Historical Case Studies of Energy Technology Innovation

CASE STUDY 7: SOLAR THERMAL ELECTRICITY (US).

TECHNOLOGICAL IMPROVEMENTS OF SOLAR THERMAL ELECTRICITY IN THE US, AND THE ROLE OF PUBLIC POLICY

Gregory Nemet
University of Wisconsin

AUTHORS' SUMMARY

Solar thermal electricity (STE) technology has improved through a combination of learning by doing and R&D investments. Even though R&D levels for this technology were small relative to other energy technology programs, R&D played an important role in making full use of the knowledge gained through experience in manufacturing, installation, and operation of STE facilities. R&D helped codify and document the often tacit knowledge that accrued to operators through experience. Most of this knowledge about technical change in STE comes from the 350 MW (mostly parabolic trough systems) that were deployed in California in the 1980s. As a result of codification, this knowledge could be shared across firms and even across countries. It also preserved at least some of the value of the knowledge over time – especially during more than a decade of stagnation in the 1990s, when essentially no large STE plants were built worldwide. The rebirth of the STE industry during the 2000s indicates that at least some of this knowledge accumulated in the 1980s informs current designs and operation. Since the mid-2000s, a new round of installations has begun, primarily in Spain and the southwestern United States. These installations encompass three types of STE systems: troughs, concentrators, and dishes. By the end of 2011 worldwide STE capacity exceeded 1.5 GW, and additional GW were close to breaking ground. Aggressive renewable electricity obligations and feed-in tariffs have driven this resurgence in STE installations in both California and Spain. Complementary policies, such as loan guarantees and tax credits, have stimlated investment as well. A distinguishing feature of STE, relative to other renewables, is that STE requires big, risky investments. Early investors may have to "eat between one and three US$200 million plants" before improvements enable profitable operation. A policy implication is that the scale of technology requires different types of incentives from smaller-scale renewables such as solar PV.

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

1 INTRODUCTION

1.1 STE Technologies

Solar thermal electricity (STE) technologies use mirrors to concentrate solar radiation onto an absorber that converts the sunlight to heat and then transfers that heat to a working fluid used to power a Rankine or Brayton cycle to generate electricity. In some cases Stirling engines are used instead. Three prominent designs are commercially available:

1. *Parabolic trough systems* heat a working fluid in a pipe running parallel to the orientation of the troughs. Solar radiation heats the working fluid, typically oil, to approximately 400^{o}C. Heat exchangers produce superheated steam which runs a Rankine cycle turbine.
2. In *tower systems*, an array of mirrors, called heliostats, concentrates sunlight on the working fluid at a single point, elevated on a tower. Temperatures are substantially higher, close to 600 ^{o}C. The working fluid, typically a molten nitrate salt, can be run through a heat exchanger to power a Rankine cycle, or can be stored for later use. An important characteristic of tower systems is the possibility of storing heat for up to 12 hours. Storage is enabled by the centralization of heat at a single point, minimizing losses in pipes, as well as by the higher initial temperatures, which allow the use of working fluids that retain heat well.
3. Typically on a smaller scale (10s of kW), *parabolic dish systems* use a mirrored dish to concentrate sunlight on a focal point to run a Stirling engine. Temperatures reach 750^{o}C.

An important difference with photovoltaic or PV-based solar power is that these concentrating STE systems require direct sunlight - cloudless skies and low humidity - because of the need to focus solar rays. This constraint limits their use to dry climates. In contrast, a fourth type of STE design, *solar updraft towers*, uses a skirt and chimney system to capture the energy from rising heat. Projects have been proposed on the scale of 100s of MW in China, US, and Spain, but to date only a few pilot plants at sub-MW scale have been built.

1.2 Knowledge generation & technological improvements in STE

Most of our historical knowledge about technical change in STE comes from the 350 MW of plants (mostly parabolic trough systems) deployed in California in the 1980s. Since the mid 2000s, a new round of installations has begun, encompassing all three types of STE systems, mainly in Spain and in the southwestern US. By end of 2011, 1.5 GW had been installed and multiple GWs of project proposals were at various stages of development

Solar thermal electricity (STE) technology has improved through a combination of learning-by-doing and research and development (R&D) investments. Even though R&D levels for STE have been small relative to those of other energy technology programs, R&D programs have nevertheless played an important role in making full use of the knowledge gained through experience in manufacturing, installation, and operation of STE facilities. R&D helped codify and document what was often 'tacit' knowledge that accrued to operators through experience. As a result this knowledge could be shared across firms and even across countries. Codification also preserved at least some of the value of the knowledge over time, especially during over a decade of stagnation in the 1990s when essentially no large plants were built worldwide. The rebirth of the STE industry during the 2000s indicates that at least some of the knowledge accumulated in the 1980s informs current designs and operation of STE plants.

