Accepted 26 May 2008 for publication in *Natural Resources Research*.
DOI: 10.1007/s11053-008-9077-6

Journal Article at http://dx.doi.org/10.1007/s11053-008-9077-6

THE SUSTAINABLE GLOBAL ENERGY ECONOMY: HYDROGEN OR SILICON?

W. E. Bardsley
Department of Earth and Ocean Sciences
University of Waikato
Hamilton, New Zealand

Associate Professor Earl Bardsley
Department of Earth and Ocean Sciences
University of Waikato
Private Bag 3105
Hamilton 3240
New Zealand

Phone (Office) : 64-7-8585011
Phone (Secretary) : 64-7-8384024
Fax (Department): 64-7-8560115

e-mail: web@waikato.ac.nz

ABSTRACT

A sustainable global silicon energy economy is proposed as a potential alternative to the hydrogen economy. This first visualisation of a silicon energy economy is based on large-scale and carbon-neutral metallic silicon production from major smelters in North Africa and elsewhere, supplied by desert silica sand and electricity from extensive solar generating systems. The resulting “fuel silicon” is shipped around the world to emission-free silicon power stations for either immediate electricity generation or stockpiling. The high energy density of silicon and its stable storage make it an ideal material for maintaining national economic functioning through security of base load power supply from a renewable source. This contrasts with the present situation of fossil fuel usage with its associated global warming and geopolitical supply uncertainties. Critical technological requirements for the silicon economy are carbon-neutral silicon production and the development of efficient silicon-fired power stations capable of high-temperature rapid oxidation of fuel silicon. A call is made for the development of research effort into these specific engineering issues, and also with respect to large-scale economical solar power generation.

INTRODUCTION

The hydrogen economy is often advocated as both a national and global response to the twin issues of global warming and depleting oil reserves (Dunn, 2002; Rifkin, 2002; National Research Council, 2004; Goltsov, Veziroglu, and Goltsova, 2006; Murray, Seymour, and Pimenta, 2007). There is already a considerable degree of research momentum for hydrogen energy – as seen, for example, in the publications of the *International Journal of Hydrogen Energy* and establishment of the information-sharing umbrella organisation *International Partnership for the Hydrogen Economy*.

However, the path to a sustainable hydrogen economy is by no means clear and there is no general agreement as to what a hydrogen economy would be like (McDowall and Eames, 2006). The combustion product of hydrogen is just water but the cheapest means of hydrogen generation is still via unsustainable hydrocarbons and associated release of carbon dioxide. Carbon-neutral hydrogen production might be achieved at some greater expense by sequestration of by-product carbon dioxide, or by using nuclear power to create hydrogen from electrolysis of water (Yamawaki and others, 2007). However, a sustainable hydrogen economy can only be achieved if the hydrogen is created entirely from renewable energy sources (Nowotny and Sheppard, 2007; Moriarty and Honnery, 2007).

The movement toward a sustainable hydrogen economy appears to be slow (van Ruijven, van Vuuren and de Vries, 2007), with only Brazil and Iceland anticipating a significant hydrogen output from renewable sources by 2030 (Solomon and Banerjee, 2006). It is even questionable whether hydrogen generation from renewable energy within a given nation is actually desirable for the purpose of reducing global warming, because the argument can be made that the renewable energy is more effectively used to directly substitute existing emission-generating electricity sources (Heiman and Solomon, 2007). A more international view of the hydrogen economy might see large-scale hydrogen generation from those nations favoured with significant renewable energy resources, with export for usage around the world. This scenario seems unlikely in reality, however, because of practical problems of storing and transporting significant amounts of hydrogen, although new technologies may offer improvements in this regard (Auner, 2007).

The development of a hydrogen economy is also likely to be vulnerable to the high value of what might be termed its “Chernobyl coefficient” , the probability that the development of a given energy mode will be halted by public dismay over a significant accident, irrespective of any subsequent degree of explanation that the accident was due to a highly unlikely combination of circumstances.

