The economics of sourcing hydrogen from hydropower

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In their earlier paper [Gummer and Head, 2003[1]], the authors proposed that the future hydrogen economy could be fuelled in part by hydrogen generated using electrolysis sourced from hydropower facilities. The world's remaining hydro potential is largely located in developing countries that currently have no demand for the energy locked in their rivers. The authors argue that this energy could be harnessed to serve a future hydrogen economy.

As with oil, the revenue generated from the new 'Hydropower to Hydrogen' industry could bring new wealth for hydro-rich developing countries, as well as providing a much-needed stimulus to international hydropower development. However this vision of a rosy future is only realistic if the promised hydrogen economy is not too far in the future, and the economics of H-to-H is not prohibitively expensive compared with other potential sources.

In this paper, the authors continue on from their second paper [Gummer and Head, 2003[2]], on the same subject and look in detail at the economics of hydrogen production from representative hydropower facilities, with particular reference to its use as a vehicle fuel.

1. The costs of hydrogen from hydropower at source ('Well' cost)

The basic equation for the Well cost of hydrogen at the point of production is:

$$W = \left\{ \frac{B_p + E_p + R_c}{E_{Eff}} \right\} x 277.7$$

where:

W = Well cost of hydrogen US$/GJ;
B_p = Cost of electricity generation US¢/kWh plus operating profits;
E_p = Unitised capital cost of electrolyser equipment US¢/kWh;
R_c = Royalty cost US¢/kWh; and,
E_{Eff} = Electrolysis efficiency (per cent).

The factor 277.7 is the conversion of US¢/kWh to US$/GJ. Hence, taking each of these factors in detail:

1.1 Cost of electricity generation plus operating profits (B_p)

As with any hydro development, the starting point for a competitive evaluation of an H-to-H project is the quality of the hydropower site itself. With today's low interest rates and competitive construction climate, one might expect a favourable site to deliver electrical energy at US¢ 3.5/kWh.

However, this is probably the lowest cost to be considered, especially when a reasonable profit for the builder/operator is taken into consideration.

Accordingly, sites that deliver up to 5 US¢/kWh may be economically sound ('viable') for hydrogen production depending on the particular circumstances and local factors. Hence, for the purposes of comparison, we shall take a range of US¢ 3.5 to 5/kWh.

1.2 Cost of electrolysis plant (E_p)

There are few precedents for the unitised capital cost of large electrolysis plant. However, from the limited information available, it would appear that 15 per cent of the cost of the hydro facility would be realistic, that is, about US¢ 0.6/kWh.

1.3 Royalty to host country (R_c)

Royalty for the host country must be both favourable to the country's economics and to the developer of the scheme. In fact, the case of hydro to hydrogen would be very similar to royalties paid by oil companies to their host source country. Traditionally, this is in the range 10 per cent to 20 per cent of the commodity price of oil. Hence, for the purposes of this exercise, a base case royalty of US¢ 0.6/kWh is assumed, but the effects of royalties greater and less than this will be examined. Royalty of US¢ 0.6/kWh is about 15 per cent of the value of the hydrogen at the point of production (taken to be at the site of the hydropower station) for the base case, which is broadly in line with oil industry practice.

1.4 Efficiency of conversion of electrical energy to hydrogen (E_{Eff})

For economic and technical reasons, the conversion of electrical energy to hydrogen by electrolysis would probably be undertaken at the site of the hydropower station. The efficiency of the electrolysis process is estimated to be about 75 per cent. This is somewhat more than the 65 per cent to 70 per cent currently being achieved with smaller installations using open-bath electrolysers, but less than the 85 per cent believed to be attainable in the future using a more efficient process that is effectively a reversal of the PEM fuel cell.

1.5 Comparison of 'Well' cost of hydrogen

Applying these factors yields 'Well' prices as shown in Fig.1. This shows a price of US$ 17/GJ for the minimum cost electricity production and royalties, rising to US$ 24/GJ for the maximum values considered. Future improvement in electrolysis efficiency should reduce these prices by about 13 per cent.

