Chapter 8
Economic and Business Perspectives

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8.1 Introduction

Mankind faces the biggest challenge in the history of energy use – to find how to store natural energy in a way that would replace the vast store created by great nature herself, a store of which we have used a half in the last 50 years [1].

This is also one of the biggest opportunities ever to arise. The market is vast for a fuel that can be conveniently stored and transported, provided from a sustainable, low environmental impact source, at an affordable price, to meet the inevitable shortfall after "peak oil."

There are many possible ways forward. One generic way is to split water, and store the resulting hydrogen. Photoelectrochemical (PEC) hydrogen production is not yet a commercial solution for this, and for it to be considered there are basic material improvements required, together with robust system implementation. Materials with parameters in the range of photocurrents of 8 mA/cm^2 in "1 Sun" with 0.8 V anode to cathode bias would open the way to exploitation of PEC-derived hydrogen, and the possibility of a cost/m^2 under \$80, excluding PV bias costs with lifetimes $>$10 years. An early demonstration model of such a system is shown in Fig. 8.1.

8.2 The Need

Our entire world economy has grown out of the availability of abundant and cheap energy supplies. The cost of energy is now under threat, and the future is by no means secure.

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Fig. 8.1 Demonstration model of a 1-m^2 PEC array

8.2.1 *Increased Demand/Reduced Supply = Rising Cost*

In the 4 years up to 2007 [2],

- Oil consumption increased by 3 million barrels/day
- Natural gas increased by 8 billion cubic feet/year
- Coal by 1.4 thousand short tons/year
- Electricity by 2.1 billion kWh/year

Projections show that demand continues to grow – and that the transport sector is elastic to price, there being no available alternative.

Oil production per capita fell from 5.26 barrels in 1980 to 4.73 barrels in 2006. The DOE/EIA give a price projection from [2]:

- \$60/barrel in 2009 to
- \$110 in 2015
- \$115 in 2020
- \$130 in 2030

8.2.2 Growth in Energy Demand Arises from Several Different Causes

These causes are

- Population growth – mainly in the developing world
- Increased standards of living within upper income sectors
- Increased size of middle income groups

The figures quoted above hint at the size of this growth in energy demand. The EIA forecast an 80% increase in consumption in non-OECD Asia, largely due to transport needs [3]. Of special interest is the ever increasing proportion of energy use in the transport sector generally, in particular road vehicles and air travel. Of total primary energy use, some 40% is used in the transport sector. This is met by the use of oil in different grades (petrol, diesel, jet fuel), and there is little prospect of a change to other energy sources here. There is an absolute need for transport fuel to be convenient and transportable – on board – which means that the use of electricity is itself dependent on storage, in batteries of some sort.

8.2.3 "Peak Oil"

Peak oil was first predicted by M. King Hubbert in 1956 [4]. He showed that every well increased its production up to a peak, coinciding with the depletion of half the total capacity of the well, then slowly declined once past this peak. He showed that this is just as true for the overall capacity of all wells. Dr. C.J. Campbell, a trustee of the Oil Depletion Analysis Centre in London, spelt out the consequences in some detail in his 1997 book "The coming Oil Crisis" [5]. In 1980, oil production first surpassed new oil discoveries. Therefore, there is a need for an alternative to augment oil and preferably from a low impact source due to climate change issues.

Renewable sources are attractive for sustainability – e.g., wind, hydro, tidal, solar etc., and geographic factors will determine where each is appropriate. However, the sheer size of overall demand points to solar – the solar resource far outstrips all others. With a global usable energy flux of 120 PW, it is some 8,000 times the current total energy use, and able to supply growing demand as far ahead as we can see [6].

There has been a huge emphasis on the production of electricity from alternative sources, and for many, "solar cells" mean photovoltaic cells. Wind, hydro, tidal, and atomic sources all tend to equate to the supply of electricity. As noted above, electricity needs to be stored if it is to meet the demands of transport, and, in the case of wind and solar, periods when the source is unavailable.

