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USE OF BARRIER AND ATTRACTOR ANALYSIS FOR IDENTIFYING HYDROGEN SYSTEM OPPORTUNITIES WITH ILLUSTRATIONS FOR LATIN AMERICA

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ABSTRACT

Many hydrogen initiatives fail because, from their inception, they are conceived to demonstrate a *technology* in isolation from the energy system in which it is embedded. Prospects for success can be greatly enhanced when technologies are selected to provide *systemic benefits* within that system. Identifying such systemic benefits requires, (i) the concept of an energy system architecture, (ii) an appreciation of the patterns of architectural evolution and, (iii) recognition that systemic evolution can be viewed as governed by barriers and attractors —such that removing barriers and introducing attractors speeds evolution towards efficient and clean provision of energy SERVICES. These three concepts can be employed to identify hydrogen technology opportunities having the greatest systemic leverage, and therefore the greatest prospects for success.

The methodology is based upon the perspective that energy system evolution is towards configurations which improve SERVICES, and is determined by barriers and attractors that can be technical, cultural, economic, or legislative. This methodology was first outlined in a report prepared for Natural Resources Canada. [1] Latin American illustrations are given to make these ideas more tangible.

1. INTRODUCTION: EXPLOITING INTERCONNECTEDNESS

This paper focuses on hydrogen technologies. But these technologies must be seen as imbedded within an ever-evolving energy system. We believe that the metrics used to evaluate the merit of any proposed hydrogen technology programs should account for the following:

- Any proposed hydrogen technology (e.g. a fuel cell) should be seen as part of a potential hydrogen system (e.g. a fuel cell powered bus fleet) aimed at delivering a SERVICE (in this case, land transportation).
- Any proposed hydrogen system (e.g. a fuel cell powered bus fleet) should always be seen as growing out of today's energy system.
- Any proposed hydrogen technology should exhibit high systemic leverage, thereby advancing the evolution of the regional (or global) energy system.

Three concepts are required to fully exploit energy system interconnectedness as a key methodology for evaluating technology development plans:

1) A generalized energy system architecture;
2) A sense of the evolutionary patterns that will determine the techno-economic envelope of component technologies that make up the architecture; and
3) The notion of barriers and attractors to systemic evolution (these can be technical, cultural, economic or legislative).

2. ARCHITECTURE OF THE ENERGY SYSTEM

The energy system may be represented by the five-link architecture shown in Figure 1. The system is driven by the SERVICES people want. The way SERVICES are delivered is selected from a menu of SERVICE TECHNOLOGIES. Service technologies are often restricted to operating on a single currency drawn from the menu of CURRENCIES. The designated currency is manufactured by one of the TRANSFORMER TECHNOLOGIES which, in turn, is designed to harvest one of the many energy SOURCES nature provides. The *examples* in columns beneath each of the five links have no direct correlation (along rows) with other *examples* in adjacent columns.

Of course the number of links that can be expanded almost without limit. For example, at a first level of expansion, another link called DISTRIBUTION can be placed between CURRENCIES and SERVICE TECHNOLOGIES, and so on. But the essential point is that SERVICES define one end of the systemic chain and SOURCES the other.

