Waste Fuels the Hydrogen Economy

The twentieth century was the century of fossil fuels. Coal, which had helped usher in the industrial revolution, had, by the 1960s, given way to oil as the major world energy source. By the 1990s natural gas was becoming increasingly popular, fuelled by concerns over air pollution. During this period an inherent conflict emerged concerning the ability of the global ecosystem to assimilate the outputs from the growing fossil fuel based economy. Amongst the principal concerns we now have are the unpredictable consequences of rising atmospheric concentrations of carbon dioxide, the long-term effects of which could be dramatic environmentally, economically and socially. Mitigation of the destructive aspects of global warming in the future will be technologically challenging and will require the development of a sustainable economy that can meet our energy demands.

The steps towards an economy based on renewable energy could see a number of unusual sources being exploited. Sewage sludge may be one of these resources. Although it is a human waste synonymous, for many, only with disease it has, for centuries, proven to be a high quality agronomic product for farmers throughout the world. Currently, the United Kingdom utilises its sewage sludge residues in many sustainable ways. Recycling to land of treated sludge is widely practised and sludge-to-energy plants burn the highly calorific material to produce electricity for export to the national grid. Higher standards imposed with the Urban Waste Water Directive (91/271/EEC) have resulted in higher volumes of sludge being produced and more treated sludge being recycled to agricultural land. The revision of the European Directive on recycling sludge to land (86/278/EEC) could, however, reduce the land bank available for recycling sludge as the permissible heavy metal concentrations are tightened. With the construction of more incinerators likely to encounter public opposition the continuation of what are considered to be the best practical environmental options for sludge recycling may prove problematic for the water industry in the future. However, alternative uses for sewage sludge are being developed. Technological developments have shown that potentially sewage sludge could become an important part of the proposed hydrogen energy economy. The association traditionally made between sewage sludge and the generation of a noxious, odorous gas could change as hydrogen generated from sludge provides us with clean air whilst supplying the power needed to run our vehicles.

The attraction of hydrogen as a fuel is that it has high energy content per unit mass and when it is burned it produces only water. Most importantly, a conversion to a hydrogen economy could help towards reversing some of the effects of climate change caused by elevated atmospheric levels of carbon dioxide and other greenhouse gases. Leading the drive towards a hydrogen based energy economy will be the development of viable hydrogen fuelled vehicles. The Energy White Paper, published by the Department for Trade and Industry, identifies transport as one of the major contributors to carbon dioxide levels, accounting for 25% of the total emissions (and 35% of energy usage). Most major car manufacturers are now investing in fuel cell technology and they foresee a future whereby cars are powered by hydrogen. The hydrogen fuelled BMW H2R recently broke records when it reached speeds of 187mph during testing in Miramas, France. The car uses a modified version of the traditional combustion engine, but cars that work on electricity generated from hydrogen fuel cells are developing fast. The Honda FCX, running on hydrogen fuel cells, can achieve speeds of 93mph and has a range in the region of 160miles. Other developments, such as fuel cell powered rickshaws that can achieve urban speeds and Transport for London's hydrogen fuel cell buses, are pioneering this rapidly advancing technology. Many technical problems do remain to be solved, however. Storing hydrogen is particularly problematic and it typically has to be compressed and cooled to allow it to be stored in a useful and practical volume. Recently, however, materials have been developed that can safely store and release, when required, pressurised hydrogen onto a nano-porous structure. Some researchers claim to have managed to store 30 litres of hydrogen on a single gram of graphite, which, if adaptable, would enable a journey from London to Calcutta to be achieved before refuelling. Developments such as these are important stepping stones if the reality of a hydrogen economy is to become viable in the future.

Hydrogen gas may be produced from a wide range of sources. Fossil fuels, and in particularly natural gas, can be used to generate hydrogen and in the medium term this would be the most practical option available for its generation. Of the options available to the UK though, the electrolysis of water using electricity generated by offshore wind power is probably the most viable method of generating hydrogen on a large multigigawatt scale. A significant proportion of hydrogen could also be generated from biomass which may come from crops, such as short rotation coppice and miscanthus, and other materials such as sewage sludge.

