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Here Comes the Sun: Solar Thermal in the Mojave Desert—Carbon Reduction or Loss of Sequestration?

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Abstract

Global climate change (GCC) is emerging as a complex and pressing issue for ordinary citizens, policymakers, and scientists alike. As more data surfaces, the enormity of the issue becomes clearer. States like California are establishing renewable energy policy that aims to reduce greenhouse gasses, carbon-intensive forms of energy and dependence on foreign oil by investing in renewable (i.e., more carbon neutral) technologies. One such technology project proposes solar thermal plants on public lands in the Mojave Desert, an area that makes up one-fifth of the state of California. While solar thermal technology itself produces no carbon emissions, the construction produces emissions in several ways. In order to build the facility, the plants, animals and soil of the native desert acreage are damaged and destroyed, which releases CO_2. Currently, developers have presented the U.S. Bureau of Land Management with 75 applications to build solar facilities in the Mojave Desert that could impact approximately 647,000 acres of land (Mieszkowski, 2009). A recent study conducted in the Mojave Desert found that the desert soil ecosystems could represent a significant carbon sink (Stone, 2008; Wohlfahrt et al. 2008). However, the recent scientific literature regarding carbon sequestration in deserts is both new and not yet fully understood.

Solar power is perceived as a ‘clean’ energy source, reducing carbon production while providing much-needed energy. The production capabilities in the Mojave Desert could supply California with most of its energy needs. In order to better evaluate the deployment of multiple solar thermal facilities in the Mojave, this ecological risk assessment seeks to determine whether the installation and operation of solar thermal plants will impact carbon sequestration capabilities of the Mojave Desert soil ecosystem to the extent that more carbon is released or inhibited from being stored than saved while utilizing solar technology. The authors conclude that the release of carbon presented by construction of solar thermal facilities and related transmission lines, while significant in the beginning, will be mitigated over time, and that solar thermal facilities are more favorable than clean coal technology in terms of carbon footprint.

Introduction

Solar Thermal in the Mojave Desert
Global climate change (GCC) is emerging as a complex and pressing issue for ordinary citizens, policymakers, and scientists alike. The majority of climate scientists concur that GCC could alter fundamental systems and biological processes—from weather patterns to ocean acidity levels—which are widely believed to be rooted in anthropogenic activities. The Intergovernmental Panel on Climate Change (2007) released an explicit statement in its 4th report regarding the validity of a changing climate: "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level."

Despite the IPCC findings, climate change has stimulated innovations in alternative energies, including solar thermal. States like California, buttressed by political support, are investing in renewable energies that aim to reduce greenhouse gasses, carbon-intensive forms of electricity generation, and dependence on foreign oil.

The solar thermal plants proposed in the Mojave Desert (sometimes referred to as Concentrating Solar Power [CSP] plants) are one such effort to increase renewable energy production. Unlike photovoltaic solar cells that use semiconductor substances like silicon, solar thermal technology relies on a series of mirrors or lenses to convert the sun's energy into high-temperature heat, which generates electricity (Mills, 2004). Because solar thermal plants can store heat before converting it into electricity, energy can be socked away for later use or supplied during overcast weather (Quaschning, 2004).

Common solar thermal plant configurations fall into three general categories: parabolic troughs, dish systems, and single towers.

As the name implies, parabolic troughs consists of long, curved reflectors that direct the sun's energy to a receiving pipe or series of pipes filled with a heat transfer fluid, which is often a synthetic oil (Mills, 2004; National Renewable Energy Laboratory, 2006). The hot oil then generates steam that powers a turbine to produce electricity (National Renewable Energy Laboratory, 2006).

Dish systems features a series of stand-alone reflectors that focus the sun's energy onto a receiver positioned within the reflector. A working fluid inside the receiver is heated and drives a Stirling engine or turbine (Mills, 2004).

Lastly, solar tower plants harness the desert sun's high radiation by using mirrors to reflect incoming light and direct it to a receiver on top of a tower. The receiver is filled with a heat transfer fluid called molten salt—a technical term for melted salt –which produces steam that drives a turbine to create energy (National Renewable Energy Laboratory, 2006). The energy is then transferred through transmission lines to consumers. Although water is used in the process, the water is air-cooled and recycled through for reuse (thus after the initial water is captured, little water is needed to sustain the process). Figure 1 depicts a single tower structure of a solar thermal power plant.

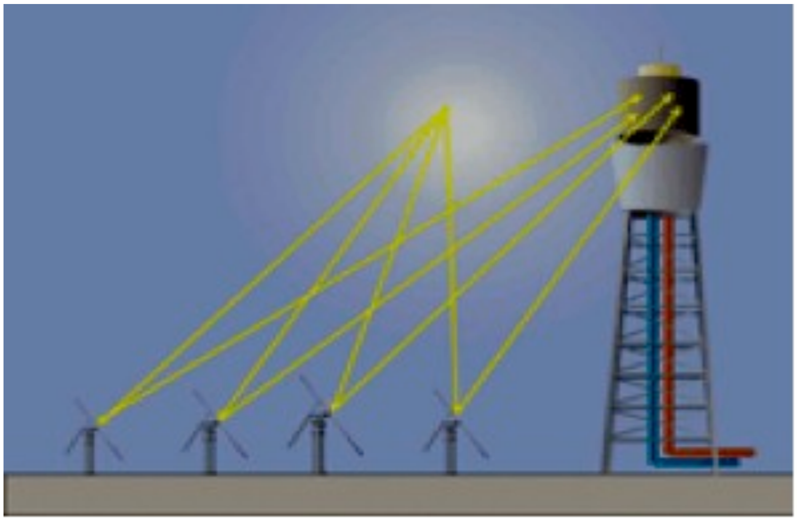

Figure 1. A single tower solar thermal plant structure.
(Source: Bright Source Energy, 2009)

While new technologies are still emerging or being refined, solar thermal plants offer a number of benefits over conventional photovoltaic systems. Large-scale plants take advantage of the economy of scale, as per KW declines with increased size (National Renewable Energy Laboratory, 2006). In Sunbelt areas where irradiation levels are high (such as the Mojave Desert), solar thermal is more economically feasible than PV systems (Quaschning, 2004). Additionally, solar thermal plants offer greater flexibility in energy generation by storing heat, which can be supplied on an "as-needed" basis.

The Global Carbon Budget

Advances in solar thermal may play a key role in reducing carbon emissions and therefore, positively affecting the planet's carbon budget. The global carbon budget can be understood as a loss and income of carbon within and between the atmosphere, the oceans, land, and fossil fuels, with some exchanges occurring almost instantaneously (photosynthesis) and other occurring over thousands of years (fossil fuel accumulation) (Houghton, 2005). Janzen (2004) illustrates the complex carbon exchange when he writes, "If we could follow a single carbon atom now in the air, we might find that it enters a pine tree by photosynthesis, returns to the air when the pine needle decays, then is fixed into a grain of rice, before escaping back into the air in a child's breath."

