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Delivering Solar Energy Projects

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Blazing overhead, the sun has always been an obvious source of energy. Early humans struggled against nature's numbing cold and wilting heat, flood and drought, predation and starvation. Newton and Einstein's understanding of force and energy has harnessed nature to elevate the life of the common man to a level of comfort that would have been envied by a prince of old. But the scale of this energy consumption has unintended consequences—the extent to which we are just now starting to find out about. All evidence is that primitive man bested nature in his struggle, and now, in a reversal, modern man must struggle to save nature's fragile life.

Solar energy contributes to that preservation effort, and this book can help you make a difference by using solar energy to reduce a building's demand on resources and its impact on the environment. Solar is clean and inexhaustible. It is distributed over the globe. Its availability is greater in sunny locations, but much of the world's population and expected growth is in those sunny areas. And in cold locations, there may be less sun, but there is a greater need for heating, so it is possible to use more of what solar heat is available.

HISTORY AND CURRENT USE OF SOLAR ENERGY

Solar has been used as a source of useful energy from early man, to the industrial revolution, and on into the space age. Hero of Alexandria is credited with inventing the first solar-powered water pump in the first century AD. A French inventor named Augustin Mouchot demonstrated a focusing solar reflector at the Universal Exposition in Paris in 1878 that he used to pump water, distill alcohol, cook food, power a printing press, and affect an absorption cooler to make ice. Remarkably, this same nineteenth-century inventor later used solar heat focused on junctions of dissimilar metals to create electricity and split water, producing hydrogen, which he stored as fuel. The inventors of semiconductor diodes at the dawn of the electronics age investigated solar photovoltaic cells as one of the first applications (Butti and Perlin 1980). And now, we find solar powering space satellites and vehicles exploring Mars. We take a closer look at the history of each technology at the beginning of each chapter.

Nowadays, the world runs on fossil fuels: coal, petroleum liquids, and natural gas. Figure 1-1 displays data from the *International Energy Outlook 2011*, an analysis published by the US Energy Information Administration, showing energy consumption of oil, natural gas, coal, nuclear, and other fuels from 2005 to 2012. Natural gas is seen to gain market share because it is a cleaner burning fuel and two extraction technologies (directional drilling and hydraulic fracturing) have increased supplies. Solar energy is counted among the "other" fuels and is increasing as well.

Of the 542 quads of energy consumed in 2012, solar accounted for only 0.1 quad. Figure 1-2 shows how that consists of solar thermal and photovoltaic applications in utility electricity, commercial uses, and residential buildings.

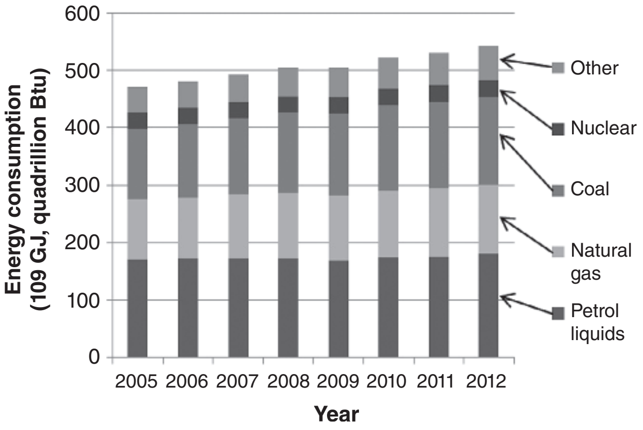


Figure 1-1. This chart of global annual energy consumption by fuel type (10^9 GJ, quadrillion Btu/year) shows the recent increases in the use of natural gas and renewable energy. (Figure by the author using data from US Energy Information Administration 2012)

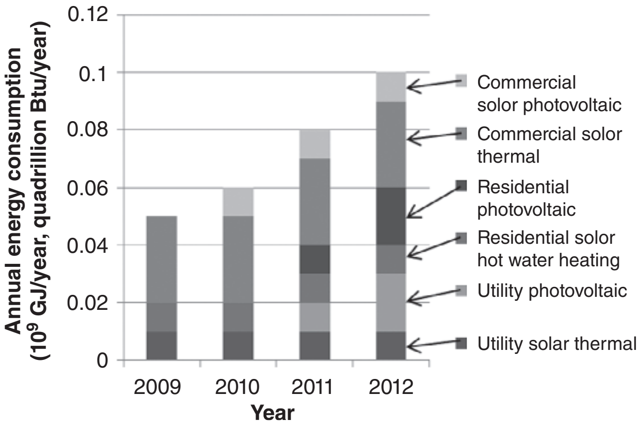


Figure 1-2. Global annual consumption of energy from solar energy applications has been increasing rapidly, with residential and utility-scale photovoltaics showing the most rapid growth. (Figure by the author using data from US Energy Information Administration 2012)

One may surmise that solar energy's contribution to world energy use is small, but what is exciting is that it is increasing rapidly. In 2012, solar electric generation increased 24 percent, a rate that has been sustained for several years now. On a percentage basis, solar is the fastest growing electric-generation resource. Figure 1-3 shows recent growth in solar electric generation capacity (GW of installed capacity) by country. For the years from 2010 to 2035, the US Energy Information Administration (EIA) predicts an average annual growth rate of 16 percent for utility photovoltaics and 11 percent for residential photovoltaics. According to this projection we should be busy designing and installing solar energy systems for some time to come.

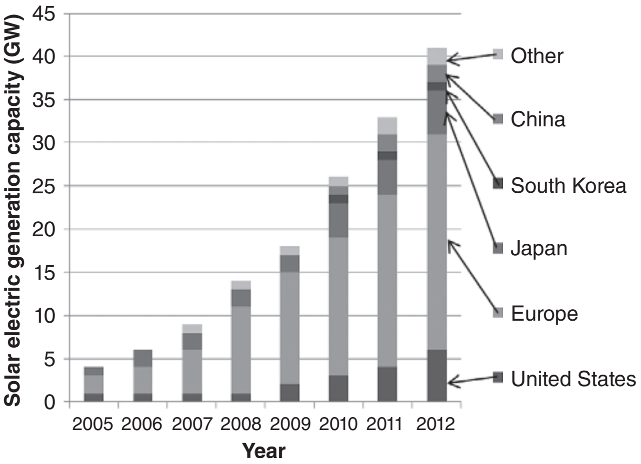


Figure 1-3. The cumulative generating capacity (GW) of solar electricity has demonstrated exponential growth, led by Japan and countries in Europe. (Figure by the author using data from US Energy Information Administration 2012)

ADVANTAGES OF SOLAR ENERGY

The main disadvantages of solar energy systems on a building are the high initial cost to purchase and install, ongoing operation and maintenance, and the risk of a failure in equipment performance. Solar also has many advantages that occur in a variety of ways to help us preserve the environment and meet our financial goals. In discussions among various stakeholders, the following advantages of solar energy are often cited:

Provide a Financial Return on Investment

Solar energy can be the least-cost option in a place where conventional energy is very expensive, such as in a location that relies on oil as a source of energy. Sunlight is delivered to even remote locations for free, so a solar project saves the cost of fuel, delivery costs, and cost of operating the conventional energy system. It is expensive to operate an electric generator in a remote location, and until 2004 such remote power applications were the largest part of the solar energy market. Since 2005, tax credits and other incentives have lowered the cost of solar energy projects to the point where utility cost savings (in not-remote locations) are sufficient to pay back the initial cost in the system with a favorable rate of return and manageable risk to the investor. Sophisticated investors serve the solar market—they combine utility cost savings, tax credits, and other incentives to construct cost-effective projects. Large projects involving third-party financing are responsible in large part for the growth in the solar market from 2005 to present.

Safety and Security of the Energy System

Solar is often added as a second source of energy along with conventional fossil-fuel systems. Depending on how the system is configured, this may serve as a redundant energy source. For example, the pump on my natural-gas-fired boiler recently failed, but I didn't have rush to get it fixed because the solar heating system provided the heat we needed. Solar electric systems may also be configured with batteries to provide power to dedicated circuits in a utility-power outage.

Recent news has been filled with tragedies related to energy. An offshore drilling rig exploded in the Gulf of Mexico, killing 11 workers and ruining the habitat with over 170 million gallons of toxic crude oil in 2010 (NRDC n.d.). Based on tracking plumes of isotopes such as iodine-131, accidents at nuclear plants in Fukushima, Japan in 2011 and Chernobyl Russia in 1986 will each be blamed for 500,000 deaths all over the world, mostly among infants less than one year old (Mangano and Sherman 2012). Little doubt remains that emission of carbon dioxide into the atmosphere from fossil-fuel use is causing a warming of the planet, with consequential changes in the climate. These catastrophic failures expose systemic distortions that high profits insert into the equation of risk versus reward (the profit being private, the risk being public).

I can't think of any way that solar could ever cause a disaster of such proportion. It is distributed and not concentrated into one facility. And while there are general safety issues related to electric systems and some hazardous materials in batteries and some types of solar collectors, solar involves no risk of explosion or of large release of toxic contaminants. While most solar systems are not designed to operate independently, they certainly can be, and if they are they contribute essential power in an emergency. Solar power systems don't require delivery of fuel in an emergency, such as a diesel-fueled generator would. Solar energy systems are located at the use of the energy, thus avoiding risk associated with failure of a large transmission and distribution system. The issue of safety and security spans all the way from an electrical outlet in a home in America to the Middle East. A complete calculation of the cost and risk of fossil fuels would have to include national security and international actions to secure stability in energy markets.

As a technological society, the tools that we have include education, incentives, and regulations; and we can use these tools to correct extreme risks before catastrophic failures occur and to limit the damage when things do go wrong.

WARNING

Safety First

Solar energy systems involve hazards encountered in any heating or electrical system, plus some encountered uniquely in solar systems. Safety should be considered during site visits, and in considering features of the design, special measures during construction, safety in long-term operation maintenance procedures, and safety in disposal of materials. General safety requirements on the worksite include helmet, safety glasses, vest, and work boots. Solar work requires long-sleeved shirt, long pants, sunscreen, and that the helmet be opaque and reflective. Roof safety is of particular importance. Roof safety usually limits access to the roof during site visits and requires different "fall protection" systems (railings, ropes) during rooftop activities and construction. Roof access for firefighters must be considered in consultation with your fire marshal when locating the solar collectors on a roof. Electrical safety applies to all parts of a photovoltaic system and entails two special characteristics of PV: 1) they are energized and cannot be turned off whenever the sun is shining and; 2) the short circuit current is not much greater than the expected operating current, so an arc can be sustained as electrical connections pull apart without tripping the breaker protecting that circuit against high current. "Arc-flash" protection is required when working on energized circuits and involves special gloves, as well as face and body coverings. "Lock-out tag-out" is a procedure to make sure nobody energizes a circuit someone else is working on. Sanitation is key to solar water heating systems, as they are often used to preheat potable hot water, and large volumes of water at tepid temperatures provide a media for bacteria, a risk that can be reduced by use of a load-side heat exchanger that does not store potable water. Some components used in solar energy systems involve toxic materials. The acid used in flooded batteries may be the most dangerous, but lead in batteries, cadmium in some types of photovoltaics modules, and spent heat-transfer fluid require custody over the life cycle of the material to properly recycle.

Less Pollution than Fossil Fuel

The myth persists that environmental damage may be "externalized" from cost in such a way that the profits are private but the damage is to the commons. The related deception is that the environment is limitless in its capacity to absorb pollution. The truth is that the environment is already at its capacity, and any further mistreatment has traceable consequences to human health. We are a technological society, so we can invent solutions to how processes interact with their surroundings. And we are civilized, so we can work together for the common good.

After hiking up to a rise above Everest base camp in Nepal, at 5.5 km above sea level (18,200 ft), I could look down on as much of the mass of the atmosphere as up. Almost half of the atmosphere's mass is below that elevation. The thinness of the atmosphere was visible on the horizon. Air pollution and radiation released anywhere are global in their reach and impact. This thin, fragile layer of air is our cabin-air on this spaceship earth. Pollution from technological activity has put a hole in the ozone layer, made rain more acidic, and warmed the atmosphere, risking the delicate balance that our only atmosphere has achieved and that we depend on. We need to take measures to check and reverse this degradation. Solar energy systems entail air pollution in their manufacture, shipping to the site, and installation effort. But once installed, every unit of solar heat or electricity delivered saves an equivalent amount of fossil fuel burned and associated emissions, plus it also saves losses in generating and delivering energy to the point of use. Solar energy may be viewed as one key strategy to reduce air pollution and associated climate change. Coal is mostly carbon, C, and a CO_2 molecule is released into the atmosphere for each carbon atom burned. Natural gas is CH_4, so for each molecule of methane, one molecule of CO_2 is also added to the atmosphere—but we also get the energy of the hydrogen converted to water so natural gas is the cleanest-burning fossil fuel. Reduction of carbon emissions may be attributed to solar energy delivery based on the heating value and the carbon content of the fuel avoided and the efficiency of the fuel-burning equipment. Utility companies report this performance data to regulators and often shareholders. Values vary from 1 $kgCO_2/kWh$ (2 $lbsCO_2/kWh$) for lignite coal with a heating value of 10 MJ/kg in a 33% efficient thermal steam cycle to 0.3 $kgCO_2/kWh$ (0.7 $lbsCO_2/kWh$) for natural gas with a heating value of 50 MJ/kg in 60% efficient combined cycle power plant. These calculations include that the CO_2 mass is higher than the fuel mass by the ratio of the molecular weight of CO_2 to that of C only: 44/12. Nuclear and hydropower generators don't have any carbon emissions. Standard values are adopted to administer uniform incentive and trading regimes, and are often calculated according to the mix of different types of generators in a utility interconnect, where the power is shared. A more sophisticated approach would identify the specific utility operation that changes as a result of the solar, often a move down the fuel consumption curve of a "peaking" gas turbine. Collecting a tax on the carbon emissions from the combustion of fossil fuels ($/ton of carbon) is one key strategy that is being implemented for mitigation of global climate change.