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

2 PUBLIC POLICIES RELEVANT TO SOLAR THERMAL ELECTRICITY

Public policy has played a crucial role in stimulating the deployment of both the STE systems built in California in the 1980s and those built in the Southwestern US and Spain in the 2000s. The Californian plants in the 1980s were built primarily in response to two key policies. The first was the Public Utility Regulatory Policy Act (PURPA) of 1978 which mandated that electric utilities purchase power from “qualifying facilities,” small independent providers of wholesale power. The second took the form of generous procurement contracts that the California Public Utilities Commission ruled utilities had to offer to the qualifying facilities (Price and Carpenter, 1999). One set of contracts that were available from 1983 - 1986 were known as “Standard Offer Contract #4,” which guaranteed prices for 10 years at rates that are equivalent to $140/MWh in present day dollars (Nemet, 2009). A third set of policies supporting STE deployment included state and federal tax credits that offset a portion of the plants’ capital costs. Investments were further incentivized by the expectations of most analysts in the first half of the 1980s for high and rising electricity prices over the next decade. This included official government forecasts.

An important implementation detail of the Californian policy regime in the early 1980s was the requirement, under PURPA, that qualifying facilities not exceed 30 megawatts (MW). The rationale for this limit was to encourage a diverse set of small-scale generation technologies, whose scale had attributes that made them unique and attractive alternatives to the much larger scales used by conventional fossil fuel and nuclear generation. This limit proved awkward for STE technologies, which were initially built at the limit size, but which needed to be substantially larger to reduce costs further. The size limit was temporarily raised to 80MW in 1987, which led to larger plants of exactly that scale. However, the legislation included substantial uncertainty and regulator discretion as to the future size limits. This uncertainty meant designs for much larger plants were never developed into serious commercial proposals.

The first STE pilot plant was a 10MW central receiver built in 1982 called Solar One. It had a capacity factor of less than 10% and was dismantled in the early 1990s (Mead and Denning, 1991). The commercialization of STE in the 1980s centered on a single company, Luz. It raised $1.2 billion from Wall Street banks to build nine parabolic trough STE plants, called the Solar Electric Generating Stations (SEGS), between 1984 and 1991 (Philibert, 2004). The company went bankrupt in 1991 shortly before its 10 year procurement contracts (Standard Offer Contracts #4) were to expire. The new rates they would have received in the early 1990s would have been much lower than those contracts and lower than the high rates anticipated in the early 1980s. Subsidies for new projects had ended by then as well. Afterwards, the plants were sold to other investors and Luz employees dispersed, with many going to NASA to work on the space shuttle program. With them went much of the industry’s experience and tacit knowledge about what configurations and operation activities worked best. Probably the best example of a compensating mechanism for this loss of knowledge was the extensive codification of testing and evaluation results conducted by Sandia National Laboratory and its contractors. This is discussed further below. The SEGS plants themselves continued to produce electricity and improve, including the addition of natural gas use so that they could generate at night. They were still in operation as of mid-2012.

In the 2000s, two other types of policies drove deployment. In Spain, the renewable energy law guaranteed high prices for solar thermal electricity. In California, a Renewable Energy Portfolio Standard mandated that utilities source 20% of their retail sales from renewable energy by 2010 and 33% by 2020

(CPUC, 2007). Like the early 1980s, expectations in the mid-2000s were that natural gas prices and so electricity would stay high and likely rise in future years. But natural gas prices fell dramatically in the last years of the decade, which provided one reason for much weaker support for STE deployment, including a substantial weakening of the STE subsidies in Spain.