Comparative figures for other means of sourcing hydrogen are given in an article in the *The Economist* [2003[3]] and are reproduced in the Table on p76.

It therefore seems inevitable that in the initial years of the hydrogen economy, there will be a heavy reliance on hydrogen generated from steam reforming of fossil fuels, primarily natural gas. However, this is not a long-term solution for the environment, as greenhouse gases are still produced and discharged into the atmosphere. At the rate at which the world's vehicle

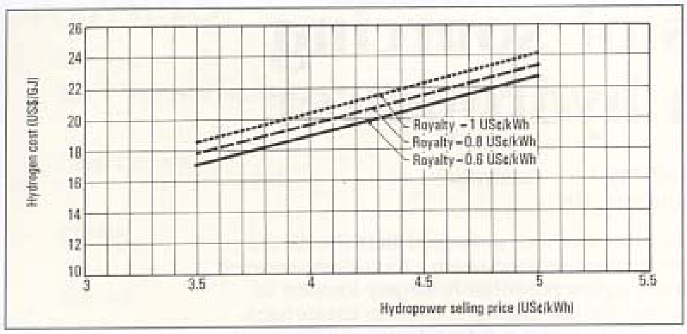


Fig. 1. Well cost of hydrogen produced from hydropower current technology; no battery.

population is increasing, the concept of "drive here and pollute elsewhere" will simply become unsustainable. A partial solution is to collect, or sequester, the carbon resulting from the reformation process and deposit it in landfills, or in the sea or down exhausted oil wells.

Even at US$ 17/GJ, H-to-H is no contender against hydrogen manufactured from steam reforming of fossil fuels without sequestration, but as soon as sequestration is included in the process, the comparative economics are much improved in favour of the non-fossil fuel alternatives. Also, it must be remembered that although sequestration techniques are technically feasible, they are currently largely untried and essentially unpriced, especially when the eventual disposal of the resulting carbon is taken into consideration. Landfills and underwater deposits for the carbon have been proposed, as have exhausted oil wells, but practical implementation of these ideas has yet to be proven.

Even though they are competitive in price with H-to-H, the popular renewable resources of wind power, wave and biomass are all too diluted or unreliable to make a major contribution to large-scale hydrogen production. This effectively implies that with existing technology the commercial production of hydrogen from non-fossil sources means using nuclear energy or hydropower. The costs of hydrogen sourced from these two is likely to be broadly similar, but the scale of demand is such that ultimately both will be needed, although nuclear power is currently still facing serious resistance in many countries.

In summary, once one moves to sustainable hydrogen production, there is a very strong technical case for hydropower. Our interest now lies in its competitiveness, specifically for use as a vehicle fuel.

2. The costs of delivery hydrogen (Well to tank cost)

The basic equation 'Well-to-tank' cost of hydro produced hydrogen is:

$$W_T = \frac{\{W + T_c\} \times 100}{T_{Eff}}$$

where:

W_T = Well-to-tank cost US$/GJ;
T_c = Transportation cost US$/GJ; and,
T_{Eff} = Transport efficiency (per cent).

2.1 Transportation cost (T_c)

The most cost-effective method of transporting hydrogen gas is by pipeline. Although there are dedicated hydrogen pipelines in many countries (especially the USA in connection with the space programme) there has yet to be a major purpose-built hydrogen pipeline for general use. However, Canada recently announced its intention to build a 900 km hydrogen pipeline in anticipation of a future hydrogen economy. Even without a current purpose-built hydrogen pipeline, indicative costs can be gleaned from the natural gas industry, the technology being very similar.