8.3 The Commercial Challenges

Energy must be affordable, but the cost of energy in different forms (with and without tax) varies widely.

8.3.1 Price Distortions

Governments distort true prices by giving subsidies on the one hand, and applying taxes on the other. The 2005 Energy Bill in the USA gave $6 billion for oil and gas, $9 billion for coal, and $12 billion for nuclear [7]. President Obama is seeking to remove those subsidies. Tax on petrol varies by country. In UK 67% is duty, in Russia 0%. In the USA, tax varies by state, with Alaska at 18 cents/gallon, and New York at 61 cents [8].

8.3.2 The Climate Change Factor

Despite the growing awareness and acceptance that climate change is real, and that it poses huge threats to our whole existence, there has been little appetite by Governments to address the issue in a robust way. The conclusion drawn from this may be that carbon-free alternatives must compete without relying on government support or coercion.

8.3.3 The Need for Clear Focus

Research effort, and the subsequent process of bringing research results to a successful product and market, is costly. It is important, therefore, to focus on well-formulated objectives. Set out below are a number of such objectives, all having in view the aim of finding a viable way to store solar energy, as an alternative to mining the natural resources we have inherited.

8.3.4 Definition of Aims

Development of an energy supply which is

- As cheap as existing “conventional” supplies
- As convenient in use
- Less environmentally damaging
- Reasonably safe in use (all energy can be dangerous!)

8.4 Storage of Solar Energy: The New Challenge, and The Hydrogen Solution

Throughout history, mankind has existed by harvesting and mining natural resources (wood, coal, oil, and gas) for his energy needs. Only with the coming of the atomic age can it be said we have ourselves invented or created energy, and even now we have still to find anything comparable with the stored energy created by nature. Her “invention” of the tree, which covers itself with disposable solar collectors during the sunny season, converts sunlight to a form of stored energy, then discards those leaves when winter comes – how elegant!

Wood, coal, oil, and gas can and do store energy for any amount of time, ready for instant use.

This is our real challenge, for whether “peak oil” has already come, or whether it is still 20 years away (“tomorrow morning”), once we are on the far side of the mining curve nothing can replace that golden resource.

So we come to our subject here – the possibility of splitting water using sunlight, to provide a source of stored energy at an affordable price. PEC is such a possibility, but many hurdles remain.

8.4.1 Can We Learn from Nature?

The sunlight/photosynthesis/fossil fuel process has been working at efficiencies well below 1%, thus needing vast land areas – land areas now committed to other uses where they are fertile, or lacking either water or sun elsewhere. There are many ways to approach this problem, PEC being only one, and this is not the place to examine the alternatives. Each has advantages, disadvantages, risks, and state of readiness.

8.4.2 There Are A Number of Ways to Split Water and Yield Hydrogen

Direct thermal splitting is one such way – and there is work going on looking at efficient catalysts for this [9, 10]. Electrolysis is another and well-understood way – the use of electric power to split water. It may be driven by electricity from any source – conventional (fossil fuelled), wind power, hydro or wave power, nuclear or PV [11]. Steam methane reformation (SMR) is at present the cheapest way to produce hydrogen, and relies on fossil fuel (natural gas). This provides a cost per kg and kWh of H_2 burnt split between capital and electrical power cost [12, 13].

The DOE target for hydrogen production from natural gas (NG) was \$3/kg H_2 by 2005, and \$1.50/kg by 2010 [2]. The volatile price of NG is the main factor here.

If NG is traded at \$1/kg equivalent, and if conversion from NG to H_2 is at a ratio of 1–2.4 (when carbon capture and storage is included) then even at very large scale the cost of H_2 is likely to be some \$2.4/kg. Thus the \$3/kg target, not yet reached, is likely to remain the lowest.

Although meeting a target cost of twice this figure using PEC is already very challenging, this aim must be kept in sight, and achievements measured in the light of such goals.