Statutes and Mandates

One good reason to consider solar energy is if a law tells you to. Language in the Energy Independence and Security Act, 2007, requires any new US federal government building to derive at least 30 percent of its hot water from on-site solar energy systems, and sets a declining scale for fossil fuel use such that by 2030 a new federal building would have to offset all of its energy consumption with on-site renewable energy. A previous law set a goal that the federal government get 7.5 percent of its electricity from renewable energy by the year 2013. Many other units of government have renewable energy goals or, more likely, carbon reduction goals, which on-site solar energy systems can contribute cost-effectively to.

Marketing Green Buildings

Solar energy systems differentiate sustainable buildings from the competition, and can increase demand over conventional construction. Many building owners are interested in incorporating solar energy for altruistic reasons, but energy cost savings and marketing help the bottom line. In a survey, 55 percent of buyers were willing to pay $5,000 to $10,000 more for green features in a new home (RS Means, 2006).

INCENTIVE PROGRAMS

Often an incentive program is what compels a consumer to install a solar energy system. Incentives are offered by units of government in the form of tax credits, tax exemptions, and tax depreciation and may be offered by utilities as rebates ($/Watt) or production incentives ($/kWh). Incentive programs are designed to make a project just barely cost-effective from the perspective of the building owner. Trends are for incentives to pay for production ($/kWh), rather than a rebate upon installation; programs phase out as they achieve their goals (often over 3 to 7 years); and programs require projects to compete for the available incentive amount. A liquid market has developed for Solar Renewable Energy Credits (SRECs), which utilities purchase from solar project developers or brokers to satisfy their regulatory requirements to use solar energy.

A very good resource to begin researching incentives available to a project is the Database of State Incentive for Renewable Energy at www.dsireusa.org.

Social Equity

In a technological society we realize that access to energy is a crucial interest, and in that way might be considered a human necessity, a human right, along with the way clean air and clean water might be. Every effort is made to deliver energy to those that pay the most for it, but there are almost 2 billion poor people on Earth without access to electricity. The well-being of society as a whole depends on affordable energy. As a resource distributed equitably to all, solar energy is able to meet the modest energy requirements of the least fortunate and provide some measure of social equity to the fabric of society. A distributed energy industry and infrastructure has social advantages, and solar, by virtue of being available directly to all, is less subject to cartel in the way an oil well or a nuclear power plant may be.

Economic Development

Every community has people working in the utility sector, but significantly more money collected through utility bills flows out of a community. The same amount of money spent on solar energy might involve local manufacturing and would necessarily employ local trades (electricians and plumbers) to install and maintain the systems. In 1925, the *Miami Herald* listed the Solar Water Heater Company as the seventh-largest construction company in Miami, an early example of the potential of the solar energy industry to create jobs (Butti and Perlin 1980). Many economic development authorities have high hopes for solar to bring jobs back into communities, and if solar were to be on every building, local jobs would certainly result.

Interview with Solar Entrepreneur Patrina Eiffert

Dr. Patrina Eiffert (pictured in Figure 1-4) is an internationally recognized expert and thought leader in the field of building integrated photovoltaic (BIPV) and field integrated photovoltaic (FIPV™) technology and holds numerous patents for related products. Dr. Eiffert was a pioneer in developing third-party financing for projects and she serves on the board of directors of four organizations: Women in Sustainable Energy (WISE), SolarFrameWorks Co., ImagineIt Inc., and Solar Angels.

Figure 1-4. "Solar Sisters" Patrina and Annett Eiffert at an installation of their "CoolPly" roof-integrated photovoltaic system at a football stadium in New England. (Photograph by Chris Bills, courtesy of Solar Frameworks.com)

You did your PhD dissertation on building integrated PV and now you are making a career in that field. What conclusions were you able to draw in your dissertation?

In the 1990s there were very few graduate programs specific to renewable energy, so I had to combine an undergraduate degree in economics with an architectural program to conduct research for my dissertation, "An Economic Assessment of Building Integrated Photovoltaics." The primary question was "Why would a building owner want to invest in a BIPV system?" In my research, I focused on the concept and value impact of avoided environmental emissions. This was probably the first doctorate in BIPV as well as the first identification of a potential market value for avoided environmental emissions for photovoltaics on buildings.

Did you know back then, when you were doing your dissertation, that you would start your own company someday?

My grandparents were Italian immigrants that came to America to start a new life in the 1920s. As a child I was always around the back rooms of commercial businesses such as a trucking business, grocery store, clothing boutiques and factories. Business was a part of life. Serving on the International Energy Agency Task on PV in the Built Environment gave me global exposure to multibillion dollar businesses and starting a business was a natural extension of that career. It has been more challenging and rewarding that I anticipated.

You've heard the saying "doing well by doing good"; how much are you motivated by profit versus saving the planet. Would you still do this if you weren't so successful?

Not only "doing well by doing good"—I was raised in the era of "dreaming big and making it happen." As a young girl I saw a man walk on the moon and tens of thousands of Peace Corps volunteers go to remote places in the world to contribute to improve the lives of others. Intellectually, I've always understood that solar must be a smart economic investment for the technology to be commercially viable. Fortunately, SolarFrameWorks has been consistently profitable from the beginning and also now in a very difficult economy. My motivation is based on the desire to contribute and help change the world. My sister and I were raised feeling empowered with a "can-do" attitude and the American spirit of innovation. We thrive on being technology leaders and working with the early adopters in different market segments. However, at the end of the day, we want our most important contribution to be through our 501 3-c nonprofit, Solar Angels, where we provide solar-powered lights, phones, and electronic equipment to remote health clinics.

Your products include roof-integrated PV (BIPV CoolPly Plus®), PV mounts that cover a landfill or brownfield (FIPV CoolPly Plus™), and special soap (PowerBoost®) to keep PV modules clean. Did these ideas come to you and then you found a market for them or did you see a need and then invent a solution?

Annett and I are strategic, and our goal is to assist in the commercialization of photovoltaic technology. The key question we ask ourselves every year is "What's next?" The ability to understand the needs of key stakeholders, understand where the technology and markets are now and where they may be going, presents Annett and I with all types of great product ideas. Years ago, as mothers of young children with solar careers, we got the idea for PowerFrames™, a plastic racking system, from the Lego® snap together toy. Investing dollars into market research, product development, market development is something we take very seriously. We are leading the way with Field Integrated Photovoltaics™ (FIPV) as we have done with Building Integrated Photovoltaics (BIPV CoolPly Plus®). When we created PowerBoost® solar panel cleaner, we laughed and called ourselves the "Molly Maids® of solar."

(continued)

At that time we saw that the market was going to incentives based on power production [$/kWh delivered], and keeping the panels clean with engineered detergent helps power production a lot. We have now sold over 20,000 bottles in the US, Australia, and Europe. Our next goal is to get this product on the shelves of big box retailers. We have a number of additional product ideas in our portfolio that we look forward to bring to the market. It's a shared passion for us.

Can you provide any advice to readers that might be thinking about starting their own company in the solar energy field?

There is so much work and innovation still to be done to commercialize solar technology. Everyone is born with certain God-given gifts and talents. It's your responsibility to truly understand who you are and share your gifts with the world. The competition is brutal and the work is hard. However, if you live in your talent, you can contribute to the solar industry and reap the personal as well as financial rewards.

SOLAR ENERGY PROJECT DELIVERY PROCESS

Goal-setting

Some organizations have set a goal as to what percentage of their energy they want to obtain from renewable energy, such as the 7.5 percent goal for the federal government set by the Energy Policy Act of 2005, or a goal of 15 percent set by a major brewer. But more often, solar energy projects are considered because they contribute to a more general goal, such as to minimize operating cost or to reduce carbon emissions. Any planning should have a goal in mind, and the nature and ambition of the goals usually shapes the development of any solar energy project. Goals are often designed to meet an optimal condition under constraints. For example, minimize carbon emissions under the constraint of same or lower cost; or minimize life cycle cost under the constraint of 20 percent carbon reduction. Planning can then figure out a way to approach that goal, but a thoughtful and inclusive process to set the goal comes first.

Team Building

A diverse team is essential to complete a solar energy project. Solar projects involve an energy manager or sustainability advocate who champions a solar project, a team, including a contracting official, facility planner, or facility manager, to contract for the system, and a team to install a system, including design engineer, equipment suppliers, installing contractors, and other agents. The goal and the plan to meet the goal decides who needs to be on the team, and it might involve a wide range of stakeholders, including other property owners in the area who can see your solar system, the local utility company, local planning and code officials, neighborhood associations, and any others depending on the particular situation. Every team member should state their understanding of the goal and their commitment to work toward it. A deer can easily outrun a lone wolf, but in a phenomenon called "heading off," one wolf chases the deer while another runs the hypotenuse to where the deer could turn. By running a shorter distance they are sure to catch the deer.

Screening

Some organizations operate a lot of real property in different locations, each with different solar resources, different utility rates, and different incentives such as tax credits. Many can point to successful solar projects on some of the buildings, often resulting from the interest of an on-site champion, but few have taken a structured approach to plan which set of solar technologies at which facilities can achieve their goal at the lowest cost. Simple calculations to screen a large number of sites for cost-effective project opportunities—photovoltaics, solar water heating, and solar ventilation air preheating separately—are described in (Walker et al. 2006). Subsequent work includes combining the effect of multiple technologies at a site, considering that you can't save the same kWh twice, and considering interactions between the technologies. An example of such interaction is that pumps and fans involved with the solar heating systems will be additional electric load and that a photovoltaic system could supply that electricity (Walker, 2009a). RETScreen is a free online tool for screening that is referred to repeatedly in this book (www.retscreen.ca). A screening calculation does often result in some details like how big a system should be, how much it might cost, and how much it might save—but the calculations are not detailed and not confirmed with a site visit, so a screening is not sufficient to inform a decision of whether to do a project or not. That requires a full economic feasibility study to establish the economic details and an engineering feasibility study to confirm that there are no technical issues that could prevent a project at the site.

A screening study involves collecting information without visiting the site. Information includes solar resource data, utility bills showing consumption and rates, incentives, true-south and orientations of building roof areas, land area, net-metering limits (kW), electrical panel rating and breakers, and any other information that can be collected without sending staff to actually visit the site. You should be able to estimate the electric load, hot water load, or ventilation air requirement before visiting the site. You might also be able to find out what requirements relate to wind speed and exposure at the site as well as seismic requirements. A screening should determine which jurisdiction a project is located in and what requirements of that jurisdiction apply (which versions of which codes). Much of this data may be found in an organization's real-property management database and in its utility-purchase database, or in publicly available data resources—which is fortunate because collecting original data is very difficult. The results of screening studies are often presented on a map with symbols that indicate "go" for properties where photovoltaics, solar water heating, and solar ventilation preheating would reduce life-cycle cost below those currently paid; and "stop" at locations where solar projects would result in higher cost. This calculation requires a value for the solar resource (kWh/m^2/day), which for screening purposes is accessed from databases such as those found at www.nrel.gov/gis.

Site Evaluation

The purpose of the site evaluation is to collect first-hand information and to observe site conditions. A detailed checklist is used to collect information from a site without visiting it, but a site evaluation is required to see the things you didn't know to ask about. A "task analysis" by NABCEP provides detailed lists of tasks that sales and technical staff would conduct (NABCEP 2011). Many companies have tried to save money by sending new staff to do the site evaluation, but have had to repeat the site evaluation with more experienced staff because information was incorrect or not obtained on the first trip. Preparation is key to an effective site visit. It is important to have a checklist of all the information that needs to be collected and the instruments to collect all that information ready to go with all required accessories and batteries charged. Items to remember include safety glasses, flashlight, pen with waterproof ink, pad with fill-in-the-blank checklist and adequate paper, sunscreen and hat to protect against sunburn, magnifying glass to read small labels, camera, current meter if you need to measure electric loads, noninvasive flow meter if you need to measure hot water use, heldheld wind-speed meter if you need to measure ventilation air duct velocity, roller wheel to measure distances, infrared thermometer or temperature probe, and a device (such as Solar Pathfinder or Solmetric SunEye) to measure effect of shading objects. Some general considerations and considerations related to photovoltaics, solar water heating, and solar ventilation air preheating are as follows:

> Roof array locations: material, type, age, and condition of roof; area, tilt, and orientation of available roof areas; measure shading; document structural framing of roof and condition/integrity. Obtain terms of roof warranty.
>
> Ground array locations: type of soil; area, degree and orientation of slope to the ground; location of underground utilities and obstructions (gas and electric lines, water pipes, and so on); measure shading.
>
> Location for balance of system: area for PV inverter, disconnects, and transformer; for solar hot water tank, pumps, and controller, for solar ventilation preheat fans; identify path and measure length for conduit or pipe runs from array to balance-of-system location; identify source of electric power for pumps and fans.
>
> Interconnection with conventional systems: identify voltage and current rating of electrical panel or other location where photovoltaic solar power could feed into building; record current rating of breaker protecting that panel; determine limits on solar power that can be supplied to panel or specify other interconnection based on code limits; identify additional equipment requirements such as new box for interconnection or transformer as required by utility interconnection policies; determine if network configuration will be compatible with back-feed of power at this location. Confirm level of solar penetration on the utility circuit and that the utility will accept power on that circuit when available from the solar.
>
> Installation issues: Determine access routes and hours for delivery and staging (lay-down) of materials, equipment, and tools. Identify any special crane access for lifting solar water heating collectors, and palettes of PV modules onto the roof. Consider means of moving heavy water tanks or inverters into a room in the building.

