

## Lessons Learned from the Growth of the Solar Industry

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### ABSTRACT

In 2017 more solar photovoltaic (PV) electricity generating capacity was installed than the net additions of coal, gas and nuclear combined. The remarkable growth of the solar industry (from about 1 GW deployments in 2004 to almost 100 GW in 2017) was not predicted. What could the geothermal industry learn from this success with the hope of duplicating it? In the 1980s, solar thermal electricity far exceeded solar PV. The Solar Energy Generating Systems (SEGS) (solar thermal) were commissioned in California between 1984 and 1990 with a total generating capacity of 354 MW, which was more than the global installed solar PV capacity at that time. Now, the global solar PV capacity is over 400 GW, compared with about 5 GW of solar thermal capacity. While there are many factors that have contributed, the success of solar PV has come largely from two factors: 1) Grass roots support for it: many environmentalists have seen solar PV as a way that individuals can participate in a renewable electricity revolution and have lobbied for government support to facilitate that happening in a big way. And 2) The modularity of PV allowed it to be tested in small size systems. The experience gained from those small systems (e.g. 1 kW) enabled the technology to evolve quickly and with less cost, compared with the solar thermal systems that have typically needed to be at least one thousand times bigger, requiring much larger (high-risk and high-cost) projects during the early development. While geothermal technology is inherently very different from solar PV, the geothermal industry would like to duplicate solar PV's success, motivating an examination of the possibilities.

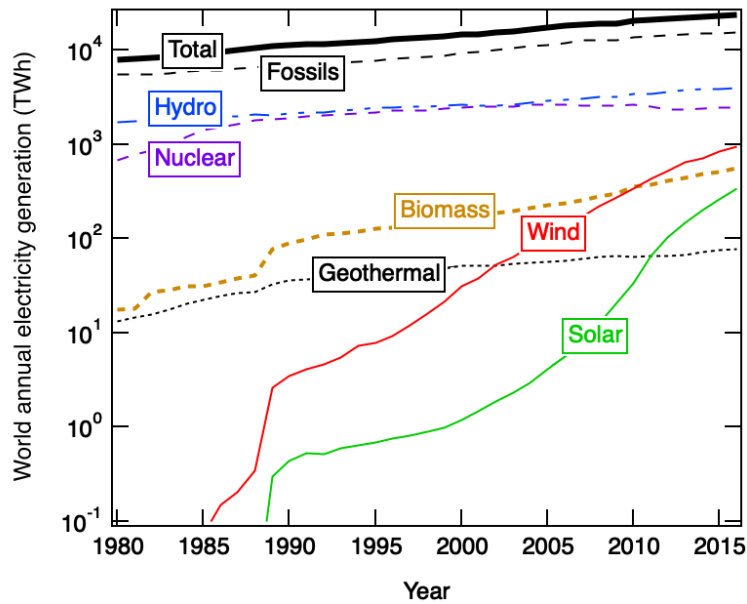
### 1. INTRODUCTION

As the world explores ways to mitigate climate change rapidly, and, ultimately, to achieve a sustainable energy system, growth of renewable energy usage will be crucial. Geothermal electricity has been successful in competing with conventional electricity sources in special situations where the geothermal resource is most easily accessed. However, despite the success of those plants, the fraction of the world's electricity generated from geothermal is still below 1%.

The vision for geothermal electricity is compelling: thermal energy from the inner core of the earth, combined with that generated naturally through radioactive decay in the earth could supply power for billions of years. The challenge is harvesting this vast resource of energy in a cost-effective way. Recent technology advances in the oil and gas industries demonstrate how new technology can revolutionize an industry. So, the question arises as to whether geothermal could experience a similar transformation.

Historically, geothermal has been much more advanced than solar electricity. In the year 2000, worldwide, geothermal plants generated about 50 times as much electricity as solar plants. By the year 2011, solar electricity generation caught up with that from geothermal, and today, solar electricity is almost 10 times that of geothermal, as shown in Figure 1, using data from the Energy Information Administration (EIA) EIA, (2019). The very rapid growth of solar electricity generation was a surprise to most of the world, but should provide inspiration to the geothermal industry.

