International Journal of Current Engineering and Technology
ISSN 2277 - 4106
© 2012 INPRESSCO. All Rights Reserved.
Available at http://inpressco.com/category/ijcet

Research Article

New SSI Technology: A Futuristic Method of Energy Generation

Rajneesh Chaudhary[a*] and Gagan Deep Chawla[a#]

[a]Department of Mechanical Engineering , JMIT Radaur, Haryana, India

Accepted 19 August 2012, Available online 1Sept 2012

Abstract

Solid state ionic technologies such as fuel cells, sensors, batteries, super capacitors, hydrogen generation, storage devices and electro-chromic windows are likely to play a major role in extending the life of existing fossil fuel resources by increasing the overall efficiency of energy generation and use. This will lead to a reduction in the emissions of greenhouse gases and pollutants. No single technology in isolation is likely to provide solutions for the energy and environmental needs of future generations. This paper briefly outlines the applications of solid state ionic technologies for sustainable energy generation and summarizes key Australian initiatives in this field. It also emphasizes the significance of a total systems approach and discusses integration of renewable and solid state ionic technologies for clean and sustainable energy generation.

Keywords: *Solid state ionic; Energy generation; Renewable energy; Fuel cells; Hydrogen; Distributed generation; Sustainable energy*

1. Introduction

Energy generation, which to date has largely been based on fossil fuels, is a major source of anthropogenic greenhouse gas emissions and other pollutants. However, future energy generation must be sustainable in terms of cost, fuel resource availability and environmental acceptability. In addition, energy must be generated and supplied in the form and quality to meet the end-user requirements. Much effort is being spent on sustainable energy supply through measures such as the development of more efficient energy generation technologies, increased end-use efficiency and greater use of renewable energy sources such as solar, wind, and biomass. At the same time, there is an increased emphasis on small-scale distributed electricity generation. Fuel cells have the potential to play a dominant role in the future distributed energy generation network, with their high fuel conversion efficiencies, and as a clean source of power (significantly lower pollution and greenhouse gas emissions compared to those of conventional, centralized power generation). Furthermore, the use of fuel cells in transport vehicles as an auxiliary power unit or a replacement for internal combustion engines will bring substantial benefits in terms of clean urban air and by extending the life of existing fossil fuel resources. While solid oxide (SOFC) and polymer electrolyte membrane (PEMFC) fuel cells and oxygen sensors are perhaps the best known and most prominent applications of Solid State Ionics (SSI) in the field of energy generation, other potential areas are starting to emerge. These include hydrogen production from solar energy and novel methods of oxygen separation from air. The latter is a major cost component for the generation of electricity in advanced technologies such as Integrated Gasification Combined Cycle (IGCC) and CO2 recycle combustion systems. Substantial demand for oxygen also exists for syngas (CO +H2) production from natural gas. Syngas is a precursor for the production of methanol and higher hydrocarbon liquid fuels. Moreover, no single technology in isolation is likely to fulfill the future energy and environment needs of our society. Furthermore, from a systems point of view, to meet end-user requirements, fuel cells may have to be combined with other technologies, such as advanced energy storage systems based on new batteries and supercapacitors. Efficient and cost-effective energy storage systems are crucial for new load levelling and electricity supply applications, as well as for the wider use of solar and other renewable energy sources in both stationary and mobile power applications. Storage technologies such as advanced batteries and high power delivery supercapacitors will play key roles, while hydrogen generated from renewable energy is seen as the fuel of the future. The use of solar thermal–fossil energy schemes for hydrogen production in combination with fuel cells is one way of integrating renewable energy with high efficiency power generation. In a major project, CSIRO is demonstrating proof-of-concept for such a technology based on the steam reforming of methane using solar thermal energy to produce solar-enriched hydrogen fuel for use in fuel cells (J.H. Edwards *et al*, 2000). Purely renewable hydrogen can be generated by the electrolysis of water using PV- or wind-derived electricity. However, this route to date has been hampered by very low overall efficiencies and high

[*] Corresponding author: Rajneesh Chaudhary

costs. One way of improving the efficiency of a solar hydrogen system in the socalled sun-belt countries is to combine high-temperature hybrid solar collectors, which can cogenerate electricity, and high-grade heat with novel high-temperature steam electrolysis in solid electrolyte systems.

