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Solar Photovoltaic Hydrogen: The Technologies and Their Place in Our Roadmaps and Energy Economics

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SOLAR PHOTOVOLTAIC HYDROGEN:
THE TECHNOLOGIES AND THEIR PLACE IN OUR ROADMAPS AND ENERGY ECONOMICS

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ABSTRACT: Future solar photovoltaics-hydrogen systems are discussed in terms of the evolving hydrogen economy. The focus is on *distributed* hydrogen, relying on the same distributed-energy strengths of solar-photovoltaic electricity in the built environment. Solar-hydrogen residences/buildings, as well as solar parks, are presented. The economics, feasibility, and potential of these approaches are evaluated in terms of roadmap predictions on photovoltaic and hydrogen pathways—and whether solar-hydrogen fit in these strategies and timeframes. Issues with the "hydrogen future" are considered, and alternatives to this hydrogen future are examined.
Keywords: solar hydrogen, system, roadmaps, electrolysis, photolysis

1. INTRODUCTION

Solar electricity *is* real and on a path as a power of choice for world consumers [1,2]. Advances in photovoltaic (PV) performance over the past 25 years—with crystalline silicon more than doubling in efficiency, thin films nearly quadrupling, and concentrator cells converting almost 40% of incident photon energy into electrical power—have been the foundation for credible electricity generation [2–4]. History has offered strong indicators for progress and reliability. Fifty years ago, one 2-cm^2 Si solar cell at Bell Telephone Laboratories broke the 5%-efficiency mark—delivering a power of 5 mW. This last year, the industry shipped over 500 million cells having an area of more than 6 billion cm^2—representing a power of nearly 0.75 GW [5]. That original cell still functions a half century later—and current module technology is warranted for 20–30 years. The versatility, clean and secure power, and scalability of this solar technology offers even more for the world energy portfolio—including perhaps serving as the perfect partner for our potential hydrogen prospects [6]. The major focus herein is to look at solar PV in this application—focusing on combining the distributed-energy delivery strengths of PV with a similar energy-distribution scheme for hydrogen and its related technologies to afford our future generations with *24-hour solar-hydrogen power.*

2. SOLAR HYDROGEN SCENARIOS

When the United States rolled out its hydrogen vision in 2002 [7,8] and its strategy in 2003 [9], the source of the hydrogen was perceived primarily to be natural gas—an approach that hardly ignited the renewables community. Within a few months of the U.S. President's announcements in his 2003 State of the Union Address, the developing natural gas shortage has precluded this source from being the primary one—and other technologies have come forward. Nuclear, wind, bioenergy, and solar have positioned themselves to serve as the energy resources to produce the required hydrogen [10–13]. Among these resources, solar possesses some special attributes that may make it the power of choice in the future. If one looks at the more than 14 TW total primary energy equivalent required currently worldwide—or the 26–30 TW predicted to be consumed at the coming half-century point, only solar of the renewable resources could actually meet this total—and only nuclear from the nonrenewables [14]. Questions about PV-for-electricity and solar-for-hydrogen production land-area requirements, water use, electricity needs, and technology production pathways/performances have been addressed—with no showstoppers identified on the horizon [15–17]. What limitations exist?

As centralized facilities, both concentrating solar power (CSP) and nuclear provide clean-generation thermal roadmaps toward generating economical hydrogen [9]. Additionally, CSP, concentrating PV (CPV), and flat-plate PV can meet electricity prices that are needed for large- scale electrolysis. However, all these centralized approaches require long-distance delivery, which is difficult and potentially the most costly segment of the hydrogen energy system.