Perhaps the most significant concern over the current emphasis on developing national or global hydrogen economies is that other potentially useful “economies” may be left out because they will start from a research disadvantage, even though they may promise better alternatives. Cherry’s warning that we do not have a good track record for picking energy winners is relevant here (Cherry, 2004). It would seem that a better strategy would be to distribute research effort over as many options as possible and for as long as possible. For example, a recent paper raises the possibility of silicon as an alternative energy carrier to hydrogen (Auner and Holl, 2006). The authors were concerned mainly with technical issues and did not overview the wider implications or workings of a "silicon economy", but their findings allow the possibility of the use of silicon as a global fuel for power generation. The purpose of the present brief paper is to present a first visualisation of a sustainable global silicon energy economy. As with the hydrogen economy, establishing a sustainable silicon economy requires overcoming a number of technological problems, outlined in the next section.

THE TECHNOLOGY OF A SUSTAINABLE SILICON ECONOMY

We envisage the use of silicon as a global carrier of renewable energy based on carbon-neutral reduction of silica (quartz) in silicon smelters to yield metallic silicon in bulk supply. The silicon is then shipped around the world for electricity generation in emission-free thermal power stations which oxidise the silicon at high temperature to provide base load electricity. The storage efficiency factor is about 30%, taking into account energy losses in silicon reduction and subsequent conversion to electric power (Auner and Holl, 2006).

The silicon dioxide product from power generation might be returned to the silicon smelters for reduction. However, the global concentrations of silica sand are so vast that this aspect of sustainability might be neglected for the present. The term "fuel silicon" is introduced here to denote the lower grade of silicon suitable for power generation. This is distinct from "solar silicon" which in the literature refers to the purer material produced for solar panels.

As is the case for hydrogen, electricity generated from fuel silicon can be considered as renewable only if the power utilised in silicon production is derived from renewable sources, with the silicon production process itself also needing to be carbon-neutral. The standard commercial process of silicon production is not applicable here because carbon is used as the reducing agent with emission of carbon dioxide. Carbon derived only from forests or other renewable sources is not an alternative because of the millions of tons of fuel silicon that would be required if it became a major global renewable fuel. It is left a subject for future work to ascertain which carbon-neutral silicon smelting technology might be best suited to large scale fuel silicon production. Auner and Holl (2006) suggest a process based on reacting silica with hydrofluoric acid. An unspecified patented energy-efficient method for silicon production is referenced by Auner (2007). Another alternative might be the solid-state reduction of silica to metallic silicon by electrolysis (Yasuda and others, 2007; Yasuda and others, 2005)

The second critical technological requirement is the construction of efficient silicon-fired power stations where the oxidation of fuel silicon can be maintained at a sufficient rate to produce the desired power output. A restricting factor here is that the SiO_2 oxidation product remains with the silicon and partially restricts its subsequent oxidation. An operating temperature in excess of 1,600 °C may be required so that both the silicon and SiO_2 remain in the liquid phase to maximise continued oxidation through oxygen diffusion into the molten material. Considerations of optimal power station design are beyond the scope of this paper but the silicon combustion process could involve maximising the surface area of the silicon fuel material in an oxygen-enhanced environment.

If silicon power stations are indeed viable, then they would be very different from their fossil fuel equivalents in that no emissions are generated and they would yield copious amounts of solid SiO_2 “ash” of some 50% greater volume than the original fuel silicon. This inert silicon dioxide might be recycled back to a silicon smelter or used locally in land fill. Some might find more specialist uses such as for glass production. Silicon-fired power stations would still have some superficial similarities with their coal-fired equivalents to the extent that there would be large adjacent fuel stockpiles. However, an important distinction here is that metallic fuel silicon can be stored almost indefinitely in the open environment without degradation. Silicon therefore represents a more practical form of long-term energy storage than coal stockpiles, taking into account that carbon and silicon have similar energy densities (Auner and Holl, 2006).

The final technological requirement in the envisaged global silicon energy scenario is the capability of emplacing large-scale economic solar power generation systems in the solar-rich regions of the world, providing the power for the smelters. Moriarty and Honnery (2007) note that solar power is presently the most expensive of the renewable alternatives, although photovoltaic (PV) technology appears close to significant breakthroughs (Morton, 2006). It may be in fact that the necessary technology has already been developed in the form of a new process for large-scale production of silicon for solar panels at significantly reduced cost (PureEnergySystems, 2007).

Assuming that the above technological issues can be overcome, the remainder of this paper attempts a first vision of how aspects of a sustainable global silicon energy economy might appear in the future.