8.4.3 End Use of Hydrogen

The end use of hydrogen is, ideally, by direct combustion. Process heat, cooling by the absorption cycle, combustion in IC vehicle engines, cooking, and water heating all make the best use of hydrogen. To generate electricity, while perfectly possible, is to lose efficiency overall. Fuel cells have yet to be proven, and have yet to show cost benefits. Hydrogen has an important role to play without the need for deployment in that way.

8.4.4 EU/US Targets for H_2 Evolution

The US DOE target has been shifting gradually upward, from \$1.50/kg delivered H_2 (2001) to \$2/kg at production site, to \$3/kg. EU targets twice the untaxed petrol cost, on the basis that petrol taxation will make H_2 competitive if untaxed.

8.5 PEC Issues

Each element of the PEC process has a bearing on the final cost of hydrogen production, and hence of commercial viability.

8.5.1 PEC Costs for Hydrogen

It is constructive to consider the optimistic cost of hydrogen produced today using PEC compared with the target prices. In this calculation, typical values of photocurrent for modified iron oxide of 2 mA/cm^2 at 1 "Sun" illumination with a bias of 1.2 Volts have been used and costs for 17% efficient PV at \$2/W peak incorporated. Clearly, the cost of hydrogen per kg produced is dependent on the location and a site in Southern Spain has been assumed with an averaged monthly insolation of 4.8 kWh/m^2/day. To produce 1 kg of hydrogen per day would require some

50 m^2 of PV and 300 m^2 of PEC with minimal overall losses and inefficiencies. Assuming that the PEC costs are around \$200/m^2 (PV costs are \$300/m^2) then this yields a cost per kg of hydrogen of \$20 (assuming a 10-year lifetime) for the capital costs alone. Even if the PEC costs were halved to \$100/m^2 then the hydrogen costs are still \$12/kg. At this lower price the PV costs are around half the PEC costs due to the large area of PEC required.

This cost of \$20/kg is clearly too high and around a factor of 10 greater than the target price and does not include additional costs of land, maintenance, installation, transport, the balance of plant costs, and profit. Clearly, an improvement in PEC efficiency would be advantageous to limit the land usage. This suggests that significant improvements in performance of the PEC device are required to meet commercial demands.

We should not ignore competitive means of producing hydrogen from a solar input via electrolysis. Given the likely timescale for improvements in PEC, we should use a comparison with other methods under development. Direct comparison with low cost PEM electrolyzers powered by PV is instructive. The US targets for low cost PEM are \$400/kW with 67% efficiency by 2012 and \$125/kW with 74% efficiency by 2017. The reported status in 2007 was \$987/kW with a cell efficiency of 67% [14]. Using this data for the site in Southern Spain with PV costs of \$2/W peak we can estimate hydrogen costs for the capital alone with a 10-year payback if the systems were implemented of \$8/kg using the 2007 figures, reducing to around \$5/kg of hydrogen with the 2017 figures. The reduction in cost is not as marked as expected from the reduction in PEM electrolyzer costs due to the influence of the PV costs which have been assumed not to reduce below \$2 per watt peak over the period. The PV costs would be 94% of the capital costs in such a system, and using the 2017 figures it would suggest this system would require around 60 m^2 of 17% efficient PV.

Using the 2012 figures the PV accounts for 80% of the cost of a PEM system, with the PEM electrolyzer capable of producing 1 kg of hydrogen per day in Spain. The estimated capital cost of some \$4,000 yields a cost per kg of hydrogen of \$6 assuming a 10-year payback.

8.5.2 Efficiency and Improved Photocurrent

It is widely held that the successful application of PEC to the water-splitting process must reach or exceed an efficiency of 10% (i.e., for a given incident solar energy, the energy content of the liberated hydrogen must be 10% or more). Put simply, at "1 Sun" (1,000 W/m^2), the aim must be for 1 m^2 of device to liberate hydrogen having an energy content of 100 W. In the following sections, we set out to expand on materials parameters that support this.

