Visual Impacts of Utility-scale Solar Energy Facilities on Southwestern Desert Landscapes

Submitted by

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Abstract

Agencies charged with the management of scenic resources, such as the United States Department of the Interior National Park Service (NPS) and Bureau of Land Management (BLM), must consider the visual impacts of development that takes place outside the boundaries of agency-managed lands, but is visible from sensitive viewpoints located within their management units. This development may adversely impact visitor enjoyment of scenic views that extend beyond lands under the direct control of the agencies. For example, NPS-managed lands are not available for utility-scale renewable energy development. However, such development on public or private lands adjacent to parks can adversely impact scenic views that extend beyond park boundaries, and that are important to the experience of park visitors.

In the open desert landscapes of the southwestern United States, the visibility of utility-scale solar energy facilities has been identified as a potential source of negative aesthetic impact on national park units, wilderness areas, national historic and scenic trail corridors, residential communities, and other visually sensitive areas. Because of their large size, strong regular geometry, and highly reflective surfaces, solar energy facilities may be visible for long distances and may contrast strongly with the natural or rural settings in which they often are located. Because there are few large-scale solar energy facilities in operation within the United States, especially those employing non-photovoltaic (PV) solar technologies, the basic visual characteristics of the facilities are not well understood; however, an understanding of these characteristics is important to predicting associated visual impacts and identifying effective visual impact mitigation strategies.

Preliminary investigations sponsored by the NPS and BLM examined the visual characteristics of several parabolic trough, PV, and power tower facilities. Field-based observations of the facilities were made to assess and document potential sources of visual contrast associated with them. Observed sources of visual contrast from parabolic trough facilities included glare from heat transfer fluid tubes or related components, geometric patterns of reflected light that created strong scintillations, plumes associated with cooling towers, and reflections from mirror supports and ancillary facilities. In some cases, glare was bright enough to cause strong visual discomfort and temporary after images when observed at distances of greater than 6 km (4 mi). A 1.6 km^2 (400 acre) parabolic trough facility also was found to be easily visible at a distance of greater than 23 km (14 mi), in both daytime and nighttime observations, while a thin-film PV facility was visible at a distance of 35 km (22 mi) in daytime observations. Other visual effects observed included dramatic and rapid changes in the apparent colors and/or reflectivity of the solar collector arrays of parabolic trough and thin-film PV facilities depending on the time of day, viewer location, and viewer movement. In addition, a five MW and a 20 MW power tower facility were observed. Reflected light from the power tower receiver structures was easily visible at a distance exceeding 32 km (20 mi), but did not cause strong visual discomfort even at short distances.

Regardless of the solar technology employed, ancillary facilities such as buildings, steam generation facilities, cooling towers, grid connection facilities, fences, roads, lighting, and cleared soil were judged to contribute significantly to observed visual contrasts.

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1 Introduction

Agencies charged with the management of scenic resources on federal lands, such as the United States Department of the Interior National Park Service (NPS) and Bureau of Land Management (BLM), must consider the visual impacts of development that takes place outside the boundaries of agency-managed lands, but is visible from sensitive viewpoints located within their management units. This development may adversely impact visitor enjoyment of scenic views that extend beyond lands under the direct control of the agencies.

Across the United States, strong support is present for the development of renewable energy facilities, including wind and solar. Many individuals even have favorable opinions about the aesthetics of wind farms and solar energy facilities (Global Strategy Group, 2007; Warren et al., 2005; SEI, 2003; SEIA, 2008). However, in the open desert landscapes of the southwestern United States, the visibility of solar facilities has been identified as a potential source of negative visual impacts on national park units, wilderness areas, national historic and scenic trail corridors, residential communities, and other visually sensitive areas (Basin and Range Watch, 2011; DOE and BLM, 2010).

Because of their large size, strong regular geometry, and highly reflective surfaces, utility-scale solar energy facilities may be visible for long distances and they may contrast strongly with natural or rural settings in which they often are located. Accompanying infrastructure associated with renewable energy facilities, such as roads and transmission lines, also can introduce large visual impacts. Concerns about potential visual impacts of utility-scale solar facilities have been raised by government agencies, environmental organizations, businesses, tribal organizations, and individuals living in potentially affected communities throughout the Southwest (Basin and Range Watch, 2011; DOE and BLM, 2010).

Federal land management agency staff must be knowledgeable about the visual characteristics of solar facilities that are likely to cause visual contrasts which may result in negative visual impacts for sensitive viewers; however, because utility-scale solar energy is relatively new, and because there is only a small number of operational utility-scale solar facilities in the world, few field-based studies of their visual characteristics have been conducted. Furthermore, several different solar technologies are utilized for utility-scale electricity generation, and the infrastructure associated with each technology has its own unique visual properties that cause different types and magnitudes of visual contrasts. As a result, many important visual characteristics of utility-scale solar plants and their associated potential impacts are not thoroughly documented or well understood.

Concerns include both daytime and nighttime sky impacts (Basin and Range Watch, 2011; DOE and BLM, 2010). Particular concerns have been raised regarding effects on views from nearby mountains, where elevated observation points would afford open views of solar collector fields, as well as potential impacts on the dark night skies that are valued scenic and tourist resources in many parts of the American Southwest.

This paper summarizes the results of field visits to several utility-scale solar facilities undertaken in April 2010, May and September 2011, and January 2012 for the purpose of observing the visual characteristics of existing and partially constructed facilities and assessing their potentials to cause visual impacts at a range of distances, viewing angles, and lighting conditions. The field visits included trips to two parabolic trough facilities located in southern Nevada and California, two thin-film PV facilities in Nevada, and three power tower facilities — two of which are located in southern California and one located in Spain. Observations primarily were made in generally sunny, daylight conditions, but also included limited nighttime observations.