3 TECHNOLOGICAL IMPROVEMENTS IN SOLAR THERMAL ELECTRICITY

The nine Solar Electricity Generation Station (SEGS) plants built in California in the 1980s became more efficient, cheaper to build, and substantially cheaper to operate and maintain over time. Taylor, Nemet et al. (2007) identify three specific improvements that were most important in improving the STE plants:

1. *Mirrors*: also referred to as “heliostats,” they are the largest component of capital cost and have fallen in cost over time (see Figure 1). Key improvements in heliostat development over time have included better optical transmission of sunlight to the receiver, lighter weight, and greater resistance to wind and storms (Lotker, 1991). Reliable heliostats were the most successful outcome of the US R&D program.
2. *Configuration*: arrangement of the solar arrays and transmission of working fluid so that sunlight absorption can be maximized while heating losses are minimized has improved the efficiency of electrical output (Kearney and Price, 2005). Better configuration was the result of learning by doing, including both reconfigurations within plants and redesigns of subsequent plants in the series of nine SEGS plants.
3. *Reheating of steam*: efficiency of the Rankine cycle has been improved by reheating the steam exiting the turbine using the working fluid. This was likely a spillover benefit from other thermal power plants, but may have been aided by R&D and learning by doing to transfer these applications to the lower temperatures in STE, rather than fossil combustion.

One can observe changes in subsequent designs for central receiver plants. For example, Figure 1 shows a factor of five decline in the costs of heliostats and other capital costs from the first Solar One plant in 1981 until the designs for a 200MW facility in 1987.

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

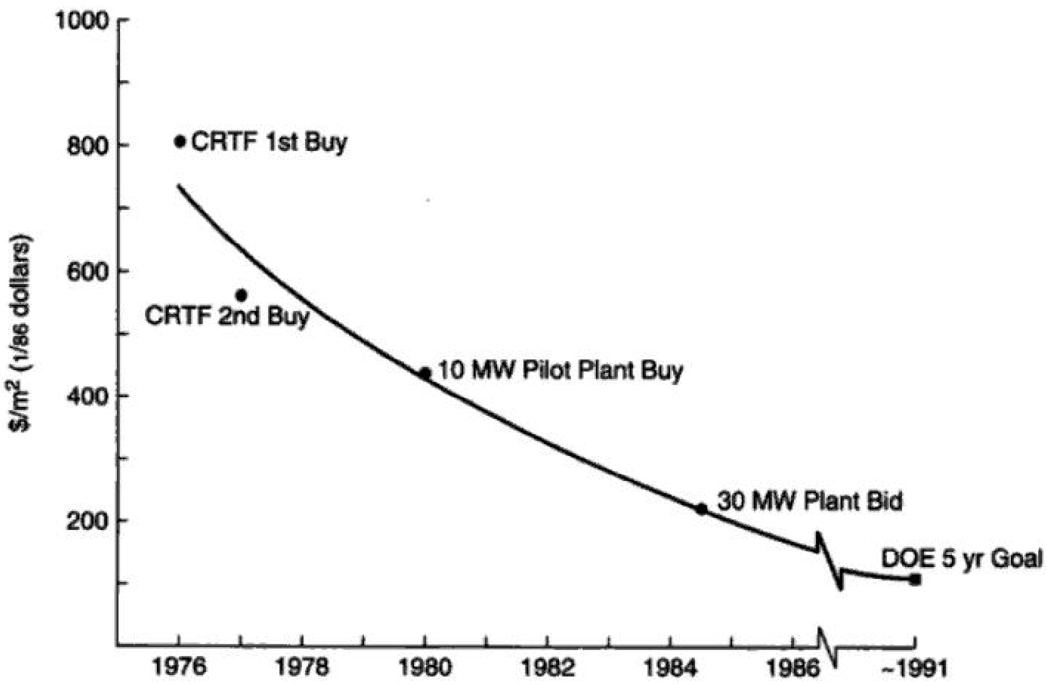

FIGURE 1. COST OF HELIOSTATS OVER TIME. NOTES: CRTF = CENTRAL RECEIVER TEST FACILITY. COSTS SHOWN IN 1986 US$. SOURCE: GROSSKREUTZ, 1996.

Changes are more dramatic in the solar trough plants. The full effect of these and other changes are summarized in Figure 2 which shows how eight factors interacted in reducing the costs of electricity from the SEGS plants. The arrows are meant to show the most important causal relationships. Other interactions certainly existed but are assumed to be minor. The three most important causal factors are learning by doing, R&D, and scale.

