ABDEL-WAHAB, M. and ALI, D. 2013. A conceptual framework for the evaluation of fuel-cell energy systems in the UK built environment. *International journal of green energy* [online], 10(2), pages 137-150. Available from: https://doi.org/10.1080/15435075.2011.642089

A conceptual framework for the evaluation of fuel-cell energy systems in the UK built environment.

ABDEL-WAHAB, M. and ALI, D.

2013

A conceptual framework for the evaluation of Fuel-Cell Energy Systems in the UK Built Environment

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Abstract

Energy efficient buildings can reduce the human-impact on the environment. Energy efficiency is not only concerned with generating more energy using fewer resources, nor reducing energy usage, but also it is about harnessing natural resources, such as wind and sun, to produce energy. The UK government is thus promoting the adoption of renewable energy in buildings. Fuel-Cell Energy Systems (FCESs) which utilises hydrogen from renewable sources (green hydrogen) is a prominent technology yet with little application in the UK built environment. FCESs can help in addressing the problem of intermittent supplies of renewable energy by allowing for energy storage which could act as a buffer to meet the variability in user-demand thereby maintaining energy security. Thus, the aim of this paper is to explore the application of FCES in the UK Built Environment, by drawing on the scant literature as well as discussion with industry experts. With the recent implementation of FCESs in Scotland, the development of guidelines for evaluation of the FCES is timely. A conceptual framework for the evaluation of FCES is thus outlined in this paper which could be piloted in Scotland (and possibly elsewhere). It is argued that such framework provides a holistic and structured approach for establishing the efficacy of FCES which is crucial for informing its wider adoption in the future and in particular when it comes to the Return-on-Investment (ROI) especially from the perspective of funders and the local community.

Keywords: Evaluation, fuel cells, ROI, renewable-energy and Built Environment

Introduction

Nowadays energy is regarded as a scarce resource particularly when considering the uncertainty of the supplies from fossil fuels. Since 2004, the UK has become a net importer of energy due to the reduction in the North Sea oil and gas reserves (ONS, 2009) and in turn this poses a risk of energy security. Moreover, the number of households in fuel poverty in the UK was estimated to be around 4.5 million in 2008, a rise of around 0.5 million from 2007 which represents about 18 per cent of all households (Annual Report of Fuel Poverty Statistics, 2010). The UK government is thus committed to promoting the use of alternative and greener sources of energy, other than fossil fuels, and in particular renewable energy.

Such commitment is reflected through schemes such as Feed-In Tariffs that was introduced in April 2010, which entitles households to claim cash back for electricity they produce from eligible renewable and low-carbon sources (Act on CO_2, 2010). The government is also investing £850m in the Renewable Heat Incentive and has earmarked a £1 billion fund for a UK-wide Green Investment Bank, which aims at encouraging significant additional investments in green infrastructure (Comprehensive Spending Review, 2010). Moreover, the UK Climate Change Act 2008 sets legally binding emission reduction targets for 2020 (reduction of 34 percent in greenhouse gas emissions) and for 2050 (reduction of at least 80 percent in greenhouse gas emissions), in addition to a five-yearly carbon budgets to ensure that those targets are met (Department of Energy and Climate Change, 2010).

The UK built environment consumes 40% of total energy required for the economy and accounts for 40% of carbon emissions (National Atmospheric Emissions Inventory, 2010) and thus it has the potential to both decrease the reliance on volatile sources of energy, i.e. fossil fuels, in addition to making a significant contribution to cutting the level of carbon emissions in the economy. In particular, remote locations can benefit from becoming energy independent. Whilst renewable energy presents an alternative and green source of energy yet only 2% of energy used in the domestic sector comes from renewable sources (Digest of the United Kingdom Energy Statistics, 2010).

The use of renewable sources of energy has its shortcomings notably its intermittent supply nature due to fluctuations in weather conditions. It is contended that *"the current government energy policy is unrealistic and overly optimistic by failing to address the fundamental problem with all renewable sources and that they are intermittent"* (Royal Academy of Engineering, 2010). Moreover, *"…we must not lose sight of the fact that the wind only blows a third of the time…"* (Foulkes, 2005).