Alternatives? Just as the distributed solar-PV system makes use of the economics of "electricity generation at point of use," an alternative distributed hydrogen system links "production" and "delivery" at the point of use [16]—*distributed solar electricity* and *distributed solar hydrogen.* The recent U.S. National Academy study of hydrogen provided a partial look at this approach, as well [18]. This concept can be visualized in two distinct implementations. The first is at the individual residence or building level [9]. This concept expands on the zero-energy home with the inclusion of production, storage, and "in-property" distribution. The primary source of energy is the sun, with PV providing the electricity and with solar thermal providing for the building's heating and cooling needs. In the longer term, this would be a hybrid electricity/thermal system integrated into the building structure. As the PV and solar thermal technologies advance, integration into the building structure will be essential in ensuring architectural integrity and desirability. But coincidentally, it will also maximize the use of the building's skin. The solar electricity is used for (1) generating daytime electricity for the building, (2) providing power to the electrolyzer to produce the hydrogen (and oxygen) for the fuel cell and storage, and (3) supplying excess electricity to the grid. The stored hydrogen could even be used to fuel the "family Freedom Car," in addition to providing the hydrogen for the fuel cell (24-hour power). Thus, this concept could fulfill the "zero-energy home" objective, but could also result in the "energy-plus" residence—providing more energy than it needs. The excess could be shared with the utility, as well as with neighbors.

This situation extends into the second distributed PV/hydrogen concept: the solar hydrogen park (Fig. 1). In this approach, a number of residences, structures, and local community buildings share the solar-collection tasks to generate the necessary electricity—and *share* the hydrogen generation from a community "plant." Thus, the stored hydrogen would feed their fuel cells for nighttime power, and community fueling stations are used for hydrogen-powered automobiles, vans, and trucks. Protected parking covers would also support PV (which would not only feed into the community power, but also be offered for electric or hybrid vehicles). Note that other smaller generation schemes could also be used, which could include concentrating PV—with small parabolic dishes. Although some individual residences might have problems with local zoning and/or covenants, the use of dishes, or even CSP troughs, could be landscaped into visual acceptability. Such approaches are currently being developed in Australia, where hybrid CPV-hydrogen production units have been demonstrated successfully. The case for the "solar hydrogen park" is that the distribution of hydrogen is over a small distance, generating the fuel very near the point of use. In fact, the efficiency of the system and the effectiveness of generating the hydrogen can be increased with technology evolution—such as a *thin-layer* electrolyzer integrated with the PV modules (e.g., integrated into the PV/thermal roof module) and/or having pyrolysis systems integrated with the PV. Both of these approaches reduce the hydrogen "transportation" distances during the production cycles. It is also possible that the hydrogen storage could be integrated into this structure, using carbon-nanotube technology in a thin-layer configuration.

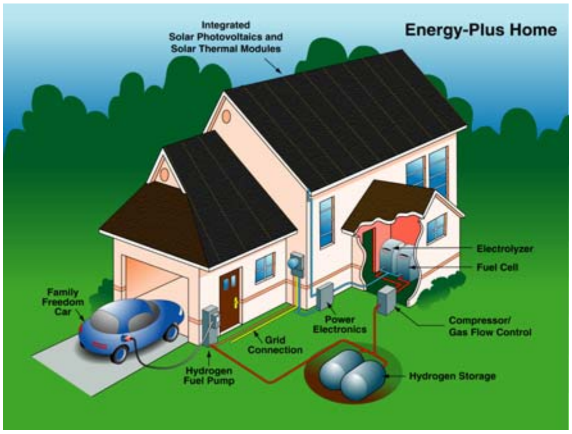

Figure 1: Distributed Solar-Hydrogen Residence Concept.

This paper examines these future possibilities—the energy-plus home and the solar hydrogen park—for technical feasibility and economics feasibility, and time-expectations are evaluated in terms of expected technology advancements and predictions from the *U.S. PV Industry Roadmap* [19].