Comparative costs of hydrogen production

Method of producing hydrogen	US$/GJ
From coal/gas/oil	1-5
From natural gas minus CO_2 (sequestration)	8-10
From coal minus CO_2 (sequestration)	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

The unitised capital cost of a natural gas pipeline per km depends on the terrain and varies considerably. However, in the case of large hydro, we are probably looking at a relatively easy terrain, for which the unitised capital cost of the line will be about US$ 2.5/GJ for a typical 1000 km pipeline.

The unitised capital cost of the alternative of cryogenic transportation will typically be less, but the additional energy required for liquefaction would limit its use to sea crossings where the economics permit. However, it is of note that for natural gas, cryogenic transportation is used extensively and, if the world demand for hydrogen warrants the additional costs, it could equally be used for the transportation of hydrogen.

2.2 Transportation and distribution efficiency (T_{Eff})

Transportation efficiency again is difficult to determine, as it will depend on the site and its distance from the end user. However, based again on natural gas experience, this is assumed to be 95 per cent.

Distribution losses will depend on the method of vehicle on-board storage finally adopted. Possible options are bottles under high pressure (most manufacturers), cryogenic (adopted by BMW) and the more elaborate metal hydrates and nanofibres (laboratory level). All these will involve some efficiency loss. As the high pressure bottle approach is favoured at the moment, a loss of 20 per cent energy in compression is assumed. Currently, research on the generation of hydrogen under pressure by electrolysis will eliminate the need for a compression plant. Hydrogen by electrolysis at 100 bars has already been produced, and further increases in pressure are expected. Hence, for future distribution, losses are assumed to reduce to 10 per cent.

The alternative of storing the hydrogen in the form of methanol and reforming the hydrogen on-board the vehicle no longer appears to be an option. The major manufacturers of automobiles who were pursuing this technology recently announced that the capital cost of the reforming equipment needed for each hydrogen-powered car would be unrealistic, and accordingly they are dropping any further development in this direction.

2.3 Price of hydrogen in the tank

Fig. 2 shows the price of hydrogen in the tank using the above factors. From this figure, it is evident that for a good site the price of hydrogen in the tank is in the order of US$ 27/GJ increasing to about US$ 35/GJ for a hydro site selling electricity at US¢ 5/kWh. As a point of comparison, petrol at US$ 1.48/USgallon is equivalent to US$ 10/GJ. However this is not the full story because the relative efficiencies of hydrogen and petrol prime movers must be taken into account, together with possible tax breaks for hydrogen use.

3. The motoring cost of hydro produced hydrogen ('Well-to-Wheel')

It is generally recognized that the use of hydrogen for transportation will not become a reality until it becomes nearly competitive with oil. Users are willing to accept some price differential to protect their environment, but not a lot. Hence, at first sight, it might appear that hydrogen from hydro could never compete with petrol from oil, but this is not the case.

The basic equation for the 'Well-to-Wheel' oil breakeven price of hydrogen is:

$$\mathrm{Oil}_{ep} = \frac{\left\{\frac{\mathrm{W_T}}{\mathrm{E}_{fc}} - \mathrm{k}_2\right\} - \left\{\frac{Tax \times (100 - \%T)}{100}\right\}}{k_1}$$

where:

- Oil_{ep} = Breakeven oil price of (W-T) hydrogen US$/barrel;
- k_1 = Conversion factor US$/GJ of petrol to US$/barrel of oil using the assumptions of 3.1 below;
- k_2 = Constant for processing and distribution of petrol using the assumptions of 3.1 below;
- Tax = Tax on petrol US$/GJ;
- $\%T$ = Tax on hydrogen as a percentage of petrol tax (0% = no tax, 100% = same tax as petrol); and,
- E_{fc} = Relative efficiency of hydrogen powered engine compared with a petrol powered engine.