Solar Energy Projects in New Construction

It is much easier to integrate solar energy systems into the design of a new building than it is to retrofit an existing building. NREL has published a guide for making buildings "solar-ready," detailing a checklist of general and technology-specific considerations (Lissel, Tetrault, and Watson 2009). Provide for the safety features required to install and maintain the solar collectors in the design of the building. For example, if the roof is sloped, harness connections should be permanently built into the ridge of the roof. Careful layout of buildings on the site can leave unshaded areas for ground-mount of solar collectors. Arrange rooftop mechanical and communications equipment to leave unshaded areas on the roof for placement of solar collector arrays. Provide roof structure to support the loads of the solar collectors, on the order of 30 kg/m^2 (6 lbs/ft^2) weight, but often less. Specify a roof type that is easy to mount solar collectors on. Ballasted systems install easily on flat membrane roofs, and generally any required roof penetrations may be sealed by standard products and methods. For sloped roofs, standing seam metal roofs are expensive initially but have a low maintenance cost. They also are very easy to attach solar collectors to because of clamps that are used for attaching mechanical and electrical equipment to the seams without penetrating the metal pan of the roof. Shingles or tiles must be removed around a roof stanchion, and the stanchion flashed in to mate with the shingles or tiles, making these types of roofs the most difficult and expensive to attach to. Install any required blocking between rafters of a roof, for the solar mounts to attach to, before the ceiling is installed.

In new construction we can designate locations for the components of a solar energy system: water storage tanks, controls, valves, inverters, electrical switchgear. This space would be in optimal proximity to the solar collectors and the point of utility interconnection. Electrical conductors and water pipes should be arranged in the shortest route possible to save on initial cost and improve efficiency. Pipe chases may be made to connect the roof to the building electrical and plumbing systems with pipe or conduit, without having to run them in exterior walls or be surface-mounted.

Consider vertical wall area facing toward the equator for a solar ventilation air preheating system. Avoid placement of sources of pollution, such as boiler flue or truck loading dock, near transpired collector. Arrange openings in wall (windows) to allow easy layout of transpired solar collector. Add additional opening in the first stage of air-handling unit to allow introduction of solar preheated ventilation air.

Feasibility Study and Life-Cycle Cost Analysis

A feasibility study establishes that the project is viable financially and also able to be constructed with regard to any physical or technical constraints. An evaluation of cost-effectiveness involves a cost estimate of how much it will cost to install the system, an estimate of utility cost savings and operation and maintenance cost, and a life-cycle cost to reduce all these cash flows to their present value according to the discount rate. Some key elements affecting feasibility of a project include:

- Solar resources: evaluation determines the amount of solar energy available at the site.
- Utility rates: details of the utility rate structure determine the actual energy cost savings.
- Incentives: payments from utilities, state and Federal tax credits
- Load: load to serve directly or other “off-taker” of the solar energy such as an agreement with serving utility to accept solar power from a system.
- Authority to improve the property: Permits from local building authority; compliance such as historic preservation or viewsheds.
- Site control: Ownership, Lease, or Easement to the land or roof area; any rights-of-way that may be required to access the location.
- Interconnect agreement: terms under which the solar system may be connected to the larger utility system and operated.
- Financing: low interest rates are required when financing solar systems due to the high initial cost and long financing period.
- Bonds and insurance: availability of construction and payments bonds, and insurance—and at what price—affect project feasibility. Construction bonds are insurance that the contractor has sufficient resource to build the project and payment bonds are insurance that any subcontractors will be paid.
- Maintenance: local expertise must be available to perform maintenance and repairs

Life cycle cost analysis (LCCA) is the only way to evaluate solar energy projects because they are characterized by a high initial cost but then a low operating cost over the life of the system. Key terms involved in life cycle cost analysis include *discount rate*, d (percent/year); *inflation rates* for various fuels and *operation and maintenance costs*, i (percent/year); and the *analysis period*, N (years). Future costs are “discounted” down to their present value according to the *discount rate*, so that a solar project which has a high initial cost but a low operating cost may be compared to an alternative fossil fuel system that may have a low initial cost but a high fuel cost over its lifetime. Like all things in life, there is an ASTM standard on how to do life cycle cost analysis, and it entails: Standard Practices E 917, E 864, E1057, E1074, and E112; and Standard Guides E1185 and E1369. These standards have been codified into federal regulation 10CFR436, which requires federal agencies to use specified rates and methods so that life cycle cost estimated by different people in different agencies in different parts of the country could be compared. Many other agencies have adopted these standards or use them as the basis of their own methods. Siglinde Fuller, Amy Rushing and the Office of Applied Economics at NIST provide guidance and software products to implement life cycle cost analysis (www1.eere.energy.gov/femp/information/download_blcc.html). Costs considered include

- Initial investment cost, C_{initial} (\$)
- Energy cost savings, C_{savings} (\$/year)
- Operating and maintenance cost, $C_{\text{O\&M}}$ (\$/year)
- Costs to replace equipment (based on C_{initial})
- Salvage value of equipment at the end of the analysis period (based on C_{initial})
- Costs related to financing (based on C_{initial}).

Economic parameters involved in the analysis include

- Discount rate, d (percent/year), rate at which future costs are discounted to present value. If you would rather have \$0.95 today than \$1.00 a year from now, then your discount rate is 5%. If you would settle for \$0.90 today, then your discount rate is 10%.
- Inflation rate, i (percent/year), rate at which costs escalate from year to year.
- Analysis period, N (years), number of years in the analysis period, usually 25 years for mechanical systems and 40 years for building systems.

Life cycle cost analysis reduces all future costs to their present value so that they can be compared. The factor used to discount the costs depends on the discount rate. Continuing with our $d = 5$ percent example, a dollar of savings one year from now would be worth \$0.95, one two years from now would be worth \$0.9025, and one three years from now would be worth \$0.8573. The present value of an annually reoccurring cash flow that starts at C_{savings} in Year 1 and persists for the

Definition

Discount Rate, *d* (percent/year)

Would you rather have \$0.95 today or \$1.00 one year from now? If you said you don't care, that they are the same, then your discount rate would be 5 percent. If you say you would rather have \$0.90 today than \$1.00 one year from now then your discount rate is 10 percent. The *discount rate* is the "time value of money" and represents the *opportunity cost* of not having that money to invest in other investments if you have purchased a solar energy system. The discount rate chosen by an organization or an individual depends on the alternative uses that they have for investment capital. The federal government has a very low discount rate of around 4 percent, as determined by Treasury bills of a term similar to that of the solar project (25 years); financial institutions that finance solar projects have discount rates between 6 and 12 percent. Most corporations considering solar projects on their own facilities tell me to use a discount rate of 15 percent, and some relax that to 12 percent as a special consideration in pursuit of carbon reduction goals to help solar projects look more cost-effective. Homeowners vary quite a bit, but may use a discount rate of at least 20 percent to inform a decision to buy a solar system. College students tell me they have discount rates over 100 percent—they need their cash now to pay rent.

entire analysis period of N years, and escalates at a rate of i as the cost of fuel increases, and that is discounted to present value at the discount rate d is

$$PV = C_{savings}\frac{(1+i)}{(d-i)}\left[1-\frac{(1+i)}{(1+d)}^{N}\right] \tag{1-1}$$

The present worth factor, *PWF* (years), is a factor that we can multiply by the first year's savings to get the present value of the life cycle of savings.

$$PWF = \frac{(1+i)}{(d-i)}\left[1-\frac{(1+i)}{(1+d)}^{N}\right] \tag{1-2}$$

Example of Calculating Present Worth Factor

For example, the present worth factor for $N = 25$ years with a discount rate of $d = 5\%$/year and an inflation rate of $i = 2\%$/year is calculated according to the equation above

$$PWF = ((1 + 0.02))/((0.05 - 0.02))*(1 - ((1 + 0.02)/(1 + 0.05))\text{^}25) = 17.5 \text{ years}$$

The present worth factor has units of years and reflects that the time-value of money reduces 25 years of savings to an equivalent 17.5 years.

The life cycle cost is calculated as the net present value of an alternative. The life cycle cost of a solar energy system would be the sum of its initial cost and its operation and maintenance cost times a present worth factor.

$$LCC = C_{\text{initial}} + PWF{*}\,C_{\text{O\&M}} - PWF{*}\,C_{\text{savings}} \tag{1-3}$$

The levelized cost of energy, LCOE (\$/kWh), is the annual cost of the alternative divided by the associated annual solar energy delivery, $E_{\text{solar,annual}}$ (kWh/year).

$$LCOE = \left(\frac{C_{\text{initial}}}{PWF} + C_{\text{O\&M}}\right) / \, E_{\text{solar,annual}} \tag{1-4}$$

The savings to investment ratio (SIR) is the ratio of life-cycle savings to life-cycle investment

$$SIR = \frac{(PWF * C_{\text{savings}} - PWF * C_{\text{O\&M}})}{(C_{\text{initial}})} \tag{1-5}$$

Where the energy cost savings C_{savings} and the operation and maintenance cost $C_{\text{O\&M}}$ could inflate at different rates. The return on investment (ROI) is the interest rate that would have resulted in the same net present value from the same initial investment. The ROI is best determined iteratively using a spreadsheet or computer program like BLCC.

Indicators of cost-effectiveness include lowest LCC (\$) among alternatives, LCOE (\$/kWh) lower than conventional energy, savings to investment ratio greater than 1.0, or rate of return greater than the discount rate. The feasibility study should determine if the results from a project could meet the owner's financial expectations.

A feasibility study should also confirm technical feasibility, including physical space on the ground or roof to mount solar collectors; condition and strength of roof; paths for conduit and pipe runs are feasible; construction may be completed considering on-going operations at the building; technical feasibility of feeding solar electricity into the existing electrical service, of supplying solar heated water into the building water heating system; and of saving fuel by preheating ventilation air. Aesthetic considerations are also technical, especially when they involve preservation of historic buildings or cultural resources such as viewsheds.

Secure Funding or Financing

The first place to find funding for a solar energy project is an organization's own capital improvement or operations budgets. However, many organizations have limited capital investment funds, and they apply a high "hurdle rate," or minimum acceptable financial rate of return, to decide whether to invest the funds that they do have. Most of the solar projects that I've been involved in have a return-on-investment of less than 10 percent. If an organization has a hurdle rate of 15 percent, as many companies would, there are two remaining possibilities: the organization could consider a return less than their hurdle rate in order to realize other benefits from the project, such as environmental benefits; or the organization could seek a financier with expectations less than 15 percent that may be able to finance the project. Such third-party financiers often take advantage of the tax credits and accelerated depreciation associated with a solar project, thus they are called *tax equity investors*. Because they can monetize the tax benefits and are satisfied with a return on investment lower than other organizations, such financiers are involved in most large solar projects.

When all the parties to the contracts are private parties, anything that does not violate law may be proposed. But when one of the parties is a government agency, that agency can only operate under "prescribed powers" and may only have certain specific legal authorizations to enter into certain types of financing arrangements. The Federal Energy Management Program facilitates different financing vehicles available to federal agencies (www1.eere.energy.gov/FEMP/financing/mechanisms.html). These include:

> Power purchase agreements (PPA): Building owner pays for power delivered from an on-site solar energy system owned and operated by a third party.
>
> Energy savings performance contract (ESPC): Payments to an energy service company (ESCO) for providing and installing a solar energy system are guaranteed to be less than savings in utility cost and associated operation and maintenance.
>
> Utility energy service contract (UESC): The same contract used to procure conventional power from the utility is amended to provide other energy services such as an on-site solar energy system.
>
> Enhanced use lease (EUL): Land-owner receives electric power or thermal energy from an on-site solar energy project as in-kind payment for lease on unused land.

Some details of tax equity financing arrangements are listed in (Walker 2009b). There are many choices to be made in structuring any kind of financing arrangement. A source of other funds, such as a rebate, may either be subtracted from the cost basis of the system, and thus not be subject of tax credit or depreciation, or if it is not subtracted from the cost basis, it would be taxed as ordinary income. Often a choice must be made to take a tax credit initially as an investment tax credit (ITC, $) or over a period of time as a production tax credit (PTC, $/kWh), which delays the tax on income into future years. A project developer may "sell" the project to the financing partnership and pay taxes on the difference between the fair market value and the cost basis as income, or the developer may "contribute" the project to a partnership in exchange for distributions paid by the partnership over time. Distributions are often taxed at a lower rate than ordinary income and defer the tax to future years, so the tax can be paid out of the distributions themselves and may improve the after-tax ROI of the project developer without reducing the ROI of the investor partner.

Interview with Solar Financier Marc Roper

Marc Roper (pictured in Figure 1-5) is vice president of sales and marketing for Tioga Energy, a solar PPA provider based in California. Prior to joining Tioga, Marc led the sales, marketing, and external affairs for Turner Renewable Energy; was vice president and board member for photovoltaic manufacturer SCHOTT Solar; managed residential market development for photovoltaic manufacturer AstroPower; and headed up renewable energy programs for the State of Colorado's energy office. Marc earned a master's of civil engineering with focus on renewable energy and building systems design, a BS in engineering physics, and a BA in music from the University of Colorado in Boulder. He is a member of the boards of directors of the Interstate Renewable Energy Council (IREC), the Solar Energy Industries Association (SEIA), the North American Board of Certified Energy Practitioners (NABCEP), the Solar Rating and Certification Corporation (SRCC), and PowerMark Corporation.