The observations and assessments were undertaken primarily to inform the visual impact analysis for a programmatic environmental impact statement undertaken by the U.S. Department of the Interior Bureau of Land Management (BLM) and the U.S. Department of Energy (DOE) and also as part of a separate study funded by the National Park Service (NPS). The Programmatic Environmental Impact Statement for Solar Energy Development in Six Southwestern States (Solar PEIS) assesses the potential social, economic, and environmental impacts of utility-scale solar energy development on public lands managed by BLM in Arizona, California, Colorado, Nevada, New Mexico, and Utah (DOE and BLM, 2010). Solar technologies evaluated in the Solar PEIS include parabolic trough, solar dish, power tower, and PV systems.

In the case of the NPS, its lands are not available for utility-scale solar energy development. However, such development on public or private lands adjacent to parks can adversely impacts scenic views that extend beyond park boundaries, and that are important to the experience of park visitors. As a result, the NPS is supporting research to understand the visual impacts associated with utility-scale solar energy development on adjoining lands, and is working with the BLM to mitigate and avoid such impacts where appropriate in order to protect shared scenic landscapes. The ongoing NPS study includes an assessment of the visual characteristics of utility-scale parabolic trough, power tower, and thin-film PV facilities.

This paper describes the site visits and methodology for data collection; the facilities visited and significant study results including the visibility of selected facilities; the dynamic nature of the visual experience of solar facilities; occurrence of glare and other reflections; the importance of viewer position, viewer elevation, and viewing geometry on visual contrast from solar facilities; visual contrasts from power block components, plumes, and other ancillary facilities; and impacts from lighting on dark night skies.

2 Site Visits and Solar Facility Descriptions

2.1 Site Visits

Site visits were conducted in April 2010, May 2011, September 2011, and January 2012. Participants included staff from Argonne National Laboratory and BLM. All participants in the site visits are landscape architects with extensive visual impact assessment experience. Not all participants visited all facilities.

2.2 Facility Descriptions

A total of eight solar facilities were observed during the four site visits, including the following facilities, which are discussed in this paper:

- Two parabolic trough facilities (Nevada Solar One and Solar Energy Generating Stations III-VII [SEGS III-VII]);
- Two thin-film PV facilities (Silver State North and Copper Mountain);
- Three power tower facilities (Ivanpah Solar Energy Generating System [Ivanpah], Sierra Suntower, and Torresol Gemasolar).

Facility information is provided in Table 1.

Table 1 – Solar facilities observed and facility descriptions.

Facility	Location	Power Output (Megawatts [MW])	Facility Type	Facility Size	Notes
Nevada Solar One	Boulder City, NV	64 MW	Parabolic Trough	1.6 km^2 (400 acres)	
Solar Energy Generating Stations III – VII	Kramer Junction, CA	30 MW each (150 MW total)	Parabolic Trough	3.9 km^2 (970 acres)	
Copper Mountain	Boulder City, NV	48 MW (Phase I)	Thin-Film PV	1.5 km^2 (380 acres)	Phase II - Construction on the 1,100-acre site is expected to begin in early 2012. Power output for completed facility will be 150 MW.
Silver State North	Clark County, NV	50 MW (Phase I)	Thin-Film PV	2.4 km^2 (600 acres)	This is one of three phases that would incorporate a project footprint between 2,967 acres and 4,818 acres in size depending on the final site configurations
Ivanpah Solar Energy Generating System	Mojave Desert, CA	392 MW (when complete)	Solar Power Tower	14 km^2 (3,400 acres)	Three separate plants are under construction. Acreage includes all three phases, the administration building, operations and maintenance building, and substation. Tower height will be 140 m (459 ft).
Sierra Suntower	Lancaster, CA	2.5 MW each (5 MW total)	Solar Power Tower	0.08 km^2 (20 acres)	Two modules with 24,000 mirrors. Tower height is 55 m (180 ft).
Torresol Gemasolar	Seville, Spain	19.9 MW	Solar Power Tower	1.85 km^2 (457 acres)	Tower height is 140 m (459 ft).

Of these facilities, the parabolic trough and thin-film PV facilities were visited multiple times and studied more intensively; therefore, results of this study are based primarily on the observations of those facilities.

The facilities observed represent a range of solar technologies that are currently in use to generate utility-scale solar power in the United States and elsewhere. Utility-scale solar power facilities vary widely in facility layout, power-generating technology, and facility size. The power tower facilities observed in this study range in size from 0.8 km^2 (20 acres) to 14 km^2 (3,400 acres), and are representative of the full range of power tower facility sizes currently in operation or proposed. The parabolic trough and thin-film PV facilities observed in this study are all less than 900 acres in size, which is substantially smaller than some facilities currently under construction or proposed in the southwestern United States.

2.2.1 Parabolic Trough Facilities

Parabolic trough facilities use large numbers of curved mirrors to concentrate the sun's rays on receiver tubes filled with a heat-transfer fluid that carries the generated heat to a heat exchanger. The heat from the fluid is used to boil water, which in turn generates steam that drives a turbine, thereby generating electricity in the same general manner that coal or nuclear power plants boil water to generate steam to drive a steam turbine. Thus, similar to coal and nuclear plants, these types of solar facilities will have steam turbine generators and their related infrastructure on site, including a cooling tower. The receiver tubes are mounted above the parabolic mirrors, which are arranged in long north-south oriented rows. The mirrors have a single-axis tracking capability, tracking the sun from east to west during the course of the day.

As indicated, two parabolic trough facilities (Nevada Solar One and SEGS III-VII) were observed in the course of this study.