A SILICON SCENARIO FOR NEW ZEALAND ELECTRICITY

New Zealand provides a good example of how the use of an international silicon energy system could be a better option for emission reduction than simply developing local renewable energy to replace existing fossil fuel usage. This small island nation is well endowed with renewable resources and there is presently a strong move towards reducing carbon dioxide emissions via a national target of 90% of electricity output from renewables by the year 2025 (Ministry of Economic Development, 2007). New Zealand is not a large economy, so this policy will have limited global impact but is consistent with Kyoto Protocol obligations. However, there is already some resistance to the policy because renewable energy development inevitably impacts on New Zealand’s scenic landscape, with a worst-case future of wind farms expanding to claim the last exposed ridge and hydrosystem cascades replacing rivers and streams.

There is also a practical problem in that most wind and hydro resources are in the south of the country while most electricity demand derives from the growing population in the north. This leads to transmission losses and also creates local issues when major new transmission lines need to pass over private farmland. But the major downside of the proposed 90% renewable dominance (mostly wind and hydro) is an increased exposure to the impact of future climatic fluctuations. At present hydro power makes up about 60% of New Zealand's electricity supply and there is insufficient hydro lake storage capacity even now to act as buffer against an extended dry period. The move toward more renewables is unlikely to be able to incorporate any significant new hydrostorage, so there will be a need to maintain stand-by coal or gas thermal stations to guarantee security of future electricity supply.

A better scenario for a New Zealand electricity future from renewable resources may be achieved from fuel silicon. The concept would be for New Zealand to construct significant solar generation capacity in Australia for carbon-neutral silicon smelting, using the Australian national grid to smooth power fluctuations. The bulk fuel silicon would be shipped to New Zealand for base load electricity generation in power stations constructed near the northern demand centres, with some silicon also stockpiled as backup reserve against climatic fluctuations. This appears a better means to achieve the desired dominance of sustainable electricity but still maintain security of supply. In fact, the silicon energy scenario would result in less carbon dioxide emissions because silicon rather than fossil fuel would be the backup power supply against climatic fluctuations.

The environmental value of fuel silicon as a New Zealand renewable energy store can be illustrated by comparison with a more traditional solution previously suggested by Bardsley (2005). The proposal was for the construction of a large pumped storage system with energy storage in the order of 10,000 GWh, which would be the world's largest such scheme by energy measure and would triple the national energy storage capacity. Engineering requirements include a 15 km rock tunnel and a 100-meter earth dam to create a new lake with active storage volume of 6×10^9 m^3, flooding 120 km^2 of land. In contrast, the same energy storage could be achieved by a fuel silicon stockpile 6 meters thick spread uniformly over 1 km^2, assuming a conservatively low 20% conversion efficiency in silicon-fired power stations.

A SUSTAINABLE SINGAPORE

The highly developed city state of Singapore is becoming increasingly aware of global warming and related environmental issues as evidenced in editorials in popular magazines (Fang, 2008). However, related suburban activities such as recycling schemes pale somewhat in the light of Singapore's almost 100% reliance on burning fossil fuels to generate the 11,000 MW required for its electricity supply. The reality is that the small size of Singapore is likely to place it among the greatest carbon-emitting nations on a per unit area basis. It is inevitable therefore that even conservation-related energy usage in Singapore has a hidden price by way of carbon emissions. For example, Singapore's Jurong Bird Park is rightly regarded as a triumph of nature conservation but maintaining the discharge of the park's artificial waterfall will release in excess of 7,000 tons of carbon dioxide per year when electricity for the water pumping is derived from gas-fired power stations.

The Jurong waterfall can presumably be powered from solar panels, but that would not alter Singapore's present status of being a rather bad global environmental citizen. However, should silicon power stations prove viable, then Singapore is well placed to use its location, technology, and monetary power to convert its electricity supply to a fully sustainable and carbon neutral status as an example to the world. The scenario would be that Singapore would develop extensive solar electric generation in excess of 30,000 MW at a suitable location in northern Australia. Depending on the location and solar electric conversion efficiency, this could be achieved by PV panels extending over an area of 500-900 km^2. This is orders of magnitude larger than the areal extent of existing solar power systems, but would not seem beyond the bounds of possibility. This electricity would then be used for carbon-neutral smelting of about 30 million tons of fuel silicon per year for shipment to one or more power stations in Singapore.