Figure 1-5. Marc Roper speaking at the opening of 4 MW power purchase agreement PV project at Hemet Unified School District in California. (Photo courtesy of Timothy Clark, Johnson Controls, Inc.)

Your company, Tioga Energy, doesn't sell solar systems but rather sells energy from solar systems under power purchase. Why?

Generally, commercial and institutional energy consumers want less-expensive electricity, a way to hedge against electric utility rate increases, and a means of operating in a more environmentally sustainable manner. PPAs offer these benefits, while eliminating the need to come up with the significant capital required to build a solar power system and then manage the construction, operation, maintenance, repair, and removal of that system over its lifetime.

We use the term power purchase agreement as if it is single agreement but it is really several, right?

The power purchase agreement is the core contract that relates to the long-term sale of solar electricity by the PPA provider to the consumer. However, there are numerous ancillary agreements that are often needed in order to secure incentives, protect an investor's interest in the solar power system, and ensure the unhindered operation of the system over the life of the PPA contract. Depending on the situation, these can include utility interconnection and net-metering agreements, site lease or license agreements, easements, state and/or local government incentive contracts, consents to assignment, and subordination and non-disturbance agreements with site lenders, and contracts for the sale of renewable energy certificates (RECs). Coordinating and developing this suite of agreements is another of the benefits of the PPA model (although some of them are necessary only for PPAs)—the PPA provider generally takes care of all of this.

The term of the PPA is long enough to pay back the investors, yet at the end of the term a customer does not own the system and has to renew or buy the system at fair market value. Why is that? Fair market value might be pretty high for a PV system that is still producing power right? Have you determined fair market value on any systems yet?

One of the things that make the economics of a PPA work for both investors and consumers is the IRS' 30 percent investment tax credit. This credit is available to the first owner of a new solar power system, and it effectively reduces the cost to build a solar power system and therefore reduces the rate that the investor must charge the consumer for electricity in order to achieve acceptable returns. However, in order for an investor to claim this credit, it must be clear that they own the system according to the rules of the IRS. Provisions in a PPA that would effectively allow the sale of the system in the future at a fixed price could cause the PPA to be viewed as an installment purchase agreement, and cloud the interpretation of who owns the system and who is eligible to take the tax credit. For this reason, every well-crafted PPA stipulates that future purchases cannot be made at less than fair market value. With regard to future fair market value, the farther into the future you gaze the harder it is to predict. Factors such as remaining life and projected future cash flows, replacement value, and resale value. It's too early to tell what this will look like at the end of a 20-year solar PPA, but I'd bet there will be a strong market for refurbishing and redeploying second-hand solar equipment emerging in about 15 years.

Stuff happens. What happens if your company goes out of business? What happens if my company goes out of business?

Power purchase agreements are based on the concepts of structured project finance, where the suite of contracts comprise the assets of a special purpose entity formed solely to carry out the obligations of the PPA and attendant agreements. The investor retains the right to step into the contract to cure defaults of the provider, and assign the contract to a new provider if necessary. The investor does take on the risk that the consumer will go out of business and won't be able to continue to purchase electricity. In order to reduce this risk, the investor typically has a very high standard of credit, and sometimes will seek easements that further protect its ability to continue to operate the system and collect revenue from incentives, the sale of electricity to the utility company or a new tenant of the building.

How do you see the market for PPAs evolving in the future?

PPAs have great potential to deliver distributed solar generation to a significant portion of the commercial and institutional electricity market. However, PPA financial structures are still relatively new and complicated by tax laws, the long-term value of solar power systems as an asset class is not well established, transactions and contract documents are not yet standard, and the regulatory environment for PPAs is not yet stable. In order for PPAs to become truly efficient and pervasive in the market, the market must mature to the point where entering into a PPA is more like getting a mortgage for a commercial building and less like financing a big power plant. We are making good progress on a number of fronts: standardizing contracts, lowering installed system costs, establishing more favorable policies for grid interconnection at the state level. These things, along with increased consumer and investor comfort with the technology and long-term value proposition of distributed solar generation, will ultimately lead to enormous opportunity and market presence for the solar power purchase agreement and derivative products.

Figure 1-6 shows the many relationships between parties in a large solar project and the various agreements between each. A project developer and a financier form a partnership agreement with the investor as the general partner and the project developer as the minority shareholder. This partnership collects payment ($) from an "off-taker" of the power (kWh) in a power purchase agreement, and the utility company may also buy excess power from the project. There would be an agreement with the utility company to allow electrical interconnection with the larger utility system. There would be a lease or an easement associated with use of the land on which the solar collectors are installed. The project developer may sell the renewable energy credits (RECs) to a broker or a utility company that needs them to progress toward their regulatory goals, and RECs are an important source of revenue to make solar projects financially viable. Taxes are paid on the dividends paid to each of the partners. The project developer and financier may switch positions in the partnership in a partnership flip. The investor can use the tax credits ("monetize" them) because she has many sources of income which result in a tax liability. The project developer, on the other hand, may not have other significant sources of income and may even be a special-purpose corporation set up just to do the solar project. Thus, in the early years of the project financing term, the investor will hold all the shares and exploit the tax credits and depreciation. After all the tax depreciation is claimed (currently six years), the partners switch positions so that the project developer holds most of the shares and receives dividends which enjoy a lower tax rate than income in the US. Thus a partnership flip delays payment to the project developer, but results in less tax being paid.

The important thing about approaching any financing arrangement is to have qualified legal and tax advice. The deal must be optimally structured in order to compete with other project developers, and that requires specialized knowledge of the tax code and each party's tax situation. Analysis requires complete cash-flow analysis and a model of each party's tax liability. All available alternatives should be considered, and each party agrees to participate based on the benefits to them.

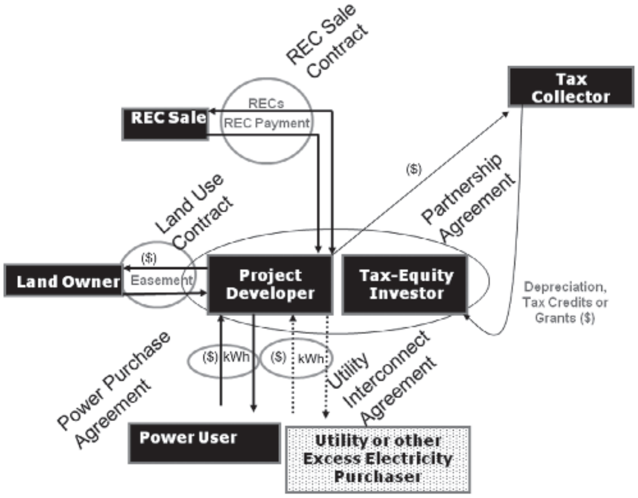


Figure 1-6. An example of the many relationships between parties in a financing arrangement for a large solar energy project is illustrated in this conceptual diagram. (Figure by the author, following those of Chandra Shah, National Renewable Energy Laboratory.)

Request for Proposals

A request for proposals (RFP) is a document issued by the building owner or project developer to solicit bids from solar suppliers and installers. The RFP may be advertised widely or may be sent only to invited offerors. The federal government advertises its project opportunities for bidders at Fed Biz Opps website (www.fbo.gov) with the intention of getting as many competitive bids as possible. This is how most suppliers find out about the sales opportunity, but it also frequent for suppliers to seek customers out with unsolicited proposals. A request for proposals should include:

Issuer: a clear definition of who is soliciting proposals and their authority to bind the owner of the building.

Performance requirements: what the project is trying to achieve in terms of delivered energy, emissions savings, or other desired outcomes.

Interface requirements: a description of the existing electrical, mechanical, plumbing, and other system that the new solar energy system must interface with in order to be able to delivery energy cost savings.

Compliance: who is responsible for complying with any regulations related to environmental, historic preservation, planning commissions, or any other compliance procedures? Who is responsible for obtaining any permits for construction and interconnection agreements for operation of a system?

Schedule requirements: required timeline to project completion. Urgent projects with short timelines should expect to pay a premium.

Information requested from offerors: technical approach to achieve the project objectives; technical qualifications (education, professional registration, certifications); past experience; references to contact from previous projects.

Selection criteria: offerors will address in their proposals the selection criteria stated in the RFP. An RFP may list out five or six different selection criteria, which may include technical approach; qualifications; and past performance. Selection criteria is perhaps the most important part of a project because if an owner gets a qualified and experienced team, then success of the project is almost certain; the obverse is also true.

Statement of work, also called scope of work: the statement of work must include all the tasks that the building owner expects the solar installer to perform. If an important activity is not in the statement of work, then the cost to perform that won't be in the bid, and the contractor won't have funds to complete that activity. To rectify that problem requires an expensive "change order." Language to make sure everything is included sounds like: "Contractor shall supply all services including design, construction management, installation labor and commissioning; and all hardware, supplies, materials, and appurtenances to make the solar energy system complete and operational." The statement of work should make it clear if the contractor is to manage compliance processes and associated permits or if the building owner will do that. The statement of work should make it clear who is responsible for improving any existing infrastructure to allow for the solar project. Any work that needs to be done to complete the solar project should be in either the statement of work document or among the expectations of what the building owners plan to do themselves or contract from other parties.

The proposals should be evaluated by a team according to the criteria laid out in the RFP. Careful review by very interested parties is essential to ensure that a good contractor is selected. One or more offerors would be requested to submit a "best and final offer" based on the details of the review and subsequent negotiations. Acceptance of an offer by the building owner signals the end of selection and the beginning of contracting.

Contract Documents

The statement of work from the RFP will be revised and become the statement of work for a construction contract. Contract documents involve many terms and conditions to make it clear how events or circumstances will be handled. For example, if it is determined during installation that a roof is in need of repair, who is responsible for that? The solar contractor or the building owner? Usually the building owner would be, and the roof repair would require a change order. The terms and conditions of the contract documents involve many important legal concepts including indemnification, payment bonds to insure that subcontractors will be paid, performance bonds to insure that the project is not left in an incomplete state, and statements of whether specific performance is required or if liquidated damages are paid when schedules slip or things go awry. It is essential here, when signing construction contracts, to have a well-proven document to start with, and full involvement and review of legal counsel.

Two common ways to structure the contract are "fixed price" or "time and materials" (also called "cost-plus" type contracts). In a fixed-price contract the building owner tries to make the contractor responsible for inaccuracies in the estimated cost and unforeseen circumstances that might delay work and increase cost. If the project is very simple and well understood, a fixed-price approach may result in competitive bids. But if there is any uncertainty in what it will cost to complete the project, a bidding contractor may either try to mitigate that risk by changing the contract language so that they are not responsible for it, or will have to charge extra to pay for that risk should it occur. In other words, with a fixed-price contract, you pay for contingencies whether they occur or not.

WARNING

Fraud in the Construction Industry

Fraud is endemic in the construction industry and solar is not immune. Examples of fraudulent contracting schemes that have surfaced on solar projects include:

- Accepting a down payment but then disappearing
- Accepting a down payment but then trying to find someone else to do it cheaper.
- Accepting progress payments but then not paying subcontractors.
- Paying cash to workers, thus avoiding income tax, employment tax, worker's compensation, and unemployment insurance.
- Inflating bills from subcontractors or forging invoices for cost-plus type contracts, or to claim a higher solar tax credit.
- Signing a request for an estimate that includes "office and legal" fees in addition to the cost of the estimate—and then fees ensue if you don't sign the contract.
- Theft from work premises, or personal information such as account numbers used improperly.

Solar companies are also cheated by fraudulent upper-tier contractors, suppliers, and even building owners. It is common for solar contractors to hear "you get paid when we get paid," from upper-tier or prime contractors, rather than to be paid according to the agreed-upon payment schedule. A building owner might inflate the cost to install a solar system in order to claim a larger rebate or tax credit, embroiling the contractor if there is a tax audit.

Investors in a manufacturer or installation company can also get ripped off—a PV company once sold its equipment and intellectual property to another company, profiting executives, but leaving investors with nothing.

Fraudsters prey on our own greed. They offer us deals that are too good to be true; and yet we believe them because we want to gain an advantage. The best defense against fraud is to check references. If the parties have a long track record of completing work on time and within budget, or paying for projects that they contract for, then that is the best indicator that they won't try to cheat. Recourse of a contractor against a building owner is a "mechanics lien," which gives the contractor an interest in the value of the improvements on the deed of the building. However, the best defense against fraud is prevention up front rather than relying on legal action to recover after damages have occurred, which is rarely fully effective.

Schematic Design

In a design-bid-build approach, the design is completed and then construction contractors bid on constructing that design. In a design-build approach, the installing contractor is also responsible for the design. Either way the design progresses through levels of decreasing options and increasing detail. Schematic design involves examining alternatives and doing an analysis to determine the size and type of major components. The design submittal includes drawings and equipment specifications, including a diagram, called a "schematic diagram," of all the major components and connections and interactions between the components and any existing building systems. The submittal would include the size and type of each component, any important component information such as efficiency, operating and control sequences, preliminary installation plan, and early identification of any safety procedures to involve or safety hazards to protect against.

This book should be useful in schematic design because it describes alternative ways to configure solar energy systems for electricity, hot water, or heating ventilation air and what major components are involved in such systems.