New solid state ionic devices and systems will be essential components of these new technologies, and considerable R&D is being conducted in this area. This paper briefly outlines the main SSI technologies for sustainable energy generation and their potential for centralized and distributed energy generation, transport applications and for advanced hydrogen production and utilization through the incorporation of new SSI technologies into novel concepts and fully integrated systems

2. SSI technologies for energy generation, storage and supply

SSI technologies that are set to play increasingly important roles in sustainable energy systems include:

- fuel cells (PEMFC and SOFC);
- advanced batteries (based on Li +, Na+ and H+ conductors);
- supercapacitors (polymer membrane capacitors);
- ionic-transport membranes (gas separation and chemical reactors);
- electrolysers for hydrogen production (low-temperature
- water electrolysis and high-temperature steam electrolysis);
- advanced sensors for process control and safety;
- electrochromic smart windows for optical modulation and energy-efficient buildings.

Several of these technologies are being commercial listed now while the others are at various stages of development. All are set to play increasingly important roles across the entire spectrum of sustainable energy generation and supply. Several projects established around the world to demonstrate these technologies for energy generation are clearly indicating the significance of a fully integrated approach to commercialization.

Although SSI technologies have high efficiencies and environmental benefits in their own right, their integration with other energy generation systems (e.g. cogeneration, tri-generation, renewables,etc) will further improve overall system performanceand emissions reduction.

2.1. SSI technologies in centralized generation

In general, most SSI technologies are essentially modular in design. The SOFCs, in particular, have the potential for larger-scale, centralized generation through their suitability for base load generation and for integration with gas turbine and IGCC technologies. The most advanced SOFC technology with potential for centralized generation is the tubular SOFC being developed by Siemens Westinghouse. Proof-of concept for linking this technology with a small gas turbine is being demonstrated with a 220-kWe system (200 kWe SOFC and 20 kWe microturbine generator). The system is expected to achieve an overall electric efficiency approaching 60%. Plans to scale up this combined cycle technology into the multi-megawatt range are in progress (S.C. Singhal *et al*, 2000). IGCC is regarded as one of the most environmentally friendly technologies for power generation from coal. Further increases in efficiency and emission reduction can be achieved by integrating SOFCs with IGCC. Ceramic membranes with high oxygen-ion conductivity or mixed ionic/electronic conduction can be used to generate oxygen or for the production of syngas (CO +H2) by the partial oxidation of methane (P.N. Dyer *et al*, 2000). In particular, membranes with mixed oxygen ion and electronic conductivity have potential applications for large-scale (tonnage) oxygen generation. The electrons in the membrane combine with oxygen in the air to create negatively charged oxygen ions, and the driving force for oxygen-ion transport is provided by the differential partial pressure of oxygen across the membrane at the operating temperature of the device. For oxygen generation, the pressure difference across the membrane is provided by having lower oxygen pressure in the chamber where oxygen is generated or by high pressure on the air side. For syngas production, the process involves combining oxygen separation from air with methane partial oxidation in a single reactor, a considerable advantage over conventional oxygen-generating technologies. The partial pressure differential across the membrane is provided by air being on one side and the natural gas on the other side of the membrane. Such membrane reactors could be significantly smaller and the cost of oxygen generation much lower than existing technologies.

2.2. SSI technologies in distributed energy generation

There is a worldwide trend away from centralized, coal-fired power generation to smaller-scale distributed systems based on gas and, where appropriate, renewable energy. Distributed energy generation systems are sited at or near the end user location and have advantages of high efficiency and low cost due to:

- Use of new technologies (e.g. fuel cells and microturbines);
- Ability for cogeneration and tri-generation of electricity, heat and cooling;
- Greatly reduced transmission losses.