In the above scenario the electricity requirements of Singapore would be met in a sustainable and carbon-neutral way from the solar radiation of a tiny portion of Australia's land area, and the shipping distance to Singapore is not particularly large. The relative ease and advantages of developing a silicon energy economy for Singapore are such the tentative prediction is made here that if technology does indeed allow a world's first prototype silicon power station, then it will most likely be constructed in Singapore.

SILICON SHIPPING

It is unfortunate that the airline industry has captured public attention for carbon dioxide emissions because it is arguably the industry which is least in a position to reduce them, short of restricting operations. Probably the only sustainable option for the airline industry is through the use of biofuels. However, this raises moral issues of diverting land away from food production and contributing to food price rises, while possibly actually increasing net carbon dioxide yield (Pimentel and Patzek, 2007; Fargione and others, 2008; Searchinger and others, 2008). Global shipping emissions have received much less prominence but carbon dioxide emission from shipping is estimated at 3.5% of the 2007 global total and greater than the airline industry (ENN, 2008). Furthermore, the use of fossil fuels in shipping is also associated with a range of other potentially harmful emissions (Institute of Atmospheric Physics, 2007; Lauer and others, 2007).

Following the Auner and Holl (2006) analogy between silicon and coal, a logical use of fuel silicon derived from renewable energy would be conversion of world shipping to sustainable "silicon steamers" to both offset the emissions of the airline industry and also for the pragmatic reason of avoiding a likely marine hydrocarbon fuel tax, presently under current (2008) discussion in the United Nations. Fuel silicon supply for shipping would be maintained by bunkering facilities at suitable locations, reminiscent of the age of coal steamships. The silicon dioxide from fuel silicon combustion could be deposited into the ocean during ship passage. With such environmentally-friendly shipping, one of the first uses of fuel silicon may be to power luxury cruise liners, taking advantage of a market appreciative of a renewable fuel without the food cropland displacement concerns of biofuels.

A SUSTAINABLE GLOBAL SILICON ENERGY ECONOMY

Technology permitting, a sustainable global silicon energy economy would be much simpler than the hydrogen economy because the latter would have to pervade all aspects of society down to hydrogen outlets over a myriad of roadside fuel stations – an infrastructure that would require some considerable investment to create (Heiman and Solomon, 2007). In contrast, the envisaged silicon energy economy would comprise just the silicon-powered shipping of fuel silicon to large power stations generating additional electric power which is distributed through existing electricity grids. The transformation would be a shift to electric cars, to electric heating systems, and generally replacing fossil fuel usage with electricity supply wherever possible. All this is in direct contrast to the present situation of oil delivery by ocean tankers which themselves are powered by fossil fuel.

The most visible manifestation of the sustainable silicon energy economy would be the conversion of some desert tracts to solar power stations. It would be uneconomical to have small distributed silicon smelters, so the scenario would be for a number of extensive regions of some hundreds of square kilometres of solar power collection to feed electricity to large carbon-neutral silicon smelters. Such solar developments ideally would not displace any significant agricultural production. One technological requirement here would be some buffering system to maintain steady electricity supply. This might be met by some energy storage system such as molten salt, flywheels or perhaps the construction of large salt water pumped storage systems along suitable desert coastlines of elevated relief.

The requirements of large-scale power concentration would appear to be most closely met in North Africa, where comparatively small continental regions could generate large amounts of power (Daviss, 2007), as well as providing new income to some of the world’s poorest nations. The regions of highest solar flux tend to be associated with desert areas least likely to have existing agricultural value. The vision then is for North African fuel silicon to provide most of the world energy needs, with developed western economies at the same time converting their energy usage as far as possible to electricity produced from the new power stations. Some alternative solar fuel silicon supply possibilities include South West Africa, the Middle East, and parts of Australia. These desert regions also have local abundance of quartz sand for silicon smelting.

If carbon-neutral silicon smelters prove technologically viable, then their actual site locations will depend on many regional economic factors which would need to be evaluated. For example, Broesamle and others (2001) identify part of Egypt as the overall most cost-effective region for North Africa solar-thermal power generation. It may be therefore that Egypt develops a major fuel silicon export industry as well as providing fuel silicon bunkering facilities for ships passing through the Suez Canal. Similarly, Australia is well situated for fuel silicon exports to power stations in Singapore and along the coast of China.

