CLOSED LANDFILLS TO SOLAR ENERGY POWER PLANTS: ESTIMATING THE SOLAR POTENTIAL OF CLOSED LANDFILLS IN CALIFORNIA

by

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Abstract

Solar radiation is a promising source of renewable energy because it is abundant and the technologies to harvest it are quickly improving. An ongoing challenge is to find suitable and effective areas to implement solar energy technologies without causing ecological harm. In this regard, one type of land use that has been largely overlooked for siting solar technologies is closed or soon to be closed landfills. By utilizing Geographic Information System (GIS) based solar modeling, this study takes an inventory of solar generation potential for such sites in the State of California. The study takes account of various site characteristics in relation to the siting needs of photovoltaic (PV) geomembrane and dish-Stirling technologies (e.g., size, topography, closing date, solar insolation, presence of landfill gas recovery projects, and proximity to transmission grids and roads).

This work reaches three principal conclusions. First, with an estimated annual solar electricity generation potential of 3.7 million megawatt hours (MWh), closed or soon to be closed landfill sites could provide an amount of power significantly larger than California's current solar electric generation. Secondly, the possibility of combining PV geomembrane, dish-Stirling, and landfill gas (LFG) to energy technologies at particular sites deserves further investigation. Lastly, there are many necessary assumptions, challenges, and limitations when conducting inventory studies of solar potential for specific sites, including the difficulty in finding accurate data regarding the location and attributes of potential landfills to be analyzed in the study. Furthermore, solar modeling necessarily simplifies a complex phenomenon, namely incoming solar radiation. Lastly, site visits, while necessary for validating details of the site, are largely impractical for a large scale study.

Chapter 1 : Introduction

This chapter provides an overview of renewable energy, solar electricity, landfills and solar radiation modeling in order to establish the environment surrounding implementation of solar technologies at closed landfill sites. The present environment of renewable energy and solar electricity is explored. Photovoltaic and solar thermal technologies are also introduced. Issues surrounding landfills are discussed along with the rational of collecting solar energy at such locations. Finally, basic theory for solar modeling is described.

1.1 The Current State of Renewable Electricity

To contextualize the potential found for harvesting solar power at landfills, present global and renewable energy environments are explored. The world's energy demands and the types of energy used to fulfill this demand are discussed to highlight the need for local and renewable energy sources. The challenges and potential of renewable energy are also discussed.

Today, the world's energy outlook is increasingly dim; although the pool of resources is shrinking, total demand for energy is rising. From a 1998 baseline, the world's energy consumption is predicted to double by 2035 if present trends continue (Demirbas 2009, 213). High energy costs and global warming concerns have influenced some nations to incentivize alternative energy sources (U.S. Energy Information Administration 2012a, 74).

Renewable energy sources like solar, wind, biomass, hydroelectric, and geothermal are often looked to as a solution to the planet's energy situation, yet the technologies make up a small fraction of energy consumption. The world uses renewables for only 14 percent of its total energy consumption (Demirbas 2009, 215). In the United States, renewables make up an even smaller share, about 8% of total energy consumption (U.S. Energy Information Administration

2012a, 76). With the exception of hydroelectric and wind energy, there are significant technological, political, and economic challenges associated with new energy technologies (Bravo, Casals, and Pascua 2007, 4879). These obstacles must be overcome in order to make the technology more appealing to investors.

In spite of these setbacks, the estimated potential of renewables is increasing. Wind energy, for instance, was once thought to only have the potential to contribute 5 percent of the energy demand, but today contributions of 25 percent seem possible. Denmark has shown the viability of an electric generation system where wind power could supply 50 percent of their total energy consumption (Bravo, Casals, and Pascua 2007, 4880).

Predictions concerning the future energy contribution of renewable energy vary. Globally, Demirbas (2011, 218) estimates a renewable energy contribution of 50 percent by 2040. Bravo, Casals, and Pascua (2007, 4892) demonstrate the possibility of renewable energy as the sole energy source for Spain by 2050. In the United States, the Annual Energy Outlook predicts that 14 percent of national energy consumption will be derived from renewable sources by 2035 (U.S. Energy Information Administration 2012a, 76). Although these figures were derived from different scopes and timeframes, they nonetheless illustrate the disparity between predictions for the future of renewable energy.

The outlook of renewable energy is dependent on somewhat unpredictable factors like policy, the private market, and technology development; even so, most agree that developing renewable energy is both inevitable and necessary. Sufficient, inexpensive, and environmentally benevolent energy sources contribute to a nations’ sustainable development (International Atomic Energy Agency and the United Nations Department of Economic and Social Affairs 2007, 2).

1.2 Solar Electricity

There are numerous advantages and challenges associated with using solar power and several types of solar power collecting technologies. While solar power is abundant, clean, and versatile, it provides only a small fraction of U.S. energy needs at the present. Solar power can be derived from photovoltaic or solar thermal technologies. These technologies can be passive or active, and concentrated or non-concentrated.

Solar energy has many advantages, the largest of which is the abundance of the resource. Solar radiation is the most plentiful energy source on Earth and is said to be sufficient to meet the present global energy needs “thousands of times over” (Byrne and Kurdglashvili 2010); Zweibel (2008, 64) states that the sunlight that strikes the earth in forty minutes is equal to the world’s annual anthropogenic energy demand. It should be emphasized, however, that this figure does not account for radiation needed to power animal and plant processes. Furthermore, capturing a significant portion of this energy is extremely difficult using current technologies given existing efficiency factors. Although solar energy is not a panacea to the world’s energy problems, solar radiation has the potential to be an abundant resource contributing to the world’s renewable energy.

In addition to the abundance of the energy source, solar power has further advantages. Technologies used for converting solar radiation into energy have the advantages of decentralization, modularity, and high potential for integration (Bravo, Casals, and Pascula 2007, 4885). These characteristics allow solar devices to be installed in a variety of environments, including those with variable terrain such as landfills.

In spite of these benefits the current U.S. solar industry is small, but is gaining momentum. Presently, solar energy produces only 0.4 percent of total renewable energy and achieves an average annualized power increase of 11.7 percent. Solar power is the fastest growing source of renewable energy according to the 2012 Annual Energy Outlook report (U.S. Energy Information Administration 2012a, 75). Byrne and Kurdglashvili (2010, paragraph 5) project that these technologies will double in efficiency within five to eight years and that the cost of production will continue to fall.

There are a variety of solar device types, each with different installation requirements, efficiency factors, and other characteristics vital to determining it's energy production potential. Probably the most basic division in solar power technologies is the difference between solar thermal and photovoltaic (PV) technology. Solar thermal technology uses heat captured from irradiation to drive thermal engines for electricity production or heat water for household use. The present study focuses on the former type of thermal energy. Contrastingly, photovoltaic cells convert electricity directly into electricity (Byrne and Kurdglashvili 2010). More about these types of solar power can be found in Section 1.3.

Solar collectors can also be passive or active. Passive solar applications harvest solar radiation without the use of mechanical devices and are therefore static. This is in contrast to active solar technology, which utilizes mechanics to dynamically reposition solar collection devices.

Finally, some solar power collecting devices are concentrated while others are not. Concentrated solar applications use lenses, dishes and other systems to concentrate radiation, directing waves to one concentrated area. Solar devices that are not concentrating do not use such systems and absorb incoming radiation without modifying the irradiation.

1.3 Solar Technologies Used in Model

To estimate the potential of harvesting solar radiation at landfills, specific technologies most suitable to these sites must be chosen. This is needed to determine values used for energy production calculation for the specified technology, and to find areas suitable for the installation of the chosen devices. The following section describes various technologies used to harvest solar energy while rationalizing this study's use of dish-Stirling and PV geomembrane technologies.

1.31 Photovoltaic Technologies

One technology used in the present study is a type of photovoltaic system; specifically PV geomembrane installations are explored. The following paragraphs describe various types of photovoltaic technologies and justify the use of PV geomembrane technology in this study.

The first photovoltaic cell was made of both p- and n- type silicon by Bell Telephone Laboratories more than fifty years ago (Beek and Janssen 2009, 321). When the sun shines on a solar cell the radiant energy is converted into direct current (DC), which is then inverted to alternating current (AC) for use. The efficiency of this operation is dependent on technical factors like the technology used, economic constraints, and the suitability of the site to the particular solar device.

Photovoltaic technology can be divided into three generations. The first uses crystalline materials to form ridged solar panels. Second generation cells use materials such as Copper Indiium Deselenide, Cadmium Telluride, and Gallium Arsenide to form a thin film solar collector. Third generation cells are made of very efficient material, but have not made it past research in laboratories (Patel 1999, 27).

First generation PV technologies are generally more efficient than second generation ones. Compared to first generation cells, thin film technology is relatively new, as the first real wave of thin film solar cells did not occur until 2007. First generation technologies have had significantly more time for development.

The lack in efficiency for second generation cells is often offset by the fact that thin cells are significantly cheaper to produce (Yang 2011, 335 - 336). The relatively little material used in second generation thin film cells significantly reduces the fabrication costs of these devices. A series of studies by the U.S. National Renewable Energy Laboratory (NREL) and Environmental Protection Agency (EPA) determined that second generation cells provided more energy per dollar invested than first generation cells (Lisell and Mosey 2010; Salasovich and Mosey 2011a; Salasovich and Mosey 2011b; Salasovich and Mosey 2011c; Stafford, Robichaud, and Mosey 2011; Salasovich and Mosey 2012). More on these studies can be found in Chapter 2 of the present work. Based on these results, the current study explored the potential of second generation PV collectors rather than first generation devices.

Second generation PV systems seem to be gaining momentum in the photovoltaic market. Yang (2011, 335) reports that thin film system efficiencies rose from 4 percent efficiency in 1995 to 11 percent by 2010. This efficiency factor indicates the technology produces electricity equivalent to approximately 11 percent of incoming solar radiation. Green (2007, 15) shows efficiencies of 4 to10 percent; however, later Green (2010, 88) explored a variety of materials to be used for thin film PV cells and showed the possibility of using $SulnGaSe^2$ modules to achieve a 27.6 percent efficiency rate. In 2011, Lee, Chen, and Kang (2011, 1271) state that conversion efficiencies are currently less than 12 percent for silicon thin film technologies. Considering these numbers, this study used 11 percent as an efficiency factor for thin film photovoltaic systems.

PV geomembrane has several advantages over other types of PV technologies. Instead of using ridged panels, the membrane lays flat over a surface; therefore, the flexible thin film can be installed in areas of high slope and adaptable to the constantly shifting terrain found in closed landfills. Also, since these devices are not raised off the ground, they are not as visible as rigid panels and therefore the geomembrane has an inherent aesthetic advantage. Lastly, PV geomembrane weighs less than ballasted systems, which can be an important factor when siting such technologies on landfills. Because of these advantages, PV geomembrane was used to determine the solar energy production of closed landfills in this study.

1.32 Solar Thermal Technologies

Solar thermal technologies are very different from PV systems. The following section provides reasoning for using dish-Stirling technologies to estimate the solar thermal energy production at closed landfills. Solar thermal technologies utilize a different method of converting the sun's rays to electricity. Rather than directly producing electricity from sunlight like photovoltaic cells, thermal power must heat up a medium to indirectly power an engine.

Solar thermal power has a few key differences compared to photovoltaic technology. Thermal systems are cheaper compared to energy output and have reduced the problem of intermittency common in solar applications. Unlike photovoltaic systems, solar thermal technology has the potential to store power in the form of heat for times when there is little or no sun; thermal solar plants also address the issue of intermittency because the technology can be supplemented with natural gas to generate power when solar radiation is absent (Lehman 2011, 5). A disadvantage of the technology is that it only takes advantage of direct solar radiation while photovoltaic systems take advantage of global radiation (Price and Margolis 2010, 53; Lehman 2011, 15).

Solar thermal technology has experienced success using lenses and reflectors to concentrate the sun's rays into high-temperature heat in what is known as concentrated solar thermal power (CSP) (Lehman 2011, 5). A CSP has three main components. The solar collector field is a set of mirrors and reflectors that focus the radiation to the receiver. The solar receiver transforms the radiation to heat. Lastly, the energy conversion system transforms the heat into usable energy (Schild 2004, 8).

Several types of CSP systems exist. One such technology is parabolic trough CSP; the parabolic shaped trough uses mirrors and an integral receiver tube. Contrastingly, central tower systems receive solar radiation through hundreds of sun tracking flat plane mirrors known as heliostats. Molten salt or synthetic oil is pumped through a solar receiver located within the tower where the hot liquid produces steam to power an engine.

Parabolic dishes are a third type of solar thermal collection device. The dishes are covered in mirrors to reflect radiation into a receiver, which uses heat to power a thermal engine, usually a Stirling type. A Stirling engine is a type of thermal engine powered by the compression and expansion of a gas. This type of CSP, previously and hereon referred to as dish-Stirling, was be explored in the current work because of the many advantages of this technology.

As a result of low costs and high efficiency, dish-Stirling systems are particularly suitable for decentralized use (Gabriel 2006, 76). Smaller installations of dish-Stirling systems are possible when compared to central tower and parabolic trough systems (Schild 2004, 12). The ability to install small-scale, high efficiency systems makes dish-Stirling systems best for CSP installation on landfills.

Additionally, dish-Stirling systems do not require large amounts of water. Water can be a key factor in determining the feasibility of a solar thermal plant, since it is necessary for cooling in the Rankine cycle which is used the generation of electricity for these technologies (Lehman 2011, 22). Unlike other solar thermal technologies, dish-Stirling systems use a Stirling engine, which does not require large quantities of water to produce electricity (Dahle 2008, 31).

Furthermore, dish-Stirling systems have a unique advantage over other types of CSP when used at closed landfills. Stirling engines have the potential to be powered by another resource available at landfills, landfill gas (LFG). Although still under development, Stirling engines are being developed capable of running on LFG (SCS Engineers, 1995, 2.27 – 2.29; Tsatsarelis et al., 2006, 5). Although an example of a combination dish-Stirling and LFG system could not be found, this potential makes LFG to energy facilities pair particularly well with dish-Stirling CSP.

Dish-Stirling technology is generally the most efficient of solar thermal systems. Currently, parabolic trough systems range from 15 - 21 percent efficiency, power towers range from 18 to 20 percent, and dish-Stirling systems operate at 25 - 30 percent efficiency (Gastli and Charabi 2009, 794). Gabriel (2006, 76) states that the technology has achieved 30 percent efficiency. Schild (2004, 9) shows an efficiency of 29 percent for parabolic dish systems linked to Stirling engines. For the purposes of this study, an efficiency rating of 25 percent was assumed for dish-Stirling systems.

1.4 Economic Rationale for Solar Development at Closed Landfills

Landfills are a necessity for waste disposal in most modern societies, yet they may result in numerous environmental and health risks. Once closed, landfills represent environmentally damaged land that is difficult to develop into lucrative facilities. Nonetheless, this study is largely motivated by the economic and environmental justification for the viable development of landfill sites to harvest solar energy.

Beginning in October, 1991, the U.S. Environmental Protection Agency set criteria for the closure and regulation of municipal solid waste landfills. These laws can be found under the EPA's Resource Conservation and Recovery Act's Subtitle D (EPA 2012b; EPA 1993, 3 - 4). Subtitle D regulations structured landfill closures and made their redevelopment safer (O'Connell 2001, 46 - 50). Landfills that closed before EPA Subtitle D regulations controlled closing procedures are undesirable for reuse, since unknown hazards and structural complications may be present.

As defined by Subtitle D, cover systems may cost a total of ten to hundreds of thousands of dollars per acre (O'Connell 2001, 47). Typical uses for closed landfills may include a park, animal refuge, golf course, parking lot, and commercial or industrial buildings; these land uses usually do not contribute enough income to absorb these closing costs (O'Leary and Walsh 2003, 44). By converting landfills to sources for renewable energy, owners may be more likely to cover these costs. Solar facilities sited on landfills represent a profitable use on land that is difficult to develop. Because of their economic and environmental advantages, the U.S. EPA supports building renewable energy facilities on closed landfills and other contaminated lands (Sampson 2009, 1).

In order to determine how much solar potential exists on landfills, the number of sites fit for particular types of solar installations must be known. However, because of the absence of modern regulations before 1991, the actual number of closed landfills in the United States is uncertain. O'Connell (2001, 47) found the number of landfills closed in the past decade to be between 4,000 and 7,400 and Suflita et al. (1992, 1486) indicate there are as many as 100,000 closed landfills in the United States. As can be seen in the large variation in these figures, there is great difficulty in obtaining accurate data on closed landfills in the United States. A significant challenge for this study was to determine the number, location, and extent of recently closed landfills in order to further assess for solar energy potential.

1.5 Landfill Gas to Energy Facilities

Landfills produce LFG, which can then be turned into energy. This process is described below. Additionally, the extent to which LFG to energy facilities have been developed in the United States is discussed.

Landfills produce methane through a three stage anaerobic digestion, where the gas is produced by methanogenic bacteria (Themelis and Ulloa 2006, 1247) which can be used to harvest energy. LFG is typically composed of predominately methane and carbon dioxide and therefore can be used for a source of energy. Once a landfill ceases to receive refuse, the gas production rate reaches its peak in one or two years, and LFG can be produced for five to eighteen years (Malik, Lerner, and Maclean 1987, 78). Some landfills have been equipped with systems to capture these gases and convert them to energy, where LFG is collected and sent to combustion engines where it is transferred to energy (Malik, Lerner, and Maclean 1987, 77 - 79).

Willumsen estimates that as of 2001, around 955 landfills recover landfill gas worldwide, with capacities ranging mostly between 0.3 to 4 MW as quoted in Themelis and Ulloa (2006, 1244). Of these, 325 reside in the United States, the most facilities in the world. This number rose to 380 by 2004 according to the U.S. EPA. The U.S. EPA also estimates that LFG to energy facilities in America have a total nameplate capacity of 1.07 GW (Themelis and Ulloa 2006, 1244 - 1255). Nameplate capacity refers to the maximum energy that may be generated by LFG to energy facilities as rated by manufacturer specifications.

Landfill gas to energy facilities are well established in the United States. For example, in 1993 the Metro Waste Authority based in Des Moines, Iowa partnered with private businesses to develop a LFG to energy facility. The site produces the energy equivalent of 112,000 barrels of oil annually (Rasmussen 2005, paragraph 3). The largest landfill gas to energy facility in the Nation is located just outside of Los Angeles, California at the Puente Hills landfill. This site uses biogas to fuel a 50 MW turbine generator (Themelis and Ulloa 2006, 1244).

The presence of landfill gas collection for energy facilities at closed landfills may provide an additional incentive to solar development because a complementary, established energy source would already be available. LFG to energy systems have the potential to power a Stirling engine and could therefore be complimentary to dish-Stirling systems (SCS Engineers 1995, 2.27 – 2.29; Tsatsarelis et al. 2006, 5). This potential shared infrastructure between the two technologies may result in higher return on investment (ROI) for these facilities. Additionally, LFG power could provide energy to the grid when solar power cannot be harvested at night or under overcast conditions. However, since the engineering for this shared Stirling engine has not yet been completed, benefits from increased ROI and decreased intermittency cannot be quantitatively measured and thus are not included in the present study.

1.6 Siting Grid-Connected Solar Power Plants on Closed Landfills

Closed landfill sites have already been used to successfully harvest solar radiation for energy using two separate types of PV systems: ballasted first or second generation panels and PV geomembrane film.

In the more traditional type of solar power development on landfills, PV panels are placed on the site using a ballasted rack tilted to receive optimal radiation. These systems can be fixed in tilt or installed with a single-axis tracking system at the price of additional monetary cost and weight. An example of a fixed tilt ballast system can be found in Middleton, Wisconsin; the landfill supports a 10 kilowatt (kW) crystalline silicon PV system that covers an area of roughly 3,400 ft^2, which is 0.9 percent of the 378,384 ft^2 site (Salasovich and Mosey 2011a, 12).

The second PV technology type used on landfills involves PV thin film placed directly over the landfill. Known as solar covered landfills, these sites utilize flexible thin film PV geomembrane to cover the landfill. The system serves a dual purpose, working as a cover to cap the landfill and as a PV collector to generate electricity. The Hickory Ridge solar covered landfill near Atlanta, Georgia is an example of one of these landfills. There are only a handful of these facilities in the United States and the technology is still being developed (Salasovich and Mosey 2012, 4). Nonetheless, the current study used PV geomembrane to estimate the inventory of potential power generation because of the inherent benefits of the technology.

1.7 Estimating Solar Radiation

The measurement of solar potential is a complex undertaking involving many interconnected variables. This process is described below, emphasizing how the phenomenon varies over space.

Solar radiation reaches the earth in three ways. Direct irradiance originates from the sun while diffuse sky irradiance is scattered by atmospheric particles before reaching the ground. Additionally, reflected radiation coming from both diffuse and direct irradiance may be reflected off of nearby terrain (Dubayah and Rich 1995, 406). A solar model ideally accounts for all three of these radiation types, which vary greatly with geography (Hetrick et al. 1993, 132 - 133; Dubayah and Rich 1995, 406 - 408; Kumar, Skidmore, and Knowles 1997, 475).

Byrne and Kurdgelashvili (2010, paragraph 1) point out that this solar influx is affected both by geographic variation and diurnal, or daily, processes. Solar radiation varies over time and space in the following ways: the Earth's geography including declination, latitude and solar angle; the location's terrain including elevation, surface inclination, orientation, and shadows; and atmospheric attenuation which includes gas in the atmosphere, atmospheric particles, and cloud cover (Hofierka and Súri 2002, 2).

The atmospheric scattering of solar radiation takes two forms. Rayleigh scattering refers to the dispersion of radiation via atmospheric gas molecules. Turbidity from water vapor and pollution further separates the sun's rays (Hetrick et al. 1993, 134). The air mass through which radiation must pass changes throughout the day since atmospheric attenuation is greater in the morning than it is in the afternoon (Kumar, Skidmore, and Knowles 1997, 478).

1.8 California as Location for Solar Inventory

California was chosen in the current study as a location to perform a first inventory measuring the potential of dish-Stirling and PV geomembrane solar facilities on closed landfills. The State has policies favorable to renewable energy development and aims to receive a third of consumed energy from renewable sources by 2020 (Office of Planning and Research 2013). While other states may receive greater solar radiation, California's mix of this resource and dense population makes the State particularly suitable for this study. Additionally, California is the leader in U.S. solar energy production, generating a larger proportion of electricity from solar power than any other EPA Emissions and Generation Resource Integrated Database (eGRID) region according to EPA's 2009 eGRID Summary Tables (EPA 2012a). Finally, California was chosen because EPA national landfill data is limited, and the State's California Energy Commission (CEC) provided supplementary data on landfills to be analyzed in this study.

Although landfills analyzed in the present study are spread throughout California, this analysis provides an inventory of individual sites at a small scale. With this in mind, the overall solar environment of California must also be kept in mind. Figure 1 illustrates the general picture of overall solar resources available at California landfills by displaying sites analyzed in the present study with incoming solar direct normal irradiance (DNI) from NREL data (2012). These sites were taken from EPA and CEC databases, and closed, or will close, between 1992 and 2022; the location data for each site was also verified to produce the landfills shown in Figure 1.

Other inventory studies for solar radiation, discussed in Section 2.4 of this work, are either site specific or measure an entire region; the current study is similar to these site specific studies, which generally measure the solar potential of rooftops. By limiting the present study to landfills, the proposed solar facilities would exist on already ecologically disturbed land; often California’s desert regions are looked to as a location for solar facilities, however this landscape is ecologically sensitive and solar installations disrupt virgin landscape and habitats (Abbasi and Abbasi 2002, 132).

