Iranica Journal of Energy & Environment 2 (3): 262-273, 2011
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology
doi: 10.5829/idosi.ijee.2011.02.03.0001

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Clean Energy for Tomorrow: Towards Zero Emission and Carbon Free Future: A Review

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(Received: May 7, 2011; Accepted: August 21, 2011)

Abstract: Fuel cell technology using hydrogen energy is an advanced green energy technology for the future use. This is green, sustainable, clean and very environmental friendly. Green house gases emission from industrial activities has been proven beyond doubt as the main cause of global warming and climate changes. The finite world energy supply that consists nearly 90% of fossil fuel which is depleted; an energy crisis because of widening fossil fuel production and demand gaps. Many nations responded to anticipate energy crisis by diversifying their fuel resources to include renewable and alternative energy and developing green energy technology for the future. Despite political announcements on renewable energy, fossil fuels will continue to dominate energy resources for some time to come and carbon emission will increase but global nuclear energy expansion is uncertain because of international tensions and general public fears of another Chernobyl or Fogoshima disasters or a nuclear terrorist attack. Biofuels are plagued by the conflict between crops for fuel and crops for food and there is a shift of interest towards crop biomass wastes. The further expansion of hydrogen energy is constrained by costs and safety in hydrogen transport and storage. Fuel cell research and development has shifted from older AFC, PAFC and MCFC whose entry into the market were stalled by intractable operational and durability problems, to more promising PEMFC, DMFC and SOFC. A new type of fuel cell, the microbial fuel cell (MFC) is also gaining some attention because of sustainable way of simultaneously reducing BOD and COD of wastewater and provide power; combined wastewater treatment and power (CWTP). The main thrust in PEMFC research and development is cost reduction of membrane and electrocatalyst by substitution of cheap and more efficient organic-inorganic nanocomposite membranes and nanoinorganic electrocatalyst as well as lower electrocatalyst loading and cost reduction of bipolar plate by material reformulation with nanomaterials for injection or compression molding. In addition, cost reduction can also be achieved by reduction of system complexity using non-hydrated or self-hydrated membranes that eliminate water management sub-system and CO tolerant anodes that eliminate CO removal of reformate hydrogen feed. PEMFC system efficiency can be further enhanced by better design of flow field in bipolar plates and fuel and air manifold in the stack as well as through process optimization using process system engineering tools. The main thrust of SOFC research and development is reduction of its operational temperature by replacement with low temperature electrolytes, anodes and cathodes. Future DMFC development focuses on methanol crossover reduction, desired water management and low manufacturing costs. Also for future development on MBC focuses on understanding the electron transfer mechanism and redox reactions in cells and developing more efficient nanostructured electrodes and cell immobilization. The main objective in hydrogen production from liquid fuels are in the development of low temperature auto-thermal steam reforming catalysts, purification of reformate hydrogen through pressure swing adsorption and membrane processes as well as membrane reactors and higher hydrogen storage capacity in carbon nano-tubes and other nanostructures. The main focus on sustainable hydrogen production is photolysis of water into hydrogen and oxygen in solar photovoltaic-electrolyzer system, direct solar photoelectrochemical reactors and solar photo-biological fermentors.

Key words: Hydrogen economy % Green energy % Fuel cell % Nanomaterials % Nanostructures % Solar hydrogen

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INTRODUCTION

In 2008, worldwide energy consumption was reported as 474 exajoules (474×10^{18} J); about 80 to 90 % of it derived from fossil fuels [1]. The finite world energy supply that consists of up to 90% fossil fuel will peak by 2020-2030 and depleted in 30-40 years time. The peak oil will precipitate an energy crisis because of widening fossil fuel production and demand gap [2]. Green house gases (GHG) emission from human activities has been proven beyond doubt; that is the main cause of global warming and climate change [3]. Kyoto Protocol has forced governments to consider cutting CO_2 emission but post-Kyoto protocol negotiations such as COP15 in Copenhagen, Denmark in 2008 and COP16 in Camcun, Mexico in 2010 were bogged down by widely different expectations of the wealthier and poorer countries.

Fossil fuels will continue to be used for some time to come before being phased out in favour of renewable and alternative fuel resources. Carbon capture and sequestration is now urgently needed to stem the rise of GHG emissions [4]. Global nuclear energy expansion is uncertain because of international tensions such as Iraq war and Iran impasse. The negative general public opinion after major disasters such as Chernobyl and Fukushima Daichi disasters may hinder nuclear energy expansion [4]. Large scale biofuel deployment is uncertain because of the conflict between crops for fuel and food [4]. Further expansion of H_2 energy that has the great promise of zero emission is constrained by costs, durability and safety of H_2 transport and storage [4]. Solar energy is still constrained by costs [4] while wind and wave energy are hindered by low energy extraction efficiency, seasonal variability and weather unpredictability [5] .

Many countries however responded to the threat of energy security and global warming by diversifying their fuel resources to include renewable and alternative energy and developing clean energy technology to replace conventional energy technologies. Malaysia has responded to the threat of energy security with 5 fuel policy for electricity generation in 2001; that introduced renewable energy as the 5th fuel [6]. Malaysia has developed a solar energy, H_2 energy and fuel cell roadmap in 2005 [7] and a renewable energy roadmap in 2010 [8] where the research, development and deployment of renewable energy, solar energy, H_2 energy and fuel cells in Malaysia are planned over the next 50-60 years. Malaysia has also developed the National Green Technology Policy in 2009 that also emphasizes further the need for adoption of green energy technologies [9]. The application of distributed renewable energy in rural areas is stipulated in a National Key Result Area for improving rural infrastructure by using green technology [10]. In 2010, the Ministry of Energy, Green Technology and Water identified a Ministry Key Results Area (MKRA) for increasing the utilization of renewable energy by using green technology [10]. Fuel cell technology using H_2 energy is an advanced green energy technology that is green, sustainable, clean, very environmental friendly and emits only water [11]. Up to 40% of fossil fuels are consumed by vehicles in transportation sector [1]. Large scale deployment of H_2 fuel cell vehicle (FCV) and portable/mobile fuel cell power generation distributed power using renewable H_2 and methanol from biomass will reduce dependence on fossil fuels in transportation and the portable power industries in the future [1].

The priority of R and D in H_2 energy has to develop renewable H_2 production technology from renewable energy such as electrolytic water splitting by solar and wind energy, chemical catalysis and biocatalysis of biomass and solar photo-electrochemical (PEC) splitting of water [7]. Solar PEC splitting of water from solar energy by using a combination of photovoltaic electrode and electrolysis in one cell is touted potentially as the ultimate renewable H_2 production technology of the future [11]. Major barrier in commercializing PEC technology is the low efficiency of 8% and electrode stability [12].