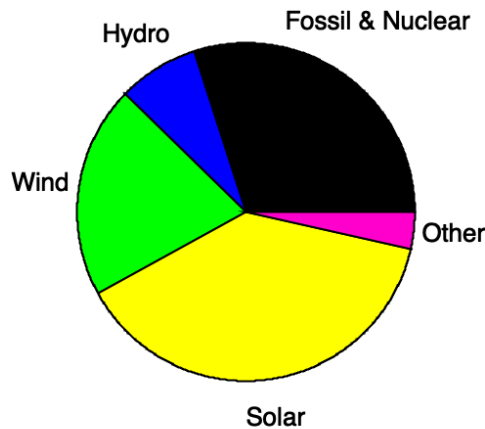
This paper explores the factors behind the success of solar energy and whether the geothermal industry may be able to learn from them. The paper starts by describing the history of how solar energy grew faster than predicted and how that growth was aided by a rapid drop in the price of photovoltaic (PV) modules, enabling solar PV to surpass solar thermal as the dominant solar technology. The paper then discusses the plausible reasons why solar energy's growth was so rapid, why geothermal complements solar energy, and what the geothermal industry may learn from the solar industry's success.



**Figure 1. History of world annual electricity generation by technology type. Data source: EIA, (2019). The EIA data do not differentiate solar thermal from solar PV; the share of solar thermal has decreased to roughly 1% of the total.**

**2. UNEXPECTED IMPRESSIVE SUCCESS OF SOLAR**

As seen in Figure 1, solar electricity generation has been increasing rapidly. A simple extrapolation of the lines in Fig. 1 (specifically, the green line for solar and the black line for the total at the top) suggests that if the relative growth rates found between 2005 and 2015 continued to the year 2025, solar electricity could provide enough electricity in 2025 to provide all of the electricity needs of the world, a quite impressive, though improbable, scenario. The relative growth rate of solar electricity has slowed in recent years, while the deployment rate has increased or held roughly steady most years since 2015. Figure 2 shows how the net expansion of solar electricity generating capacity in 2017 exceeded the expansion of fossil and nuclear electricity generation capacity combined.



**Figure 2: Net expansions from 2016 to 2017 for electricity-generating capacity by fuel type REN21, (2018).**

This rapid growth of the solar industry was not predicted by most organizations, even when predictions were designed to identify pathways to mitigate climate change and enhance renewable energy usage, Haegel, et al (2017). Figure 3 shows predictions by the International Energy Agency (IEA) in their annually issued World Energy Outlook (WEO) Scenarios and how these have historically underestimated the growth of solar energy and the associated cost reduction in their 2017 report, enabling their projections to begin to reflect the lower solar energy prices, which have dropped by about a factor of ten over the last ten years as shown in Figure 4. The price of solar PV systems has not decreased as rapidly as the cost of the PV modules, but the rapid decrease in module price between 2008 and 2010 had a large effect on the industry, with many companies declaring bankruptcy as they scrambled to develop products that could be made at much lower cost.

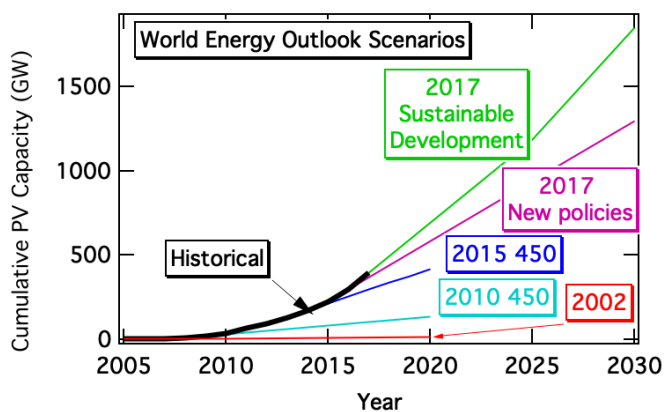


Figure 3. Comparison of actual (historical) growth of cumulative global solar PV electricity generating capacity (black line) relative to scenarios predicted by the IEA in World Energy Outlook Scenarios from 2002 (red), 2010 scenario designed to limit CO<sub>2</sub> to 450 ppm (light blue), 2015 same scenario (dark blue), and 2017 two scenarios, as labeled (green and pink).