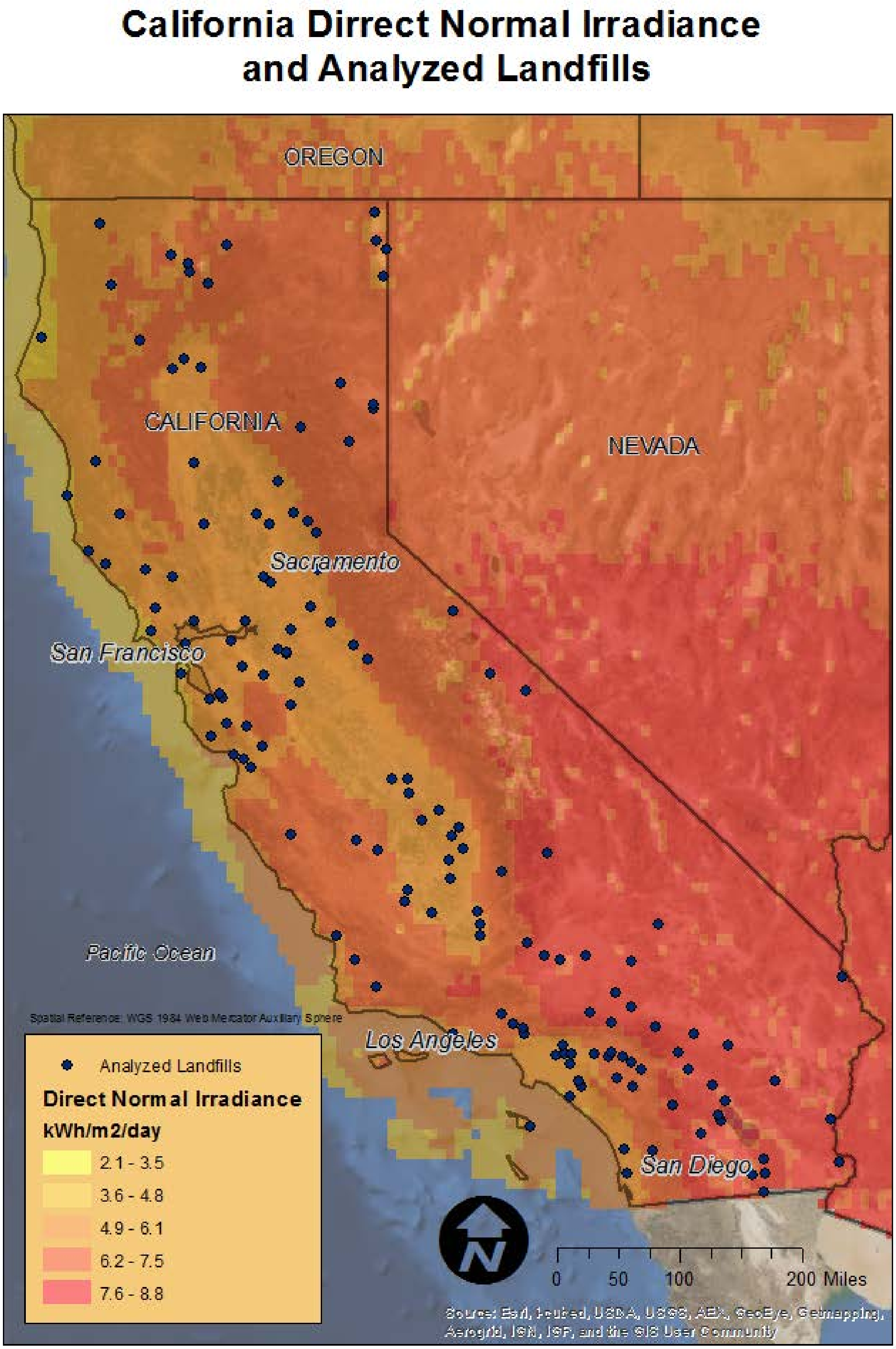


Figure 1 - California Direct Normal Irradiance and Analyzed Landfills

1.9 Document Structure

The remainder of this report is organized as follows. Chapter 2 discusses literature concerning models and studies relevant to estimating solar radiation. Next, methods used in the current study are identified and explained. Results from this analysis are then presented in Chapter 4. Finally, Chapter 5 discusses these findings and contextualizes them.

In the literature review of the present work, past studies and models are reviewed to illustrate various methods for modeling solar radiation. Models using GIS to estimate irradiance are explored in addition to studies using fuzzy membership to predict the phenomenon. Furthermore, studies that take an inventory of solar potential of a given area are summarized since they share a common goal with the current work. Lastly, a series of studies estimating PV potential in specific landfills conducted by NREL and EPA are described. These studies are particularly relevant because, like the present work, they estimate solar power production potential at landfill sites.

The methodology of this study's analysis is broken up into a three part process. It was first necessary to compose a list identifying landfills with potential for harvesting solar radiation collection methods; these sites were then prescreened based on the age of the landfill, presence of accurate location data size, and proximity to roads and transmission lines. A sample was taken from sites that met prescreening requirements, which was then analyzed for solar potential for both PV geomembrane and dish-Stirling using ArcMap. ArcMap was utilized to analyze terrain and estimate solar irradiance. Results from this sample were then generalized to estimate the solar production capacity of landfills in California.

The results chapter reviews the outcomes from the methodology described above. Both prescreening and detailed analysis results are examined. Furthermore, sampling theory is used to generalize results from sampled landfills to the total population of California.

These outcomes, and the study in its entirety, are discussed in this work's final chapter. Results are contextualized by comparing them to the current energy environment in California and past studies. Chief findings from this study are also illustrated here. Assumptions and limitations of this work's methods are then discussed. Finally, areas where future work is needed are explained.

Chapter 2 : Literature Review

The following literature review discusses past studies and models in order to take advantage of modern advances in the field of modeling for solar potential. Various GIS models designed to estimate solar radiation are described. Because of its extensive use in the field of spatial solar modeling, studies using fuzzy logic are also explored along with the variables used in these models that go beyond solar radiation.

The present work takes an inventory of solar radiation potential, specifically at landfill sites. Therefore studies that also take inventory of such potential are reviewed. Additionally, a series of studies conducted by EPA and NREL that explore the potential of landfill sites producing solar power from various PV technologies are summarized.

2.1 GIS Models for Solar Analysis

GIS models have been developed to estimate a location's incoming solar radiation, and these models are outlined in Table 1. The following spatial models utilize different software and parameters, and a brief introduction to such systems is provided. The present analysis utilizes one such model, Esri's Solar Analyst, for incoming solar radiation estimates.

One of the first GIS based solar radiation models was SolarFlux, which was developed for Esri's ArcInfo. Hetrick et al. (1993) created a model to integrate the many influences on solar radiation utilizing a GIS framework. SolarFlux determines solar potential from an area's surface orientation, solar angle, horizon shading, and atmospheric conditions (Hetrick et al. 1993, 133).

Similarly, solar analysis was performed using automation mark-up language (AML) script with the commercial GIS software, GIS Genasys. GIS Genasys solar radiation algorithms worked similarly to the Solar Flux model, but uses different software (Hofierka and Súri 2002, 1-2).

Using Microsoft Windows, a standalone model called Solei was used to estimate solar radiation and was linked to the GIS software, IDRISI, by using identical data formats. The model differs from the two previously discussed models by accounting for elevation through a raster Digital Elevation Model (DEM). However, all three models discussed thus far use spatially averaged parameters according to Hofierka and Súri (2002, 1 - 2).

The r.sun model proposed by Hofierka and Súri (2002) aimed to overcome the limitations of the aforementioned models. The application is appropriate for large areas, considers the effects of terrain and shadowing, and can simulate overcast conditions and its effect on irradiation. R.sun utilizes Geographic Resources Analysis Support System (GRASS) GIS, taking advantage of advanced interpolation techniques and accounting for land use and environmental concerns to model the complex process of solar radiation.

Pons and Ninyerola (2008) developed a simple model whose only input is a DEM, yet this radiation model had demonstrated significant accuracy. The methodology is composed of a physically based model to determine potential solar radiation and a process that uses meteorological data to refine this potential. Using MiraMon GIS software, Pons and Ninyerola's model estimates solar radiation and accounts for astronomic, atmospheric and geographical variables. The success of this model highlights the importance of elevation in general, and DEMs in particular, in estimating solar potential.

Table 1 - GIS Models for Solar Analysis

Model's Name	*Source*	*Technology Used*	*Summary*
SolarFlux	Hetrick et al. (1993) Hofierka and Súri (2002)	ArcInfo	Based on solar and atmospheric conditions
GIS Genasys solar radiation algorithms	Hofierka and Súri (2002)	GIS Genasys AML script	Algorithms similar to SolarFlux
Solei	Hofierka and Súri (2002)	Microsoft Windows and GIS IDRISI	Estimates solar radiation from DEM
R.sun	Hofierka and Súri (2002)	GRASS GIS	Considers terrain, shadowing, and climate using interpolation techniques
MiraMon GIS Model by Pons and Ninyerola	Pons and Ninyerola 2008	MiraMon GIS	Accounts for astronomic, atmospheric and geographical variables and uses DEM
Solar Analyst	Fu and Rich 1999	ArcInfo/ArcGIS	Uses DEM and location data with advanced algorithms

2.11 Esri's Solar Analyst

The most commonly used GIS program for solar analysis today seems to be Solar Analyst, available in Esri's ArcGIS. Solar Analyst uses elevation data to measure solar radiation over time. This tool was created by Fu and Rich (1999) as part of the Spatial Analyst Extension. Solar Analyst was utilized in the present work because of its accuracy and ease of use.

Esri's Solar Analyst model, summarized in Table 1, combines various algorithms to estimate incoming solar radiation over time. The model uses an input raster, such as a digital elevation model, a latitude value, time configuration, and additional parameters to model solar radiation. The tool estimates global, direct, or diffuse radiation for a given period of time. As of ArcMap 10.1, the Solar Analyst calculations are available via the Area Solar Radiation tool, which requires the Spatial Analyst Extension (Esri 2012). Additional details and specific methods used by Solar Analyst can be found in the Chapter 3 of the present work and Esri's help page for the tool (Esri 2012).

Fu and Rich (1999, 1) created the Solar Analyst extension out of a need for "expanded functionality, accuracy, and calculation speed" of GIS solar radiation modeling. Optimized algorithms were created to account for the complexities of solar irradiance including viewshed, hillside, surface orientation, atmospheric conditions, and elevation calculations. The model's accuracy was validated by comparing the outcomes to empirical results within the vicinity of Rocky Mountain Biological Laboratory (RMBL) located in Gothic, Colorado.

The RMBL hosts four weather stations. The first of which was established in 1989 by the EPA while the other three were completed in 1997 to monitor climate change and global solar radiation. Data from these monitoring stations were averaged and recorded in both hourly and two-hour intervals. An analysis of this empirical data was then compared to those produced by the model (Fu and Rich 1999, 18).

Solar Analyst has been used by several studies because of its accuracy and usability. Gastli and Charabi (2009, 793) used it in their study of solar electricity prospects in Oman and cited several benefits of the model. It enabled them to analyze and map the effects of solar radiation over time and space while accounting for atmospheric effects, latitude, elevation, slope, aspect, shifts of the sun angle over time, and the effects of shading from local topography. Huang and Fu (2009) used the tool to create solar and temperature distribution maps for Yellowstone National Forest. The Spatial Analyst enabled the team to "efficiently implement time consuming processing of this data in a timely fashion" (Huang and Fu 2009, 28).

A DEM, which serves as the primary input of the tool, is a well-established data format for elevation. In their work Huang and Fu (2009, 28) state that topography is the major factor in determining the spatial variability of insolation. It is therefore fitting that a DEM is the primary input for the Solar Analyst model. Fu and Rich used a 30 meter DEM constructed from United States Geological Survey (USGS) 7.5' quadrangles (Fu and Rich 1999, 18), though the model accepts DEM's of various sources and resolutions.

2.2 Studies using Fuzzy Logic Modeling for Solar Analysis

Fuzzy logic modeling has widely been used to analyze an area's solar potential. This multi-criteria approach is able to find optimal areas for solar energy harvesting and is especially useful for screening large areas such as counties, states, and nations. Investigating specific, predetermined and widespread land uses negates the need for this large scale prescreening analysis and instead dictates a more detailed examination of each site. Nonetheless, the following studies display the importance of multi-criteria modeling when analyzing an area for solar power harvesting potential.

Fuzzy membership models have been created at national scales. Badran and Sarhan (2008) developed a model that uses fuzzy logic to assess Jordan's solar potential. Parameters such as solar resources, site capacity, site accessibility, soil condition, water availability, grid connection distance, land cost, land roughness, and wind speed were used in the model. Salim (2012) used a fuzzy logic model to determine the viability of solar desalination in Egypt, considering solar radiation, aquifer depth and salinity, proximity to water sources, and the presence of hazards or seawater intrusion. Aydin (2009) utilized fuzzy membership rules to assess Turkey's wind and solar potential considering protected and agricultural areas, transmission line distance, slope, and other parameters.

Janke (2010) studied the solar and wind power potential of Colorado using both GIS and a multi-criteria membership analysis. The study considered incoming solar radiation, environmental and land use considerations, and proximity to resources. An area's distance to nearby resources, as seen in many of the above studies, was an important part of this study's prescreening analysis.

Furthermore, Lehman (2011) created a model to estimate the feasibility of concentrated solar thermal facilities in San Bernardino County, CA. This study made use of the Weighted Overlay tool in ArcMap to establish fuzzy membership, while taking into account many environmental variables. The present study also took advantage of ArcMap software, while focusing on analyzing specific sites rather than conducting a site selection analysis.

Rylatt, Gadsen and Lomas (2001) developed a decision support model for energy planning that focused on a specific land use, the rooftop of buildings. The model's parameters included latitude, mesoclimatic factors, microclimatic characteristics, building codes, roof angle and space, and socio-economic characteristics of homes. Socio-economic factors, which included information on income, residency, and ownership, where used in a fuzzy membership application. The model was used to find homes with ideal socio-economic conditions, and this data was inserted into the rest of the model.

2.21 Non-Solar Radiation Variables used in Solar Models

The best models that estimate solar resources consider variables beyond solar radiation. Rylatt, Gadsen and Lomas (2001) used socio-economic factors to determine find the optimal homes to install a roof solar system. Lehman (2010) used inputs such as the location of Bureau of Land Management lands, Wilderness, parks, forests, conservation areas, Critical Habitats, and proposed Wilderness in order to account for environmental concerns. Aydin (2009) uses similar environmental parameters. Bravo, Casals, and Pascua (2007) supplemented their model with land use restrictions and local environmental constraints. Badran and Sarhan (2008) used soil condition, water availability, grid connection distance, and land cost in addition to parameters that assess solar resources and capacity.

It should be noted that in the present study environmental and land use constraints are less constricting than in the above models since landfills are already disturbed land. Even so, there may well be competing potential land uses for the area. Nevertheless, considering these contending land uses is out of scope for this study because the relevant factors are very site specific.

Some non-solar radiation variables can be useful when siting renewable energy on disturbed land. Distances from a site to a usable transmission lines, roads, or natural gas pipelines for instance, are still important to consider when siting such facilities. There are precedents for using these factors in past studies measuring solar potential. Badran and Sarhan (2008) and Janke (2010) used transmission line distance as a parameter in their models. Additionally, Lehman (2011) used a site's distance to a natural gas pipeline to estimate the viability of installing CSP.

A landfill's proximity to resources like transmission lines and graded roads were used in the current study to add another dimension to suitability modeling. A site existing nearby transmission lines greatly simplifies the project development from the standpoint of public acceptance and lower overall costs. The site also needs to be located nearby a graded road, for practical maintenance and construction access.

A landfill's distance to natural gas lines was also observed. Natural gas lines are a resource since a nearby solar power facility could use natural gas to power thermal engines in times of little or no sunlight without the need to construct costly new gas lines. This could be used in addition to the LFG, and natural gas could take over when LFG runs low. However, because of the existence of a secondary power source at a landfill, LFG and the presence of gas lines are not strict preconditions for suitability.

2.4 Inventories of Solar Potential

Since the current study aims to take an inventory of potential solar power collection facilities on closed and soon to be closed landfills in California, studies that also take an inventory of such potential are explored. Some previous solar inventory site studies estimate the potential of PV systems, while others analyze solar thermal systems. Such inventory studies are listed in Table 2. Regardless of specific methods used in the following studies, a majority of them measure solar potential from total energy production, and this same type of measurement was calculated in the current study.

Table 2 - Inventories of Solar Potential

Type	Citation	*Subject*	*Location*	*Method*
Photovoltaic	Carrión et al. (2008)	Large-scale photovoltaic solar farms	Andalusia, Spain	R.sun GIS model and interpolation techniques
	Tadlock (2009)	Photovoltaic collectors for rooftops	Huntington, WV	Measurement of rooftop areas excluding north-facing slope
	Janke (2010)	Inventory for photovoltaic potential	Colorado	GIS and multi-criteria models used to rank areas for solar potential
	Van Hoesen and Letendre (2010)	Baseline inventory of incoming solar radiation from rooftops	Poultney, VT	Portion of rooftop multiplied by average annual solar radiation
	Arnette and Zobel (2011)	Large-scale photovoltaic solar farms	Appalachian area of the United States	GIS modeling with spacing and derate factors, economic analysis also conducted
Solar Thermal	Turchi et al. (2011)	Augmenting existing fossil-fired power plants with either power tower or parabolic trough CSP	United States southeast and southwest	ArcMap ranking system with minimum requirements
	Pan, Kao, and Wong (2012)	The authors investigate the potential of solar water heaters (SWHs) in Taiwan	Taiwan	SAM and regression analysis used to estimate capacity

2.41 Photovoltaic Inventories

Several studies conduct an inventory of photovoltaic potential using GIS models. First, studies that take inventory of solar potential of an entire region are discussed. Studies modeling rooftops are also summarized; like the present work, these studies take inventory of a particular land use.

Arnette and Zobel (2011) conducted an analysis of renewable energy within the greater southern Appalachian mountain area of the United States. A GIS model was created to determine the most suitable locations for large-scale photovoltaic solar farms within the region, an end goal analogous to the present study. The model considered both slope and aspect, rejecting areas with unsuitable terrain. Potential locations were narrowed further by only considering sites with an area greater than ten acres.

Arnette and Zobel (2011) found 477 individual sites within the greater southern Appalachian Mountains area; the potential of each location was based on associated cost and generation capacity. The productivity for each site was determined by its average kW/m^2, with 25 percent of the site removed to address spacing and shading concerns. An efficiency factor of 14 percent was then multiplied by this figure.

A derate factor, representing the energy lost when converting Direct Current (DC) to Alternating Current (AC), of 77 percent was also used. This derate factor means that the AC produced after converting it from DC is 77 percent as powerful as the original DC created by the power source. This factor represents a loss in electricity that some other models do not account for and is necessary to consider in inventory studies for solar farms, since solar devices produce DC, not AC which for the transmission grid.

The current work used a similar methodology to that used by Arnette and Zobel (2011). Although different specific criteria were used, the present study's prescreen analysis too rejected landfills that did not meet certain requirements. A slope and aspect analysis of the location's terrain was conducted in addition to estimating incoming solar radiation from average kW/m^2. Spacing and derate factors of 25 and 77 percent, respectively, were borrowed from Arnette and Zobel (2011) and an assumed efficiency factor was also be applied.

Janke (2010) conducted an inventory for photovoltaic technology, exploring the potential of solar farms within Colorado. Using weighted multi-criteria GIS modeling, Janke (2010) considered Watts of solar irradiation per m^2/day, nearby distance to transmission lines, close proximity to cities and population, and nearby distance to roads to characterize a favorable area. Based on this ranking, areas were given a score between 0 and 100. Scores of existing solar power facilities were noted to compare the model to real world solar production.

Carrión et al. (2008) calculated an inventory for large-scale photovoltaic solar farms in Andalusia, Spain. The study estimated solar radiation using the r.sun model and interpolation techniques described by Hofierka and Súri (2002). Since the study was focused on grid-connected facilities, only lands within 4 km of the outer limits of the city center were accepted. Additionally, areas with a slope more than 2 percent were eliminated because of shading concerns. A similar method is used in the present study's terrain analysis, which rejects areas of high slope.

For each suitable area, the total electricity generated was calculated from the product of the maximum power installed in kW, the performance ratio of the technology, the average daily global irradiation, and 365 days per year. A similar calculation was conducted in the current study. From this equation, Carrión et al. (2008) developed a map of annual photovoltaic electricity production in MWh within Andalusia, Spain. This map represents areas of suitable land and estimated power production from grid-connected photovoltaic power plants.

The above study is dissimilar than the present work in that its scope is an entire country, rather than one specific land use. Because its goal was to conduct a site suitability analysis as a basis for an inventory, many parameters used to eliminate potential areas differ from the current work. This inventory is measured, however, in total annual MWh. Such a measurement provides production potential of a given area. This figure is straightforward and easy to understand and is also the measurement chosen in the present inventory to represent the solar harvesting potential for landfills in California.

Van Hoesen and Letendre (2010) study the potential of multiple renewable resources in Poultney, Vermont, providing a baseline inventory of local and green energy sources. Solar potential of rooftop systems was calculated using GIS by digitizing rooftops and eliminating areas that are not south-facing by only considering 25 percent of the rooftop area, a figure was taken from the proportion of south-facing roof for the average Poultney building. The simplification of aspect is unfit for modeling specific land uses, including both rooftops and the landfills examined in the current work.

Tadlock (2009) studied the potential of applying photovoltaic collectors for rooftops in Huntington, West Virginia. Three neighborhoods were selected within Huntington, each representing different land use and socioeconomic patterns. The final study area consisted of four randomly chosen blocks within each of these neighborhoods. Rooftop areas were digitized and summed to find the usable space for solar installations. Potential power production was calculated based on these areas matched with various sized photovoltaic systems and irradiation values.

To account for non-south facing slopes, the total digitized rooftop area was divided by half, a similar method to that used by Van Hoesen and Letendre (2010). Calculating usable area in this way to account for slope orientation may be too general for estimating usable area at this small scale; chances are slight that nearly 50 percent of the rooftops analyzed did not face south. Additionally, this measurement does not account for areas that may be occupied by structures such as chimney or satellites and those shaded by nearby structures or vegetation. Lessons learned from these aspect analyses were applied to the methods used in the present work, which measured aspect and did not consider areas containing obstacles.

2.42 Solar Thermal Inventories

The following studies take inventory of solar potential from solar thermal technologies. In a study investigating the potential of solar water heaters (SWHs) in Taiwan; Pan, Kao, and Wong (2012) base solar potential on the annual ratio of effective days to non-effective days and effective solar radiation measurements. To evaluate the potential of these sites, the National Renewable Energy Laboratory's Solar Advisor Model (SAM) and regression analysis were used to estimate capacity factor and relative cost index. Satellite DNI data were used as irradiation values for these calculations and the sums of these calculations were added, finding the total annual Terra Watt hours produced. The study by Pan, Kao, and Wong (2012) is very different from the current work in that it estimates personal, residential systems that do not provide energy to the grid. Comparable to the present study, however, Pan, Kao, and Wong (2012) illustrate a multifaceted inventory of solar thermal systems that considers economic, technical, and solar environments.

Turchi et al. (2011) observed the potential of augmenting existing fossil-fired power plants with concentrated solar thermal power for sixteen states in the United States southeast and southwest. The augmentation of solar power to an existing power source is analogous to adding solar power facilities to landfills, which may have existing LFG to energy facilities. Turchi et al. (2011) used minimum requirements for a power plant to be considered, and then ranked them. The age and capacity of the fossil plant, DNI amount of available land, topography, and solar-use compatibility were all considered in this ranking system. Newer sites with large capacity, plentiful area, mild topography, and high compatibility for combination systems were ranked the highest.

The study by Turchi et al. (2011) provides lessons for the current work. The inventory considers the characteristics of fossil-fired power plants to rank the facilities potential for CSP augmentation. Some of the same characteristics used for this ranking system, such as the age, size, and topography were accounted for in the present work when analyzing the potential of landfills to host solar energy. Additionally, the above study uses minimum requirements to eliminate unfavorable areas before they are analyzed further. Likewise, the present work utilized a prescreening analysis that sorts out sites with low potential before a more detailed examination is conducted.

2.5 EPA and NREL Photovoltaic Potential in Landfill Studies

This study is not the first to analyze the solar potential of closed landfills. The United States Environmental Protection Agency and the National Renewable Energy Laboratory conducted a series of studies between 2010 and 2012 that investigated the feasibility of solar photovoltaic energy collection at brownfield sites, many of which included landfills (Salasovich and Mosey 2011a; Salasovich and Mosey 2011b; Salasovich and Mosey 2011c; Stafford, Robichaud, and Mosey 2011; Salasovich and Mosey 2012). Similarly, Lisell and Mosey (2010) explore siting renewable energy on a variety of brownfield sites in Nitro, West Virginia. This research was performed to encourage renewable energy at potentially contaminated locations as part of the EPA's Re-Powering America's Land initiative.