Distributed generation, thus, has great potential for reducing greenhouse gas emissions and represents huge opportunities for SSI technologies. They will be an important part of energy supply to industry, commercial buildings and down to individual households. For example, the smart house concept (Fig. 1) shows how a fuel cell, combined with suitable technologies for utilising the waste heat, could be used to supply a house’s total requirements of electricity, hot water and space heating/cooling. The overall energy efficiency of such a configuration could approach 90% (A.C. Lloyd *et al*, 1999). Both SOFCs and PEMFCs have the potential of being the leading technologies over the next 20 years for use in distributed energy generation systems, ranging in size from a few kilowatts to megawatts. Several small-size units to 10 kWe incorporating PEMFCs are being demonstrated for the residential and remote area power supply markets. A 100-kWe SOFC generator developed by Siemens Westinghouse has been tested in The Netherlands for 2 years and 250-kWe PEMFC systems are being supplied by Ballard for evaluation in several countries. In Australia, the planar-type SOFC technology, being developed by Ceramic Fuel Cells, is targeting systems at the tens of kilowatt scale for a full range of distributed energy applications. More than A$70 million has been invested over a 9-year period beginning in 1992.

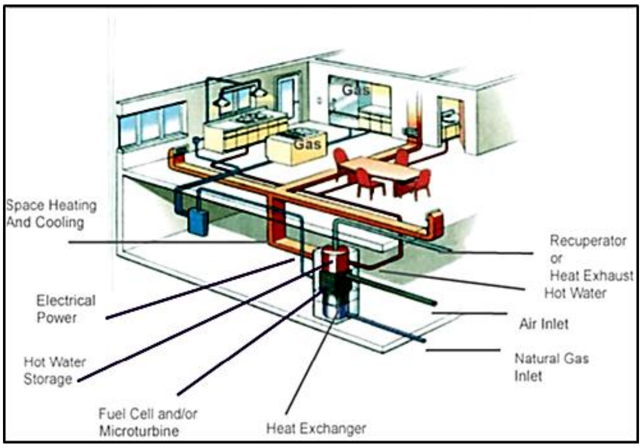

Fig. 1 Smart House Concept of Energy Technology

The CSIRO Centre for Distributed Energy and Power (CenDEP) is an association of industry and government organisations with a common aim of facilitating distributed generation in Australia. The Centre will facilitate substantial market penetration for distributed energy and power generation systems by providing a focus for technology development and demonstration, and the associated scientific and engineering research. It will optimise and integrate innovative fossil fuel and renewable energy technologies in a manner that is commercially relevant, able to influence government policy and regulation, and will deliver substantial environmental and greenhouse benefits.

2.3. SSI technologies in transport applications

SSI technologies are set to play key roles in future transport systems, both through the use of advanced supercapacitor/battery systems in hybrid electric vehicles, and fuel cells to power passenger cars, buses, light commercial trucks and heavy transport trucks. Ballard Power Systems/Daimler- Chrysler is the leading group commercializing PEMFC technology for the passenger vehicle (50 kWe) and buses (250-kWe generator) (C. Stone *et al*, 2002). Most major car manufacturers (Ford, General Motors, DaimlerChrysler, Toyota, Honda, Nissan, Renault, etc.) are now showing interest in the development of an all-electric- and/or hybrid-drive trains utilizing fuel cell technology, either in isolation or in combination with supercapacitors and/or batteries. Both SOFCs and PEMFCs in the 3–10 kWe range are also being considered as auxiliary power units for automotive applications. The Australian hybrid, electric, low-emissions vehicle project was established to design and construct parallel- and series-drive hybrid electric vehicles (D. Lamb *et al,* 2000). The parallel-drive ECOmmodore vehicle demonstrated the capabilities of CSIRO and Australian car makers to construct a full-size, hybrid, electric car, while the series-drive aXcess low-emissions vehicle demonstrated that CSIRO and Australian component manufacturers could design and construct a mid-size car that reduced fuel consumption and greenhouse gas emissions by 50% and all other pollutants by 90%. As part of the DaimlerChrysler's Cleaner Urban Transport for Europe (CUTE) proposal, three DaimlerChrysler fuel cell buses are to be tested in Perth over a 2-year period from late 2002 (Aust, 2010). Hydrogen fuel will be produced by BP from refinery waste gases and a range of hydrogen supply; infrastructure-related options will be tested. Longer-term hydrogen production will be by steam reforming of natural gas and ultimately, from renewable sources.