Clearly, the intermittency issue of renewable energy underlies the need for exploring new and innovative approaches for harnessing natural resources to have a reliable back-up supply of energy. As such, this paper explores the application of Fuel Cell Energy Systems (FCES) as a possible means for addressing the shortcomings of renewable energy in the context of the UK built environment. Currently, there is a paucity of application of FCES in the UK, including the built environment, which is evident by the absence of specific data on the usage of hydrogen in the UK economy (see Digest of the United Kingdom Energy Statistics, 2010).

The paper commences with an overview of FC and its application in the built environment including demonstration projects and in particular recent developments at the Hydrogen Office in Scotland. A conceptual framework for evaluation of the efficacy of adopting FCES is then outlined with a view to informing future application particularly in the context of energy refurbishment of the existing housing stock[1] as well as informing the application at larger demonstration projects which currently do not exist in the UK (see Edberg and Nash, 2010).

Research Method

[1] *Most of the buildings in 2050 have already been built (Blomdahl, 2010)*

The paper is based on a thorough literature review in addition to discussions with industry experts through a telephone interview and email. Reliance on experts as a key source of information is indispensable (Tedmori, 2008) particularly when it comes to exploring a relatively new area of research.

According to Cross *et al* (2001), the purpose of seeking information from experts can be categorised into five groups namely: 1) finding solutions to a problem under consideration; 2) providing the knowledge seeker with pointers to alternative valuable sources of information; 3) problem reformulation (the interaction associated with seeking information from other people allows viewing the problem from a different perspective); 4) validation of plans or solutions; and 5) legitimation (seeking information from an expert in the field and citing them as having reviewed the solution increases the credibility of the proposed solution). In the context of this paper, the purpose of expert view fits with category 2, 3 and 5. The focus of the discussions with experts was centred on establishing the need for developing guidelines for the evaluation of Fuel Cell Energy Systems (particularly when it comes to ROI) in addition to getting up to-date information on the progress of the project.

There was a semi-structured telephone interview[2] with the Design Engineer at the PURE (Promoting Unst Renewable Energy) project[3]. Email exchange with the Managing Director of the pure Energy Centre[4], and former Hydrogen Development Officer at the Hydrogen Office project[5], was a source for extracting expert knowledge. Research suggests that with the prevalence of using email as source of communication in organisations it presents a good resource for extracting, creating, and sharing knowledge (see Tedmori, 2008). Results from the industry discussions are incorporated within the literature review and relevant citations made where appropriate.

An overview of Fuel Cells

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[2] *Semi-structured interviews allow for flexibility when eliciting information from the respondents.*
[3] *Information on the PURE project is available at: www.pure.shetland.co.uk/html/pure_project1.html*
[4] *The Pure Energy Centre was established on the back of the PURE Project in 2005 which delivered a zero emissions, off-grid renewable hydrogen hybrid power supply to an industrial estate on the most northerly island in the UK. Further information on the Pure Energy Centre is available at: www.pure.shetland.co.uk*
[5] *Information on the Hydrogen Office project is available at: www.pure.shetland.co.uk/html/pure_project1.html*

What is a Fuel Cell

A fuel cell is analogous to a battery. In a battery reactants are stored internally and when used up the battery must be replaced or recharged, while reactants of fuel cells are stored externally and can easily be recharged. Fuel cells size range from those producing quite small amount of electric power to devices such as portable computers right up to very high powers for electric power stations. Similar to a battery each fuel cell has two electrodes and an electrolyte that allows protons to pass through while blocking electrons (Brandon and Hart, 1999). Generally hydrogen is fed to the anode where it splits into a proton and electron; the protons pass through the electrolyte to the cathode while electrons are forced around an external circuit creating electricity. The hydrogen protons and electrons combine with oxygen from air at cathode producing pure water and a small amount of heat. Below is a typical fuel cell reaction (Brandon and Hart, 1999; Perry and Kotso, 2004).

At Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

At Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$

There are six main types of fuel cells, namely: Polymer Electrolyte Membrane Fuel cells (PEMFC), Solid Oxide Fuel cells (SOFC), Direct Methanol Fuel cells, Alkaline Fuel cells, Phosphoric acid Fuel cells, and Molten Carbonate Fuel cells. According to Graham *et al* (2002), PEMFC and SOFC are the most suitable to the domestic sector. All the heat and power requirements of private households or small business could be met by small units less than 50kW of low temperature Polymer electrolyte membrane fuel cells (PEMFC) or cheaper Phosphoric acid fuel cell (PAFC). The benefits of FC residential application include: conversion efficiency, grid independence, grid connection, environmental advantages, renewable compatibility, fuel flexibility for sourcing hydrogen, ease of use and maintenance (Barlow, 1999). A FC requires hydrogen to be powered which can come from different sources.

