# Optimizing an Integrated Solar-Electrolysis System

## Cooperative Research and Development Final Report

## CRADA Number: CRD-18-749

NREL Technical Contact: Josh Eichman

**NREL is a national laboratory of the U.S. Department of Energy**
**Office of Energy Efficiency & Renewable Energy**
**Operated by the Alliance for Sustainable Energy, LLC**

Contract No. DE-AC36-08GO28308

**Technical Report**
NREL/TP-5400-76888
July 2020

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# Cooperative Research and Development Final Report

**Report Date**: March 30, 2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

**Parties to the Agreement**: Pacific Gas and Electric Company (PG&E)

**CRADA Number**: CRD-18-749

**CRADA Title**: Optimizing an Integrated Solar-Electrolysis System

**Joint Work Statement Funding Table showing DOE commitment**:

| Estimated Costs | NREL Shared Resources a/k/a Government In-Kind |
|---|---|
| Year 1 | $75,000.00 |
| TOTALS | $75,000.00 |

## Abstract of CRADA Work:

Electrolysis powered by renewable sources provides a range of potential values such as carbon-free fuel for power, heat, or transportation; storage; and ancillary grid services. Each of these potential benefits has been studied as individual value streams. However, real-world demonstrations of these benefits working in concert are limited in the United States today as electrolyzers lack access to wholesale electricity prices. High power prices make electrolysis uncompetitive compared to traditional steam methane reformation (SMR).

A potentially cost-effective way to demonstrate the value of renewable electrolysis is by powering an electrolyzer directly from a renewable generation source rather than from the electric grid. Integrated with a renewable generation source, the cost of fueling an electrolyzer is the opportunity cost of not selling power from the renewable plant to the grid – effectively, the wholesale electricity price. Additionally, an electrolyzer tied directly to a renewable generator potentially reduces excess generation and increases the value of the ancillary services that the renewable generator can provide to the grid.

## Summary of Research Results:

Hydrogen is a versatile energy carrier that is used in a wide variety of chemical and industrial processes. Producing hydrogen with electricity using electrolysis can enable integration of multiple sectors including electricity, heating, and industrial sectors; however, the cost for producing hydrogen from electrolysis is currently considered too high to encourage greater adoption. With growing amounts of renewable generation on the California grid, there is downward pressure on wholesale electricity prices, particularly during the afternoon from photovoltaics (PV). These lower, or even negative prices, challenge the business cases for new and existing PV plants. In addition, as the grid transitions to less flexible loads, there is greater need for system flexibility.

To help improve the economics for both PV and electrolyzers, we explore the benefit of combining PV and electrolysis systems. The optimal breakeven hydrogen production cost for six unique market participation configurations is calculated at six candidate locations owned by Pacific Gas and Electric (PG&E) that already have PV installed. The cost includes production, storage and compression in preparation for gaseous delivery trucks. The six market configurations are depicted in Figure 1 and include islanded, separated, retail, net energy metering (NEM), hybrid retail/wholesale and wholesale.