3. SSI technologies for sustainable hydrogen production

Hydrogen for PEMFCs is currently produced by reforming or partial oxidation of fossil fuels such as natural gas and coal. For transport applications and for on-board generation of hydrogen, reforming gasoline and partial oxidation of methanol are other options being considered. These processes are strongly greenhouse- intensive and not sustainable in the long term, thus, sustainable hydrogen must ultimately be derived from water splitting or electrolysis using renewable energy such as solar, wind, biomass or off-peak hydroelectric power. In the interim, hybrid concepts involving renewable and fossil energy are important steps towards renewable energy-based hydrogen production. One such hybrid concept under the development of CSIRO in Australia is briefly described below and is given in more detail elsewhere.

3.1. CSIRO's ''towards sustainable energy'' project

A major project is being undertaken to demonstrate a solar, thermal-gas hybrid energy concept for producing hydrogen and using it to generate electricity with potential for high thermal efficiencies and for greatly reduced CO_2 emissions. The concept features:

- Reforming of CH_4-containing gases using concentrated solar energy to generate a mixture of CO and H_2.
- The further conversion of this gas to H_2 and CO_2 followed by recovery of CO_2 in a concentrated form,

as required for any subsequent CO2 disposal or utilisation scheme.
- Use of H2 for electricity generation in a PEMFC system, as these offers the maximum energy conversion efficiency based on hydrogen fuel.

The project involves the construction and operation of a facility to demonstrate the key steps in the technology so that its commercial prospects can be more accurately assessed. The basic steps of the concept are shown in Fig. 2. The gas can be any methane-containing gas such as natural gas, coal seam gas or landfill gas, etc. Solar thermal energy is used to reform the gas to generate a synthesis gas (CO and H2), which can be used directly as a fuel or as a chemical feed stock containing substantial embodied solar energy. Alternatively, the reformed gas can be further converted, via the water gas shift reaction, to a mixture of CO2 and H2. This gas is treated, prior to using the H2 as a fuel, to recover CO2 in a concentrated form. This process is greatly facilitated by having high CO2 partial pressures and relatively small gas volumes, compared with the alternative of recovering CO2 from power station flue gas where the CO2 is at low partial pressure and is heavily diluted with nitrogen. The recovered CO2 can be permanently disposed in various CO2 ‘‘sinks’’. These include injection into subterranean cavities or reservoirs such as aquifers, depleted oil and gas fields, deep unminable coal seams (possibly to assist in the recovery of coal bed methane) and in the deep ocean, by far the largest potential CO2 ‘‘sink’’.

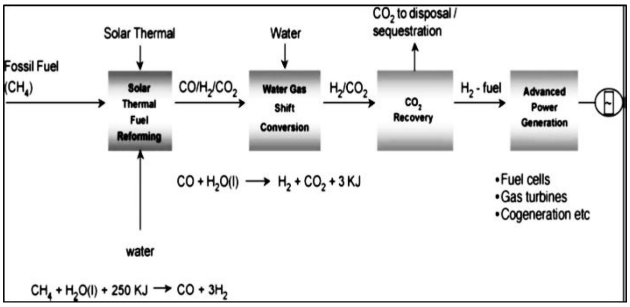

Fig. 2 Process steps for advanced power generation

The combination of advanced energy conversion technologies based on H2 fuel, together with CO2 disposal, allows the highly efficient utilisation of fossil fuels with a dramatic reduction in atmospheric CO2 emissions. The demonstration facility (Fig. 3) is designed for a methane feed rate of 44 kWth (Lower Heating Value basis) and consists of:

- feed supply and treatment units;
- a 107-m2 paraboloidal, solar, thermal-concentrating dish;
- catalytic reactors for steam reforming and water gas shift;
- CO2 separation units;
- a unit to reduce the CO level in H2 to < 10 ppm;
- a 10-kWe PEM fuel cell system from Air Liquide/DeNora.

Supporting this project is also a state-of-the-art PEMFC test facility that is being used to test and evaluate the performance of PEMFC stacks on a range of simulated fuel mixtures. The facility described in more detail elsewhere consists of:

- test beds with capacity to test up to 3-kWe size PEMFC stacks;
- equipment for the fabrication of membrane electrode assemblies with at least 400 cm2 active area cells;
- all associated gas supply, handling and safety equipment.