Sources of Hydrogen

Whilst hydrogen is primarily sourced from the reformation of natural gas (see Crabtree *et al.*, 2004), biohydrogen, and electrolysis that is powered by renewable energy *(green hydrogen)* present alternative sources of hydrogen. Biohydrogen is technically feasible and greenhouse gas neutral (Peppley, 2006). The abundance of biomass waste from various industries (such as food and starch-based wastes, dairy wastes, and palm oil mill effluent) is a potential source of biohydrogen production (Chong *et al.*, 2009). In one study involving dark fermentation[6], cheese whey wastewater was used for hydrogen production (Azbar *et al.*, 2010). Green hydrogen is sourced by using an electrolyser that is powered from a renewable energy source (such as a solar panel, wind-turbine or micro-hydro-generator) to breakdown water molecules into hydrogen and oxygen, and then hydrogen is stored to be used in a Fuel Cell (FC) – as shown in figure 1 below. Figure 1 depicts a closed system as none of the products or reactants (water, hydrogen and oxygen) are lost to the outside environment.

INSERT FIGURE 1 HERE

Energy storage in a FC enables the continuity of supplying energy from intermittent renewable sources thereby addressing energy insecurity caused by fluctuations in energy supply. The electrical power generated from renewable sources could be stored at times when there is a surplus in renewable power production and then converted back to electricity when renewable production is low (or not available). Hydrogen is used as an energy storage mechanism, where water (H_2O) is split through an electrolyser into H_2 and O_2 when excess renewable energy is available. H_2 is then stored as fuel and O_2 vented or re-used. FC will then use the stored H_2 to generate electrical power when renewable production is not available. A FC can keep on supplying power as long as there is hydrogen. Indeed the use of renewable energy to power an electrolyser for sourcing hydrogen offers a carbon-free source for powering a FC which can potentially reduce the reliance on oil and natural gas in the long-run (The Hydrogen Office, 2010). Using hydrogen as a storage mechanism for energy is not without its shortcomings, such as requiring a bigger space for storage, which has to be considered in future evaluations of a FCES.

[6] *Dark fermentation refers to the fermentative conversion of organic substrate to biohydrogen.*

Application of FCES in the Built Environment

There is limited and sporadic application of FCES in the built environment. In the UK, the University of Birmingham has installed a hydrogen fuel cell and a reformer in a garden’s shed, which converts the natural gas piped through existing infrastructure into hydrogen. The device generates 1.5 kilowatts of electricity and three kilowatts of heat which is sufficient to power the newly-built home's electricity, water and central heating (Low Carbon Economy.com, 2010). Moreover, the first micro combined heat and power (mCHP) heating unit is tested at a manufacturing facility in Hull and is regarded as a breakthrough in small-scale electricity generation as it is the size of a dishwasher and can produce twice the electricity needed to power an average home, with the surplus electricity being sold back to the grid (Renewable Energy Focus, 2010). Another example of FC application is at the Woking Park scheme in the UK which uses a CHP Fuel Cell to power Woking Park and a number of homes (Woking Borough Council, 2010). In Europe, the Technical University of Denmark (DTU) is developing prototypes of FC units for homes but with no mass-production as yet. A concern in Denmark has been the lack of mechanism in-place for selling excess power back to the grid. However, the UK could be regarded as better prepared in that aspect with the introduction of feed-in-tariffs last April (Emspak, 2010).

Common barriers for the wide adoption of FC in the built environment include: cost, unproven technology, and continuous parasitic loads (Barlow, 1999). Whilst FC is proving to be a viable technology, as evident by the aforementioned examples, yet its wider adoption in the built environment remains limited due to its high cost and nature of the construction industry which has a slow-pace of up-taking new technologies in addition to its low investment levels in R&D when compared to other industries (ONS, 2009). A key shortcoming of the aforementioned examples of FCs in the built environment is that they still predominately rely on fossil fuels as a source of hydrogen for powering the FC except for two sporadic examples in Scotland, namely at the Berwickshire Housing Association (which has an eco-home that generates hydrogen through a 4.5kW electrolyser from surplus wind and solar electricity generated on site) and the Lews Castle College (which generates hydrogen from on-site wind turbines at which is then stored in “K” type cylinders for use in the college’s hydrogen laboratory). Demonstration projects thus become an important means for assessing the viability and reliability of FCES, particularly with the use of green hydrogen, in order to inform the future application of FCES in the built environment.