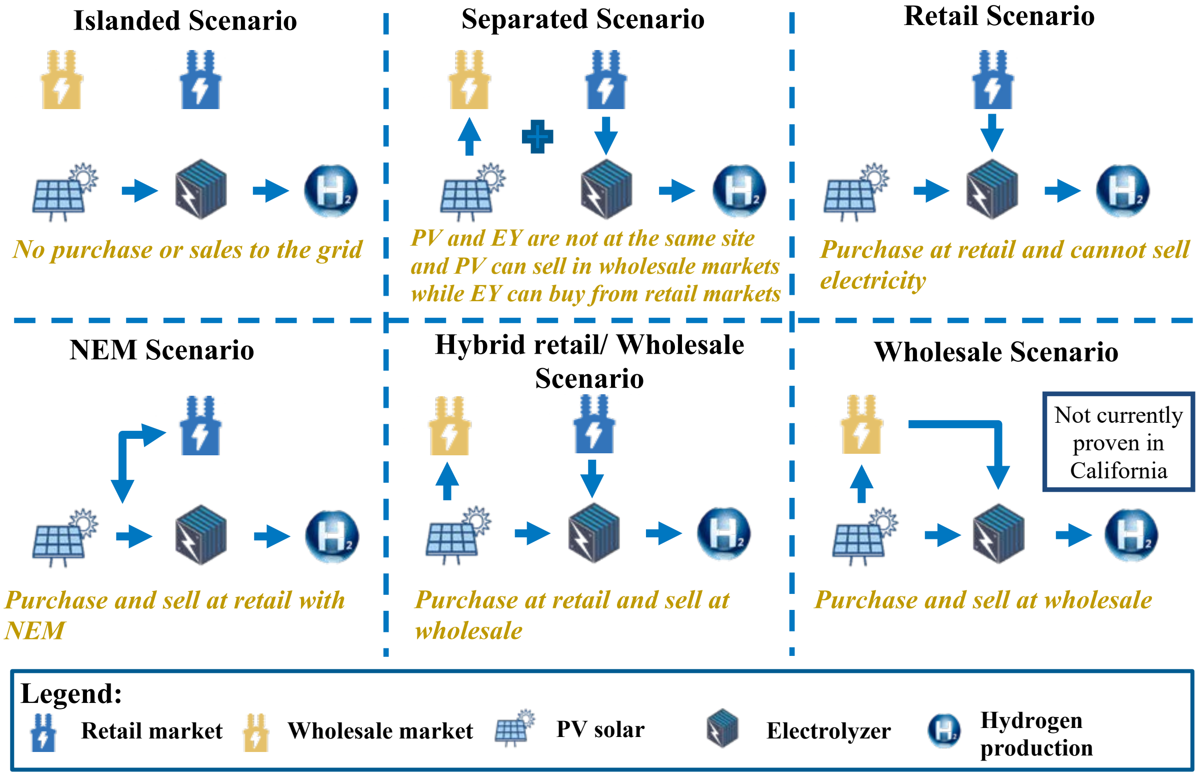

**Figure 1. PV + Electrolysis market configurations**

### Task 1.1. Collect necessary location and resource data

Data was collected for solar resources, electricity prices, and other data. Solar resource data was drawn from the National Solar Radiation Database and processed using the System Advisor Model (SAM). SAM was used to characterize 6 locations of interest in the project. Retail electricity prices for E-20 tariff was drawn from PG&E's tariff sheets available online. Wholesale market prices were pulled from ABB Velocity Suite, which catalogs and organizes data freely available on the California Independent System Operator's Open Access Same-time Information System (OASIS). Cost and other assumptions are shown in the complete report.

### Task 1.2. Determine eligible credits and incentives

Potential value for several credits and incentives was explored. These include renewable electricity sale for Renewable Energy Credits (RECs), carbon reduction from hydrogen use in transportation (i.e., the Low Carbon Fuel Standard (LCFS)) as well as tax and credit incentives. A detailed description of the inputs and their effect on system operation is detailed in the full NREL technical report which can be accessed here https://www.nrel.gov/docs/fy20osti/75635.pdf

### Task 2.1. Prepare optimization model to integrate PV and electrolysis and setup desired scenarios

Using the RODeO model, the optimal breakeven hydrogen price over the lifetime of the equipment is calculated. Revenue streams included in the optimization are the sale of hydrogen, LCFS credits, renewable electricity sold to the grid, RECs and also electrolyzer interaction with the grid to reduce costs including through retail and wholesale rate optimization. The costs included are the electricity costs, capital and fixed operation and maintenance cost (FOM) for the electrolyzer, PV, and storage and compression systems as well as taxes and financing costs.

### Task 2.2. Perform integrated solar-electrolysis optimization at candidate locations

The resulting breakeven hydrogen production cost for all candidate locations is presented in Figure 2. These results use current costs for PV from the annual technology baseline and electrolysis costs from the DOE H2A model. For all locations, the breakeven hydrogen production cost results show that, in the order of decreasing cost, the system configurations are islanded (highest), separated, NEM, retail, hybrid retail/wholesale and wholesale (lowest).