Learning by doing is captured by the cumulative amount of capacity constructed and the cumulative amount of electricity generated. Two important and observable technical improvements that are most attributable to learning by doing are the near elimination of component failures and the decrease in operation and maintenance (O&M) costs. Both of these reduced the levelized annual cost to operate the plant.

Federal R&D investment was highest at the beginning of the program and declined steadily over the life of the STE plants. These programs helped improve efficiency as well as capital cost.

Another important change was the up-scaling of the subsequent plants by nearly an order of magnitude in less than 10 years. The pace of up-scaling was limited at least in part by policy that restricted the size of plants eligible for the generous procurement contracts.

An important observation from the data shown in Figure 2 is that technical improvement was not monotonic. Component failure rates increased in some new plants, as did capital costs, and even levelized cost of electricity. These short-term adverse outcomes may be attributable to design changes and experimentation.

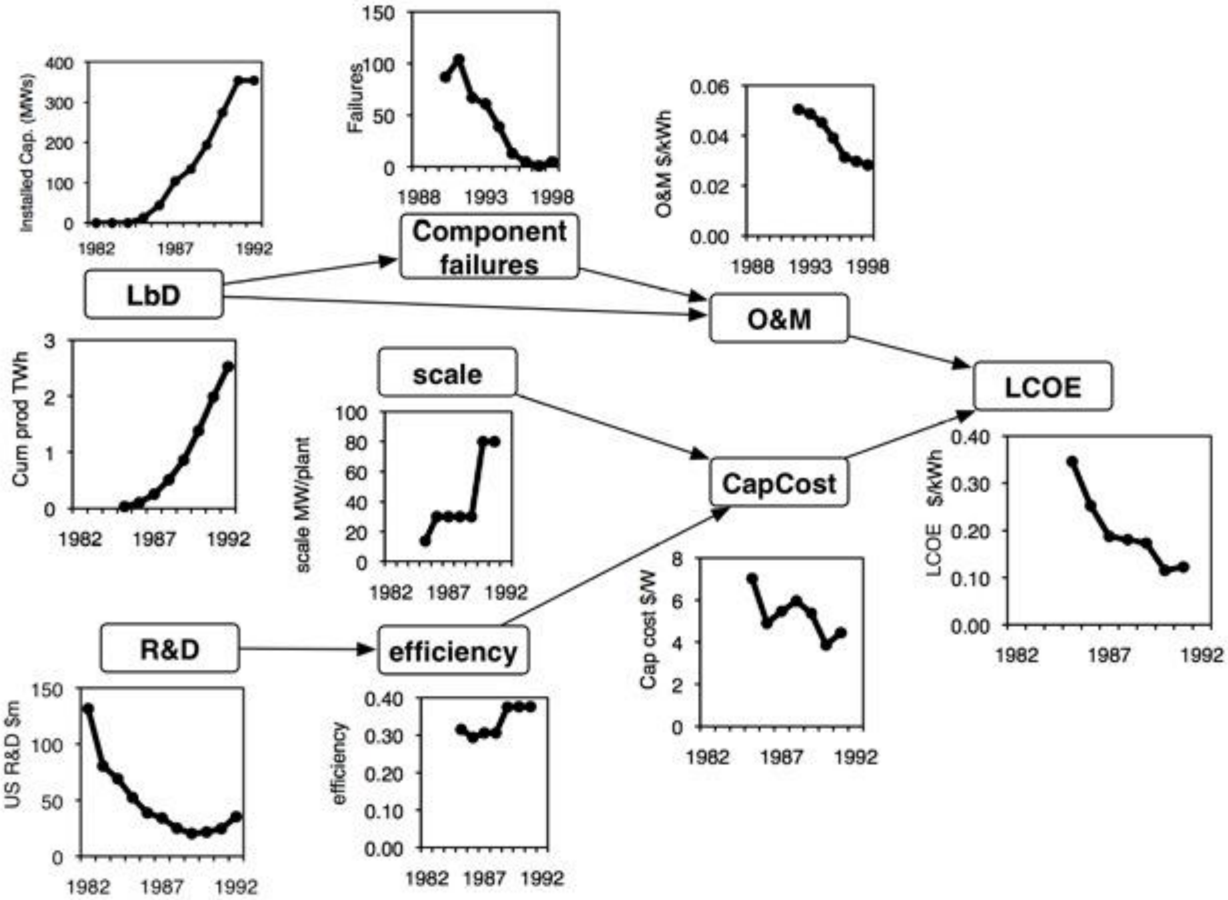

FIGURE 2. INDICATORS OF TECHNOLOGICAL CHANGE FOR STE PLANTS IN CALIFORNIA. NOTES: LBD = LEARNING BY DOING; O&M = OPERATION AND MAINTENANCE COSTS; LCOE = LEVELIZED COSTS OF ELECTRICITY PRODUCTION.