The secound priority of R and D in portable fuel cells is to develop cheaper and more durable fuel cell technology that can match conventional energy conversion technology costs and durability in niche energy applications such as portable, mobile distributed power and combined waste treatment and power (CWTP) [13]. The focus of fuel cell R and D is on emerging fuel cell technologies such as PEM fuel cell (PEMFC), direct methanol fuel cell (DMFC), solid oxide fuel cell (SOFC) and microbial fuel cell (MFC) that use a variety of renewable fuels: H_2, methanol and wastewater. A cost reduction of 35% in PEMFC for transportation achieved in the past two years is still less than the 50% cost reduction required to reduce the cost to the target of \$30/kW (2015) that will be competitive with conventional technology [13]. In addition, the fuel cell stack lifetime of 2500 h achieved in 2009 has to be doubled to meet the target of 5000 h [13]. Both the cost and durability targets can be achieved by a greater fundamental understanding of the inter-related and complex processes occurring in the fuel cell stack and balance of plant as well as in the fuel cell vehicle and the portable power system during fuel cell operation [14]. Social networking lifestyle that is becoming more dependent on internet and mobile phone networks requires more powerful portable/mobile power pack to lengthen the operating time for laptop computers and mobile phones [14]. DMFC is now the preferred choice for portable/mobile power pack because of its higher power density and hence longer online time compared to lithium ion battery technology [14]. The use of new materials such as new nanostructures, nanomaterials and nanosystems have great potentials in improving H_2 production and fuel cell technologies [12-14]. Portable fuel cell systems like FCV and DMFC power generators and process systems like sustainable H_2 production (SHP) can be optimized by a new holistic technique for resource minimization that includes elimination and outsourcing in addition to reduction, reuse/recycling and regeneration [15]. Application of DMFC can be used for portable power generation by using a new inverter technology for DMFC stack [16].

A stable front-end DC-DC converter with high voltage gain for the varying low-voltage high-current portable fuel cell power requires a large inductor between the DC source and inverter for the varying switching frequency and a large output capacitor to lower total harmonic distortion (THD) [17,18]. To increase portability of the fuel cell system, a current-source sine-waves voltage inverter via the voltage-clamping and soft-switching techniques is proposed to replace both the large inductor and capacitor. Economic and social impacts of new clean energy technologies may be unpredictable and must be understood to help countrries cope with them [19, 20].

Hydrogen Energy: Hydrogen can be produced from fossil fuels by reforming and be used alongside fossil fuels in hybrid fuel systems in the transportation, electricity generation, residential, commercial and industrial sectors. Subsequently as solar hydrogen and other renewable hydrogen technologies become more mature and viable, hydrogen will be used in fuel cells in all sectors of the energy market. Ultimately both solar and hydrogen energy will merge to produce renewable hydrogen. This is considered the likeliest path towards a full commercial application of hydrogen energy technologies where solar energy and fuel cell technologies play crucial roles [6, 7].

Research activities on hydrogen production and storage technologies were focused on auto-thermal steam reforming catalysts for both gas and liquid fossil fuels, gasification/pyrolysis thermochemical cycle, solar photovoltaic- electrolyzer splitting of water, photo-electrochemical and photo-biological splitting of water and carbon nanotube hydrogen storage. The first three are improvements of current technologies but the latter three are new technologies for hydrogen production and storage. Solar photo-electrochemical splitting of water, a one-step process of splitting water directly from solar energy by using a combination of photovoltaic electrode and electrolysis in one cell, is touted potentially as the ultimate renewable hydrogen production technology of the future. Major barrier in commercializing this technology is the low efficiency of 8%, larger energy band gap for redox electrochemical reaction and electrode corrosion.

Fuel Processed Hydrogen: Hydrogen needed for fuel cells operation should ideally be produced by using renewable energy resources but in order to introduce fuel cells technology early, hydrogen is produced from fossil fuels using catalysts. The fuel processing group at the Fuel Cell Institute UKM has developed catalysts for autothermal reforming of methanol for hydrogen production based on CuZn [7] which has also been characterized [21-23]. The group studied the effect of metal loading in the alumina supported catalyst on CO reduction [24] and multi metal composition of ZSM supported catalyst for hydrogen production [25].

Hydrogen produced by autothermal reforming of methanol contains CO which can poison the catalyst in the MEA and reduces PEMFC performance. The group has developed a pressure swing adsorption system using activated carbon impregnated with SnCl that can remove CO very well to less than 10 ppm [26-30]. The group has also invented a four stage compact PSA that can reduce CO level even further [31] using adsorption[32]. A membrane reactor consisting of a Pd membrane on a ceramic tube surrounded by the catalysts in the shell is also developed to produce and separate the hydrogen in one unit [33, 34]. Hydrogen storage, a critical issue in commercial application of fuel cells was critically reviewed by the fuel processing group at UKM [35].

Solar Hydrogen: Hydrogen was successfully produced by electrolysis of water using power from a hybrid solar photovoltaic and wind energy system [36]. Hydrogen can also be produced by direct photolysis of water by solar energy in photoelectrochemical cells. The solar hydrogen group at the Fuel Cell Institute UKM has successfully synthesized and characterized three forms of the tetraalkylammonium tetrathiotungstate, a precursor to a tungsten tris(1-acarboxyl-2-phenyl-1,2-ethylenodithiolenic-S,S') [37], a dye photocatalyst complex which was subsequently successfully synthesized and characterized[38] using a two inorganic reaction steps. The group has also successfully synthesized and studied stability of the photocatalyst tungsten tris(1,2-bis(3,5- dimetoksifenil)-1,2-etilenodithiolenik-s,s')(MTDT) through a 4 organic steps. The photoelectron produced from the photoelectrode sensitized by MTDT in a homogenous photoelectrochemical test was found to be larger than those without[39].

Photoelectrochemical cells produces oxygen when the anode is illuminated and hydrogen at the cathode. The main problem in photoelectrochemical cell is availability of a stable anode, maximum light exposure to the anode, collection of hydrogen gas [40] and unimpeded ionic movement [12, 41]. The solar hydrogen group at UKM compared the performance of photoelectrochemical cells using TiO_2, WO_3, Fe_2O_3 and combined TiO_2-WO_3-Fe_2O_3 electrodes for water splitting and found the photoelectrode WO_3 gave the highest current density [12, 40, 42].

Biohydrogen: Renewable hydrogen could also be produced from photoautotrophic microorganism such as cyanobacteria dan microalgae in anaerobic condition using CO_2 with hydrogenase which is cheaper and by photoheterotrophic microorganism such as nitrogen fixing bacteria using more costly organic carbon with nitrogenase. The main weakness of biohydrogen is low efficiency (1 - 10%) and enzyme inhibition. The biohydrogen group at Fuel Cell Institute UKM has recently produced hydrogen from clostridium saccharoperbutylacetonicum by glucose fermentation at the rate of 3.1 mole hydrogen per mole glucose at pH 4.0, 37°C and initial glucose concentration of 10 g LG^1 [43]. A second biohydrogen group in UKM has produced hydrogen from clostridium acetobutylicum by glucose fermentation at the rate of 391 mL hydrogen per g glucose at pH 7.0, 30°C dan initial glucose concentration of 25 g LG^1 [44, 45].