3.2. Hydrogen from renewable energy

Hydrogen is widely regarded as the cleanest fuel of the future, provided it can be generated using renewable rather than fossil energy. A totally sustainable energy cycle would involve hydrogen generation by water electrolysis using electricity generated from solar, wind, biomass or off-peak hydroelectric sources, its storage/transportation and recombustion in a hydrogen-based internal combustion engine or in a PEMFC system to generate electricity and heat on site. PEMFCs, with some design considerations, can be used to produce highpurity hydrogen and oxygen when operated in reverse mode . They offer the advantages of being an all-solid-state device with potentially high-conversion efficiency, small footprint and a less hazardous process configuration. However, hydrogen generated by this route is currently uneconomical and substantial effort is required to make the technology viable.

Fig. 3 CSIRO’s solar thermal– gas hybrid energy demonstration facility

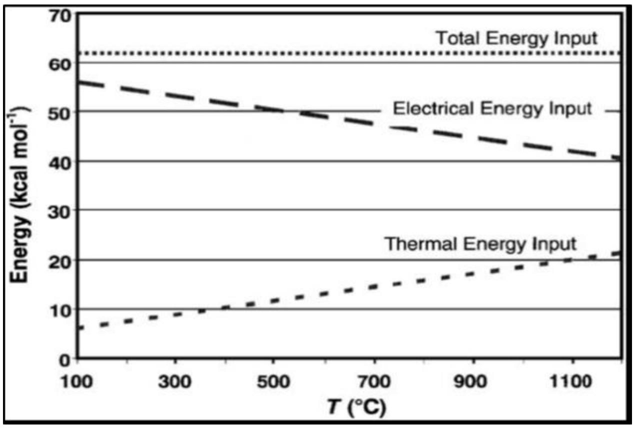

Fig. 4 Theoretical electrical and thermal energy inputs for water decomposition as a function of temperature

3.3. *High-temperature steam electrolysis*

High-temperature electrolysis of water has been known for some time to offer advantages in terms of high efficiency, as the electricity required for water splitting can be significantly reduced if it is conducted at elevated temperature. This is shown in Fig. 4, which gives the theoretical electrical and thermal energy inputs for water decomposition as a function of temperature (J. Padin *et al*, 2000). For example, although the total energy required is essentially independent of temperature, the electrical energy required at 1000^0C is only around 43 kcal mol $^{-1}$ compared with 56 kcal mol $^{-1}$ at 100^0C a 23% reduction.

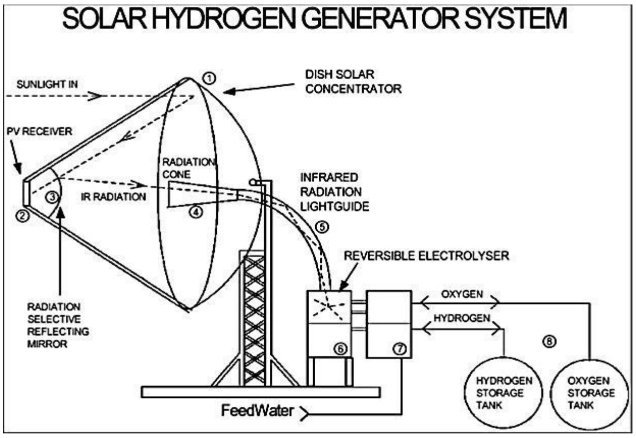

Fig. 5 A block flow diagram of Solar Systems' hydrogen generation system using solar\ concentration and beam splitting. (1) Tracked parabolic dish concentrator; (2) Photovoltaic receiver; (3) Selective reflecting mirror; (4) Radiation cone; (5) Light guide; (6) Ceramic electrolyser; (7) Heat exchanger/phase separator; (8) Storage vessels.

Solar power systems have two technical limitations however, which prevent them from becoming the ideal mainstream energy providers:

(i) Intermittent operation due to lack of sun during periods of cloud cover and overnight,

(ii) Low efficiency (resulting in high power costs).

