Hydrogen, hydropower and world poverty

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In the light of problems of urban air pollution and global warming, the concept of a hydrogen economy is rapidly moving towards reality. The authors speculate on the role hydropower could play, if a 'hydropower to hydrogen' industry could be established; a particularly interesting aspect is the increased role hydro could play in povery reduction, by helping to develop the economies of some of the poorest countries which have significant hydropower potential.

Hydropower has always been closely linked with the process of development. In the nineteenth century, pioneers such as Francis and Pelton designed larger and more efficient turbines to power the factories that were springing up throughout the industrialized world. In the twentieth century, hydro was in the forefront of the evolving electricity industry, which has possibly been the single most important catalyst for development in the history of mankind.

Although it has yet to be widely recognized, we stand on the threshold of another industrial revolution, based on using hydrogen as a clean fuel in a wide variety of applications. The greatest benefit is likely to come from its use in transportation as a replacement for the hydrocarbons (petrol, diesel, LNG) currently being consumed in such large quantities as to be unsustainable in terms of both resource depletion and the detrimental effect on the environment.

Being emission-free, hydrogen goes a long way towards solving the environmental problem, but the full benefit can only be realized if it is produced from renewable energy sources. While this could encompass a wide range of technologies, most are unsuitable for the production of hydrogen on a large scale. Hydropower is one of the few renewable energy sources that could make a significant impact by providing electricity in sufficiently concentrated form for the large-scale production of hydrogen by electrolysis. If this happens, it could dramatically change the face of our industry, and the resulting impact would be felt far beyond its boundaries.

This paper describes the background to this statement, and speculates on what the future may hold if an H-to-H (hydropower to hydrogen) industry is established. In a companion paper [Gummer and Head, 2003[1]] to be given at the Hydro 2003 international conference in Dubrovnik (3-6 November), the authors examine in more detail the economic case for hydropower as a source of hydrogen for use as a vehicle fuel.

The hydrogen economy

Everybody in the energy business is talking about the hydrogen economy. Something which started as a scientific curiosity only 30 years ago has now reached the stage where it has moved from the test-bed to being a practical reality. Faced with the problems of global warming and urban air pollution, the allure of a fuel that burns cleanly and is totally emission-free is irresistible. The fact that the fuel might be manufactured from renewable resources, thereby reducing our dependence on dwindling oil and gas supplies, further enhances the attraction.

Given this 'glittering prize', it is not surprising that the hydrogen economy continues to find support at the highest level. Vast sums of money have already been invested in research and development. Only last year the European Commission announced a $2 billion programme furthering its 'hydrogen vision'. In his 2003 State of the Union address, US President George W Bush committed a further $1.2 billion, on top of the billions already spent by the US Government, specifically for the development of hydrogen-fuel transportation.

It is in the transportation area that the benefits are likely to be first noticed, and most major automobile manufacturers now expect hydrogen-powered cars to be in mass production within a decade. Some vehicles burn hydrogen in modified internal combustion engines, but this is relatively inefficient and the consensus is that the future lies with the fuel cell, which achieves much higher energy conversion efficiencies by effectively reversing the electrolysis process. Prototype hydrogen vehicles using both propulsion systems are now on the road in many parts of the world including California (for taxis), London (for waste collection trucks), Tokyo (for Federal Express deliveries) and for buses in Reykjavik, Iceland, where Shell has recently opened its first retail hydrogen refuelling station.

All of this is very exciting, but it leads to the obvious question: from where will the hydrogen be sourced?

Sources of hydrogen

Hydrogen is widely used on a relatively small scale in a number of industries such as agrochemicals, so there are already well established methods of commercial production. In fact, there are many ways of manufacturing hydrogen, all involving an energy-conversion process. The most common involves the reformation of fossil fuels, usually gas or oil, but sometimes coal, the primary reason being that it is cheaper than the alternatives. But unfortunately reformation does noth-

A Honda fuel cell vehicle.

Table 1: Estimated costs of hydrogen production*

Method of production	Cost (US$/GJ)
From coal/gas/oil	1-5
From natural gas minus CO_2	8-10
From coal minus CO_2	10-13
From biomass	12-18
From nuclear power	15-20
From onshore wind	15-25
From offshore wind	20-30
From solar cells	25-30

* Source: The Economist [2003[2]].