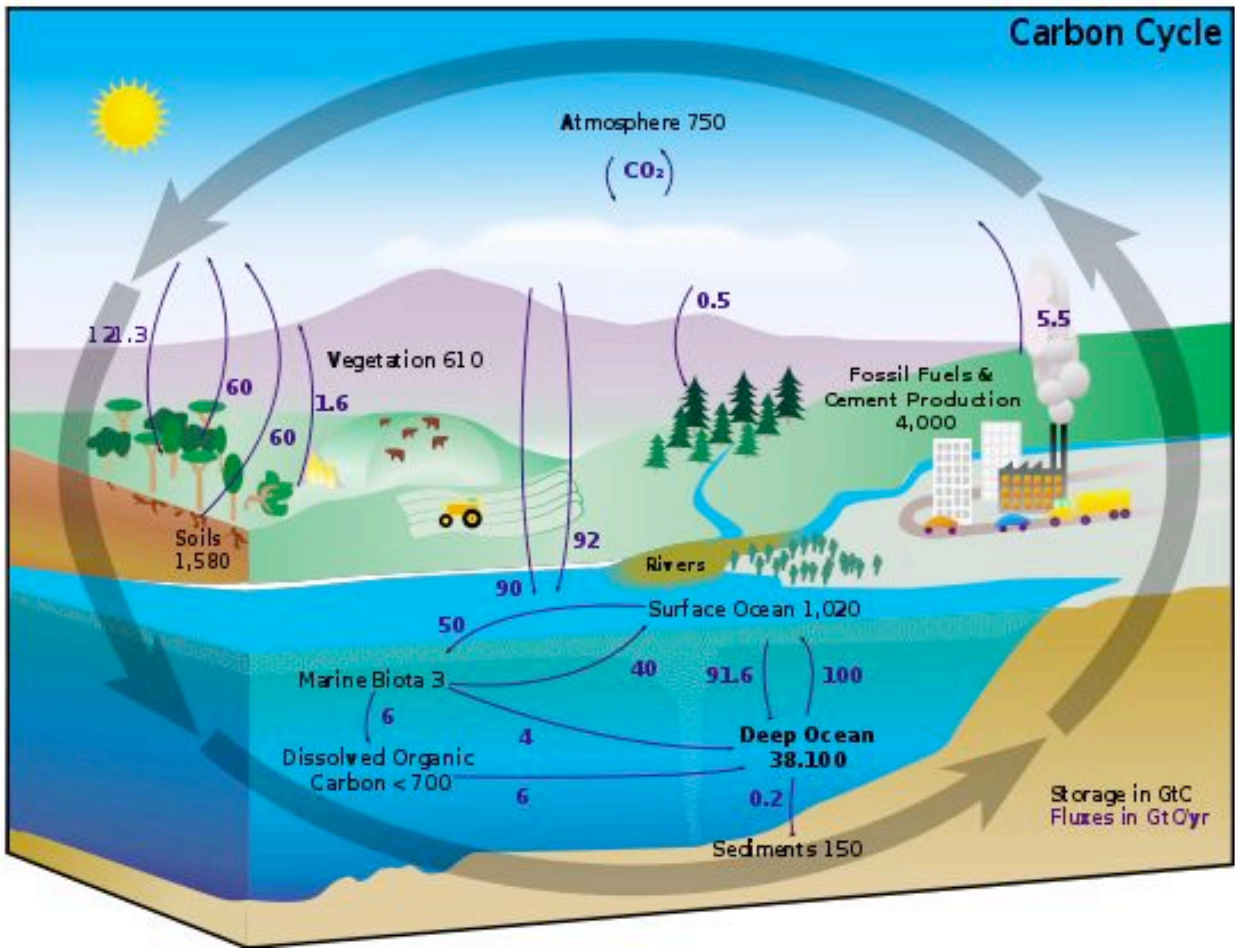

Figure 2: The Carbon Cycle. Black numbers indicate reservoirs of stored carbon in GigaTons (billions of tons) circa 2004. Purple numbers follow the movement of carbon between reservoirs, also known as the annual flux (Source: http://en.wikipedia.org/wiki/Carbon_cycle).

For millennia, carbon exchanges have remained relatively stable. With the onset of the Industrial Revolution, however, human activities began to alter the carbon cycle through two primary practices: burning of fossil fuels, and altering land use, principally through expansion of agriculture (Janzen, 2004).

In 2003, U.S. fossil-fueled power plants accounted for 2.25 billion metric tons of CO_2 emissions; by one account, electricity generation is the largest emitter of pollutants responsible for GCC of all other industries (Sovacool & Cooper, 2007).

Agrarian practices and increased farmland acreage have reduced stocks of stored soil carbon and consequently redirected carbon flows from terrestrial reservoirs to the atmosphere. In fact, the world's pasture and cropland area has increased 30% over the last 400 years, while forest and grassland acreage continue to diminish (Janzen, 2004). Global land-use changes have resulted in carbon losses approaching 2 Pg C per year, while historic loss of soil organic carbon due to desertification and degradation is estimated at 20–30 Pg (Janzen, 2004; Lal, 2003).

Solar thermal has been branded by industry proponents as a viable alternative to fossil fuel energy sources and as a method to combat the effects of re-allocated carbon. However, solar thermal infrastructure could impact wildlife, water resources, vegetation, soil and overall quality of life for nearby residents—discussed in detail throughout this assessment.

Risk Assessment Outline:

This paper will provide a qualitative and quantitative analysis of establishing solar thermal as an impact on carbon sequestration capabilities of desert soils. The assessment will begin with a problem formulation, followed by analysis of stressors, exposure, effects, and cost versus benefit. The paper will also provide a characterization of risk and conclude with recommendations based on the analysis findings.

Problem Formulation

California's Renewable Energy Transmission Initiative (RETI) is a statewide effort that will facilitate renewable energy policy, transmission designation, and project siting and permitting, among other aspects (California Energy Commission, 2008a). Additionally, California aims to switch to 20 percent of its energy to renewable sources by 2010, as mandated by a statewide initiative (Marquis, 2009; California Energy Commission 2008a).

In light of the aforementioned policy and mandate, the Mojave Desert has been cited by developers and private companies as a viable space to build large solar thermal plants, due in part to the steady solar energy supply, the 20 million acre expanse of flat land, and the relatively sparse population (California Department of Fish and Game, 2009a). Additionally deserts, when viewed as barren landscapes devoid of biota, could be seen as ideal settings for renewable energy projects.