Demonstration projects

Demonstration projects help in testing the application of FCES and understanding the challenges encountered in practice. Graham *et al* (2002) argued that demonstration projects help in ascertaining the performance, reliability, installation and servicing of FC. Two examples of such demonstration projects are presented by the Hydrogen and Renewables Integration (HARI) Project at West Beacon Farm, Leicestershire in England, and the Hydrogen Office project in Scotland – which are subsequently discussed.

The Hydrogen and Renewables Integration (HARI) Project

Renewable energy, including photovoltaic, wind and micro-hydroelectric, has been used at West Beacon Farm site in Leicestershire (UK) to supply electrical power to domestic and office loads. A Fuel cell energy system was also used, as an energy storage mechanism, because the renewable supplies rarely matched the fluctuating demand of the end-users. The system comprised of: a 36 KW electrolyser, a pressurized gas store (2856 Nm^3 of hydrogen at 13.7 MPa (137 bar) and fuel cells (2 kW and 5 kW)). The purpose of the project was to experiment with the integration of hydrogen energy storage and renewable energy systems and to develop software models that could be used to inform future application. It was contended that some of the key components of the system, in particular the electrolyser and hydrogen storage could be reduced in size. There was also a need for conducting a thorough cost-benefit analysis (Edberg and Nash, 2010).

The Hydrogen Office

The demonstration project of a FCES at Methil Docks Business Park Fife in Scotland which is known as 'The Hydrogen Office' has been fully operational since January 2011. The building was designed so that energy demand is reduced, in addition to utilising renewable sources of energy. It has a number of environmentally-friendly features: increased insulation, natural ventilation and maximum natural light in the building, ground source heat pump[7] (which also recovers waste heat from the fuel cell and electrolysis unit) to provide most of the heating and hot water for the building (The Hydrogen Office, 2010). The FCES at the Hydrogen Office comprises of the following components: wind turbine, electrolyser, hydrogen storage and a fuel cell, and ground source heat pump -as shown in the diagram below.

INSERT FIGURE 2 HERE

The efficiency of electrolysis is high but the turnaround efficiency is low. A formal interview with one of Scotland's industry experts with more than 8 years experience in FC technology, Mr Ross Gazey - Design engineer of the PURE project in Shetland, highlighted that the energy loss in the process can help in maintaining the electricity network balance. He explained that the turnaround efficiency ranges from 20% to 40% for power only and can go up to 60% in combined heat and power. However, this efficiency should be regarded as a recovery of 20% to 40% of energy that would have been otherwise dumped to maintain a network balance rather than considering it as a loss of 80% to 60%. According to Garcia *et al.* (2006), the overall efficiency (electricity to hydrogen and back to electricity) known as *round-trip or turn-around efficiency* ranges from 30% and 50% depending on conditions. The energy conversion process in turn-around efficiency of hydrogen powered electric power plants is similar to pumped storage hydro-electric power plants.

[7] *No matter how much the temperature changes on land, the temperature even just a few metres below the ground remains constant. By drilling boreholes to a depth at which the rocks are approximately 12°C all year round, water for the heating system can be pumped down, be warmed by the surrounding rocks, and then used to heat the Hydrogen Office. The system is very efficient: by using a GSHP, every unit of electricity used by the system will generate 4 or 6 times that of heat.*

Although the overall **turnaround efficiency** for hydrogen powered electric power plants is low, the heat from the electrolysers and fuel cells can be used for process heating, thus increasing this efficiency. Moreover, Dr Daniel Aklil (Managing Director of the Pure Energy Centre) reinforced the point that capturing and storing excess renewable energy in a FC, that could have otherwise been wasted, is a logical thing. He further explained that a full cycle from energy generation to storage back to energy generation ranges from 30% to 40% efficiency with electrical power generation only and up to 60% with combined heat and power generation. The Hydrogen Office is incorporating a store for 30kg of hydrogen under pressure. The hydrogen is generated from the surplus electricity of an on-site wind turbine and is reconverted to electricity through a fuel cell (The Hydrogen Office, 2010).

