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Fuel cell added value for early market applications

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HIGHLIGHTS

- Case studies of SFC Energy and Bloom Energy are presented.
- These two companies have seen notable success in the marketing of fuel cells (FCs).
- FCs for aircraft APUs are discussed as a promising perspective application.
- FCs for fire prevention is discussed as another perspective application.
- FCs should be marketed as solutions to many problems, not just power providers.

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ABSTRACT

Fuel Cells are often considered in the market place as just power providers. Whilst fuel cells do provide power, there are additional beneficial characteristics that should be highlighted to consumers. Due to the high price premiums associated with fuel cells, added value features need to be exploited in order to make them more appealing and increase unit sales and market penetration. This paper looks at the approach taken by two companies to sell high value fuel cells to niche markets. The first, SFC Energy, has a proven track record selling fuel cell power providers. The second, Bloom Energy, is making significant progress in the US by having sold its Energy Server to more than 40 corporations including Wal-Mart, Staples, Google, eBay and Apple. Further to these current markets, two prospective added value applications for fuel cells are discussed. These are fuel cells for aircraft APUs and fuel cells for fire prevention. These two existing markets and two future markets highlight that fuel cells are not just power providers. Rather, they can be used as solutions to many needs, thus being more cost effective by replacing a number of incumbent systems at the same time.

1. Introduction

Fuel Cells (FCs) are electrochemical devices that combine hydrogen rich fuel with oxygen to produce electricity and water. The inherent simplicity of this reaction means they can provide power with zero tailpipe emissions and at far greater efficiencies than incumbent technologies. FCs hold great potential as power providers for a wide range of applications from consumer electronics to stationary power [1]. They are of course not without problems and many authors [2–5] cite cost reductions as a prerequisite of successful FC market entry. FC power is currently more expensive than almost any other power solution; for this reason FCs are often deemed too expensive compared to incumbent technologies such as internal combustion engine's (ICE) or batteries. This is of course partly due to the early stage of development. Nevertheless it can be hypothesised that due to the high performance materials used in FCs, the cost per kW might always remain high. However, comparisons with incumbent's technologies are not appropriate as FCs offer power in a way that no other technology is capable of. FCs should not just be marketed as power providers. FCs do not actually offer individual characteristics that no other energy products have for example, the added values of; quietness, flexibility, quick refuelling times, zero tailpipe emissions and long run times can all be found in other technologies. However, the benefit of FCs is that they possess a unique combination of characteristics in one package. FCs should be marketed with these in mind, and not just as prime power providers. These added values are potentially:

- Quiet Operation
- Zero Tailpipe Emissions

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- Long Run Times
- Can operate in extreme conditions
- Quick Refuelling
- Scalability
- Fast Start Up
- Minimal User Intervention
- Low Vibration
- Fast Deployment/Installation
- High Fuel Efficiency
- 'Green' Image
- Fire Prevention
- Production of Water
- Production of Heat

Clearly there are other technologies that have some of these features. However, FCs have all of these features simultaneously which culminate in significant benefits in certain applications. FCs are a new market entrant, and one that is a disruptive innovation [6]. In order to achieve market penetration, it is necessary to find markets that demand not just one of these features but a multitude of them. In such markets FCs will out-compete incumbent technologies, causing redundancy of existing market leading products. However, niche markets where these benefits are highly valued need to be found. Due to the flexibility and scalability of FCs applications have been considered and successfully implemented in a number of products, including FCs for portable applications [7], buses [8], passenger vehicles [9], scooters [10], remote power [11], forklifts [12], submarines [13], aircraft [14] and more. This paper investigates the potential of FC back-up power, remote power, APUs in aircraft and FCs for fire prevention, this leads to a greater understanding of how FCs can be marketed more effectively. Two companies, SFC Energy and Bloom Energy, have identified markets that demand many FC features and this has led to them achieving successful market entry with significant revenue generation. These companies have been able to achieve market entry firstly due to intelligent product positioning. The companies were able to introduce their products to markets where their features are highly valued by consumers. SFC Energy entered the motorhome and camping market where consumers desire power that is quiet, long lasting and requires minimal user intervention. Further to these examples, two prospective applications of FCs in markets that have yet to be fulfilled are explored. These markets are aircraft APUs and FCs for fire prevention in data centres. In these applications FCs are more beneficial than any other technology the authors are aware of. Indeed, due to the many benefits of FCs in these two markets they are often referred to as Multi-Functional Fuel Cells (MFCs) [14].

1.1. Fuel cell types

Four types of FCs are discussed in this paper. These are: Polymer Electrolyte Fuel Cells (PEFC) which are offered by Airbus for aircraft APUs, Phosphoric Acid Fuel Cells (PAFC) which are developed by Fuji Electric and used by N2telligence for fire prevention and back-up power, Direct Methanol Fuel Cells (DMFC) which are offered by SFC Energy for portable power supply and Solid Oxide Fuel Cells (SOFC) which are offered by Bloom Energy for back-up power supply. The main principles of these FC types are described in Table 1.

Most PEFCs are operated at temperatures of between 60 and 80 °C. They have a solid Nafion electrolyte membrane with platinum on carbon cathode and anode. The platinum electrode means that they do suffer from CO contamination and to avoid this, the hydrogen fuel source needs to be 99.999% pure. PEFCs are highly modular, have good electrical efficiencies (40–45%), have high power density, have rapid start up due to low operating temperatures and have good dynamic load response [15].

DMFCs are similar to PEFCs in that they have a Nafion membrane and platinum on carbon cathode and anode. However DMFCs have more platinum on both the cathode and anode compared to a PEFC. More catalyst is required due to their being a greater resistance to the methanol oxidation reaction compared to the hydrogen oxidation reaction. DMFCs have fast start up and the methanol fuel is easier to store than hydrogen. However they suffer from low cell voltage due to poor anode kinetics, low power density, high catalyst loadings and high cost [15].