3. ECONOMICS AND TIMES VERSUS ROADMAPS

The economics of producing hydrogen using PV has been examined by a number of sources [20–27]. A simplistic economic potential might be gauged by comparing the "market" selling price of hydrogen to the corresponding solar production cost—and the portion of this cost that is attributed to the electricity. Currently, purified, noncompressed hydrogen is *produced* for about $0.75/kg to $2/kg, depending on the volume and quality purchased. Currently, PV electrolysis is about an order of magnitude more expensive ($7/kg–$25/kg), depending on the tax credit and rate and on the internal rate of return [7–9,12,19]. (There is no current "cost" for hydrogen from PV photolysis because there is no production, except in the research laboratory. However, some analysts still estimate this cost near the $20/kg level—with ample assumptions!) Hydrogen (from natural gas) is currently delivered at about $5/kg to a car at a refueling station. Of this, about $1.90/kg is credited to the electricity (at a rate of $0.035/kWh). For a smaller electrolysis system, the current cost is $7.40/kg to $8.00/kg), with the electricity portion at $4.10/kg (at a $0.06/kWh rate). These two cases correspond to the distributed-generation scenarios in Figs. 2 and 1, respectively. Of course, current PV electricity is generated at a rate in the range of $0.18/kWh–$0.25/kWh—higher than conventional electricity without some incentives. Can PV eventually meet the price criteria for generating electricity competitive for the distributed hydrogen requirements? As a basis, we will use the *U.S. PV Industry Roadmap* as a guide to 2020—and some preliminary (not finalized) targets from the in-progress industry roadmap *realignment* (which provides a new set of targets because funding and policy assumptions were not met for the original strategy)—as well as learning or experience curves to predict the futures to 2050. The requirements for hydrogen (and the electricity cost to produce it) will be taken from the new Multi-Year Technical Plans. Levelized electricity costing (LEC) is used.

Table 1 presents a comparison of relevant costs, goals, and predictions over the timeframe of 2003 through 2050. Current (2003) PV electricity prices are certainly not competitive. Neither the end-of-the-decade goal of $3–$4/W for systems in the current roadmap nor the $3/W (2015) for the realigned roadmap can be expected to lower the electricity price to the levels required by the hydrogen Multi-Year Plan for the defined cost-competitive region. The major goal is $0.06–0.08/kWh in 2020 (for both the Roadmap [19] and the U.S. DOE Solar Energy Technologies Program [12]). With more aggressive policies, the realigned roadmap could bring about electricity prices below this. This electricity price meets the hydrogen goal for 2010, but is still below the more sound expectation of about $0.04/kWh, reached in 2030—or about 2025 possible in the realignment. Prices beyond the roadmap timeframes can be deduced from the learning curve data [28], which shows that PV has historically followed an "80% learning curve" (i.e., for each doubling of cumulative production, the price decreases by 20%) [28]. Similar timeframes can be anticipated for both the residential and the solar village concepts—if the PV Roadmap goals are met & the learning curve continues past 2020. For a central PV station, by comparison, the required electricity price is the wholesale electricity price, which will not be reached until at least 2040 (about 5–8 years sooner in the realignment). This corresponds to hydrogen at about $1.60–$1.70/kg, which, in the case of transportation, is equivalent to $1.25–$1.35/gallon of gasoline with a 0.2%/year escalation [7,9].

This analysis shows that even the roadmap projections allow PV to fit well into an eventual hydrogen economy in the United States. But how can we get there sooner? If some of the "predictors" are off, then certainly the competition with other energy sources can bring about this solar scenario faster. For example, if the Energy Information Administration gasoline escalation was higher than 1%/year, this would mean that roughly $0.35/kWh to $0.45/kWh PV would be economical—realizing the 2040 centralized goal about 10 years sooner, or accelerating the 2030 expectations by 3–5 years. However, it is difficult to propose such an alternative without also pointing out that the roadmap goals may not be reached, that the learning curve for PV might be 85%, or that prices and availabilities of competing fuel sources might be more, rather than less, favorable. Moreover, the realigned roadmap would accelerate the longer-timeframe goals (e.g., beyond 2025) by as much as a decade—*if* the realigned roadmap conditions are met.