Taking into account smelting and transport costs and the associated inefficiencies, it follows that electricity will be expensive if derived from fuel silicon by way of the solar scenario proposed here. However, increasing concerns about climatic change may be a factor in addition to purely economic considerations (Heiman and Solomon, 2007). Also, the suggestion has been made that a modified energy market might be formulated so that technologically immature systems will not be able to compete in the initial stages of development (Madlener and Stagl, 2005).

The ability of fuel silicon to store large amounts of energy almost indefinitely for supply security is a further offsetting factor against higher electricity prices. Coal is cheaper of course but cannot be stockpiled for lengthy periods, so broken transport linkages between mines and power stations can lead to power disruption. For example, some electricity supply failed in China in January 2008 because a few coal-fired power stations shut down after heavy snowfalls closed some rail and road supply links.

Silica sands are so abundant that it is conceivable that fuel silicon stockpiles could be built up to be large enough to maintain the economy of any nation which had moved to have electricity as its main form of energy consumption. Such a power supply buffer might represent several years of power supply even for an economy as large as that of the United States. Aside from security through stockpiling, fuel silicon output at source could also be secured by distributing smelters and solar power utilisation over a significant number of different "solar nations". In contrast, many writers (e.g., Asif and Muneer, 2007) have commented on the present insecure geopolitical situation of oil and gas sources and associated transport routes.

A silicon-based sustainable global energy economy driven in large part by a solar Africa would need to offer benefits to both suppliers and end users. It has been recognised that solar power generation creates some negative environmental impacts (Tsoutsos, Frantzeskaki, and Gekas, 2005), but this might be more than offset by positive effects with careful planning. In particular, field observations and modelling studies in the recent literature suggest that land use changes at certain scales can give rise to enhanced local convectional activity and increased rainfall (D'Almeida and others, 2007; Patton, Sullivan and Moeng, 2005; Mölders and Kramm, 2007).

It may even happen that relatively small changes in land use could trigger a disproportional but desirable change in some sensitive environments (Foley and others, 2003). One suggestion is for land use and land cover changes to be engineered by optimal spatial distribution to achieve desirable modifications of the local climate (Pyke and Andelman, 2007). In the context of solar power, the spatial distribution of surface albedo changes associated with large-scale solar power systems might be optimised to enhance cloud development and rainfall in support of local agriculture. Any increased cloud cover could also offset the small decrease in the Earth's albedo from major solar power developments, with due account taken of local weather conditions to avoid reduced electricity output because of cloud shadowing.

The above comments represent an ideal solar-driven scenario for a sustainable and carbon-neutral global energy economy. Another pathway might be the development of silicon smelters driven by nuclear power, analogous to the proposal by Yamawaki and others (2007) for hydrogen generation from nuclear power. Nuclear-generated fuel silicon would enable the effective export of nuclear power to nations such as New Zealand with a reluctance to move toward direct nuclear power supply. However, this approach would not be sustainable in the long term because of limitations of global uranium supply. There is also the additional issue of disposal of nuclear waste. One sustainable variation that would nonetheless be highly undesirable environmentally would be to use the production and export of fuel silicon as the basis for a new wave of large hydro dams in major rivers around the world.

DISCUSSION

It might be argued that both the silicon and hydrogen sustainable economies could be bypassed by electricity supply from coal-fired power stations coupled with carbon dioxide sequestration. However, such a scenario is unlikely as a means toward reducing emissions from coal fired power stations generally because of the scale and costs of the operation involved (Pearce, 2008). Biofuel may be seen as another sustainable alternative but this carries the significant risk of actually increasing emissions and contributing to food price rises. Another variation might be to use aluminium rather than silicon as an energy carrier. However, deposits of bauxite are relatively rare compared to natural silica concentrations and there would be inevitable competition with existing aluminium usage.

Sustainable hydrogen and silicon "economies" both require solution of significant technological problems to become reality, although the respective issues are very different. Large-scale storage and delivery systems of hydrogen remain under consideration, while storage and shipping delivery of fuel silicon would be straightforward. The critical issues for a sustainable global silicon economy are the development of carbon-neutral silicon smelting and the need to construct power stations capable of significant electrical output through continuous and rapid high-temperature oxidation of fuel silicon.