Mojave Desert Land and Proposed Solar Projects
There are approximately 75 applications submitted to the Bureau of Land Management (BLM) to build solar facilities in the Mojave Desert that could impact nearly 647,000 acres of land (Mieszkowski, 2009). The Mojave Desert occupies about 20 million acres in California, or one-fifth of the state. Management and ownership the 20 million acres are broken down by the CDFG (2009a) as follows:

- 80% of the land is managed by federal agencies; the BLM manages 8 million acres, or 41%;
- 26% of the region is National Park Service lands, specifically Death Valley, Joshua Tree National Park and Mojave National Preserve;
- 13% of the region is maintained by the Department of Defense (DOD), primarily as military bases;
- 0.32% of the area is entrusted to California State Parks and CDFG; and
- 18% is owned and occupied by private landowners or municipalities.

All permits for solar projects will apply to BLM land. If all current permits were accepted, an estimated 12% of BLM land would be converted into solar plants. This is strictly for the plant facilities and does not account for the infrastructure required for roads, transmission lines, water access, etc. (this will be discussed in more detail in the analysis). Figure 3 illustrates the current proposals for solar plants in California (BLM, 2009).

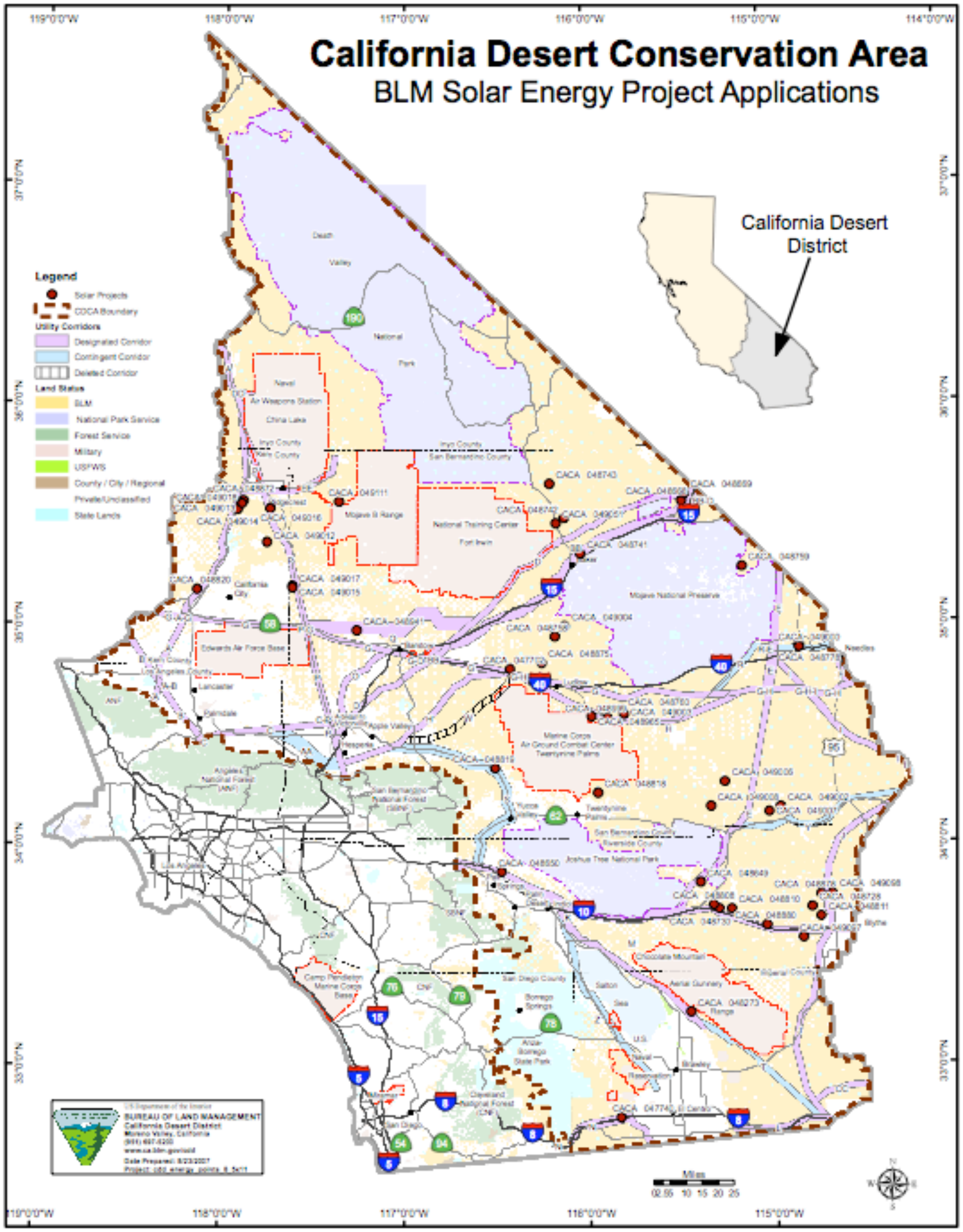

Figure 3. Solar energy project applications. Currently, 75 applications have been submitted to the Bureau of Land Management to develop solar thermal power plants. (Source: BLM, 2009).

Conceptual Model of Risks Associated with Solar Thermal:
The conceptual model (Figure 4) identifies the potential impacts that may occur with the installation and operation of solar thermal plants in the Mojave Desert. The working hypotheses relate exposure to effects, identifies the media for transport, and relates the extent and mode of exposure to the effect and assessment endpoint. There are ecological, social, economic, and ecosystem services that may be affected by the installation and operation of solar thermal plants. Given the large number of potential impacts and following the guidelines provided by the course instructors, we identified and analyzed one focus pathway, highlighted in red, for the purposes of this risk assessment.