Expectations that disruptive technologies will favorably alter the learning curve also present risk. However, the risk depends on reasonable science, rather than speculation. These breakthrough technologies lower prices and open markets more rapidly. An example is that of the transistor, which was continuing on a 90% learning curve until the late 1950s. With the introduction of the integrated circuit—certainly a disruptive technology from business as usual—that electronic technology followed a 50%-60% learning curve for a brief period, until it settled on an 80% characteristic, similar to that of PV. Thus, as the cumulative units that were produced quickly increased due to the integrated processing, the cost per unit fell—and the demand for this new technology increased substantially. This "integrated" innovation is not much different than the second and third generations of PV that are already being pursued. This same impact of innovation can bring about PV—and PV for hydrogen—more rapidly. Thin-film technologies (especially multijunction polycrystalline approaches), nanotechnologies, and "plastic" cells all address low-cost breakthrough PV, primarily for our distributed scenarios [2,29]. On the other hand, super-high-efficiency PV using quantum dots, rods, or pods, ultra-multijunctions, impurity or intermediate layer cells, thermophotovoltaics or thermophotonic all pose breakthrough possibilities on the other end of the technology spectrum [2,29]. They are aimed at both centralized and distributed power-park applications. Additionally, the direct production of hydrogen by photolysis (electrochemical methods) is also a breakthrough technology. This has considerable potential for cost effectiveness—but the problems of performance (efficiency

Table 1: Competitiveness comparison of PV-hydrogen based roadmaps and multiyear plans. *Italiciced numbers projected from roadmap using technology learning/experience curves.* Proposed (not final) roadmap targets and projected indicated in grey tones.

	2004–05	2010	2015	2020	2030	2040–50
PV System Price	$6–$15/W	$3–$4/W	[$3/W]	$1.50–$2.00/W [<$1.50/W]	*~$1.00/W*	*~$0.50/W*
PV Electricity Price	$0.18– 0.25/kWh	$0.11– 0.16/kWh	[$0.061– $0.10/kWh+]	$0.06–0.08/kWh *[$0.05–0.07/kWh]*	*~$0.045/kWh* *[<0.04/kWh]*	*~0.03/kWh*
U.S. PV Capacity or Shipments (for that year or cumulative installed)	0.2–0.4 GW/yr	0.8– 1.0GW/yr	[2-2.75GW/yr U.S.]	7–8GW/yr of which 3.1GW/yr U.S.	*[130GW installed cumulative]*	*1000–1600TWh/yr* *[2000–3000TWh/yr]* *[450–630GW installed cumulative]*
Targets				15% of new (added) U.S. generation capacity*	10% of total U.S. generation capacity**	*15%–18% of total U.S. generation capacity* [50% of all buildings; 1/4–1/3 of U.S. electricity]
Performance-Efficiency Range for *Best* Commercial (Cell/ Module/ System)* **	10–20%/ 11–15%/ 7–12%	18–25%/ 14–17%/ 9–14%	*[Likely at higher end of 2010 goals]*	*20–28%/* *16–20+%/* *13–18%* *[20+-35%/* *18–24%/* *14–20%]*	*20+–40%/* *18+–28%/* *16–20%* *[22–40+%/* *20–30%/* *18–25%]*	*Ultra-high-efficiency modules: >40%* *Ultra-low-cost modules: >20%*
Distributed Hydrogen: Solar Park (Electrolysis) **Total Price** **Electricity Price**	 $4.70/kg $1.90/kg	 $2.50/kg $1.60/kg				
Distributed Hydrogen: Residence (Electrolysis) **Total Price** **Electricity Price**	 $7.40/kg $4.10/kg	 $3.80/kg $2.80/kg				
Distributed Hydrogen: Photolysis (Electrochem) **Price** **Efficiency** (solar-hydrogen)	 N/A 7%	 $22/kg 9%	 $5/kg 14%			

Roadmap assumptions: R&D budget (original: $100 million/year, never reached; new $150 million/year, 10–15 years)
Major aggressive policy changes (incentives, etc.) on state and federal levels; 30-year system lifetime

+Depends on discount rate
*Target reached in 2018 with new roadmap.
**Target reached in 2026 with new roadmap.
***Higher efficiencies are noted in the 2020–2050 timeframe for concentrating PV technologies and preliminary ultrahigh-efficiency concepts leading toward commercialization.

and reliability) need to be proven (see Table 1). In the 1980 timeframe [30], a rooftop system was demonstrated, but it used hydrogen bromide—which had inherent environmental concerns. If the same type of system could be realized using water splitting, the distributed hydrogen scenario would be widespread. If the performance levels for modules and systems, indicated in Table 1, are reached, the solar-PV hydrogen option will certainly be one of choice, not imposition. The increased focus on R&D through enhanced budgets—providing a balanced investment between now-, near-, and next-term PV technologies would certainly lower the risk for the required technology developments in these timeframes.