CONCLUSIONS

An initial vision has been presented of a sustainable global energy economy based on international trade of fuel silicon derived predominantly from solar power. It may be that some specific technological or economic factor will be demonstrated to be so difficult that there can never be a global silicon economy as envisaged here. On the other hand, if such a silicon economy appears to a possibility then it would be useful to rapidly ramp up research funding into the many economic, technological, and social facets of the subject. This would include optimal design of silicon power stations from the ship scale to large land-based units, efficient carbon-neutral silicon smelting, determination of maximum impurity levels for fuel silicon, development of large-scale solar power generation and electricity transmission to silicon smelters, optimal geographical distribution of smelters and power stations, and optimal regional side benefits from large scale solar power development.

A hope for the future is that sufficient research momentum could be achieved to establish a *Journal of Silicon Energy* and other information-sharing mechanisms similar to the current hydrogen energy research effort. Of course, some silicon economy aspects such as developing efficient and economical solar power generation will continue in any case as renewable energy research in its own right.

Both silicon and hydrogen economies might even develop in different directions at the same time. Heiman and Solomon (2007) note that small-scale hydrogen economies are suited for localities such as Iceland or Hawaii, which are well endowed with renewable energy resources. A silicon economy is better suited to the large scale distribution and storage of renewable energy to make optimal use of sustainable global energy resources for the collective good. Technology permitting, a best outcome for the future would be for a sustainable global silicon energy economy developed to the extent that carbon dioxide emissions are reduced to less than ocean absorption, marking the peak carbon change point to a condition of declining atmospheric carbon dioxide.

Acknowledgement

The author wishes to thank two anonymous reviewers for their helpful comments.

REFERENCES

Asif, M., and Muneer, T., 2007, Energy supply, its demand and security issues for developed and emerging economies: Renewable and Sustainable Energy Reviews, v. 11, no. 7, p. 1388-1413.

Auner, N., 2007, Energy economy based on silicon: facts and perspectives: Nachrichten aus der Chemie, v. 55, no. 6, p. 627-633. (English translation).

Auner, N., and Holl, S., 2006, Silicon as energy carrier - facts and perspectives: Energy, v. 31, no. 10-11, p. 1395-1402.

Bardsley, W.E., 2005, Note on the pumped storage potential of the Onslow-Manorburn depression, New Zealand: Journal of Hydrology (NZ), v. 44, no. 2, p. 131-135.

Broesamle, H., Mannstein, H., Schillings, C., and Trieb, F., 2001, Assessment of solar electricity potential in North Africa based on satellite data and a geographic information system: Solar Energy, v. 70, no. 1, p. 1–12.

Cherry, R.S., 2004, A hydrogen utopia? : International Journal of Hydrogen Energy, v. 29, no. 2, p. 125-129.

D'Almeida, C., Vorosmarty, C.J., Hurtt, G. C., Marengo, J.A., Dingman, S.L., Keim, B.D., 2007, The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution: International Journal of Climatology, v. 27, no. 5, p. 633-647.

Daviss, B., 2007, Our solar future: New Scientist, v. 196, no. 2633, p. 33-37.

Dunn, S., 2002, Hydrogen futures: toward a sustainable energy system: International Journal of Hydrogen Energy, v. 27, no. 3, p. 235-264.

ENN, 2008, Ship CO_2 emissions at 3.5 pct of global total: IMO: http://www.enn.com/pollution/article/27055

Fang, C., 2008, Editorial: Time Out Singapore (April issue), p.3.

Fargione, J., Hill, J., Tilman, D., Polasky, S., and Hawthorne, P., 2008, Land clearing and the biofuel carbon debt: Science, v. 319, no. 5867, Vol. 319, p. 1235-1238.

Foley, J. A., Coe, M. T., Scheffer, M., and Wang, G., 2003, Regime shifts in the Sahara and Sahel: interactions between ecological and climatic systems in northern Africa: Ecosystems, v. 6, no. 6, p. 524-539.

Goltsov, V. A., Veziroglu, T. N., and Goltsova, L. F., 2006, Hydrogen civilization of the future - a new conception of the IAHE: International Journal of Hydrogen Energy, v. 31, no. 2, p. 153-159.

Heiman, M. K., and Solomon, B. D., 2007, Fueling U.S. transportation: the hydrogen economy and its alternatives: Environment, v. 49, no. 8, p. 10-25.