Fuel Cells: Fuel cells play an important role in the renewable hydrogen economy because it is the most efficient, sustainable, clean and extremely environmental friendly energy converter of hydrogen. A fuel cell is an electrochemical energy conversion device that converts chemical energy of hydrogen and oxygen into electricity and heat by means of electrochemical redox reactions at the anode and the cathode of the cell respectively with only water as its byproduct.

The six common types of fuel cell technology are Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC) and Direct Methanol Fuel Cell (DMFC). The seventh less common type of fuel cells is the Microbial Fuel Cell (MFC). Although RandD activities on the first three fuel cell types have been well established but their niche commercial applications are still facing teething problems. On the other hand, intense RandD activities on the last four fuel cell types are now being carried our all over the world [11, 46].

The major areas of fuel science and technology research and development are in process system engineering of fuel cells on more efficient fuel cell systems, low Pt/non-Pt/nanostructured electrodes and nanocomposite proton exchange membranes, nanocomposite bipolar plates, µdirect methanol fuel cells, low temperature SOFC and microbial fuel cells for power from wastewater [46].

Process System Engineering of Fuel Cells: The main problem of process system engineering of PEMFC is the lack of good engineering understanding of major components of a PEMFC system such as the PEMFC stack, gas humidifier, pressure swing adsorbers, fuel processing reactor and membrane gas separation module; and water management. The fuel cell process system engineering group at Fuel Cells Institute UKM has successfully developed models for pressure swing adsorbers [31, 32, 47], gas separation membrane modules [48-52] and studied the interaction between the two technologies [51, 53]. The group has also modeled a 5 kW PEMFC system with an on board fuel processing system [48, 50, 54, 55] and with various methods of hydrogen purification [56, 57]. The failure of water management in the PEMFC stack can lead to PEMFC failure because of flooding and short circuiting. The group has successfully modeled a humidifier system for fuel cells [29] and has proposed a new model of water flow in the PEMFC and a better way of managing water in the fuel cell [58]. The group is also developing a better model for design of the PEMFC [59], a better gas flow field design as well as the effect of mechanical stress on the electrical contact resistance in PEMFC stacks [60] .

The group has also designed and built the PEMFC prototypes: hydrogen fueled air cooled, open cathode, 50 - 500 W PEMFC system (Malaysian Patent Pending) and a water cooled, 1 - 5 kW PEMFC system have been developed (Malaysian Patent Pending). Two fuel cell powered motorcycles prototypes called SERINDIT I (50 W) and SERINDIT II 200 W have been designed, fabricated and tested (Malaysian Patent and Trade Mark Pending). A 500W - 1 kW portable fuel cell power module called LESTARI 1000 (Malaysian Patent Pending) has been designed, fabricated and tested. A 5 kW portable fuel cell power module called LESTARI 5000 (Malaysian Patent Pending) has also been designed, fabricated and tested.

Proton Exchange Membranes and Membrane Electrode Assemblies: Currently available proton exchange membrane fuel cells (PEMFC) that uses Nafion from Dupont as its proton exchange membrane cannot operate more efficiently at a temperature higher than 90°C because its proton exchange membrane suffers from thermal instability above that temperature [61, 62]. The fuel cell electrochemical processes research group at the Fuel Cell Institute has successfully developed a new high temperature composite Nafion-silicon oxide (SiO_2)-phosphotungstic acid (PWA) composite membrane with lower resistance, higher proton conductivity, higher current density and better thermal stability at 90°C than the Nafion membrane from Dupont [63, 64] and the Aciplex membrane from ASAHI [65]. The research group has also begun research in inorganic membrane that can operate at high temperature without humidification based cesium diphosphate (CDP) [66].

Membrane electrode assemblies loaded with costly Pt, key components of the PEMFC, contribute to the high cost of PEMFC which prevent the latter's early commercialization. The group developed a local carbon source for the electrode [64, 67-69]. The research group has successfully developed high performance MEAs with low Pt loading and gas diffusion layers [70, 71]. The group has also developed a new dimensionless spray number for the manufacturing of improved MEAs using a spraying machine [72].

Bipolar Plate Material and Manufacturing: The cost of manufacturing bipolar plates can be reduced by substituting the graphite material with polymer composite. Suitable polymers for the polymer composite are thermoplastic polymers such as polyethylene, polypropylene dan polivenylfluoride and thermoset resins such as phenolics, epoxy dan venyl ester. The fuel cell material and manufacturing group at the Fuel Cell Institute UKM has successfully developed a polymer composite from polypropylene and graphite [73-75].

Micro Direct Methanol Fuel Cells: The main problem of micro direct methanol fuel cells is methanol crossover and electrode degradation that diminishes the power of DMFC after a short time of operation, high cost of catalysts and electrolyte membrane and heat and water management [50, 76, 77] . The micro direct methanol fuel cell group at the Fuel Cell Institute UKM developed a design advisor tool to help design, predict the performance and optimize the design of the direct methanol fuel cell [78]. The group began by developing a passive air breathing single cell direct methanol fuel cell to study the effect of methanol concentration on direct methanol fuel cell performance [79]. It went on to develop a passive, air-breathing polymethyl methacrylate (PMMA) based single-cell and a multicell stack micro-direct methanol fuel cell (DMFC) with 1.0 cm^2 active area with a novel cathode plate structure and assembly layer for better air access and water removal by gravity[80]. A ìDMFC with low catalyst loading was also developed by the group [81, 82]. The effect of methanol concentration and mass transport on the current density of unsteady state operation of a direct methanol fuel cell was also studied by the group [83, 84]. Hybrid membranes was also considered to replace Nafion[81]. The use of nanomaterials and nanostructures as nanocatalysts in DMFC was explored [85, 86]. The design of ìDMFC was also optimized [82]. In microfabrication of ìDMFC's flow field, a relatively inexpensive thermally grown SiO_2 layer was successfully used as the silicon etch mask in a KOH wet etching process[87].