The efficiency of PEC is directly related to the magnitude of the photocurrent produced by exposure to light. Clearly, doubling the efficiency or photocurrent halves the area of PEC required to produce a given mass of gas.

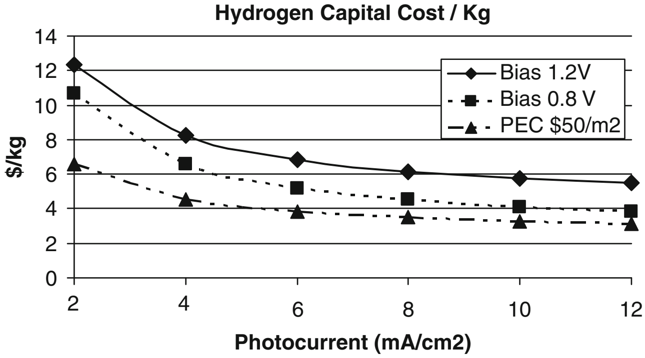

Fig. 8.2 Capital cost of hydrogen per kg as a function of photocurrent

The solid line in Fig. 8.2 represents the capital cost per kg of hydrogen produced with a 10-year payback assuming a PEC device requiring a bias of 1.2 V that can be manufactured for \$100/m^2. To match the low-cost PEM equivalent price of \$6/kg would require an improvement in efficiency to yield a "1 Sun" photocurrent in excess of 8 mA/cm^2. At this value the area of PEC required in Spain would be around 75 m^2 compared to 50 m^2 of PV and 60 m^2 of PV for a low-cost PEM. As can be seen increasing the photocurrent further provides decreasing gains in lower cost hydrogen as the PV costs, which do not decrease with increasing PEC photocurrent, begin to dominate the total costs. At a "1 Sun" photocurrent of 12 mA/cm^2 the PV costs, assuming \$2/W peak, would be \$15,000 compared to \$5,000 for the PEC. The most advantageous method to reduce cost further is to reduce the bias requirements and so reduce the amount of PV required.

8.5.3 Voltage Issues and Reduced Bias

Increasing the efficiency reduces the cost of PEC to produce a given mass of gas but not the cost of PV. Since PV dominates the cost overall, then lower cost of PEC does not itself produce a significant saving. How can we reduce the amount of PV power needed? This can only be achieved by reducing the bias voltage as the mass of hydrogen produced is proportional to the current.

Water splitting by electrolysis has a threshold minimum of 1.23 V and in a PEC device this is effectively reduced by the photocatalyst, the reduction being in part related to the band gap of the material and the positioning of the energy bands relative to the hydrogen and oxygen evolution potentials. However, an overvoltage is observed for realistic devices. The size of this overvoltage is critical and must be minimized.

By comparison of the solid line for a PEC device manufactured for \$100/m^2 with a bias of 1.2 V and the single dashed line for a PEC device with a bias of 0.8 V (Fig. 8.2) it can be seen that the hydrogen cost per kg can be reduced below that of a low-cost PEM at reasonable photocurrent values above 5 mA/cm^2. Efforts to reduce the bias are essential to achieve a meaningful advantage over low-cost PEM and ideally PEC systems requiring no external bias would be highly attractive.

It is important to note that with devices exhibiting “1 Sun” photocurrents of 8 mA/cm^2, currents of the order of 80 A for a single m^2 can be expected. A 1 mΩ resistance in a pathway carrying 80 A would result in a resistive voltage drop of 0.08 V which is significant when efforts to reduce the bias are hard won. Hence, very low electrode resistances and interconnections are crucial to a PEC system. Also sources of electrode overpotential, losses due to gas separation membranes, and reactor designs all play a part in minimizing the external bias requirements for a PEC device.

From a system view point anything that loses voltage, e.g., electrode resistance, interconnections, over potentials, reactor design, electrolyte, H_2 evolving electrode, etc., is important.