Nevada Solar One

Nevada Solar One is a 64-MW parabolic trough facility located approximately 20.1 km (12.5 mi) south-southwest of Boulder City, Nevada, in the Eldorado Valley in southern Nevada. Nevada Solar One is located approximately 2.7 km (1.7 mi) west of U.S. 95 and immediately north of Eldorado Rd. The facility encompasses approximately 1.6 km^2 (400 acres) and occupies a north-south oriented rectangle that is 1.85 km (1.15 mi) north to south and 0.8 km (0.5 mi) east to west.

The facility includes a power block with a steam turbine generator and pipes, a cooling tower, an operation and maintenance building, an administration building, a parking area, and a surrounding fence. The cooling tower generates a visible plume under certain atmospheric conditions.

SEGS III–VII

SEGS III–VII are a group of five 30 MW parabolic trough facilities located immediately northwest of Kramer Junction, California, north of California State Highway 58 and west of U.S. 95. The facilities are located at one site encompassing approximately 4 km^2 (1,000 acres). The site occupies a staggered, north-south-oriented, double rectangle that measures about 2.6 km (1.6 mi) from the north end of the western rectangle to the south end of the eastern rectangle and roughly 1.8 km (1.1 mi) from east to west across both rectangles. The facilities include natural gas boilers for backup, which are operated to augment solar power generation during times of peak demand. The facilities generate visible plumes under certain atmospheric conditions.

2.2.2 Power Tower Facilities

Similar to parabolic trough systems, power tower systems concentrate sunlight to create heat that is used to boil water to run a steam turbine that then will generate electricity; however, instead of using curved mirrors to concentrate sunlight on horizontal tubes, power towers use flat mirrors (i.e., heliostats) to concentrate sunlight on a receiver unit atop a tower that is generally hundreds of feet tall. The heliostats may be arranged in concentric rings around the tower or placed in blocks on one or more sides of the tower. Multiple towers may be located in one facility. Hundreds to many thousands of heliostats may be used to concentrate sunlight on the receiver unit.

A characteristic of power towers is that the concentrated sunlight reflected from the heliostats surrounding the tower will cause the receiver at the top of the tower to "shine" brilliantly with reflected light when the facility is operating. As will be discussed, the reflected light from the receiver may be visible for long distances.

Three power tower facilities (Ivanpah, Sierra Suntower, and Torresol Gemasolar) were observed in the course of this study.

eSolar Sierra Suntower

The eSolar Sierra Suntower is a 5-MW solar power tower demonstration facility located in Lancaster, California. The facility occupies about 0.20 km^2 (49 acres). The facility includes two "eSolar Modules" — each of which includes one 2.5-MW tower and a heliostat field containing approximately 12,000 heliostats — arranged in two rectangular arrays of 6,000 heliostats north and south of the tower, which is located between the two heliostat fields. The power towers are 55 m (180 ft) tall. Each heliostat has a surface area of 1.14 m^2 (12.2 ft^2).

Ivanpah Solar Energy Generating System (Ivanpah)

The Ivanpah facility, under construction at the time of this writing, is a power tower facility located in California's Mojave Desert on 14 km^2 (3,500 acres) of BLM-administered public land (NREL, 2011b). The location is near the Nevada border in San Bernardino County approximately 7.2 km (4.5 mi) south of Primm, Nevada and 0.8 km (0.5 mi) west of the Primm Valley Golf Club (BLM, 2010a), and 2.3 km (1.4 mi) from the boundary of Mojave National Preserve, a unit of the National Park System, and elevated terrain in the preserve around Clark Mountain (2,416 m [7,929 ft]).

When completed in 2013, the facility will generate 392 MW using 214,000 heliostats to focus power on solar receivers atop three towers (BrightSource, 2011a). Each heliostat consists of two mirrors that are 2.1 m (7.2 ft) high by 3.2 m (10.5 ft) wide, mounted on pylons inserted directly into the ground. The pylons are arranged in concentric circles around the tower in order for the heliostats to track the sun. Once complete, the receiver towers will be 137 m (450 ft) tall (BrightSource, 2011b). Due to the height of the towers, lighting and lightning poles that are required by the Federal Aviation Administration (FAA) will extend above the top of the towers by approximately 3 m (10 ft). Each tower will be accompanied by a steam turbine generator set, air-cooled condensers, and other auxiliary systems (BLM, 2010a; NREL, 2011b). The facility will be dry-cooled and will utilize a natural gas back-up. Other facilities at Ivanpah will include an administration building, an operation and maintenance building, a substation, and access roads (BLM, 2010a).

Gemasolar 2006 SAU

The Gemasolar facility is located in Fuentes de Andalucia in Seville, Spain, and is the first commercial scale solar facility to apply a central tower receiver and molten salt heat storage technology. The facility has a rated electrical power production of 19.9 MW (NREL, 2011a). It consists of 2,650 heliostats on 1.8 km^2 (457 acres) (Torresol Energy, n.d.). The heliostats consist of sheet metal with an aperture area of 120 m^2 (1,290 ft^2). The central tower is 140 m (459 ft) tall. The facility incorporates molten salt as the heat transfer fluid and uses wet cooling.

2.2.3 Thin-Film PV Facilities

PV solar facilities do not concentrate sunlight to generate heat to boil water; instead, they convert solar energy directly to electrical current, utilizing panels or modules coated with special materials that can capture photons and convert the energy into electric current.

Because PV solar facilities do not require infrastructure associated with heating, transporting, boiling, and cooling water and other heat transfer fluids, generally speaking, they are visually simpler than parabolic trough and power tower facilities.

Two thin-film PV facilities (Silver State North and Copper Mountain) were observed during the course of this study.

Silver State North Solar Project

The Silver State North Solar Project is located on approximately 2.4 km^2 (600 acres) of BLM-administered public land in Clark County, Nevada, approximately two miles east of Primm.