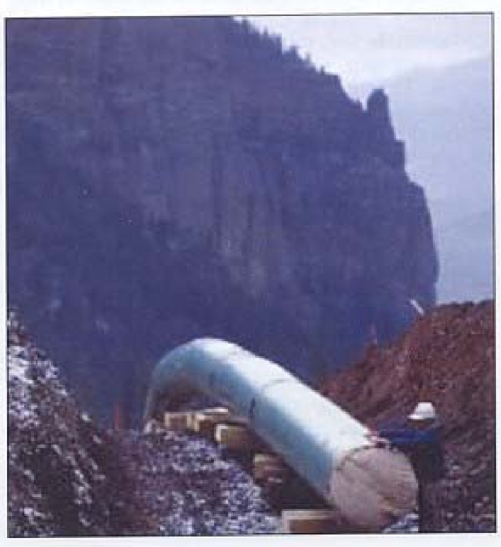
ing to alleviate the pressure on scarce resources, and furthermore it does nothing to solve the greenhouse gas problem, unless accompanied by a process of removing carbons through sequestration. This reduces CO_2 emissions by about 40 per cent, but at greatly increased cost, and it still leaves unresolved the question of the disposal of the sequestered carbon in an environmentally acceptable manner.

Everyone agrees that the preferred solution would be to manufacture hydrogen from renewable sources. This has to be the ultimate objective to achieve sustainability, although with existing technology, it looks doubtful that we shall see anything other than a partial fulfillment of this goal.

Ignoring the distant prospect of generating substantial quantities of hydrogen directly from biomass, 'sustainable hydrogen' has to be manufactured by a two-stage process in which renewable energy is used to generate electricity that, in turn, is converted to hydrogen using electrolysis. Electrolysis is a well established and proven technology, with plants of up to 150 MW in operation but it needs a cheap, concentrated and reliable source of electricity to be competitive.

Most forms of renewable energy do not fall into this category because they are either too expensive, or too diffused and intermittent, to make the commercial production of hydrogen on a large scale a viable proposition. Comparative costs of hydrogen production, based on IEA data, were recently published in *The Economist* [2003[2]] and are reproduced here as Table 1.

Figures to be given in the companion paper show that a favourable hydro site could be developed to produce hydrogen at a 'busbar price' of around US$ 15-17/GJ. If this is the case, it is evident that in cost



A natural gas pipeline.

An LNG ship.

terms, hydro is likely to be as competitive, and probably more competitive, than most other renewable energy technologies, although it is evidently more expensive than using fossil fuels.

However, it is not just a question of price or quality. When one begins to look at the quantity of power needed for electrolysis, it quickly becomes apparent that the numbers are very large.

If we focus only on transportation, which is about 30 per cent of global energy consumption, the scale of the problem is immediately obvious. In 1999, about 56 million barrels of oil per day were used to power the world's fleet of vehicles (equivalent to about 95 TWh/day of energy). Despite advances in improving fuel economy, this number is rapidly increasing as the world's vehicle population increases. In China, for example, the number of vehicles on the road is doubling every five years.

A hydrogen fuel cell is currently about 2.7 times more efficient in converting heat to mechanical energy than an internal combustion engine. Hence the amount of hydrogen that would be needed to support all the vehicles in the world would be the equivalent of about 35 TWh/day. If all of this were to be produced from renewable resources by electrolysis, approximately 62 TWh/day of renewable energy would be needed, after allowing for the efficiency of electrolysis and transportation/distribution. This is nearly 50 per cent more than the total global electricity production in the year 2001.

As the most optimistic forecasts only envisage 10 per cent of electricity being supplied from non-hydro renewable sources by the year 2020, it looks highly improbable that these same resources could simultaneously make a serious impact on the production of hydrogen. The situation becomes even less tenable if, as intended, renewable energy is to increase its share in the generation of electricity, for which the worldwide demand is forecast to increase by more than 80 per cent in the next 20 years.