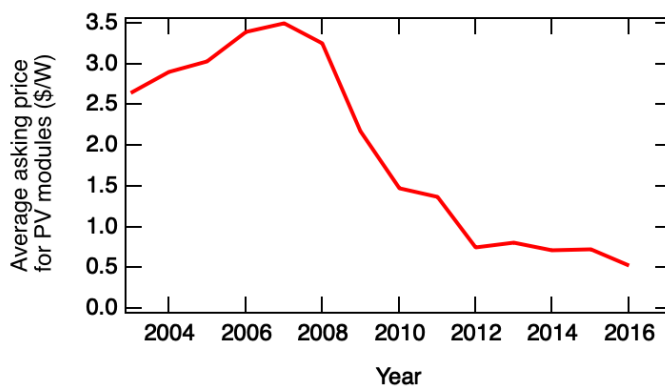


Figure 4. Average asking price of solar PV modules in dollars/watt. Data Source: Mints (2017).

### 3. WHY DID SOLAR PV GROW FASTER THAN PREDICTED?

We present several plausible explanations for why solar PV grew faster than predicted in the following sections.

#### 3.1 Benefit of enthusiasm – movement toward clean energy and energy independence

Arguably, the most important reason why solar PV has grown so quickly has been the grassroots movements toward policies favorable to solar PV growth, including the adoption of renewable energy targets and incentive programs. Japan stimulated the first wave of growth, followed by a large program in Germany. Since then, although the global growth has increased almost steadily, the growth in individual countries has been highly variable with rapid growth of deployment most commonly followed by a decline in local deployment rates. The policies that have stimulated deployment have also facilitated cost reduction. Lower costs have increased the ability of policy actions to reach even larger deployment volumes, leading to a strong positive feedback loop, as shown schematically in Figure 5.

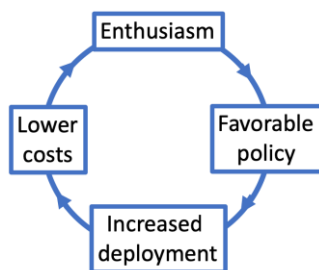


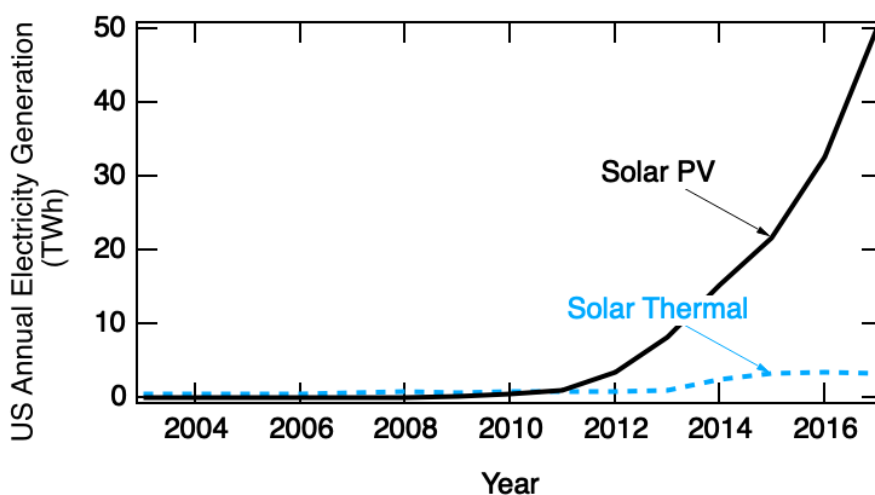
Figure 5. Positive feedback loop that has leveraged enthusiasm from segments of the public for solar PV to develop favorable policy and drive growth of deployment of solar PV and associated cost reduction.

One of the keys to the increased growth rates has been financial innovations that enable customers to install solar PV systems without needing upfront investment. In many of these financial models, everyone benefits because the customer obtains reduced electricity bills, the investor receives interest payments, and, often, another company receives a reduction in tax liability, *e.g.* associated with the Investment Tax Credit offered by the U.S. Federal government.

Much of the excitement around solar PV has been the idea that individuals can generate their own electricity. Especially within the United States, some of the grassroots movements have leveraged desire to be independent from the utility. The enthusiasm to be able to supply one's own electricity needs by installing solar panels on one's roof and become independent of the utility has been a key contributor to differentiating solar PV from solar thermal, resulting in much faster growth of solar PV, as discussed next.