8.5.4 Scale-Up Problems

Research is typically carried out using small samples on which to try alternative coatings or application processes. By this means, many great experiments can be made with a relatively small use of materials and other resources. However, in the context of PEC development, the question of electrical resistances must not be overlooked.

At small scale, only small travel distances will be involved – the question of resistance may not well arise. But once a promising process comes to be scaled up to commercially realistic units, current flows then rise from milliamps to amps, and the need for a low resistance pathway may rule out the concept of a semitransparent conducting coating on glass (for example) – only highly conductive metallic electrodes which are nontransparent may suffice.

8.5.5 “Real Estate” Issues

There are many ways in which the area of land required per unit of energy harvested can affect cost. These include location (level of insolation to be expected), urban or off-grid siting, the need for support infrastructure, and other competing land uses.

For example, if we compare the 2012 low-cost PEM figures with the PEC estimates based on performance today we see that the PEC system would require around 20% less area of PV and hence the cost of PV. However, the land area used by the PEC system today would be dominated by the 300 m^2 of PEC which is some five times the area of a compact PEM system in which the PEM electrolyzer does not need exposure to light and can be located beneath the PV. The capital cost of hydrogen produced per kg is around double from the PEC system assuming it can be manufactured at costs of \$100/m^2. This would suggest that to be competitive with proposed low-cost PEM it is essential to reduce the area of PEC required through increased efficiency.

8.5.6 Solar Spectrum Considerations

In general, it is clear that having PV and PEC side by side is less efficient than using the same area to harvest different parts of the spectrum for the two requirements, so light harvesting is itself an issue relating to cost.

The tandem/hybrid approach seeks to address this question. A collaboration between EPFL and the University of Geneva leads to a proposal for a “Tandem Cell” which sought to use different parts of the spectrum of white light for different purposes. A patent was granted for this idea, based on harvesting energy from the blue end of the spectrum in a PEC application, and the red end of the spectrum for generating the required bias to achieve water splitting, using PV.

This elegant solution appeared to offer a way of “taking two bites from the same cherry,” and did function at very small scale. Care with such designs must be taken not to limit the transmitted light through the PEC device and into the underlying PV, otherwise PV outputs will be reduced which will result in increased costs of the PV. The need for highly conductive substrates at any reasonable photocurrent density and area of device within PEC devices will severely limit the light transmission and limit the commercial viability of this approach.

8.5.7 Durability

Products must be durable, and pay-back calculations will be influenced by the expected product life-time. As can be seen in Fig. 8.2, even with an external bias of 0.8 V and a PEC manufacturing cost of \$50/m^2, which is one sixth that of current PV and a “1 Sun” photocurrent of 12 mA/cm^2 the hydrogen cost of the capital costs alone are still in excess of the EU and US targets assuming a 10-year pay back. These targets can only be met by increasing the durability of the PEC to give lifetimes approaching 20 years. To put this in perspective a 20-year lifetime operating 9 h per day is in excess of 65,000 h, which is challenging when you consider that a 10,000-h auto engine test would be considered impressive.

Although there may well be markets for shorter life-time products, in the longer term there will be an absolute requirement for products capable of operating for 15 or 20 years, comparable with other core technologies.

For these reasons, durability testing should be built into the overall PEC development program from the earliest stages. In some cases, it will be found that durability cannot be achieved for reasons of fundamental material science, thus in such cases there will be little reason to pursue an otherwise interesting line.