3.1 Cost of petrol and its component parts

For a cost comparison with petrol, USA prices have been used in the analysis. Fuel taxes in Europe, and most of the world, are much higher than those in the USA, and hence the scope to manipulate the pump price, and differentials with hydrogen, is greater. The past few months have seen significant instability in petrol prices because of political influences on the price of crude oil. Accordingly, year 2000 prices are used with petrol at US$ 1.48/US gallon, with the oil content representing 46 per cent of the cost of petrol, at an oil price of US$ 30 per barrel. The constant k_1 is therefore 0.154. The other components of the petrol price of US$ 1.48/US gallon are 26 per cent for processing and distribution and 28 per cent tax. Therefore, in the above equation, k_2 is 2.61 US$/GJ, and, for the purposes of this analysis, is considered to be independent of the price of oil.

3.2 Hydrogen as a vehicle fuel (E_{fc})

The fuel cell is rapidly becoming the preferred energy conversion unit, with internal combustion engines running on hydrogen now losing favour in the light of the efficiency advantages of the fuel cell. In fact, as can be seen from Fig. 2, hydrogen has no possibility of competing with petrol unless there is an efficiency advantage in the prime mover, which is not the case if hydrogen is burnt in an internal combustion engine.

Fuel cell development has moved on considerably since its year 2001 review in Reference 4 [Gummer, 2001[4]]. Coming out in front of the fuel cell alternatives is the Proton Exchange Membrane (PEM) running on hydrogen and air, or the Alkaline Fuel Cell (AFC) operating with hydrogen and pure oxygen. Both use well tried technologies and meet the zero pollution and zero emission goals of all advocates of the hydrogen economy. The world's first production-ready fuel cell car, the Honda FCX, was launched in March 2003, and uses a PEM fuel cell. However, the platinum necessary for the electrodes of a PEM still makes it prohibitively expensive and, in the end, the AFC may well prove to be the most viable alternative. Currently, the AFC uses oxygen derived from atmospheric air via a conversion unit. As with reformer technology, this may prove to be an economically unacceptable addition to each vehicle, and it may prove to be more viable to carry the oxygen in pressured bottles and refill them along with the hydrogen (as is done in the space shuttle). This can only make the electrolysis alternative of hydrogen production more viable, as this process also produces oxygen.

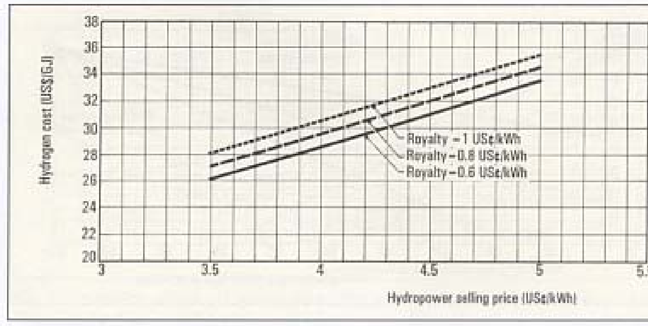


Fig. 2. Tank cost of hydrogen produced from hydropower current technology: no battery.

Fuel cell efficiencies are currently about 60 per cent, but 70 per cent and higher are possible. They are expected to improve as the technology advances; hence 70 per cent fuel cell efficiency has been assumed with today's technology. The efficiency of an internal combustion engine is a maximum of about 30 per cent when at constant speed on an open road, but it will reduce to near zero in city traffic. However, this is not the full story, as the efficiency losses in gear trains and electric motors have to be taken into consideration. Hence a typical ratio (E_{fc}) with today's technology is 2.7.

A contributing factor to its efficiency is the relatively low efficiencies of the fuel cell at part load. A solution to this problem, advocated by Toyota, is to provide auxiliary battery storage such that the fuel cell delivers to the battery at constant near-optimal load, and the battery charges and recharges depending on the required motive power. Accordingly, the efficiency of fuel cells with battery storage quoted by Toyota [Gummer and Head, 2003[2]] on their FCHV automobile is 3.1 times more than a petrol-driven vehicle. Furthermore, Toyota predicts that the fuel cell with battery storage will be 3.8 times more efficient than the gasoline engine in the near future.