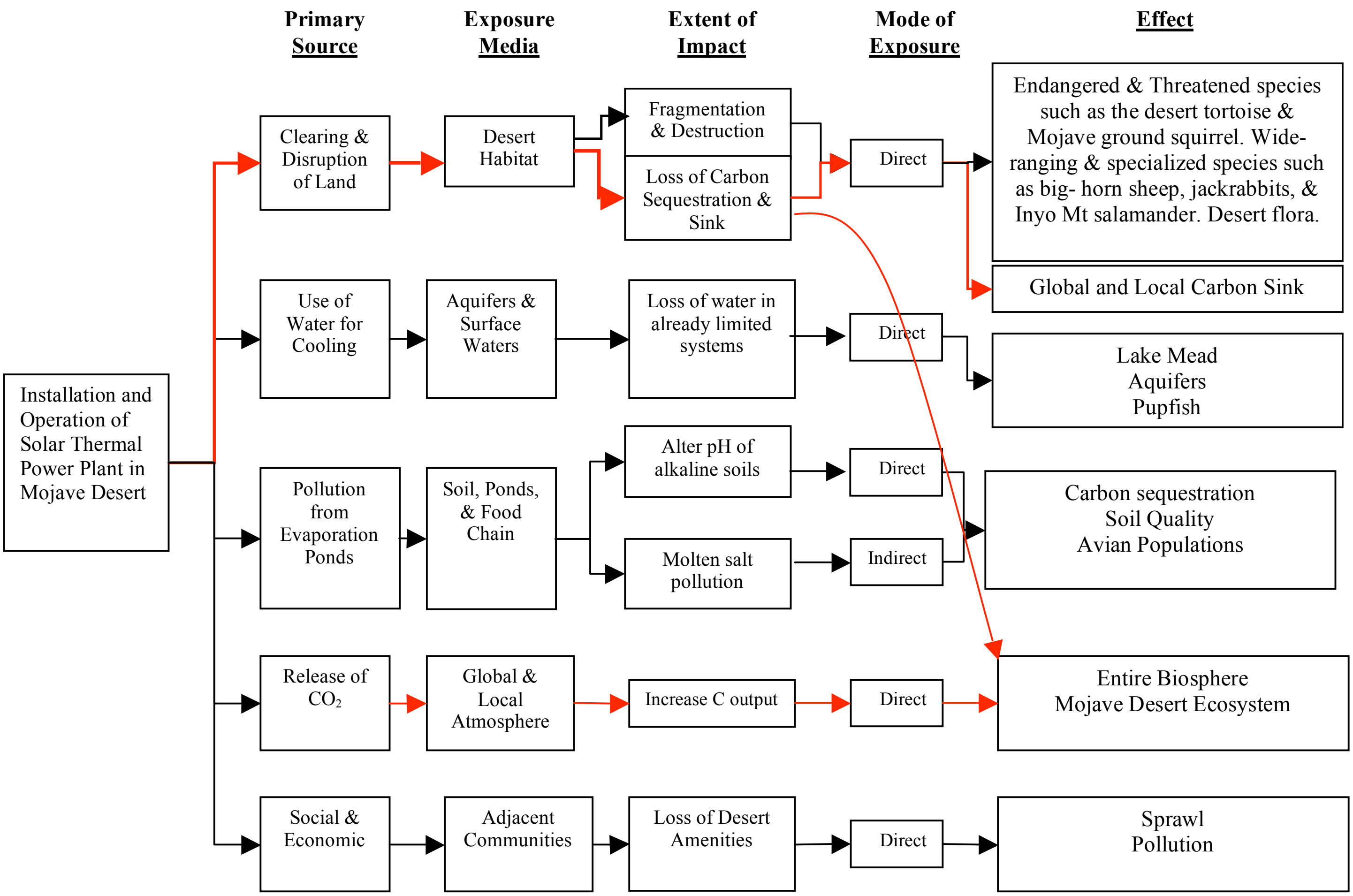

Figure 4. Conceptual model of potential impacts that may occur with the installation and operation of solar thermal plants in the Mojave Desert. The red lines indicate the focus pathway for the purposes of this risk assessment.

Social and Economic Impacts of Solar Thermal

The Mojave Desert solar boom will inevitably impact social and economic dimensions of the region. Nearby residents and national park visitors will face the burden of increased traffic, pollution, noise, and infrastructure that will diminish the aesthetic qualities of the desert. Some residents are already responding to solar parks by forming opposition coalitions such as the Desert Communities Protection Campaign of the Center for Community Action and Environmental Justice (Maloney, 2008).

A fringe impact of solar parks is increased land prices caused by growing demand from private industry. In the last five years, the cost of private land in the Mojave Desert has increased 20 fold, from around $500 an acre to $10,000 an acre (Marquis, 2009).

Economically, solar thermal parks will produce manufacturing and construction jobs. One project featuring 250 acres of parabolic solar-thermal collectors 0.5 mile west of the Mojave River will provide an annual operations payroll of $5.4 million and secondary income impact of approximately $23.4 million in 2007 dollars (California Energy Commission, 2008b). These jobs could provide more revenue for the surrounding community, increased investment in the local economy, and a larger tax base.

Impacts of Solar Thermal on Vegetation, Wildlife, and Water

The Mojave Desert is home diverse species and ecosystems, and large solar parks could be physical stressors on these desert systems. Of the 2,500 species of plants and animals that populate the area, more than 100 are considered in peril (Bureau of Land Management, n.d.). Under the State of California's Endangered Species Act, the Desert Tortoise is listed as threatened and the Mojave Ground Squirrel is a species of concern (CDFG, 2009b).

Mojave Desert flora range from the creosote bush (*Larrea tridentata*) to Mojave sage (*Salvia mohavensis*), and about 25 percent of plant species are endemics, or those found nowhere else (Bureau of Land Management, n.d.).

Like the desert flora, the fauna of the Mojave are composed of highly specialized species—such as the Inyo Mountain's slender salamander (*Batrachoseps campi*) and several species of pupfish (*Cyprinodon sp*.). The Mojave Desert also provides a critical corridor for wide-ranging species such as the jackrabbit and desert bighorn sheep (*Ovis canadensis*). (Marquis, 2009; BLM, n.d.). Furthermore, several desert species including the desert pupfish (*Cyprinodon macularius)*, desert tortoise (*Gopherus agassizii),* and Mohave ground squirrel (*Spermophilus mohavensis*) are listed by the state of California as endangered or threatened (CDFG, 2009b). Considering the fragility, diversity, and complexity of the Mojave Desert, large solar thermal parks could disrupt healthy ecosystems and augment pressures on already stressed species.

Limited water supplies also complicate the benefits of solar thermal. Solar thermal towers depend on a concentration of mirrors that route sunlight to a central tower filled with liquid, where the energy is stored. The tower is prone to overheating, and water is an inexpensive and effective cooling method (Marquis, 2009).

However, it's not clear where the cooling water will come from. Nearby Lake Mead, for example, already has a 50 percent chance of drying up by 2021, a problematic future for the millions of people in the southwestern United States who depend on the lake for water (Monroe, 2008). The Lake Mead prediction is based on trajectories of climate change and water use, therefore adding solar thermal water demands into the equation will only accelerate the consequences.

Impacts of Solar Thermal on Desert Soil Ecosystems: Assessment Endpoint

Aside from being drought prone, the Mojave Desert has recently caught the attention of scientists because of its ancient origins and carbon sequestration capabilities. Made up of sedimentary, igneous, and metamorphic rocks, Mojave landscapes are over half the age of the Earth, or 2.7 billion years old (BLM, n.d.).