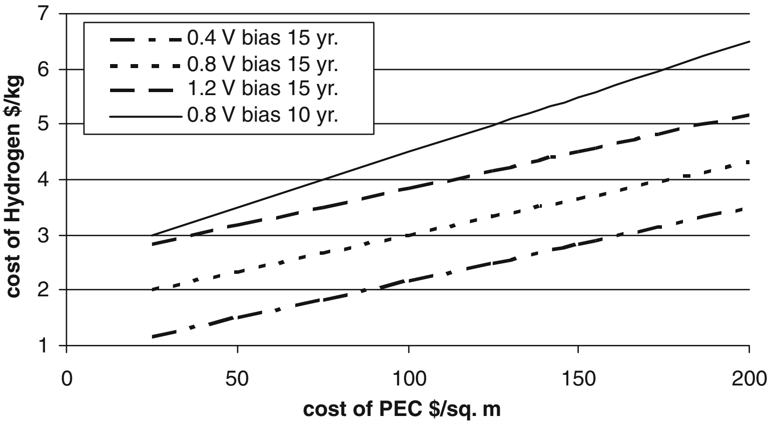

Fig. 8.3 Hydrogen costs per kg (capital costs only) for PEC with 1 Sun photocurrents of 8 mA/cm^2 in Southern Spain assuming $2/W$_{peak}$, 17% efficient PV

8.5.8 Commercially Attractive Targets

Figure 8.3 highlights that for PEC with a 1 Sun photocurrent of 8 mA/cm^2 and a bias of 0.8 V, capital costs of hydrogen per kg less than $3/kg, with a 10-year payback, cannot be achieved (solid line). Equally, PEC at similar photocurrents with 1.2 V bias cannot achieve sub-$3/kg hydrogen costs even with a 15-year payback (large dashed line). To achieve sub-$3/kg hydrogen capital costs for PEC with photocurrents of 8 mA/cm^2, the bias must be at least as low as 0.8 V with a 15-year payback and PEC costs below $100/m^2 (small dashed line). If the bias can be reduced further to 0.4 V then with a 15-year payback PEC costs as high as $150/m^2 can be sustained, which is around half the current cost of PV.

Clearly, the performance of PEC today is not ready for commercial exploitation. However, with defined improvements it offers a route to the production of hydrogen on a large scale which would meet EU and US targets and be comparable with current methods of hydrogen production. To achieve this, “1 Sun” photocurrents in excess of 8 mA/cm^2 are required, using materials that require less than 0.8 V bias, exhibiting much greater than 10-year lifetimes, that can be deposited and incorporated into reactors which cost less than $100/m^2.

8.5.9 Material Parameters

Several determinants for the choice of materials will contribute to a commercially viable device. These include

- High photocurrent leading to high efficiency
- High photon capture

- High photon-to-electron conversion efficiency
- Low electron–hole loss
- 1.6 eV $<$ band gap $<$ 2.2 eV matching hydrogen and oxygen evolution potentials to minimize bias
- Low cost of source material
- Abundant supply
- Durability in aqueous environment
- Resistance to high solar irradiance
- Resistance to high temperature
- Electrode structures supporting high current flows
- Avoidance of poisonous or contaminating materials
- Electrolyte choice, ideally, commonly available, nontoxic, noncorrosive

8.6 Other Issues

Only issues of relatively direct impact on PEC research are touched on here. These include the following.

8.6.1 Hydrogen Storage

Sometimes seen as an "Achilles heel," the problem of how to store and transport hydrogen remains to be solved. Historically, heavy steel cylinders have been and are still used to contain the gas at a range of pressures which ensure that the volume is not unacceptably large.

Only a small number of companies specialize in this field, and the development of much lighter weight containers based on carbon fibers, special resins, and so on is now well advanced, ready to supply the needs of the automotive industry, where the overall weight of gas plus container is a constraint.

Carbon nanotubes are being investigated, and metal hydrides are already available. Other solutions based on storing hydrogen in another form are also under review. Ammonia has its advocates, being a material which is handled in bulk by the fertilizer industry, and is composed of just two elements – N and H. However, transforming the hydrogen into and then back out of this chemical is troublesome, and other solutions are sought.

One interesting alternative is formic acid (H_2CO_2), as the CO_2 component may be usefully abstracted from power plants.