The facility supplies approximately 50 MW of power using fixed tilt mounting structures with thin-film solar modules. The PV modules are mounted so they are south-facing. Each module is about 600 mm (2 ft) wide and 1200 mm (4 ft) long. Three modules are mounted side-by-side on the sloped mounting unit and arranged in long east-west oriented rows. The modules' surfaces are black.

Interspersed at regular spacings amongst the solar array are inverter boxes that house electrical equipment. The inverter boxes project several feet above the solar module array and they are painted shadow gray to reduce associated visual impacts. Other onsite facilities consist of a substation, collection and transmission lines, an operation and maintenance area (BLM, 2010b), and a small operations and maintenance building.

Sempra Copper Mountain

The Copper Mountain facility is located on a 380-acre site approximately 32 km (20 mi) southeast of Las Vegas, off U.S. 95. The facility includes approximately 775,000 PV modules, which rest on 103,000 steel poles (Copper Mountain, 2011). It generates approximately 48 MW of electrical power.

The general layout of the facility is similar to that of the Silver State North facility in that it consists of long east-west rows of fixed tilt mounting units with south facing black modules and inverter boxes at regular spacings. At the Copper Mountain facility; however, the inverter boxes are painted white.

3 Methods

For each facility site visit, the following general procedures were followed:

1. The facilities were observed and photographed from a variety of distances ranging from less than 0.2 km (0.1 mi) to more than 35 km (22 mi) from the facility perimeter, such as in the case of the Silver State North facility. Where possible, facilities were observed and photographed from multiple directions and from both elevated and non-elevated viewpoints.
2. At each viewpoint, the visual characteristics of the facility (e.g., its apparent form, line, color, and texture) were noted, as well as the occurrence of glinting and glare and other visual phenomena, such as shimmering or scintillations, as applicable. The visibility and appearance of ancillary components, such as cooling towers, transmission structures, and steam turbine generators were noted, as was the presence of vapor plumes.
3. Multiple photographs of the facility were taken from each viewpoint at a variety of focal lengths with either a Ricoh Caplio 500SE GPS-enabled digital camera (April 2010) or a Nikon D7000 GPS-enabled digital camera (all other visits).
4. In many locations, multiple panoramic photograph sequences were taken, and the photographs eventually were "stitched" together using appropriate software to

create interactive or still-image panoramas; useful for wide-angle views of the larger solar facilities.

5. Several short video clips were also recorded by the Nikon D7000 camera during the May 2011 and January 2012 site visits.
6. Selected photographs and panoramas were mapped, and the observation data was entered into a database created by Argonne for the NPS project. Many of the photos and observation data were also exported to a .KMZ file format for viewing in Google Earth.

During the four trips, several hundred observations were made and more than 3,000 photographs were taken, many of which were linked to the Google Earth .KMZ file.

4 Results

Because there are a wide variety of technologies employed for utility-scale solar generation, the visual characteristics of solar facilities vary more than is typical for most other utility-scale electricity generating systems. They differ from most other utility-scale power facilities in that they exhibit tightly-spaced, strong, regular geometry; mostly low-height profiles; highly-reflective surfaces in many cases; and a high-degree of variability in appearance, depending on sun angle and viewing geometry.

4.1 Visibility of Solar Energy Facilities

Relative to most other utility-scale energy facilities (wind power excepted), solar facilities are very large in area for the level of power output generated. For example, the Ivanpah power tower facility will require approximately 14 km^2 (3,500 acres) of land — most of which would be needed for the heliostat fields — to produce 392 MW of electricity; the Nevada Solar One parabolic trough facility requires approximately 1.6 km^2 (400 acres) of land to produce 64 MW of electricity; and the Silver State North thin-film PV facility requires 2.4 km^2 (600 acres) of land to produce 50 MW of electricity, in its current configuration. Consequently, from nearby locations with clear views, solar facilities can occupy a significant portion of the visual field. The partially completed Ivanpah facility is shown in Figure 1.

Figure 1. Partially completed Ivanpah power tower facility, as seen from a distance of 6.8 km (4.2 mi) from the Unit 1 tower (at center). The cleared area at center is approximately 2 km (1.25 mi) across, and covers 3.66 km^2 (900 acres). Cleared areas and two additional towers are visible in the distance at left. The facility eventually will cover 14 km^2 (3,400 acres). Photo taken January 20, 2012, 10:14 AM, looking northwest, solar azimuth of 139° and solar elevation of 23°.

The large size, strong regular geometry of solar facilities, and the use of mirrors or glass panels with metal supporting structures, may result in high visual contrast that is visible for long distances in many instances. In favorable, but not uncommon viewing conditions, the large facilities observed in this study were easily visible at distances exceeding ten miles, and even the low-profile Silver State North PV facility viewed from the north (not facing the panels) was visible at more than 35 km (22 mi). When viewed from long distances, the facilities may not be recognizable as solar facilities. Depending on the projects' layouts and contrast, in some cases they may appear to be natural features, while in other cases, they may appear non-natural, but lack sufficient visual detail to be identified positively as solar facilities. Figure 2 shows the Copper Mountain thin-film PV facility photographed from a distance of approximately 13 km (8 mi). Figure 3 shows the Nevada Solar One parabolic trough facility photographed from a distance of approximately 23 km (14 mi).

Figure 2. Copper Mountain thin-film PV facility (1.5 km^2 [380 acres]), as seen from a distance of approximately 13 km (8 mi). The facility is the black line across the center of the photograph; lighter objects immediately above the facility are components of a natural gas power plant. Photo taken May 2, 2011, 6:39 PM, looking northeast, solar azimuth of 275° and solar elevation of 21°.

Figure 3. Nevada Solar One parabolic trough facility (1.6 km^2 [400 acres]), as seen from a distance of approximately 23 km (14 mi). The Nevada Solar One facility is the narrow white band at the center of the photo. Photo taken May 5, 2011, 12:14 PM, looking southwest, solar azimuth of 131° and solar elevation of 63°.