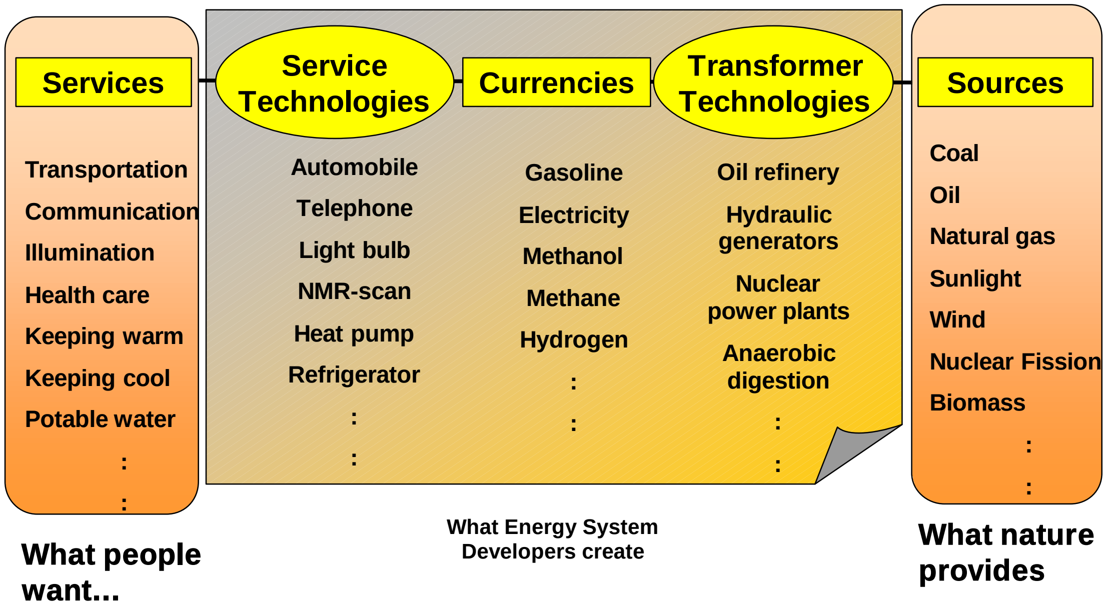

Figure 1: The Architecture of The Energy System

Environmental Impact

In the late 20th century, the environmental impact of any proposed energy system is important. Since the delivery of an energy service is always sustained by some pathway running back through the energy system chain – from service back to source – to evaluate environmental impact we must consider, *at each link of the chain:*

- Material extracted from the environment (eg. oal, oil, or uranium);
- Material diverted within the environment (eg. re-configuring river flows, such as dams for hydraulic electricity generation); and
- Emissions to the environment (The most understood aspect of environmental intrusion, and examples include such things as NO_x, CO_2 and many others).

To weigh the impact of an emission, we must not only consider its *direct* impact – for example the odour of H_2S emitted from a pulp mill – but also *how the emission modifies nature's equilibria or intrudes on nature's fluxes*. A good example is CO_2. The direct impact of CO_2, as something smelly or as a toxin, is zero. Rather, the fact that atmospheric CO_2 intervenes in nature's fluxes, reducing the flux of outward bound long-wavelength (IR) radiation from Earth to the universe, is what causes the potential for environmental disruption. The other well-known example is CFCs that alter nature's equilibria – in this case the equilibria between O_3 and O_2 in the upper atmosphere. In turn, this change in equilibria (which lowers the O_3/O_2 ratio) alters nature's fluxes – increasing the flux of inbound short-wavelength (UV) radiation to Earth.

Moreover, the ability to mitigate environmental impact of an emission depends not only on *what* is emitted, but from *where* in the system chain, and in what *concentrations*. To illustrate, consider transportation as the service and methane (CH_4) as the source. If the system chain has methane as the CURRENCY being carried onboard, then the emitted CO_2 comes out of a *mobile* tailpipe *diluted* by the nitrogen contained in the air that carried the oxygen into the engine. On the other hand, if the service-to-methane chain implies steam methane reforming (SMR) as the TRANSFORMER TECHNOLOGY to produce hydrogen – with hydrogen used as the on-board currency – then the CO_2 will be emitted from a *stationary* site: the SMR plant. In this second case, some or all of the CO_2 (depending upon the source of exogenous heat) is relatively pure – making it not only easy to collect but also presenting a commercial opportunity. There are several ways of either *using* or *disposing* of relatively pure CO_2 if it comes from a stationary source. But if it comes from a moving vehicle these opportunities vanish.