One can also measure the amount of inventive and entrepreneurial activity associated with STE technology. This activity, as measured by counts of successful patent filings, corresponds well with the two periods of intense policymaking and expectations of high energy prices. Figure 3 shows patents filed for STE technologies through 2005. One can see only occasional patents before a dramatic increase in the mid-1970s. A steady decline occurs after the mid-1980s with a new round of patenting activity in the mid-2000s. The most prolific STE patent filers were US aerospace companies.

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

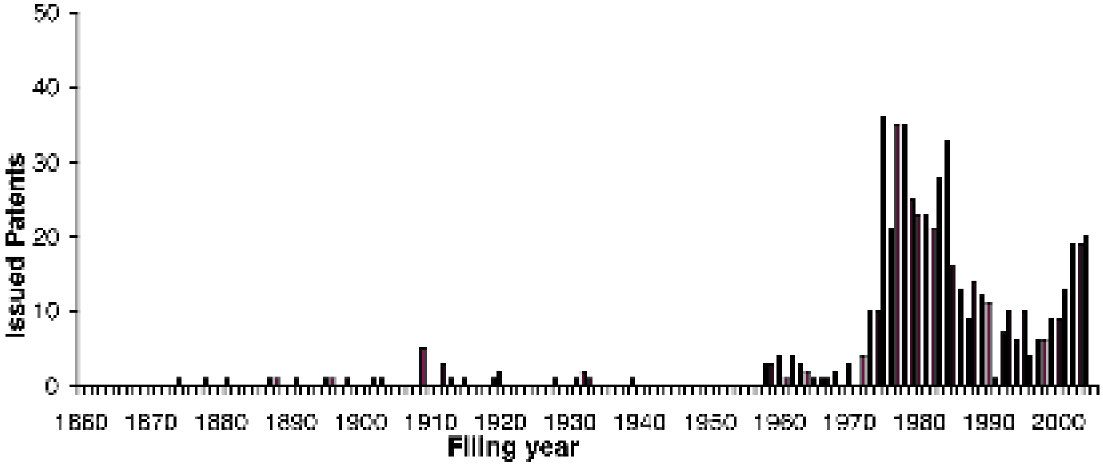

Figure 3. US Patents Filed for STE Technologies. Source: Taylor et al., 2007.

3.1 Learning by doing

Learning by doing was central to well-documented improvements in STE. The dominant STE firms of the 1980s, Luz was successful in reducing the O&M costs on their plants by 40% (Lotker, 1991). Learning by doing at SEGS plans in California was particularly important to this improvement; it was also aided by cost-shared studies conducted by federal laboratories (Cohen et al., 1999). Part of the performance improvements were also anecdotally attributed to having "someone looking over them," a reference to the Wall Street banks, which invested over one billion dollars in California SEGS plants in the 1980s (Taylor et al., 2007).

3.2 R&D

The combination of PURPA and Standard Offer Contracts that guaranteed 10 years of above-market prices drove one firm (Luz) to build nine commercial plants. All other STE installations until the 2000s were funded by R&D or were demonstrations (Taylor et al., 2007).

R&D investment had several specific outcomes on STE costs. Government R&D produced the heliostats, the mirrors that concentrate sunlight on focal points or axes. For example, Figure 1 shows the costs of heliostats over time. R&D studies also improved reliability by assessing the source of failures and damage. This led to cost savings. One example is the outcomes of R&D on central receivers. Table 1 lists the accomplishments of the federal R&D program on central receiver technologies (Grosskreutz, 1996). Note that R&D outcomes occur at multiple levels: there are improvements in the individual components, such as heliostats and receivers; there are also experiments with larger systems, such as the use of molten salts; and finally, there is the construction of a testing facility, an aspect of R&D programs that has been important for other technology programs, such as wind power testing facilities at Riso, Denmark and Golden, Colorado.