PAFCs are high temperature FCs operating at 160–220 °C. They have a liquid phosphoric acid in silicon carbide electrolyte. The anode and cathode are again platinum supported on carbon. They are one of the most mature FCs commercially, have a high tolerance to fuel contaminants and have high-grade heat so can be used for heating and cooling. However, they suffer from slow start up and high costs [15].

SOFCs operate at temperatures as high as 1000 °C. The charge carrier in an SOFC is O^{2-} rather than H^+. They use a solid yttria-stabilised zirconia (YSZ) electrolyte and have a Nickel-YSZ anode with a strontium-doped lanthanum manganite cathode. They typically use natural gas as a fuel. They have high electrical efficiencies (50–55%), high-grade heat, are tolerant to contaminants, can internally reform the fuel and use inexpensive catalysts. They do however have a slow start up due to their high-temperature operation, material requirements are stringent due to the extreme temperatures, they suffer from high-thermal stress and can suffer from poor durability [15].

In all of the cases (Table 1) the oxidant supplied to the FC is air. As power is drawn from the FC the oxygen content is lowered to around 8–15% vol. on the cathode side of the FC [16]. This is particularly useful in the case of N2telligence and for FC APUs as the oxygen level is lower than the level at which combustion can occur, meaning fires can be prevented. All of these FCs also produce water which in the case of FC APUs is an advantage as the water can be used on-board aircraft.

1.2. Disruptive innovation and non-consumption

Christensen and Christensen & Dryerson pioneered the idea of non-consumption [19,20]. The idea is that many consumers cannot access technologies that fully serve their needs; therefore they attempt to serve their needs with technologies that do not fully satisfy them. These markets where consumers are not satisfied represent an opportunity for innovations such as FCs. It is the belief of the authors that the reason for success of both SFC Energy and Bloom Energy is due to them identifying markets where users were not being satisfied by existing technologies. These customers were dissatisfied due to; higher operating costs, a multitude of user inputs, high maintenance costs, high emissions, low performance and high vibration and noise levels along with poor reliability. For these reasons they were more willing to adopt more effective solutions, such as FCs, to meet their energy requirements despite FCs requiring greater initial investments. Consumers will be willing to offset the higher capital investment due to the added value benefits of employing a FC. The applications discussed in this paper have been successful due to the identification of markets where this non-consumption situation exists.

2. Methodology

The data gathered in this paper is mostly secondary data taken from a variety of sources. The use of case studies in the literature

Table 1
The four FC types considered in this study and their main characteristics [17,18].

	PEFC	DMFC	PAFC	SOFC
Electrolyte	Polymer	Polymer	Phosphoric acid	Ceramic
Operating temperature	60–80 °C	60–80 °C	160–220 °C	750–1000 °C
Fuel	H_2	MeOH	H_2	$H_2/CO/CH_4$
Oxidant	O_2/air	O_2/air	O_2/air	O_2/air
Efficiency (HHV)	40–45%	25–30%	40–45%	50–55%
Anode half-cell reaction	$H_2 \rightarrow 2H^+ + 2e^-$	$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
Cathode half-cell reaction	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	$3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	$O_2 + 4e^- \rightarrow 2O^{2-}$
Overall reaction	$2H_2 + O_2 \rightarrow 2H_2O$	$CH_3OH + 3/2\ O_2 \rightarrow 2H_2O + CO_2$	$2H_2 + O_2 \rightarrow 2H_2O$	$2H_2 + O_2 \rightarrow 2H_2O$

has often been discussed, with many authors supporting their use [21–23]. Comparable methods to the ones used in this study were employed in Refs. [24–26] to aid in the understanding of FC vehicle market entry. Similar to those studies, this manuscript uses data from financial filings, media reports following the companies in question as well as patent data. These data sources are first located using search platforms such as Google, Google Scholar and Google Patents. Once the data sources are located they are systematically reviewed in order to locate the data. The data is then recorded. In some cases not all of the information required is available from these sources. In these case media reports are used. All data sources are referenced within the text and figures. The case studies of SFC Energy and Bloom are presented in 3. Results and Discussion. The prospective applications, aircraft APUs and fire prevention, are then discussed in section 4. Prospective Applications.

The data for SFC Energy is taken from financial filings. SFC is a publically listed company. As such reports are filed in order to be compliant with regulation. This is done quarterly and annually. The reports are reviewed in order to gather financial data and strategic information for each year from 2006 to present. The technical data for SFC's FCs is taken from their website where they provide data sheets for each of the FC they produce. SFC energy do not publish unit price information, this data is taken from third party sources that are distributors of these units. SFC Energy financial filings are available here [27].

Bloom is a notoriously secretive organisation and hence data is difficult to find. They are not publically listed and therefore are not required to submit filings to the US Securities and Exchange Commission. Some information is available from their website, this is however limited. The data for Bloom Energy is taken from media reports [28,29], and financial websites [30,31]. Due to the high profile nature of the company many media outlets have published information on Bloom. Further to this companies that use the Bloom Energy Servers are often keen to publicise the fact that they are using them. For example eBay publish news reports and blog posts about their use of the Bloom Box which can be found here [32,33]. They have also produced a video about their Utah Data Centre where they have 6 MW of FCs installed [34].

The data for Fire Prevention is taken from N2telligence's website and their financial filings. N2telligence publish information on how the technology works along with clients they have supplied their units to. Additionally they are a publically listed company so financial information can be gathered. These reports are only available in German and are available here [35].