Evaluation of FCES

Evaluation of FCES tends to primarily focus on the technical side at different stages of development from laboratory demonstration through to fully operational installations (Ulleberg *et al.*, 2007). Whilst the technical aspects of evaluation are crucial for assessing the performance of FCES, they do not provide information to policy makers on the efficacy of investments in such systems in terms of the value for money as well as its impact on the economy in terms of job creation and skills development, which is often a claim made by government organisations when it comes to the investment in such schemes. The evaluation of the Hydrogen Office demonstration project, in particular, becomes crucial in the absence of information about the costs and benefits of energy storage at a local level (Edberg and Nash, 2010).

It follows that what is proposed in this paper is an evaluation framework which provides a holistic and structured approach for evaluation as opposed to focusing solely on modelling of performance, e.g. using computer software or simulation to model performance as was the case with the HARI project. The FCES at the Hydrogen Office has been fully operational since the beginning of 2011, and as such the framework presented in this paper is timely. Moreover, the Director of the Pure Project, Dr Daniel Aklil, alluded to the potential need to develop guidelines to assess the performance of FCES at the Hydrogen Office. A framework for the evaluation of FCES is thus outlined with reference to the Hydrogen Office. It has to be noted that scope of this paper is limited to presenting a conceptual framework for evaluation and thus future research is required for its piloting and testing in the context of the UK.

A conceptual framework for evaluation

The proposed framework is based on the ROI (Return-On-Investment) methodology. The ROI methodology was originally developed in the US for the evaluation of the impact of investment in training in the workplace. However, it is now widely adopted as a framework for evaluating the impact of green or carbon reduction initiatives. The ROI methodology comprises of a hierarchy of five-levels for evaluation, as shown in Figure 3 below.

INSERT FIGURE 3 HERE

This conceptual framework should provide a holistic and structured approach for the evaluation of the efficacy of FCES in the built environment, and indeed could be transferrable to other sectors. The evaluation domains represent the perspective from which it can be carried-out. Each level is subsequently discussed but it has to be viewed independently whilst accounting for the diverse expectations of stakeholders involved in the project, namely: end-users, local community, companies, funders, and other government agencies (which are interested in endorsing the project but not necessarily funding it).

It has to be noted that the discussion below is not meant to be a comprehensive application of the ROI methodology, but it only provides examples of some of the issues (with reference to the Hydrogen Office where appropriate) that could be addressed at each level in order to highlight the value of adopting the proposed evaluation framework. Each level of evaluation warrants further investigation in its own right and could be used as a basis for informing future research.

Level 1: Reaction and perceived value

Gauging the reaction of stakeholders involved in the project is essential for ensuring that there is a continued support for the project. FCES could help in supporting the wider use of renewable energy sources which is advocated by both the government and environmental pressure groups. Indeed the share of renewable energy from wind, water and sun could increase further as these sources are not suited to cover the electrical base load due to their irregular availability. A FCES can also contribute to energy security concerns by ensuring the continuity of energy supplies particularly for remote locations. Fuel cells only produce water and heat as by-products, thus eliminating locally all emissions otherwise caused by electricity production. However, do all stakeholders perceive such benefits of the project or there is a lack of awareness on such issues?

Establishing the views of end-users is important to establish if they are in favour of the project or not, in addition to highlighting any potential concerns. For instance, in the Hydrogen Office the local community were concerned about the damage to the landscape of the countryside caused by erecting a wind-turbine. Failing to identify and address the concerns of the local community can potentially affect the progress of the project and create bad publicity.

From the perspective of an organisation (directly involved in the development of the FCES) the initial perceived value of investing in the project is deemed as favourable. Intuitively companies' involvement in the project through investing both time and resources is an indication of commitment to innovation and preparedness to take risk with the trial of new technologies. As for the government agencies and funders, the perceived value of the adoption of FCES is high because it involves committing tax-payers' money for that investment. The government often claims that green energy initiatives could create new jobs locally.

For example, the government claims that the Hydrogen Office project currently employs 10 people and that number will reach 1,350 in 25-years (The Hydrogen Office, 2010). It is not clear as to what are the underlying assumptions for that high projection particularly given the uncertainty associated with future forecasts.

More fundamentally, it is not clear as to what jobs (more precisely in what occupations) and training will be needed as a result of implementing a FCES and to what extent they fit with the current Standard Occupation Codes (SOCs), and current economic activities as represented by the Standard Industrial Classification (SICs). Providing an answer to these questions requires the identification of skills needs as a result of the application of FCES at the Hydrogen Office, in order to inform future training provision for the local community and engagement with learning providers (e.g. universities, colleges and private establishments).