### 3.2 Benefit of modularity and applicability

As just mentioned, part of the surprise of the growth of solar PV was that it so rapidly passed solar thermal. In the late 1900s and early years after 2000, solar thermal electricity generation was substantially greater than that of solar PV (Fig. 6). In 2003 in the U.S., solar thermal generated more than 20 times the electricity generated by solar PV. By 2011, solar PV caught up, and today, solar PV generates much more electricity than solar thermal (Fig. 6). One reason for this was that often the grassroots movements favored creation of attractive policies for solar PV, *e.g.* through net metering and other incentive programs that promoted rooftop solar installations. But, even when both solar technologies benefited equally from a policy, solar PV was seen to grow faster. A plausible reason is the modularity of solar PV.



**Figure 6. Electricity generation from solar sources (PV and thermal) as a function of year. Data source EIA. The initial data for 2003 were 2 GWh and 532 GWh for solar PV and solar thermal, respectively. The solar PV data reflect EIA's estimations of rooftop solar PV generation.**

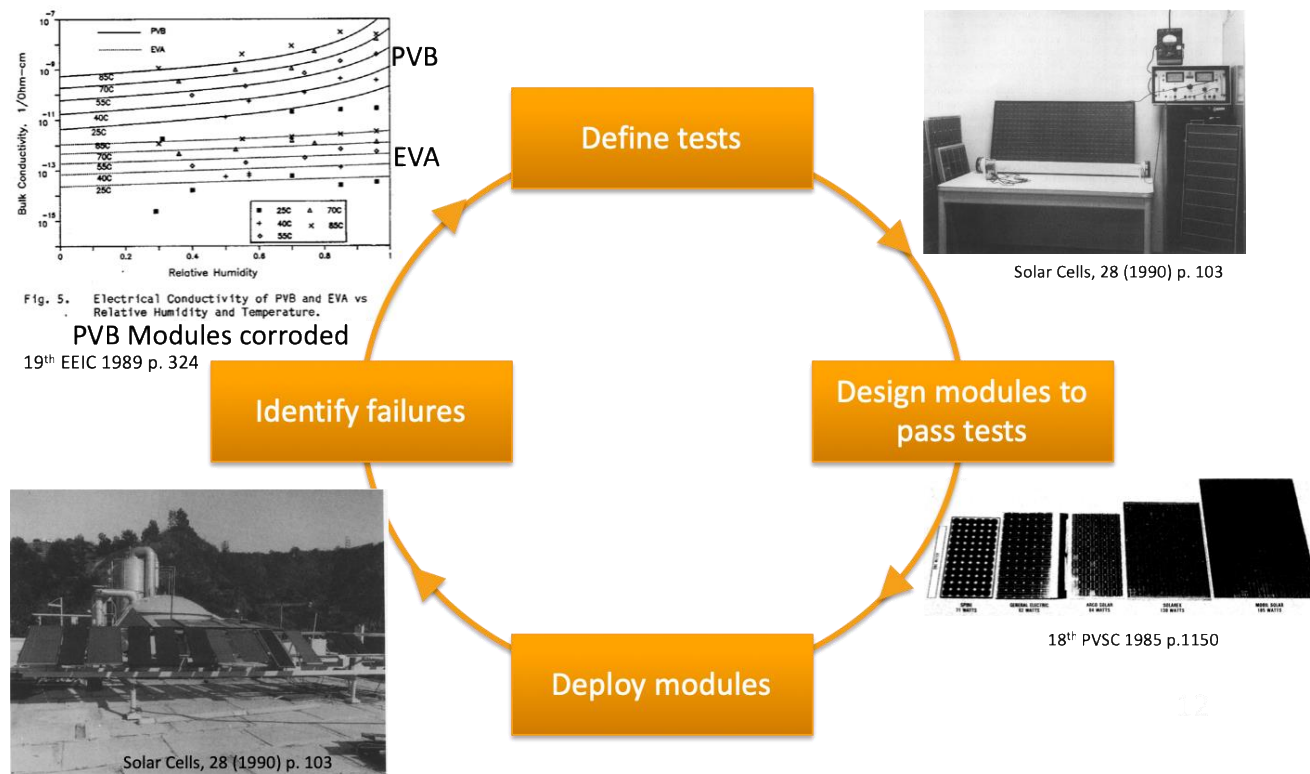
The solar thermal plants are generally built to be quite large to achieve the high temperatures needed to drive conventional steam turbines. Thus, the decision to invest in a solar thermal project has always represented a huge investment, which many new customers and investors treat cautiously. In contrast, solar PV projects can be implemented on most any scale, with some consumer products (*e.g.* solar walk lights) requiring only a few watts of solar capacity while large plants may be deployed at the GW scale. Investors have been able to work within their comfort zone as they take on larger and larger projects, reducing risk by using experience from smaller projects. This has not been possible for solar thermal projects.