For Aircraft APUs data is taken from publications and patent reports. Due to the early stage of this technology no commercial market yet exists. Therefore no financial data is reported. Rather the state of the technology and its future potential are discussed. This section looks at patents filed by Airbus [36–39] and Rolls Royce [40–42] amongst others. The is also some limited data from company websites, for example [43].

3. Results and discussion

3.1. SFC-remote & portable power

3.1.1. History

SFC Energy is a German based FC company producing energy solutions for consumers, defence and industrial customers. The company was founded in 2000. SFC Energy use DMFCs, which are known for having a high cost. This is due to high platinum loadings and also because of specialised materials that are used, for example the Nafion membrane [45,46]. The company mainly concentrates on low power FCs typically between 25 W–100 W, therefore keeping overall costs relevantly low. Historically, joint development agreements, defence clients and the consumer sector have been important sources of revenue for SFC Energy. More recently there has been a shift towards industrial clients. SFC Energy had previously been looking to incorporate some of their products into e-mobility in the form of on-board range extenders or battery chargers and hybrid drive trains specifically for light electric vehicles [47]. However, they are no longer interested in this market.

One important market that SFC Energy has always targeted and that has remained a significant source of revenue is the Recreational Vehicle (RV), Motorhome and Caravan market. This was one of SFCs first commercially successful markets [48]. SFC Energy has also concentrated on traffic management systems, monitoring, security systems and off-grid power; these markets are now important sources of revenue for SFC Energy. In 2011, industrial sales overtook declining sales to the consumer segment (Fig. 1). Today the most important market for SFC Energy is the industrial segment with 77.1% of revenue coming from this sector. 14.7% comes from the Consumer market and 8.2% is from the Defence and Security sectors.

3.1.2. Achievements

By the end of Q4 2012 SFC Energy had reached sales volumes of

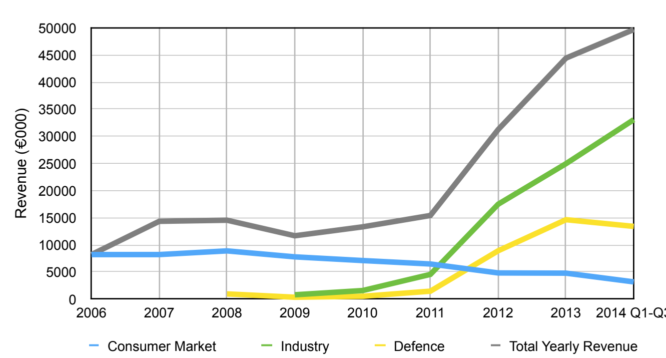

Fig. 1. Revenue generation by market sector and total yearly revenue. Sales in the defence and industry sectors did occur before 2008 and 2009 but no data is available in SFC Energy reports [47–54] (Note: 2014 Results are only from Q1–Q3).

24,000 FC units worldwide. Today this figure is over 30,000. In 2013, SFC Energy generated €44,418,000 in revenue (Fig. 1), of which €4,800,000 was from consumer sales of FCs. Based on the first three quarters of 2014 SFCs yearend revenue should exceed €60,000,000. The cost per kilowatt for the consumer FC units is very high at approximately €50,000/kW. As of 2015, the 105 W_{el} EFOY COMFORT units cost €5000 [55]. Sales are mainly to the RV market, with a smaller number of units also being installed in yachts and stationary cabins. SFC Energy has won over 26 awards for innovation, product design and enterprise. By 2008, 37 European manufacturers of motorhomes offered EFOY FCs as a standard or optional extra [52]. In general, the majority of SFC Energy's customers are in Europe; with 60.3% of revenue coming from this market, with 31% from North American customers. The remainder is from the rest of the world, but primarily Asia (5%). In 2013 industrial sales made up €24,969,000 (€33,079,000 Q1–Q3 2014) of revenue, making it the largest market sector. The growth has been partly attributed to growth in the Oil and Gas sector and in Traffic Technology [54], and has been achieved partly by the acquisition of Canadian distribution company, Simark.

3.1.3. Status

SFC Energy currently sells a range of products to a number of markets. The main product in the consumer market is their EFOY COMFORT FC power unit. The unit was originally only marketed to motorhome and caravan users. However, recently marketing towards yacht users has increased where the challenges for power provision are similar to motorhomes. In 2013, EFOY began selling fuel cartridges in the Caribbean in order to increase fuel access to users in this region. A number of yacht companies including Marex Boats and Leonardo Yachts install EFOY COMFORT's as factory fitted options on their boats. In 2013, SFC Energy sold 1697 units of the EFOY Comfort; this is far lower than the peak year in 2008 when they achieved 4210 unit sales.

When consumers are purchasing items for recreational purposes, they are often more willing to spend greater sums of money [24]. There are also a high proportion of consumers with disposable incomes in the motorhome and RV markets. For example, in Germany, one of SFCs most important markets, 70,000 Campervans, RVs and motorhomes were produced in 2013 alone. Today, sales of the EFOY COMFORT are declining (Fig. 2). This could be due to fewer sales of caravans and motorhomes or due to saturation of the market resulting in reduced demand for SFC Energy units. SFC Energy is continually exploring new opportunities including the yacht market, as well as sales on other continents.