Design reviews should be conducted early in design, about halfway through design, and at the final design submittal. Comments from reviewers are only useful early in the design process; subsequent design steps only add detail to decisions already made. Reviewers should include building owner's representative, objective solar expert, operation and maintenance staff, utility staff regarding any utility interconnection, and the commissioning authority that will be responsible for commissioning throughout the duration of the project.

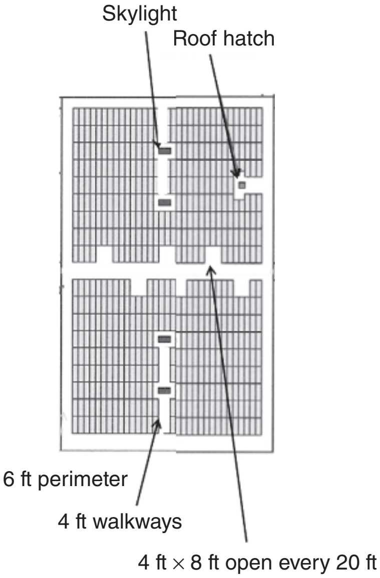


Figure 1-7. Leaving aisles open on the roof for access to existing equipment and skylights, and access required for firefighting, are considerations involved in locating the position of solar collectors on a roof during design development. (Figure by the author after those by US General Services Administration)

Design Development

Once the schematic design has been reviewed and agreed upon, the design team fills out detail according to the decisions made in schematic designs. Where the schematic design had size and type of components, design development adds specific manufacturers and model numbers. Design development reconciles all electrical or plumbing standards related to interconnections between components or control protocols used to communicate with components. The intention of design development is to add enough detail to the design, through narrative, drawings and specifications, so that anybody using those drawing would build the system the same way. Again, the developing design should be reviewed early in the process to confirm decisions before the design effort is expended filling out the details. For example, comments from a fire marshal would modify the access and laydown areas depicted in Figure 1-7 as the design is developed. A checklist to refer to when evaluating a design is included in (Stoltenberg and Partyka 2010).

Construction Documents

Once the design is completely developed, a final set of construction documents will be prepared by the design team. These consist of

- Narrative: text, photographs, and graphics describing the intent of the design
- Drawings: set consisting of site plan, roof plan, and structural, electrical, mechanical, plumbing, and controls drawings.
- Specifications: details of the requirements of each component.

This set of plans will be used for code compliance and permitting. There are no decisions remaining to be made in the preparation of construction documents—just adding detail regarding how the products are installed and connected. The installing contractor will begin construction using this set of plans, and will add shop drawings as particular assemblies are fabricated. The design team may also add "as built" drawings to reflect the details of the actual installation and any variances from the construction documents.

Construction Administration

Construction administration is a very detail-oriented profession. The construction manager will often stay on site and report back to the building owner regarding daily progress on construction activities. Proper timing and phasing is critical: equipment must arrive on site on time and needs to be installed in the right order. Financial damages may result if a subcontractor is not able to start work due to delays of another subcontractor. Upon failure of a window wall recently, the glass manufacturer blamed the mullion supplier, who blamed the installer, who blamed the window manufacturer. The construction manager must keep all the subcontractors working together as a team to deliver a successful project, so that they can all get paid.

The construction manager collects *requests for information* (RFIs) from subcontractors to clarify questions about how the design shall be implemented. The construction manager must also handle *change orders*, which are changes to the scope of work that result in changes to the schedule or budget. The owners may object to changes that cost more money, but quick resolution of disagreements is needed to keep the construction moving toward completion. All parties must be available or have delegates available to quickly respond during the construction period.

TIP

Change Orders and Requests for Information (RFIs)

During the construction process, the construction manager is busy requesting change orders and information from the building owner or design team. A change order is requested whenever any condition is encountered that was not expected in the RFP or in the contract. Say, for example, water damage to the roof deck is discovered during installation of solar collector roof mounts. The building owner may change the contract to pay the solar contractor for fixing the damage or may argue that repairing such damage was within the original statement of work and the contractor should fix it without additional pay.

It is a very common strategy among contractors to bid a low price, even lose money, to get the contract signed, but with the intention of making up for the low bid, and profiting more, with change orders as the project proceeds. Some contractors openly teach this tactic to their sales staff.

Requests for information are routine as long as they only seek clarification on design or building details, but they become contentious when the inquiry is to whether a lower cost material or component may be substituted.

Interview with Solar Project Manager Brett Jackson

Brett Jackson (pictured in Figure 1-8) manages solar energy projects as the Energy and Mechanical Engineering Program Lead for the Construction Facility Management Office of the Colorado Department of Military Affairs. He previously served as an Army Corps of Engineers officer. He has an undergraduate degree in mechanical engineering from the Colorado School of Mines and a master's in engineering management from the University of Colorado at Boulder. Additionally, Brett is a Professional Engineer, a Certified Energy Manager (CEM), a LEED-AP, and a Project Management Professional (PMP).

Figure 1-8. Brett Jackson at the Windsor Readiness Center, site of one of the solar energy projects that he is managing for the Colorado Army National Guard. (Photo by Michael Jaurrieta, courtesy of Colorado Army National Guard.)

The Colorado National Guard provides defense and emergency services in blizzards, floods, wildfires, search and rescue, and tornadoes. How does solar energy fit into that mission?

The Department of Defense has strategic sustainability goals aimed at lessening our dependence on foreign fossil fuels. In addition to energy load reduction, we feel that a renewable energy portfolio for energy source offset provides a robust approach to achieving this reduction. Regarding our mission to support the state and local communities during times of natural disaster, when the likelihood increases that power will be offline, we and the DOD are exploring ways to allow grid-connected PV systems that can remain operational when there is a loss of power.

What goals has the Colorado Army National Guard set with regard to renewable energy use, and how did you go about deciding on a goal?

The Colorado Army National Guard has established four sustainability action plans, one of which is centered on renewable energy generation. Through this action plan, it is our intent for our organization to be a net-zero electrical consumer by 2030. Our 2030 date was based on the Executive Order 13514 requirement that all federal buildings built by 2030 meet the net-zero-energy building requirement.

You've completed several solar projects—which are you most proud of and why?

We are very proud of our 172 kW PV system that was completed in August 2010 at our Grand Junction Field Maintenance

(continued)

Shop. This was our agency's first PV system and it was designed and built without a single change order. Additionally, what makes this PV system special is that when we built the maintenance building a few years before we installed the PV, we had designed into the building the necessary conduits as well as the upsized electrical switchgear, enabling all the PV project money to go into the PV panels and not into the building infrastructure. Through the efficient use of project funds, we were able to turn what was supposed to be a net-zero electricity system into a system that produces 20 percent more electrical energy than the building consumes.

What would you warn someone starting a solar project to watch out for?

When a solar project is being considered, be prepared to defend the project, as there will be many naysayers who raise objections that the project can't or shouldn't be done. Many times the solar project will be competing with other corporate projects/priorities. Complete a comprehensive life-cycle cost analysis and gain all the necessary stakeholders' involvement and support as early into the planning as possible. Finally, two items that can totally derail a solar project are an overestimation of the applicable electrical demand (kW) savings [as opposed to energy (kWh) savings] and also overestimating the payments obtained for Renewable Energy Credit (REC) payments.

Commissioning

Commissioning is formally confirming that a system is operating as intended, but the independent, third-party commissioning authority should be involved very early in design. First, the commissioning authority must fully understand the intent of the design, but also may add to the design in terms of instrumentation and controls required for monitoring and operation of the system. The commissioning authority should be involved in the review of each major design submittal (25 percent design, 50 percent design, etc). Standards related to commissioning of solar systems are described in each chapter (photovoltaics, solar water heating, and solar ventilation air heating), and they usually have three parts: physical inspection, solar array testing, and whole-system performance test. Physical inspection is to see that the system was installed as designed and that there are no mistakes in the installation. Of special interest in the inspection is to check that all specific code requirements and safety concerns that apply have been satisfied. This is facilitated with checklists that are specific to the type of system being inspected. Array testing measures the energy delivery of the array and the coincident solar radiation to assess the performance of each segment of the solar collector system, and the whole-system performance test tracks performance over a period of days to document all changes in modes of operation and overall solar delivery efficiency.

Long-term Monitoring and Verification of Performance

Some level of long-term monitoring is recommended for all projects. In order to deliver their cost-effectiveness, solar energy systems must operate for a very long performance period (25 to 40 years). Without some indicator of system performance, building owners would not know that their system is in need of repair.

Guidelines for the monitoring of solar energy systems describe several options, depending on the needs of the project participants (Walker et al. 2003). Options are described in four categories:

1. Determining the capability of the system to deliver solar energy as designed based on a detailed inspection of the system;
2. Measuring the energy delivery of the system with a meter;
3. Inferring the performance of the solar energy systems by analysis of utility bills; and
4. Calibrating a computer model of a solar energy system based on a short-term (one day) test.

There are different types of solar energy systems, but they have one thing in common that distinguishes them from energy efficiency measures—they supply energy rather than reduce energy use, and the supply, whether it is electric power, hot water, or heated air, may be measured directly with the right instrumentation. To meter the output of a solar energy system is thus the preferred monitoring option. The power delivery of each type of solar energy system may be measured as a flux multiplied by a potential:

- For photovoltaics, current (amps) is multiplied by the delivered voltage (volts), measured at the location that solar power is interconnected into the building power system.
- For solar water heating, it is mass flow rate of water, multiplied by the specific heat of water (kJ/s/C) and multiply by the temperature difference (C) between the cold water coming into the solar preheat system and the preheated water being delivered to the conventional water heating system.
- For solar ventilation air preheating, it is mass flow rate of ventilation air, multiplied by the specific heat of air (kJ/s/C) and the difference between the temperature (C) of the ambient air and the temperature of the preheated air

being delivered to a room or into the conventional ventilation air heating system.

- The measurement and verification program should be designed with an audience in mind. As much as possible reports should be "pushed" to interested parties: building owner, manager, utilities procurement contact, operations and maintenance managers, and even to the staff and visiting public through lobby displays.

INTEGRATION OF SOLAR ENERGY INTO THE EXISTING INFRASTRUCTURE

Solar energy systems must integrate into existing systems on many levels. First, there must be physical integration into the building, then there must be operational integration so that the solar energy system actually does result in the maximum amount of savings in conventional energy; and finally the solar energy system must be integrated into the larger utility system in such a way that the entire system is safe and reliable and economic benefit for the solar system owner is maximized.

Physical integration refers to space for the solar collectors on the roof, space for balance-of-system components within the building, and integrity of the structural connections. Operational integration refers to the performance of the system, such as feeding solar electric power into the building electrical system, preheating water for the conventional heating system, preheating ventilation air for the conventional ventilation air handler. For example, a gas-fired furnace would have to be controlled to allow a space to be heated by solar energy before heating it with gas. Making sure that intermittent and somewhat unpredictable solar energy delivery actually results in a commensurate savings of conventional energy requires some care in design and controls (in short, the conventional system must be modified and reprogrammed to step aside and let the solar energy system serve the demand first, and engage only if solar proves insufficient).

Grid-Integration: Effects of Intermittent Solar Energy Sources on the Utility System

Integration of solar energy systems into the larger utility grid is also a topic of much research currently. At very low levels of solar energy use (say, for example, 5 percent of a building's annual energy use), the conventional energy system could accommodate the intermittent nature of the solar energy without any problems. However, as solar projects on individual buildings get larger, and the number of buildings installing solar increases, there are increasing effects on the larger utility system that spans all the way from the local meter to the electric generation plant.

Impacts on the local meter include reverse power flow. If the building is served by multiple power feeds from multiple substations, as large buildings often are for reliability reasons, then there may be ”network protectors” to prevent a backflow of power from the building to the grid. These are often marked with an "NP" on building electrical drawings. Such an arrangement limits the size of the solar system to one which never exceeds the load or and may require a programmable inverter to curtail solar power and avoid tripping a network protector.

Impacts on the local distribution system include the potential for voltage fluctuations; problems with voltage regulation equipment, and reverse power flows. Electric current flows from a high voltage to a low voltage. In order to push their current onto the utility systems, multiple inverters on a circuit increase their voltage, causing a high-voltage condition.

Impacts on the transmission system include increase in the cost of reserve transmission capacity caused by uncertainty in forecasts in solar power generation. At times transmission may be insufficient to convey the solar power or inefficient in its scheduling. Generation resources without matching transmission capacity may be curtailed when transmission capacity is unavailable.

At the level of the electric generating system (power plants), the ability to respond to changes in the output of large amounts of solar energy on the grid is limited by the *ramp rate* of generation equipment. The ramp rate is how fast the output of the generator may be increased. Improved forecasting could inform power plant operators of when clouds will shade the solar generators in an area, so that they would know to ramp up conventional generators in advance of the need for the power. The potential for a sudden decrease in solar power requires an almost equivalent amount of *spinning reserve*. Spinning reserve is generating capacity that is already ramped up and ready to serve the load. Spinning reserve costs the utility money because it requires fuel to keep the generator spinning and maintenance required of the generator accrues by the hour not by the kWh. This is one of the arguments invoked by utilities as to why they shouldn't accommodate solar power or any intermittent generation. There are strategies discussed below to reduce the amount of spinning reserve required due to solar energy generators on the utility system during the day, due to intermittent clouds.

Utility system operation occurs at several time scales:

Power quality: Power quality refers to power factor (phase alignment of current and voltage waves), harmonic distortion (frequencies other than 60 Hz), and tolerances in voltage and frequency. The time scale of interest in power quality is less than one second. Electronic inverters are capable of delivering solar power to the utility with a power quality equal to or better than that of the utility grid as a whole.