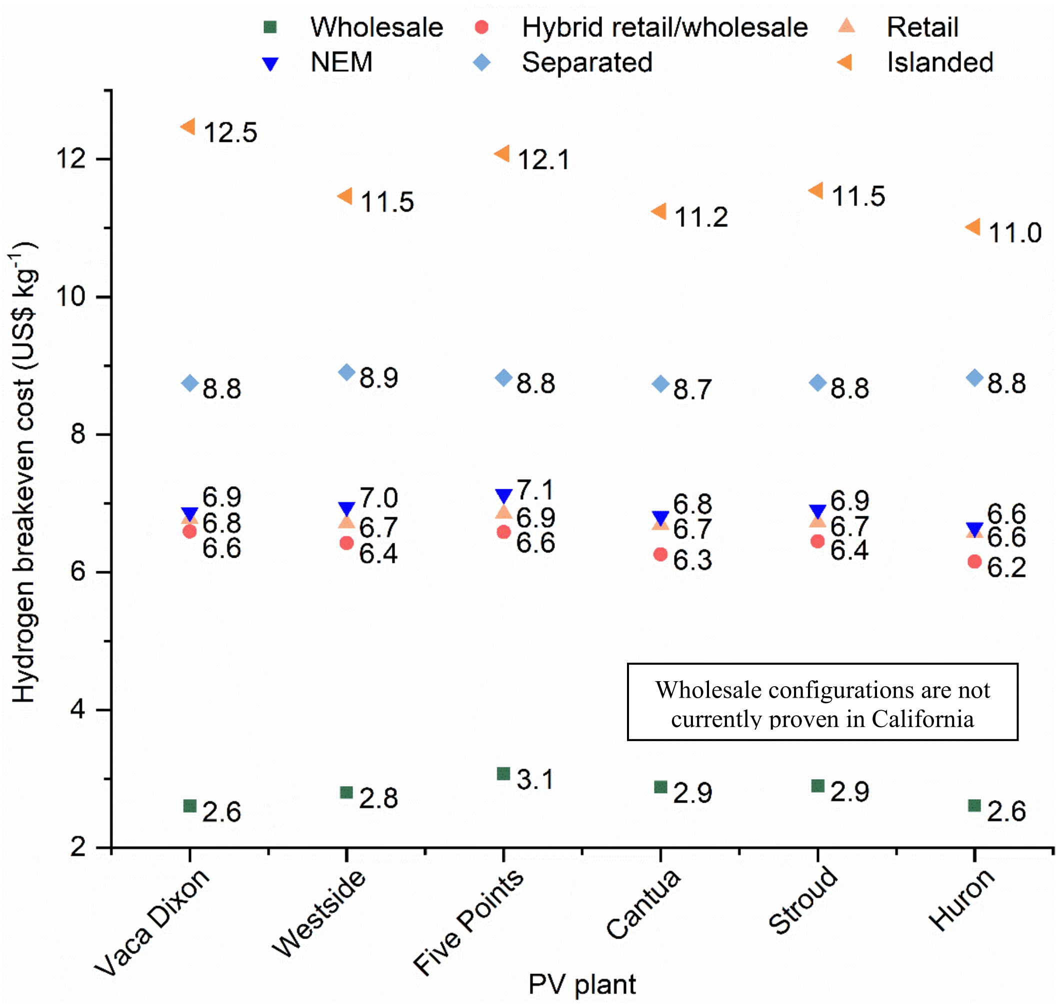

**Figure 2. Current hydrogen breakeven production cost for PV + Electrolysis systems with six market configurations and six candidate locations**

While there are no electricity costs for the islanded configuration, the reduced utilization of the electrolyzer caused by limited hours of PV production results in the highest cost. The separated configuration provides a comparison point for the cost of operating both systems independently. Excluding islanded systems, integration of PV and electrolysis reduces the costs from around $8.8/kg to around $6.7/kg for the NEM, retail and hybrid configurations and to around $2.8/kg for the wholesale configuration. Wholesale market access for flexible loads is not currently proven in California. While there are several programs in California that allow device access to wholesale markets (direct access, non-generator resource (NGR), proxy demand resource (PDR)), none are either open or give flexible loads sufficient exposure to wholesale markets.

The lowest cost operation for a proven configuration is for hybrid retail/wholesale at around $6.4/kg. This system improves slightly on the retail only system with the ability to sell renewable electricity to the grid when prices are high and also receive renewable energy credits.

A breakdown of the cost components for Vaca-Dixon is presented in Figure 3. These values represent current costs and market conditions. For each of the configurations, there is a balance between the capital and maintenance cost components, the operation costs (i.e., electricity costs) and the additional market revenues. Depending on the cost or value for each of those components the size and utilization of the equipment changes to minimize the breakeven hydrogen production cost. Excluding islanded systems, these results show that greater integration with the grid improves the competitiveness of the combined system, largely by reducing the cost of electricity.