Finally, to properly evaluate the potential environmental impact of new energy technologies, it is essential to consider the whole system from service back to source. To do otherwise is to almost guarantee that a proper evaluation of environmental impact cannot be achieved.

Technology Cost, Convenience, Cultural Priorities and Efficiency

Governments and industry often wish to consider criteria for prioritising RD&D or development projects. Prioritising requires an appreciation of how the energy system is *evolving* – and how it *should* evolve. Emerging technologies are a key factor that drives or retards this evolution.

We often think that all technological change is motivated by cost – the cheapest way of providing a service wins. But this idea presumes the service is provided in an *identical* manner, without collateral benefits or disadvantages that might result from using different technologies to deliver the same basic service but in a somewhat different manner. When choosing between alternative *pathways* to provide a service *category* – for example, choosing between mailing a letter, sending a FAX, or making a phone call for communication – cost is often not the over-riding issue. The *way* the SERVICE is *delivered* is the issue.

Without dismissing the importance of relative economic cost, in the late twentieth century three additional forcing functions drive systemic evolution:

- The *quality and convenience* of the way the service is delivered;
- The *(energy) efficiency* of the technological system delivering the service; and
- The *environmental gentility* of the technological system delivering the service.

Rate of Systemic Evolution

The historical rate of energy system evolution has been discussed by many authors. [2][3][4] The published data reflect two patterns of energy system evolution:

- The life cycle for total renewal of the systemic components is between 75 and 100 years; and
- The trend in SOURCES is a progressive weaning from reliance on fuels containing carbon.

Figure 2 provides a sense of this evolution for a representative service category by indicating a possible slice through the energy system: land transportation. This cannot be interpreted as a firm prediction of the future for surface transportation but, we feel, it represents an increasingly probable evolution as we extend the projection over sufficient long times.

Of course, to represent the *entire* energy system we would need to include all the SERVICES identified in Figure 1 – communication, health, etc. Still, Figure 2 which illustrates the kind of transportation system evolution that has occurred in the past and is likely to occur in the future, mirrors the evolution that may be expected for the full system. Figure 2 also reflects the systemic response to the forcing functions: quality and convenience, efficiency and environmental gentility.

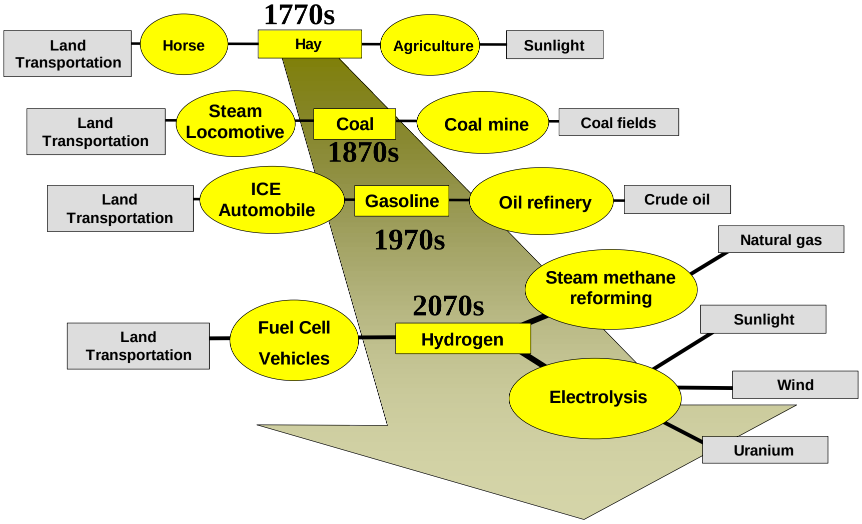

Figure 2: Land Transportation through Time

Attractor: All Sources have Equal Access to All Service Markets

Another aspect of the future is illustrated, symbolically, in Figure 2. When hydrogen becomes the staple currency for transportation then *many* SOURCES can supply the hydrogen. This contrasts with how, historically, the system restricted the SOURCES to one: first sunlight, then coal, and today, crude oil. Using hydrogen as the transportation currency, the systemic effect will be to allow all energy SOURCES to have "equal access" to supply hydrogen. Figure 2 shows that, in the fullness of time, any energy source will be able to supply the transportation market. In this way, energy SOURCES will be liberated.