Solid Oxide Fuel Cells: Solid oxide fuel cells research is primarily on low and intermediate temperature (500-600°C) solid oxide fuel cells[88]. The solid oxide fuel cell group the Fuel Cell Institute UKM is developing intermediate and low temperature based on ceria (CeO_{2-x}) doped with Gd, lanthanum gallate (Perovskite) doped with Sr and Mg (LSGM) and inter metallic bismuth oxide [89, 90] and cathodes from lanthanum cobaltite (pevroskite) embedded with Fe such as $La_{1-x}Sr_xCo_{1-y}Fe_yO_{3-\delta}$(LSCF, typically x ~ 0.2, y ~ 0.8)[91]

Bio Fuel Cell: Palm Oil Mill Effluent (POME) is a waste water reeking of very high COD 50 g LG^{1} and very high BOD 20 mg LG^{1}. Biofuel cell group at the Fuel Cell Institute UKM used the biohydrogen produced from anaerobic fermentation of POME using mixed culture from POME at pH 7 directly without combustion to produce electricity in a dual chambered microbial fuel cell that could reach a current density of 500 mA cm^{-2} and power density of 250 mW m^{-2} [92]. The group has also studied microbial fuel cell using pure culture Clostridium butyricum from POME at pH 4 producing a current density 150 mA cm^{-2} and power density 56 mW cm^{-2} [93]. The open circuit voltage obtained ranged from 0.3 - 0.5 volt [94-96]. The microorganisms used varies from mixed culture from POME, *Clostridium butyricum*[43, 97] , *Pseudomonas putida*, *Lactobacillus*, *Escherida coli*, *Aspegillus niger* and *Saccharomyces cerevisia* [94-96]. The microbial fuel cell has been proven to produce power from waste water and reduce the COD and BOD of the wastewater

A recent study on future hydrogen demand and supply network in Peninsula Malaysia concluded that liquefied hydrogen produced by natural gas steam reforming and delivered via tanker trucks is the optimum hydrogen supply chain method [97]. Eighteen new hydrogen plants of 50,000 tonne/year capacity are required for the optimum supply chain which is therefore more expensive than the future hydrogen infrastructure cost in the UK because the existing hydrogen infrastructure in the latter is more established.

Future Work on Fuel Cells and Hydrogen Energy: The most important barrier to PEMFC commercialization is cost reduction of PEMFC in FCV. This issue should be addressed by understanding material formulation and manufacturing of new cheaper non-Nafion polymer composite proton exchange membranes (PEM), electrocatalysis of H_2 oxidation and O_2 reduction in catalyst layers (CL) of cheaper non-Pt electrodes and advanced manufacturing of cheaper bipolar plates by pressure and injection moulding [13].

The second important barrier to PEMFC commercialization is durability of PEMFC for FCV. This issue should be addressed by understanding proton conductivity and water diffusion in PEM to prevent membrane drying, CL degradation due to Pt dissolution and agglomeration, liquid-water transport /evaporation in electrodes and gas flow channels (GFCs), designs of GFCs and cooling channels in bipolar plates to reduce hot spots and PEMFC stack design for uniform distribution of gases [13].

In the same way, cost reduction of DMFC in portable/mobile power generation is the ost important issue in commercialization of DMFC. This issue should be addressed by studying new material formulation and manufacturing of cheaper non-fluorinated hydrocarbon and composite PEM and electrocatalysis of methanol oxidation and oxygen reduction in CLs of cheaper non-Pt electrodes.

Another important issue in DMFC commercialization is durability of DMFC. This should be addressed by studying methanol crossover in PEM and its effects on electrode reaction kinetics, methanol crossover reduction by selective flux barrier, electrode degradation by Pt and Ru dissolution and agglomeration, water and heat management [14].

The main issue in hydrogen production from renewable resources is raising the efficiency. of biomass pyrolysis into H_2 and carbon is done by understanding wet biomass drying and carbon fouling and in biomass gasification by understanding tar reduction in syngas and subsequent WGS into H_2 by cheaper non-noble metal catalyst [98]. Raising bioH_2 production efficiency from dark fermentation to > 80% is addressed by coupling to an anoxygenic photosynthetic H_2 production from soluble dark fermentation products by purple non-sulfur bacteria[99]. Raising photoelectrode efficiency and stability in photoelectrochemical cell for H_2 production are addressed by synthesizing new organic dyes for dye sensitized photoelectrode on TiO_2 and maximizing light exposure of PEC [12] .

In order to sustain the fuel cell and hydrogen production technologies with new next generation devices and materials, it is essential to understand how nanostructures and nanomaterials improve performance of these new devices and materials. The approach to be adopted should be to create/invent new nanostructures and nanomaterials at atomic, molecular and crystal levels and to model and simulate them for the desired nanoeffects in the catalyst [68, 100].This is followed by synthesis and manufacturing of nanostructures and nanomaterials and finally the design, fabrication and testing of the catalysts containing the nanostructures and nanomaterials.

Another neglected area is system design of fuel cell systems like the FCV and portable/mobile power generator. An optimum fuel cell system design with minimum fuel, energy and water consumption and waste generation can be created by understanding a new holistic technique for resource minimization that includes reduction, reuse/recycling, regeneration, elimination and outsourcing [15].

An important area that has been neglecting is conditioning and conversion of fuel cell power. In the past, converting the varying low voltage high current source of the fuel cell was solved by having large inductor and capacitor which increase the volume of the fuel cell system. In order to decrease the size of the fuel cell system, a new power inverter for portable fuel cell power generator is to be created by understanding the soft -switched current-source inverter that replaces the large inductor and capacitor with a current-source sine-waves voltage inverter [17, 18] .

A major problem in deploying renewable energy technologies is their social and economic effects. It is recommended that the economic and social impacts of green energy technology is assessed by using an economic and environmental-based computable general equilibrium (CGE) model for a country to simulate policy change in the mix of conventional energy use to more environmentally friendly energy sources such as solar and hydrogen energy in selected polluting sectors similar to those done to China [19] and South Korea [101]. The impact of policy implementation on society, environmental quality and economic competitiveness is then appraised. The impact of clean energy adoption and adaptation among households (urban and rural areas) including strategies to facilitate such adoption is assessed through a survey instrument and focus-group sessions.

CONCLUSION

RandD in hydrogen energy is focused on catalyst development for autothermal reforming of liquid fuels into hydrogen, solar hydrogen by solar energy assisted water splitting using photoelectrochemical cells and biohydrogen by anaerobic fermentation of wastewater. On the other hand research and development in fuel cells are centered around design and prototyping of PEM fuel cells, membrane electrode assemblies, bipolar plate materials, micro direct methanol fuel cells, intermediate and low temperature solid oxide fuel cell materials and microbial fuel cells producing power from waste water. Hydrogen is currently produced by steam reforming and electrolysis and is used mainly in the petrochemical and oleochemical sectors as well as in metal cutting. Renewable hydrogen will be produced by electrolysis using excess capacity of hydropower or off-peak electricity and ultimately directly from solar energy by photoelectrochemical means..

ACKNOWLEDGMENT

The author would like to thank the Ministry of Science, Technology and Innovation Malaysia for funding the Fuel Cell and Hydrogen Research Program from 1996-2010 and its continued support that contributed greatly to most of the cited work in this paper.