The automobile industry is generally very optimistic about hydrogen-powered vehicles, and predicts that it could be less than a decade before they become a common sight on the roads of developed nations. Whatever the final outcome in terms of the type of fuel cell ultimately adopted, or the way batteries might be used to optimize their operation, it is evident that there is still significant scope for improvement in the energy conversion process. But like any new technology, there will be initial cost barriers to be overcome and much will depend on the encouragement that governments will provide, in terms of taxation relief and other incentives, in pursuit of sustainable and environ-

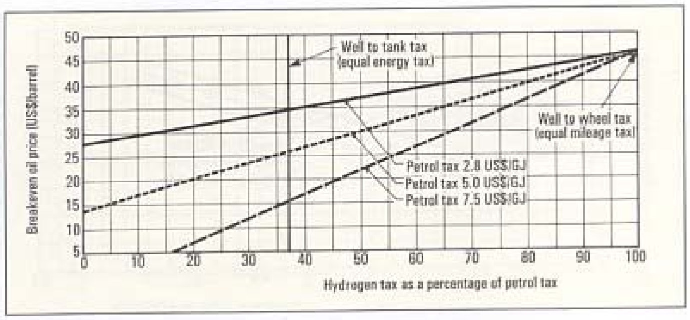


Fig. 3. Breakeven oil price. Generation selling price: US¢3.5/kWh. Royalty: US¢0.6/kWh. Current technology; no battery.

mentally clean transportation.

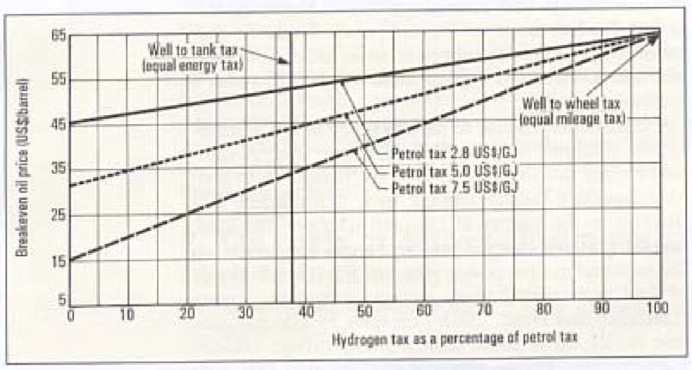
As can be seen , there are many possibilities for the future and it would be impossible to consider all of them. Accordingly, in the absence of hard statistics, this analysis is carried out under three efficiency scenarios, assuming:

- Current technology based on fuel cells without batteries $E_{fc} = 2.7$, $E_{Eff} = 75$ per cent, $T_{Eff} = 75$ per cent.
- As above, but with the conjunctive use of batteries $E_{fc} = 3.1$, $E_{Eff} = 75$ per cent, $T_{Eff} = 75$ per cent.
- Future technology with improved efficiencies in electrolysis, transportation/distribution and fuel cells design $E_{fc} = 3.8$, $E_{Eff} = 85$ per cent, $T_{Eff} = 85$ per cent.

3.3 Effect of taxation (%*T*)

In attempting to persuade people to switch to greener fuels, governments have shown themselves willing to accept a higher level of cost being passed on to the consumer, as in the case of electricity tariffs in a number of countries, or sometimes a readiness to accept a lower taxation revenue, as in Iceland where the tax on hydrogen is currently zero. If the pressure on governments towards sustainability and on reducing pollution and greenhouse gas emissions increases, we can expect similar measures to continue.

Fig. 4. Breakeven oil price. Generation selling price: US¢5/kWh. Royalty:US¢0.6/kWh. Current technology; no battery.