An analogous situation exists today in the business of manufacturing electricity. It is difficult to conceive of any energy source that could not be used to manufacture electricity and that, therefore, would not have the opportunity to supply any service delivered by an electricity technology. In contrast, firm systemic barriers block many SOURCES from powering most SERVICES now fed by liquid hydrocarbon fuels – especially, transportation. Sunlight, nuclear energy or hydraulic power are effectively blocked from transportation.

3. BARRIERS AND ATTRACTORS TO ENERGY SYSTEM EVOLUTION

Energy system evolution is accelerated by "attractors" and retarded by "barriers". These barriers and attractors block or enhance the evolution towards systems which improve:

- the *quality* of the service;
- the *convenience* of the service;
- the *economic efficiency* of the system chain delivering the service;
- the *energy efficiency* of the system chain delivering the service; and
- the *environmental gentility* of the system chain delivering the service.

In addition, they block or enhance systemic evolution towards a progressive weaning from the carbon atom.

BARRIERS can be *technical*, such as the difficulty of on-board storage of low-carbon fuels – in particular natural gas and hydrogen. They can be *cultural*, such as the public perception that we were running out of natural gas of the late '70s and early '80s, or that hydrogen and nuclear energy are dangerous. They can be *economic*, like the effect of sunk costs, or the high costs of liquefaction. They can be *legislative*, such as the (now removed) regulations that prevented natural gas from being used to generate electricity, or today's regulations that inhibit cross-utility (e.g. gas and electricity) cooperation that would enhance integrated resource planning.

Similarly, ATTRACTORS can be *technical*, such as the fuel cell. They can be *cultural*, like the growing public sensitivity to the need for clean atmospheres and the dangers of atmospheric emissions that could increase climatic instabilities or bring climatic change. They can be *economic*, like various monetary policies. Or, they can be *legislative*, such as clean air laws, and most important for hydrogen systems – the emerging CO_2 protocols of which the Kyoto Agreements may be viewed as merely precursors.

The largest opportunities emerge from knocking down the largest barriers. The larger the barrier the larger the business, environmental or cultural opportunity – and the greater the positive impact on systemic evolution if it is removed. This may be better understood if a barrier is seen as a kind of "snag" to orderly systemic evolution. If the snag is removed, evolution is accelerated due to elasticity in the release process.

Today, one of the clearest examples of a "snag" is the absence of an inexpensive, convenient technology for storing low-carbon fuels on-board transportation vehicles. If this snag were removed, it is easy to visualize the elastic release processes that would, first, greatly accelerate the use of natural gas vehicles and, second, open pathways to the introduction of hydrogen vehicles.

Attractors can also accelerate systemic evolution, although often without the vigour that accompanies removing a barrier. This is because the system typically develops greater elastic tensions when trying to break past a snag than it does when responding to the tug of an attractor. This differentiation in the relative strength of release processes (barrier compared with attractor) may be less strong for legislative attractors/barriers than it is for technological attractors/barriers.

Synergies from Combining Barriers and Attractors

Sometimes, especially in the context of technological barriers/attractors, combinations of "next rank" barriers and attractors can be especially fertile for hunting down opportunities. Since these arguments are now becoming increasingly abstract, we will illustrate this concept by an example.

Example 1: LH_2 onboard Fuel Cell Vehicles

First, consider fuel cells (FCs) which, resulting from their high energy conversion efficiencies and environmental gentility, are an attractor technology for transportation. Unfortunately, however, oxygen reduction is the rate-limiting step on fuel cell performance. To reduce the oxygen electrode constraints, most manufacturers employ pressurized air. Air compressor and pumping power can become significant parasitic loads on the total FC stack output (e.g., 15% of the total load in a fuel cell powered bus).