REFERENCES

1. Anon. Yearbook Statistical Energy Review: Enerdata. URL: http://yearbook.enerdata.net/#accessed on 7th October 2010.
2. Wild, M., 2010. World energy briefing hears of peak oil by 2020. Energy Bulletin URL: http://www.energybulletin.net/52204. accessed on 7th October 2010.
3. Pachauri, R.K. and A. Reisinger, (Ed.): Climate Change: 2007 Synthesis Report: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.
4. Anon. Shell Energy Scenarios to 2050, The Hague, The Netherlands: Shell International BV (2008)
5. Da Rocha, A.B., C.C. Rey, M. La Boulluec, J. Dalen, H. Jeffrey, F.G. Nielsen, G. O'Sullivan, N. Rousseau, E. Sweeney and J. Wolf , 2010. Marine Renewable Energy, European Marine Board Vision Document. 2: 28 .
6. Sopian, K., M. Othman, B. Yatim and W. Dauds, 2005. Future directions in Malaysian environment friendly renewable energy technologies research and development. Science and Technology Vision, 1: 30-36.
7. Sopian, K. and W. Dauds, 2008. Development of the hydrogen energy roadmap and current status for Malaysia. ISESCO Science and Technology Vision, 4(95): 12-15.
8. Malek, B.A., 2010. Renewable Energy (RE) Policy and Action Plan, Sustainable Energy Division, Ministry of Energy, Green Technology and Water, 14th May.
9. Jørgensen, M.S. and U. Jørgensens, 2009. Green technology foresight of high technology: a social shaping of technology approach to the analysis of hopes and hypes. Technology Analysis and Strategic Manage.,m 21(3): 363-379. http://dx. doi. org/10. 1080/09537320902750764.
10. Anon. Program Transformasi Kerajaan; Pelan Hala Tuju, Kuala Lumpur: Unit Pengurusan Prestasi dan Pelaksanaan (PEMANDU), Jabatan Perdana Menteri (2010), Bab., 10 p. 210, Bab 12 p. 244.
11. Sopian, K. and W.R. Wan Dauds, 2006. Challenges and future developments in proton exchange membrane fuel cells. Renewable Energy, 31(5): 719-727. http://dx. doi. org/10. 1016/j. renene. 2005. 09. 003.

12. Minggu, L.J., W.R. Wan Daud and M.B. Kassims, An overview of photocells and photoreactors for photoelectrochemical water splitting. International J. Hydrogen Energy, 35(11): 5233-5244. http://dx. doi. org/10. 1016/j.ijhydene.2010.02.133
13. Wang, Y., K.S. Chen, J. Mishler, S.C. Cho and X.C. Adrohers,A review of polymer electrolyte membrane fuel cells: Technology, applications and needs on fundamental research. Applied Energy.
14. Kamarudin, S., F. Achmad and W.R.W. Dauds, 2009. Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices. International J. Hydrogen Energy, 34(16): 6902-6916. http://dx.doi.org/10.1016/j.ijhydene.2009.06.013
15. Bahiyah Handani, Z., S .R. Wan Alwi, H. Hashim, Z. Abdul Manan and S.H.Y. Sayid Abdullahs, Optimal design of water networks involving multiple contaminants for global water operations. Asia Pacific J. Chemical Engineering.
16. Selvaraj, J. and N. Rahims, 2009. A novel pulse width modulation for grid-connected multilevel inverter. Journal of Renewable and Sustainable Energy, 1: 053102. http://dx.doi.org/10.1063/1.3204460
17. Zhao, Q. and F.C. Lees, 2003. High-efficiency, high step-up DC-DC converters. Power Electronics, IEEE Transactions,. 18(1): 65-73.
18. Itoh, R., K. Ishizaka, H. Oishi and H. Okadas, 2001. Soft-switched current-source inverter for single-phase utility interfaces. Electronics Lett., 37(20): 1208-1209. http://dx. doi. org/10. 1049/el:20010845
19. Del Rio, P. and M . Burguillos, 2008. Assessing the impact of renewable energy deployment on local sustainability: Towards a theoretical framework. Renewable and Sustainable Energy Rev., 12(5): 1325-1344. http://dx. doi. org/10. 1016/j. rser. 2007.03.004
20. Lu, X., J. Pan and Y. Chens, 2006. Sustaining economic growth in China under energy and climate security constraints. China and World Economy, 14(6): 85-97. http://dx. doi. org/10. 1111/j. 1749-124X. 2006.00047.x
21. Lwin, Y. W.R.W. Daud, A.B. Mohamad and Z. Yaakobs, 2000. Hydrogen production from steam-methanol reforming: thermodynamic analysis. International J. Hydrogen Energy, 25(1): 47-53. http://dx.doi.org/10.1016/S0360-3199(99)00013-0
22. Lwin, Y., M.A. Yarmo, Z. Yaakob, A.B. Mohamad and W. Ramli Wan Dauds, 2001. Synthesis and characterization of Cu-Al layered double hydroxides. Materials Research Bulletin, 36(1-2): 193-198. http://dx.doi.org/10.1016/S0025-5408(01)00491-3
23. Lwin, Y., A.B. Mohamad, Z. Yaakob and W.R.W. Dauds, 2000. XRD and TPR studies of Cu-Al hydrotalcite derived highly dispersed mixed metal oxides. Reaction Kinetics and Catalysis Lett., 70(2): 303-310. http://dx. doi. org/10. 1023/A: 1010345017627
24. Yaakob, Z., A. Jaharah, S. Kamaruddin, W. Daud and K. Lims, 2009. The Effect of Catalyst Metal Loading and Temperature on the Reduction of Carbon Monoxide Concentration in Hydrogen Production by Steam Reforming of Methanol (SRM). European J. Scientific Res., 26(2): 238-246.
25. Yaakob, Z., M.N.S. Kumar, M. Ibrahim, W. Daud and A. Kadhums,2009. Multi-composition Cu-Zn-Al catalyst supported on ZSM-5 for hydrogen production. European J.Scientific Res., 28(1): 141-154.
26. Mohamad, A., S. Iyuke, W . Daud, A. Kadhum, Z. Fisal, M. Al-Khatib and A. Shariffs,2000. Adsorption of carbon monoxide on activated carbon-tin ligand. J. Molecular Structure, 550: 511-519. http://dx.doi.org/10.1016/S0022-2860(00)00509-3
27. Iyuke, S., W. Daud, A. Mohamad, A. Kadhum, Z. Fisal and A. Shariffs, 2000. Application of Sn-activated carbon in pressure swing adsorption for purification of H2. Chemical Engineering Sci., 55(20): 4745-4755. http://dx.doi.org/10.1016/S0009-2509(99)00602-8.
28. Iyuke, S.E., A.B. Mohamad, W.R.W. Daud, A.A.H. Kadhum, Z. Fisal and A.M. Shariffs, 2000. Removal of CO from process gas with Sn-activated carbon in pressure swing adsorption. J. Chemical Technology and Biotechnol., 75(9): 803-811. http://dx.doi.org/10.1002/1097-4660 (200009) 75:9<803:: AID-JCTB283>3.0.CO;2-G
29. Iyuke, S., W. Daud, A. Mohamad, A. Kadhum, Z. Fisal and A. Shariffs, 2001. Application of Sn-activated carbon in pressure swing adsorption to purification of H-2 (vol 55, pg 4745, 2000). Chemical Engineering Sci., 56(23): 6801-6801.
30. Al-Khatib, M.S., 2002. The effect of impregnation of activated carbon with SnCl2. 2H2O on its porosity, surface composition and CO gas adsorption. Carbon, 40(11): 1929-1936. http://dx.doi.org/10.1016/S0008-6223(02)00026-X.