SFC Energy has packaged a unique combination of added values into the COMFORT and has sold these to a market where consumers desire these values. Importantly, in these markets, alternative solutions do not exist. This means that the COMFORT allows

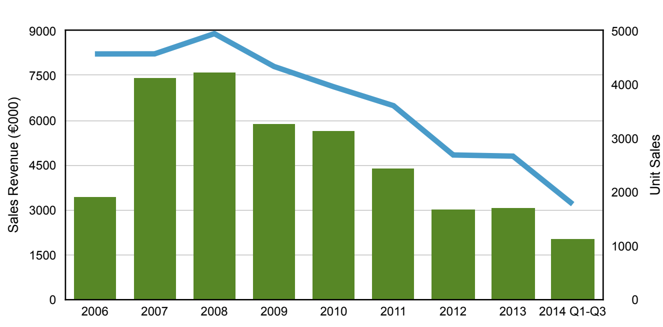

Fig. 2. SFC Energy sales to the consumer sector, which includes RVs, Caravans, Boats and Cabins [47,48,50–54] (Note: 2014 Results are only from Q1–Q3).

consumers to do things that were previously not possible. In Motorhomes and RVs the COMFORT serves as a replacement for a leisure battery or a diesel ICE generator. Compared to both of these technologies the COMFORT has clear benefits. As can be seen in Table 2 the EFOY COMFORT benefits from high charge capacity, low weight, low noise, a wide range of operating temperatures and a long run time. It also has zero tailpipe emissions. The system weighs only 16 kg including a 10 L methanol fuel cartridge. It can provide power for up to 30 days, which is far longer than a leisure battery or ICE generator. The unit only produces 25 dB of sound, which is far less than a typical ICE generator (96 dB). In addition to these benefits, the COMFORT is supported by legislation. In many US and Canadian national parks, ICE generators are banned or their use is highly restricted [56,57]. This is also the case in some Australian National Parks [58]. In these scenarios, the EFOY COMFORT offers a quiet and environmentally benign way to generate power. The unit is significantly more expensive than comparable battery or ICE but consumers are willing to pay this in order to access the benefits of the technology. The EFOY COMFORT is not without compromise. The longevity of the FC may not be as long as an ICE generator or batteries. SFC Energy only guarantees their FC units for 4500 h. This would mean under continual use the unit would not last long, however when used in a motorhome this issue is mitigated. Motorhomes are used infrequently and users do often not keep them for long periods. This generally means that a new motorhome would be purchased prior to the FC failing.

The EFOY COMFORT is marketed towards consumers who are known to value products based on a number of factors. The values presented in Table 2 are all functional values. However, consumers value products based on functional, emotional, social, conditional and epistemic reasons [59,60]. It is possible that in this case consumers value the EFOY COMFORT for additional reasons beyond functional values. Emotional reasons for purchasing the EFOY COMFORT could be due to the positive feeling of green consumerism. Social values arise from what the EFOY COMFORT communicates to others; this would be prestige value due to the high cost of the system or because of environmental or green prestige values. Epistemic values arise due to the novel nature of the technology, which will appeal to curious consumers who enjoy owning and learning about an innovative product. All of these values are difficult to quantify, but nevertheless are present.

SFC Energy markets its EFOY PRO range of products to industrial customers specifically for the monitoring of remote terminals in the oil and gas industry. SFC Energy list Canada as an important market as it has 175,000 gas wells and 125,000 oil wells currently in operation. In this sector, FCs are used for pumps, monitoring, the transmission of data and pipeline security monitoring. EFOY PRO's are also used in wind farm monitoring, telecommunications backup and continuous power, mobile and stationary surveillance, environmental data measurement and traffic management systems in off grid locations. In order to break into the North American market, SFC Energy acquired Simark who specialise in the distribution, service, supply and product integration for power products to the Canadian oil and gas industry. This market has been a significant source of growth for SFC Energy (Fig. 3) and will hopefully lead to continual increases in unit sales and revenue in SFCs most important market sector [53].

Often in remote locations, battery packs, solar or diesel generators are used to monitor oil and gas terminals. Solar is only able to provide power for part of the year due to the short duration of sunlight in the winter. Batteries need to be changed regularly and diesel generators require regular maintenance and refuelling. The maintenance and refuelling of these systems is time consuming and costly due to the remoteness of the locations. This means helicopter trips, which can cost in the region of $3000–$5000 CAD (ca.

Table 2
Comparison of the EFOY comfort with a leisure battery and a diesel ICE generator [61].

	EFOY COMFORT	Leisure battery	Diesel ICE generator
Purchase price	€5000.00	€170.00	€530.00
Max. nominal power	105 W	–	2500 W
Charge capacity	210 Ah	115 Ah	–
Nominal voltage	12 DC	12 DC	12 DC
Weight	16 kg*	25 kg	40 kg
Noise	25 dB	–	96 dB
Operating temperature	−20 to 40 °C	–	–
Run time	30 days	72 h	10 h
Fuel supply	10 L methanol	–	15 L diesel
	*Including fuel cartridge		

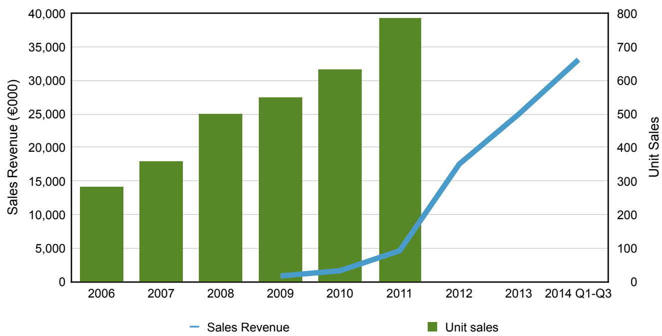

Fig. 3. Sales of SFC Energy products to the industrial sector. Pre 2009 revenue figures and post 2011 unit sales are not available in any SFC Energy filings [47,48,50–54] (Note: 2014 Results are only from Q1–Q3).