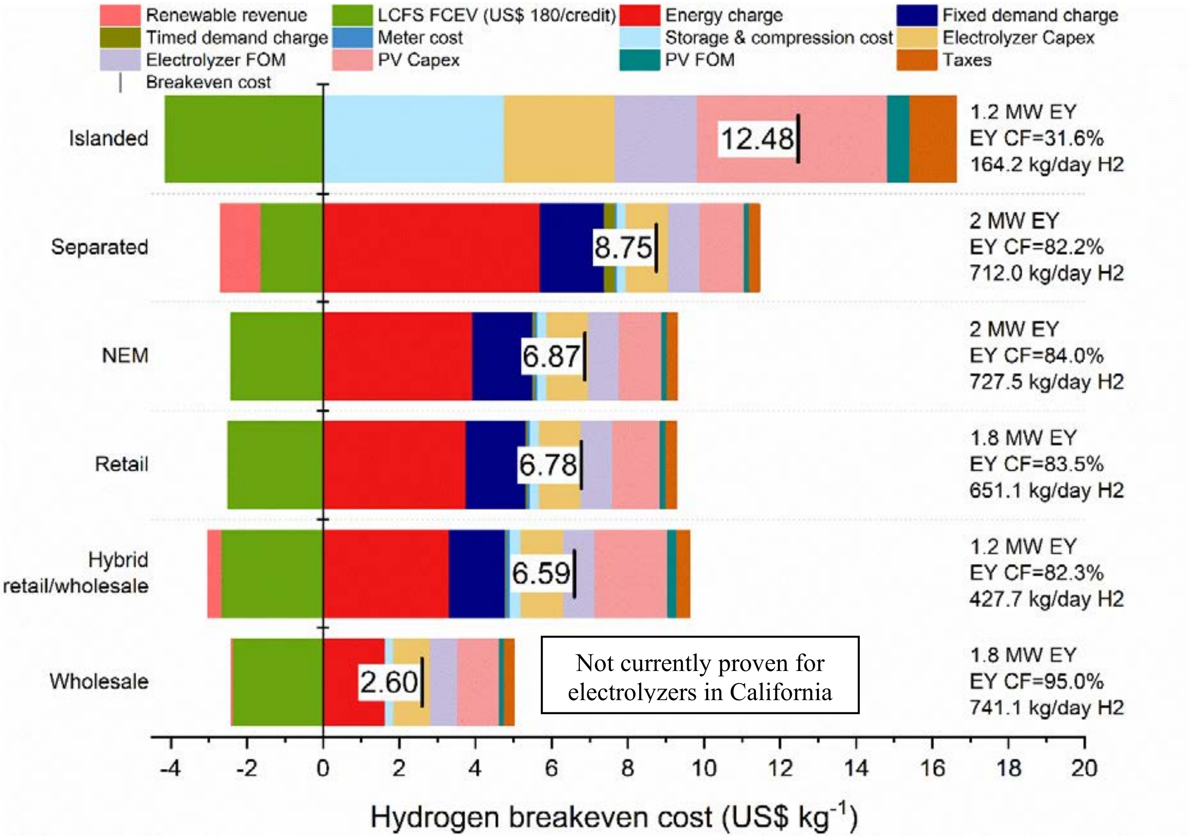

**Figure 3. Comparison of current breakeven hydrogen production cost for Vaca-Dixon with 2MW of PV. EY = Electrolyzer, CF= Capacity Factor**

The integration of solar PV and electrolysis is shown to provide a mutually beneficial relationship, both operational and economic. With the exception of the islanded system, when PV and electrolysis are integrated, the breakeven cost for producing hydrogen reduces between 20% (NEM) and 70% (wholesale). For PV, integration with electrolysis offers the potential to hedge against wholesale market price volatility, particularly in a future with additional PV putting downward pressure on wholesale prices in the afternoon. Additionally, integration with electrolysis may offer the potential to defer or avoid transmission investment to deliver power to the point-of-use and instead use it on-site.

When compared with SMR, PV + Electrolysis systems with current costs are likely not competitive; however, with cost reductions for electrolysis equipment consistent with DOE projections, it was found that systems with wholesale market access would be competitive, largely on account of both low capital costs and low-cost electricity. It was also determined that electrolysis units can provide greater flexibility than what is required to optimize retail rates, so there is an opportunity for a utility or CAISO to increase system flexibility with PV + Electrolysis systems in return for commensurate compensation. In this way, there are potentially several solutions that fall between the hybrid configuration and the wholesale configuration that could provide sufficient compensation for a PV + Electrolysis unit to compete with SMR while also providing greater flexibility to the grid.