Additionally, solar PV can be applicable to almost every location. Although some locations are sunnier than others, the resource for solar PV typically only varies by a factor of 2 to 3. (For example, considering fixed systems at latitude tilt, Daggett, CA – an excellent site for solar – is estimated to receive 6.6 kWh/m<sup>2</sup>/day compared with 2.5 kWh/m<sup>2</sup>/day in Barrow, Alaska – a particularly poor site for solar.) The variation for the direct-beam solar resource needed for solar thermal may be a factor of 4 or 5. (For example, 6.6 vs 1.4 kWh/m<sup>2</sup>/day for the same two sites) RREDC, (2019). The variability of wind resource is typically even greater, with variations of more than a factor of 10, or even 30.

The modularity of solar PV combined with its being potentially attractive all over the world has facilitated its rapid growth. In contrast, the required large scale and limited range of applicability of solar thermal electric plants has slowed their adoption, relative to solar PV. These same challenges and tradeoffs are also seen and debated for the nuclear industry, with some arguing that electricity cost is reduced by deploying large plants and others arguing that a smaller plant might actually be built, while large nuclear projects have been impossible to bring to completion in recent years in the U.S..

### 3.3 Benefit of early investment in reliability testing

In the 1970s and 1980s, the U.S. Department of Energy funded the Jet Propulsion Laboratory (JPL) to develop test standards for solar PV modules, JPL (2019). As shown in Figure 7, this Block-Buy Program started by deploying modules and identifying how they failed. They then defined tests that they observed could reproduce those failures rapidly in a laboratory environment. Companies were asked to redesign their modules to be able to pass those tests and JPL deployed the new set of modules. Modules in the fifth block buy were observed to exhibit far fewer failures in the field and the fifth block buy set of tests became the basis of today's internationally used qualification tests (e.g. IEC 61215).

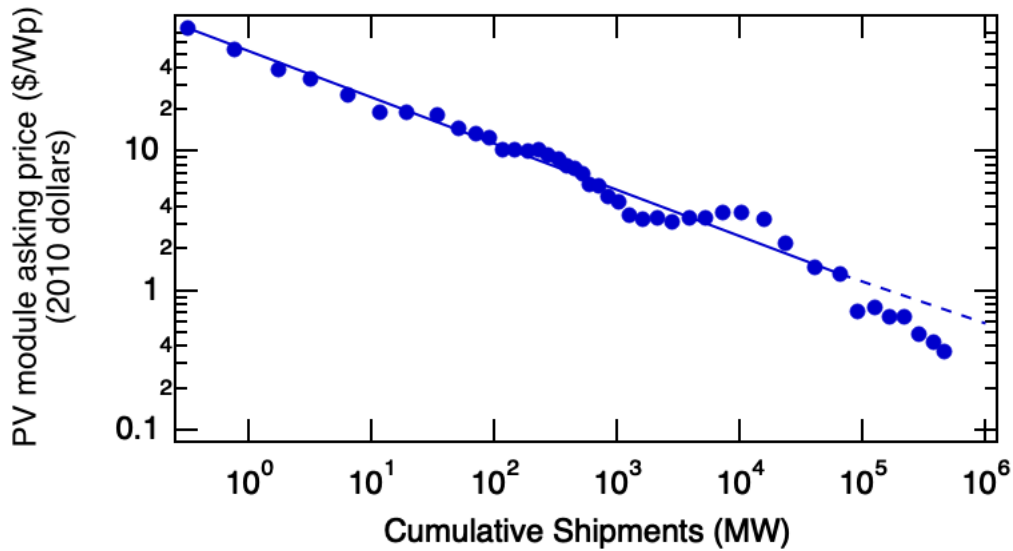


**Figure 7. JPL Block-Buy Program's approach. Starting at the bottom, JPL procured and deployed a set of modules. After some time in the field, they documented failures that occurred. They defined tests to reproduce the failures rapidly in a test lab. They requested companies to produce modules that could pass the defined tests. Then, they repeated the cycle. The references in the figure are examples for each step.**

The early development of qualification tests that enabled deployment of modules that could last years in the field was pivotal for growth of a new industry. Expenditures of \$100 billion/year would not occur for a technology with a significant failure rate. These early investments by the U.S. Department of Energy and other organizations around the world laid the foundation for healthy growth. Some other renewable energy industries have suffered setbacks when deployment got ahead of reliability development.