31. Majlan, E.H., W.R. Wan Daud, S.E. Iyuke, A.B. Mohamad, A.A.H. Kadhum, A.W. Mohammad and M. Takriffs, 2009. Hydrogen purification using compact pressure swing adsorption system for fuel cell. International J. Hydrogen Energy, 34(6): 2771-2777. http://dx. doi. org/10. 1016/j. ijhydene. 2008.12.093.
32. Iyuke, S.E. and F.R. Ahmaduns, 2002. Adsorption and solid catalysed reaction between activated carbon impregnated with SnO2 and CO at ordinary temperature. Applied Surface Sci.,187(1-2): 37-44. http://dx.doi.org/10.1016/S0169-4332(01)00742-5
33. Sari, R. , Z. Yaakob, M. Ismail and W. Dauds, Preparation of Palladium-Alumina Membrane Tube by Combine Sol-gel Process with Electroless Plating for Hydrogen Permeation. J. Applied Sci., 10: 1151-1156.
34. Zernina, I., D. Kazakov and V. Volkhins, The Investigation Of Aspects Of Transesterification Hydrodynamic During Biodiesel Production. Catalysis For Renewable Sources: Fuel, Energy, Chemicals: pp: 158.
35. Lim, K.L., H. Kazemian, Z. Yaakob and W.R.W. Dauds, Solid state Materials and Methods for Hydrogen Storage: A Critical Review. Chemical Engineering and Technol., 33(2): 213-226. http://dx. doi. org/10.1002/ceat.200900376
36. Sopian, K., M.Z. Ibrahim, W.R. Wan Daud, M.Y. Othman, B. Yatim and N. Amins, 2009. Performance of a PV-wind hybrid system for hydrogen production. Renewable Energy, 34(8): 1973-1978. http://dx. doi. org/10. 1016/j. renene. 2008.12.010.
37. Rahman, F.H., W.R.W. Daud, R. Daik and M. Kassims, 2008. Synthesis and Characterization of Tetraalkylammonium Tetrathiotungstate Complexes: X-ray Crystal Structure of Tetrapropylammonium Tetrathiotungstate,[{C3H7) 4N} 2WS4]= Sintesis dan Pencirian Kompleks Tetraalkilamonium Tetratiotungstat. Sains Malaysiana, 37(2): 195-199.
38. Rahman, F.H., W.R.W. Daud, R. Daik and M. Kassims, 2008. Synthesis and Characterization of Tris (1-carboxy1-2-pheny1-1, 2-ethyleno dithiolenic-S, S') Tungsten Complex as Photocatalyst for Photolysis of H2O Molecules= Sintesis dan Pencirian Kompleks Tris [1-karboksil-2-fenil-1, 2-etilenoditiolenik-S, S']. Sains Malaysiana, 37(2): 201-203.
39. Kassim, N.M., S. McDonald, O. Reid, N. Bennett, D. Gilmore and A. Paynes, 1997. The effects of pre- and postnatal exposure to the nonsteroidal antiandrogen flutamide on testis descent and morphology in the Albino Swiss rat. J. Anatomy, 190(04): 577-588. http://dx.doi.org/10.1046/j.1469-7580.1997.19040577.x.
40. Memar, A., W.R.W. Daud, E. Eftekhari, L.J. Minggu and S. Hosseinis, Study on photocurrent of bilayers photoanodes using different combination of WO {sub 3} and Fe {sub 2} O {sub 3}. Solar Energy, 84(8).
41. Chae, S.Y., J.B. Yadav, K.J. Kim and O.S. Joos, Durability study of electrospray deposited Pt film electrode for hydrogen production in PV assisted water electrolysis system. International J. Hydrogen Energy.
42. Memar, A., W.R.W. Daud, S. Hosseini, E. Eftekhari and L.J. Minggus, Study on photocurrent of bilayers photoanodes using different combination of WO3 and Fe2O3. Solar Energy, 84(8): 1538-1544. http://dx. doi. org/10.1016/j.solener.2010.05.016.
43. Alalayah, W., M. Kalil, A. Kadhum, J. Jahim, A. Zaharim, N. Alauj and A. El-Shafies, Applications of the Box-Wilson Design Model for Bio-hydrogen Production using Clostridium saccharoperbutylacetonicum N1-4 (ATCC 13564). Pakistan J. Biological Sci., 13(14): 674-682.
44. Alshiyab, H., M.S. Kalil, A.A. Hamid and W.M.W. Yusoffs, 2008. Trace Metal Effect on Hydrogen Production Using C. acetobutylicum. OnLine J. Biological Sci., 8(1): 10-14.
45. Alshiyab, H.S., M.S. Kalil, A.A. Hamid and W.M.W. Yusoffs, 2009. Improvement of biohydrogen production under increased the reactor size by C. acetobutylicum NCIMB 13357. American J. Environmental Sci., 5(1): 33-40.. http://dx. doi. org/10. 3844/ajes.2009.33.40
46. Lens, P., Biofuels for fuel cells: renewable energy from biomass fermentation. 2005: Intl Water Assn.
47. Hashim, N., S. Kamarudin and W. Dauds, Reka Bentuk dan Pembangunan Mikro Sel Fuel Metanol Langsung (SFML) untuk Aplikasi Mudah Alih. Sains Malaysiana, 39(6): 1015-1023.
48. Kamarudin, S.K., W.R.W. Daud, A.M. Som, A.W. Mohammad Jr and M. Takrifs, 2004. Optimization of 5-kW Mobile and Portable PEMFC System via Energy Integration. ASEAN J. Chemical Engineering, 4(2): 19-23.