Second, imagine that liquefied hydrogen (LH_2) becomes the staple on-board storage methodology for hydrogen, perhaps caused by anticipating a breakthrough in liquefaction technologies. If LH_2 is used on-board, then the thermomechanical exergy[*] of this cryofuel will be wasted unless a way is found to extract this exergy before the gaseous H_2 enters FC. Using the barrier/attractor analysis we find that, if the liquefaction barrier were removed, an opportunity could be created in the form of an exergy-extraction technology. Using this technology, the exergy of the LH_2 could be used for several applications. For example, a cryogenic air separation mechanism could be devised to produce O_2-rich gas to improve FC performance at lower pressures.

Example 2: Co-Production of Hydrogen and Electricity

A second category of synergy is that which arise due to the cohabiting of two or more industrial processes, producing multiple products, in the same region. With the capital cost of electrolysis plants expected to drop by up to an order of magnitude, the marginal cost for including hydrogen production on electricity generation facilities is becoming very attractive.

Harvesting the "spinning reserves" of almost any electricity generation plant becomes an attractive option for load levelling. In particular, this may be one of the most economical ways to manufacture hydrogen from natural gas as the energy source. A combined cycle (gas turbine topping a steam turbine) can be used for the primarily shaft power conversion. Then the shaft power can be swung between electricity and hydrogen output determined by instantaneous electricity demand. If the H_2 has a local use, such as in fertilizer production or heavy oil up-grading, H_2 co-production can be synergistic with combined cycle co-generation.

These are but two examples of many opportunities that can be brought into focus by exploring the barriers/attractors enhanced by either technical or location synergies.

Summary on Barrier and Attractor Analyses

A hierarchy of methodologies can exploit the concept of barriers and attractors. It can be used to find high potential pay-back projects for businesses and research organizations. And, of course, it can be used as a *metric for evaluation* by governments and industry when weighing the merits of competing projects.

The preceding paragraphs have shown that barriers and attractors come in many forms – including technical, cultural, economic and legislative. Although our analysis focuses mostly on technologies, the interlocking relationship between all four forms is so tight that projects that would make a large contribution to any category should be given serious consideration.

4. JUDGING THE SYSTEMIC IMPACT OF HYDROGEN TECHNOLOGIES

Example 1: Fire detector

The first example "imagines" a project to develop a fire-detection device that employs metal hydrides. The principle is simple: A metal hydride will be designed to release hydrogen in a sealed unit when it reaches a predetermined "indication of fire" temperature. The device will be self-contained, requiring no external electrical power. The hydrogen contained within the device will simply be a "working fluid" that, when released as the temperature reaches the hydride design temperature, will activate a pressure sensitive switch which, in turn, will activate the fire alarm or sprinkler system. As the temperature is reduced below the "indication of fire" temperature, the hydride re-absorbs the released hydrogen, thereby resetting the fire alarm to "off." It is possible to imagine a candidate project of this type seeking funding for product development. Further, imagine that the proposal demonstrates a well-conceived R&D plan and marketing plan, together with competent technology development, management, and marketing teams. In short, it is possible to imagine a proposal of this type that (i) was aimed at developing a hydrogen technology and (ii) exhibited a high prospect of commercial success, yet (iii) would provide almost no synergistic support for the deployment of hydrogen energy systems.

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[*] Exergy is a composite thermodynamic property (it depends on both the system and its environment), and is a measure of the maximum work that may, ideally, be recovered by bringing the system into equilibrium with its environment. Exergy is made up of thermomechanical and chemical components.

Example 2: On-board storage

The second example "imagines" a project to develop a unique method of storing hydrogen that promises high densities combined with light weight. If successful, the technology could be used in both stationary and mobile applications but it will have special advantages in transportation. The physical principles of the technology are well established but reduction to engineering practice faces a number of hurdles. The R&D team has credibility but only a rudimentary market analysis has been performed.