Regulation: As the demand load (kW) on the electric system varies, the output of generators is controlled in order to maintain voltage and frequency. This occurs at a scale of seconds.

Load following: The output of a generator or system of generators is modulated in such a way to supply whatever load is imposed by utility customers at the time. This occurs at a scale of seconds and minutes. Forecasting the output of a solar plant through sky observation, modeling, or conventional weather forecasting provides advance notice that additional generation is required from other generators in order to meet the load.

Cyclic charging and discharging of storage: this is of principal importance in off-grid systems (using batteries) that don't have a utility connection where storage to serve several days of load is required, but is also conceivable in a large utility system. Intermittent solar energy could be put into storage and used later. Large battery systems are common in utility systems, but at large power levels they cycle in short time periods (minutes). In a sense, some measures to improve power quality involve storage, such as the capacitors to improve power factor. These have time-scale of 1/50 or 1/60 seconds, and storage is also very useful at longer time-scales: sub-seconds; minutes; hours; days; and even seasonal. Pumped-hydro storage is an example of a utility-scale storage that can store energy for a long period of time.

Unit commitment: As far in advance as is practicable, a combination of generators is planned to provide the expected load profile (kW over time). This planning of generators (also called *units*), is called *unit commitment*. Sophisticated computer algorithms to accomplish this planning have the objective of minimizing operating costs. Generators are scheduled to operate days, weeks, and years ahead, depending on the type of generator and the load profile. It is difficult for solar to play in this market because units are committed in advance and with a specified high level of certainty that the power can be delivered at the specified time. Forecasting the output of solar plants hours or days in advance is a technology that will enable solar plants to make some level of commitment to deliver power at a specified time.

All of this is conducted with the objective of minimizing cost for the utility system to deliver the energy, the reliability, and the environmental stewardship required by customers and regulators.

Utility Regulatory Policy

Utility companies provide a vital service to society. It is impractical to serve every customer with competing utility companies, and yet reliable energy is essential for survival in many climates. So governments allow utilities to operate as monopolies; and to prevent abuse, governments subject utilities to regulations, including how much they can charge for energy. The process of regulating them plays out in hearing rooms of state Public Utility Commissions (PUCs) across the country. Present in those hearing rooms are commissioners appointed by the governor of each state, their staff, the utility company, lawyers hired by large industrial energy users, lawyers hired by environmental groups or other "interveners" in a case, and a lawyer provided by the state representing consumers—each arguing why they should be entitled to more of the benefits of utility company operations and less of the cost. To "rate-base" a cost means the utility will collect that cost from all the ratepayers rather than only from those that benefit directly. If you are not in that hearing room…well then…you get what you deserve. The process only approximates fairness. For example, an environmental group might convince the commission to rate-base free energy efficiency audits for buildings; but the commission might then allow the utility company rather than the building owner to select the audit firm, thus broadening the hegemony of the utility and putting other firms that must charge building owners for audits out of business.

How does solar fare in this fray? Actually pretty well in many states, at least initially. Most solar projects these days benefit from a rebate ($/Watt) or production incentive ($/kWh produced by a solar energy system) paid by the utility in pursuit of goals set by regulators. These goals are often in the form of a "Renewable Energy Portfolio Standard" (RPS), which specifies that the utility companies operating in a state get a certain fraction of their energy from renewable energy. In order for this to benefit solar, which is often more expensive than wind, there has to be a "solar set aside" that ensures some of this goal be met by solar energy systems. Utilities have found that they can profit from this by installing their own solar power on their side of the meter. This results in large utility-scale plants to meet the regulatory goal. In order to promote "distributed generation" on each load, a program may require that the utility pay others an incentive to complete smaller projects in distributed locations.

Net Metering

"Net metering" is a utility policy that allows a solar energy system to deliver power in excess of the building load into the utility distribution system. Then, when the building load exceeds the solar delivery, the building draws power back from the utility. The monthly utility bill is calculated based on the difference between these two. Thus, in terms of the cost, net metering is like using the utility system as a battery but one that is 100 percent efficient and free. The benefit of net metering is that solar power generation saves fossil-fuel generators some fuel; but the savings in fuel might be less than the solar energy delivery due to less efficient operation of the generator plant. Fuel savings is about the only benefit of the solar power—it doesn't save any other utility operating costs. Once a large number of buildings on a utility circuit install large solar energy systems, there is no more load on that circuit to use additional solar power, and the solar generation may need to be curtailed. For example, Hawaii limits solar generation to 15 percent (up from previous 10 percent) of the peak load on a utility circuit without a special study

Interview with Solar Advocate Renee Azerbegi

Renee Azerbegi (Figure 1-9) was president of the Colorado Renewable Energy Society at a time when the state's constitution was amended to require a renewable energy standard with an amount set aside for solar energy in particular. She earned a bachelor of science in environmental science and geography from University of California at Berkeley and a master's in engineering from University of Colorado. She is now president of Ambient Energy Inc., a company providing energy modeling, sustainability ratings, and professional services for buildings.

Figure 1-9. Reneé Azerbegi was president of the Colorado Renewable Energy Society when the state's constitution was amended to require utility companies to utilize solar energy. (Photo by the author.)

What is a Renewable Energy Portfolio Standard?

It's a requirement that the power producers in a state use at least some fraction of renewable energy. Under Amendment 37, which passed in 2004, the state's largest electricity providers were to obtain 10 percent of their power from renewable energy resources by 2015, with 4 percent of this coming from solar electric sources. The measure also required qualifying utilities to offer customers a minimum rebate of $2 per watt for solar electric generation, provided incentives for utilities to invest in renewable energy resources that provide net economic benefits to customers, and limited the retail rate impact of renewable energy resources to 1 percent of the total electric bill annually for each customer of a qualified retail utility. This measure plus the federal solar tax credits jump-started Colorado's solar power industry. More recently the requirement was raised to 20 percent renewable energy by the year 2020.

How were you involved in Colorado's renewable energy portfolio standard?

I was president of the Colorado Renewable Energy Society (CRES) in 2004 when Amendment 37 passed. CRES played a major role in supporting Amendment 37. The authors of Amendment 37 included lawyer Ron Lehr, representing CRES, and lawyer Rick Gilliam, representing Western Resource Advocates, and others.

What do you mean by "Amendment 37"?

Colorado is unusual among states because it is possible for citizens to sign a petition to put an amendment on the ballot, and amend the state's constitution if it is passed by a vote of the people. Amendment 37 is a ballot issue that voters approved in 2004 to establish a renewable energy standard for the State of Colorado.

Why was the passage of Amendment 37 unique?

This was the first voter-backed renewable energy measure with a solar set-aside (a specific goal for solar energy)] in the United States.

Why did you have to do a constitutional amendment—aren't there easier ways to change the law?

Despite the best efforts of a few legislators from both political parties who introduced bills, and despite constituents telling them they wanted solar power, the Colorado state legislature voted down standards in three separate attempts in three years. Inexplicable. Coloradoans want cleaner air and more renewable energy jobs. So we took it to the people in the form of a constitutional amendment. It was a hard-fought campaign. The utility company spent over a million dollars on television advertisements which included menacing black clouds and thunder and lightning. The solar energy industry contributed about $70,000, and the wind industry contributed about $45,000 to promote the measure. A lot of the advocacy of the measure was grass-roots. We weren't downtown [Denver] the night the ballot measure passed, and the level of excitement was awesome. It became Amendment 37 to the Constitution of the State of Colorado.

You must have made enemies in the legislature by going around them to their boss—the people.

On the contrary, we found a lot of new friends in the legislature. In March 2007, the Colorado legislature adopted and the governor signed HB 1281, which increased the renewable energy requirement to 20 percent by 2020 for investor-owned utilities, and increased the number of utilities involved by including all rural electric cooperatives.

documenting the impacts of the solar generation on the local circuit and the larger utility system. Net metering also introduces a socioeconomic problem because it foists more of the cost of operating the utility on those least able to afford it—rich people install enough solar to bring their utility bill to zero, yet still use the utility power on a daily basis under a net-metering arrangement. Those unable to afford an expensive solar energy system are saddled with a higher bill.

So we understand net metering to be an incentive offered by utilities for solar energy systems at the expense of other ratepayers. In addition to this economic reason there are also technical reasons why not everyone can net-meter. Thus net metering is not the long-term solution for integrating large amounts of intermittent solar energy resources onto the utility system. In order to ease the economic constraints to net metering, there are several cost-recovery measures that a utility could take, including a “wholesale” or “buy-back” rate (c/kWh) that is lower than the retail rate for power. In other words, the utility may sell power according to their rate schedule but pay for power put back on their system at only the “avoided cost” that they actually save as a result of the solar power. The utility may also charge “stand-by charges” ($/kW/month) to pay for the utility infrastructure (distribution, transmission, generation, spinning reserve) that supports your building regardless of your solar generation.

Technically, net energy metering solves the *thermodynamics* problem of where energy (kWh) comes from and where it ends up, but not the *transport phenomenon* concerning volts, amps, frequency and waveform delivered where and precisely when. These details are the topic of the next section.

Predicting and Achieving Utility Cost Savings (Performance Simulation)

It is easy to overestimate the utility cost savings associated with a solar energy system. First, the system must be configured to physically save energy. For example, a solar water heating system must be configured to heat the cold water coming in before it mixes with water that has already been heated by conventional fuels. Then, the actual effect of this energy delivery on the cost of operating the energy system must be evaluated. It is not possible to put a value on the energy delivered by a solar energy system without considering the entirety of the utility bill and the details of the applicable utility rate schedule. In order to calculate the energy cost savings of a solar energy system it is necessary to calculate the utility bill with and without the contribution of the solar energy system.

Time-series simulation is often used to predict the energy delivery of a solar energy system under changing conditions (sunlight, temperature). In time-series simulation, the state of the system and associated energy delivery are calculated in the first time-step, and the results of that calculation become the initial conditions for the next time-step. By sequencing through all the time-steps in an analysis period, an integration of the power quantities (kW) over time (hours) gives the energy savings (kWh) and cost savings ($/month, $/year) associated with a solar energy project. Most computer programs use time-steps of one hour and an analysis period of one year, so they perform energy balance calculations for each of the 8,760 hours in a year (24 hours/day*365 days/year). Some accuracy is achieved by doing the solar analysis in small time-steps such as hourly. Solar resource information, such as that in Typical Meteorological Year (TMY) weather files, reports solar energy incident on a surface in an hour, in units of kWh/hour. A typical value for this data in an hour may be 500 Wh/m^2/h, for example. Three alternative interpretations of that value are presented here:

(a) Most hourly simulation programs (HOMER, SAM, TRNSYS, each to be discussed later in the chapter) interpret this to be mean a power of 500 W/m^2 incident for the full hour, as illustrated in Figure 1-10a. This would accurately state the condition under overcast sky, when the solar radiation is not changing with time. It would also represent effect of the angle at which the sunlight would hit the surface of a solar collector that was in a fixed position, which would not change by much over the hour.

(b) A second approach interprets the energy in an hour as a specified power level of a solar energy system (the rated power level, kW, associated with full sun) and a fraction of the time (hours) that the system delivers this power, so a value of 500 Wh/m^2/h from the weather data would be interpreted as 1,000 W/m^2 for only half of the hour, such as shown in Figure 1-10b. This method, used in the REO computer program (Walker 2009a), is convenient because solar energy products are rated considering a solar intensity of 1,000 W/m^2. This method would be accurate under partly cloudy conditions, when a solar collector is either in full sun or fully

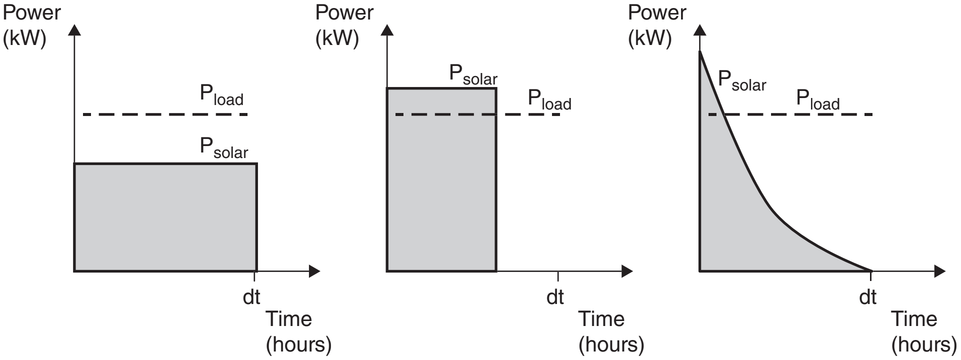


Figure 1-10. Three alternative ways of considering the same energy delivery (kWh) within a time-step: **(a)** solar power is constant over the full time step; **(b)** solar power is at a rated value for a fraction of the time step; and **(c)** solar power varies as the distribution of Equation 1-6 within the time step. (Figure by the author)

shaded by a cloud. It would also represent solar collectors that track the sun as it moves across the sky. The reason we are limited to these two alternatives is that we only have one number as input: the amount of solar energy in the hour (in kWh/m^2/hour). So we can solve for only one unknown, which is the power level (kW) in the first alternative or the fraction of time (hours) in the second alternative.