In ''sun-belt'' countries such as Australia, it is possible to use solar energy to provide both the thermal and electrical energy needed for steam electrolysis. One potentially attractive method for doing this combines the solar-concentrating and beam-splitting technologies of Solar Systems Pty. Ltd. With high-temperature, ion-conducting membrane technology for steam electrolysis as shown in Fig. 5. This patented solar hydrogen production process is theoretically capable of delivering solutions to both these limitations, that is, providing a continuous power source and operating at a high efficiency (J. Lasich *et al*, 1997). In this process, hydrogen is produced from water using solar-generated DC electricity and the cogenerated heat to drive a ceramic electrolyser. The DC electricity and the cogenerated heat are produced via a single solar concentrator unit to drive a ceramic electrolyser to split water into hydrogen and oxygen. The hydrogen and oxygen can be stored for reconversion to electricity through a fuel cell on demand or exported as a fuel. This system promises high efficiency, and the storage of hydrogen eliminates the intermittent nature of solar energy collection from affecting the user, as well as being an energy carrier which can be readily transported to other sites. The generator incorporates a photovoltaic (PV) receiver, a thermal receiver and a large (130 m2), parabolic dish which concentrates, separates and converts solar radiation into electricity and high grade heat. The electricity and heat may be used directly or converted (at a high efficiency) into hydrogen fuel for storage. In Fig. 5, the tracked parabolic dish concentrator (1) concentrates solar energy to the photovoltaic (PV) receiver (2) via the selective reflecting mirror (3). The infrared (IR) energy is selectively reflected by (3) to the radiation cone (4) which channels IR radiation to the high temperature electrolyser (6) via the light guide (5) to deliver thermal energy at 1000^0C. Simultaneously, the short wavelengths which pass through (3) excite the photovoltaic (PV) receiver which produces DC electricity, which is also delivered to the electrolyser (6). The hydrogen and oxygen generated in the electrolyser (6) are fed via the heat exchanger/phase separator (7) systems to storage vessels (8). To provide a continuous supply of electricity, the hydrogen and oxygen may be converted back to electricity through the reversible electrolyser (or a fuel cell). Alternatively, hydrogen may be used for chemical processing in the industry or used directly to fuel transport vehicles. The technique capitalises on the high efficiency and intense beam produced by a large solar concentrator capable of delivering up to 112-kW radiation to the receiver zone. The present electrical system has a design output of 24 kW and a system efficiency approaching 20% for PV conversion only. Splitting the spectrum in the intense beam provides an option to use a second receiver and cogenerate other energy forms such as high-grade heat. In the case of high-temperature electrolysis using a zirconia-based cell, all the energy input requirement can be provided by cogenerated heat from the split solar spectrum. Fig. 6 is an illustration of a working spectrum splitting prototype test unit developed at Solar Systems Pty. Ltd. Radiation is concentrated to a primary PV receiver, where the short wavelength is utilized by the solar cells and the long wavelength is reflected through a light guide (being held by the operator). The infrared radiation is delivered at the end of the guide (accompanied by some visible light). A temperature of 1100 ^{0}C has been achieved using this type of configuration. A theoretical efficiency of approximately 50% is possible using the process described above. Preliminary experimental results to date show that the major components will function as required by the concept and that a practical efficiency of 30% or more is achievable.

4. Other SSI technologies for energy efficiency

There are a number of SSI technologies which are not within the scope of this paper but contribute directly or indirectly to the energy efficiency. These include batteries and supercapacitors that are not continuous sources of power and as such, are not considered as energy generation devices. However, they are important elements in the overall systems design providing short- or long-term energy storage when used in combination with other power generation technologies. Both hydrogen and oxygen sensors are used widely for safety monitoring, combustion control and process control/monitoring, and are key elements in power generation equipment and contribute indirectly to the reduction of energy consumption and greenhouse gas emissions (W. Go¨pel *et al*, 2001). Electrochromic smart windows, although not in widespread use, have the potential to reduce energy usage through optical modulation of radiation (J. Bell *et al*, 2002). Electrochemical membrane reactors based on solid state ionic systems can provide efficient and clean routes for the production of chemicals .