The conclusion, as already indicated in an earlier paper [Gummer, 2001[3]], is that the demand for hydrogen is likely to exceed by far the supply available from renewable resources. Whether we like it or not, the hydrogen economy will be heavily dependent on fossil fuels for the foreseeable future, with all that this implies. But another way of looking at this same conclusion is that there is likely to be an unlimited market for hydrogen produced from renewable energy resources, provided the cost is within reach of the fossil-based price.

When questions of cost, concentration and reliability are considered, it is evident that there are only two non-fossil energy sources that could make a serious impact on hydrogen production. These are nuclear energy and hydropower. Given the public concerns over the acceptability of the nuclear option, this leaves hydropower as the most plausible source of renewable energy for the hydrogen economy if it is to move in the direction of long-term sustainability, as it inevitably must.

Hydropower for hydrogen

Currently accounting for about 18 per cent of global electricity production after coal (35 per cent) and natural gas (20 per cent), the global hydropower capacity amounts to about 800 GW installed or under construction. It is estimated that another 1500 to 2000 GW of economically feasible hydro remains to be developed. These figures may be only approximate, because of doubts over the definition of economic feasible and the constraints of environmental acceptability, but it is nevertheless evident that the world's hydropower potential is far from being exhausted.

Many of the most promising undeveloped sites lie in Africa, Asia and South America (Fig. 1). Their huge energy resources remain untapped for a variety of reasons, principally related to the lack of local demand and the economic fragility of the regions in which the sites are located. Despite our ability to transmit power over long distances, it remains a fact that the feasibility of any hydropower prospect is largely determined by the regional economy and the political stability of the host country where it is located. In particular, it is not easy to attract private investors when the commercial justification for a project is founded on a single bilateral relationship between the owner and a monopoly buyer whose own financial strength is based on a revenue stream in local currency.

These geographically related problems largely disappear as soon as the product from a hydropower scheme becomes hydrogen instead of electricity. The revenue stream is then secured from the sale of a commodity that is transportable and freely tradable for hard currency on world energy markets. This change would be as fundamental as the one that occurred in 1896, when electrical energy was first transmitted over the then extraordinary distance of 20 miles (32 km) from Niagara Falls to Buffalo, NY, thereby opening up completely new markets to the owners of hydropower facilities.

Although in principle electrolysis could be carried out anywhere, the probability is that for technical and economic reasons it would be at the site of the hydropower scheme itself. There would obviously be no shortage of water, and it is estimated that the electrolysis plant would add only 15 to 20 per cent to the cost of the basic hydropower project. In fact it is generally cheaper to transport energy as a gas or liquid in a pipeline, rather than along a transmission line as electricity, and the hydrogen would normally be evacuated by pipeline under pressure using technology which already exists. Hydrogen pipelines are currently in operation in Europe, the UK and the USA.

In many cases pipelines will be the only form of transportation needed to reach the nearest distribution point. However, for projects located in undeveloped markets where there is insufficient internal demand, the gas would have to be shipped over the border, and maybe even overseas at extremely low temperatures in cryogenic container vessels similar to those currently in use in the natural gas industry. There are of course many issues still to be resolved concerning the establishment of a viable gas distribution infrastructure, but these relate to hydrogen generally and are not specific to hydropower. The essential point is that hydrogen produced at a distant hydropower site can be transported to world markets.

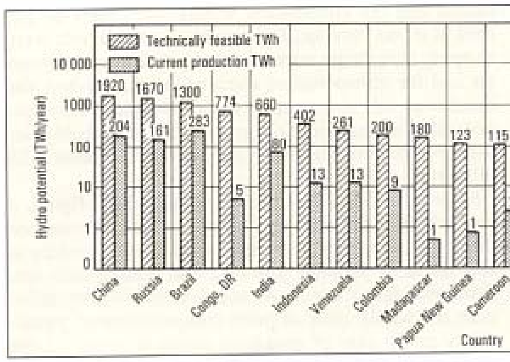


Fig. 1. Examples of countries with hydropower surpluses.

Will hydropower be cost-competitive?