The EPA and NREL recognize that PV installation is a "promising and innovative use of closed landfills" (Salasovich and Mosey 2011a, 1). Because of this potential, the organizations analyze landfills and brownfield sites in several areas, including West Virginia, Puerto Rico, a Massachusetts Military Reservation, Wisconsin and Kansas (Lisell and Mosey 2010; Salasovich and Mosey 2011a; Salasovich and Mosey 2011b; Salasovich and Mosey 2011c; Stafford, Robichaud, and Mosey 2011; Salasovich and Mosey 2012).

2.51 General Methods

Some of these studies began with a site selection analysis. Salasovich and Mosey (2011b) and (2011c) preformed such an analysis to select landfills most suitable for PV installation in Puerto Rico. Sites passed the analysis that had a minimum size of 14 acres, were within one mile from 38kV transmission lines, and were near graded roads. The Puerto Rico study also screened the slope of sites, rejecting sites with more than 20 percent slope (Salasovich and Mosey 2011b, 8 - 10). A similar prescreening process was performed in the current work, considering size and proximity to transmission lines and roads before a more detailed analysis was performed.

After prescreening, many of the studies used on-site visits to find the total usable area for each site. Sometimes Google Earth was used in order to discover obstacles and other spacing concerns in place of a physical visit. The present study used the latter method for this task.

In order to predict the possible system size and production for each landfill or brownfield, the NREL used a combination of PVWatts and either SolOpt or the Solar Advisor Model (SAM).

PVWatts is a NREL PV system performance calculator used to estimate the performance data of a PV system and these data were used to determine annual revenue for each site. SAM is another NREL application that complements these data and can be used to model impacts of various costs, system performance, government incentives, return of investment, and other financial and performance characteristics (Blair, Mehos, Christensen, and Cameron 2008, 1). Alternatively, the SolOpt Optimization Tool analyzes system production, design and financial components and provides data regarding the most effective system for a given environment and tool utilizes unique parameters unavailable in SAM and therefore may be better suited for certain studies (Lisell, Metzger, and Dean 2011, 23). These tools were used to estimate optimal performance for each site using various technologies and additional financial calculations were made to estimate costs and payback periods for each location and technology included in the study.

2.52 Results

All sites, with the exception of the Johnson County Landfill, were found to be feasible for PV installation (Salasovich and Mosey 2012). Of the 311 acres analyzed at this landfill, 43 percent of the area was either presently feasible for PV installation or will be viable in the future when refuse disposal ceases in the area. The remaining 57 percent of the landfill was too sloped or had an unfavorable orientation for PV installation (Salasovich and Mosey 2012, 1 - 8). This does not necessarily mean that the Johnson County Landfill is less suited for PV installation; rather Salasovich and Mosey (2012) represent their results more specifically by indicating exact areas within the site suitable for solar power harvesting. Because the current study performs a similar detailed analysis, the Jonson County Landfill study proved to be the most influential of the EPA and NREL studies to the present work.

Each analysis compared fixed and single axis crystalline silicon and fixed axis thin film ballasted photovoltaic technologies. For each study, the thin film panels were found to provide the quickest return on investment. Although these systems produced less energy output than crystalline silicon panels, the cost effective thin film system made up for this fact in terms of return on investment. The present study relies on these NREL and EPA findings that thin film PV systems provide the quickest return on investment to reinforce the choice of using the technology for solar power harvesting on closed landfills. Furthermore, the present study assumes that PV geomembrane will provide the same type of cost effectiveness as PV thin film ballast systems.

Chapter 3 : Methodology

The methodology for this study is separated into a three part procedure. First, a baseline population of landfills was created using state and national lists. Next, these landfills were prescreened for size and age of the landfill in addition to its proximity to transmission lines and roads. Pre-screened landfills were selected using simple random sampling (Dixon and Leach 1977, 13). For each location sampled, solar irradiation was calculated as appropriate for either or both PV geomembrane and dish-Stirling systems using Esri's Solar Analyst. Radiation was translated to energy using mathematical formulas, and statistics were used to generalize these results to the state level, providing an estimation of solar potential of California landfills.

This study intends to answer the following question: How much potential solar energy for electricity generation exists in closed, or soon to be closed, landfill sites in California? This state was chosen based on data availability, the size of the state, and the variety of climates that exist there. To inventory solar energy potential, the study considered two types of technologies - PV geomembrane or dish-Stirling systems, considered best for sites with varying characteristics.

3.1 Site Identification

The present study required a list of spatially referenced landfills within California to form a baseline population for such sites in order to take inventory of solar potential. This database was composed from two sources, one from the EPA and another from the State of California.

The Landfill Methane Outreach Program (LMOP) database (EPA 2012a) contains a list of over 2,800 landfills, both open and closed, along with the location's city, county, and state; from this list 370 records were found in California. Although this was the most complete database that EPA has released, this list may not provide a sufficient starting point for this study. Since national landfill regulations did not go into effect until 1991, an empirical measurement of such sites is extremely difficult to produce. Estimates for closed landfills in the United States vary, but have been as large as 100,000 sites (Sampson 2009, 1).

To attempt a more complete list of sites, state data were added to the EPA data. The CEC CalRecycle database was found to have 314 records listed in California and was the most complete state list found (CEC 2012). This database was compared and added to EPA's LMOP database (EPA 2012a) to create a newly compiled list.

It should be noted that both of these databases were established for the purposes of identifying potential and existing LFG to energy projects. It is likely that landfills fit for LFG energy projects share many characteristics as those well suited for solar development. Landfills potentially useful for either system must be both fairly large and recently closed. The compiled database of landfills then favors landfills that could potentially be used for solar harvesting, making these sources particularly relevant to the current work.

Each record on the list of landfills was investigated. Although the databases have a combined total of 684 records, some of these records refer to different LFG projects on the same landfill. There were also redundancies between the two databases, so duplicates were omitted. Additionally not all landfills were associated with closing dates; only records with closing information moved onto the subsequent prescreen tests. A total of 324 landfills constituted the final list of landfills used for the prescreening portion of this analysis.

3.2 Prescreening

Once a list of California landfills was created it was necessary to conduct a prescreen analysis of these sites to eliminate those unsuited for solar power development, this method is summarized in Figure 1. Landfills that did not pass any portion of the test were considered unsuitable for power generation; those that did underwent a more detailed analysis. This way, locations that did not meet minimum requirements for practical solar installation were excluded before more time intensive analyses are performed. The compiled list of landfills from the CEC and EPA contained information used in this analysis regarding the landfill's closing date, location data, and size. Next, the proximity from landfills to resources like roads and transmission lines were measured using ArcMap. The existence of LFG to energy facilities nearby natural gas lines were examined as a complementary energy source to solar power, although these requirements were not prerequisites for a given site to pass this analysis.

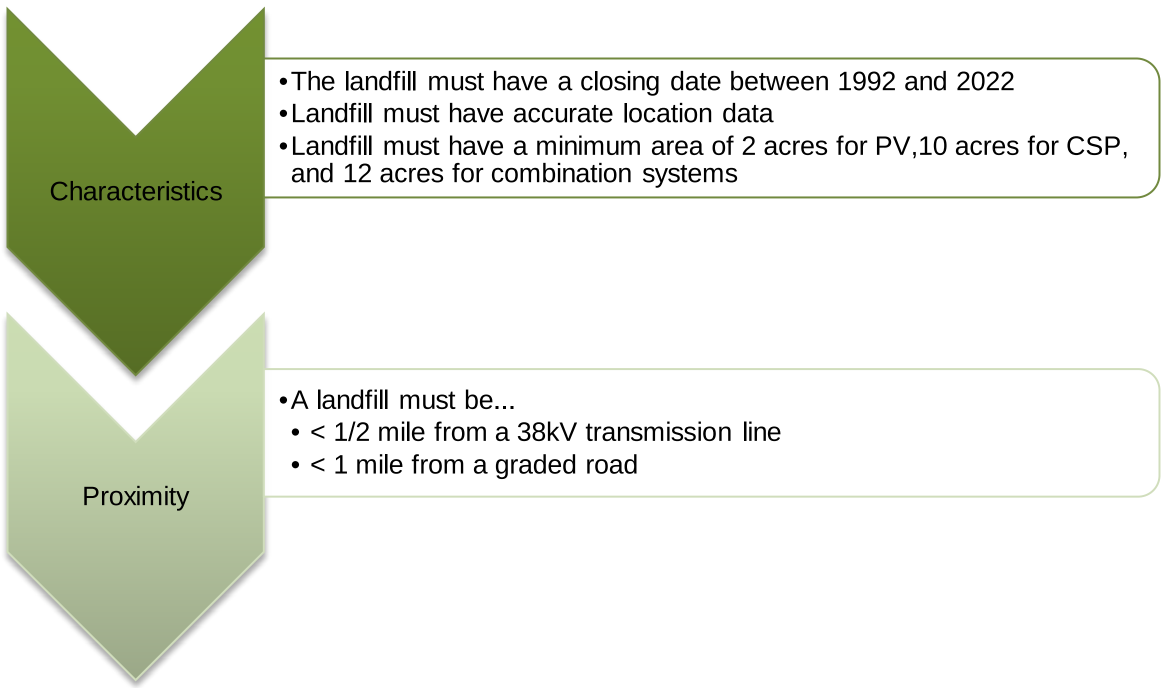


Figure 2 - Prescreening Requirements

Locations that have been closed too recently, or not recently enough, may be undesirable. As seen in Figure 2, a landfill must have been closed between 1992 and 2022 to pass the prescreening portion of this analysis. Landfills that have been recently closed are prone to settling as waste compacts; this process must be nearly complete before any major structures can be placed on the area.

In order to give a landfill time to settle and to begin initial construction, the present study considered landfills that have a planned closing date of 2022 or earlier. This included landfills that will close within ten years that can start being converted into solar power farms within fifteen years. Although this number is somewhat arbitrary, it nonetheless establishes a limit to define landfills available for construction in the near future.

Furthermore, a potential site should be lined or capped properly in order to minimize the risk of structural and environmental issues. Landfills closed after the landmark Subtitle D regulation best fit this criterion, this study considered landfills closed after 9 October 1991 (EPA 2012b, 4). Because the data used in this study only provides the year of closing dates, this date was rounded up to 1992. This study therefore considered landfills that closed after 1992, but before 2022.

Many landfills on the list were attached to coordinates or other location data; landfill locations that could not be found after a comprehensive search were rejected, in addition to sites being reused or with future reuse plans. Some landfills were, or will be, converted into a park, golf course, or similar facility. A major reason that closed landfills are attractive sites for power generation is because they are typically underutilized, not generating revenue or providing a service to the public. If the landfill has a redevelopment plan or is currently being utilized, this benefit is lost (EPA and NREL 2012, 5 - 6). Location and land use data were found using a combination of maps, digital imagery, municipal publications, and newspaper articles.

The size of a landfill is also important to note, because sites that are too small may not produce enough electricity to make the project economically viable. Most landfill size information was taken from the compiled landfill list, although a few locations without footprint data were manually calculated using ArcMap's measure tool and digital imagery. Landfills that were smaller than ten acres were considered unfit for dish-Stirling installations while those smaller than two acres were deemed too small for either dish-Stirling or PV geomembrane facilities.

A landfill's distance from resources like roads and transmission lines is important to consider when predicting the viability of a project. Landfills that are close to the transmission grid provide relatively cheap access to the transmission grid, reducing the cost of creating the power plant. Likewise, roads provide access to the site for maintenance and initial construction without the need for creating new roads for these purposes.

According to the EPA and NREL document, “Screening Sites for Solar PV Potential” (EPA and NREL 2012, 4), the distance from transmission lines should be less than 0.5 miles. Additionally, these transmission lines must have capacity for a large scale solar project. The present analysis uses 38kV as the smallest transmission line needed for this task, a figure also used by Salasovich and Mosey (2011b). Transmission line shapefiles from Federal Emergency Management Agency (FEMA) were compared to landfill locations using the ArcMap measure tool (FEMA 2012).

Additionally, a landfill’s distance from a graded road should be less than one mile in order to maximize accessibility (EPA and NREL 2012, 4). Salasovich and Mosey (2011b, 10) also used this criterion. To find this attribute, ArcMap’s measure tool was again used, with road data from Bing Hybrid imagery available at ArcGIS.com.

While the distance between a landfill and natural gas pipeline was not a precondition for sites to be identified for dish-Stirling potential, all sites passing the prescreen requirements were analyzed for this useful attribute for dish-Stirling technology. Leman (2011, 23) states that natural gas lines are about twice as costly as transmission lines. Since this study uses a distance of 1/2 mile to define a transmission line as being viable, this distance was halved and 1/4 mile was used to define a landfill with natural gas connection potential. However, because of the additional power supply found on landfills from LFG, proximity to natural gas lines was not chosen as a criterion for dish-Stirling installation.

The National Pipeline Mapping System is an online GIS application that allows the user to view natural gas pipelines over a base map a single county at a time (National Pipeline Mapping System 2012). The application's measure tool was used to calculate the distance between a landfill's border and the closest pipeline.

3.3 Detailed analysis

The detailed analysis of the present study determined if a landfill is suited for specific solar technologies and estimates the annual production of those facilities. Figure 3 outlines the steps taken in the analysis.

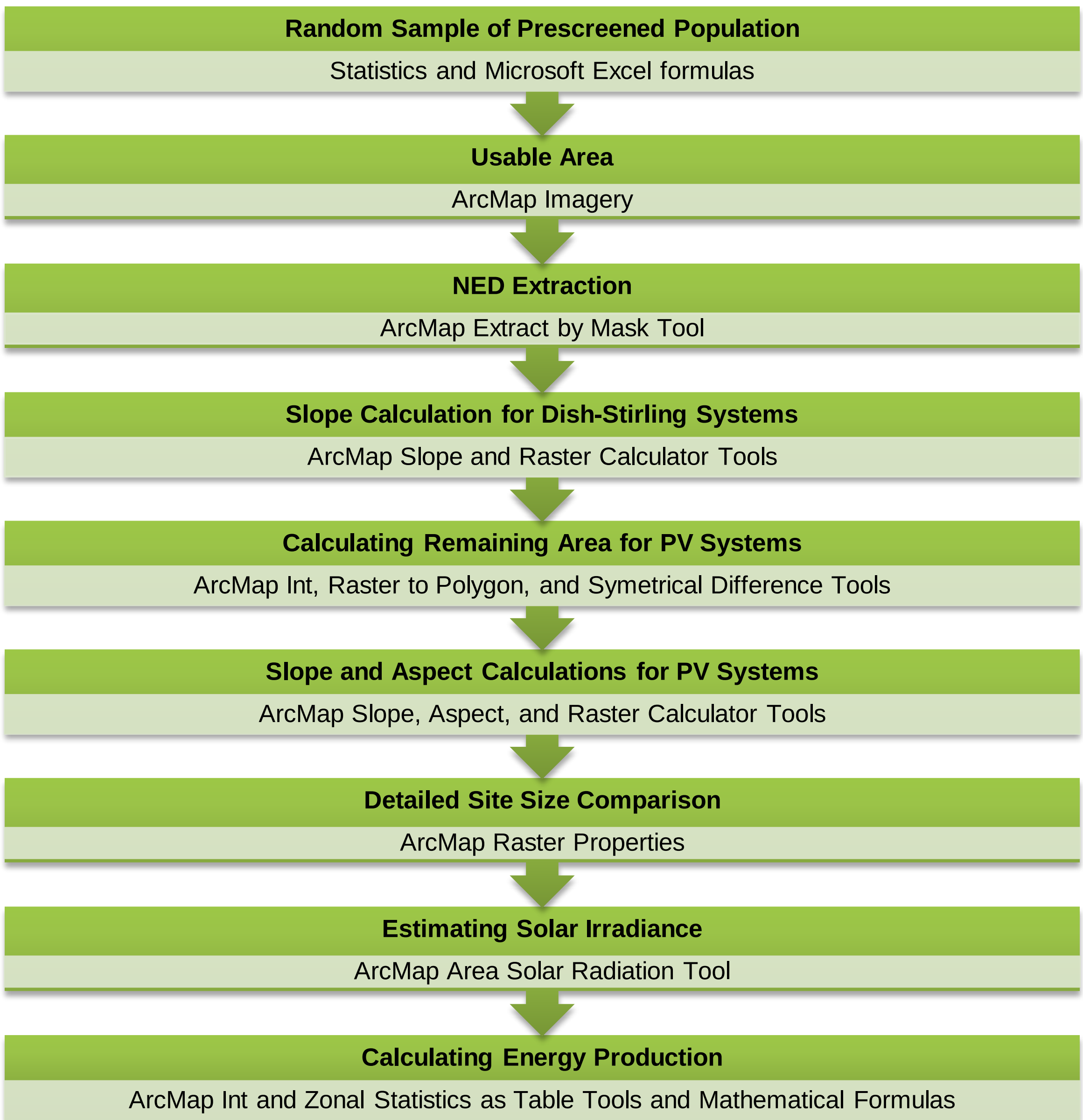


Figure 3 - Detailed Analysis Summary Listing Tools Used

First a random sample was taken from the prescreened population. The usable area from each site sampled was digitized and elevation data was extracted from this usable area. By analyzing the terrain in each landfill, areas appropriate for dish-Stirling and PV geomembrane were determined. The size available for each technology was compared to the size of a viable system; technologies without ample space available on the landfill were rejected for the site. Solar Analyst was used to estimate solar radiation, which was converted to energy output using mathematical formulas.

Sites that passed the prescreen analysis constituted the sampling frame for this study. The sample size was chosen, noting the sample's confidence interval and confidence level. These figures were used in this study's final calculations to determine how well the sample analyzed represents the population as a whole. A simple random sample was taken from this population using an Excel formula to generate random numbers. The locations that were chosen in this sample proceeded to a more detailed analysis.

Usable areas were found using ArcMap by digitizing a vector layer representing unobstructed areas of the landfill from Bing imagery, eliminating areas containing trees, shrubs, structures, or other obstacles. Many of these obstacles could be removed by developers to make room for solar collection devices, however determining whether or not each structure is essential, or if removal of such obstacles is worth the costs, is a task beyond the scope of the current study. Therefore the present work considers areas of the landfills free of obstacles.

National Elevation Dataset (NED) raster files of 1/3 arc second resolution were downloaded from the USGS National Map Viewer (USGS 2012). NED raster files represent the primary and most recent digital elevation data from the USGS. Each raster file was clipped using ArcMap's Extract by Mask tool creating a raster file with elevation data fit to the size, shape, and location of the landfill.

Sites may be appropriate for: 1) dish-Stirling 2) PV geomembrane 3) a combination of both technologies or 4) unsuitable for solar installation. Areas appropriate for dish-Stirling systems have a slope less than 5° (Gastli and Charabi 2009, 794). Furthermore, since parabolic dishes used in dish-Stirling devices follow the sun as it moves, eliminating non south-facing slopes to the usable area for these systems was not necessary. Locations fit for thin film PV geomembrane installation must have a slope less than 60°, and have a southward aspect. For the purposes of this study southward is defined as any aspect facing southeast, south, and southwest.

As a priority, all areas that could host dish-Stirling installations were assigned as such. This is because of the superior efficiency of dish-Stirling systems compared to PV geomembrane. Implementation of dish-Stirling systems also may benefit from natural gas lines and existing LFG projects. If the area suitable for dish-Stirling systems was large enough for a viable system (i.e., 10 acres), the location was analyzed for incoming direct solar radiation.

Additionally, landfills that showed potential for dish-Stirling systems were compared to LFG to energy projects in the State. LFG to energy data was taken from LMOP and CEC databases and matched with landfills with dish-Stirling potential. Like a location's proximity to natural gas pipelines, containing a LFG to energy project was not a prerequisite for a landfill with solar potential and does not factor into the inventory calculation. Both the presence of natural gas pipelines and LFG projects are reported separately in the results.

It was assumed that dish-Stirling would yield higher energy output than PV geomembrane because of its higher efficiency factor and lack of slope orientation requirements.

To test this hypothesis, sites assigned entirely as dish-Stirling facilities were also analyzed for PV. These PV comparisons did not contribute to this study's inventory and were used only to back up the assumption that dish-Stirling systems would be more productive.

Areas unfit for dish-Stirling systems were then analyzed for PV systems. In cases where the area suitable for dish-Stirling systems in a site was too small, the entire landfill was tested for PV. If the area analyzed for PV geomembrane was larger than 2 acres, the minimum size required for an economically viable system, the landfill was considered to have potential for PV installations in these areas.

An analysis of clipped elevation data determined usable slope within each site using ArcMap's Slope tool, which converts elevation data to slope values in degrees. Resulting values were analyzed using the Raster Calculator tool. General Raster Calculator comparisons and the SetNull function were used to eliminate areas of unfavorable slope. Equations 1 and 2 show two separate Raster Calculator processes ran to accomplish this.

First, a Boolean raster was created which returned the number one if slopes were equal to or less than 5°.

("Landfill_Slope" <= 5)

Where "Landfill_Slope" = The output of the Slope tool/ usable area raster

Equation 1 - Boolean Slope Function for CSP

Secondly, the SetNull function was used to eliminate areas with unfavorable slope. Using the Boolean raster from Equation 1 as the conditional raster, the function produced a raster with values equal to the original clipped NED. However, this dataset only contained areas with slopes equal to or less than 5°. This formula can be seen in Equation 2.

SetNull("Landfill_Slope_RasterCalculator ","Landfill_ UsableRaster", "VALUE < 1")

Where "Landfill_Slope_RasterCalculator" = The output raster from Equation 1

"Landfill_UsableRaster" = The output of the Slope tool/ usable area raster

Equation 2 - SetNull Raster Calculator Function for CSP

Small, unconnected areas were removed by digitizing a new polygon feature around large and connected areas of the raster file. This process was repeated as necessary until all islands of raster cells were removed.

In order to account for all areas unassigned to dish-Stirling systems, including small unconnected areas with less than or equal to 5° slope that were excluded, the ArcMap model pictured in Figure 4 was used to determine areas to be analyzed for PV thin film systems:

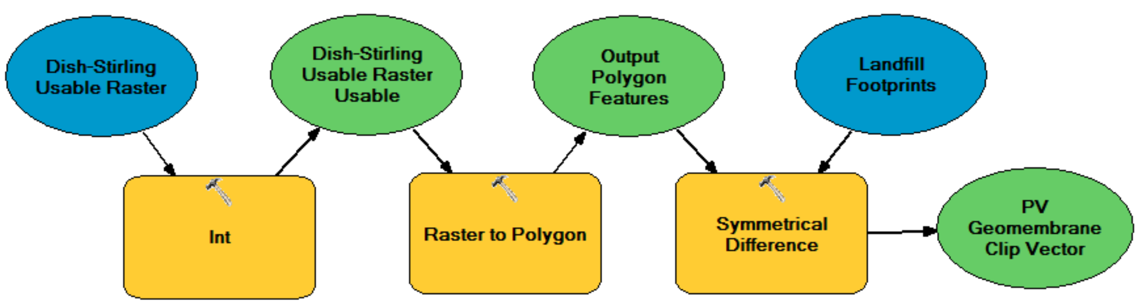


Figure 4 - ArcMap Model for PV Geomembrane Raster Creation

First, values for the raster file used for dish-Stirling suitable areas were converted to integers. This was necessary in order to convert the raster file to a vector format, a conversion necessary to compare the space with that of the entire landfill. Areas of the entire landfill that did not overlap with the vector file representing areas analyzed for dish-Stirling installations were then extracted to create the file produced by the model in Figure 4. The resulting vector file was used to clip the NED representing terrain data for the landfill. The resulting raster layer represented the area of the landfill analyzed for PV suitability.

When considering a site for PV geomembrane technology, the recommended slope is 60° or below ("Installation Manual for PVL" 2010, 8). The slope of areas being tested for PV geomembrane potential was analyzed using Raster Calculator comparisons and the SetNull function in ArcMap. Equations 1 and 2 were used for these calculations, replacing the requirement of 5° with 60° to account for technology specific requirements of PV geomembrane.