A recent study conducted in the Mojave Desert found that the desert soil ecosystems could represent a significant carbon sink (Stone, 2008; Wohlfahrt, Fenstermaker, & Arnone, 2008). Whether a result of biotic crusts, vegetation, alkaline soils, or an increase in average precipitation, the rate of carbon absorption in the soil has scientists postulating whether desert ecosystems play a more critical role in the carbon cycle than previously believed (Stone 2008; Wohlfahrt et al., 2008). Some scientists, however, dispute these findings and attribute them to an anomaly caused by increased rain for the study period reported (Schlesinger, 2009).

The recent scientific literature regarding carbon sequestration in deserts is both new and not yet fully understood. However, this poses a potential problem regarding the proposed solar thermal plants in the Mojave. In order for permits to be issued, both the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA) require either an Environmental Impact Report (EIR) or an Environmental Impact Statement (EIS) respectively to identify potential environmental concerns (in the case of NEPA an environmental assessment [EA] may be required in lieu of an EIS).

Solar power is perceived as a ‘clean’ energy source, reducing carbon production while providing much-needed energy. The production capabilities in the Mojave Desert could supply California with most of its energy needs. The application furthest along in the process is from BrightSource Energy, whose Ivanpah project, “…could power 142,000 homes and reduce CO_2 emissions by more than 280,000 tons per year” (Mieszkowski, 2009). However, it must be established if the reduction of CO_2 emissions by employing solar projects in the Mojave would reduce enough CO_2 to justify the potential loss of a carbon sink.

Therefore, the goal of this project is to determine whether the installation and operation of solar thermal plants will impact carbon sequestration capabilities of the Mojave Desert ecosystem and ecosystem services (assessment endpoint) to the extent that more carbon is released or inhibited from being stored than saved while utilizing solar technology.

Analysis: Possible Effects of Solar Thermal Plants on the Mojave Desert

It is clear that the desert ecosystem will be disturbed and destroyed during the installation of the Concentrating Solar Power (CSP) plants in the Mojave Desert. However, it is unclear, and therefore our primary question for this analysis, whether the sum gain of carbon saved by building and operating new solar thermal plants rather than operating fossil fuel power plants is greater than the sum loss of carbon that occurs when the desert habitat is disturbed and destroyed, thus altering the carbon sequestration abilities of the ecosystem. We approached this analysis in both a qualitative and quantitative manner. We will first describe the descriptive analysis of the risks associated with installation and operation of the CSP plants, followed by the quantitative approach of applying a cost-benefit analysis to compare net carbon gains by using CSP plants rather than an Integrated Gasification Combined Cycle (ICGG) plant, which uses "clean coal" technology.

Carbon Loss Due to Installation of Solar Thermal Power Plants

Carbon sequestration is thought to occur on a variety of levels within desert and semi-arid ecosystems. The primary stressor in this analysis is the physical destruction of the habitat that will occur with the installation of the solar collecting facilities, roads, and transmission lines or towers. While CSP plants are large, some estimate they use less land area than hydroelectric dams (including the size of the lake behind the dam) or coal plants (including the amount of land required for mining and excavation of the coal) (Solel, 2007). Nonetheless, existing vegetation, including the aboveground biomass and belowground plant tissue and roots will be cleared prior to installation of CSP plants. Additionally, it is assumed that biological soil crusts will be destroyed and alkaline soils will be removed during the CSP installation process, especially if land leveling, contouring, and construction of stabilizing features for high desert winds are needed. While the soil may only be displaced and later deposited in other desert areas, we assumed the stored carbon was released into the atmosphere. This may be an overstatement of the potential effect; however, we decided to assume the scenario causing the greatest impact given the limited available information.

Numerous studies conducted over the past 40 years have attempted to identify and quantify the major pools of carbon uptake for the various components of desert ecosystems as well as desert ecosystems as a whole (Schlesinger et al., 2009). The estimates of carbon uptake vary immensely between sites and researchers. For example, net carbon uptake in the aboveground biomass of shrublands was estimated to about 25 g C m^{-2} in the Mojave Desert (Schlesinger & Jones, 1984), 46g C m^{-2} yr^{-1} (Whittaker & Niering, 1975) and 70 g C m^{-2} yr^{-1} in Arizona (Chew & Chew, 1965), and 72 g C m^{-2} yr^{-1} in New Mexico (Huenneke & Schlesinger, 2006).

Additionally, alkaline soils and biological soil crusts (BSCs), composed primarily of photosynthetic cyanobacteria, algae, lichens, and mosses, play a key role in arid and semi-arid ecosystems and are able to fix carbon (Belnap et al., 2004). Schlesinger et al. (2008) point out, however, that those pools of carbon that biological crusts fix are relatively small (42 g C m^{-2}; J. Belnap unpublished data). New evidence suggests alkaline desert soils may be responsible for uptake of carbon. Xie et al. (2009) estimated absorbing intensity in alkaline and saline soils at 62-622 g C m^{-2} yr^{-1} and Lal (2004) estimated the amount of carbon stored in 109 cm of soil was

2.01 kg/m^2. There is much uncertainty regarding where and how carbon is stored in desert ecosystems but the recent evidence suggests desert soils have the potential to be a carbon sink.

Loss of Future Carbon Sequestration with the Operation of Solar Thermal Power Plants

In addition to the loss of stored carbon, the CSP facility and supporting infrastructure will likely inhibit the future sequestration of carbon across the inhabited area. Recent studies have estimated the desert biome absorbs an average of 100 g C m^{-2} yr^{-1}, which is comparable to temperate forests and grassland ecosystems (Wohlfahrt et al., 2008). John "Jay" Arnone, an ecologist with the Desert Research Institute's Reno lab, states that "if the Mojave readings represent an average CO_2 uptake, then deserts and semiarid regions may be absorbing up to 5.2 billion tons of carbon a year – roughly half the amount emitted globally by burning fossil fuels" (Stone, 2008). Some researchers such as Schlesinger et al. (2009) are skeptical of the high flux rates especially given the lack of information to support where the carbon is stored and whether carbon sequestration within desert biomes has increased since the Industrial Revolution. However, if these desert ecosystems do sequester large carbon pools, then large alterations of the ecosystem will likely result in the loss of future sequestration capabilities for the global carbon budget.

Other Potential Impacts as a Result of Installation and Operation of Solar Thermal Power Plants

Although the majority of this analysis has characterized solar thermal as a physical stressor, CSP plants also pose chemical risks. CSP plants may use molten salts to store the thermal energy (Kearney et al., 2003) and these oxidizing salts may pose both health and ecological risks (Cotell et al., 2004). A study conducted by David B. Herbst (2006) revealed that saline evaporation ponds formed by solar thermal wastewater impact abundance and size of invertebrates, the presence of algae, and potentially the amount of avian foraging. Some solar projects require chemical spraying to inhibit vegetation growth that prevents solar panels from optimal performance (Maloney, 2008).