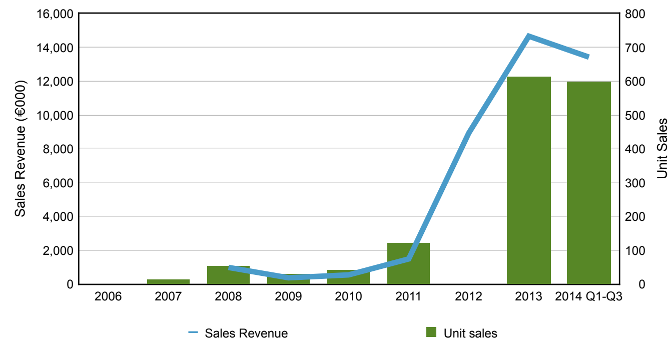

Fig. 4. SFC Energy sales to the defence sector. Pre 2008 revenue figures and 2012 unit sales are not available in any SFC Energy filings [47,48,50–54] (Note: 2014 Results are only from Q1–Q3).

€2000–€3500) in North America, are a regular occurrence, for instance [53]. Due to the EFOY PRO being fully autonomous and its ability to run for extended periods of time, helicopter trips are reduced, thus saving customers' time and money. According to Mark Wheeler, President of Simark Controls. Ltd, the EFOY PRO [53] can achieve a payback time of 18 months in these situations. Table 3 shows the technical details of the EFOY PRO, it is clear that the system is well suited to this application, with long run times and the ability to operate in extreme conditions. The technology also has the added benefits of being quiet and zero emission.

SFC Energy has a range of products for Defence and Security applications. The added values that SFC Energy's products offer in this market arise mainly due to significant weight savings. This market has seen substantial growth in recent years and is the second largest contributor to SFC Energy's revenue (Fig. 4). SFC Energy products offer longer run times, lighter operational weights and quieter operation compared to competitor technology. On vehicles, the EMILY 3000 can be used to power electrical systems when the vehicle is stationary. This means the engine does not need to be idling, thus saving fuel, resulting in longer mission times, and reduced noise and heat signatures.

The JENNY 600s and 1200 provide personal power for soldiers. The most important consideration in this application is weight savings. By having less weight, soldiers are able to carry larger quantities of more valuable supplies. This means they can stay in the field for longer periods. The JENNY 600s results in an 80% weight reduction on a 72-h mission compared to using batteries. The JENNY 600s uses a 25 W FC to provide 29.5 V DC power to soldier's personal electronic equipment (Table 4). When coupled with 4 methanol cartridges the system will provide power for 72 h with a total weight of only 3 kg. To achieve this with batteries a solider would be required to carry 15 kg.

3.1.4. Summary

Prior to adopting SFC Energy's products, consumer, industrial and defence clients would have mostly been using ICE or battery power products to meet their energy requirements, with some clients using solar or wind power. All of these energy sources are

Table 3
Technical details of the EFOY PRO, which is used for oil and gas terminal monitoring [62].

	EFOY PRO 2200
Purchase price	€10,000.00
Max. nominal power	110 W
Charge capacity	2200 Wh
Nominal voltage	24 V DC
Weight	31.3 kg*
Noise	42 dB
Operating temperature	−40 to 50 °C
Run time	up to 65 days
Fuel cartridge	28 L methanol
Cost to refuel	€150.00
	*Including fuel cartridge

Table 4
Technical Details of the JENNY 600S power pack [63].

	JENNY 600s
Max. nominal power	25 W
Charge capacity	600 Wh
Nominal voltage	29.4 V DC
Weight	3 kg*
Noise	37 dB
Operating temperature	−32 to 35
Run time	72 h
Fuel cartridge	4 × 350 ml methanol
	*Including fuel cartridges

not without issues. Batteries are quickly depleted, provide low amounts of power and have long recharge times. ICEs are noisy, not always permitted for use, cause vibrations and pollution. Solar and wind are both intermittent and require storage. Users of these technologies users could be considered to be in non-consumption and therefore are willing to adopt alternative technologies that better serve their needs. FCs are useful in these markets because they are not just marketed as power providers, they are marketed with added value features meaning the high costs of the solutions are justified by the beneficial attributes.

3.2. Bloom energy-stationary power & back-up power

3.2.1. History

Bloom Energy is an American company that was founded in 2001 as Ion America. Originally Bloom Energy began as a spin out of research that formed part of the NASA Mars program. Their primary focus is providing energy solutions in the form of their Energy Servers. Since its founding in 2001, Bloom Energy quickly acquired venture capitalist funding which allowed them to develop their technology [64]. Their technology is based on SOFCs and a lot of the development work that they have done is propriety. In 2006, Bloom Energy released their first trial unit, which was a 5 kW SOFC. This was set up at the University of Tennessee followed by additional trials in California and Alaska. In 2008, their first commercial SOFC product was sold to Google [64]. This was a 100 kW SOFC system. Since then, Bloom has sold their Energy Server to multiple clients including Wal-Mart, Staples, AT&T, The Coca Cola Company, eBay, Google, FedEx, Safeway, Nokia, Apple and many more [64].

3.2.2. Achievements

Bloom Energy's biggest strength has been the ability to market their Energy Servers to large corporations who are able to easily absorb the high capital cost. By doing this they have developed brand equity. Furthermore, the benefits of the Bloom Energy Server mean that the corporations using them have greater strategic and economic advantages. One example of this is the added value of reducing carbon emissions. Typically, smaller businesses do not see a large economic benefit to reducing their carbon emissions and thus have little interest in using a FC system. However, a reduction in carbon emissions is greatly advantageous to these large corporations. Indeed these corporations often have to report their carbon emissions [65] and so implementing technology to reduce this helps. Alongside the direct economic benefits of emissions reductions, organisations can indirectly benefit from creating a 'green' image. Many high profile companies, such as the ones mentioned in section 3.1 are often keen to develop a positive corporate social responsibility. In recent years this has seen companies improve their environmental performance in order to generate a more positive image. Corporations hope that this will lead to increases in revenue due to consumers choosing to use their products or services because they are considered to be green, or at least greener than competitors.