Compared to the "fire detector", the "on-board storage" project has (i) a higher level of technological risk, (ii) a less well-formed business plans and yet, if successful, it would not only (iii) boost the commercal feasibility of a wide category of hydrogen technologies especially in the huge transportation market, but also (iv) act as a catalyst for the integration of component hydrogen technologies in numerous emerging hydrogen energy systems. Therefore, the success of this project would significantly improve the feasibility for a mosaic of hydrogen energy systems and, most particularly, would eliminate a major technical barrier to hydrogen vehicles – significantly improving the attractiveness of, for example, hydrogen-fuelled urban public transit vehicles.

These two "hydrogen technology" examples, one a fire detector, the other an on-board storage technology, demonstrate why we recommend that hydrogen projects selected for development *must* exhibit a *synergistic systemic impact* that enhances the viability of hydrogen energy systems in general.

5. PROJECT SELECTION METHODOLOGY

Qualitative Procedures

The three concepts discussed in Section 1 are needed to fully exploit the many aspects of energy system interconnectedness. This paper attempts to make tangible these three concepts. But tangibility "grows in the using." When applied to project evaluation, the benefits of what we call "barrier/attractor analysis" can emerge as much from "awareness" as from quantification "methodologies." This is accomplished as those involved in project selection use the issue of systemic leverage as a *staple question* when considering any proposal.

Quantitative Procedures

When the barrier-attractor optic provides a quantitative expectation, but greater specificity is desired, such quantification may be provided by employing scenario development and computer modelling. The approach is to develop scenarios, which explicitly incorporate not only the expected techno-economic envelope of the new technology but also such factors as:

- discount rates for the cost of money;
- existing or possible environmental legislation;
- ultimate energy service(s);
- likely energy SOURCES (costs, availabilities, etc.); and
- technology diffusion rates.

The resulting scenarios can be used as the basis for computer models or applied to provide whatever level of quantification is deemed appropriate – consistent with the reliability of the input data. Performed by modellers, this approach can provide remarkably good indications of the systemic impact of a candidate technology from the viewpoints of:

- life-cycle costs;
- environmental impacts (integrated over *all* parts of the system chain);
- return on investment;
- impact on other parts of the service-to-source chain;
- impact on other parts of the total energy system; and
- systemic robustness in response to legislative, economic or geopolitical surprise.

6. OPPORTUNITIES IN LATIN AMERICA

South America, Central America and Mexico appear, to us, to be rich in settings where it may be possible to employ H_2 as metaphorical tether to assemble synergistic system opportunities. These settings could include the following:

Example 1: Heavy Oil & The Attractor of NFD H_2 Upgrading

Regions rich in heavy oils, such as Venezuela, require some form of hydrogen upgrading. All crude oil is hydrogen deficient when its H_2/C ratio is compared with the H_2/C ratios of the desired petroleum products. This is especially true with heavy oil, tar sand and oil shale. Given the increasing concern for anthropogenic CO_2 emissions, typified by the Kyoto protocol, and given the international move to introduce pollution trading credits as one way of reducing such emissions, there may be an opportunity in such processing industries to substitute non-fossil derived (NFD) H_2 giving substantial CO_2 credits.

To give an example of the advantages of from NFD H_2, Table 1 shows the effect of different upgrading processes for a plant producing 735 TJ/day (approx. 1700 tons /day) of synthetic crude. These data apply to the Athabasca oil sand fields of western Canada [5] but are typical for all heavy oil upgrading.