Furthermore, impacts will occur on water supplies and resources, as water is piped from limited aquatic systems; desert flora and fauna, some of which may have declining populations; and nearby human communities. These impacts were not evaluated in this risk analysis but should be considered in a more comprehensive evaluation.

Cost Benefit Analysis

The objective of this cost benefit analysis is to weigh the possible costs of building a solar thermal plant in the Mojave Desert. The scope of this cost benefit analysis will be limited to solar thermal plants located in California, and the currency used will be carbon. It is important to note that these values are estimates and the quantitative analysis is limited to carbon. In a comprehensive risk assessment, a full ecological cost benefit analysis would be conducted in order to measure the true costs of a solar thermal plant. Other parameters that would be considered include impacts on the flora and fauna of the region, water resources, social and economic implications and land costs.

Carbon costs of construction and operation of the solar thermal plant were calculated based on a review of the primary literature. Carbon released from disruption of Mojave Desert soil, construction of the solar thermal plant, and disruption of carbon sequestration capabilities were considered in the evaluation (equations 1-4, Table 1). A 4,500-acre site for a 500 MW solar thermal plant was considered for this analysis. Sites have ranged in size from 6,000 to 1,000 acres (Hudson, 2008). Our 4,500-acre estimate assumes that all land in the site will be impacted by the development. This is a proposed site, located 35 miles east of Barstow, CA, and if permitted, construction will commence in 2011 (Stirling Energy Systems, 2009). Full cycle carbon emissions (which looks at all the carbon emissions created by an entire process including but not limited to emissions from transportation of materials, construction of materials and onsite construction) of the construction of a solar thermal plant are estimated to be 3 metric tons (mt) C (Owen, 2004). Loss of sequestration capabilities from the entire desert ecosystem and sequestration from desert soils were also calculated. It was assumed that roads to and from solar thermal sites already existed. A summary of these calculations and final estimates are found in Table 1.

The amount of carbon released by clearing 4,500 acres of land was determined based on a review of the primary literature. There are varying estimates of the amount of carbon stored in desert soils (Lal, 2004; Xie, 2009), and because Lal (2004) provided an estimate of carbon within 109 cm of desert soil, we assumed an equal depth for soil disruption by construction of the solar thermal plant. Carbon stored in vegetative brush above ground was assumed to be 25 g C cm^{-2} based on work by Schlesinger and Jones (1984). Carbon stored in belowground vegetative roots was assumed to be between 50 and 65 g C cm^{-2} (Schlesinger, 2009). These components of a soil matrix were combined to determine the total amount of carbon lost by clearing the land for construction of the solar thermal plant.

Soil disturbance (109 cm): equation 1a

$$.00201 \text{ mt Cm}^{-2} \times 18{,}210{,}854 \text{ m}^2 = 36{,}603.81 \text{ mt C}$$

Vegetative brush above ground: equation 1b

$$0.000025 \text{ mt C m}^{-2} \times 18{,}210{,}854 \text{ m}^2 = 455.27 \text{ mt C}$$

Vegetative roots below ground: equation 1c

$$0.0000575 \text{ mt C m}^{-2} \times 18{,}210{,}854 \text{ m}^2 = 1{,}047.12 \text{ mt C}$$

Total of above parameters: equation 1d

$$36603.81 \text{ mt C} + 455.27 \text{ mt C} + 1047.12 \text{ mt C} = 38{,}106.2 \text{ mt C}$$

Carbon released due to construction of solar thermal transmission lines was also calculated. It was assumed that transmission lines were buried to a depth of 109 cm, to be consistent with previous assumptions regarding carbon content in 109 cm of desert soil, and that a 1 meter wide section of soil needed to be disrupted for 35 miles in order to lay the transmission lines. Based on the same parameters as described above, the amount of carbon released due to transmission line installation was calculated. It was assumed that a soil surface would be left after initial disruption and that the size and presence of the cable would have a negligible impact on the long-term sequestration ability of the Mojave Desert.

Soil disturbance (109 cm): equation 2a

$$.00201 \text{ mt C m}^{-2} \times 56{,}327.04 \text{ m}^2 = 113.21 \text{ mt C}$$

Vegetative brush above ground: equation 2b

$$0.000025 \text{ mt C m}^{-2} \times 56{,}327.04 \text{ m}^2 = 1.41 \text{ mt C}$$

Vegetative roots below ground: equation 2c

$$0.0000575 \text{ mt C m}^{-2} \times 56{,}327.04 \text{ m}^2 = 3.24 \text{ mt C}$$

Total of above parameters: equation 2d

$$113.21 + 1.41 + 3.24 = 117.86 \text{ mt C}$$

The amount of carbon not sequestered by the Mojave Desert system due to the presence of a solar thermal plant was also calculated. An annual net ecosystem carbon exchange between the Mojave Desert and the atmosphere was estimated in 2005 and 2006 to be 102 and 110 g C/m^2, respectively (Wohlfahrt, 2008). As this is the net ecosystem carbon exchange, it was assumed that this lower bound accounted for all ecological parameters for carbon sequestration in Mojave Desert soil.

$$0.000106 \text{ mt C m}^{-2} \times 18{,}210{,}854 \text{ m}^2 = 1930.35 \text{ mt C} \quad \text{equation 3a}$$

$$1{,}930 \text{ mt C} \times 75 \text{ years} = 144{,}776.2893 \text{ mt C} \quad \text{equation 3b}$$

The amount of carbon not sequestered by the soil due to the presence of a solar thermal plant was also calculated. The rate at which dryland soils within the U.S. sequestered carbon has been estimated to be 0.03 MG C ha^{-1} y^{-1} (Schlesinger, 1997). This was a qualitative estimate of the amount of carbon sequestered by the desert soils.

$$0.03 \text{ mt C ha}^{-1} \text{ y}^{-1} \times 1821.09 \text{ ha} = 54.6327 \text{ mt C yr}^{-1} \quad \text{equation 4a}$$

$$54.6327 \text{ mt C yr}^{-1} \times 75 \text{ years} = 4097.4525 \text{ mt C} \quad \text{equation 4b}$$

Table 1. Carbon Costs of 500 MW Solar Thermal Plant in Operation over 75 Years

Parameter	Estimate of CO_2 Emissions (mt C)	Equation/Source
Lost C due to Construction of Solar Thermal Plant	3	Owen, 2004
Lost C due to Clearing Land	38,106	1
Lost C due to Installation of Power Cables	118	2
C not sequestered by soil for 75 years (ecosystem)	144,776	3
C not sequestered by soil for 75 years (soil)	4,097	4
Total (soil)	42,324	
Total (entire ecosystem, including soil)	183,003	

Carbon emissions from a solar thermal plant were compared against an alternative plant of a similar energy production capability. An Integrated Gasification Combined Cycle (IGCC) plant was chosen for comparison, as this is one clean coal option currently considered for construction. IGCC with carbon capture shows potential to be the leading technology to produce reliable energy from coal (EPA, 2008).