Level 2: Learning and awareness

The implementation of FCES is undoubtedly a new experience for many stakeholders involved in the project at the Hydrogen Office. As such, there is an element of learning that has taken place over the course of the project through the acquisition of knowledge, skills, and/or information to prepare individuals to move the project forward, which would not have been possible if the project was not implemented. The Hydrogen Office project was delayed by approximately 12 months due to problems associated with implementing a complex funding model for the project, and in procuring a single wind turbine in the required size range (The Hydrogen Office, 2010). A capturing of the knowledge created (or lessons learnt) since the inception of the project going through its completion and operations will provide valuable information for future application in the form of case studies (Philips and Philips, 2010).

Level 3: Application and implementation

Possible questions to be addressed at this level of evaluation can include: 1) Does the FCES work effectively; 2) Does it meet the end-user requirement; and 3) What are the challenges for implementation?

In addressing question 1, it is important to monitor closely the performance of the FCES by collecting relevant data, such as energy consumptions for heating and hot water kWh/m^2.a; energy prices used for each energy source in £/kWh; and amount of hot water consumed (liters/year/m^2). Information on maintenance costs, breakdown periods (if any) and a record of problems encountered during operation, would also help in assessing the effectiveness of the FCES. For question 2, a thorough Post Occupancy Evaluation (POE) is essential to assess the extent that the building match users' needs, and identify ways to improve building design, performance and fitness for purpose (Post Occupancy Evaluation, 2010).

Finally for question 3, one of the main challenges would be to deal effectively with the inherit uncertainty in the operation of the system and address any issues as they crop-up. Not only will this require close monitoring of the FCES as addressed in question 1, but also testing new ideas in order to enhance the performance of the existing system. One idea that might be considered in the context of the Hydrogen Office is to test the viability of smart grid systems. Currently a smart grid system is a simple device installed for a given customer. The smart grid system monitors the cost of power, when power is least expensive it turns on selected home appliances such as washing machines or factory processes that can run at arbitrary hours. On the other hand, at peak times the smart system could turn off selected appliances to reduce demand. Smart grid systems could be taken to a new level. Instead of using smart grid system only for small appliances in houses, they could be used to allow for energy storage during the grid off-peak times when power is cheap to be used during peaks when power is expensive thereby minimising the dependence on peak demand power station. A smart device may allow the electrolyser to generate hydrogen (as an energy storage mechanism), when excess renewable energy is available (or during the grid off-peak times when the power is cheap). FCs could then be used to convert the stored H_2 to generate electricity and supply the home with electrical power when its demand exceeds the renewable supply (or during peaks when power is expensive).

Levels 4 and 5: Impact and ROI

Impact and Return-On-Investment (ROI) are paramount for the project funders. In monetary terms, there is a need to ensure that there is a good ROI, in addition to establishing the extent the project has actually resulted in reducing carbon emissions. An assessment of the impact and ROI of FCES requires a thorough cost/benefit analysis in addition to a whole-life cost analysis that would take into consideration the high capital cost of fuel cells, given that it is one of the main obstacles for the wider implementation of the technology (Graham *et al.*, 2002), in addition to any other associated maintenance and training costs.

The complexity of the funding models adopted at the Hydrogen office, as mentioned above, has resulted in a delay in the project that was further compounded by the main contractor of the project going bankrupt (The Hydrogen Office, 2010). An estimation of the ROI of a FCES could help in addressing the question as to whether it is worthwhile investing in similar schemes in the future. Indeed the ROI becomes particularly crucial when considering that *"the main challenges to date have been associated with finding a means of funding such an energy system in a market that does not place any value in storing intermittent renewable energy"* (former development officer at the Hydrogen Office).

Future research

It is intuitively appealing that the application of FCESs can bring about numerous benefits, such as: reducing the carbon footprint of buildings; cancelling intermittency issues related to renewable energy; reducing transmission and distribution charges especially to remote locations; potentially eradicating fuel poverty; reduce reliance on the national grid and thus achieving energy independency; and potential income generation for households and housing associations by selling electricity back to the grid through schemes such as the Feed-in-Tariff scheme. However, there is no empirical evidence to support the aforementioned benefits of FCES.