Deriving hydrogen from sewage sludge is already an established process and fuel cells have been demonstrated to run successfully on sewage sludge digester gas. Phosphoric acid fuel cells have been installed at Wastewater sites in the United States and 2005 will see RWE install Europe's first 250kW carbonate fuel cell power plant, using anaerobic digester gas from a Wastewater Treatment Works in Ahlen, Germany. The potential total global electric power that could be generated using anaerobic digester gas has been estimated to be as high as 13000 MW. The anaerobic digestion process uses mesophilic bacteria to break down the sewage sludge substrate and the gas produced during this process consists of approximately 65% methane and 35% carbon dioxide. The relatively high methane ratio means that digester gas has a high calorific value not far below that of natural gas and fuel cells use this methane-rich digester gas as a feed. Sewage Treatment Works often use the methane produced to run Combined Heat and Power (CHP) plants from which electricity is produced for use on site or for export to the national grid. CHP plants have proved to be a significant development for the water industry, which is the third most energy intensive sector in the UK. Therefore, the use of the methane in fuel cells would have to compete with CHP plants, although one of the principal advantages of fuel cells is that their energy returns are potentially higher. When it comes for use in fuel cells the impurities in digester gas, which include hydrogen sulphide, ammonia, carbon monoxide and siloxanes mean it must be extensively cleaned prior to usage. The methane from the anaerobic digester gas is electrochemically converted into a hydrogen-rich gas using a fuel reformer attached to the fuel cell. Upon entering the fuel cell the hydrogen can react with oxygen in the air to create the electricity and heat. A number of different types of fuel cell are on the market or under development. Phosphoric Acid Fuel Cells (PAFC) are commercially available and with their general tolerance for impurities it has led them to be the most widely used type, currently, for this application. In the longer-term high temperature Molten Carbonate Fuel Cells (MSFC) and Solid Oxide Fuel Cells (SOFC) are predicted to become the most promising for biomass based fuel applications.

Although hydrogen can be produced from the methane of digester gas, recent work has shown that hydrogen can be generated directly from sewage sludge and similar biomass substrates. This hydrogen, if enriched and purified, could then be used directly in a fuel cell to generate electricity. Direct hydrogen production from sewage sludge is mediated, in a natural process, by a variety of microorganisms. Photosynthetic routes to produce hydrogen are known which can utilise either algae or photosynthetic bacteria. However, in terms of deriving hydrogen from sewage sludge the work, to date, has concentrated predominantly on non-photosynthetic facultative or obligate anaerobes to produce hydrogen in a fermentative process. The anaerobic conditions are important since the presence of oxygen inhibits the action of the enzyme hydrogenase, which plays a vital role in the chemistry of the process.

A number of microorganisms appear to be particularly well adapted to hydrogen production. Thermophilic bacteria such as Thermoanaerobacterium, Thermatoga maritima and Clostridium thermocellum have all been investigated for their hydrogen production potential but experiments have also been carried out on bacteria suited to the mesophilic temperature range, around 35^{O}C. Clostridium species appear to be particularly well adapted and are often indigenous to sewage sludge samples from which they can be isolated.

The process conditions are important in order to optimise hydrogen production by this method. A preheat treatment of the sewage sludge is carried out that helps to select for the desired microbial species, namely Clostridium. Methanogens, which may compete for nutrients and consume hydrogen, are also reduced during this step. Combining the sewage sludge with carbohydrate rich substrates has been shown to increase the growth of Clostridium cultures. Amongst the parameters shown to be most significant, temperature, retention time and pH have all been demonstrated to have an impact on the hydrogen yields from the process.

A number of factors can inhibit the process though. Hydrogen itself, when it reaches higher concentrations, acts as an inhibitory agent as do other metabolic products, such as acetic acid and propionic acid. Stripping off the hydrogen as it is produced, for example by purging the system with nitrogen, has been shown to help increase yields. Hydrogen stripping is also important in that if it remains then it will become consumed in a subsequent part of the process. The quality of the gas is important for the viability of the process. The biogas produced during the "dark fermentation" process, as it is known, is relatively rich with a composition of approximately 60% hydrogen. Actual yields are increasing, as the process becomes better understood. Bench scale trials have shown that hydrogen volumes of $210m^3(H_2)$ per ton of dry solids are achievable and, when using a glucose substrate, yields of 11mg H_2/g dry solids have been demonstrated.

Although there is great potential to use sewage sludge as a feed stock it can be a difficult material to work with. The constituents that make up the sludge will vary both daily and from season to season. Rainfall variations, which increase during the winter months, and changes in the organic matter content, could be difficult to control. Festive overindulgence at Christmas, for example, can cause a 25% increase in fats entering sewers. This, combined with the possible presence of potentially inhibitory agents, such as heavy metals and organic contaminants, make the challenge for large-scale fermentative hydrogen production greater. The indications are, though, that the process is robust and using indigenous bacteria for inoculation should help make the system adaptable to local flow variations. Although this technology is in the early stages of development as hydrogen yields are increased its potential for the future will only increase.

On its own facultative bacteria would not be capable of bringing about a conversion to a hydrogen based energy system. But, as the Energy White Paper makes clear, for the health and security of our energy-intensive economy in the future a diverse number of energy sources should be nurtured. Hydrogen generation from the "dark fermentation" of biomass, such as sewage sludge, could therefore find itself an important niche within an emerging hydrogen economy. The twenty first century may see our reliance on fossil fuels eventually come to an end and the dirty world of sewage sludge could find itself part of the green technology of the future.

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