Since this site inventory is for the Northern Hemisphere and PV geomembrane is stationary, the slope of a landfill must have south, southeast, or southwest orientation. Inappropriate slope orientations were found and removed using ArcMap's Aspect and Raster Calculator tools. First, a raster file representing elevation data for areas suitable for PV geomembrane installation was used as an input for the Aspect tool, which produces a raster file containing the slope orientation for each cell, representing a 10 m^2 area, in degrees. Next, Aspects were kept ranging from southeast (112.5°) to southwest (247.5°), flat areas were also used (-1°). This was done by using the output from the Aspect tool in the Raster Calculator formula shown in Equation 3:

```
(("Landfill_Aspect" >= 112.5) & ("Landfill_Aspect "<= 247.5)) | ("Landfill_Aspect " == -1)
```

Where "Landfill_Aspect" = The output raster from the Aspect tool

Equation 3 - Boolean Aspect Function for PV

The output from the above Raster Calculator calculation was modified with another formula, as seen in Equation 4. This calculation was necessary in order to remove areas without south-facing or flat slopes.

SetNull("Landfill_Aspect_RasterCalculator ","Landfill_ UsableRaster", "VALUE < 1")
Where "Landfill_Aspect_RasterCalculator" = The output raster from Equation 3
"Landfill_UsableRaster" = The output of the Slope tool/ usable area raster
and "VALUE < 1" is the where clause which sets all cells with non-south facing aspects to null

Equation 4 - SetNull Raster Calculator Function for PV

A solar power harvesting system must be able to provide enough electricity to make it economically viable; otherwise the system is economically unfeasible and therefore not considered in the present analysis. Because the size comparison conducted in the prescreen portion of this analysis was based on the total footprint of each landfill, it was necessary to check the area of a location again after obstacles and areas of unsuitable slope and aspect were removed. According to (EPA and NREL 2012, 5) after deducting areas with obstacles present, the usable land for a PV facility should be greater than two acres.

The minimum size needed for an economically viable dish-Stirling system is 10 acres. This estimation was taken from the following studies. Schild (2004, 12) states that a dish-Stirling installation should have a capacity of one MW. Dahle (2008, 25) establishes that dish-Stirling systems require approximately ten acres of space per one MW of capacity. Although this figure assumes a certain level of radiation is available to the site, it provides a minimum size of which a dish-Stirling system could be viable. Locations that do not contain enough usable land for either PV or CSP systems were not analyzed any further for that technology.

For each site and technology combination, the usable area raster layer was assigned as an input raster for the Area Solar Radiation tool. By using the parameters and inputs described below, Solar Analyst produced a raster layer representing the solar radiation in watt hours (Wh) that reached each cell of the elevation over a year.

Although the tool only requires elevation data for input, Solar Analyst parameters must be configured properly to yield results suitable to the study. Such parameters include which dates to analyze incoming solar radiation since irradiation values fluctuate throughout the year. The sky size, or resolution of the viewshed, sky map, and sun map, in units of cells per side, must also be chosen. Since it would be computationally intensive to analyze solar radiation for each hour of each day of the year, Solar Analyst allows the user to define both daily and hourly intervals (Fu and Rich 1999).

Because of the variances in solar angle through one year, this study uses Solar Analyst to survey incoming solar radiation for an entire year. However, the tool also asks for a specific year to analyze. This study did not use the year of that the analysis was conducted, 2012, because it is a leap year and is therefore not a good representative of an average year. Instead, 2011 was analyzed in this study since it contains a typical 365 days, a result visible in Figure 5. It does not matter which specific year is chosen, it only matters how many days are in that year. The calculation was run from the first to last day of the year to account for seasonal variations.

Daily and hourly intervals need to be optimized to yield the most accurate results from Solar Analyst. According to Esri (2012), four days is the smallest recommended day interval suggested, since sun tracks three days apart tend to overlap. A large sky size of 2800 was chosen to complement the small day interval used as recommended by Esri (2012). This means that the viewshed, sky map, and sun map used were 2800 x 2800 cells large, each cell representing 10 m^2. These parameters were used to optimize the results of the model. The default hourly interval, 0.5, was also used and can be seen in Figure 5.

In the tool's output parameters, the user can chose an output raster indicating direct, diffuse, or global radiation values (Fu and Rich 1999). Solar thermal technology only utilizes direct solar radiation while photovoltaic systems take advantage of global radiation (Price and Margolis 2010, 53; Lehman 2011, 15). Therefore, while evaluating for dish-Stirling systems, only the direct radiation output from the Solar Analyst was used. Locations suitable for photovoltaic systems were analyzed using a global radiation raster.

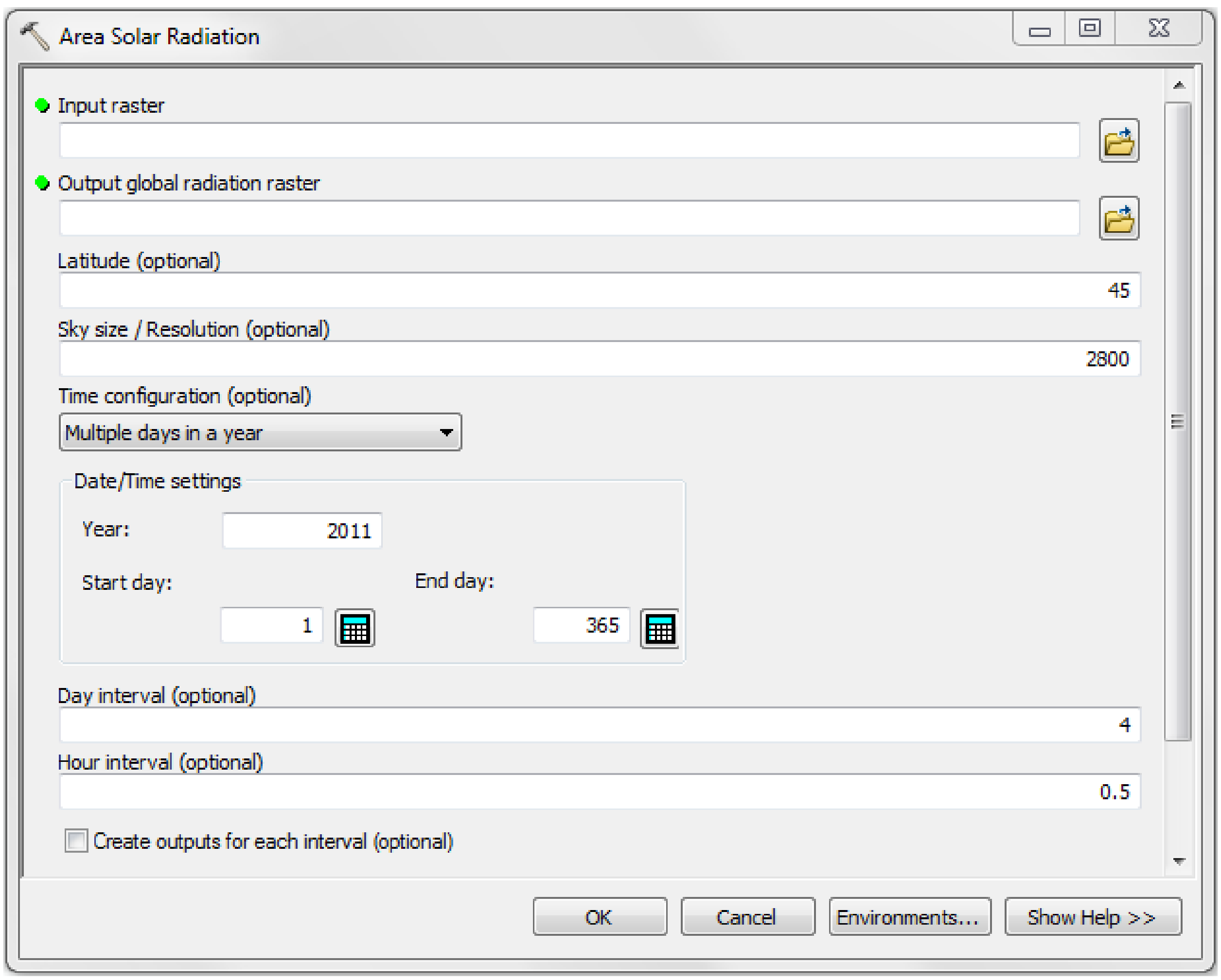


Figure 5 - Area Solar Radiation Tool Parameters

Esri's Solar Analyst is composed of several calculations that together account for direct and diffuse radiation, and the hemispherical viewshed algorithm is among the most important of these calculations (Fu and Rich 1999, 4). Solar Analyst calculates a veiwshed for every cell contained in the input DEM. A viewshed is composed of an area that is visible from a static vantage point; in this case that viewpoint is a cell in the Digital Elevation Model viewing upwards to the sky. The calculation finds the maximum angle of sky obstruction, or horizon angle, in each direction. Each cell is finally assigned a value describing visible and obstructed sky directions.

Solar Analyst also creates a sun map, where the sun's location is calculated based on time and latitude, represented via zenith and azimuth angles. These angles are placed into a two-dimensional hemispherical projection with the same resolution of the viewshed (Fu and Rich 1999, 4). A map is created for December to June, and another from June to December; both maps are divided into sectors where time duration, azimuth and zenith angles are calculated for each sector's centroid.

A skymap must be calculated for diffuse solar radiation. This map begins with the entire sky and is then divided into zenith and azimuth angle increments. These angles are calculated for the centroid of each sector (Fu and Rich 1999, 8).

When complete, the sunmap and skymap are each overlaid with the viewshed and a gap fraction is calculated. This fraction represents the percentage of obstructed to unobstructed areas in the overlain map. When the sun is blocked by nearby terrain or other obstacles, the area is considered obstructed. This figure is found by dividing the number of unobstructed cells in the viewshed by the total in that sector (Fu and Rich 1999, 9).

Once these maps are created and gap fractions are calculated, Solar Analyst can compute direct radiation. For each unobstructed sunmap sector, direct radiation is found based on the gap fraction, atmospheric attenuation, sun position, and ground receiving surface orientation. A transmission model is used that begins with the solar constant and uses transmittivity and air mass depth to account for atmospheric effects. The total direct insolation for a location equals the sum of the direct radiation for all sunmap sectors. Fu and Rich (1999, 10) show the direct insolation value from a sunmap sector, which has a centroid at zenith angle θ and azimuth angle α, as calculated in Equation 5.

$$Dir_{\theta,\alpha} = SConst * \tau^{m(\theta)} * SunDur_{\theta,\alpha} * SunGap_{\theta,\alpha} * \cos(AngIn_{\theta,\alpha})$$

Where,

$Dir_{\theta,\alpha}$ = Total Direct Insolation

SConst = Solar Flux Constant

τ = Transmittivity of the Atmosphere

$m(\theta)$ = Relative Optical Path Length

$SunDur_{\theta,\alpha}$ = Duration of Sunlight

$SunGap_{\theta,\alpha}$ = Gap Fraction

$\cos(AngIn_{\theta,\alpha})$ = Cosine of the angle of incidence between the axis normal to the surface and the centroid of the sky sector

Equation 5 - Solar Analyst Direct Insolation

Solar Analyst calculates diffuse radiation for every sky sector, combined over the time interval, and adjusted by the gap fraction and angle of incidence. Fu and Rich (1999, 11) provide the diffuse insolation calculation shown in Equation 6:

$$Dif_{\theta,\alpha} = Rglb * Pdif * Dur * SkyGap_{\theta,\alpha} * Weight_{\theta,\alpha} * \cos(AngIn_{\theta,\alpha})$$

Where,

$Dif_{\theta,\alpha}$ = Total Diffuse Insolation

Rglb = Global Normal Radiation (the sum of direct radiation from each sector without accounting for the angle of incidence)

Pdif = proportion of Rglb that is diffused

Dur = Time Interval Used

$SkyGap_{\theta,\alpha}$ = Gap Fraction

$Weight_{\theta,\alpha}$ = Proportion of Diffuse Radiation Coming from a Given Sky Sector

Equation 6 - Solar Analyst Diffuse Insolation using the Uniform Sky Diffuse Model

Global solar radiation is the sum of both direct and diffuse radiation. Reflective radiation, while technically part of global radiation, is not included in Solar Analyst because of its complexity and the relatively small influence it has on total radiation (Fu and Rich 1999, 29; Huang and Fu 2009, 30; Gastli and Charabi 2009, 793).

While Solar Analyst is a sophisticated model, it is not without its faults. The most notable limitation is that the model generalizes overcast conditions. Cloud cover is an important factor when determining incoming solar radiation of an area and is addressed through radiation parameters in Solar Analyst by estimating the proportion of radiation that passes through overcast skies, and the proportion of diffuse radiation. These parameters, however, do not directly account for the local overcast. The present work uses the default radiation parameter values, which assume ‘generally clear skies’. This point is addressed further in Chapter 5 of this work.

In order to estimate energy production at each location, the raw solar radiation produced by the Area Solar Radiation tool was analyzed using spatial and non-spatial tools. Statistics for each raster file were found using ArcMap. The cell count and mean values were copied from

ArcMap tables to an Excel spreadsheet to calculate estimated annual energy output for each location in MWh.

Raster outputs from the Area Solar Radiation tool provided the total Wh that reached each cell of the input raster during the year surveyed. The cell count was taken from each raster and multiplied by the cell size of that raster, 129.60189 m^2, to calculate the area for the site. 25 percent of this area was removed to account for service roads and other spacing considerations. This method of accounting for spacing was also used by Arnette and Zobel (2011) and Van Hoesen and Letendre (2010).

The area of each landfill was multiplied by the mean value of that site, which represents the average incoming solar radiation in watt-hours (Wh). Following Arnette and Zobel (2011), radiation values were multiplied by efficiency and derate factors to produce an approximation of the energy produced at each site. Raw irradiation values were multiplied by an efficiency factor of 11 percent for PV estimates and 25 percent for CSP installations to find an estimated annual energy output for each location. The energy calculated represents DC energy, which must still be converted to alternating current using a derate factor. Arnette and Zobel (2011) and Salasovich and Mosey (2011a) multiply energy produced by 77 percent to account for this phenomenon, the derate factor is also used in the current study.

Lastly, combination systems were added together and dish-Stirling and PV geomembrane outputs were compared. Output values at locations able to support combination PV geomembrane and dish-Stirling installations were summed to find the total output for the system. Additionally, locations suited for CSP were compared to a PV installation at the same location, to ensure that CSP was indeed the most efficient option for the location.

3.4 Aggregate Estimates for the Total Population

After each location was analyzed, the output for all sites was summed and divided by their quantity to find the average output of landfill installations analyzed. To generalize results from the sampled landfills to the total population, the average annual MWh generated per acre from analyzed landfills was applied to the total acreage found in landfills that passed the prescreening portion of this study. Acreage data was taken from CEC and EPA databases. This calculation represents an estimation of the annual energy output potential for solar power installations on closed or soon to be closed landfills in California.

Sampling theory, discussed by Dixon and Leach (1977), provided an estimate for the likelihood of a random sample being a good representative of the total population. Based on these calculations for simple random sampling, a sample size was drawn of seventeen, which gives an uncertainty of +/- 20 percent at a 95 percent confidence level. This indicates a 95 percent chance that the actual value of potential solar power from the total lies within 20 percent of the number determined from a sample.

Chapter 4 : Results

The outcomes from this study's analysis are illustrated below. Results from prescreening and detailed analyses are discussed and illustrated. Additionally, outcomes from sampled landfills are generalized to estimate energy contribution from all landfills. This study's prescreen analysis began with a list of landfills from CEC and EPA sources. As previously stated, a total of 324 landfills were included in this study. These sites had an average size of 101 acres. The largest site analyzed was 2,290 acres and the smallest was 0.8 acres.

4.1 Outcomes of Prescreen Analysis

Results from the prescreen portion of the analysis are discussed below. First, outcomes from analyzing landfill characteristics like closing date information, location data, and landfill size are presented. Additionally, results from the analysis of a site's proximity to transmission lines and roads are shown. Finally, landfills nearby natural gas pipelines and those with LFG to energy projects are revealed. Parameter ranges, common reasons for exclusion, and the number of sites that passed each step are summarized herein.

The landfills analyzed displayed a wide range of closing dates. Landfills closed as early as 1958 and others were estimated to close as far as hundreds of years into the future. A total of 205 landfills had closing dates within the range between 1992 and 2022.

Location data was verified for each of the 205 landfills. Many records had accurate coordinates or addresses, while others could not be so easily found. Eight landfills were currently being used as dog parks, public parks, golf courses, and similar facilities. After searching a variety of sources, forty five landfill locations could not be verified. 152 landfills were location verified.

To determine which landfills are large enough to host either PV or CSP installation, the size of a landfill was compared to the minimum size of an economically practical facility: 2 or 10 acres depending on the technology. Landfills showed much variation in size, ranging from 0.8 to 600 acres. Four locations were smaller than 2 acres and therefore deemed unfit for PV or CSP installation. Twenty one locations fell between 2 and 10 acres and were considered viable options for PV facilities, but not for CSP. 126 locations were feasible for either technology. A total of 147 sites were found with an area over 2 acres and could therefore support feasible solar power production.

Locations were also judged based on their vicinity to transmission lines and roads. All landfills were at least one mile from a graded road and many sites had roads present that lead to the site directly. After comparing landfills to FEMA transmission line data, some transmission lines were located on top of landfills while others were as much as 50 miles away. Fifty four locations passed this final condition of the prescreening process. These sites were location verified and found to possess favorable closing dates, sufficient size to support a solar power facility, and a location nearby the transmission grid and road systems.

Landfills that passed this prescreening analysis had an average size of 139 acres. The largest site that passed prescreening requirements was 600 acres while the smallest was 5 acres. A map of landfills that passed prescreening requirements can be seen in Figure 6. Sites are dispersed throughout California with slightly larger concentrations surrounding areas of high population such as Greater Los Angeles and San Francisco areas.

California Dirrect Normal Irradiance and Prescreened Landfills

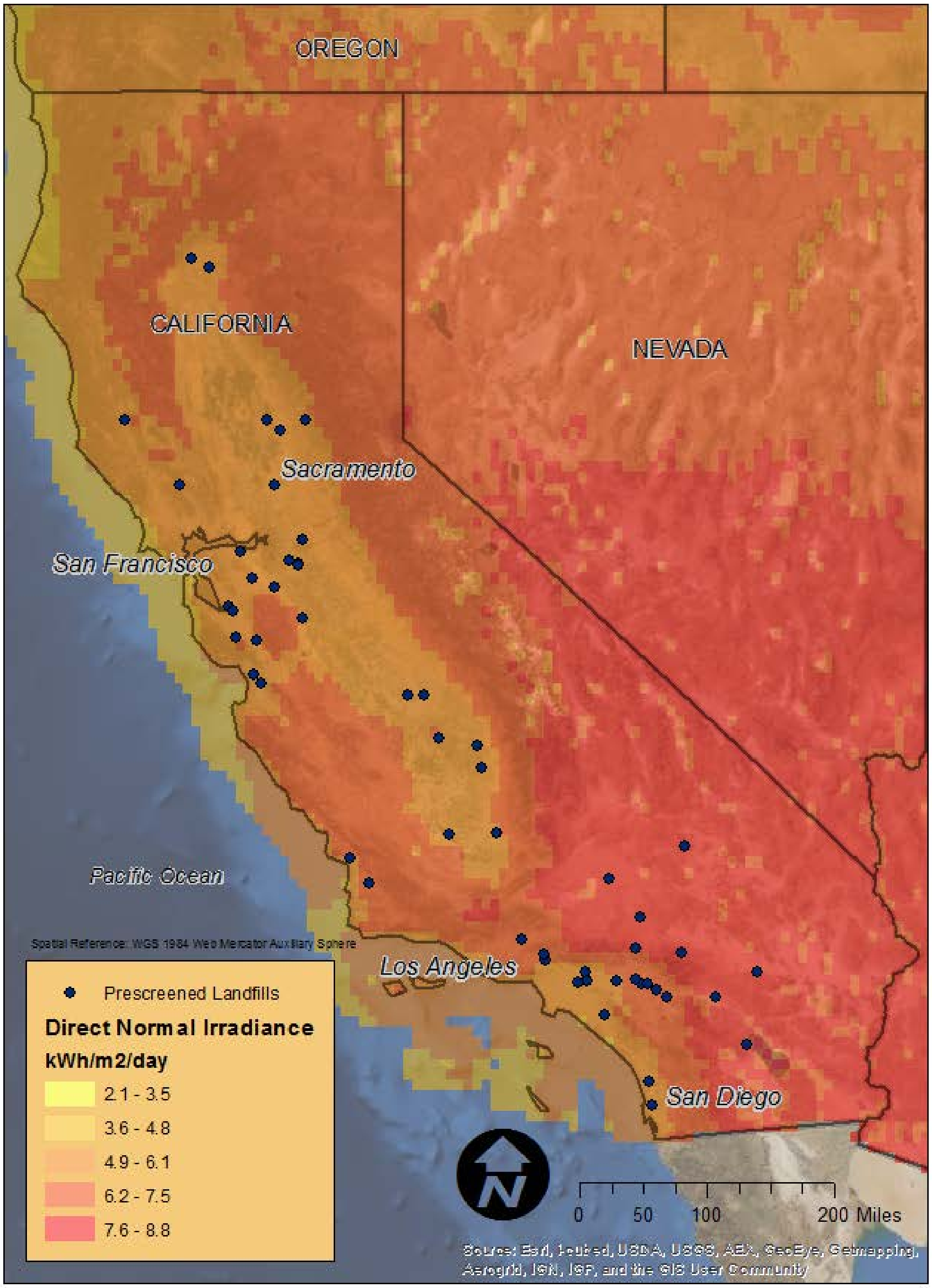


Figure 6 - Prescreened Landfills

The distance from natural gas pipelines to landfills that passed the above prescreening prerequisites was calculated. While not a criterion, a location's close proximity to natural gas lines displays the landfill's potential to integrate the energy source into a solar facility. Table 3 lists landfills that are estimated to have such potential by being at least 1/4 mile from a natural gas pipeline and therefore have the added benefit of supplementing thermal engines.

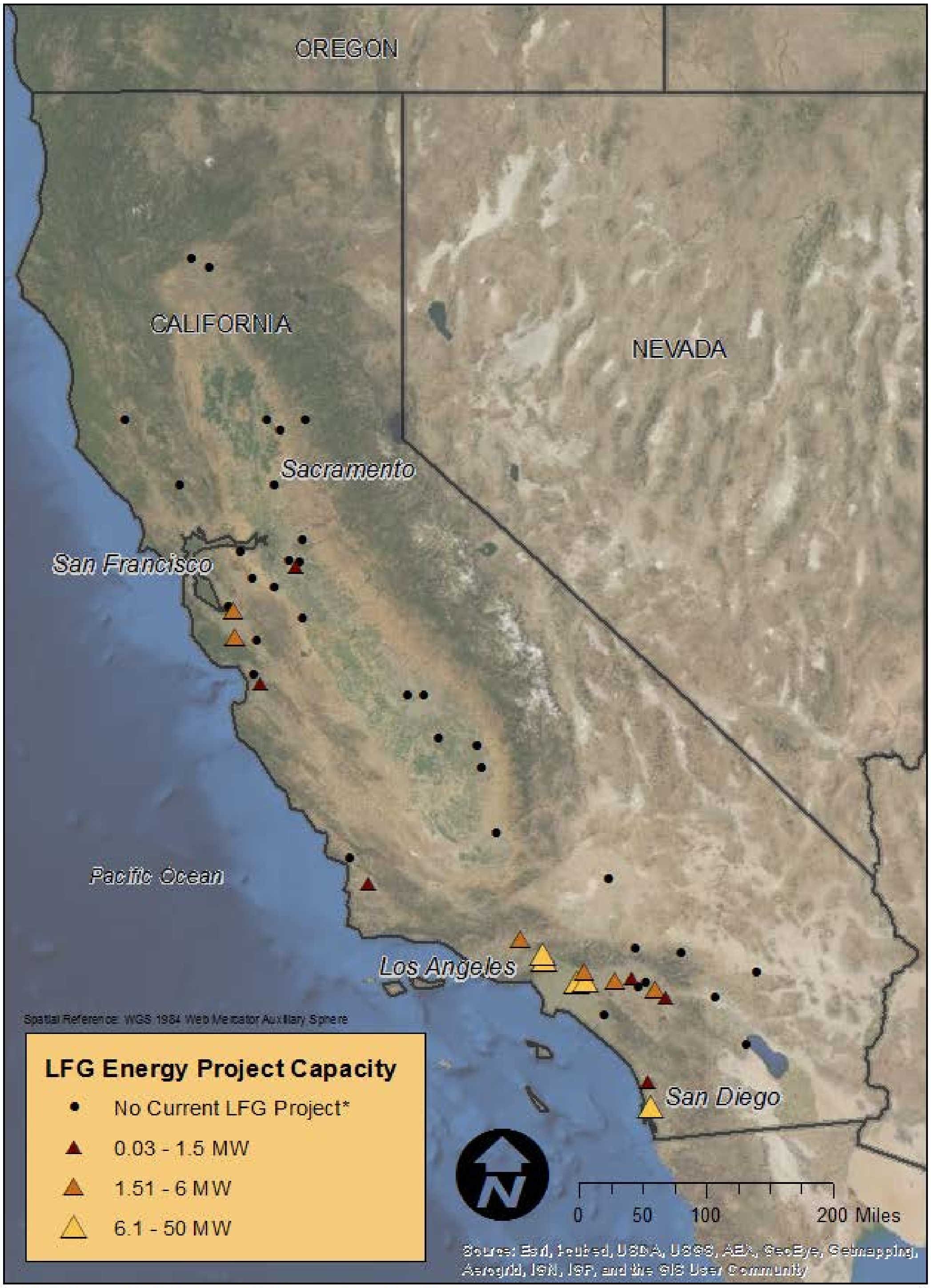
Table 3 - List of Landfills with Natural Gas Supplementation Potential

Landfill	*City*	*County*	*Distance from Natural Gas Pipeline (Miles)*
Vasco Road	Livermore	Alameda	0.25
Central Contra Costa	Antioch	Contra Costa	0.05
Chateau Fresno	Fresno	Fresno	0.2
Orange Avenue	Fresno	Fresno	0.25
China Grade	Bakersfield	Kern	0.15
Boron	Boron	Kern	0.05
Bradley	Sun Valley	Los Angeles	0
Miramar	San Diego	San Diego	0.05
Cold Canyon	San Luis Obispo	San Luis Obispo	0.16
Newby Island	Milpitas	Santa Clara	0.2
Fink Rd	Crows Landing	Stanislaus	0.15
Beale Air Force Base	Beale Air Force Base	Yuba	0

Because of the potential compatibility between LFG to energy and dish-Stirling engines, landfills that passed the above requirements that also had a footprint larger than 10 acres are shown in Figure 7 along with LFG to energy project data at those locations. The size of the LFG project is illustrated to show locations with the greatest potential for dish-Stirling and LFG to energy combination systems. It should be emphasized that these landfills were only prescreened and were not necessarily submitted to the more detailed analysis performed later in the study.