### Task 2.3. Characterize the opportunity for solar-electrolyzer systems in other regions of California

The project performed extensive analysis on six specific renewable sites in California. Finding the appropriate location for a production facility requires balancing several different factors including electricity rates available (wholesale or retail), distance from end-use, costs for transporting the fuel, and renewable resource availability.

Since electricity is such an important factor for the cost of electrolyzed hydrogen, the electricity rate plays a similarly important role in cost effectiveness of a site. A site must consider both retail rates available in the area and the potential for accessing wholesale markets. Retail rates are independent of location within a service territory. Wholesale pricing nodes can have very different Locational Marginal Prices (LMP) as shown in Figure 4. LMPs in areas of high congestion and long distances from generation, which leads to high loses, have a higher cost than LMPs that are close to the generation source without any congestion. The nodes selected for this analysis have average prices that are in the middle of price range.

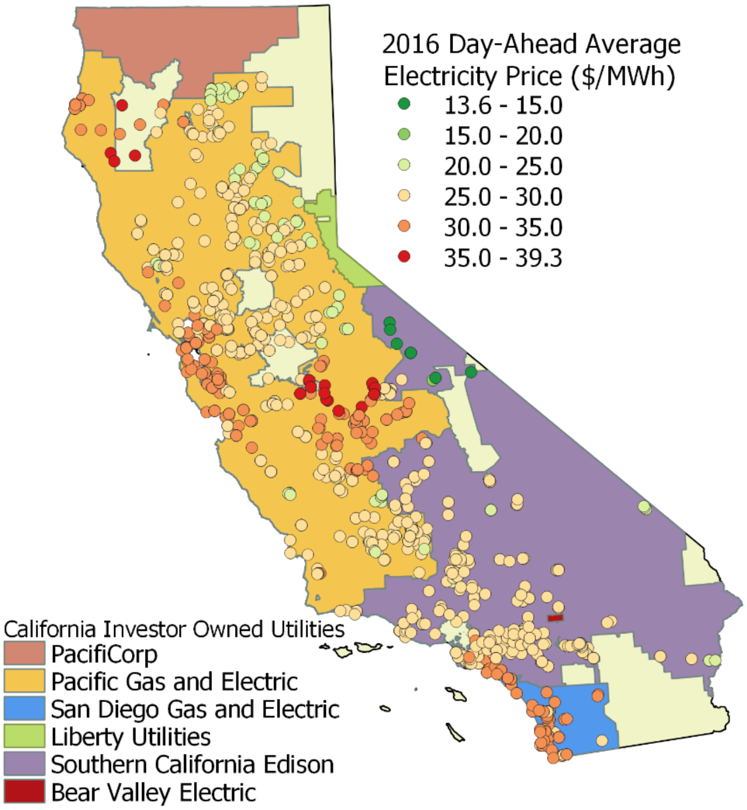

**Figure 4: 2016 Day-ahead average electricity prices for California generation nodes**

The distance and method of transporting hydrogen must also be considered when determining the least cost location. For instance, the tradeoffs between a gaseous truck, liquid truck and pipeline delivery will affect the cost that a company delivering hydrogen must charge to consumers, which in turn affects the overall cost of hydrogen. Longer distances and lower volumes of product delivery will affect the cost. A map of current and planned station locations curated by the California Fuel Cell Partnership is shown in Figure 5.