4.2 Occurrence of Glare

At times, the Nevada Solar One and SEGS III-VII parabolic trough facilities observed in this study produced glare sufficient to cause annoyance or discomfort during extended viewing, for some observers. Glare was observed from the front, sides, and tops of the parabolic trough arrays, and it was observed from viewpoints approximately level with the facilities as well as from elevated viewpoints. Figure 4 shows a strong glare "spot" on the Nevada Solar One array, as observed from the east, from a slightly elevated viewpoint on U.S. 95.

Figure 4. Glare spot on Nevada Solar One parabolic trough facility (1.6 km^2 [400 acres]), as seen from a slightly elevated viewpoint on U.S. 95. Photo taken April 21, 2010, 12:00 PM, looking southwest, solar azimuth of 131° and solar elevation of 57°.

Glare sources are believed to be associated with reflections from heat transfer fluid tubes and/or associated components attached to the tubes, as shown in Figure 5.

Figure 5. Glare sources on Nevada Solar One parabolic trough facility. The glare sources appear to be associated with the heat transfer fluid tubes and/or associated components attached to the tubes. Photo taken May 5, 2011, 8:42 AM, looking southwest, solar azimuth of 86° and solar elevation of 23°.

Glare is a relatively common occurrence in the intense sun of the southwestern deserts, as any reflective surface, such as a fence railing, a metal roof, the surface of a lake, or an automobile may cause glare. However, very large solar facilities with an expanse of reflective surfaces can cause unusually intense or prolonged glare that exceeds that commonly encountered in everyday situations. As observed in this study, the occurrence of glare was highly variable, with it appearing and disappearing suddenly in some instances, while in others, it varied greatly in intensity over a short period of time. Seemingly, glare was a routine occurrence at the facilities observed. At the Nevada Solar One facility, for instance, glare was observed almost every sunny day that observations were made, from both the eastern and western sides of that facility. Glare was observed at distances of up to 6 km (4 mi) from an elevated viewpoint; at this distance it was still strong enough to cause discomfort and after images for some observers. It is likely that glare may have been observable at even longer distances, but this could not be verified because of road access limitations.

4.3 Geometric Patterns of Reflected Light

A related phenomenon that was frequently observed at both parabolic trough and PV facilities can be described as geometric patterns of reflected light — sometimes glittering or shimmering strongly — caused by simultaneous reflection of sunlight from regularly spaced metal surfaces in the collector array. Based on the observations made in this study, it appears that a variety of surfaces may be involved, such as the ends of heat transfer fluid tubes or the supporting structures for the tubes in parabolic trough facilities, or metal surfaces in the gaps between the PV modules for thin-film PV facilities. While these reflections are not bright enough to cause discomfort, they may appear as straight lines or grids of light across the entire collector array or large portions of it. They may change dramatically as the observer moves, and in general, they may create striking visual effects that capture and hold an observer's visual attention. Geometric patterns of reflected light on the SEGS III-VII parabolic trough and the Silver State North thin-film PV facility are shown in Figures 6 and 7, respectively.

Figure 6. Geometric pattern of reflected light on SEGS III-VII parabolic trough facility (3.9 km^2 [970 acres]). Photo taken October 29, 2008, 1:30 PM, direction of view not available, solar azimuth of 179° and solar elevation of 41°.

Figure 7. Geometric pattern of reflected light on Silver State North PV facility (2.4 km^2 [600 acres]). Photo taken January 26, 2012, 4:06 PM, looking south-southeast, solar azimuth of 228° and solar elevation of 19°.

4.4 Effects of Viewer Position and Viewing Geometry on Observed Contrast

For all of the observed facilities, the degree of contrast was found to be highly dependent on the viewer position with respect to the facility, lighting, and sun angle (as determined by the season and time of day). Because mirrored surfaces reflect the objects around them, if viewed from a particular angle at a specific time of day and under certain lighting conditions, the mirrored surfaces might reflect the blue of the sky, the white or gray of the clouds, or even the greens or browns of the surrounding soil and vegetation. When the mirrored surfaces are not facing the observer, the view may be of painted or unpainted and potentially reflective support structures, or of earth or vegetation between the rows of the collector arrays.

Based on the observations made, both parabolic trough and thin-film PV facilities are highly variable in appearance. In the course of the study, the parabolic trough arrays exhibited a range of colors from black to silvery white, and they included blues, grays, browns, and greens. The collector array of PV facilities varied from black, through a range of blues, to white. These large color shifts can cause dramatic increases in the visual contrast from the facility, but in some cases may make the facility blend in with the background more effectively, or make it appear to mimic a natural feature, such as a lake. Figure 8 shows four different views of the Nevada Solar One parabolic trough facility taken from two locations east of the facility at different times of day, with colors ranging from black to silvery white to medium gray to bright blue. Repeated observations of the facility on different days and in different season suggest that these dramatic color changes occur frequently, if not daily.

Figure 8. Color shifting of Nevada Solar One parabolic trough facility (1.6 km^2 [400 acres]) shown in the center of the four views. The color of the collector array may vary widely based on mirror position and the environmental features, such as clouds or sky that are reflected in the mirrors. Top photo: April 24, 2010, 8:04 AM, looking southwest, solar azimuth of 83° and solar elevation of 13°. Second photo: April 21, 2010, 12:00 PM, looking west-southwest, solar azimuth of 131° and solar elevation of 57°. Third photo: April 23, 2010, 2:32 PM, looking northwest, solar azimuth of 211° and solar elevation of 64°. Bottom photo: April 21, 2010, 9:49 AM, looking northwest, solar azimuth of 100° and solar elevation of 33°.