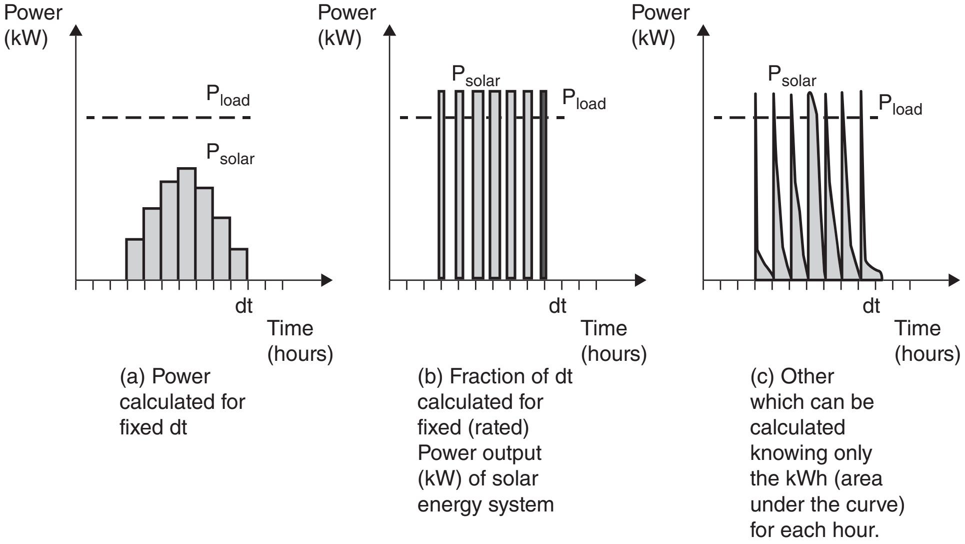
(c) A third alternative is to use a distribution, as shown in Figure 1-10c. Since we only have one equation (the kWh for the hour), our distribution must also involve only one unknown. The value of the actual power output of a solar energy system, P_{solar} (kW), depends on the underlying solar resource at location and may be displayed as a "duration curve" which show the value of the power output of a solar system of rated size P_{rated} (kW) over a time period T (hours). P_{rated} may be thought of at this point as the maximum output under full-sun, but will have more specific definitions in subsequent chapters. An equation that agrees very well with empirical duration curves for how power, P_{solar}, varies over the time period T, is given by the distribution

$$P_{solar} = P_{rated}\,(1 - (t/T)^n) \tag{1-6}$$

Where t/T is the fraction of time through the time period, from a minimum of $t/T = 0$ to a maximum of $t/T = 1$. For solar energy generators that are powered by sunlight, only the 4,380 daytime hours in a year are included and $T = 4380$. Conservation of energy (First Law of Thermodynamics) requires that the coefficient $n = CF/(1\text{-}CF)$, where CF is the "capacity factor" for a given location. The capacity factor is derived from solar or wind resource data at a location and is reported in the resource databases described in Chapter 2 of this book. To relate this to the 500 Wh/m^2/h resource number that we used as an example above, 500 Wh/m^2/h would equate to a capacity factor of 0.5 if the rated power level, or "capacity" is associated with full sun at 1000 Wh/m^2/h. All three figures 1-10a, 1-10b and 1-10c have the same value of the capacity factor, and it is illustrated as the area under the curve divided by the whole area of the diagram. In 1-10a capacity factor is the fraction of the rated capacity for the hour; in 1-10b it is the fraction of the hour at rated capacity; and in 1-10c it is a distribution which splits the difference between these extremes.

The area (kWh) under all three of the curves of Figure 1-10 is the same, but the curves bear some important differences—in (a) the solar energy is used fully on-site, as the solar power never exceeds the load; in (b) solar energy is generated in excess of the load for part of the time-step, but not generated for the remainder of the time-step; and in (c) the distribution splits the difference between these two extremes, with the solar power exceeding the load for a small fraction of the time-step. Power in excess of the load could be sold back to the utility, could be saved in batteries, or could be wasted. Thus, while the three alternative ways of looking at the curve of kW versus hours within a time step all yield the same delivery of solar energy (kWh), they may have different operational effects and utility cost savings associated with them. The first assumption of constant power within each timestep is suitable only for short timesteps as is used in all of the hourly simulation programs currently available. The second method of assuming fixed power for a calculated fraction of the time-step provides acceptable accuracy at longer time-steps and has been used for time periods as long as one-half day in the REO computer program. The third method of using the distribution maintains accuracy with timesteps up to a full year under some circumstances, and then $T = 8760$ hours where 8760 is the number of hours of a single year.

Figure 1-11 shows what an hourly simulation would look like for a 12-hour day using each of the three alternative treatments



(a) Power calculated for fixed dt

(b) Fraction of dt calculated for fixed (rated) Power output (kW) of solar energy system

(c) Other which can be calculated knowing only the kWh (area under the curve) for each hour.

Figure 1-11. Construction of an hourly simulation for one day showing alternative assumptions: **(a)** calculated power level for fixed time; **(b)** calculated fraction of time for fixed power level; and **(c)** a distribution with the same area (same kWh) as the first two. (Figure by the author) of Figure 1-10. In each case, what we know is the kWh/m^2/hour of incident solar power for an hour, and then we infer either: (a) a calculated power level for the fixed period of time dt (one hour); (b) a calculated fraction of time for a fixed power level (rated kW); or (c) a distribution which also has only one variable. All three of these profiles accumulate the same number of kWh in the day.

Once the power serving the on-site load (P_{load} or P_{solar}, whichever is less) and the power sold back to the utility or put into a storage battery ($P_{\text{solar}} - P_{\text{load}}$) are ascertained by assuming one of the profiles of Figure 1-10, we may integrate from time-step to time-step over the duration of the analysis period (usually hourly simulation for one year, 8,760 hours) to calculate total energy purchased from the utility:

$$E_{\text{from utility}} = \int_0^{8760} Max(0,(P_{\text{load}} - P_{\text{solar}}))\,dt \tag{1-7}$$

And total excess energy sold back to the utility over the analysis period

$$E_{\text{to utility}} = \int_0^{8760} Max(0,(P_{\text{solar}} - P_{\text{load}}))\,dt \tag{1-8}$$

Where P_{load} is the rate at which power is consumed on-site (kW), on the customer side of the utility meter. The utility cost savings or revenues associated with each of these would have to be integrated, similarly over the 8,760-hour year, by calculating the utility bill with and without solar energy, using the details of the utility rate schedule.

The time period T is arbitrary, but needs to be small if we assume a constant output power from the solar system. If we assume the distribution profile (c in Figure 1-10), then we can maintain an acceptable accuracy at time periods up to one year. Here assume the time period T to include only the 4380 daytime hours of the year- then power purchased at night must be calculated separately and added to this to the total to account for all of the power purchased from the utility. The load, P_{load} (power requirement), is taken to be constant, limiting the application of this simplification to those with constant demand. Substitution of Equation 1-6 into 1-8 and integrating gives an equation for energy sold back to the utility

$$\begin{aligned} E_{\text{to utility}} &= (P_{\text{rated}} - P_{\text{load}})Te^{(ln(1-\frac{P_{\text{load}}}{P_{\text{rated}}})/n)} \\ &\quad - \frac{P_{\text{rated}}}{T^n(n+1)}\left(Te^{(ln(1-\frac{P_{\text{load}}}{P_{\text{rated}}})/n)}\right)^{(n+1)} \end{aligned} \tag{1-9}$$

And substitution of 1-6 into equation 1-7 and integrating gives the expression for energy purchased from the utility when solar is insufficient to meet the load.

$$\begin{aligned} E_{\text{from utility}} &= (P_{\text{load}} - P_{\text{rated}})T + \frac{P_{\text{rated}}T^{(n+1)}}{(n+1)} \\ &\quad -(P_{\text{load}} - P_{\text{rated}})t_{lm} - \frac{P_{\text{rated}}t_{lm}^{(n+1)}}{(n+1)T^n} \end{aligned} \tag{1-10}$$

TIP

Calculating Cost Savings: Utility-Bill Analysis

Many hand calculations and computer programs multiply calculated solar energy delivery (kWh) by a value for delivered solar power ($/kWh) in order to calculate utility cost savings ($). But that is fundamentally incorrect and there is only one way to calculate utility cost savings associated with a solar project: calculate the utility bill **with** and **without** solar using the same calculation that the utility would use to calculate your bill. Utility rate schedules are often complicated, involving time-of-day, seasonal rates, demand rates ($/kW peak demand), and block rates ($/kWh for the first block of kWh, then less). The value of the solar energy delivery can be evaluated only in the context of the overall utility bill for a building.

In Equation 1-10, t_{lm} is the time period that P_{solar} exceeds P_{load}, and is found by setting P_{solar} equal to P_{load} in Equation 1-6 $t_{lm} = T(1 - P_{\text{load}}/P_{\text{rated}})$^(1/n).

Optimizing the Size of a Solar System

So we see that the economic returns diminish as we satisfy larger fractions of the energy demand with solar, and it is rarely cost effective to meet 100 percent of a load with solar. Solar systems are too often sized with only a "sweet spot" in mind, such as meeting the daytime demand (kW), meeting the average daily load (kWh/day), or a size that maximizes an available incentive payment. A more careful approach to sizing and design of a solar system would be to use optimization techniques to determine the size that minimizes life cycle cost while still meeting all the design criteria and constraints of a site. The objective is to minimize life cycle cost; the variables are design parameters such as solar collector area, battery or thermal storage volume; and constraints customize the problem for the situation including such things as maximum budget, maximum available roof area, and goal of some minimum fraction of energy use from solar. For an example of optimizing four design parameters of a residential solar water heating system (solar collector area, storage tank volume, heat exchanger area, and circulating fluid volume) to minimize life cycle cost see (Walker, 1991). Optimization techniques that have been used to size solar energy systems include calculus, linear programming and non-linear search techniques.

OPTIMIZATION USING CALCULUS (DERIVATIVE EQUAL TO ZERO)

This approach uses analytical methods (fundamental theorem of calculus) rather than numerical methods to determine the size (capacity, kW) of a renewable energy generator, P_{rated} (kW), that minimizes life cycle cost. We seek the value of P_{rated} that satisfies that condition:

$$\frac{dLCC}{dP_{\text{rated}}} = 0 \tag{1-11}$$

Utility energy cost savings are most often evaluated by time series simulation using a computer, but we can proceed with a simple hand calculation by assuming a very simple utility rate schedule consisting only of two rates: c_{retail} = retail cost of utility electricity paid for energy from the utility (\$/kWh); and $c_{wholesale}$ = wholesale price received for electricity sold back to the utility. Life cycle cost is the sum of initial cost, $C_{initial}$ (\$/kW) times P_{rated}, plus the present value of operation and maintenance costs and the present value of costs involved with purchasing power from the utility company and revenue from the sale of excess electricity back to the utility

$$\begin{aligned} LCC = {} & C_{initial}P_{rated} + C_{O\&M}P_{rated}PWF \\ & + C_{ratial}E_{from\ utility}PWF - C_{wholesale}E_{to\ utility}\ PWF \qquad (1\text{-}12) \end{aligned}$$

Where $C_{O\&M}$ (\$/kW/year) is the cost to operate and maintain the system per-year, per kW of rated capacity. Substitution of equations 1-9 and 1-10 into 1-12 and taking the derivative with respect to P_{rated} produces the expression that will be set to zero to ascertain the optimal value of P_{rated} that minimizes life cycle cost.

$$\begin{aligned} & \frac{dLCC}{dP_{rated}} = 0 = (C_{pv} + (C_{O\&M}*pwf) + (c_{retial}*pwf*((T*(-1 + \\ & ((1 + n)\hat{}(-1)) + EXP((LN((1 - (P_{load}/P_{rated})))/n)))) - \\ & ((P_{load} - P_{rated})*T*((((1 - (P_{load}/P_{rated}))*n)\hat{}(-1))*P_{load}*(P_{rated}\hat{} \\ & (-2))*(EXP(LN((1 - (P_{load}/P_{rated})))/n)))) - ((T\hat{}(-n))/(1 + n)* \\ & ((T*EXP((LN((1 - (P_{load}/P_{rated})))/n)))\hat{}(1 + n))) - (P_{rated}* \\ & (T\hat{}(1 - n))*((T*EXP((LN((1 - (P_{load}/P_{rated})))/n)))\hat{}n)* \\ & (((1 - (P_{load}/P_{rated}))*n)\hat{}(-1))*P_{load}*(P_{rated}\hat{}(-2))*(EXP(LN \\ & ((1 - (P_{load}/P_{rated})))/n)))))) - (cwhsl*PWF*((T*EXP((LN((1 - \\ & (P_{load}/P_{rated})))/n))) + ((P_{rated} - P_{load})*T*((((1 - (P_{load}/P_{rated}))*n)\hat{} \\ & (-1))*P_{load}*(P_{rated}\hat{}(-2)*(EXP(LN((1 - (P_{load}/P_{rated})))/n)))) - ((T\hat{} \\ & (-n))/(1 + n)*((T*EXP((LN((1 - (P_{load}/P_{rated})))/n)))\hat{}(1 + n))) - \\ & (P_{rated}*(T\hat{}(1 - n))*((T*EXP((LN((1 - (P_{load}/P_{rated})))/n)))\hat{}n)* \\ & (((1 - (P_{load}/P_{rated}))*n)\hat{}(-1))*P_{load}*(P_{rated}\hat{}(-2)*(EXP(LN((1 - \\ & (P_{load}/P_{rated})))/n))))))))) \qquad (1\text{-}13) \end{aligned}$$

This is a transcendental equation, which means that the variable P_{rated} appears both in exponential terms and as a product multiplied by the exponential term, and may be solved by iteration (guess a value of P_{rated} and check to see if the equation equals zero, if not guess a higher or lower value), or software products, such as the "goal seek" function in Microsoft Excel spreadsheet may solve for P_{rated}.