4. HYDROGEN LOOKS GREAT...BUT MAYBE NOT

What are the limitations for this approach? Certainly, the arguments for hydrogen are abundant—and at first glance, compelling. However, if the academic exercise were given to a graduate student to find the best fuel alternative to transportation, for example—perhaps hydrogen would not be the answer. Because of its density, it has to be compressed to high pressures. Because of its atomic number, the constraints on the distribution (e.g., leaks) are very rigid. Because of the nature of hydrogen (and the pressure requirements), there are safety issues raised, as well. It might be better to choose a liquid that could be generated from the solar source. Such is the interesting approach proposed by Lewis [31]—the "methanol economy." His careful analysis is based on considering the best options, using closed approaches to control the carbon emissions, and examining all the "electricity sources." His conclusion is liquid methanol, produced by solar (and actually, solar photovoltaics). Lewis is strong in his belief that the total energy must be considered in any long-term energy planning [31]—not just electricity (which he reports is only 10% of the world's primary energy now), chemicals, fuels, etc. In some sense, this is a parallel to the hydrogen approach just discussed: conversion of solar energy to electricity via PV, driving a "methalyzer" to produce liquid methanol, and then transporting the liquid fuel (from central sites in the Lewis concept) to the point of use. Of course, it might also be possible to use the distributed approach—depending on the efficiencies of the processes involved. Other approaches exist, as well (e.g., other fuels, hybrids, pure electrical economies [32]). However, the ensemble of metrics (relative economics, materials availability/security, impacts on related products, technological feasibilities, and, of course, politics) will lead to the eventual winners. Hydrogen is certainly a promising technology that is an ideal partner to solar. But do not close the deal; do not rule out other approaches yet. It is too early to lock in on a single approach. We should remain technically flexible...and provide the innovation and creativity to provide our coming generations with coming generations of abundant clean, secure energy.

5. SUMMARY

Future energy can (should) include PV and hydrogen. The concept of the zero-energy building can be envisioned to expand to the "energy-plus home" that produces more energy (electricity for the residence, hydrogen for night-time power and the family "Freedom Car"). The solar-hydrogen park or village is an extension of this, in which the solar energy and hydrogen is shared in the community. Again, additional electricity can be supplied to the grid and any excess hydrogen can be sold through the community's refueling stations. The marriage between hydrogen and solar brings secure, clean energy—as well as making PV a *"24-hour power"* option.

The "but when?" can be estimated from the predictions of the *U.S. PV Industry Roadmap*, the hydrogen and solar Multi-Year Technical Plans, and considerations of the learning curves for the technology. Centralized PV-hydrogen will not likely be available until the 2040 timeframe. Decentralized approaches can be reached by 2035, depending on the escalation factors for other fuels. Through the acceleration of technology fueled by the policies, investments, and strategies of the new realigned U.S. PV Industry Roadmap, distributed and decentralized approaches can be accelerated by 5–8 years. The result would be an acceleration, similar to that anticipated in the United States by the current hydrogen program. Disruptive technologies—second-generation thin films, organics, and nanotechnologies—can accelerate the nearer term by 5–10 years or more. Third-generation higher-cost approaches (such as quantum technology cells, ultra-multijunctions, new materials, novel structures, and novel concentrators having performances beyond 50% efficiencies) can accelerate both distributed and centralized approaches. The further investment and careful strategy-controlled path into these next-generation breakthrough technologies will benefit the learning curve to bring not only solar-PV electricity, but also, solar-PV hydrogen significantly closer. They can be realities within a generation of our population.

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