The most attractive hydro schemes for hydrogen production would be large base-load stations, typically more than 1000 MW. The best of these sites should be able to produce electrical energy for less than US¢ 3.5/kWh. By the time that the cost and efficiency of electrolysis, and a royalty payment, are taken into account, the equivalent cost of hydrogen at the plant in heat terms is about US$ 15-17/GJ [Gummer and Head, 2003[1]].

Table 1 demonstrates the cost advantage of producing hydrogen from fossil fuels without sequestration. However, if concerns over global warming remain unabated, it seems inconceivable that this practice will be allowed to continue indefinitely. When sequestration costs are added, the price of hydrogen from fossil fuels rises to between US$ 8 and 13/GJ, depending on the type of fuel used. Natural gas lies at the lower end of this price range, but with the electricity supplies of so many countries already uncomfortably over-dependent on this resource, it is questionable whether in the long term gas will be acceptable for use in hydrogen production.

Nuclear power is shown as costing US$ 15 to 20/GJ, although it is unclear whether these figures cover the full decommissioning costs. It is probable that they do not, because these costs remain largely unquantified. Given that nuclear is at present the only practicable non-fossil fuel without limitation on its ultimate output, it might well provide a guide to the long-term marginal cost for the production of hydrogen from renewable energy resources. If this turns out to be the case, it would bring many hydro sites within competitive reach in financial terms.

Irrespective of whether or not nuclear ultimately determines renewable energy costs, it is apparent that hydropower is in a position to compete with most alternative energy sources. It may be more expensive than fossil fuels, even with sequestration, but that gap would rapidly be closed by an increase in fossil-fuel prices, or changes in fiscal measures such as taxation.

When considering hydrogen as a vehicle fuel, the position on comparative costing is obfuscated by a number of cost factors that lie far outside the scope of this paper (for example, the distribution infrastructure, the price of the vehicle and taxation). However, taking as an example the USA, where tax on vehicle fuel is low, it can be shown that hydrogen sourced from hydropower at US¢ 3.5/kWh would become competitive as a vehicle fuel when oil reaches about US$ 35/barrel, assuming the same taxation levels in heat terms. However, because of the higher efficiency of the fuel cell over the internal combustion engine, this means that the government would lose nearly 65 per cent of its tax revenue. If the same taxation levels were to apply in mileage terms, so that government revenue on fuel for transportation remained undiminished, the breakeven oil price becomes US$ 46/barrel. One suspects that in practice the correct solution probably lies somewhere between these two, perhaps around US$ 40/barrel.

Although US$ 40/barrel may sound a high figure, it has to be remembered that oil prices have approached this level in the past, and they are unlikely to reduce in real terms as supplies diminish and control falls into fewer and fewer hands. As taxation can heavily influence the whole issue of price competitiveness, particularly in the case of countries where it forms a large component of the ultimate selling price, the attitude of individual governments is crucial. In this respect, the policy of the Icelandic Government in pursuit of its plans for a hydrogen economy based on the country's extensive hydro and geothermal generating facilities is an interesting example; hydrogen is sold tax-free.

The breakeven oil price could significantly reduce in the future with the expected advances in hydrogen fuel cell design and the judicious use of onboard battery storage to maintain the fuel cells operating at their optimum efficiency.

With future technology hydrogen sourced from hydropower could be competitive at an oil price of less than US$ 20/barrel assuming tax on an equivalent mileage basis, with no overall reduction in tax revenue [Gummer and Head, 2003[1]].

Financing issues

Given the priority that renewable energy now enjoys, and the obvious merits of hydropower, it is surprising that we are not seeing a resurgence in the construction of new hydro projects. In fact, the rate of new hydro development has fallen in recent years, and it is widely recognized that this is largely because of changes in the way projects are financed.

The restructuring of the power industry around the private ownership of generating and distribution assets has had a profound effect on the hydropower industry. The majority of the recent investment in power generation has gone into gas-fired power stations. We are now in the contradictory position of being highly concerned about global warming, and yet at the same time building increasing numbers of fossil-fuelled power stations.