Institute of Atmospheric Physics, 2007, Comparing fuel consumption, CO_2 and other emissions from international shipping and aircraft. http://www.pa.op.dlr.de/SeaKLIM/Fuel_Emissions_International_Shipping.html

Lauer, A., Eyring, V., Hendricks, J., Joeckel, P., and Lohmann, U., 2007, Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget: Atmospheric Chemistry and Physics, v. 7, no. 19, p. 5061-5079.

McDowall, W., and Eames, M., 2006, Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: a review of the hydrogen futures literature: Energy Policy, v. 34, no. 11, p. 1236-1250.

Madlener, R., and Stagl S., 2005, Sustainability-guided promotion of renewable electricity generation: Ecological Economics, v. 53, no. 2, p. 147-167.

Ministry of Economic Development, 2007, New Zealand Energy Strategy to 2050: http://www.med.govt.nz/templates/MultipageDocumentTOC____31948.aspx

Mölders, N., and Kramm, G., 2007, Influence of wildfire induced land-cover changes on clouds and precipitation in interior Alaska - a case study: Atmospheric Research, v. 84, no. 2, p. 142-168.

Moriarty, P., and Honnery, D., 2007, Intermittent renewable energy: the only future source of hydrogen? : International Journal of Hydrogen Energy, v. 32, no. 12, p. 1616-1624.

Morton O., 2006, A new day dawning? : Nature, v. 443, no. 7107, p. 19–22.

Murray, M. L., Seymour, H. E., and Pimenta, R., 2007, Towards a hydrogen economy in Portugal: International Journal of Hydrogen Energy, v. 32, no. 15, p. 3223-3229.

National Research Council, 2004, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs:
http://www.nap.edu/openbook.php?isbn=0309091632

Nowotny, J., and Sheppard, L. R., 2007, Solar-hydrogen: International Journal of Hydrogen Energy, v. 32, no. 14, p. 2607-2608.

Patton, E. G., Sullivan, P. P., and Moeng, C-H., 2005, The Influence of idealized heterogeneity on wet and dry planetary boundary layers coupled to the land surface: Journal of the Atmospheric Sciences, v. 62, no. 7, p. 2078-2097.

Pearce, F., 2008, Cleaning up coal: New Scientist, v. 197, no. 2649, p. 36-39.

Pimentel, P., and Patzek, T., 2007, Ethanol production: energy and economic issues related to U.S. and Brazilian sugarcane: Natural Resources Research, v. 16, no. 3, p. 235-242.

PureEnergySystems, 2007,
http://pesn.com/2007/05/02/9500469_RSI_Silicon_wins_MIT_contest/

Pyke, C. R., and Andelman, S. J., 2007, Land use and land cover tools for climate adaptation: Climatic Change, v. 80, no. 3-4, p. 239-251.

Rifkin, J., 2002, The hydrogen economy: The creation of the worldwide energy web and the redistribution of power on Earth: Penguin Putnam, New York, 294 p.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T-H., 2008, Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change: Science, v. 319, no. 5867, p. 1238-1240.

Solomon, B. D., and Banerjee, A., 2006, A global survey of hydrogen energy research, development and policy: Energy Policy, v. 34, no. 7, p. 781-792.

Tsoutsos, T., Frantzeskaki, N., and Gekas, V., 2005, Environmental impacts from the solar energy technologies: Energy Policy, v. 33, no. 3, p. 289-296.

van Ruijven, B., van Vuuren, D. P., and de Vries, B., 2007, The potential role of hydrogen in energy systems with and without climate policy: International Journal of Hydrogen Energy, v. 32, no. 12, p. 1655-1672.

Yamawaki, M., Nishihara, T., Inagaki, Y., Minato, K., Oigawa, H., Onuki, K., Hino, R., and Ogawa, M., 2007, Application of nuclear energy for environmentally friendly hydrogen generation: International Journal of Hydrogen Energy, v. 32, no. 14, p. 2719-2725.

Yasuda, K., Nohira T., Hagiwara, R., and Ogata, Y. H., 2007, Direct electrolytic reduction of solid SiO_2 in molten $CaCl_2$ for the production of solar grade silicon: Electrochimica Acta, v. 53, no. 1, p. 106-110.

Yasuda, K., Nohira T., Ogata, Y.H., and Ito, Y., 2005, Direct electrolytic reduction of solid silicon dioxide in molten LiCl-KCl-$CaCl_2$ at 773 K: Journal of the Electrochemical Society, v. 152, no. 11, p. D208-D212.