The construction industry today is in an urgent need for reliable information[8] on the actual energy and carbon performance of recently constructed or refurbished buildings (The Royal Academy of Engineering, 2010). Most notably, it is not clear as to what is the ROI of these technologies, performance-related shortcomings, and impact on building occupants. These issues present a real obstacle for informing the decision of future investments by policy makers, households and organisations. Therefore, universities must develop new fields of multi-discipline research in building design, engineering, energy and carbon efficiency, directed towards providing the industry with feedback on the success or otherwise of current initiatives. This will create numerous opportunities for industrial and international partnerships, supported by a wide range of new funding and revenue streams, not traditionally available to academic researchers (The Royal Academy of Engineering, 2010).

It follows that the conceptual framework outlined in this paper could help in bringing together multi-disciplinary academic teams to collaborate for assessing the efficacy of FCES (as well as other green technologies) using a holistic and structured approach. After all, the purpose of

[8] *This information is essential for the establishment of benchmarks and standards, for the validation of new designs and techniques, for the development of robust national policy and for the development of up to date and authoritative teaching materials.*

evaluating projects is to improve the quality of projects and outcomes, determine whether a project has achieved its objectives, identify strengths and weaknesses in implementation, enable cost-benefit analysis, and inform the development of future projects (Phillips and Phillips, 2010).

Conclusion

The application of FCES in the built environment, despite being in its infancy, presents a plausible way for addressing the variable nature of renewable electricity thereby making buildings more resilient to fluctuations in energy supply (The Royal Academy of Engineering, 2010). Localised energy storage at demonstration projects such as the Hydrogen Office presents a unique opportunity for assessing the efficacy of energy storage and its operation in practice. Whilst the use of green hydrogen in FCES applications in the built environment presents a potential of an all-green or carbon free energy, there is a need for an in-depth understanding of the benefits (e.g. ROI) and challenges associated with the adoption of FCESs in practice using a holistic and structured framework that would draw on multi-disciplinary academic expertise.

Acknowledgement

The authors are grateful for the help and support of the following people: Dr Daniel Aklil, Managing Director Pure Energy Centre, Mr Ross Gazey, Design Engineer, PURE project, and the former Hydrogen Development Officer. The views expressed in this paper are solely of the authors and any error remains their responsibility.

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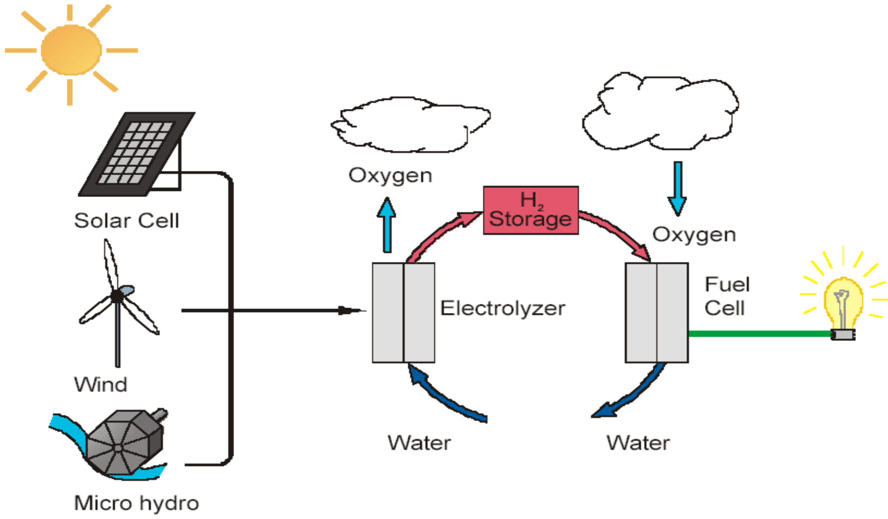

Figure 1: Green hydrogen in a FCES

Source: (Cook, 2001)