Potential dish-Stirling facilities are found throughout California, especially in the western and central areas. Locations with current LFG energy projects, however, seem to be focused in the southwest part of the state. Of these seventeen sites, twelve are located in neighboring Los Angeles, San Bernardino, Riverside, and San Diego Counties of southwest California. The remaining four landfills are situated to the north in Monterey, Santa Clara, and San Joaquin Counties in a region nearby San Francisco.

California Landfills with CSP and LFG Energy Production Potential



*Indicates that no MW capacity was reported in LMOP or CEC databases

Figure 7 - Potential Locations for LFG Energy and CSP Solar Combination Systems

4.2 Detailed Analysis Results

The following section discusses the results from the detailed analysis portion of the present study. Sites that constituted the random sample chosen for the detailed analysis are introduced. Next, results from slope and aspect analyses are described. Solar Analyst outputs, representing incoming solar radiation, are also discussed. Finally, results comparing dish-Stirling systems to PV geomembrane on the same location are presented. Table 4 outlines the seventeen landfills chosen in this analysis.

Table 4 - Sampled Landfills

Landfill Name	*City*	*County*
BKK	West Covina	Los Angeles
Central Contra Costa	Antioch	Contra Costa
City of Ukiah	Ukiah	Mendocino
Clover Flat	Calistoga	Napa
Cold Canyon	San Luis Obispo	San Luis Obispo
Echo Gold	Fort Irwin (Mil Res)	San Bernardino
Exeter	Lindsay	Tulare
Forward	Manteca	San Joaquin
Guadalupe	San Jose	Santa Clara
Hanford	Hanford	Kings
Lewis Rd	Watsonville	Monterey
Milliken	Ontario	San Bernardino
Miramar	San Diego	San Diego
Oasis	Thermal	Riverside
Orange Ave.	Fresno	Fresno
Redding	Redding	Shasta
Twentynine Palms	Twentynine Palms	San Bernardino

The slope and aspect characteristics of each landfill were unique. When analyzing for dish-Stirling installations, fourteen of seventeen landfills passed minimum size requirements after areas of high slope were removed. The City of Ukiah, Clover Flat, and Lewis Road landfills did not have 10 acres of flat land left to justify an economically viable dish-Stirling installation. While five landfills lost no usable area during this step of the analysis, the Clover Flat Landfill lost over 97 percent of potential space for solar installations. The amount of land lost for dish-Stirling slope requirements are summarized in the histogram shown in Figure 8. Overall, more land was available with gentle slope for dish-Stirling systems than PV geomembrane. This was favorable to the estimated potential of solar power projected from the present study. The size of the remaining areas ranged from just over 10 acres to over 300 acres, as seen in Figure 9.

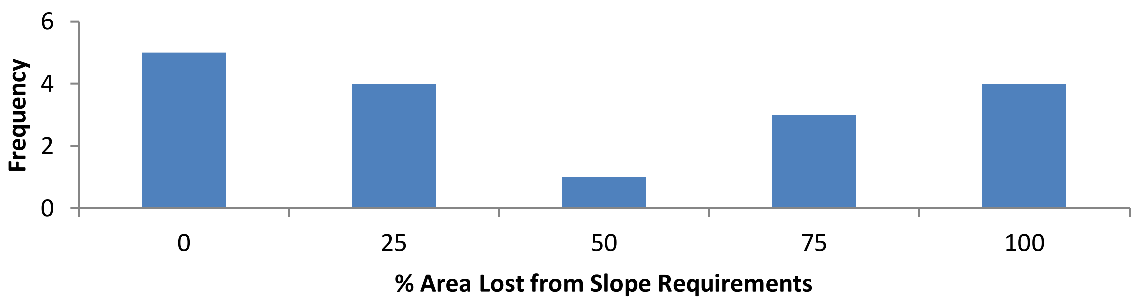


Figure 8 - Percentage of Area Remaining After Slope Analysis for Dish-Stirling Installations

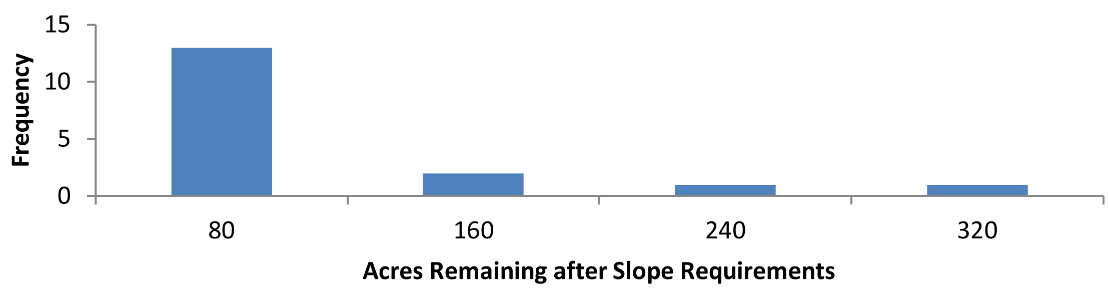


Figure 9 - Acreage Remaining After Slope Analysis for Dish-Stirling Installations

In the case of combination systems, the residual area unsuitable for dish-Stirling installations at each landfill was then tested for slope and aspect requirements for PV geomembrane installations. No slope on any landfill analyzed was greater than 60°; however prospective PV geomembrane space was lost to dish-Stirling facilities in the case of combination facilities. At the Central Contra Costa and Milliken landfills, less than 2 acres remained after dish-Stirling areas were designated. These two landfills were not analyzed further for combination systems and instead were considered for dish-Stirling only facilities.

Of all requirements used in this detailed analysis, the southern-facing aspect criterion proved to be the most restricting. An average landfill lost approximately two-thirds of its previously usable area for PV geomembrane cells from this step. This is compared to the slope requirement for dish-Stirling systems, which only claimed an average of just over one-third of previously usable land. The City of Ukiah and Twentynine Palms landfill lost over 99 percent of potential land for PV installations from this requirement. The histogram presented in Figure 10 display percentages of area lost from PV geomembrane aspect requirements.

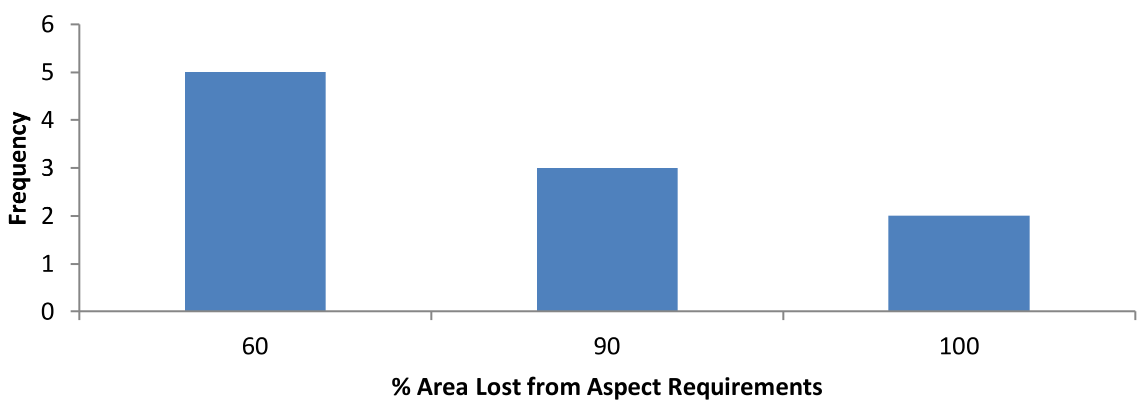


Figure 10 - Area Remaining After Aspect Analysis for PV Geomembrane Installations

Out of three locations being tested for PV only installations, the City of Ukiah landfill was the only site that did not pass the aspect requirement. The City of Ukiah location was also the only location found to be unsuitable for any solar development including dish-Stirling, PV geomembrane, or a combination system.

Potential Oasis and Twentynine Palms landfill combination facilities did not have enough area remaining for PV geomembrane after the aspect requirement was applied. These landfills, in addition to the Central Contra Costa and Milliken locations, were found to be unsuitable for combination systems due to PV geomembrane requirements. Therefore, these four landfills were tested only for dish-Stirling systems in this inventory.

Table 5 provides a summary of landfill and technology combinations that were found to be viable through the analysis of a landfill's slope, aspect, and size. BKK, Cold Canyon, Guadalupe, Miramar, and Redding landfills illustrated potential as combination systems. Central Contra Costa, Echo Gold, Exeter, Forward, Hanford, Milliken, Oasis, Orange Avenue, and Twentynine Palms landfills were analyzed for hosting dish-Stirling facilities, but were also compared to a PV installation on the same location. Clover Flat and Lewis Road landfills only showed potential for PV geomembrane systems while the City of Ukiah landfill was found to be unsuitable for any solar development.

Table 5 - Landfill and Technology Combinations Tested in Analysis

Landfill	*Technology*	*Acreage for PV*	*Acreage for CSP*
BKK	CSP/PV Combination	167	20.4
Central Contra Costa	CSP Only	0	78.6
City of Ukiah	Unsuitable for Solar Development	0	0
Clover Flat	PV Only	16.7	0
Cold Canyon	CSP/PV Combination	46.5	29.5
Echo Gold	CSP Only	0	10.0
Exeter	CSP Only	0	43.6
Forward	CSP Only	0	113
Guadalupe	CSP/PV Combination	23.1	33.0
Hanford	CSP Only	0	86.2
Lewis Road	PV Only	10.4	0
Milliken	CSP Only	0	169.6
Miramar	CSP/PV Combination	74.1	310
Oasis	CSP Only	0	26.4
Orange Avenue	CSP Only	0	32.5
Redding	CSP/PV Combination	22.3	40.4
Twentynine Palms	CSP Only	0	42.0

Once viable location and technology combinations were found, direct and global incoming solar irradiance were estimated for each using ArcMap's Area Solar Radiation tool and mathematical formulas. Table 6 summarizes these results for each landfill. Appendix B provides greater detail on these calculations.

Table 6 - Estimated Annual Electricity Potential Summary

Landfill	*Technology*	*Annual MWh from PV*	*Annual MWh from CSP*	*Total Annual MWh*
BKK	CSP/PV Combination	82,900	16,900	99,800
Central Contra Costa	CSP Only	0	57,900	57,900
City of Ukiah	Unsuitable for Either	0	0	0
Clover Flat	PV Only	7,810	0	7,810
Cold Canyon	CSP/PV Combination	22,200	23,400	45,600
Echo Gold	CSP Only	0	11,600	11,600
Exeter	CSP Only	0	34,000	34,000
Forward	CSP Only	0	84,300	84,300
Guadalupe	CSP/PV Combination	11,400	25,500	36,900
Hanford	CSP Only	0	66,900	66,900
Lewis Road	PV Only	4,770	0	4,770
Milliken	CSP Only	0	141,000	141,000
Miramar	CSP/PV Combination	36,900	259,000	296,000
Oasis	CSP Only	0	21,200	21,200
Orange Avenue	CSP Only	0	25,000	25,000
Redding	CSP/PV Combination	9,790	28,800	38,600
Twentynine Palms	CSP Only	0	35,600	35,600
	Total	175,770	831,100	1,007,000

4.21 Outcomes from Detailed Analysis

Below, landfills characteristic of various outcomes from the solar analysis are shown and discussed. The Miramar and BKK Landfills have the potential to host large combination solar energy harvesting facilities. The Milliken Landfill was shown to have the largest potential for dish-Stirling systems only while the Clover Flat Landfill has the largest potential for PV geomembrane only facilities. Lastly, the City of Ukiah Landfill was shown to not have any potential for solar facilities. Maps of solar potential for remaining landfills analyzed in this study can be found in Appendix C.

The Miramar Landfill is in the City of San Diego and is just south of the Marine Corps Air Station Miramar. The site is located nearby the San Clemente Canyon Freeway and Convoy Street in northern San Diego. The location shown in Figure 11 was the largest surveyed, with an area of nearly 500 acres. Open space, commercial, and residential areas surround the facility and no significant obstacles were present at the location. The Miramar Landfill was shown to have the largest potential to harvest solar radiation with an estimated 296,000 MWh of annual output potential coming from both dish-Stirling and PV geomembrane systems.

Owned by the BKK Corporation, the BKK Landfill is located in West Covina of Los Angeles County and pictured in Figure 12. The landfill is the third largest analyzed and seems to host dense vegetation, likely trees or shrubs, on its west side, presenting obstacles to solar installations. Galster Wilderness Park is located on the north side of the park, commercial and residential developments surround the western and southern boarders of the location. The BKK Landfill was shown to have the second largest potential for a combination dish-Stirling and PV geomembrane systems with an estimated annual 99,800 MWh energy output.

The Milliken Landfill, illustrated in Figure 13, is located in Ontario at the junction of Milliken Avenue and East Mission Boulevard. Ontario is located in San Bernardino County. The landfill is surrounded by industrial and commercial development. No significant obstacles were present as seen in the imagery. The Milliken Landfill was estimated to be the largest potential plant for dish-Stirling systems, with a projected annual output potential of 141,000 MWh.

The landfill illustrated in Figure 14 was built in Calistoga, California of southwest Napa County. Set at the foot of Clover Flat Road, the Clover Flat Landfill is completely surrounded by vegetation and open space. The northwest side of the landfill is covered in trees or shrubs. The surrounding area is mostly composed of open space, farms, vineyards, and wineries. The Clover Flat Landfill displayed great potential for PV geomembrane installations, with an estimated 7,810 annual MWh of potential output.

The City of Ukiah Landfill is located in Ukiah, the largest city in Mendocino County. The landfill pictured in Figure 15 is north of Vichy Springs Road in an area with little development. The site did not have any significant obstacles present. The facility is surrounded by open space, although commercial and residential neighborhoods are located within a quarter mile of the site. The City of Ukiah Landfill was found to be unsuitable for either dish-Stirling or PV geomembrane systems. The terrain outlined in Figure 15 consisted of terrain with steep slope (over 5°), most of which was not facing south. Given the terrain requirements for dish-Stirling and PV geomembrane, this landfill does not contain enough land to host economically viable facilities for either technology.