In addition to the benefits of emissions reductions and green image, the energy servers have further added value over incumbent solutions. For large corporations like eBay, Google and Apple a power outage would be incredibly damaging to their business. Many of these organisations have vast data centres with high power demands. If grid power fails, these companies need reliable back-up power to be available 100% of the year. Existing solutions consist of large diesel generators and battery packs. These systems have a poor cost/benefit ratio, meaning that they are installed at a high cost and are not used for much of the year so little benefit is gained. In addition to this, they are not always reliable and require constant maintenance even when not in use. A high profile example of this poor reliability was in the wake of Hurricane Sandy in 2012. During this disaster, back-up generators failed including the New York University Langone Medical Centre causing the hospital to be evacuated [66], and at a data centre operated by Peer1 Hosting [67].

Bloom's system is still capital intensive but can be used all year round meaning a better cost/benefit ratio for the users. The added value provided by the Energy Server includes; 100% availability of power, higher reliability, quietness, low vibrations and low emissions. This means that the Energy Servers are an active asset unlike diesel generators that are dormant much of the year.

Despite Bloom Energy's great success at selling many units of their Energy Server, they are still not a profitable company and have been relying on venture capitalist funding. However, they are expected to become profitable in the coming years. One of the reasons that Bloom has been able to survive so long has been due to this venture capitalist support. Indeed, in 2008, Bloom Energy made a loss of $85 million (€74 million) [68]. In 2012, it was reported that Bloom Energy had received a total $974 million (€850 million) in venture capitalist funding, making it one of the five largest recipients of such funding in history whilst at the same time, their retained earnings were reported at negative $873 million (€761 million) [30]. However, Bloom is on the way to becoming profitable with a quarter on quarter increase in sales revenue and a fast increase in their client base.

3.2.3. Status

Currently, Bloom Energy sells a range of products, which are collectively called the Bloom Energy Server. This SOFC based FC system operates at 980 °C and can be run on a variety of different fuel types. The smallest Bloom Energy Server is a 100 kW system that was reported to cost between $700–800 K (ca. €550,000 to €620,000) [28]. In addition to the 100 kW unit, Bloom produces 160 kW and 200 kW energy servers.

Thus far, the majority of customers have purchased the Bloom Energy Server due to its ability to provide uninterruptable power. In 2007 (the last year such information is publically available), the US had 240 min of grid black-outs which cost an estimated $100 bn (€87 billion) [69]. The US gas grid, which the Energy Servers utilise, has close to 100% reliability [70]. This, along with the added values mentioned allows users to capitalise on the benefits of FCs. For example, eBay installed 6 MW worth of Energy Servers at their Salt Lake City (Utah) data centre site [32]. In this case the Bloom Energy Servers are used as the primary power source. For eBay, the main added values of the FC system are as follows [32]:

1. Helps eBay to meet their targets of carbon emission reduction.
2. Helps eBay to reduce their energy usage.
3. Helps eBay to reduce the cost of purchasing and maintaining costly generators and UPS components.
4. Helps eBay to promote themselves as a green corporation.
5. Provides reliable back-up power.

The added values of the Bloom Energy Server are therefore attractive to large corporations, especially in the USA, where power outages are a more common event and can last between 90 and 240 min [69]. Corporations cannot afford to be out of power as revenue will be lost. The importance of maintaining websites 100% of the time is demonstrated by the case of Amazon.com. In 2013 the website went down for 15–40 min, during this time Amazon is estimated to have lost $1–2.5 million (€0.87–2.18 million) in sales alone [71]. Further to this their share price fell by c. 10%. As a result, this situation highlights the benefits and added value of a FC system that operates independently of the main power grid and can maintain power 100% of the time.

Bloom Energy's success in this market is partly due to incentive support from national and state incentives. In 2010 alone Bloom Energy and its clients received over $200 million (€175 million) in subsidies from the California Self-Generation Program (SGIP) [72]. There are several levels of support on offer from the SGIP, which also varies by system. FC based generation systems receive a flat rate of $1.65/W (€1.43/W) in subsidies [73] as long as the amount of power generated is below 1 MW. Between 1–2 MW and 2–3 MW, subsidies are $0.83/W (€0.72/W) and $0.41/W (€0.36/W), respectively. For example, a 100 kW Bloom Energy Server running on natural gas would receive a subsidy of $165,000 (€143,000) off its purchase price. For systems above 30 kW, 50% of this subsidy would be paid upfront which would significantly help with installation costs. This means that it is in fact possible to get a significant return on investment in 5 years from installation. If run on biogas the subsidies can rise to $8.25/W (€7.20/W) [73].

A comparison of the 100 kW Bloom Energy Server to a diesel ICE and battery system can be seen in Table 5. A comparable diesel generator would cost approximately $20,000 (€17,500) and a battery based UPS that could provide 50 kW of power would cost approximately $42,000 (€36,000). Typically in data centres a hybrid system comprising of both a battery system and diesel generator is used. The batteries are used for immediate power supply when a power outage occurs. Once started the diesel generators are used for the remainder of the power outage. A diesel and battery system would represent a lower capital investment. Despite these lower costs, Bloom Energy servers are often preferred due to longer run times, less noise and less CO_2 emissions.

3.2.4. Summary

Prior to using Bloom Energy Servers, companies like eBay can be considered to be non-consumers, because their needs were not being properly met. Prior to using Energy Servers, eBay along with many other companies used back-up power systems comprising of batteries and large diesel ICE generators. These systems were the only back-up power solution available to the companies, but were not truly fit for purpose. They did indeed supply back-up power to the companies, but this was in an undesirable package; the systems were capital intensive, underutilised, maintenance intensive, polluting, noisy and had a high risk of failure. A FC system can be used 100% of the time, requires less maintenance, has zero tailpipe emissions, is quiet, helps towards giving large corporations a 'green' image and benefits from subsidies from government organisations in the US.