The reason for this is that private investors are inevitably focused on relatively short time horizons, and are looking for projects with an early positive cash flow and few risks. Hydro projects being developed on a stand-alone basis as IPPs, with all the risks contained within the single project, seldom meet these criteria. As a result, project financing becomes a long and costly exercise, and many projects fail to reach financial closure. Another problem is the reluctance of prospective investors to become involved with the NGOs on environmental issues.

If hydrogen becomes a major energy industry, it can reasonably be assumed that it will attract large international companies such as the petrochemical giants. As noted above, Shell has already opened its first branded retail site selling hydrogen. There is an obvious analogy to be drawn here with the past, for in the early part of the last century oil fields were developed in locations that were every bit as remote and risky as some of the best hydro sites today. The oilfield projects were highly site-specific, and the actual development costs and production rates were no doubt subject to the same uncertainties as they are for hydro projects. But the developments were successfully financed because the companies could spread the risk over many projects, and the returns were sufficiently attractive to make it all worthwhile. The same analogy can be drawn with the international mining industry.

The 'H-to-H' industry would be no different. Projects would be financed by major international companies with the resources to raise the capital and spread the risks across a portfolio of hydrogen-producing projects, not necessarily all hydropower. This injection of a broader capital base would overcome most of the current problems being experienced in the financing of new hydropower projects, and unlock new sources of funding which hitherto have not been available to prospective hydropower developers.

Table 2: Global estimate of royalty income (assuming 65% development)

Country	GDP[1] (10^6 US$)	Export earnings[2] (10^6 US$)	Remaining feasible[3] (TWh/yr)	Royalty income[4] (10^6 US$/yr)	Royalty as % of exports (%)	Royalty as % of GDP (%)
Angola	11,380	7000	106	413	6	4
Bhutan	594	154	103	402	261	68
Cameroon	9060	2100	112	435	21	5
Chile	64,154	18,500	128	500	3	1
Colombia	82,194	12,300	163	636	5	1
Congo, DR	5704	750	768	2995	399	53
Costa Rica	16,887	5000	37	146	3	1
Ethiopia	5989	442	258	1006	228	17
Gabon	4971	2500	79	308	12	6
Kyrgyzstan	1632	475	89	346	73	21
Lao PDR	1680	325	99	385	118	23
Madagascar	4514	680	180	700	103	16
Nepal	5493	757	225	877	116	16
Papua New Guinea	2793	1800	74	287	16	10
Pakistan	60,521	8800	244	952	11	2
Paraguay	5389	2200	33	129	6	2
Peru	56,901	7300	300	1168	16	2
Russia	346,520	104,600	1496	5834	6	2
Tanzania	9383	800	17	68	8	1
Turkey	182,848	37,600	171	666	2	0
Venezuela	94,340	29,500	200	781	3	1
Zambia	3683	876	21	80	9	2

1. Source: World Bank database
2. Source: CIA Factbook
3. Technically feasible hydro potential less existing production. Source: *Hydropower & Dams World Atlas & Industry Guide*, 2003.
4. Assuming 65% of remaining technically feasible used for hydrogen, at CO.06/kWh.

Environmental issues

No paper on this subject can avoid making reference to the environmental opposition that now seems to face so many hydro projects. Unfortunately, much of this opposition tends to be founded on a doctrinaire objection, by a small hard-core of NGOs, to any development on rivers, irrespective of their merits or demerits, and without regard to the consequences of the alternative of not building the project. While many developers are working hard to satisfy the environmental lobby, there nevertheless remains a serious risk that the multitude of (often conflicting) interests now presenting themselves as stakeholders will result in nothing being built, other than paper mountains.

It is an indisputable fact that there is an inexorable demand for electricity. Some power projects may not be environmentally acceptable, but it has to be recognized that these difficult judgements need to be made by balancing alternatives and ultimately accepting the least damaging option. When the environmental advantages of the hydrogen economy become evident, and there is a better understanding of the limited range of options for producing renewable hydrogen, it is to be hoped that debate will reflect the hard fact that there are few, if any, energy solutions with no negative impact.