5. Concluding remarks

Solid State Ionic technologies have the potential to contribute substantially to future energy and environmental needs of our society. Comprehensive SSI technology R&D programs are tackling the key technical problems. A combination of renewable and SSI technologies have the potential to move energy generation to a totally sustainable energy cycle. However, future efforts must focus on complete systems development and integration for different end user applications that include:

- SSI technologies alone;
- integration of SSI with other fossil energy technologies;
- SSI and renewable energy hybrid systems.

Each application must address cost, performance, power quality and reliability, along with grid-interfacing issues.

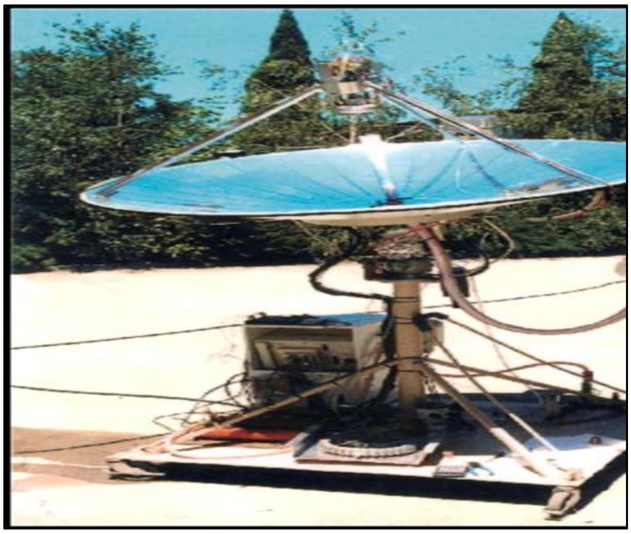

Fig. 6 A solar beam-splitting prototype test unit of Solar Systems

References

J.H. Edwards, G.J. Duffy, R.G. Benito, K.T. Do, N.C. Dave, R. McNaughton, S.P.S. Badwal, S.P. Jiang, S. Giddey, Renewable Energy for the Next Millennium, March 8 – 10, Sydney, Australia, 2000.

J.H. Edwards, G.J. Duffy, R.G. Benito, K.T. Do, N.C. Dave, R. McNaughton, S.P.S.Badwal, Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5), August 13– 16, Cairns, Australia, 2000, p. 863.

S.C. Singhal, Solid State Ionics 135 (2000) 305.

T.J. Mazanec, Electrochem. Soc. Interface (1996) 46.

S.P.S. Badwal, F.T. Ciacchi, Adv. Mater. 13 (12–13) (2001) 993.

P.N. Dyer, R.E. Richards, S.L. Russek, D.M. Taylor, Solid State Ionics 134 (2000) 21.

A.C. Lloyd, The power plant in your basement, Sci. Am., July 1999, pp. 80– 86. Adapted by N. Lockhart, CSIRO Energy Technology.

C. Stone, A. Morrison, Solid State Ionics (2002) in press.

D. Lamb, Seoul 2000 FISTA World Automotive Congress, June 12–15, Seoul, Korea, 2000, p. 1.Aust. Energy News (March 2001) 50.

S. Giddey, F.T. Ciacchi, S.P.S. Badwal, V. Zelizko, J.H. Edwards, G.J. Duffy, Solid State Ionics (2002) in press.

W. Smith, J. Power Sources 86 (2000) 74.

J. Padin, T.N. Veziroglu, A. Shahin, Int. J. Hydrogen Energy 25 (2000) 295.

J. Lasich, The Production of Hydrogen From Solar Radiation with High Efficiency, US Patent 5658448 (1997).

R.A. Huggins, Solid State Ionics 134 (2000) 179.

R.M. Dell, Solid State Ionics 134 (2000) 139.

W. Go¨pel, G. Reinhardt, M. Ro¨sch, Solid State Ionics 136–137 (2001) 519.

J. Bell, J.P. Matthews, I.I. Skryabin, Solid State Ionics (2002) in press.

P.J. Gellings, H.J.A. Koopmans, A.J. Burggraaf, Appl. Catal. 39 (1988) 1.