4. Prospective applications

The following FC applications are ones that have yet to emerge as significant markets for FCs however offer great potential to capitalise on FC added value. The first application, APUs in passenger aircraft, is one that is still in an early stage with Airbus testing PEFC systems in A320 aircraft. An APU does not provide motive power to the vehicle on which it is installed. Rather an APU provides power to on-board electrical systems such as heating or cooling, entertainment systems or vehicle electronics. The second market, FC Fire prevention, is more developed with systems having been shipped to a number of users. This application of FCs has greater potential for growth into more global markets. These applications demonstrate how the many benefits of FCs can be leveraged to make the systems more cost effective.

Table 5
The Bloom Energy Server compared to a Diesel and Battery back-up power unit.

	Diesel ICE	Battery	Bloom energy server
Purchase price	$20,000	$42,000	$700,000
Max nominal power	100 kW	50 kW	100 kW
Noise	96 db	–	70 db
Run time	c. 8 h	6.4 min	Continuous
CO_2 emissions	675 kg CO_2/MWh	–	386 kg CO_2/MWh

4.1. Airbus-aircraft APUs

The application of FCs in aircraft was first mentioned by Seidel in 2001 [74]. With their history in NASA, it is not difficult to see how FCs could be used in aircraft given their successful use in many space missions [75–78]. Boeing and Airbus have reportedly been interested in this technology since 2001 [79]. The main driver for FC use on aircraft is power provision, but also the production of water & inerting gas [79–81]. This aids in the reduction of emissions and fossil fuel consumption in air travel, by increasing electrical efficiency and reducing the weight of the aircraft. FCs cannot currently be used for propulsion due to poor power densities. They are instead useful for providing auxiliary power [79]. In addition to power, water and inerting gas, FC APUs can provide heat for wing de-icing, heat and cooling for the cabin and back-up power replacing the Ram Air Turbine (RAT). Owing to the many uses of the FC and its waste products, in this application the units are referred to as Multifunctional Fuel Cells (MFCs) [14,79].

Airbus is working with the German Aerospace Centre (DLR) and Parker Aerospace in the development of FC APUs. Airbus are interested in the system for a number of reasons. Current kerosene turbine APUs have <20% efficiency, are noisy, have high vibrations and result in NO_x and CO_2 emissions [14]. FC APU systems for aircraft are still in the testing phase with scale testing beginning in 2008 with the goal of full-scale tests in 2015 [44]. The first test flight of a FC APU system on an Airbus was in 2008. On this test a 25 kW unit was trialled [44]. Peters and Samsun [79] considered 10 different FC systems and concluded that for short range travel PEFCs using hydrogen as a fuel would be most suitable, and for mid to long range travel HT-PEFCs using the planes kerosene fuel would be most suitable.

Interest in APUs for use in aircraft continued throughout 2014 with a number of companies filing patents. For example, Rolls-Royce Corporation (US) filed patents for FCs to provide power for ground movements by using the FC electrical power to drive the wheels [41]. Similarly Airbus Operations GmbH filed a patent for using FC power to drive the aircraft wheels during taxi [39]. They also filed for a novel connection for installing a FC APU in the tail cone of aircraft, with the APU being used to provide on board power and emergency power replacing the RAT. This particular APU would easily be swappable out of the plane so that a new unit would be installed in case of maintenance requirements [38]. A number of French companies also filed for on-board electricity production using FCs [82,83]. Airbus is still working with the German Aerospace Centre (DLR) and Parker Aerospace in the development of a FC APU [44]. The application of FCs in an aircraft are currently being considered for the following reasons:

1. The FC would be used to supply on-ground power when the aircraft is on taxi and stationary, this would reduce NO_x and ground related CO_2 emissions [84]. This would help to meet the 2020 goals for 50% CO_2, 80% NO_x and 50% noise reductions for aircraft [44]. The power can be used for cabin pressurisation, galley power and for entertainment equipment.
2. The water which is emitted from the FC can be used mainly as refuse water [43], but could also be used as drinking water if EPA and FDA approval is met and can be used for cabin humidification [14]. This reduces the need for carrying water as it is produced inflight by the FC. This is beneficial as passenger aircraft can carry up to 1,700 L of water. Using FC APUs will

result in weight reductions, fuel savings and emissions reductions, especially because take-off weight is reduced [43]. An additional benefit of this is that airlines do not have control of the water that is pumped into their aircraft. In some locations this can be of poor quality and contaminated with bacteria, thus putting passengers' health at risk. By using a FC, this risk can be avoided.
3. The FC exhaust gas can be used as inerting gas for fire retardation in the aircraft fuel tanks. The exhaust gas of FC is deoxygenated air, sometimes as low as 8% oxygen by volume [14].
4. The heat from the FC could be used for de-icing of the wings and for cabin heating.
5. The FC can also provide back-up power supply in case of power system failure to spoilers, ailerons and actuators [43] replacing the RAT.
6. The FC can provide motive power for ground movements.

FCs are ideally suited for use as aircraft APUs due to the large number of added values that can be capitalised upon in this application. By making use of the wide range of benefits, they can become economically viable. Additionally the FC is replacing existing fire prevention, power provision, water storage, heating systems and the RAT that already have a high combined weight and cost. This can mean that the FC systems can be lighter and economically beneficial in addition to having environmental benefits.