Because the degree of contrast is highly dependent on viewer position and the precise viewing geometry, as the observer moves, or as the mirrors of parabolic troughs move, or with the passage of time, the appearance of the collector array may change, and this was observed at both the parabolic trough and thin-film PV facilities monitored in the study. The changes were most notable when driving at high speeds past the parabolic trough and PV facilities, such that the viewer's position changed both rapidly and substantially. Under these circumstances, both the parabolic trough and PV facilities often would exhibit pronounced shifts in color, sometimes accompanied by the sudden appearance, disappearance, or change of geometric patterns of light as described above. For parabolic trough facilities, glare spots or lines sometimes suddenly flared up, fluctuated in intensity, moved across the facility (e.g., appearing as if it followed the observer), and then rapidly diminished or disappeared suddenly.

Changes in visual contrasts that resulted from changes in observer position were found to be different in nature depending on whether viewer movement was parallel to the rows of solar collectors or perpendicular to the rows of collectors. In the latter case, changes were often more pronounced, as the angle of view with respect to the collectors would change such that the view would, at various points, include the front, sides, and backs of the collectors, as well as the ground between the rows of collectors. When travelling parallel to the rows of collectors, the same side of the collectors was always in view, with only the angle of view changing substantially; there would be less change in contrast as a result. For example, when driving past the thin-film PV facilities perpendicular to the collector rows from the north, the array first would appear to be black when viewed from the north, but would lighten in color considerably as the automobile passed the facility, changing from black through various shades of blue to white, before changing back to blue and then black, as the automobile drove beyond the facility to the south. The shift in color was pronounced, and visually striking, as shown in Figure 9.

Figure 9. Color transition Copper Mountain thin-film PV facility (1.5 km^2 [380 acres]). Color changes from black to blue to white and back again as the facility is passed. Photo taken January 27, 2012, 4:13 PM, looking west, solar azimuth of 230° and solar elevation of 18°.

4.5 Effects of Elevated Viewpoints on Observed Contrast

The degree of contrast also was found to be much greater for observations from elevated viewpoints. In the Southwest, utility-scale solar facilities are generally located in flat valleys. Because the collector arrays generally have very low vertical profiles, when viewed from the valley floor or other low-elevation viewpoints, the arrays may blend in with the typically strong horizon line, or be at least partially screened by vegetation or minor undulations in topography. Even if the array is in plain view, a relatively small surface area is in view, and from relatively short distances, the facility typically will appear as a thin line just above or below the horizon. While the strong horizontal line of the collector array may be evident, the large size and strong gridded geometry of the array often will be concealed. Because less of the facility is visible, glare and other reflections may be diminished, and contrasts between lit and shadowed surfaces will be concealed. This is illustrated in Figure 10.

Figure 10. SEGS III-VII parabolic trough facility (3.9 km^2 [970 acres]) from non-elevated viewpoint at a distance of 2.4 km (1.5 mi). Photo taken April 26, 2010, 10:05 AM, looking northeast, solar azimuth of 99° and solar elevation of 36°.

However, if the solar facility is observed from a sufficiently elevated viewpoint, the top of the collector array will be seen, the full breadth of the facility will be visible, and its strong, regular geometry will be apparent. Both the strong outline of the perimeter of the facility (often a polygon) and the collector array will be evident, as will the strong internal geometry of the collector array itself. Spaces between the collector array rows will be apparent, and these often are a source of strong contrast. If there is glare or if there are other reflections from the tops of the collectors, these effects also will be visible. From elevated positions, no screening by vegetation or small undulations in topography will conceal the facility. As a result of these observations, a conclusion of this study is that the vertical angle of view is a major factor is determining the degree of visual contrast from a given solar facility. This is illustrated in Figure 11.

Figure 11. Silver State North thin-film PV facility (2.4 km^2 [600 acres]), as seen from an elevated viewpoint at a distance of 8 km (5 mi). Photo taken January 26, 2012, 10:29 AM, looking west-southwest, solar azimuth of 142° and solar elevation of 26°.

4.6 Power Tower Observations

Power tower observations were limited largely to the receiver towers themselves, rather than the heliostats; however, the observations suggest that the "lit" towers can be seen for long distances and that their light is generally steady, regardless of viewer location and movement. The Sierra Suntower 2.5 MW (tower height of 55 m [180 ft]) and the Torresol Gemasolar 19.9 MW (tower height of 140 m [459 ft]) receivers were both observed as bright points of light at distances exceeding 32 km (20 mi) in poor visibility conditions and would likely have been visible at greater distances, if topography had permitted viewing at greater distances. The two operating facilities had relatively low-power receivers, but in both cases, the receiver lights could be viewed for extended periods without serious visual discomfort even from distances of less than a few miles. It is possible that this will not be the case for future, higher-power output towers; in these new developments, the higher-output towers would be brighter; and thus, likely visible for greater distances.

At the Gemasolar facility, in addition to the intensely white receiver light, reflected light from dust particles in the air around the receiver was plainly visible from nearby locations, estimated to be 8 km (5 mi) from the tower. The light appeared to stream both downward and, at times, upward from the receiver, as shown in Figure 12.

Figure 12. Torresol Gemasolar 19.9 MW Power Tower (1.85 km^2 [457 acres]). In addition to the intensely white receiver light, reflected light from dust particles in the air around the receiver is plainly visible. The light appears to stream both downward and upward from the receiver. The central tower is 140 m (459 ft) tall. Heliostats are visible at right. Photo taken Spetember 23, 2011, 5:50 PM, looking north, solar azimuth of 246° and solar elevation of 28°.