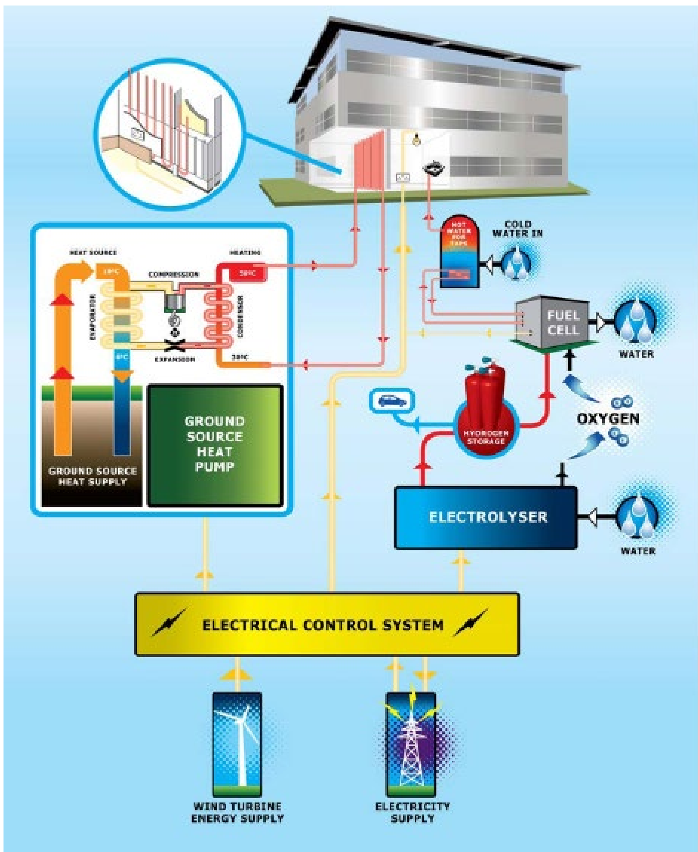

Figure 2: The Hydrogen Office FCES

Source: (The Hydrogen Office, 2010)

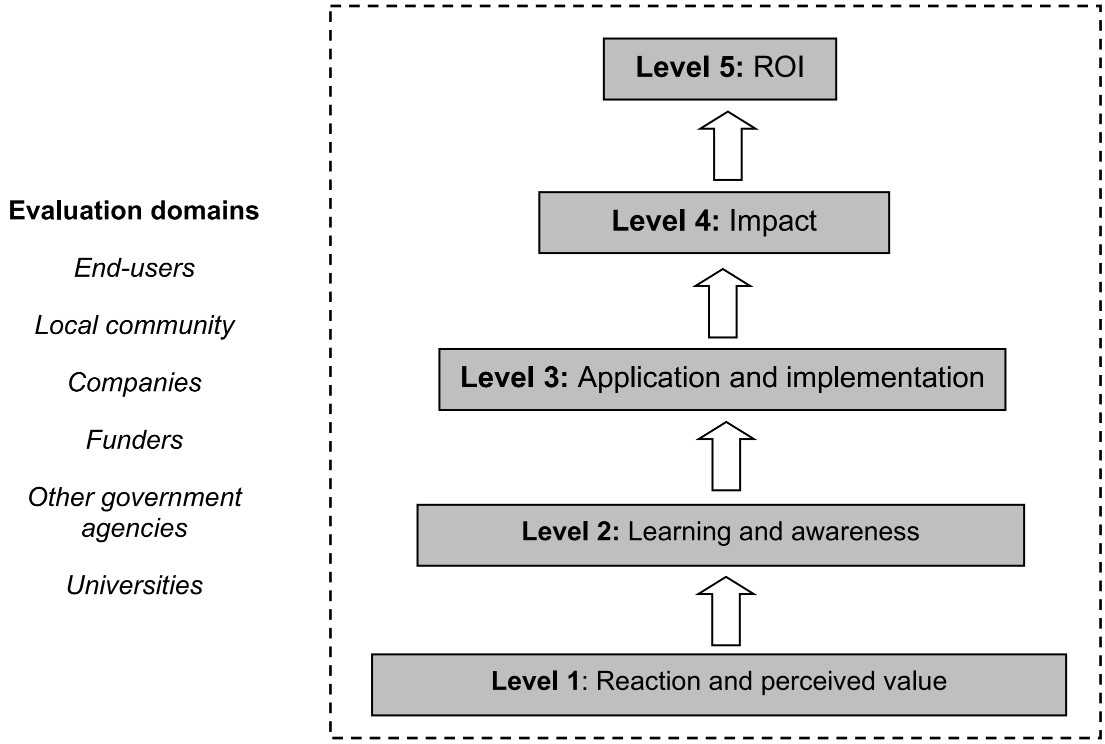

Figure 3: A conceptual framework for the evaluation of FCES

Based on (Phillips and Phillips, 2010)