Values for the amount of carbon emitted by a 543 MW IGCC plant with 90% carbon capture were derived from Ruether et al.(2004). Parameters for carbon release included operation and maintenance of the plant (not including the fuel). Coal mining for the plant, transportation of coal to the plant, and consumption of coal were based on national averages. Construction of the IGCC plant was also considered as a one-time full cycle emission of 260,000 mt C (Ruether et al., 2004). All values were given in units of metric tons (mt) of carbon (C) emitted annually. A summary of the calculations are included in Table 2. The total savings of carbon by constructing and operating a solar thermal plant rather than an IGCC plant is presented in Table 3.

Operation and maintenance: equation 5

21,500 mt C x 75 years = 1,612,500 mt C over 75 years

Coal mining for plant: equation 6

16,450 mt C x 75 years = 1,233,750 mt C over 75 years

Transportation of coal to plant: equation 7

8,250 mt C x 75 years = 618,750 mt over 75 years

Coal consumption:

3,250,000 mt C (no carbon capture)

90% carbon capture is considered a feasible IGCC plant standard (Ruether et al., 2004)

3,250,000 mt C x .1 = 325,000 mt C equation 8a

325,000 mt C x 75 years = 24,375,000 mt C over 75 years equation 8b

Table 2. Carbon Costs of 543 MW IGCC Plant w/ 90% Carbon Capture over 75 years

Parameter	Estimate of CO_2 Emissions (mt C)	Equation
C emitted by operation and maintenance	1,612,500	5
C emitted by coal mining for plant	1,233,750	6
C emitted by coal transportation to plant	618,750	7
C emitted by coal consumption	24,375,000	8
C emitted by construction	260,000	Ruether et al., 2004)
Total Emitted for 75 years	28,100,000	

Table 3. Benefits of Carbon Saved by Converting to Solar Thermal Power over 75 years w/ construction costs of IGCC Plant

Parameter	Estimate of CO_2 Emissions (mt C)
C saved (soil only) compared to IGCC w/ 90 % carbon capture	28,057,676
C saved (ecosystem) compared to IGCC w/90 % carbon capture	27,916,997

Lastly, a comparison of varying estimates of carbon within desert soils was included to analyze the sensitivity of this parameter (Table 4). The calculations were conducted assuming 125 and 150% more and 25, 50, and 75% less carbon sequestration by the soil than the reported values of 2.01 kg C m^{-2} (Lal, 2004). While this sensitivity analysis does not directly address the assumption of soil degradation to a depth of 109 cm, it does provide a range of sequestration estimates for the soil. This uncertainty is very small when included in the total savings of carbon by constructing and operating a solar thermal plant rather than an IGCC plant (Table 5).

Table 4. Sensitivity Analysis of Carbon Sequestration Uncertainty in Desert Soils.

Parameter	150%	125%	100%	75%	50%	25%
Construction (mt C)	3	3	3	3	3	3
Lost C due to Clearing Land (mt)	57,159	47,632.5	38,106	28,579.5	19,053	9,526.5
Lost C due to Installation of Power Cables (mt)	177	147.5	118	88.5	59	29.5
C not sequestered by soil for 75 years (ecosystem) (mt)	217,164	180,970	144,776	108,582	72,388	36,194
C not sequestered by soil for 75 years (soil) (mt)	6,145.5	5,121.25	4,097	3,072.75	2,048.5	1,024.25
Total (soil) (mt C)	63,484.5	52,904.25	42,324	31,743.75	21,163.5	10,583.25
Total (entire ecosystem, including soil) (mt C)	274,503	228,753	183,003	137,253	91,503	45,753

Table 5. Benefits of Carbon Saved by Converting to Solar Thermal Power over 75 years w/construction costs of IGCC Plant at varying levels of carbon sequestration by desert soils.

Parameter	150 %	125 %	100 %	75 %	50 %	25 %
C saved (soil only) compared to IGCC w/ 90 % carbon capture (mt)	28,036,516	28,047,096	28,057,676	28,068,256	28,078,837	28,089,417
C saved (ecosystem) compared to IGCC w/90 % carbon capture (mt)	27,825,497	27,871,247	27,916,997	27,962,747	28,008,497	28,054,247

Risk Characterization

In this step, we will use the Risk Analysis to estimate the individual risks associated with carbon production or release involved in establishing a single (representative) solar thermal plant in the Mojave Desert. We will discuss the degree of confidence in the risk estimates, and note research supporting these estimates. In view of the above, we will interpret or "characterize" the adversity that the risks pose by answering the following questions.

•Is the risk acute or chronic?
•How severe are the effects?
•Will the risk affect one species or many?
•How many organisms are at risk?

1. Characterizing the Risk of Carbon Loss Due to Installation of Solar Thermal Power Plants

•Risk: Removal of Mojave Desert Soil and Biomass in Advance of Facility Construction

As stated in the Risk Analysis, the estimates of carbon uptake vary immensely between sites and researchers. The estimates of net carbon uptake in the aboveground biomass of shrublands varied from a low estimate of 25 gCm^{-2} in the Mojave Desert (Schlesinger & Jones, 1984) to a high estimate of 72 $g\ Cm^{-2}yr^{-1}$ in New Mexico (Huenneke & Schlesinger, 2006). Moreover, the Mojave region is subject to strong, dry winds mainly in the afternoon and evening. Disturbance of soil (that was once hard-packed carbonate) makes erosion by wind much more likely, which makes it difficult for the native soil to reestablish microbacterial, plant and lichen communities that bind it and help absorb water and nutrients.

•Acute or Chronic?
Based on the assumption of a mean estimate (48.5 gCm^{-2}) we would characterize this risk as acute. The reason the risk is acute rather than chronic is due to two factors. The soil disturbance occurs at the beginning, but then stops after the plant is built and operating. Second, the solar thermal technology will reduce the need for more carbon-intensive coal-fired power over time.