4.2. N2telligence

FCs have long been used as back-up and primary power providers [85–88], for example Bloom Energy. German company N2telligence has employed a modular 100 kW FC system that can be used for power provision and fire prevention. The fire prevention comes about thanks to reduced oxygen content in the cathode exhaust gas. The company was founded in 2006 and partnered with Fuji Electric as the FC supplier. N2telligence call their system “Quattrogeneration”. This means the system provides; heating, cooling, power and fire prevention [89]. N2telligence install oxygen-monitoring systems to ensure the oxygen content of the air remains below a level at which fires can start. They claim this to be the only fire prevention system based on FCs in the world. The patent for FC fire prevention was filed by Airbus Operations GmbH in 2006 and was granted in 2012 [36], N2telligence license this IP from Airbus.

The system is expensive at €7300/kW, which would mean that the 100 kW system would cost €730,000, a comparable price to the Bloom Energy Server. The benefits of the system, however, are great, meaning that fires and power outages are avoided. N2telligence systems have been shipped to a number of users including Daimler-Benz, Daimler-AMG, ThyssenKrupp Marine Systems and Airbus Deutschland [89]. The company signed a development agreement with AFC Energy in 2011, however there is no longer any mention of this on their website, and they are now known to work with Fuji Electric using PAFCs [89].

The systems are especially beneficial in a number of markets. Data centres in particular can benefit for a number of reasons; data centres are a high fire risk, due to the risk of technical defects and short circuits, high fire loads and accelerated rate of fire spreading. Data centres also stand to have significant losses in the event of a fire. In addition to being beneficial for data centres, the systems are beneficial to any facilities that have a fire risk and require back-up power. In 2013 N2telligence achieved a net income of €141,000 which is up from €-114,554 from 2012. These figures are low, but nevertheless the application does have potential for the future.

5. Conclusion

Firstly this paper shows how both SFC Energy and Bloom Energy have achieved market entry by producing FC products with added values, and not by attempting to directly compete with incumbents. Both organisations market and sell an added value product to niche markets. In the target markets, consumers are in a non-consumption situation, meaning that their needs are not being sufficiently met by incumbent technologies. In these applications, no other technologies can provide the service that Bloom Energy's and SFCs' products provide. Both companies have produced products with a large number of added value features, which were then marketed to niche market consumers that desired these features. SFC Energy was able to sell a product to markets that require long lasting power, independent power, quiet power, emission free power, quick refuelling and high reliability. They also targeted consumers who had high willingness to pay for these attributes: motorhome users and the oil and gas industry. Bloom Energy was able to sell a product to consumers that require back-up power at 100% availability, emissions free power and high reliability. Bloom Energy targeted data centres of high tech companies such as eBay, Google and Apple. These companies valued the benefits of Bloom Energy's power solutions highly as power outages would be damaging to their business.

This paper outlines two prospective applications of FCs, both making use of additional attributes of a FC. These are the use of FCs as aircraft APUs and for fire prevention in data centres, although both of these applications have yet to achieve their full potential. Aircraft APUs are currently in a testing phase with Boeing, Rolls-Royce and Airbus all showing interest in the technology. In this application FCs are able to produce power, water, inerting gas and heat, simultaneously making them the only one-package solution. FCs for use as fire prevention is also a novel application, with no other technology being able to do this whilst still providing power. Data centres already need back-up power to ensure systems continuously operate, and need fire prevention to avoid any economic loss due to fire. The ability of a FC to replace two systems is a logical solution making data centres more secure and less at risk.

These two current and two prospective applications indicate how FCs should not be marketed merely as power providers. If this were the case they would have a high risk of being outcompeted by incumbent technologies. In order for FCs to be competitive within the market they should be sold as solutions to a number of problems, rather than just one. Bloom Energy and SFC Energy have both been successful in marketing their FC solutions as added value power providers and they have achieved notable success. Fire Prevention and aircraft APUs are both applications that highlight how the features of a FC can be exploited so that it replaces more than one system. By using FCs to provide fire prevention, water, heat, cooling, back-up power along with primary power, a FC can become more cost effective compared to incumbent technologies that would be used for these purposes. This will be the most effective route to market for FCs and it means that cost reduction targets will not be as stringent, and early market entry will be possible.

FC developers looking to enter markets may be able to position their products such that they have clearly demonstrated added values over incumbents. When developers are considering markets they should seek out opportunities where consumers are forced to use incumbent technologies that do not fully meet their needs. These consumers will be in a situation of non-consumption. To illustrate this situation, consider FC powered material handling equipment, which would be more expensive than an incumbent, and would also require the installation of a hydrogen filling station. This means that it would not be suitable for all situations. However if a warehouse is in operation 24 h per day, is a sealed environment and has a large fleet of forklifts, an opportunity may exist. Such a warehouse would be unable to use ICE forklifts due to the enclosed environment, therefore they would be required to use battery electric units. Battery electric units are plagued by two problems. First they cannot operate 24 h per day and therefore they require recharging, which takes many hours. To solve this companies often have two fleets of forklifts, one that is used whilst the other is charged. This increases capital costs significantly, and can also consume valuable warehouse space. Secondly, battery electric units suffer from poor power output when batteries are low, this slows down mobility, reduces lifting power and hinders productivity. If such a situation exits, and the fleet is large enough to justify the installation of a hydrogen refuelling unit, FC material handling equipment could result in reduced capital expenditure, increased productivity and more available space.

When these situations have been identified it will be possible to develop a FC product that can more effectively meet consumer needs. Once such a product has been developed it should be marketed towards niche market segments, which will further ensure their penetrative success within this market. A targeted and specific approach that exploits the added value features of a FC is needed. This will lead to increased acceptance by early adopters and ultimately lead to increased rates of overall market uptake for FCs with the long term goal of cost reductions and eventually mass market entry.

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