel fuel as well as improve the maintenance requirements of off-grid BTS power systems.

Fuel cells may be a well-suited alternative for powering off-grid BTS and have been considered in several previous studies, though with mixed results, depending on the status of the fuel cell technology examined [6,7]. Compared to diesel generators, fuel cells have the potential for higher energy conversion efficiency, higher operational flexibility, simpler and less expensive maintenance

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http://dx.doi.org/10.1016/j.jpowsour.2014.11.023
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requirements, and much lower direct polluting emissions [4,6]. Even if the fuel used to power the fuel cell is fossil based, the higher conversion efficiency of the fuel cell is expected to lead to reduced overall primary energy consumption and greenhouse gas emissions. Increased fuel efficiency combined with reduced maintenance requirements may even make fuel cells economically competitive with diesel generators for difficult to reach remote locations. However, both the storage and distribution of the commonly used gaseous hydrogen fuel are difficult and expensive and may limit its use as an energy carrier [8], so that alternative hydrogen carriers, such as ammonia have been investigated [9–14]. Project "Alkammonia" (www.alkammonia.eu), conducted within the European Union's Seventh Framework Programme, aims to design and test an ammonia-fuelled Alkaline Fuel Cell (AFC) system that could power an off-grid BTS.

Ammonia can be thermally cracked at temperatures above 300 °C into its constituent parts, nitrogen and hydrogen, without a prohibitive energy penalty [11,14]. AFCs are particularly suited to using cracked ammonia as a source of hydrogen because of their tolerance to small percentages of ammonia in the fuel feed that would damage acid based fuel cells [10,15]. Similar to hydrogen, ammonia can be energetically consumed in an environmentally benign way, producing only water and nitrogen [9], but has a lower cost per unit energy, higher volumetric energy density, as well as greatly simplified handling, distribution, and storage [14]. Moreover, ammonia already has a worldwide distribution network with production over 160 million tons per year in 2011 [16]. Compared to other potential hydrogen carriers, liquid ammonia has the highest volumetric hydrogen content of any liquid fuel, including gasoline, liquefied natural gas, ethanol, and even liquid hydrogen [17]. Furthermore, ammonia is carbon free and does not directly contribute to the greenhouse effect. Although ammonia production is currently dominated by fossil fuels, renewable pathways using electrolysis and biomass gasification were used on an industrial scale until the 1990's and are seeing renewed interest in the literature today [18–21].

There is surprisingly little literature available regarding the life cycle assessment of AFCs. The only complete LCA of an alkaline fuel cell found in the literature was an assessment of the manufacture and disposal of a 1 kW stack integrated into a combined heat and power (CHP) system by Staffell and Ingram [22]. This study is based almost exclusively on literature review and contains only limited primary data based on the Eloflux electrode from fuel cell manufacturer Gaskatel. This primary data was, however, kept confidential and was not published. The fuel cell Balance of Plant (BoP) used in the study by Staffell and Ingram was based on data for other fuel cell types adapted from literature. Further, Wilson et al. [23] present a thorough LCA of the production of the Raney nickel catalyst for use in AFCs. In terms of the costs of AFCs there is also relatively little reliable information in the literature, which varies widely depending on assumptions made in the analysis, and is often derived from cost estimates made for other fuel cell types [6,24–27].

There is a wealth of studies available in the literature regarding the design of off-grid power systems, which often perform system optimisation in terms of costs or greenhouse gas emissions [1,4–7,28–40]. These studies typically focus on the integration of location specific renewable energy sources for off-grid power and use a diesel generator to benchmark results. As the main purpose of this study is to examine the performance of the Alkammonia system for providing off-grid power, results are only compared to a diesel generator system and more advanced systems including renewable energy sources are excluded. A comparison with different system designs including combinations of renewables, batteries, fuel cells and generators should follow in a second step.

2. Methodology

The AFC and diesel generator systems are examined in the application of powering an off-grid BTS using the methodology of Life Cycle Assessment (LCA) and Levelised Cost of Electricity (LCOE).

2.1. Life cycle assessment

The construction, operation and end-of-life treatment of all kinds of products, including AFCs, is related to a large network of direct and indirect use of material, energy and transportation inputs as well as to production of waste and emissions. Such networks are best analysed by means of Life Cycle Assessment (LCA), with which the impacts on the environment and human health are compiled and quantified over the whole life cycle of a product. Results can be used for benchmarking, decision making processes or sustainable product design. The variation of specific parameters according to expected technology developments also makes it possible to generate highly informed perspectives on the potential burdens of the technology in the future.

The LCA presented in this study conforms to the standards set out by ISO 14040 and ISO 14044 [41,42], and follows the recommendations of the guidance document for performing LCAs on fuel cells and hydrogen technologies created by the Fuel cell and Hydrogen Joint Undertaking [43] except for the use of the underlying database and the chosen Life Cycle Impact Assessment method. The four phases of an LCA specified by the ISO norms and applied to this study are presented in the following paragraphs.

Goal and Scope definition: This LCA quantifies the environmental and human health impacts of power production, for use at off-grid BTS, with a cracked ammonia fuelled AFC system and compares them to the impacts of diesel generators. As no complete inventory data for such a system are available in the literature, detailed primary data are collected from the "Alkammonia" project partners and complemented with literature data. The Alkammonia fuel cell is currently under development by a project consortium under the lead of the company "AFC Energy" in Great Britain.

The basic functional unit of the study is defined as the production of 1 kWh of net electricity with near 100% reliability with a system that can produce 3 kW baseload and 5 kW peak direct current (DC) electricity at an off-grid location in Europe, 50 km from the nearest city with a system lifetime of 10 years. The reference flow is 1 system with a nominal capacity of 3 kW. The system boundary is taken to be "cradle to grave" and includes raw materials, fabrication, transport, use phase, fuel production, refurbishment, recycling and final disposal (see Fig. 1). Load factor and reliability are taken to be 100% for simplicity, so that no back-up system is modelled.

Recycling of the foreground system components is modelled using the End-of-Life-Recycling (EOLR) approach where 100% primary material is assumed to be used in the production phase of the components, and the environmental burdens of recycling are modelled using datasets for the production of secondary materials. In return, the environmental burdens that are avoided by displacing primary material production with material recycling are subtracted from the total impacts of the product system. As a base case, 100% of the stacks and 75% of all other components are assumed to be returned for recycling where common metals, plastics and glass are separated and recycled. Components that are not recycled are sent to landfill. Where required, hazardous materials are treated before disposal.

Data collection (Life Cycle Inventory LCI): No existing LCI of an ammonia fuelled AFC is known to the authors. Primary data for the foreground system, which consists of the production, operation, and end-of-life treatment of the alkaline fuel cell system, are taken