There is certainly no other form of hydrogen production that would have the wider international spin-off that an H-to-H project would create, not only by providing clean, sustainable energy but also in terms of developing the economies of some of the world's poorest countries. It could have a noticeable impact on the distribution of wealth between the developed world, which is generally energy deficient, and some developing countries that are lucky enough to find themselves with an abundance of hydro resources.

The world poverty dimension

It has already been noted that most of the remaining hydro potential lies in the developing world, where one finds many countries with hydropower resources far exceeding domestic energy requirements. A number of these are listed in Table 2.

It would be reasonable to assume that where an H-to-H plant is established, the host country would receive a royalty for the use of its natural resources. If we draw again on the analogy of the oil industry, the royalty might be of the order of 15 per cent of the bulk price of the hydrogen produced. In monetary terms, this might mean US¢ 0.6/kWh of electrical output. With this sort of margin, a country producing, say, 50 TWh/year of hydropower for electrolysis (equivalent to about 10 000 MW at 60 per cent capacity factor) might receive around $300 million in royalties every year. In addition, there would be the obvious downstream economic returns and additional tax revenue that would be created by the construction and operation of such a major project in the country.

There naturally has to be a balance between the amount of money that the host country accrues from a project and the competitiveness of the end product. Equally, it would be unrealistic to imagine that all the remaining undeveloped hydro potential could be harnessed for the production of hydrogen. However, as a very approximate indication, Table 2 shows the royalties that might be accrued on an annual basis, assuming that 65 per cent of the remaining technically feasible potential is used for hydrogen production, paying a royalty of US¢ 0.6/kWh. To set these figures in perspective, they are shown as a percentage of current export earnings and GDP.

As with any natural resource, the benefits are unevenly distributed, but from Table 2 it is clear that for a number of countries the potential income would significantly boost export earnings and, in some cases, increase GDP by more than 15 per cent. Included in this list are economies which have little else to offer the export market other than hydropower. Fig. 2 shows the potential impact, in terms of the uplift to export earnings, for the countries most affected in this respect.

Conclusions

In the course of its long history, the hydropower industry has evolved beyond all recognition. A little more than 100 years ago it was providing mechanical energy for local mills, then electricity on a regional basis. Perhaps we are now about to witness another equally momentous change, with new projects being built to deliver hydrogen to world markets. On the evidence available it seems highly possible.

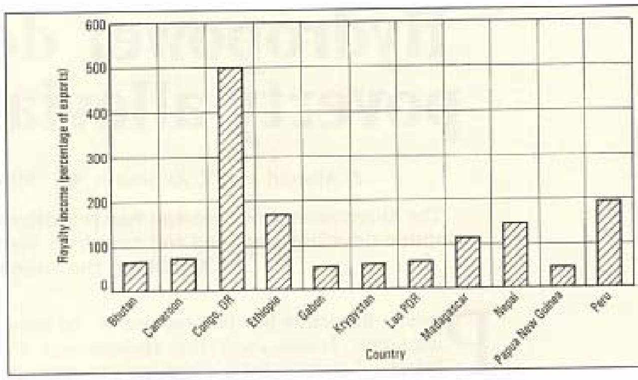


Fig. 2. Representative royalties as a percentage of current export earnings.

Unfortunately, the goal of a totally renewable hydrogen economy looks unattainable because the quantities of energy required are so large. Hydropower is never going to displace the need for other methods of hydrogen production, which will inevitably continue to be heavily reliant on hydrocarbons, presumably with sequestration of CO_2, and probably also nuclear energy.

By producing renewable hydrogen, hydropower can do much to contribute towards a cleaner and safer world. But it can also play a major role in poverty reduction by transferring wealth from the relatively affluent (but energy deficient) industrialized countries, to some of the poorest parts of the globe.

It is perhaps no coincidence that in the francophone countries hydropower is sometimes referred to as 'la houille blanche' - white coal (in a reference to the days when coal was the only real alternative for industrial energy). But unlike coal, or any other fossil fuel for that matter, there should be no concerns over depletion of reserves. As long as it rains the revenue will flow, and hydro will continue to play its traditional role in the forefront of development. ◊

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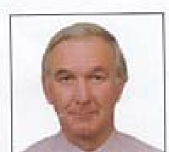

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