8.6.2 System Costs

To achieve the stated aim of competing with existing energy sources, without reliance on subsidy or tax hedge, the relevant bench mark is that of hydrogen production by SMR. This is a moving target, as the source for SMR is natural gas, itself a hydrocarbon under pressure from rising demand, and dwindling supply. However, we can compute the following using some assumptions:

- A 10% efficient device with bias requirements less than 0.8 V
- A 15-year minimum life
- A capital cost for the system (PEC + PV) of \$160/m^2

With these assumptions PEC hydrogen could cost less than \$3/kg. A clear statement of aims such as these is essential for the development of a commercially convincing product.

8.6.3 Solar Concentration and Tracking

Modest solar concentration, in the 3× to 10× range, may be helpful in boosting output with a low capital cost increase, provided a nonsolar tracking configuration is adopted.

High concentration schemes are needed for high-temperature applications, but in the context of PEC cannot be recommended. The extra cost of the tracking component is likely to put the overall energy cost beyond an acceptable limit. Remember too that solar tracking implies clear beam radiation, thus reducing the number of locations where such applications can be sited.

8.6.4 The Issue of Intellectual Property ("IP")

The world of "risk capital" funds, hedge funds, and the like places great reliance on the protection of IP by patents, and typically a family of patents is sought, covering all aspects of the given technology. Without seeking to detract from this viewpoint, it may be more important to rely on "know-how" and practical experience. For example, the original "dye-cell" patent has already expired, but the dye-cell team is busier than ever with applications for their know-how. However, there is a conflict between the wish for researchers to publish their work, and the need to maintain secrecy until patent cover has been applied for.

8.6.5 Further Issues

Maintenance/support in operation – the simplicity or otherwise of the PEC solution will affect the ongoing costs – what elements will need cleaning, and at what intervals? What elements will need replacement and at what frequency?

Hydrogen transportation from point of production to point of use will be an issue, especially since every pipe joint represents a potential leak of this finest of all gases.

8.7 Route to Market

Section 8.2 showed the huge sector represented by transport energy. For transport fuel, large scale and large company development is needed to make an impact. This will only happen when the requirements of cost, convenience, and safety have been met. At this point all the other uses of conventional fuels will be opened too.

That said, fleet vehicles tied to a refueling base (taxis, buses, delivery vehicles) avoid some of the "chicken-and-egg" problems associated with the eventual need for fully distributed infrastructure, while small fleet vehicles (fork-lift trucks, airport tugs) are even more readily serviced.

8.7.1 Other Markets

There are as many potential markets as there are activities in this world. The broad divisions noted above can also be subdivided into "grid connected" and "remote" or "off-grid" locations. The latter is of interest in that the price of energy at remote sites is already much higher than where grid connection exists. Niche markets alone do not justify great expenditure, so there is a need to think big – once a competitive process has been developed.

8.7.2 A Comment on "growth"

The idea that we need our world economy to grow for it to be healthy must be treated with caution. If population grows, then growth of supplies is needed. Apart from that, it would seem that the economic and banking crisis of 2008–2009 shows us that growth is chiefly needed to satisfy greed, and leads to collapse. *Sustainability is a much more relevant criterion.*

8.8 Conclusions

The opportunity to find a way to store solar energy poses huge challenges, but offers a huge reward – not just financial, but deeply satisfying in terms of achievement in an entirely new field for humanity. Clear targets must be set, ideally leading to system costs that are easy to accept in being no more than the fossil fuel alternative. Here, proposed is a figure of under \$3/kg of hydrogen produced. To achieve this, we see that

- More efficient materials are needed, and a target of 8 mA/cm^2 is set (to reach $>$10% efficiency)
- Bias requirements must be reduced, with minimal resistive voltage drops
- Durability must be increased to 15, or better 20 years
- System costs must be reduced, and a price not exceeding \$160/m^2 for both PEC and PV is set

By splitting water directly – in one step –the need for increased independent electricity generation is avoided, as is the need for grid connection. More importantly, the way would be opened to a real reduction in CO_2 emissions at the most basic level. The tasks involved are large, and higher levels of funding are likely to be needed, especially if results are to be achieved in the near term.

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