Annual Incoming Solar Radiation at the Miramar Landfill

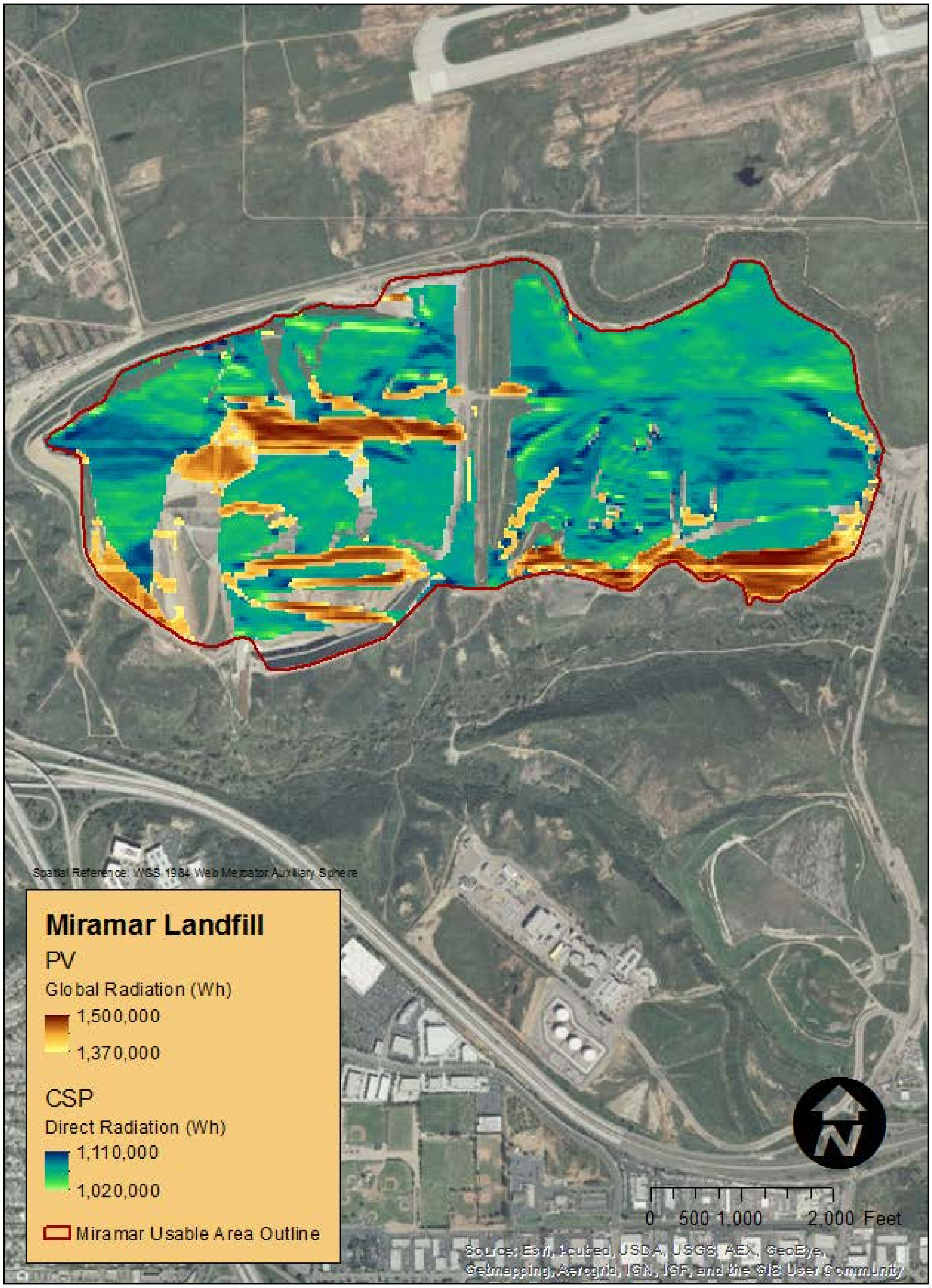


Figure 11 - Miramar Landfill Solar Potential

Annual Incoming Solar Radiation at the BKK Landfill

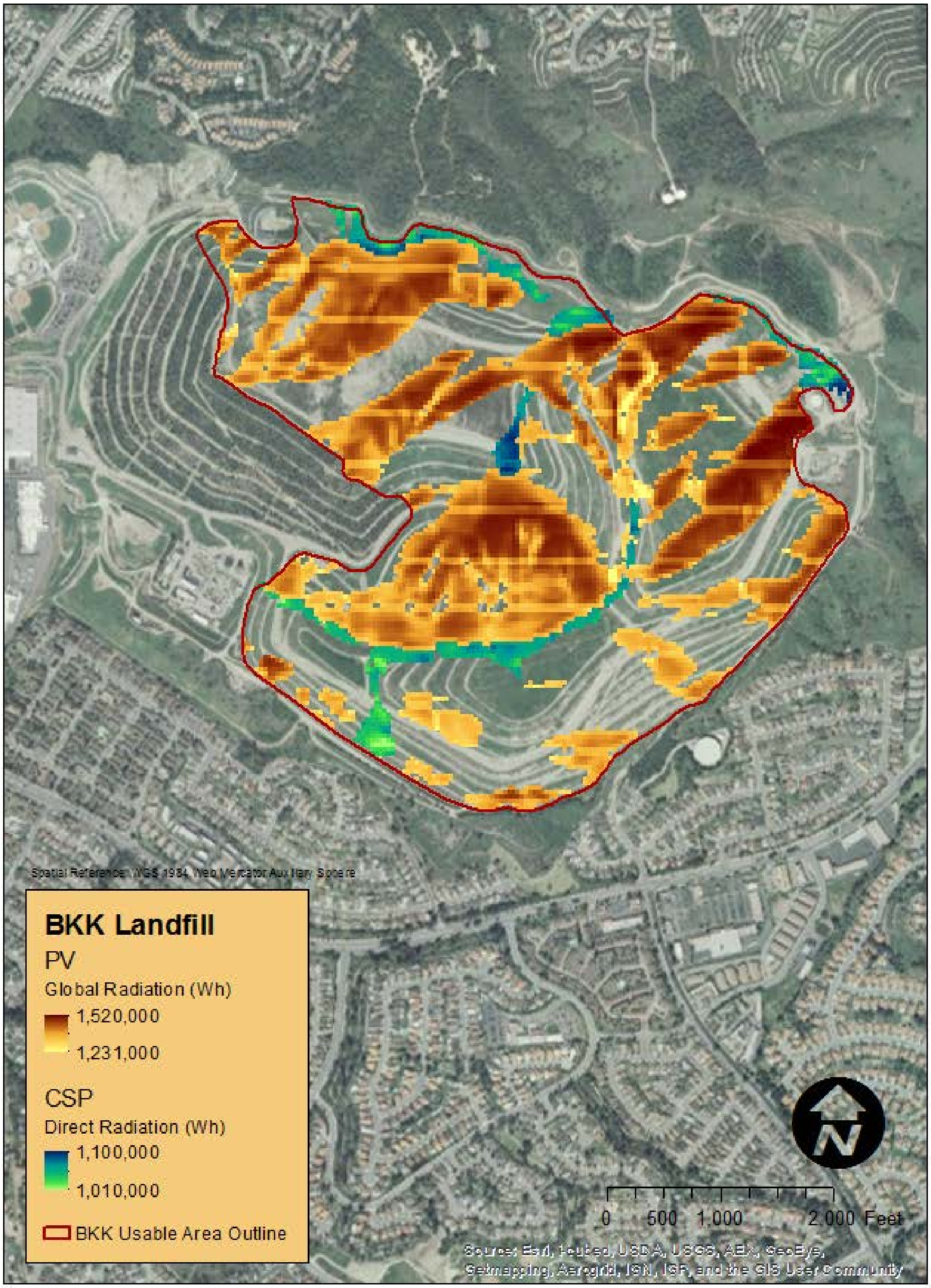


Figure 12 - BKK Landfill Solar Potential

Annual Incoming Solar Radiation at the Milliken Landfill

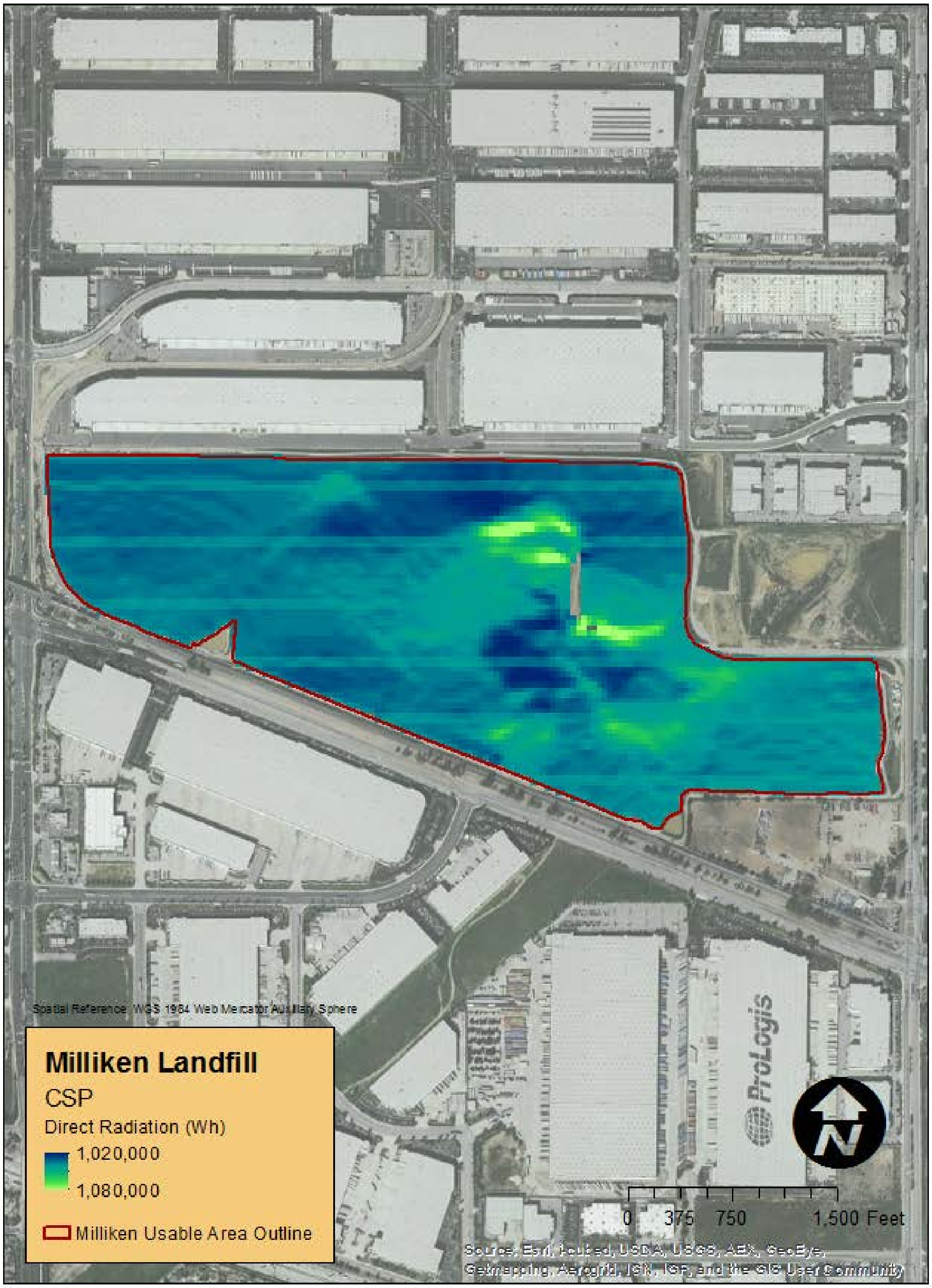


Figure 13 - Milliken Landfill Solar Potential

Annual Incoming Solar Radiation at the Clover Flat Landfill

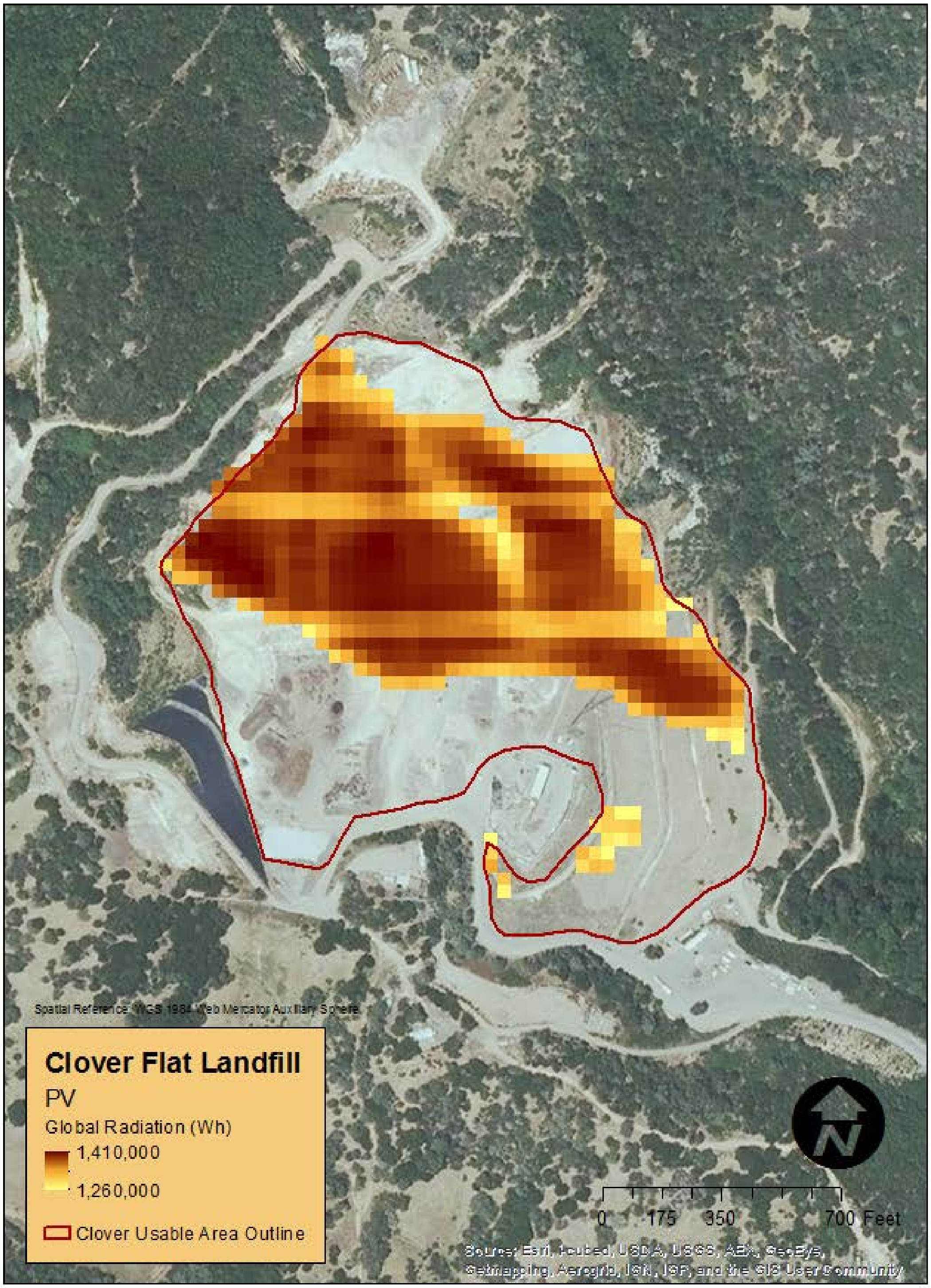


Figure 14 - Clover Flat Landfill Solar Potential

Annual Incoming Solar Radiation at the City of Ukiah Landfill

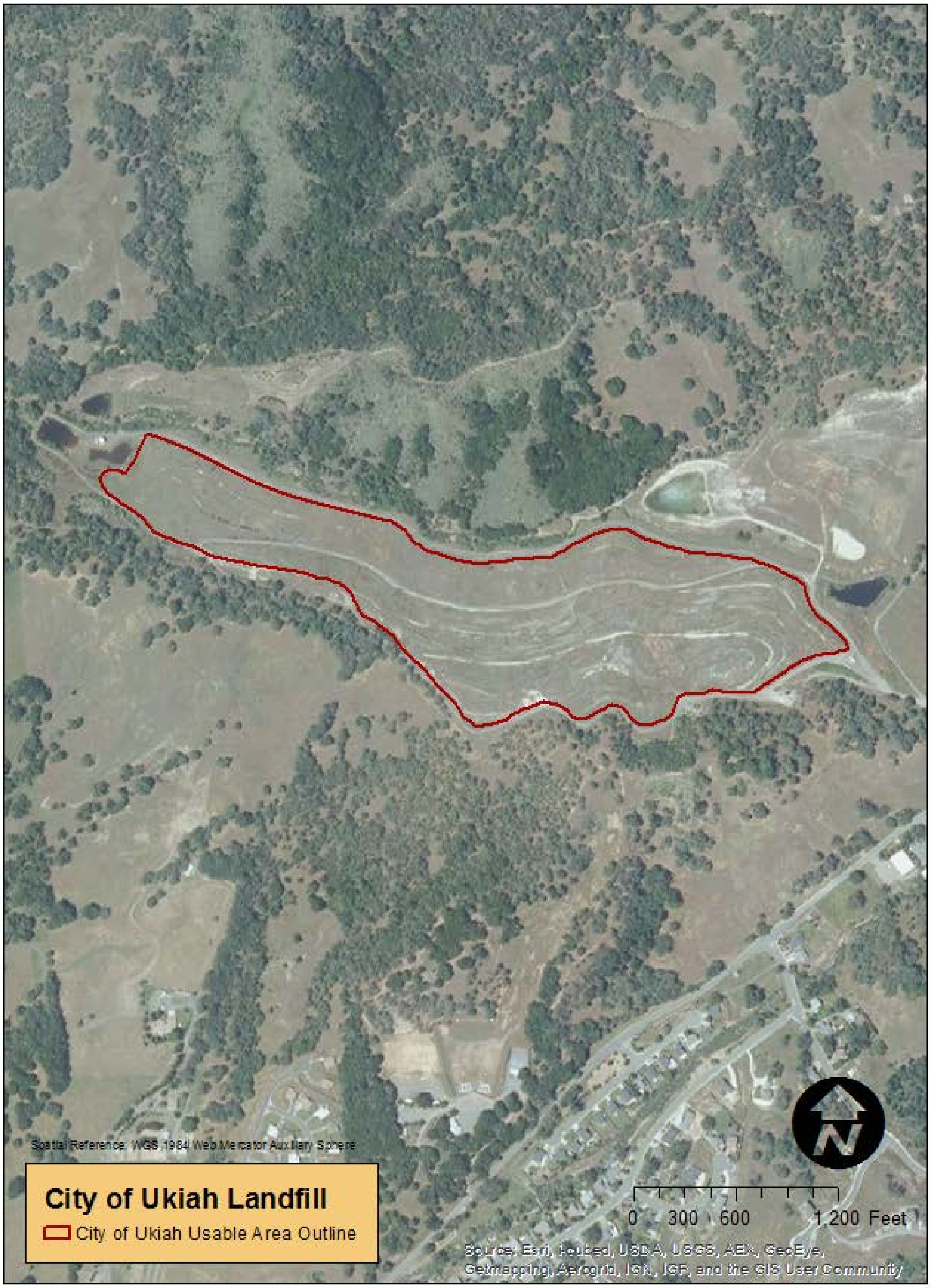


Figure 15 - City of Ukiah Landfill Solar Potential

4.3 Estimates for the Solar Potential of Landfills in California

This study calculates the annual electrical contribution of solar power from California landfills. The estimated annual potential of the landfills analyzed in this study totaled 1.01 gigawatt hours (GWh). Using acreage data from the CEC and EPA databases, this figure was divided by the total size of sampled sites, 2,000 acres, to find the average annual MWh output per acre. This figure, 0.520 MWh/acre, was multiplied by the acreage of each landfill that passed the prescreen analysis. From these calculations, it is estimated that landfills in California have the potential to contribute 3.78 GWh of solar energy to the electric grid annually. Considering the average California home uses 567 kWh monthly, or 6804 kWh per year, it is projected that an average of 555 homes could be powered annually from the solar energy projected in this study (Energy Information Administration 2012b).

It would be illogical to assume that the landfills analyzed were perfect representatives of the population sampled, as this is rarely the case; the uncertainty of this assumption must be addressed using sampling theory. Given fifty-four landfills were included in this inventory and seventeen of them were analyzed in detail, sampling theory suggests that the results from this analysis are within 20 percent of 3.7 GWh with 95 percent confidence. Therefore, this study estimates the potential annual solar energy generation from landfills to be between 3.02 GWh and 4.54 GWh.

Chapter 5 : Discussion

This study's projected findings are explored in the following chapter. First, results are put into context by comparing them to California energy statistics and past studies. Next, major findings from this study are defined. Limitations and assumptions of the present study are then acknowledged and, finally, future areas of work are outlined.

5.1 Analysis Results

The present work estimates that landfills with closing dates between 1992 and 2022 could generate a potential 3.7 GWh in California annually; this figure is compared to overall energy generation and consumption. In 2010 California produced 204 GWh and consumed 259 GWh, by retail sales, according to the U.S. Energy Information Administration State Electricity Profiles of 2010 (Energy Information Administration 2012c, 25). The energy potential at closed, and soon to be closed, landfills for California is therefore equivalent to 1.85 percent of the State's 2010 energy generation and 1.46 percent of consumption based on the these figures. Relative to California's overall energy market, the potential contribution of solar power from closed landfills is fairly small.

The State Electricity Profiles 2010 report shows that renewable energy contributed 28.9 percent of California's electric power net generation for that year, or 28,793,591 MWh (Energy Information Administration 2012c, 27). Renewable energies in the report include solar, hydroelectric power, wind, biomass, LFG, sludge waste, and agricultural byproducts. Using this figure, the prospective solar power estimated in this study is equivalent to 13 percent to the State's 2010 renewable energy production.

Overall, the results show significant potential to use landfill sites to expand California's solar energy production. According to the EPA's eGRID, the CAMX subregion, which encompasses most of California and no other states, solar power contributed 0.3003 percent of 212,768,947 MWh net generation for 2009. This means solar energy added 638,945 MWh to the electric grid in that year. The potential annual contribution of 3.7 GWh estimated from closed, and soon to be closed, landfills in this study is about 5.9 times California's current solar electricity production. These results show the significant potential found in California landfills to produce solar energy as estimated in this study when compared to the current solar generation in the State.

Next, the current study's result is compared to similar past works. The analysis by Carrión et al. (2008), estimated that Andalusia, Spain has an annual potential of 38,693 GWh on 406,000 acres of land. With an average annual generation of 95 MWh/acre, results from Carrión et al. (2008) were exponentially higher than the present study, which estimates 0.520 MWh/acre. This may be a result of Carrión et al. (2008) using technologies with a very high efficiency factor, 78%, in their analysis and also because Andalusia receives plentiful incoming solar radiation. This comparison shows that results found from the present analysis, based on energy produced per acre, are not incredibly high by comparison.

Arnette and Zobel (2011) found a potential of 6,599,651.7 MWh of solar power annually in the greater southern Appalachian Mountains area, a region similar in size to California. The Appalachian study used similar land use requirements to Carrión et al. (2008) to find 405 sites suitable for solar installation. Arnette and Zobel (2011), however, do not disclose the total area of these analyzed sites in their report. Therefore, a comparison of the Appalachian study and the current work based on estimated electricity generation per acre is not possible. This highlights a challenge in conducting studies that take inventory of solar potential: there are few good points of reference to compare one's results to past studies, a point that is elaborated in Section 5.4.

5.2 Major Findings

In this section, three principal findings from the present study are discussed. First, while relatively insignificant to the overall energy production of California, closed landfills have been shown to be a significant source of solar energy in the State. Secondly, combining dish-Stirling systems with PV geomembrane and LFG to energy facilities warrants further investigation. The last major finding of the current analysis is that there are many unique assumptions, challenges, and limitations when conducting a solar inventory of a specific land use.

As shown in the previous section, solar facilities on closed landfills have the potential to provide a significant contribution to California's solar energy generation. In fact, electricity generation from these sites could potentially represent nearly six times the current solar energy industry in the State. While it is unlikely that all of these sites could be developed in reality, only 1/6 of this energy is needed to double California's solar energy production. Furthermore, since closed landfills are already sited on disturbed land, it is likely that these sites could provide this energy with relatively little ecological damage. Other locations often looked to for siting these projects often displace native species and disrupt virgin land with large scale solar farms; siting medium sized solar facilities on closed landfills represents a solution to this ecological damage (Abbasi and Abbasi 2002, 132).

This study has also shown the potential of combination systems for PV geomembrane, dish-Stirling, and LFG to energy technologies for electricity production on closed landfills. The first combination system type involves siting both PV geomembrane and dish-Stirling on the same location. Because of the technologies' varied terrain requirements, one system can often be located on topography unfit for the other; combing both technologies at a single location results in more usable land available for that site overall and therefore more electricity production. Secondly, LFG to energy facilities utilize similar thermal engines to those used by dish-Stirling systems. LFG to energy systems could potentially power the Stirling engine used in dish-Stirling systems. Since there exists a large potential in closed landfills for siting solar power, and many of these sites have LFG to energy facilities in place, these types of combination systems warrant further technical investigation.

Lastly, this study has called to attention major challenges in conducting an inventory using a specific land use type; these issues are discussed further in the next section. However, the following challenge is applicable to a wide range of inventory studies: it is both imperative and surprisingly difficult to find data to use as a base population for an inventory regarding a specific land use. An analysis can be extremely detailed, but if potential sites are not included in this analysis, the study's results will be inaccurate. This study incorporated the most complete data sources available to address this issue. However, it is likely that there are numerous landfills with potential for solar installations that were not contained in this list. The quality of these data is also important, for instance this study could not consider forty-five landfills because they were missing spatial data and these locations could not be found.

5.3 Limitations and Assumptions

In this section limitations and assumptions of the current study are addressed. First, there are many necessary simplifications involved in modeling solar radiation. The Solar Analyst tool used to estimate solar radiation does not account for all factors that influence irradiation, such as reflective radiation and empirical cloud cover data, and these limitations extend to the present study. Additionally, there exists a lack of accurate and complete data regarding landfills in California. Furthermore, this study's methodology required transformations between raster and vector data types, which can also yield inaccuracy.

This study encountered additional limitations. For instance, there are likely discrepancies between the elevation data used in this analysis and actual landfill topography. Moreover, site visits were not conducted in the current study and this may have caused inaccuracies in the digitization of available area at landfills. Finally, the current work is a purely technical study and neglects to account for many economic or policy factors that might make the development of given technologies for specific sites more or less viable.

The present study is dependent on two large assumptions. First of all, dish-Stirling systems have not been reported to be installed on landfills. This study assumes these systems could physically be installed on such sites. Furthermore, because of a lack of data on the technology, several attributes used for PV geomembrane systems were taken from general PV thin film characteristics.

Providing an estimate for the solar potential of closed landfills presents challenges that stem from the uncertainties in modeling solar radiation and converting this figure to energy output. Esri's Solar Analyst, used in this study to estimate solar radiation, does not empirically measure incoming solar radiation and therefore is only an estimate of the power source. For instance, Solar Analyst does not consider reflective radiation when calculating global radiation. While this type of radiation is very small compared to direct and diffuse irradiance, incoming radiation available for PV geomembrane cells could in theory be slightly higher than values estimated by Solar Analyst.

Solar Analyst also does not model cloud cover directly, rather it uses radiation parameters such as transmittivity and diffuse proportion to estimate the average fraction of radiation passing through the atmosphere or irradiance that is diffuse. In many cases, these parameters are sufficient to account for cloud cover in solar radiation estimations over multiple days (Fu and Rich 1999, 29). The defaults of 0.3 and 0.5 were used for diffuse proportion and transmittivity parameters, respectively, in all analyzed landfills; these parameters account for 'generally clear skies' (Esri 2012). Since the cloud cover of all landfills accounted for in this study do not necessarily fall into the category of 'generally clear skies', results from the present work do not fully account for cloud cover of the analyzed sites.

To address the concern of cloud cover effects on solar radiation, NREL (2012) DNI data, which accounts for the phenomenon through remote censored data, was compared to the average $kWh/m^2/day$ from Solar Analyst estimates. This assessment found that Solar Analyst results were typically smaller, with an average of 3.7 $kWh/m^2/day$, compared to values between 2.2 and 8.8 $kWh/m^2/day$ found in NREL data (2012). Figures 1 and 6 illustrate NREL DNI data used for this comparison. It can then be projected that, while Solar Analyst does not directly account for variation in overcast conditions, radiation predicted in the current study is lower that from empirically measured data.

There is a lack of accurate data regarding landfills in the United States and this is another challenge faced in the current study. As addressed in the previous section there is currently no official, accurate, and comprehensive database of landfill data necessary to conduct a more thorough inventory of these facilities.

GIS files used to represent landfill areas in this study were converted between vector and raster formats multiple times in the present study to work around limitations of the data types. Outlines of landfills were digitized in vector format, which were then used to clip raster elevation data. The geoprocessing necessary to find areas leftover for PV geomembrane systems after locations were assigned to dish-Stirling facilities, as shown in Figure 3, converted raster to vector data. This vector data was then used to clip raster elevation data. Raster and vector transformations were necessary three times in the present study. The intrinsic differences between these two data types cause another source of error for this study since the two data types cannot overlap perfectly.

On average, this inaccuracy should not affect the results of the current study in any particular direction. However, if the raster representation of an area is larger or smaller than the area digitized in vector format, converting between the data types may increase or decrease the area analyzed for solar potential accordingly. Results, in watt hours, derived from this area would be skewed lower than predicted if the raster representation of the area was smaller than the digitized landfill size. This inaccuracy, however, is extremely difficult to quantify and was therefore not accounted for in the present study.

Modeling the terrain of a landfill using the NED is another source of uncertainty in this process. The NED data used to obtain slope and aspect information represents the most current elevation data from the USGS. However, unless a landfill was already closed for five years at the time of the NED creation, the location's terrain will change significantly from accepting additional waste due to the settlement and grading of that waste. This would have a direct impact on the usable land available at the site.

No site visits were conducted in the present study. Therefore, some presumptions were necessary to digitize usable area at each site surveyed. It is possible that structures, vegetation, and other obstacles visible in the imagery have since been removed or additional obstacles to solar power systems have been created.

An economic analysis was not conducted for the present study. While dish-Stirling systems are more efficient than PV geomembrane technology, it is possible that the latter could be a better financial investment after relevant economic factors are considered. Furthermore, siting solar power facilities on landfills, as proposed in the current work, could present financial challenges unaddressed in the present study's analysis.

The present study assumes that dish-Stirling systems can be installed on top of landfills. However, an example of such an installation could not be found. A detailed analysis is therefore necessary to determine if dish-Stirling systems have this capability. Such an analysis is described in the following section.

This study assumes that attributes for PV geomembrane technologies are similar to other second generation PV technologies. EPA and NREL studies found that ballasted thin film PV systems were the most effective PV technology for landfills, but these studies did not test for PV geomembrane (Salasovich and Mosey 2011a). It was assumed that PV geomembrane would be economically comparable to ballasted thin film panels. Likewise, efficiency factors for PV geomembane were not readily available. Therefore this study also assumes that PV geomembrane has an efficiency factor similar to other thin film PV technologies. These assumptions were necessary because PV geomembrane technology is relatively new and little data are available on the subject.

5.4 Future Work

Since this study is the first to estimate the potential of landfills for hosting dish-Stirling and PV geomembrane technologies, several areas of future work are presented. A technical study is necessary to yield information on combination dish-Stirling, PV geomembrane, and LFG to energy facilities. A further study regarding the ability of landfills to host dish-Stirling systems is needed; more data on PV geomembrane's use on landfills are also required. Studies that measure effects of overcast conditions on the analyzed landfill sites are also an area for future research.