49. Kamarudin, S., W. Daud, A.M. Som, M. Takriff, A. Mohammad and Y. Lokes, 2004. Design of a fuel processor unit for PEM fuel cell via shortcut design method. Chemical Engineering J., 104(1-3): 7-17. http://dx.doi.org/10.1016/j.cej.2004.07.007
50. Kamarudin, S.K., W.R.W. Daud, S.L. Ho and U.A. Hasrans, 2007. Overview on the challenges and developments of micro-direct methanol fuel cells (DMFC). J. Power Sour., 163(2): 743-754. http://dx. doi. org/10.1016/j.jpowsour.2006.09.081.
51. Kamarudin, S., W. Daud and A.M. Soms, 2005. Clean cheap and compact (3c) power generation system for mobile and portable application: PEM fuel cell. J. Solid State Sci. Tec., 12(1): 151.
52. Baker, R.W.S, 2002. Future directions of membrane gas separation technology. Industrial and Engineering Chemistry Res., 41(6): 1393-1411. http://dx.doi.org/10.1021/ie0108088
53. Kamaruddin, S.K., W.R.W. Daud, A.M. Som and M.S. Masdars, 2007. Conceptual design of 5 kW PEM fuel cell stack. Jurnal Kejuruteraan, 19: 43-54.
54. Kamarudin, S.K., S.M. Tasirin, W.R.W. Daud and A.M.A. Al-Hweage. Local Behavior of Solid Mixing in Bubbling Fluidized Bed. 2006.
55. Kamarudin, S. and W. Dauds, 2006. Technical design and economic evaluation of a PEM fuel cell system. J. Power Sour., 157(2): 641-649. http://dx. doi. org/10.1016/j.jpowsour.2005.10.053.
56. Kamarudin, S.K., W.R.W. Daud, A.MD. Som, M.S. Takriff and A.W. Mohammads, 2006. Technical design and economic evaluation of a PEM fuel cell system. J. Power Sou., 157(2): 641-649. http://dx. doi. org/10.1016/j.jpowsour.2005.10.053.
57. Kamarudin, S.K., W.R.W. Daud, A.MD. Som, M.S. Takriff and A.W. Mohammads, 2006. Synthesis and optimization of a PEM fuel cell system via reactor-separation network (RSN). J. Power Sour., 159(2): 1194-1204. http://dx. doi. org/10. 1016/j. jpowsour. 2005.11.087.
58. Hassan, N.S.M., W.R.W. Daud, K. Sopian and J. Saharis, 2009. Water management in a single cell proton exchange membrane fuel cells with a serpentine flow field. J, Power Sour., 193(1): 249-257. http://dx.doi.org/10.1016/j.jpowsour.2009.01.066
59. Erni, M., N. Suhaimi, M. Hassan, W. Daud, W. Ramli, E.H. Majlan and K. Miftahs,Operating Temperature Effects on Water Transport Behavior in a Single Cell PEMFC. Applied Mechanics and Materials, 52: 1153-1158.
60. Achmad, F., S. Kamarudin, W. Daud and E. Majlans, Passive direct methanol fuel cells for portable electronic devices. Applied Energy.
61. Rowe, A. and X. Lis, 2001. Mathematical modeling of proton exchange membrane fuel cells. J. Power Sour., 102(1-2): 82-96. http://dx.doi.org/10.1016/S0378-7753(01)00798-4
62. Ghassemi, H., J.E. McGrath and T.A. Zawodzinskis, 2006. Multiblock sulfonated-fluorinated poly (arylene ether) s for a proton exchange membrane fuel cell. Polymer, 47(11): 4132-4139. http://dx. doi. org/10. 1016/j. polymer.2006.02.038
63. Mahreni, A., A. Mohamad, A. Kadhum, W. Daud and S. Iyukes, 2009. Nafion/ silicon oxide/ phosphotungstic acid nanocomposite membrane with enhanced proton conductivity. J. Membrane Sci., 327(1-2): 32-40. http://dx. doi. org/10. 1016/j. memsci. 2008.10.048.
64. Daud, W.R.W., A.B. Mohamad, A.A.H. Kadhum, R. Chebbi and S.E. Iyukes, 2004. Performance optimisation of PEM fuel cell during MEA fabrication. Energy Conversion and Manage., 45(20): 3239-3249. http://dx. doi.org/10. 1016/j. enconman.2004.01.011.
65. Wang, S., F. Dong, Z. Li and L. Jins, Preparation and properties of sulfonated poly (phthalazinone ether sulfone ketone)/tungsten oxide composite membranes. Asia Pacific J. Chemical Engineering.
66. Mokhtaruddin, S.R., A.B. Mohamad, L.K. Shyuan, A.A.H. Kadhum and M. Akhmads,Preparation and Characterization of Nafion-Zirconia Composite Membrane for PEMFC. Advanced Materials Res., 239: 263-268.
67. Turmuzi, M., W. Daud, S. Tasirin, M. Takriff and S. Iyukes, 2004. Production of activated carbon from candlenut shell by CO2 activation. Carbon, 42(2): 453-455. http://dx. doi. org/10. 1016/j. carbon. 2003.11.015.
68. Thiam, H., W. Daud, S. Kamarudin, A. Mohammad, A. Kadhum, K. Loh and E. Majlans, Overview on nanostructured membrane in fuel cell applications. International J. Hydrogen Energy.
69. Kamarudin, S., W. Daud, M. Ayub and A. Mohammads, 2008. A Review on Fuel Cell as Advanced Power Source. ASEAN J. Chemical Engineering, 2(1): 75-86.