Table 1: Effect of Different Upgrading Processes

External fuel	Upgrading method	Amount of CO_2 (tons/day)
Coal	Thermal cracking	44,600
Natural Gas	Hydrocracking	20,900
Nuclear	Hydrocracking	6,400
Nuclear	Direct H_2 enrichment	0

We have arbitrarily chosen nuclear as the non-fossil source of electricity for electrolysis, in part because the most attractive nuclear technologies operate most effectively if they have steady shaft output. This means that they can be designed to co-produce electricity and hydrogen, following the electricity load while filling the under-capacity with H_2 product. With the imploding capital cost for electrolysis plants, this scenario becomes increasingly practical. The CO_2 emission numbers remain the same, however, whether hydraulic, solar, wind or any other non-fossil source was employed.

Example 2: Steel Production & The Attractor of NFD H_2 Direct Reduction

Although the processing of Fe_2O_3 to produce steel is entirely different than the processing of heavy oils to produce synthetic crude, the advantages of employing NFD H_2 rather than C in the reduction process has many similarities. Except that reduction by carbon emits large quantities of CO_2, not only in steel making itself, but also in producing coke for the steel making processes. In this case, the co-produced O_2 that results from electrolyticaly produced H_2 can often be usefully employed in the industry.

We understand that there are large deposits of relatively pure iron ore in regions of Latin America. Some of these deposits, are in proximity to undeveloped hydraulic potential. These locations could make excellent sites for NFD H_2 reduction of Fe_2O_3. Moreover, if harvesting this hydraulic potential required the damming of waterways to produce reservoirs, then the de-oxygenation that so often accompanies such land flooding can be compensated by re-oxygenation using electrolysis by-product (O_2).

Clearly, Fe_2O_3 reduction by NFD H_2 could become a national source for tradable CO_2 credits, just as in the case of heavy oil upgrading described previously.

Example 3: Gas Pipelines in Central America

In March of this year, ministers of energy from the Central American countries will be meeting to discuss a natural gas (NG) pipeline between Mexico and Panama. Pre-feasibility studies by the Economic Commission for Latin America and the Caribbean (ECLAC) estimate that the cost for this project would be in the neighbourhood of US$1 billion. The 2,200-km pipeline would start in Pemex City, Mexico, and pass through Guatemala, El Salvador, Nicaragua, and Costa Rica. This project is still in its earliest stages of political planning, and it may take years to materialise. However, because this infrastructure would be built from scratch, there is a window of opportunity to leapfrog to technologies compatible with H_2 energy systems.

For example, molten carbonate and solid oxide fuel cells (MCFCs and SOFCs) operate at relatively high temperatures (650-1,000°C). These systems are attractive for stationary power generation because of the higher achievable efficiencies, low emissions, and modularity. The operating temperatures are high enough to allow internal reforming which can produce H_2 from several fuels (including NG). In addition, the high-grade heat is suitable for co-generation schemes. The new pipeline could be planned to include decentralised power generation plants based on these technologies. It could also include refuelling stations for non-traditional fuels such as compressed and liquefied NG (the incremental cost of a refuelling station is small when compared to the cost/km of pipeline).

Example 4: Strategic Advantage of Moving Downstream Towards SERVICES.

The J/$GDP ratio has been falling at a rate of between 1.3 and 2.4% per annum in all developed nations for several decades. Currently, the world's lowest J/$GDP values are lowest in Western Europe and the Pacific OECD, with ratios just a little higher in North America. These data say several things. First, the general trend is for greater economic growth towards the SERVICE end of the energy system chain rather than towards the SOURCE end—so, whenever possible, industries and national planners should move as far as possible downstream towards SERVICES. Second, it makes clear again—if it isn't already abundantly clear — that robust economies should use their unique indigenous energy SOURCES to value-add raw materials toward finished products.

7. FINAL THOUGHTS

In closing, we return to the optic that the energy system chain being driven by the SERVICES people want—and not the SOURCES. Industries and governments can benefit by examining the fundamental SERVICES people want and the collateral benefits that they desire while the service is delivered. Often, these collateral benefits can be delivered by H_2 systems. The objective, however, should be improving the system, not simply introducing hydrogen via disconnected pieces of technology.

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