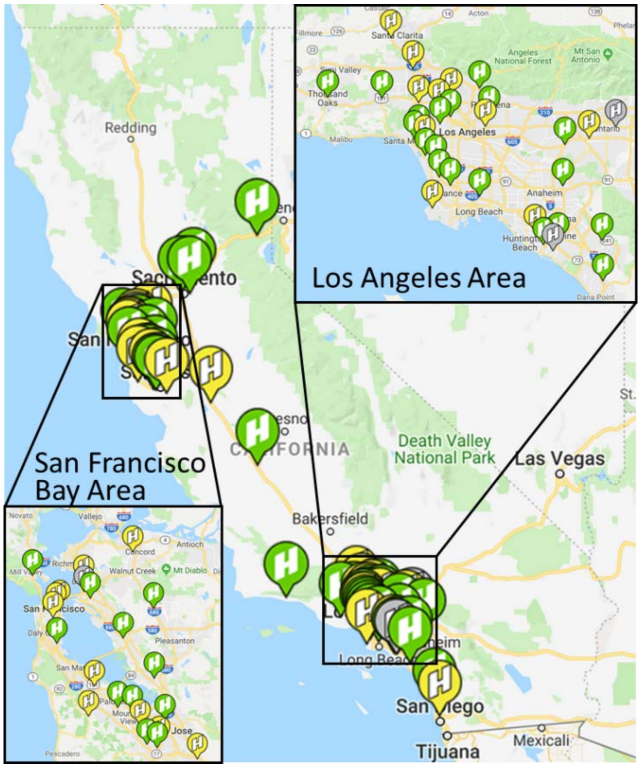

**Figure 5: Map of current and planned hydrogen stations in California**[1]

Lastly, the land and resource availability for renewable power production and the associated costs of produced power should be considered when siting PV+electrolysis systems. Both land and resource availability are high in the South-Eastern California, while closer to the load centers in cities, the land is more expensive, and the resource is lower. Figure 6 shows the solar resource in California. Similarly, if the systems are placed near renewable power plants that have excess generation from either transmission congestion or lack of demand, then a PV+electrolysis system could more readily access the available energy. Additionally, there are opportunities to locate the electrolysis system near gas pipelines depending on the developments with hydrogen blending in the natural gas system, hydrogen methanation or dedicated hydrogen pipelines. Maps of electricity transmission and natural gas transmission are shown in Figure 7.

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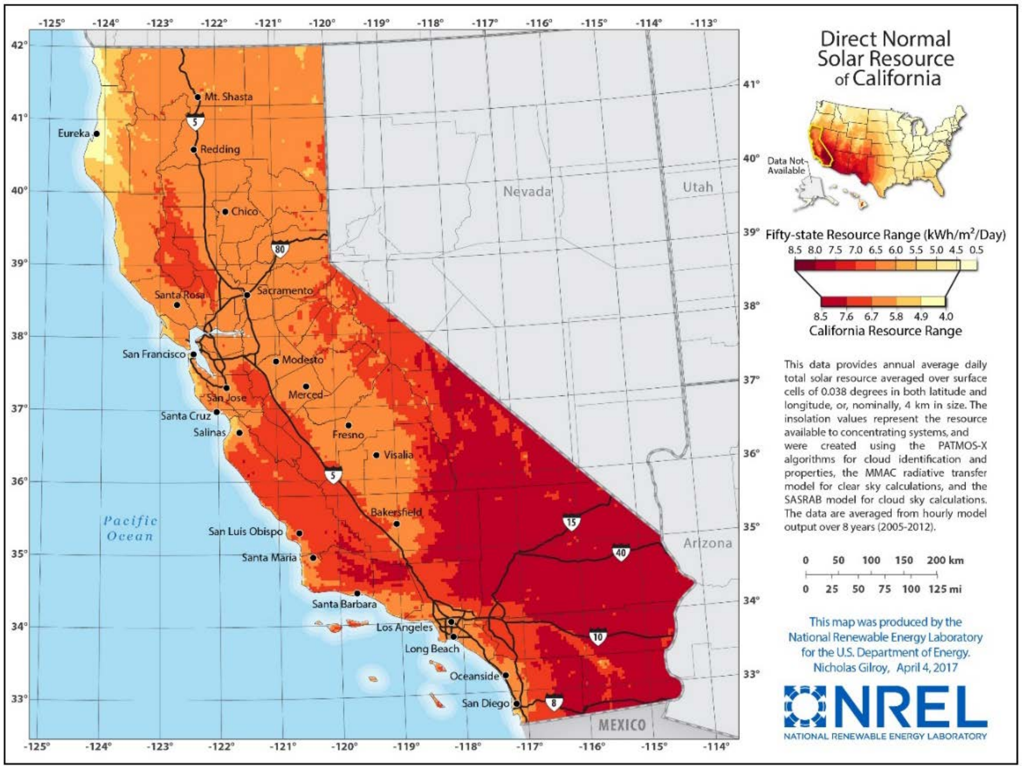
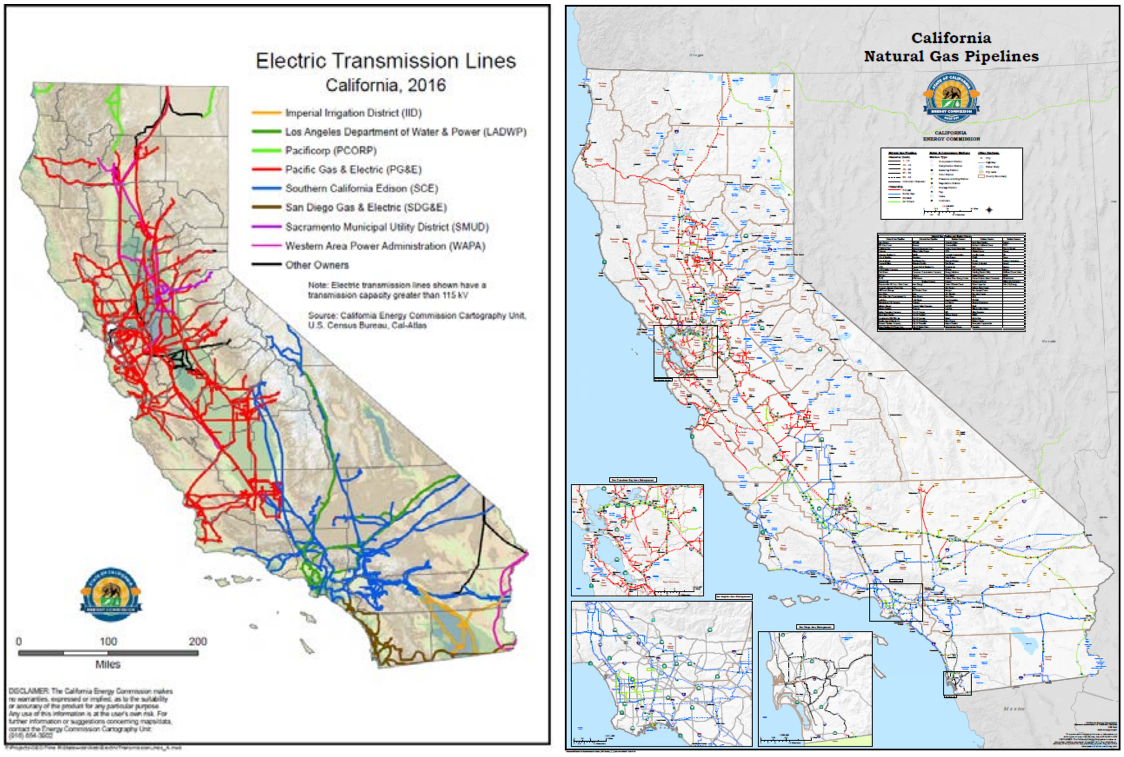
[1] Pulled from the California Fuel Cell Partnership's Station Map website (https://cafcp.org/stationmap)