70. Iyuke, S.E., A.B. Mohamad, A.A.H. Kadhum, W.R.W. Daud and C. Rachids, 2003. Improved membrane and electrode assemblies for proton exchange membrane fuel cells. J. Power Sources, 114(2): 195-202. http://dx.doi.org/10.1016/S0378-7753(03)00016-8.
71. Chebbi, R., A. Beicha, W. Daud and R. Zaamouches, 2009. Surface analysis for catalyst layer (PT/PTFE/C) and diffusion layer (PTFE/C) for proton exchange membrane fuel cells systems (PEMFCs). Applied Surface Sci., 255(12): 6367-6371. http://dx. doi. org/10. 1016/j. apsusc.2009.02.017.
72. Sitanggang, R.m A.B. Mohamad, W.R.W. Daud, A.A.H. Kadhum and S. Iyukes, 2009. Fabrication of gas diffusion layer based on xy robotic spraying technique for proton exchange membrane fuel cell application. Energy Conversion and Manage., 50(6): 1419-1425. http://dx. doi. org/10. 1016/j. enconman. 2009.03.006.
73. Dweiri, R. and J. Saharis, 2007. Electrical properties of carbon-based polypropylene composites for bipolar plates in polymer electrolyte membrane fuel cell (PEMFC). J. Power Sour., 171(2): 424-432. http://dx. doi. org/10.1016/j.jpowsour.2007.05.106.
74. Dweiri, R. and J. Saharis, 2007. Computer simulation of electrical conductivity of graphite-based polypropylene composites based on digital image analysis. J. Materials Sci., 42(24): 10098-10102. http://dx.doi.org/10.1007/s10853-007-2092-x
75. Dweiri, R. and J. Saharis, 2008. RETRACTED: Microstructural image analysis and structure-electrical conductivity relationship of single-and multiple-filler conductive composites. Composites Science and Technol., 68(7-8): 679-1687. http://dx.doi.org/ 10.1016/j.compscitech.2008.02.006
76. Basri, S., S. Kamarudin, W. Daud, Z. Yaakub, M. Ahmad, N. Hashim and U. Hasrans, 2009. Unsteady-state modelling for a passive liquid-feed DMFC. International J. Hydrogen Energy, 34(14): 5759-5769. http://dx. doi. org/10. 1016/j. ijhydene.2009.05.092.
77. Lu, G., C. Wang, T. Yen and X. Zhangs, 2004. Development and characterization of a silicon-based micro direct methanol fuel cell. Electrochimica Acta, 49(5): 821-828. http://dx. doi. org/10. 1016/j. electacta. 2003.09.036.
78. Basri, S., S. Kamarudin, W. Daud and M. Ahmads, Non-linear optimization of passive direct methanol fuel cell (DMFC). International J. Hydrogen Energy, 35(4): 1759-1768. http://dx. doi. org/10. 1016/j. ijhydene. 2009.12.057.
79. Ho, S., S. Kamarudin, W. Daud and Z. Yaakubs, 2009. Performance evaluation of a passive direct methanol fuel cell. J. Applied Sci., 9: 1324-1330. http://dx. doi. org/10.3923/jas.2009.1324.1330.
80. Hashim, N., S.K. Kamarudin and W.R.W. Dauds, 2009. Design, fabrication and testing of a PMMA-based passive single-cell and a multi-cell stack micro-DMFC. International J. Hydrogen Energy, 34(19): 8263-8269. http://dx. doi. org/10. 1016/j. ijhydene. 2009.07.043.
81. Ahmad, H., S. Kamarudin, U. Hasran and W.R.W. Dauds, Overview of hybrid membranes for direct-methanol fuel-cell applications. International J. Hydrogen Energy, 35(5): 2160-2175. http://dx. doi. org/10. 1016/j.ijhydene.2009.12.054.
82. Ahmad, M., S. Kamarudin, W. Daud and Z. Yaakubs, High power passive [mu] DMFC with low catalyst loading for small power generation. Energy Conversion and Manage., 51(4): 821-825. http://dx.doi.org/10.1016/j.enconman.2009.11.017.
83. Basri, S., S.K. Kamarudin, W.R.W. Daud, Z. Yaakub, M.M. Ahmad, N. Hashim and U.A. Hasrans, 2009. Unsteady-state modelling for a passive liquid-feed DMFC. International J. Hydrogen Energy, 34(14): 5759-5769. http://dx. doi. org/10. 1016/j. ijhydene.2009.05.092.
84. Basri, S. and S. Kamarudins, Process system engineering in direct methanol fuel cell. International J. Hydrogen Energy.
85. Basri, S., S. Kamarudin, W. Daud and Z. Yaakubs, Nanocatalyst for direct methanol fuel cell (DMFC). International J. Hydrogen Energy, 35(15): 7957-7970. http://dx.doi.org/ 10.1016/j.ijhydene.2010.05.111.
86. Zainoodin, A., S. Kamarudin and W. Dauds, Electrode in direct methanol fuel cells. International J. Hydrogen Energy, 35(10): 4606-4621. http://dx. doi. org/10.1016/j.ijhydene.2010.02.036.
87. Hasran, U., S. Kamarudin, W. Daud, B. Majlis, A. Mohamad and A. Kadhums, A simple thermal oxidation technique and KOH wet etching process for fuel cell flow field fabrication. International J. Hydrogen Energy.

88. Ormerod, R.M.S, 2002. Solid oxide fuel cells. Chem. Soc. Rev., 32(1): 17-28. http://dx. doi. org/10. 1039/b105764m.
89. Jarot, R., A. Muchtar, W. Daud, W. Ramli, N. Muhamad and E.H. Majlans, Fabrication of Porous LSCF-SDC Carbonates Composite Cathode for Solid Oxide Fuel Cell (SOFC) Applications. Key Engineering Materials, 471: 179-184. http://dx. doi. org/10.4028/www.scientific.net/KEM.471-472.179.
90. Jarot, R., A. Muchtar, W. Daud, W. Ramli, N. Muhamad and E.H. Majlans, Porous NiO-SDC Carbonates Composite Anode for LT-SOFC Applications Produced by Pressureless Sintering. Applied Mechanics and Materials, 52: 488-493.
91. Hamid, N.S., 2009. Microstructure characterization of La-Sr-Co-Fe-O cathode for intermediate temperature solid oxide fuel cell (IT-SOFC). Sains Malaysiana, 38(6): 857.
92. Shari, S.N., J.M.D. Jahim, S.K. Kartom and W.R.W. Daud, Development of micro biofuel cell for power generation. Proceedings of the 15th Regional Symposium on Chemical Engineering and the 22nd Symposium of Malaysian Chemical Engineers RSCE-SOMCHE 2008, 2-3 December 2008, Kuala Lumpur, Malaysia, II: 561-566.
93. Lim, S.S., W.R.W. Daud, J. Md. Jahim, M. Ismail, S.K. Kartom and S.N. Shari, Electricity generation in microbial fuel cell by local isolate of clostridium butyricum from palm oil mill effluent. The 2nd Microbial Fuel Cell Conference, pp: 10-12. June 2009, Gwangju, Korea.
94. Rahimnejad, M., N. Mokhtarian, G. Najafpour, W. Daud and A. Ghoreyshis, 2009. Low voltage power generation in a biofuel cell using anaerobic cultures. World Applied Sciences J., 6(11): 1585-1588.
95. Najafpour, G., M. Rahimnejad, N. Mokhtarian, W.R.W. Daud and A. Ghoreyshis, Bioconversion of Whey to Electrical Energy in a Biofuel Cell Using Saccharomyces Cerevisiae.
96. Rahimnejad, M., N. Mokhtarian, G. Najafpour, A.A. Ghoreyshi and W.R.W. Dahud, Effective Parameters on Performance of Microbial Fuel Cell: IEEE.
97. Kamarudin, S., W. Daud, Z. Yaakub, Z. Misron, W. Anuar and N. Yusufs, 2009. Synthesis and optimization of future hydrogen energy infrastructure planning in Peninsular Malaysia. International J. Hydrogen Energy, 34(5): 2077-2088. http://dx. doi. org/10.1016/j.ijhydene.2008.12.086
98. Holladay, J.D., J. Hu, D.L. King and Y. Wangs, 2009. An overview of hydrogen production technologies. Catalysis Today, 139(4): 244-260. http://dx. doi. org/10. 1016/j.cattod.2008.08.039.
99. Lee, H.S., W.F.J. Vermaas and B.E. Rittmanns, Biological hydrogen production: prospects and challenges. Trends in Biotechnol., 28(5): 262-271. http://dx.doi.org/10.1016/j.tibtech.2010.01.007.
100. Centi, G. and S. Perathoners, Creating and mastering nano-objects to design advanced catalytic materials. Coordination Chemistry Reviews.
101. Kim, M.H., E.K. Lee, J.H. Jun, S.J. Kong, G.Y. Han, B.K. Lee, T.J. Lee and K.J. Yoons, 2004. Hydrogen production by catalytic decomposition of methane over activated carbons: kinetic study. International J. Hydrogen Energy, 29(2): 187-193. http://dx. doi. org/10.1016/S0360-3199(03)00111-3.