### 3.4 Increased rate of learning

Learning curves are a tool that can be helpful in tracking and predicting subsequent progress of an industry. For many years, the learning curve for solar PV modules showed a fairly constant slope, as shown in Figure 8. Then, a shortage of PV modules in the 2006-2008 timeframe led to an increase in prices. One might expect that when the shortage ended the data would return to the original line, but, in recent years, the data appear to be following a steeper slope below the original line. There is some speculation in the community that the learning rate may be higher in recent years because of more sharing of advancements between companies as the manufacturing has become concentrated in China. The protection of intellectual property in China is not as rigorous as in the U.S., facilitating faster learning. While some of this is informal sharing of information between employees of competing companies, the sharing is often by design when companies that develop an improved component quickly offer it to many module manufacturers and new developments that are useful can be adopted broadly by the large module manufacturing base. The recent unexpected (based on the historical learning curve) drop in prices has been a key contributor to solar PV becoming cost competitive with conventional electricity sources in most sunny locations.

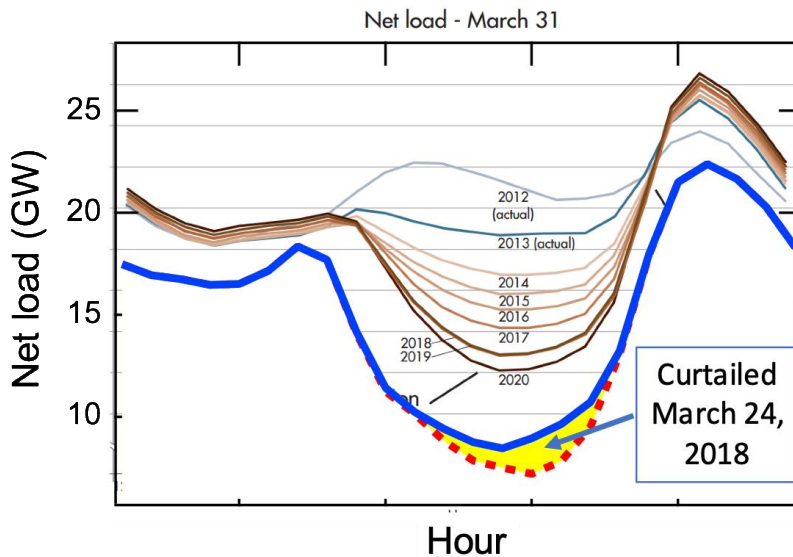


**Figure 8. Learning curve for solar PV modules with average asking price (adjusted to constant 2010 dollars) plotted as a function of the cumulative PV module shipments, with one point plotted per year starting in 1976, ending in 2018. The historical learning rate is shown by the blue line. In recent years, the learning rate appears to have increased as shown by how the data fall below the historical line in the time period of the dashed line. Data sources: Navigant, Mints, 2017. Recent data are estimated.**

With the low prices that have now been achieved and the large deployment volume, solar PV is now entering a new era in which future growth will slowly shift to being linked to increased electrification, which increases demand, and to increased investment in various storage and load-shifting technologies, which will maintain a stable grid at high solar penetration.

**3. WHY MIGHT SOLAR AND GEOTHERMAL MAKE GREAT PARTNERS?**

As solar PV has grown in the state of California, there has been increasing interest in solving the problem of what to do when the sun isn't shining. The challenge has been described with the "duck curve," which highlights 1) the need for curtailment if the belly of the duck gets too deep and, 2) the challenging load ramp at the end of the day when the sun is setting. Figure 9 shows a spring day when abundant renewable electricity challenged the grid, resulting in some curtailment (essentially, throwing away some electricity). Imports were used to keep supply balanced with demand throughout the day. As more solar generating capacity is installed, the daytime load can be met, but the night time load will require either massive amounts of storage or a complementary renewable energy type to provide electricity at night.