Additional areas for future work can be cited. Because there is a lack of studies analyzing solar energy potential that report power production per acre, studies that give this point of reference are needed. Furthermore, a financial analysis of the proposed facilities would answer questions concerning the economic feasibility of these systems. Also, a site specific study is necessary for a practical installation of solar capturing technologies on a landfill. Finally, as solar energy facilities sited on landfills are constructed, empirical data must be collected from these locations to calibrate the model proposed in this study.

The present work shows the theoretical potential of combining PV geomembrane, dish-Stirling, and LFG to energy systems. A combination of dish-Stirling and LFG to energy systems deserves particular attention, since the two technologies could share a Stirling engine. Although PV geomembrane and dish-Stirling systems could share transmission lines and related equipment, these savings would likely be relatively small compared to two technologies powering the same thermal engine. Because such a Stirling engine has not yet been engineered, there is a future need to explore cost benefit calculations for these sites after these shared systems are established. LFG to energy facilities would both increase ROI for these facilities and provide a secondary power source that can be utilized when solar energy is low to match the timing of electrical demand. This analysis would further refine landfill solar inventory modeling for future studies.

Technical research is required to explore the feasibility of placing dish-Stirling systems on landfills and to acquire additional information regarding the use of PV geomembrane on such sites. Since dish-Stirling systems have not been installed on landfills in the past, it is unknown if such an installation is feasible. Additionally, installation requirements used in the present study should be compared in detail to empirical data from existing PV geomembrane installations on landfills. Because such specifics were unavailable, this comparison was not possible in the current work.

Economic studies such as cost-benefit analyses are necessary for a comprehensive analysis of solar potential on closed landfills. A landfill must produce adequate electricity to cover initial capital costs and ongoing operation and maintenance costs for a site to be economically viable. The price that local utilities are willing to pay for electricity from these plants determines how much revenue the location makes for a given amount of electricity produced. Additionally, government policies affect the economic viability through grants, government aid, limitations on grid-connected facilities, and other political variables that differ from place to place. These issues were outside the scope of the present study but must be addressed nonetheless by solar power developers.

As discussed in the previous section, radiation parameters used in Solar Analyst for this study's irradiation estimations were calculated under 'generally clear skies'. In reality, each site would have unique values for transmittivity and diffuse proportion depending on local climate. If landfills presented in this study were to be analyzed more thoroughly, it would be necessary to find radiation parameters that optimize Solar Analyst to account for local weather patterns.

There are few inventory studies estimating solar energy potential that report power production per acre. Of all studies reviewed in the literature review of the present work, Carrión et al. (2008) was the only report that provided enough information to compare results on an acre to acre basis. Therefore, it was difficult producing a point of reference to relate this study's results to other works. It would be beneficial to any inventory study measuring solar potential to compare energy produced per acre to past works; hence, a study comparing results of several analyses in this way is needed to establish a good basis for comparison.

The methodology presented in this study represents a rough estimate of potential locations and productivity available on closed landfills. A more detailed study is needed if any of these sites were to be developed. A collaboration of landfill owners, engineers, experts in dish-Stirling and PV geomembrane solar technology, and related professionals is necessary to provide enough data to justify an actual installation at these sites.

Lastly, as solar facilities are installed on landfills in practice, the assumptions of the current work will be tested. Solar electricity is a relatively new technology and siting these systems on landfills is still an emerging concept with few real world examples. Because of this, the present work was forced to make several assumptions. As more solar power is harvested on landfills, the proposed model must evolve to take advantage of knowledge accumulated from the successes and failures of these facilities related to specific site characteristics. With this knowledge, inventory studies of such sites around the world using GIS modeling could be accomplished with greater precision.

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Appendix A - Landfills Passing Prescreen Requirements

CEC List Name	*EPA List Name*	*Landfill City*	*Landfill County*	*Coordinates*
	Twin Bridges LF	Anderson	Shasta	40.495803, -122.202519
Contra Costa SLF (aka Pittsburg or GBF LF)	Central Contra Costa SLF	Antioch	Contra Costa	37.9875, -121.845
Azusa LF	Azusa Land Reclamation Company, Inc.	Azusa	Los Angeles	34.119639, -117.927593
China Grade SLF	China Grade SLF	Bakersfield	Kern	35.425, -118.929
Beale AFB LF	Beale Air Force Base SLF	Beale Air Force Base	Yuba	39.072978, -121.392578
Lamb Canyon DS	Lamb Canyon Disposal Site	Beaumont	Riverside	33.88389, -116.99722
Big Bear RDS	Big Bear Refuse Disposal Site	Big Bear City	San Bernardino	34.305549, -116.819583
Boron SLF	Boron SLF	Boron	Kern	34.9903, -117.647
Buttonwillow SLF	Buttonwillow SLF	Buttonwillow	Kern	35.4121, -119.46678
Clover Flat LF	Clover Flat Landfill	Calistoga	Napa	38.584, -122.534
Chiquita Canyon	Chiquita Canyon SLF	Castaic	Los Angeles	34.434664, -118.645356

CEC List Name	*EPA List Name*	*Landfill City*	*Landfill County*	*Coordinates*
Colton LF	Colton Sanitary Landfill	Colton	San Bernardino	34.04553, -117.345575
Fink Rd LF	Fink Road LF	Crows Landing	Stanislaus	37.3882, -121.136
Edom Hill DS	Edom Hill Disposal Site	Desert Hot Springs	Riverside	33.88196, -116.438735
San Marcos LF	San Marcos LF	Escondido	San Diego	33.090004, -117.197451
Echo Gold	Goldstone Deep Space Comm Complex	Fort Irwin (Mil Res)	San Bernardino	35.304479, -116.798329
Tri-Cities LF	Tri-Cities Landfill	Fremont	Alameda	37.49277, -121.99229
Chateau Fresno LF	Chateau Fresno LF	Fresno	Fresno	36.687607, -119.945266
Orange Ave.	Orange Avenue Disposal Inc.	Fresno	Fresno	36.687211, -119.761645
McCourtney Rd LF	McCourtney LF	Grass Valley	Nevada	39.1726, -121.112
Hanford LF	Hanford SLF	Hanford	Kings	36.297902, -119.598116
Hesperia RDS	Hesperia Refuse Disposal Site	Hesperia	San Bernardino	34.34728, -117.3483
Highgrove LF	Highgrove SLF	Highgrove	Riverside	34.006708,-117.282228
Exeter DS	Exeter Disposal Site	Lindsay	Tulare	36.228947, -119.151619
Vasco Road LF	Vasco Road SLF	Livermore	Alameda	37.753182, -121.722447
Harney Lane LF	Harney Lane SLF	Lodi	San Joaquin	38.0994, -121.1364
Austin Rd. LF	Austin Road Landfill	Manteca	San Joaquin	37.879122, -121.191308
Yuba Sutter Disposal Area LF (YSDA)	Yuba-Sutter Disposal Area	Marysville	Yuba	39.17018, -121.550807
Newby Island	Newby Island SLF Phases I, II, & III	Milpitas	Santa Clara	37.459837, -121.943829

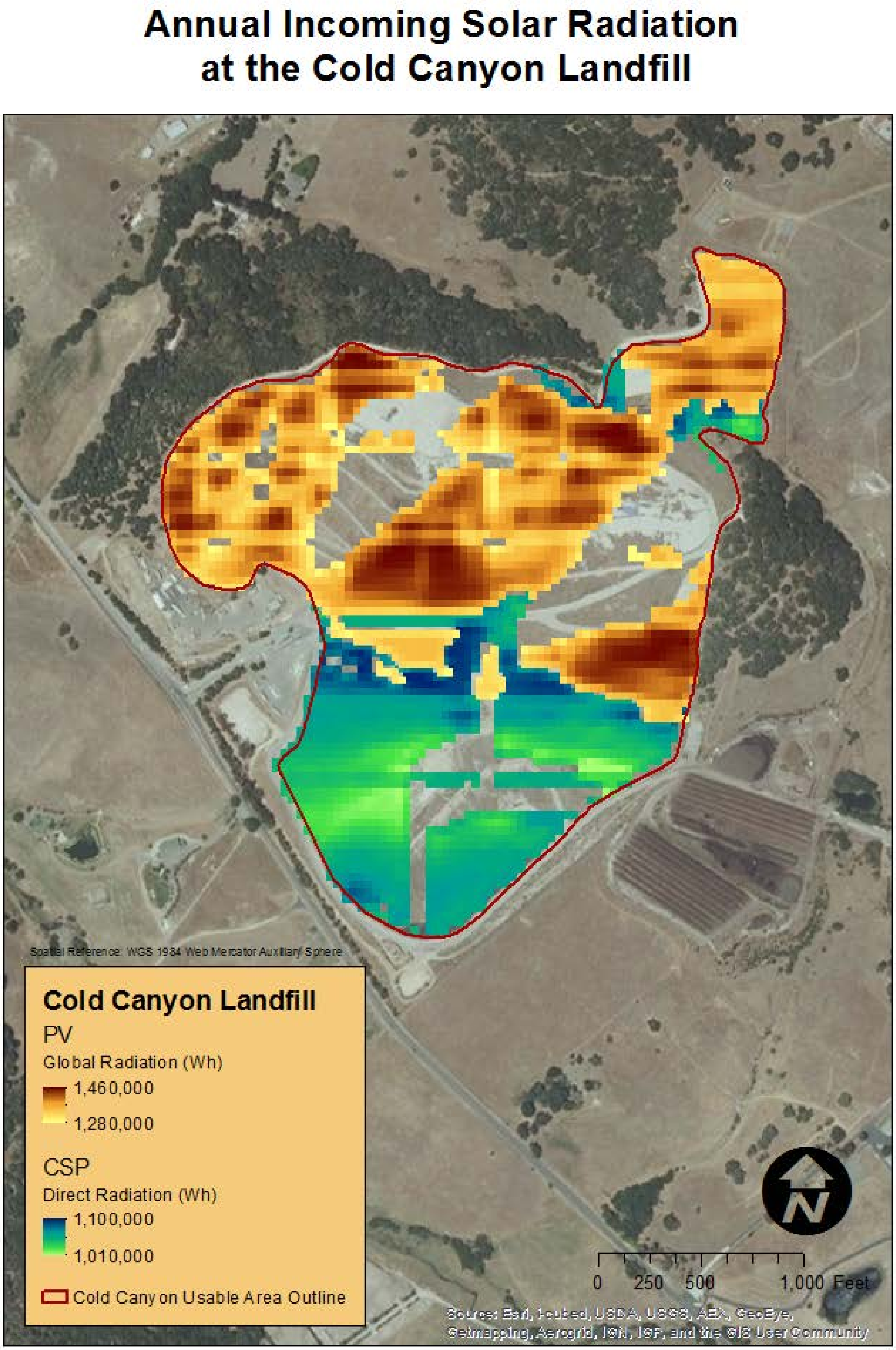
CEC List Name	*EPA List Name*	*Landfill City*	*Landfill County*	*Coordinates*
Badlands DS	Badlands Disposal Site	Moreno Valley	Riverside	33.9535, -117.118
Kirby Canyon LF	Kirby Canyon Recycling & Disposal Facility	Morgan Hill	Santa Clara	37.18507, -121.67109
Oasis DS	Oasis Disposal Site	Oasis	Riverside	33.439, -116.081
Milliken	Milliken SLF	Ontario	San Bernardino	34.0365, -117.558
Oro Grande	Oro Grande LF	Oro Grande	San Bernardino	34.634903, -117.306705
Lewis Rd. LF	Lewis Road SLF	Pajaro	Monterey	36.880753, -121.699169
Redding SLF (Benton)	City of Redding/ Benton LF	Redding	Shasta	40.571425, -122.411256
San Timoteo SWDS	San Timoteo Sanitary Landfill	Redlands	San Bernardino	34.01283, -117.21477
Sacramento City LF	Sacramento City LF	Sacramento	Sacramento	38.58736, -121.45592
Crazy Horse LF	Crazy Horse Landfill	Salinas	Monterey	36.80365, -121.618273
Miramar SWLF	West Miramar SLF	San Diego	San Diego	32.856, -117.162
Guadalupe SLF	Guadalupe Sanitary Landfill	San Jose	Santa Clara	37.2114, -121.901
Cold Canyon	Cold Canyon LF Solid Waste Disposal Site	San Luis Obispo	San Luis Obispo	35.1873, -120.596
City of Santa Maria LF	City of Santa Maria Refuse Disposal Site	Santa Maria	Santa Barbara	34.950187, -120.377115
French Camp LF	French Camp Landfill	Stockton	San Joaquin	37.916, -121.295

CEC List Name	*EPA List Name*	*Landfill City*	*Landfill County*	*Coordinates*
Bradley Ave East & West	Bradley Landfill	Sun Valley	Los Angeles	34.240171, -118.384513
Lopez Canyon LF	Lopez Canyon SLF	Sylmar	Los Angeles	34.293849, -118.392602
Corral Hollow	Corral Hollow LF	Tracy	San Joaquin	37.67, -121.457
Twentynine Palms DS	Twentynine Palms Disposal Site	Twentynine Palms	San Bernardino	34.1192, -115.965
City of Ukiah SWDS	City of Ukiah Solid Waste Disposal Site	Ukiah	Mendocino	39.169731, -123.165457
Buena Vista DS	Buena Vista Disposal Site	Watsonville	Santa Cruz	36.91738, -121.81142
BKK West Covina DS	BKK Landfill-Phases I & II	West Covina	Los Angeles	34.037973, -117.902573
Puente Hills LF	Puente Hills LF	Whittier	Los Angeles	34.0203, -118.006
Teapot Dome DS	Teapot Dome Disposal Site	Woodville	Tulare	36.0211, -119.106
Forward LF	Forward Inc. Landfill		San Joaquin	37.874599, -121.188254

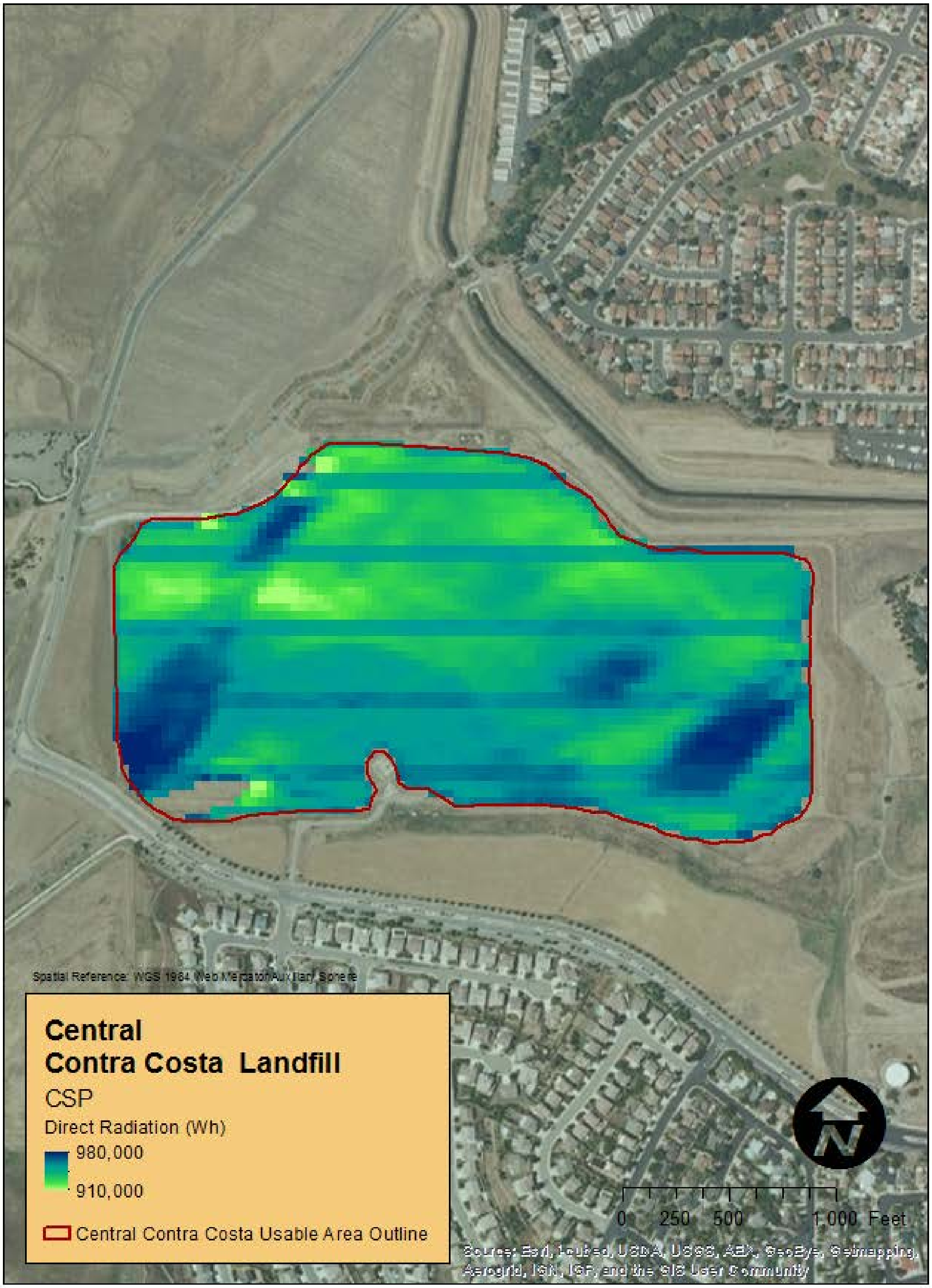
Appendix B - Solar Calculations

Landfill	*System*	*Raster Cell Count*	*Raw Area (m^2)*	*Final Area (Acres)*	*Mean Wh/m^2*	*Raw Annual Wh for Landfill*	*Annual AC Produced (Wh)*	*Annual DC Produced (Wh)*	*Total Annual Energy from Landfill (Wh)*	*Total Annual Energy from Landfill (MWh)*
BKK	PV	6,963	902,417.96	167.24	1,446,888.00	979,273,288,057.32	107,720,061,686.31	82,944,447,498.46		
BKK	CSP	852	110,420.81	20.46	1,057,375.00	87,567,153,202.36	21,891,788,300.59	16,856,676,991.45	99,801,124,489.91	99,801.12
Clover Flat	PV	695	90,073.31	16.69	1,364,949.00	92,209,109,442.57	10,143,002,038.68	7,810,111,569.79	7,810,111,569.79	7,810.11
Cold Canyon	PV	1,936	250,909.26	46.50	1,395,041.00	262,521,527,730.32	28,877,368,050.33	22,235,573,398.76		
Cold Canyon	CSP	1,229	159,280.72	29.52	1,019,117.00	121,744,269,290.97	30,436,067,322.74	23,435,771,838.51	45,671,345,237.27	45,671.35
Central Contra Costa	CSP	3,271	423,927.78	78.57	946,137.90	300,820,606,194.68	75,205,151,548.67	57,907,966,692.48	57,907,966,692.48	57,907.97
Echo Gold	CSP	417	54,043.99	10.02	1,480,695.00	60,016,997,253.11	15,004,249,313.28	11,553,271,971.22	11,553,271,971.22	11,553.27
Exeter	CSP	1,817	235,486.63	43.64	999,151.70	176,465,153,113.70	44,116,288,278.43	33,969,541,974.39	33,969,541,974.39	33,969.54
Forward	CSP	4,712	610,684.11	113.18	956,180.40	437,943,129,332.06	109,485,782,333.02	84,304,052,396.42	84,304,052,396.42	84,304.05
Guadalupe	PV	964	124,936.22	23.15	1,430,941.00	134,082,271,790.75	14,749,049,896.98	11,356,768,420.68		
Guadalupe	CSP	1,373	177,943.39	32.98	992,714.80	132,485,281,311.72	33,121,320,327.93	25,503,416,652.51	36,860,185,073.18	36,860.19
Hanford	CSP	3,590	465,270.79	86.23	995,551.20	347,400,666,323.44	86,850,166,580.86	66,874,628,267.26	66,874,628,267.26	66,874.63
Lewis Rd	PV	432	55,988.02	10.38	1,339,951.00	56,265,899,002.79	6,189,248,890.31	4,765,721,645.54	4,765,721,645.54	4,765.72
Milliken	CSP	7,060	914,989.34	169.57	1,066,866.00	732,128,265,626.84	183,032,066,406.71	140,934,691,133.17	140,934,691,133.17	140,934.69
Miramar	PV	3,089	400,340.24	74.19	1,450,874.00	435,632,432,079.52	47,919,567,528.75	36,898,066,997.14		
Miramar	CSP	12,941	1,677,178.06	310.83	1,070,763.00	1,346,895,157,082.20	336,723,789,270.55	259,277,317,738.32	296,175,384,735.46	296,175.38
Oasis	CSP	1,098	142,302.88	26.37	1,033,737.00	110,327,810,490.97	27,581,952,622.74	21,238,103,519.51	21,238,103,519.51	21,238.10
Orange Ave.	CSP	1,353	175,351.36	32.50	988,864.20	130,049,009,645.12	32,512,252,411.28	25,034,434,356.69	25,034,434,356.69	25,034.43
Redding	PV	930	120,529.76	22.34	1,278,695.00	115,590,598,891.65	12,714,965,878.08	9,790,523,726.12		
Redding	CSP	1,682	217,990.38	40.40	915,046.60	149,603,516,338.77	37,400,879,084.69	28,798,676,895.21	38,589,200,621.34	38,589.20
Twentynine Palms	CSP	1,749	226,673.71	42.01	1,088,693.00	185,083,557,436.25	46,270,889,359.06	35,628,584,806.48	35,628,584,806.48	35,628.58