4.7 Effects of Ancillary Facilities and Ground Clearing on Observed Contrast

The study observations suggest that while the collector array is generally the most significant contributor to visual contrasts from utility-scale solar facilities — power blocks, substations, and other ancillary facilities may contribute substantially to observed visual contrasts — particularly for concentrating solar facilities. This is particularly true for low-angle, low-elevation views of the facilities, such as views from valley floors where the facilities are typically located in the Southwest. From low viewing angles, taller ancillary facilities project well above the generally low-profile collector arrays so that they are often more visible than the arrays, and they may project above the horizon, breaking the continuity of the collector array with the strong horizon lines typical of western landscapes.

Regardless of viewing angle, ancillary structures typically contrast strongly with the uniform geometry of the collector arrays. In addition, they are often the source of glinting — or even glare in some instances — that may contribute significantly to the overall level of visual contrast from a particular facility. Where wet cooling is used, or where solar facilities have other plume sources, the plumes may add substantially to contrasts, because of their generally vertical orientation and height, their potentially strong color contrasts, and their irregular form and movement. Their height, form, and movement may contrast noticeably with the strong regular geometry of the low, horizontal collector arrays.

For the two thin-film PV facilities, the shadow gray paint applied to the inverters at the Silver State North facility was judged to be very effective as a visual impact mitigation measure, based on comparisons with the white inverters employed at the Copper Mountain PV facility. In many views of the Silver State North facility, especially at distance beyond a few miles, the gray inverters were invisible or difficult to detect, while the white inverters at the Copper Mountain facility were easily visible at a distance of approximately 13 km (8 mi), as shown in Figure 2. However, as discussed above, in certain instances, the PV facilities can appear to be white or silver, and in those instances dark colored inverters might actually increase contrast, as shown in Figure 7.

For many observations, regardless of the facility involved, cleared ground in and around the facility contributed noticeably to observed visual contrasts. The light red or tan soils common in the Southwest often contrast strongly with existing vegetation around the facility, and also may contrast strongly with the color of the collector array or shadows of the array that are cast upon the ground. The contrast from soil clearing can be visible for long distances. For example, a narrow strip of cleared soil around the Silver State North collector array was easily visible from a distance of approximately 24 km (15 mi).

4.8 Night Sky Impacts

The study included limited observations of impacts on night skies from lighting at the Nevada Solar One parabolic trough and Copper Mountain thin-film PV facilities. Assessment of the lighting impacts at the Copper Mountain facility was difficult because there was a natural gas power plant immediately adjacent to the Copper Mountain facility, and it was difficult to determine which lights belonged to which facility; however, there appeared to be no lighting associated with the collector array.

The Nevada Solar One parabolic trough facility had substantially more lighting than the Copper Mountain PV facility. The power block was brightly lit by multiple unshielded lights and there were additional lights associated with buildings and the facility entrance gate. There were single lights at each corner of the collector array field. The light exhibited a range of colors and intensities. The facility lighting was easily visible from a well-lit area in Boulder City, Nevada at a distance of approximately 23 km (14 mi).

5 Summary and Conclusions

As the first generation of very-large-scale solar plants are being built in the southwestern states, potential visual impacts from these facilities are emerging as public concerns and as possible reasons for public opposition to their development in the desert landscapes of the region. Because so few of these facilities exist in the world today, relatively little is known about their visual characteristics or about the sources of visual contrasts associated with them that could be perceived as negative visual impacts. The research reported here is a preliminary assessment of the visual characteristics of parabolic trough, power tower, and thin-film PV facilities, as observed in typical desert landscapes.

Because of their large size, reflective surfaces, and regular geometry — under favorable viewing conditions — even relatively small solar facilities may be visible for long distances, in excess of 32 km (20 mi); however, they generally cannot be recognized as solar facilities at these distances and may sometimes blend in well with the surrounding landscape.

A major conclusion of this study is that the visual experience of parabolic trough and thin-film PV facilities is very dynamic, primarily because of the large number of reflective surfaces these facilities employ. Their appearance varies substantially, depending on the horizontal and vertical viewing angle and distance — as well as the time of day — and it may change dramatically as the observer moves or as even short stretches of time elapse.

Glare from parabolic trough facilities is an important source of potentially negative visual impact. Non-glare visual effects from both parabolic trough and thin-film PV facilities include pronounced changes in apparent color and texture, scintillation, glinting, and geometric patterns of star-like points of reflected light associated with the collector arrays. These visual phenomena can have major effects on the apparent contrast of the facility with its surroundings. Ancillary facilities and plumes also can contribute substantially to perceived contrast levels.

The vertical angle of the view was observed to be a major determinant of perceived visual contrast from solar facilities. From elevated viewpoints, the full size and geometry of the facility is generally more apparent, and stronger visual contrasts may result. From non-elevated viewpoints, the low profile of the collector array helps the facilities blend into the strong horizon lines typical of the open landscapes of the southwestern deserts.

If the facilities observed are representative examples of the visual characteristics of the two types of solar facilities, the results of this study suggest that although both parabolic trough and thin-film PV facilities may be strong sources of visual contrast in some situations, in general, parabolic trough facilities are stronger sources of visual contrast. First and foremost, they may generate strong glare that may be visible for several miles, at least. Second, they utilize silver mirrors that reflect more brightly than the black thin-film PV panels. The parabolic trough mirrors track the sun, which makes their appearance change as the mirror assumes different positions relative to the observer, but also makes them reflect a wider range of objects as they move. The collector arrays of parabolic trough facilities are usually slightly higher in profile than PV collector arrays. Parabolic trough facilities have ancillary facilities in the power block and other infrastructure that increases the visual complexity of the facility and may be the source of strong visual contrast in their own right. Parabolic trough facilities also will have lighting requirements that may make trough facilities greater sources of night-sky impacts than PV facilities.