R&D was also spent on constructing demonstration plants for central receiver stations and parabolic dish systems (the term R,D&D captures demonstration as well as research and development activities).

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

Neither plant was deployed beyond demonstration scale in the 1970 - 1990s, although currently both of these designs are being used for 100MW scale projects.

TABLE 1. OUTCOMES OF FEDERAL R&D ON CENTRAL RECEIVER STE TECHNOLOGY. SOURCE: GROSSKREUTZ, 1996.

	Elements	**Outcomes**
Test facilities	Central Receiver Test Facility (CRTF)	5 MW_{th} facility built and successfully operated for 11 years at Sandia National Laboratories
Components / sub-systems	Heliostats (glass / metal)	Three generations built and tested
		Over 2100 heliostats deployed
	Receivers	Three generations of water / steam receivers built and tested
		One sodium receiver built and tested
		Two generations of molten nitrate salt receivers built, tested and operated
	Thermal storage	Oil / rock system built, tested and operated
		Molten salt system built, tested and operated
	Steam generators	Hot molten nitrate salt-to-steam system built, tested and operated
		Hot sodium-to-steam heat exchanger built, tested and operated (International Energy Agency, IEA)
Systems	Proof-of-concept experiments	0.5 MW_e sodium/steam experiment built and operated (Almeria, Spain)
		750 kW_e molten salt experiment built and operated at the CRTF (Albuquerque, NM)
	Pilot plant	10 MWe water/steam plant built and operated (Barstow, CA)

As a second example of beneficial R&D outcomes, an important source of improvement came from a $6m 50/50 cost shared project between Sandia National Laboratory and Luz to find opportunities for cost reductions in the SEGS plants (Cohen et al., 1999). Part of the value of this work is that it was formally reported and publicly available. These aspects became crucial with the demise of Luz and the entire STE industry in 1991, as the industry was dormant for over a decade. As a result, the knowledge codified in these reports was not lost, as opposed to the tacit knowledge of plant operators that was almost all lost. As an example, the cost data shown in Figure 4 is derived from this codified knowledge.

Like other energy technologies, quality control problems were important barriers to the widespread commercialization of STE. To some extent, these issues were addressed. For example, see the declining rate of component failures in Figure 2. Still, quality control was an issue that might have needed to be addressed by technical fixes or policy remedy. In the case of STE, quality control became an irrelevant concern with the dissolution of the industry in the 1980s. Some of the changes to improve reliability, specifically damage to heliostats from weather, were codified in government reports and have the potential to inform subsequent installations. The performance of the new plants deployed in Spain and the southwestern US over the past few years will show whether quality control continues to be a concern.

3.3 Scale

There are economies of scale in constructing larger plants partly due to: (1) relatively fixed costs for the turbine and generator units; (2) the ability to mass produce components, such as heliostats, and for the working fluid transmission system. As a result, larger STE plants are less expensive on a $/W or $/kWh basis (see Figure 4).

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

Scale itself has been important to cost reductions (see Figure 4). Larger scale combined with learning-by-doing derived O&M improvement drove the levelized cost of STE energy down by factor of 4 (Enermodal, 1999; Sargent-Lundy, 2003; Mariyappan and Anderson, 2001; Neij et al., 2006). And while the US spent several hundred million on STE R&D in the late-1970s and early-1980s, it is important to realize that the concept behind the Luz facilities originated in Israel, when an American engineer found financing to build an early pilot plant (Shinnar, 1993). A 15 MW demonstration plant was subsequently constructed in California, followed by the 30 and 80 MW SEGS installations (Kearney and Price, 2005).

Plant-level scaling (15 to 30 to 80 MW plants) was initially constrained by policies that were primarily focused on encouraging small-scale distributed generation. The upper limit of 30MW/plant was later raised to allow construction of the 80MW units. By 2012, the SEGS plants were still the largest ones operating but 5 projects of over 100MW were under construction and expected to come on-line beginning in 2013. These plants are intended to satisfy California's renewable portfolio standard.