Appendix C - Maps of Analyzed Landfills

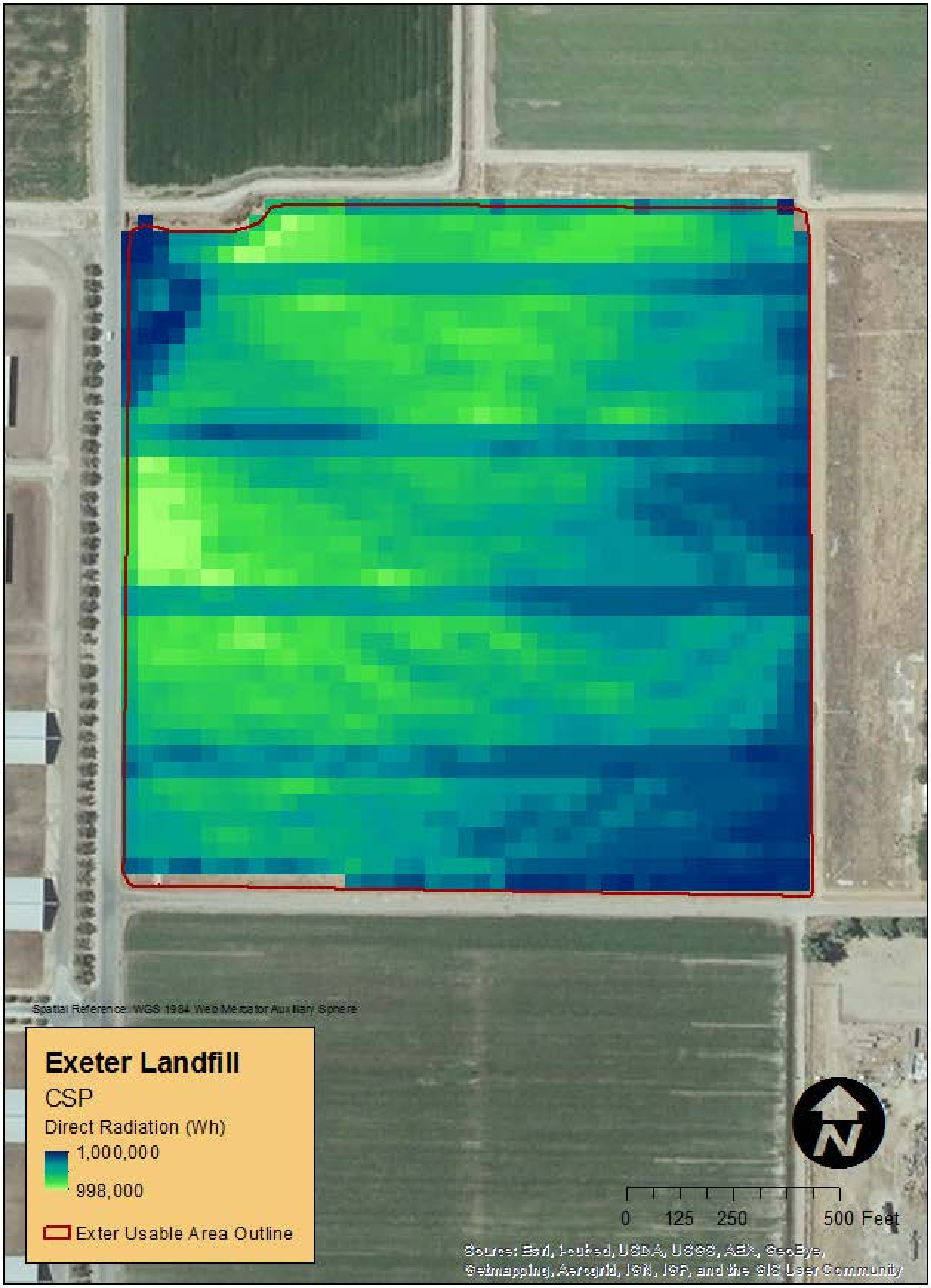


Annual Incoming Solar Radiation at the Central Contra Costa Landfill



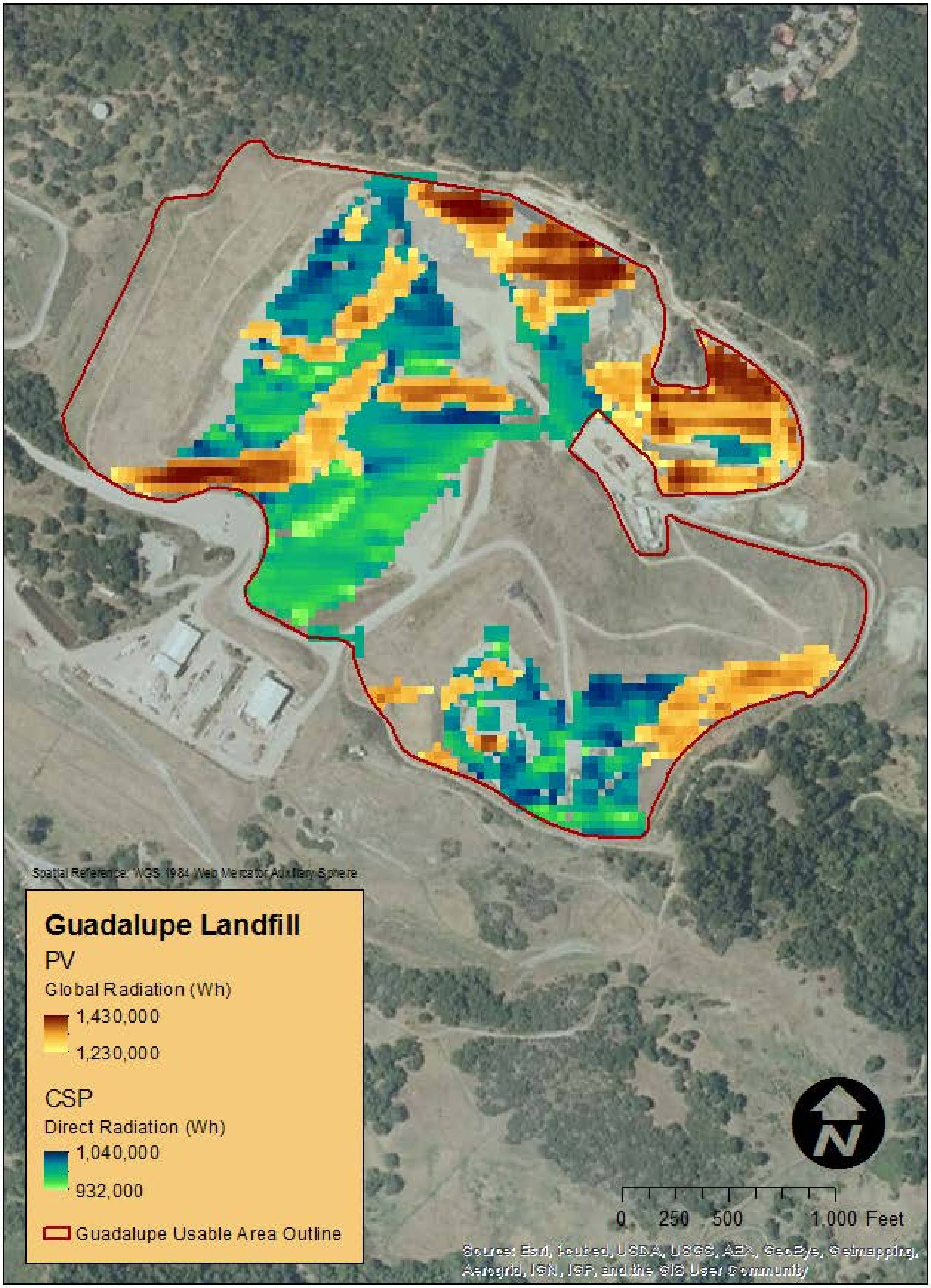
Annual Incoming Solar Radiation at the Echo Gold Landfill

Annual Incoming Solar Radiation at the Exeter Landfill



Annual Incoming Solar Radiation at the Forward Landfill

Annual Incoming Solar Radiation at the Guadalupe Landfill



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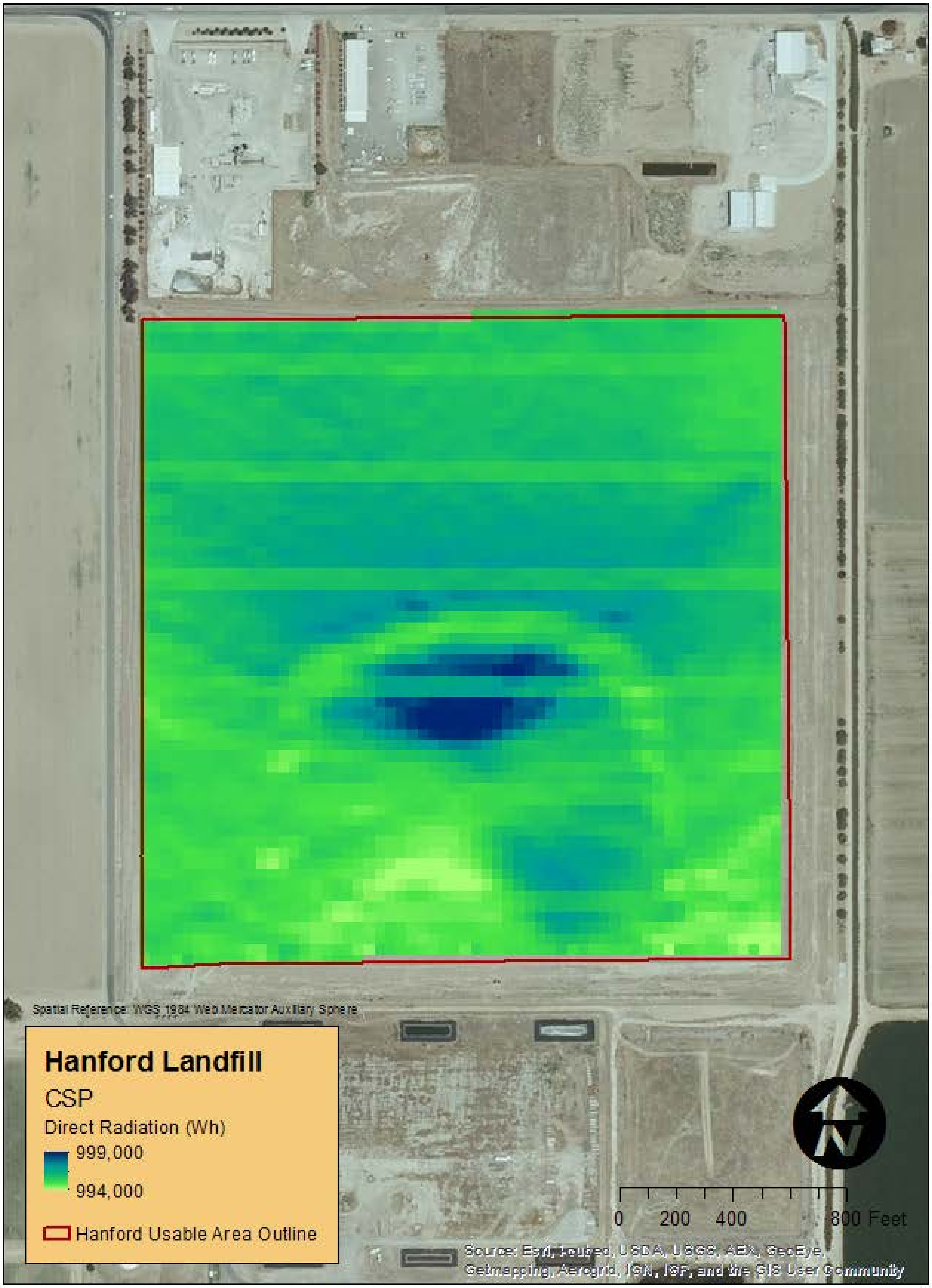

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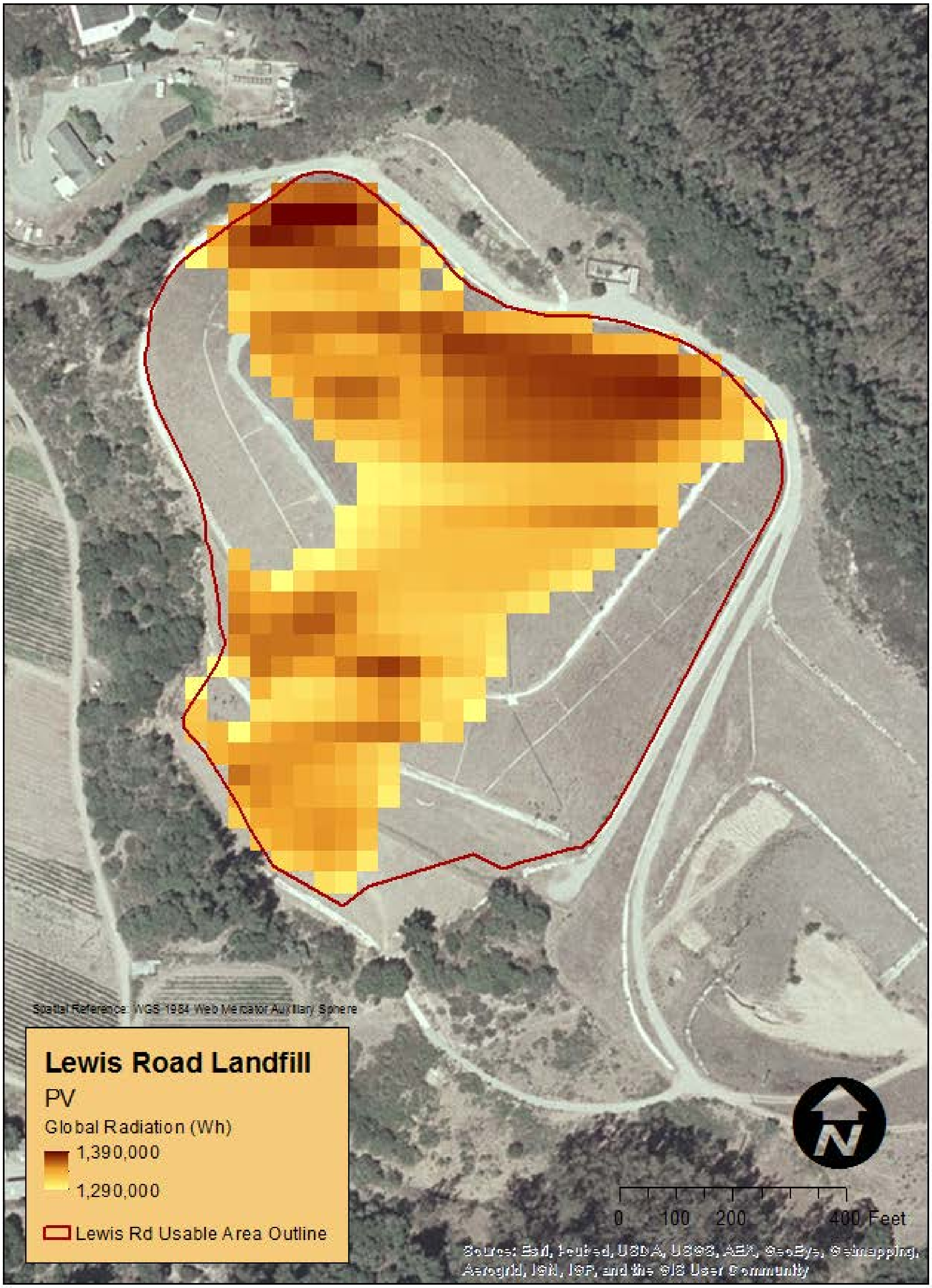
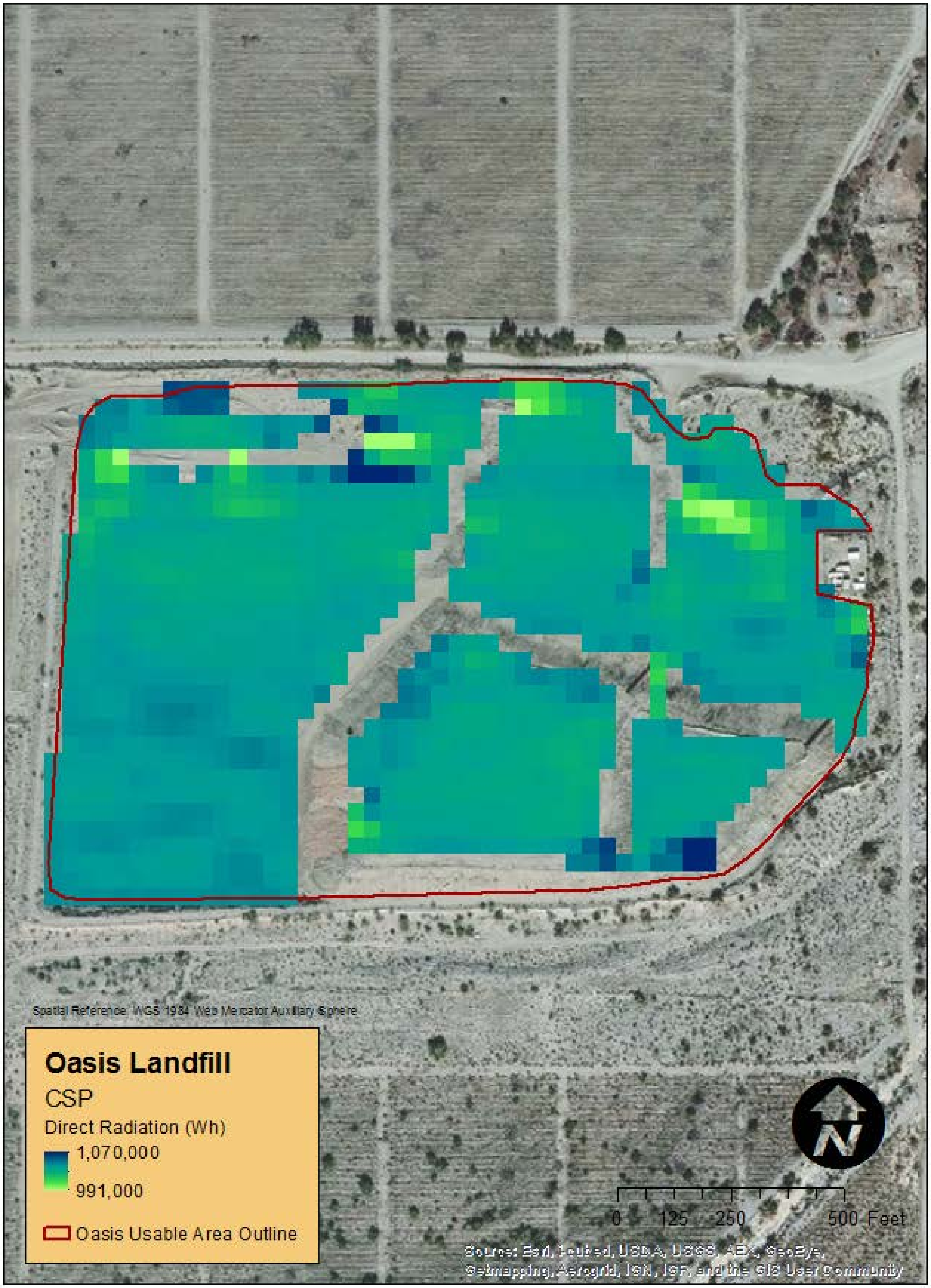
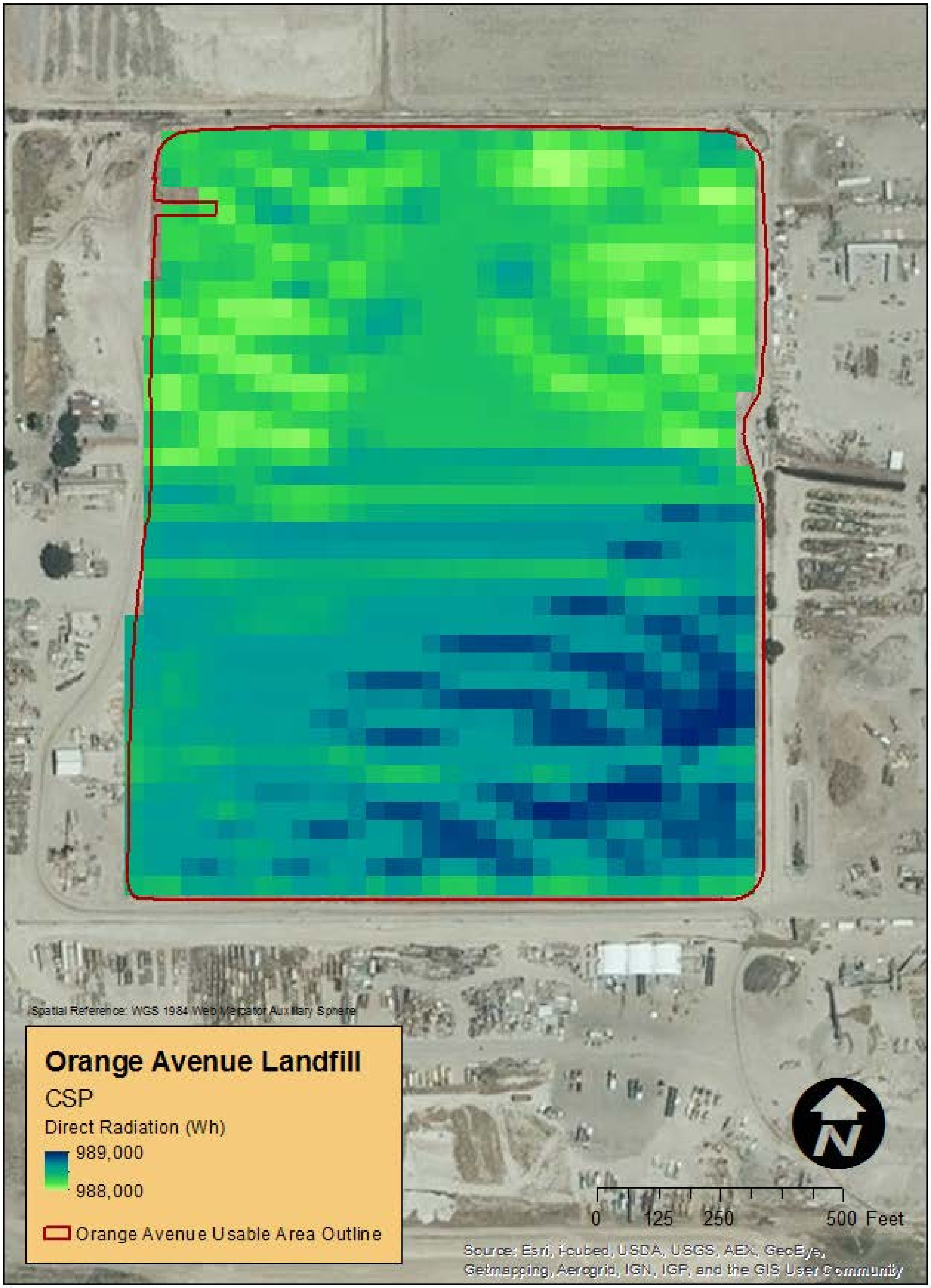


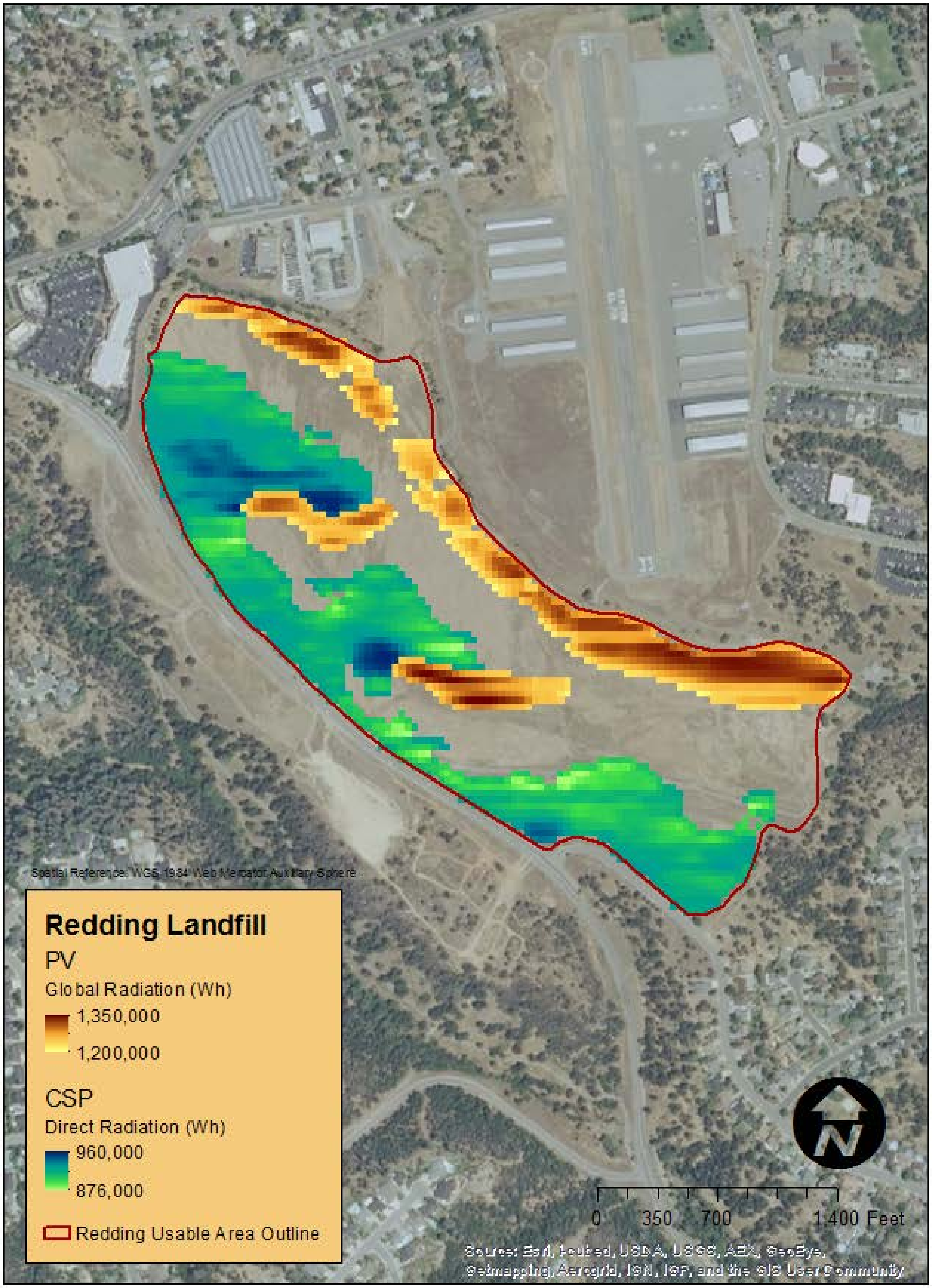
Annual Incoming Solar Radiation at the Oasis Landfill



Annual Incoming Solar Radiation at the Orange Avenue Landfill



Annual Incoming Solar Radiation at the Redding Landfill



Annual Incoming Solar Radiation at the Twentynine Palms Landfill