Example Calculation of Optimal Solar System Size

TABLE-1. EXAMPLE OF DETERMINING THE SIZE OF A PV SYSTEM USING CALCULUS OPTIMIZATION TECHNIQUES.

Site	Athens GA
Load, P_{load} (kW)	3
C_{pv} (\$/kW)	\$2,670
$C_{o\&m}$ (\$/kW/year)	\$8.50
PWF (years)	22.03
c_{retail} (\$/kWh)	\$0.12
$c_{wholesale}$ (\$/kWh)	\$0.06
CF	0.35
T, Time period (hours)	4380
Total Hours per year	8760
n, Equation 1-6	0.54
P_{rated} (kW), Equation 1-13	6.52
Energy to Utility (kWh) Equation 1-9	1,714
Energy from Utility (kWh) Equation 1-10 (T = daytime hours only)	4,865
Total load, L*8760 hours (kWh)	26,280
Life cycle cost Equation 1-12	\$63,950

Here we consider a constant load of 3 kW in Athens, Georgia (Table 1.1). The solar resource experts tell us that the capacity factor for solar photovoltaics feeding power to the utility grid is CF = 0.35 based on daylight hours (T=4380 hours). The utility charges \$0.12/kWh for every kWh provided and pays \$0.06/kWh for every kWh put back onto the utility system by the PV system. The cost of PV is taken at C_{pv} = \$4.00 per Watt, but minus a 30 percent tax credit resulting in \$2.70/W. Maintenance costs, $C_{O\&M}$ for this simple grid connected system without batteries is taken at \$8.50 per kW per year. The present worth factor of 22 years corresponds to a 5 percent discount rate and a 4 percent inflation rate for 25 years. Equation 1-13 is typed into a cell of a Microsoft Excel spreadsheet and solved using the "iteration" feature of Excel. The optimal size of the system is found to be P_{rated} = 6.5 kW. From this we can calculate the initial and maintenance costs as well as utility costs and life cycle cost.

OPTIMIZATION USING LINEAR PROGRAMMING

Linear programming refers to computer programs which solve a system of simultaneous equations to explicitly calculate the optimal solution. The objective function of life cycle cost and each of the constraints are written as linear equations of the design variables to be optimized. This requirement is accommodated by making curved dependencies piecewise linear. For example, a curve of cost versus size might be approximated by three straight-line segments. Governing equations (such as conservation of energy) are coded as constraints that must be satisfied within the system of linear equations. These equations result in three matrices: one for the coefficients associated with each of the design variables; a second for the design variables themselves; and a third for the values of the objective function. Matrix inversion or iteration is used to solve for the matrix of the design variables that minimizes life cycle cost and satisfies all the constraints. Branching logic of multiple solutions accommodates binary variables that are not linear (solves the linear algebra problem for each possible permutation of the other variables that have binary or discrete values). Researchers at NREL have used this approach in the REOpt computer program to provide a recommendation for sizes of different renewable energy technologies (solar, wind, biomass, and so on) for a given load and conditions (NREL 2013).

OPTIMIZATION USING NONLINEAR SEARCH TECHNIQUES

If I formulate the solar design problem as it naturally comes to me, it involves a lot of non-linear, non-smooth, and discontinuous functions in the calculation of life cycle cost, so linear programming techniques are hard to implement and abstract. Many search techniques have been devised to try to find an optimal value among non-linear equations. Three that I have experience with are exhaustive search, gradient-reduction method, and evolutionary method. Exhaustive search refers simply evaluating all the possible sizes of a system or component to determine the value that minimizes life cycle cost. The HOMER computer program takes this approach by evaluating all the possible permutations of component sizes that the user specifies. Gradient reduction method refers to calculation of a derivative, but unlike the calculus method described above which explicitly calculates the optimal size in closed form equation, the gradient descent method uses the gradient (derivative in multiple dimensions) to inform a better solution and iterates until convergence criteria are satisfied. Evolutionary search technique has usefulness in my opinion because it can be set to try a very large number of solutions across the entire domain of the search, thus finding close to the optimum. It tries different combinations of variables in solutions that improve until convergence criteria are met. An example of convergence criteria is that the life cycle cost changes by less than 1 dollar in 5 sequential iterations. None of these search techniques is perfect. They all have advantages and disadvantages in certain applications. Non-linear optimization is not for the faint of heart. I often use the evolutionary algorithm to find a near-optimum solution, and then the gradient descent algorithm to make the recommended solar system size more exact. Both of these methods are available as free add-ins to the Microsoft Excel spreadsheet program and they are also sold as separate programs (for example: Premium Solver by Frontline Systems www.solver.com). The Renewable Energy Optimization (REO) spreadsheet computer program has used these optimization techniques to recommend solar system sizes that minimize life cycle cost for dozens of facilities including manufacturing plants and military bases (Walker 2009a).

Strategies for Maximizing Integration of Solar Energy with Conventional Utilities

Operational measures and changes to existing electrical and fuels systems will be needed in order to accommodate increasing amounts of intermittent and distributed solar energy. Following are strategies to incorporate more solar energy into the conventional utility energy system.

ACCOMMODATE A TWO-WAY FLOW OF ELECTRICITY AND INFORMATION

The existing utility transmission and distribution system was designed to distribute power from central power plants to users. The system involves loops, or more than one electric circuit to a facility, so the utility circuits are equipped with “network protectors” that prevent a flow of electric power in the reverse direction, which might be indicative of a fault (if power comes back it thinks it has a fault with another utility circuit). With distributed generation, the system must be modified to allow power to flow both ways: from the utility to energy consuming systems of a building and from the rooftop solar system back into the utility. There would also have to be a two-way flow of information and control. This will require much more automated data processing and active controls than today’s rather inert system.

RECONFIGURE UTILITY CIRCUITS

Utility circuits may have to be reconfigured to allow excess solar generation on one utility circuit to be used on another circuit. This will involve additional switchgear and legs between circuits in utility substations. For example, a housing area with solar on every roof but very little electricity use during the day (parents at work; kids at school) would be configured to send power back through a substation and on to commercial or industrial loads during the day.

DEMAND RESPONSE

Demand response is the control of some loads, turning the load off or down if necessary. Demand response may be used to limit any sudden transitions in the load on the conventional system due to the intermittency of the solar resource. A noncritical load could be turned off when the solar energy is interrupted, and then turned back on again as a conventional generator’s output is ramped up. This reduces the need for spinning reserve. An example would be cycling the heating elements of electric water heaters so that 25 percent of them are off at a time—the demand would be controlled but the energy would eventually be delivered and no one would even notice.

SPATIAL DIVERSITY

Solar energy systems spread around an area, such as a city, have a much steadier output than a single system all in one place, due to the scattered nature of clouds.

FORECASTING

Forecasting the output of solar power systems hours or days in advance based on weather forecasts, modeling, or sky observations can give advance notice that conventional generators will need to be started to make up for a drop in solar output due to approaching clouds. This advance notice reduces the requirement for spinning reserve.

DIVERSITY OF RESOURCES

It is a myth that there is one central solution that is best for all. Rather, a diversity of generation resources (solar, wind, fossil, hydro, etc.) is most robust. Overreliance on any one energy generation resource results in operational and economic problems and increases the risk of catastrophic failure.

TRACKING SOLAR COLLECTOR MOUNTS

Tracking mounts that follow the sun as it moves across the sky produce a steady output that does not fluctuate with sun angle. Moving the solar collector to face toward the sun provides essentially the same output from sunrise to sunset, removing one of the major sources of fluctuation in the solar resource (the other one being clouds).

ISOLATE CRITICAL CIRCUITS

Important loads that require a higher reliability may be isolated in order to serve them with available power first and exercise demand control over less important loads.

ENERGY STORAGE

A means to store solar energy, either as electrical battery or tank of heated fluid, and either at the location of the solar energy system or in a central location, would couple the intermittent solar energy delivery to the load. It is not feasible to store solar energy over from summer to winter, but it is quite possible to store enough solar energy to serve the load while a conventional generator is started (minutes) or to increase the output of a thermal power plant (hours) or to store solar energy for use overnight or even over a period of three to five days. Even a small amount of storage increases the value of the solar energy and smoothes the integrations with conventional systems substantially. Energy storage will be required in the grid of the future. Very short term storage (capacitors) controls voltage and power quality; storage of a few seconds (compressed air/hydraulic motor) could smooth transitions; storage of a few minutes (ultracapacitors, batteries) provides enough time to start or ramp up the power from other generators; storage of a few hours (batteries, flow batteries) enables peak-shifting, demand response, and storage of the intermittent renewable energy resource. Storage of end-use product is often more efficient that electric storage. Examples include storage of chilled water for cooling; hot water for heating; or pumping water for livestock into a tank only when the sun is shining. Storage of energy for days or from summer season to winter season would be very desirable for solar energy development, but lacks feasibility due to the scale of the storage—thus we may expect fossil fuel or nuclear to be in our energy mix for a very long time, but full use of solar energy can extend their supply and reduce their environmental impacts.

Example of Solar Storage

Sacramento Municipal Utility District (SMUD) initiated an 18-month trial on 42 homes in Rancho Cordova, California. The demonstration project provides each of 15 homes with one lithium ion (Li-ion) battery that is a 2-foot cube providing 3 hours average load, and costing $25,000 each. The project also installs three larger Li-ion batteries, each a 4-foot cube costing $75,000 to store energy for 27 more homes in groups of 9. Assistant General Manager for Power Supply and Grid Operations Paul Lau said “want to see what benefits SMUD gains from load-shifting and having the batteries and rooftop PV available to smooth out our load” (SMUD 2012).

Microgrids

Microgrid strategies provide the flexible configuration and control to operate a system regardless of the state of the utility or any individual generator. These strategies also provide the ability to transition between modes and respond to dynamic and transient events. Microgrid controls maintain required frequency and voltage levels; disconnect and seamlessly resynchronize with the grid; start with no utility power (“black start”); control loads by interfacing with system control and data acquisition (SCADA) and energy management and control systems (EMCS); and control of the output of generators, such as the solar energy systems. Microgrid research is not into any particular technology, but how various energy technologies may be integrated by smart controls.

The most important thing for now regarding integration of solar energy into the utility system is to involve the utility early in the planning of your solar energy project. The utility will study how the proposed project impacts reliability and integrity of the utility grid system. Backup and standby requirements imposed by utilities will probably increase with increased use of intermittent solar energy.

REFERENCES

Butti, Ken, and John Perlin. 1980. *Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto, CA: Cheshire Books.

Lissel, Lars, Tim Tetrault, and Andrea Watson. 2009. *Solar Ready Buildings Planning Guide.* Technical Report NREL/TP-7A2–46078. Golden, CO: National Renewable Energy Laboratory.

Mangano, Joseph J., and Janette D. Sherman. 2012. “An Unexpected Mortality Increase in the United States Follows Arrival of the Radioactive Plume from Fukushima: Is There a Correlation?” *International Journal of Health Services* 42:47–64.

NABCEP. 2011. *PV Technical Sales Job Task Analysis*. www.nabcep.org. (August 8). www.nabcep.org/wp-content/uploads/2011/08/NABCEP-PV-Technical-Sales-JTA-8-8-11-Web.pdf (accessed August 2, 2012).

Natural Resources Defense Council (NRDC). n.d. "Disaster in the Gulf."]www.nrdc.org/energy/gulfspill (accessed July 29, 2012).

NREL. 2013 *Upgrade to REopt Tool Means a More Robust Resource* http://www.nrel.gov/tech_deployment/news/ 2013/2073.html, Janurary 13, 2013; accessed March 20, 2013.

RS Means. 2006.*Green Building: Project Planning and Cost Estimating* (2nd ed.). Kingston, MA: Reed Construction Data.

Sacramento Municipal Utility District. 2012. "SMUD, Partners Kick-off Energy Storage Project" news release, June 29, 2012. https://www.smud.org/en/about-smud/news-media/news-releases/2012-06-29.htm (accessed July 29, 2012).

Stoltenberg, Blaise, and Eric Partyka. 2010. *Procuring Solar Energy: A Guide for Federal Facility Decision Makers*. DOE/GO-102010–3030, Office of Scientific and Technical Information. www.osti.gov/bridge. Oak Ridge, TN: US Dept of Energy.

US Energy Information Administration (USEIA). 2011. *International Energy Outlook 2011*. www.eia.gov/forecasts/ieo/pdf/0484%282011%29.pdf (accessed July 29, 2012).

Walker, Andy. 1991 "Thermodynamic Analysis and Economic Optimization of a Two -Phase Self-Pumping Solar Water Heater." Colorado State University, University Microfiche International Dissertation Information Service No. 5712.

——— 2009a. "An Heuristic Approach to Renewable Energy Optimization." ASME 2009; 3rd International Conference on Energy Sustainability, July 19–23, 2009, San Francisco, CA.

——— 2009b. "Tax Incentives for Renewable Energy." (August 19). www.govenergy.com/2009/pdfs/presentations/Financing-Session03-Walker_Andy.pdf (accessed August 3, 2012, no longer active link, contact author for copy).

Walker, Andy, Donna Heimiller, Alicen Kandt, and Anne Crawley. 2006. "Renewable Energy Screening: Identifying and Prioritizing Solar Opportunities in Federal Facilities." ASME/ASES Solar 2006. Denver, CO: American Society of Mechanical Engineers.

Walker, Andy, Greg Katz, David Mills, and Anne Grette Hestnes. 2003. *International Performance Measurement and Verification Protocol*. Vol. 3 of *Concepts and Practices for Determining Savings in Renewable Energy Technologies Applications.* Washington, DC: Department of Energy.