**Figure 9. Effect of solar electricity on the net load in California on March 24, 2018, including curtailed electricity.**

Geothermal has the potential to be an excellent source of base load electricity to complement solar PV's more variable generation. A partnership between geothermal and solar PV will be even more extensive if the rate structure and business models for geothermal are changed to take advantage of greater price for electricity generated during times when electricity is scarce. In such a scenario, the geothermal plant may be turned down during a sunny day and then ramped up in the evening as the sun is setting, reducing the ramp in demand shown in Fig. 9.

Not only does geothermal electricity nicely complement solar electricity, but the development of regional geothermal heating may help to develop low cost hardware for massive storage of thermal energy – a probable low-cost strategy for storing solar PV energy for use after the sun sets.

#### 4. WHAT MIGHT GEOTHERMAL LEARN FROM SOLAR?

Geothermal implementation is usually very different from solar PV implementation, so it's not clear that the experience of the solar PV industry will be useful to the geothermal industry. Nevertheless, we discuss a few possibilities in this section. These have some similarities to a somewhat similar discussion by Li (2015).

The geothermal industry is not well positioned to benefit from the grassroots movement toward energy independence since most geothermal projects require a fairly large company rather than being feasible for a home owner. An exception is the use of ground-source heat pumps. Although these are not electricity sources, they can reduce electricity consumption, providing benefit to those who are seeking energy independence. Ground-source heat pumps have become common in new construction in some parts of the world enabling the technology to improve reliability and reduce cost.

It may be possible for geothermal electricity systems to benefit from grassroots movements, but many potential advocates are concerned about the disruption to the environment. The solar PV industry has found that scientific evaluation of the risks coupled with education can allay many concerns that otherwise are barriers to adoption. For example, concerns of deployment of cadmium telluride photovoltaic panels have been addressed in most countries through careful analysis and education. If environmental activists could identify when geothermal can be implemented as a relatively clean form of renewable energy, they might provide stronger support.

It may be that for the geothermal electricity industry, the oil and gas industries could play the role that grassroots movements played for solar PV. The oil and gas industries now have technology to drill deeper and to crack rock. While this technology has not been widely applied to geothermal systems, if the world takes serious action to reduce fossil fuel use, the oil and gas companies may find that geothermal is their next big opportunity.

One of the biggest challenges for the geothermal industry is developing new technology that can harvest geothermal energy most everywhere when every project is a little different and every project can cost many millions of dollars. If geothermal applications can be developed that are more modular in nature, it may help the industry grow from relatively small to relatively big by progressing incrementally. For example, technology that can be coupled with existing oil pumps could be deployed on many existing small oil pumps, making use of the thermal energy in a cost-effective way. Similarly, regional heating systems and small-scale geothermal plants may help the technology mature more quickly than a business model that focuses only on large-scale plants. We recognize that large-scale plants are likely to be more cost effective than small ones, but if the small ones can move faster down a learning curve as is shown in Figure 8, the smaller systems may be able to achieve lower costs in the near term.

The protection of intellectual property is a fundamental principle that we all support – it encourages companies to invest in technology in order to be able to gain market share. However, as noted above, costs can be reduced faster if companies share information. This could happen by intentional business choices for geothermal companies to partner or by government funding of coordinated research. Such collaboration coupled with other efforts suggested in this section could, together, be pivotal in enabling geothermal to duplicate solar PV's impressive growth.

#### 5. CONCLUSIONS

Solar has grown much faster than most organizations had predicted for reasons including:

- *Enthusiastic support* from grassroots movements, especially from those who would like to independent from the utility. These resulted in friendly policies and associated faster growth in deployment rates than expected.
- *Rapidly reduced cost* that came from the faster deployment and maybe from enhanced collaboration between companies.
- *Achievement of good reliability and reduced risk*, even for rapidly evolving products. This benefited from early government investment coupled with the modular nature of the technology. The ability to combine relatively high reliability with small project sizes reduced barriers to market entry.

The geothermal industry may look for opportunities to

- Identify groups that could provide enthusiastic support and actively develop friendly policies and business models. The geothermal industry would benefit from incentive programs and streamlining of permitting processes, especially if these are successfully designed to motivate investment in geothermal deployment.

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- Identify and pursue geothermal applications that are more modular in nature, allowing implementation of many small systems as a path to more advanced technology.

The world would greatly benefit if the geothermal industry could grow as rapidly as the solar PV industry has in the last ten years. Perhaps using these strategies and a partnership between solar PV and geothermal industries the world will move more quickly to 100% renewable electricity.

#### **ACKNOWLEDGMENTS**

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