For non-tracking thin-film PV facilities, while the array may look different when viewed from different positions, the modules always present the same geometry to viewers at a given location. The array will almost always appear mostly black when viewed from the north, because the panels always face south, and the undersides are generally in shadow. The facilities were not observed to generate glare, though they did exhibit glinting and bright specular reflections at times. Overall, the facilities are visually simpler than the parabolic trough facilities, usually with a lower height profile. If the inverters are painted to match the surrounding area, as was done for the Silver State North facility, a major source of visual contrast from ancillary facilities can be greatly reduced.

Ancillary facilities — particularly for parabolic trough and power tower facilities — may also be important sources of visual contrast from utility-scale solar facilities, in both daytime and nighttime settings. Cleared soil in and around the facilities may also contribute to visual contrasts.

Sunlit power tower receivers, even those for a small commercial facility, can be visible for long distances. It is likely that the larger facilities planned and under development will have substantially larger visual impacts and be visible at greater distances.

This study is a preliminary effort to identify visual impacts associated with a limited number of utility-scale solar energy facilities and a limited range of solar technologies. The study has shown that the visual characteristics of utility-scale solar facilities are highly variable and the visual displays of solar facilities are highly dynamic. Different solar technologies have distinctive visual properties and the visual contrast observed at any given moment results from a complex interaction of the various reflective surfaces of the facility, their orientation to the sun and to the observer, the time of day, the season of the year, the weather, the observer's location, the air quality, and the colors and textures of the surrounding environment. Small changes in these variables can result in dramatic changes in the contrasts associated with the facilities, literally from minute to minute, and the rapid and pronounced changes in contrast could potentially result in large changes in perceived visual impacts from the facilities.

The ultimate goal of research on the visual characteristics of utility-scale solar facilities is to develop strategies (including alternative siting locations) for reducing the visual impacts associated with these very large energy developments that are visible for long distances and that often create strong visual contrasts with the desert landscapes of the Southwest. A great deal of additional work needs to be done to better understand the nature and magnitude of visual impacts from these facilities; for example, a study is needed to examine how perceived impacts may change with distance and viewing geometry. Studies to assess the viewers' perceptions and responses to the visual experiences of solar facilities are also badly needed, as is research to develop cost-effective visual impact mitigation strategies that are acceptable from an engineering perspective.

A major deployment of large solar facilities is underway in the southwestern United States that promises to have substantial impacts on some of the nation's most highly valued scenic and historic landscapes. Additional research on the visual impacts of utility-scale solar facilities should be undertaken quickly to assure that the achievement of critical national renewable energy goals is accomplished in a manner that also safeguards our nation's important visual and cultural resources.

6 References

Power-Technology.com. Projects. 2011. *Copper Mountain Solar 1, United States of America*. http://www.power-technology.com/projects/copper-mountain-solar-1/. Accessed 31 January 2012.

Bureau of Land Management (BLM). 2010a. *California Desert Conservation Plan Amendment/Final Environmental Impact Statement for Ivanpah Solar Electric Generating System. FEIS-10-31*. http://www.blm.gov/pgdata/etc/medialib/blm/ca/pdf/needles/lands_solar.Par.19048.File.dat/1-CDCA-Ivanpah-Final-EIS.pdf. Accessed 31 January 2012.

BLM. 2010b. Volume 1: Final Environmental Impact Statement for the Silver State Solar Energy Project. DOI No. FES 10-50. http://www.blm.gov/pgdata/etc/medialib/blm/nv/field_offices/las_vegas_field_office/energy/nextlight_-_other/FEIS_FedReg_NOA.Par.21644.File.dat/Silver%20State%20Solar%20FEIS%20Volume%20I.pdf. Accessed 31 January 2012.

Basin and Range Watch. 2011. *Visual Summary of Solar Projects in the Desert*. http://www.basinandrangewatch.org/Summary-Solar.html. Accessed 31 January 2012.

BrightSource Energy, Inc., Projects 2011a. *Ivanpah*. http://www.brightsourceenergy.com/projects/ivanpah. Accessed 31 January 2012.

BrightSource Energy, Inc., Ivanpah. 2011b. *12.16.11 Construction Highlights: October and November*. Construction Highlights: October and November. Accessed 31 January 2012.

DOE and BLM (U.S. Department of Energy and U.S. Department of the Interior Bureau of Land Management). 2010. *Draft Programmatic Environmental Impact Statement for Solar Energy Development in Six Southwestern States*, DES 10-59, DOE/EIS-0403, Dec., http://solareis.anl.gov. Accessed 31 January 2012.

Global Strategy Group. 2007. Memorandum to Yale Center for Environmental Law and Policy: *2007 Environment Survey—Key Findings*. http://envirocenter.research.yale.edu/uploads/epoll/YaleEnvironmentalPoll2007Keyfindings.pdf. Accessed 31 January 2012.

NREL. 2011a. Concentrating Solar Power Projects. *Gemasolar Thermal Power Plant*. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=40. Accessed 31 January 2012.

NREL. 2011b. Concentrating Solar Power Projects. *Ivanpah Solar Energy Generating Station*. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=62. Accessed 31 January 2012.

SEI (Sustainable Energy Ireland). 2003. Attitudes Towards the Development of Wind Farms in Ireland. http://www.sei.ie/uploadedfiles/RenewableEnergy/Attitudestowardswind.pdf. Accessed 31 January 2012.

SEIA (Solar Energy Industries Association). 2008. *Poll Reports 94% of Americans Say It's Important for the U.S. to Develop and Use Solar Energy*. http://www.seia.org/cs/news_detail?pressrelease.id=113. Accessed 31 January 2012.

Torresol Energy, n.d. Plants. *Gemasolar*. http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en. Accessed 31 January 2012.

Warren et al. 2005. 'Green on Green': Public Perceptions of Wind Power in Scotland and Ireland, *Journal of Environmental Planning and Management*, 48(6), 853-875. http://www.your-energy.org/pdf/windfarmpaper121205.pdf. Accessed 31 January 2012.