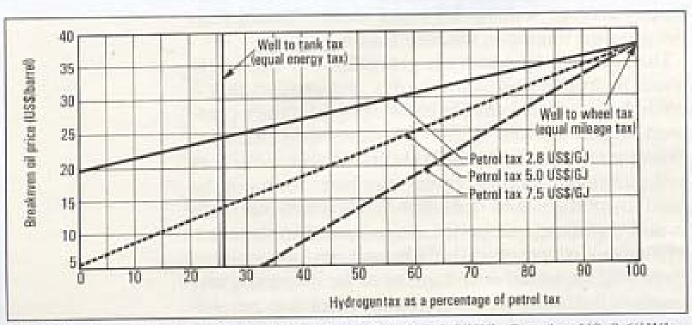


Fig. 5. Breakeven oil price. Generation selling price: US¢3.5/kWh. Royalty: US¢0.6/kWh. Current technology with battery.

The dilemma with the fuel cell is that if governments levy the same taxation in heat terms (Well-to-Tank) they will receive only about one-third of the tax revenue from the same amount of motoring because of the far greater efficiency of the fuel cell. It is unlikely that they would be prepared to go this far, but equally it would be unwise to go to the other extreme, which is to maintain effectively the same tax level in mileage terms (Well-to-Wheel) so that there is no change in revenue from transportation. The latter would clearly be counterproductive in terms of moving towards a sustainable hydrogen economy.

Figs. 3 to 6 show breakeven oil prices for different hydrogen tax scenarios, levels of petrol taxation and current and future technologies. From these figures, it is evident that the higher the tax on petrol, the more competitive H-to-H becomes for any tax benefit given to hydrogen. Thus the Iceland situation, where petrol taxes are relatively high and there is zero tax on hydrogen, makes hydrogen extremely attractive.

The overall conclusion is that with generation at US¢ 3.5/kWh, the breakeven oil price with current technology, assuming the same Well-to-Wheel fuel tax, is between US$ 38 and 46/barrel, depending on whether the fuel cell is used in conjunction with a battery or not. With future technology, this figure might drop to as little as US$ 18 or 28/barrel, even with a more expensive hydro site selling at US¢ 5/kWh (Fig.6). As is evident from the figures, in all scenarios H-to-H becomes far more competitive if it is accorded a tax relief. However, while it is conceivable that governments would forfeit taxation revenue for a transition period, it is improbable that any government would allow it to continue unchecked if the hydrogen economy results in the future efficiency gains contemplated in this paper.

3.4 Effect of varying the hydropower price

In practice, there will obviously be a wide range of costs at which hydropower sites can produce electricity. The effect of this on the breakeven oil price is also shown in Figs. 3 to 6, from which one might draw the following conclusions:

- With current technology, an attractive hydro site selling energy at, say, US¢ 3.5/kWh could be brought within economic reach of alternative fossil fuels at oil prices of around US$ 45/barrel. If taxation levels are lowered, this breakeven oil price could be significantly reduced, down to perhaps US$ 30/barrel.
- The more expensive hydro sites are likely to be uncompetitive with current technology, unless oil rises to above US$ 50/barrel, or governments are prepared to forfeit significant tax revenues in the interests of fostering sustainability. In the latter case, the more expensive sites could still be competitive at around US$ 40/barrel or less, depending on the actual tax regime and technology used.
- In the future, improved efficiencies (in electrolysis, transportation and fuel cells) should make even the more expensive hydro sites competitive, with a breakeven oil price of US$ 28/barrel for an electricity selling price of US¢ 5/kWh. If taxation levels are reduced, H-to-H could be competitive even under oil prices of US$ 15/barrel or lower.

Again it must be emphasized that we are considering a USA scenario where taxation on petrol is relatively low, even at the maximum US$ 7.5/GJ considered in the analysis. The figures for H-to-H with modest levels of percentage tax relief are far more favourable in countries where tax on petrol can be as high as 25 US$/GJ.