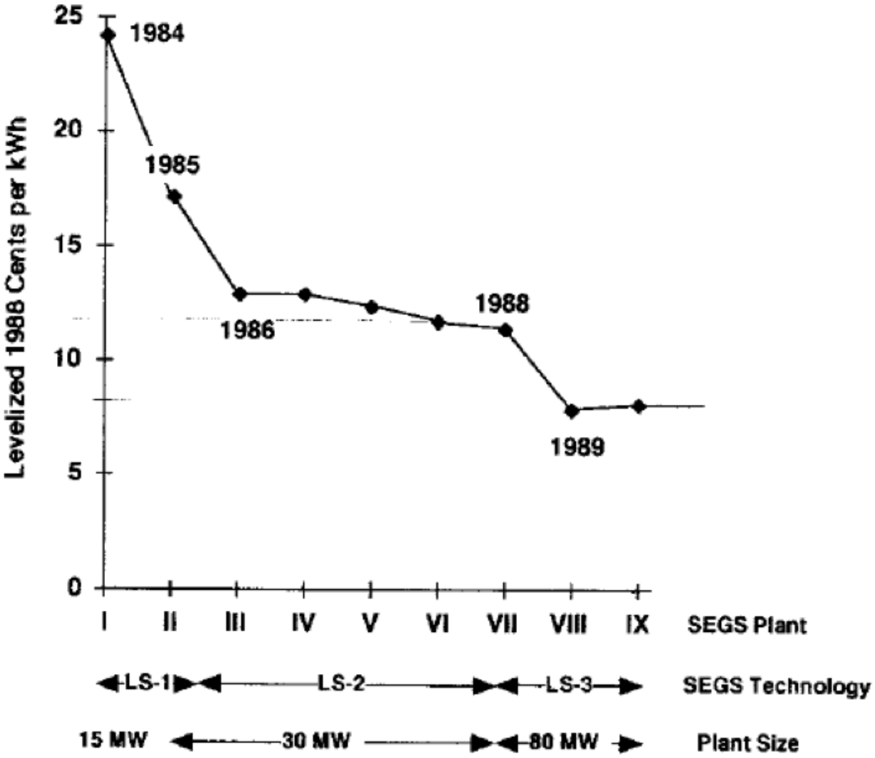

FIGURE 4. DOCUMENTATION OF COST REDUCTIONS IN STE PLANTS. SOURCE: LOTKER, 1991.

4 PROSPECTS FOR STE & RECENT EXPERIENCE IN SPAIN AND THE US

Two policy instruments have driven the resurgence in STE installations over the past ten years: California's aggressive renewables obligation and Spain's feed in tariff for renewables. California's Renewable Portfolio Standard originally obligated utilities to generate 20% of their retail sales from renewables by 2020. In 2006 that 2020 target was increased to 33% and the original 20% target was met by 2011. Almost 3GW of new renewables had come online by 2012. Over 1GW of STE projects were under construction in California as of mid-2012. Spain's feed-in tariff began in 1998 but was substantially increased in 2007. At its peak, STE projects were receiving nearly 30 euro cents/kWh, guaranteed for 25 years. These tariffs have been reduced in the past 5 years and in 2012 the feed in tariff program was cancelled. Still, over 500MW of STE capacity was installed and is operating as of mid-2012.

An important implication for effective STE policy relates to a distinguishing feature of STE compared to other renewables. STE requires large investments approaching the magnitude of fossil plants. Early investors may therefore have to "eat between one and three $200m plants" before improvements enable profitable operation (Taylor et al., 2007). A policy implication is that the scale of technology requires different types of incentives from smaller scale renewables such as PV. For example, the existence of capital constraints implies that STE depends more on instruments such as investment tax credits rather than on incentives for electricity production. While it has been essential to stimulate deployment, policy has also had adverse effects on STE: deregulation increased risk, which discouraged large-scale investments; early policies included limits on scale to encourage small producers, but these limits were detrimental to reducing STE costs.

Notwithstanding these issues, further cost improvements in STE remain possible. These include: scale increases (e.g., from 100 to 200MW), the use of advanced technologies—such as molten salts as working fluids and reflective films instead of mirrors—and increases in capacity factor driven by improved O&M and also by location decisions (Kutscher, 2009).