This data provides annual average daily total solar resource averaged over surface cells of 0.038 degrees in both latitude and longitude, or, nominally, 4 km in size. The insolation values represent the resource available to concentrating systems, and were created using the PATMOS-X algorithms for cloud identification and properties, the MMAC radiative transfer model for clear sky calculations, and the SASRAB model for cloud sky calculations. The data are averaged from hourly model output over 8 years (2005-2012).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. Nicholas Gilroy, April 4, 2017

**Figure 6: California Direct Normal Solar Resource**[2]



Note: Electric transmission lines shown have a transmission capacity greater than 115 kV

Source: California Energy Commission Cartography Unit, U.S. Census Bureau, Cal-Atlas

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**Figure 7: California electric transmission network (left) and natural gas network (right)**

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[2] Solar resource maps produced by NREL can be found here https://www.nrel.gov/gis/solar.html.

At each desired location, it is necessary to balance the importance of electricity prices, land availability and cost, and resource availability as well as proximity to electric or gas infrastructure and fueling stations or other end users. There are several other layers that could be considered as well including ancillary service market prices, water availability, sales and use taxes, etc. As mentioned earlier, retail rates are the same across a utility's service territory while wholesale rates vary for each node across the state. Comparing Figure 4 to Figure 7, the lowest wholesale electricity prices, are not near fueling stations or large electrical or gas infrastructure. Conversely, closer proximity to stations, electrical infrastructure, and gas infrastructure also typically has wholesale higher electricity prices. One interesting exception is for connector stations or hydrogen end users that are close to lower wholesale price regions. Connector stations could have lower cost wholesale electricity and access to large electricity and gas infrastructure. In summary, the feasibility of PV+electrolysis production centers can be affected by the site selected and the specific properties of the site. Electrolysis system developers should consider the items listed above (and more) when selecting sites.

**Subject Inventions Listing**:

None

**ROI #**:

None

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Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office