In summary, one might conclude that when oil prices rise past 30 US$/barrel, we should be beginning to look seriously at the H-to-H option. When it reaches 40 US$/barrel, as it inevitably will, we should be able to use hydropower to produce hydrogen at competitive cost levels. Although these breakeven oil prices might sound high at the present time, they have to be viewed against the uncertainty of future oil supply; and the tax scenarios must be judged against on-going concerns over the potential disruption of the world economy as a result of global warming. In the end, the competitiveness of H-to-H will be determined as much by external factors as by advances within the industry itself.

3.5 Impact of royalty levels

In the previous paper [Gummer and Head, 2003[1]], a preliminary estimate was made of the potential revenue that certain developing countries might derive from hydrogen, based on an assumed royalty level of US¢ 0.6/kWh. Attention was drawn to the fact that in some cases the royalty could more than double export earnings, and make a significant contribution to GDP. In particular, countries like Nepal, Lao DPR, Peru, Ethiopia and the Congo DR are among many that could see a substantial economic uplift from H-to-H activities (see Fig.7).

In practice, there will be a lot of latitude in the negotiation of the royalty, because, the impact of changes in royalty levels on hydrogen cost is relatively muted (Fig. 1). For example, in the case of US¢ 3.5/kWh hydropower, a royalty increase of a third to US¢ 0.8/kWh will drive up the breakeven oil price by only about 5 per cent. It could be argued, therefore, that there is scope for the countries with the more attractive hydropower sites to drive up their royalties, which could be appreciably higher than the US¢ 0.6/kWh considered in Reference 1, especially as the technology improves. By the same token, those with the less favourable sites might have to take a reduction to make the project viable.

4. Conclusion

It will not be so long before hydrogen-powered vehicles are a common sight on the roads. Some of these could well be supplied with fuel from hydropower stations.

As things stand today, the economics and technology may not be quite to the point of implementation, but the potential should not be ignored because indications are that H-to-H will become competitive as oil prices rise. For hydropower, which is the world's oldest and most established renewable and sustainable energy source, the opportunities offered by the coming of the hydrogen economy should be an ongoing challenge to be met with a proactive and sustained promotional campaign at the highest levels of government.

Above all, our industry now needs to stand up and demonstrate to the world that hydropower has an important role to play in achieving a sustainable hydrogen economy, and in the battle against world poverty. ◊

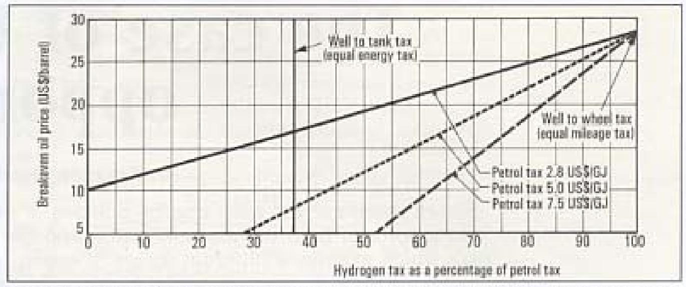


Fig. 6. Breakeven oil price. Generation selling price: US¢5/kWh. Royalty: US¢0.6/kWh. Future technology with battery.

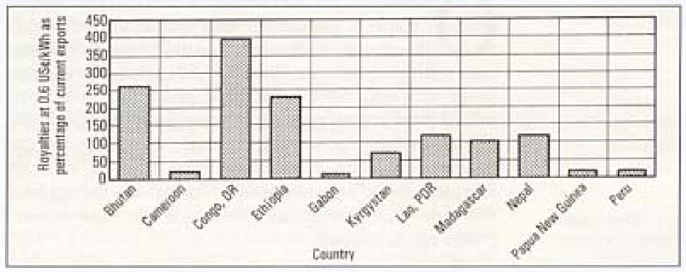


Fig. 7. Representative royalties from hydrogen produced from 65 per cent of technically feasible hydro. (This figure supersedes and corrects Fig. 2 of Ref. 1.).

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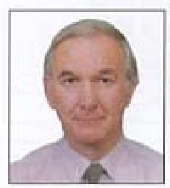

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