5 SUMMARY AND CONCLUSION

STE projects were widely viewed as failures in the 1990s. They were seen as expensive uses of public funds that benefitted a few entrepreneurs and early investors and were simply unnecessary given low energy prices. But this 'failure' of the California SEGS plants was due to expectations of falling energy prices rather than to technical failures. Indeed all 9 plants themselves are still in operation. The reemergence of the technology in the 2000s is striking in how similar the designs are to those experimented with and deployed in the 1980s. At least some of the experience and new knowledge produced in the 1980s was not lost.

Several concluding observations can be made about the innovation histories of the STE plants built in the 1980s:

- STE technology appears to be one for which higher levels of R&D investment could not have substituted for deployment. Learning by doing was essential due to the systemic issues of operating these plants in ambient conditions for several years while producing electricity for real customers.
- The interaction between learning by doing and public R&D investment, even if small, was important for the substantial decline in operating costs observed from 1984-1991.
- Part of the value of the R&D investment was the formal documentation of cost improvement efforts, which was publicly available, and non-proprietary. These investments may benefit the more recent round of plant construction.
- Initial investments required were large and lumpy due to the need to produce plants at the scale of 10s of MW. Firms knew they would need to absorb losses on the first few plants in order to learn from experience that they could only glean at real commercial scale. This situation was a classic 'valley of death' between demonstration and market application that, in this case, was overcome by

a combination of generous subsidies and an alternative energy “bubble” on Wall Street in the early 1980s that supplied a large appetite for risk. Early plants needed both guaranteed tariffs as well as capital cost subsidies.

6 FURTHER READING

The following references provide useful additional insights and detail into the innovation history of solar thermal electricity: Lotker, 1991; Sargent-Lundy, 2003; Shinnar, 1993.

7 REFERENCES

Cohen, G. E., Kearney, D. W. & Kolb, G. J., 1999. *Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants* Oak Ridge, TN, Sandia National Laboratories.

CPUC, 2007. *Progress of the {California Renewable Portfolio Standard} As Required by the Supplemental Report of the 2006 {Budget Act},* San Francisco, California Public Utilities Commission.

Enermodal, 1999. *Cost Reduction Study For Solar Thermal Power Plants,* Washington, DC, The World Bank.

Grosskreutz, J. C., 1996. High Temperature Technologies. *In:* Larson, R. & West, R. E. (eds.) *Implementation of Solar Thermal Technology.* MIT Press.

Kearney, D. & Price, H., 2005. Recent Advances in Parabolic Trough Solar Power Plant Technology.

Kutscher, C., 2009. Concentrating Solar Power. *Summer School on Global Sustainability.* Santa Fe, NM.

Lotker, M., 1991. *Barriers to Commercialization of Large-Scale Solar Electricity: Lessons Learned from the {LUZ} Experience*, Sandia National Laboratories.

Mariyappan, J. & Anderson, D., 2001. *Solar Thermal Thematic Review,* Washington, The Global Environment Facility (GEF).

Mead, W. J. & Denning, M., 1991. Estimating Costs of Alternative Electric Power Sources for California. *In:* Gilbert, R. (ed.) *Regulatory Choices: A Perspective on Developments in Energy Policy* Berkeley, CA: University of California Press

Neij, L., Borup, M., Blesl, M. & Mayer-Spohn, O., 2006. *Cost development: an analysis based on experience curves*.

Nemet, G. F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. *Research Policy,* **38**(5): 700-709.

Philibert, C., 2004. *International Energy Technology Collaboration And Climate Change Mitigation Case Study 1: Concentrating Solar Power Technologies,* Paris, International Energy Agency.

Price, H. & Carpenter, S., 1999. *The Potential for Low-Cost Concentrating Solar Power Systems,* Oak Ridge, TN, National Renewable Energy Laboratory.

Sargent-Lundy, 2003. *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts,* Golden, CO, National Renewable Energy Laboratory.

Shinnar, R., 1993. The rise and fall of Luz. *Chemtech,* **23**: 50-53.

Taylor, M., Nemet, G., Colvin, M., Begley, L., Wadia, C. & Dillavou, T., 2007. *Government Actions and Innovation in Clean Energy Technologies: The Cases of Photovoltaic Cells, Solar Thermal Electric Power, and Solar Water Heating, {CEC}-500-2007-012,* Sacramento, California Energy Commission.

If referencing this chapter, please cite:
Nemet, G. (2012). Technological Improvements of Solar Thermal Electricity in the US, and the Role of Public Policy. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.