•How Severe are the Effects?
Severity depends on scale. From the standpoint of the loss of a specific area of the Mojave ecosystem and the plants and animals that live there, the loss is severe. The likelihood of normal ecosystem operations being restored after construction is zero for plants, and nearly zero for the insects, birds, and other animals that depend on them. However, by characterizing the risk in terms of global carbon and in comparison to clean coal technology (1:1 solar thermal facility to clean coal facility) the effects are less severe. The effects will be mitigated over time.

•Will the Risk Affect One Species or Many?
The risk will likely affect the full complement of Mojave Desert species.

•How Many Organisms are at Risk?
The number of organisms at risk will vary slightly from site to site, but the number is not known.

•Ranking of Uncertainty
There is much uncertainty regarding where and how carbon is stored in desert ecosystems, but recent evidence suggests altering and removing soils and BSCs may release stored carbon. In the context of the global carbon cycle and compared with a clean coal plant, the loss of future carbon storage by the ground directly affected by a solar thermal plant is mitigated.

2. Characterizing Loss of Future Carbon Sequestration by Desert Alteration and Removal

•Risk: Negation of Future Carbon Sequestration Capability of Existing Desert Site

The data from the Desert Research Institute Reno Lab was based on direct measurement and is not derived from a theoretical model. DRI scientist John "Jay" Arnone states that "if the Mojave readings represent an average CO_2 uptake, then deserts and semiarid regions may be absorbing up to 5.2 billion tons of carbon a year – roughly half the amount emitted globally by burning fossil fuels" (Stone, 2008). However, other researchers are skeptical that carbon flux rates could be this high. To date, the mechanism for and location of stored carbon are not well understood. Assuming that desert ecosystems do sequester large quantities of carbon, removal of the ecosystem will likely result in the loss of future sequestration capability.

•Acute or Chronic?
Chronic, because it will persist indefinitely.

•How Severe Are the Effects? Unknown. However, by characterizing the risk in terms of global carbon and in comparison to clean coal technology (1:1 solar thermal facility to clean coal facility) the effects are mild to moderate (less severe). The severity will be mitigated over time.

•Will the Risk Affect One Species or Many?
The risk will permanently remove habitat thereby affecting the full complement of Mojave Desert species.

•How Many Organisms are at Risk?
The number of organisms at risk will vary slightly from site to site, but the number is not known.

•Ranking of Uncertainty
There is much uncertainty regarding where and how carbon is stored in desert ecosystems but the recent evidence suggests altering and removing soils and vegetation, or sealing the ground with impermeable surfaces or structures may permanently destroy the affected area's carbon storage capability. However, when viewed in the context of the global carbon cycle and a clean coal plant, the loss of future carbon storage by the ground directly affected by a solar thermal plant is mitigated. Human population is growing. Society has to derive power from some source; there are no free sources of energy.

3. *Characterizing Potential Chemical Effects of Solar Thermal Power Plants*

•Risk: Exposure to Chemical Stressors

Although the majority of this risk analysis has characterized solar thermal as a physical stressor, CSP plants also pose chemical risks. One type of CSP plant employs molten salts to store the thermal energy (Kearney et al., 2003) and these oxidizing salts may pose both health and ecological risks (Cotell et al., 2004). A study conducted by David B. Herbst (2006) revealed that saline evaporation ponds formed by solar thermal wastewater impact abundance and size of invertebrates, the presence of algae, and therefore the food base for avian foraging. Some solar projects require chemical spraying to inhibit vegetation growth that prevents solar panels from optimal performance (Maloney, 2008).

Acute or Chronic?
Chronic, because it will persist indefinitely.

•How Severe Are the Effects? Unknown.

•Will the Risk Affect One Species or Many?
The risk may affect the full complement of Mojave Desert species via direct exposure, indirect exposure, synergistic effects with other anthropogenic chemical stressors, bioaccumulation, potential endocrine or other biological disruption, as well as exacerbating other cumulative risks over time.

•How Many Organisms are at Risk?
The number of organisms at risk will vary slightly from site to site, but the number is not known.

•Ranking of Uncertainty
EPA only registers a fraction of the compounds available. There is much uncertainty regarding what chemicals will be applied in these areas, where used, in what quantities and in what time frames. Moreover, there is only emerging science on a tiny fraction of synergistic effects of chemicals in the environment, their transport and fate singly or in combination.

Summary and Conclusion

Although not carbon-free, solar thermal facilities in the Mojave Desert might emerge as the best alternative for California. The technology is perhaps one of the most promising renewable energy sources on the market—with clear advantages over rooftop solar and clean coal technology in terms of reliability and carbon emissions, respectively. While there is no ecologically neutral energy source, environmental impacts can be mitigated by selecting the option that poses the least ecological damage and the greatest net energy gains. Considering the alternatives, such as coal, solar thermal provides a viable option for meeting energy demands.

Our analysis found the total savings of soil-based carbon by constructing and operating a solar thermal plant rather than an IGCC plant to be approximately 28 million mt over a 75-year period, a significant figure. We conducted our analysis based on one CPS facility and comparing it to the carbon emitted from a coal-powered facility generating similar quantities of electricity. However, it is important to note that if all 75 pending permits through the BLM are approved (representing 647,000 acres of potentially impacted land), the cumulative effects may be greater than the summation of individual impacts caused by the installation and operation of each plant. Additionally, solar thermal should be examined within the larger context of ecological, political, social and economic needs.

In making difficult policy decisions it is always useful to ask critical questions. For example, is the best decision for the public well-being to build solar thermal facilities on public land that possesses unique and perhaps irreplaceable features?

Considering the uncertainty of the full-scale impact of solar thermal, policymakers must proceed with caution. In order to ensure prudent decision making as solar thermal technologies develop, we recommend the following:

1. Maximize energy efficiency and conservation through financial incentives and mandatory legislative measures.

2. Analyze alternative energy options that are less land intensive. For example, instead of using raw public land with special features, explore building on already degraded land, such as closed military bases.

3. Maximize ecological research and collaborative approaches to mitigating effects of establishing solar thermal facilities in desert landscapes. Examples include reducing the number of permitted projects, reducing the projects' acreage footprint or placing the facilities on a single structure to minimize soil and ecosystem disturbance. Finally, mitigate by restoring damaged desert and especially forest ecosystems elsewhere.

References

Belnap, J. S. L. Phillips, and M.E. Miller. 2004. Response of desert biological soil crusts to alterations in precipitation frequency. Oecologia. 141: 306–316.

Bureau of Land Management (n.d). “Shaping the ‘Classic American Desert’”. Retrieved from www.blm.gov/education/00_resources/articles/mojave/mojave01a.html

Bureau of Land Management. 2007. “California Desert Conservation Area: BLM Solar Energy Project Applications”. Map of solar project applications retrieved from http://www.energy.ca.gov/siting/cdd_energy_points_8_5X11_solar.pdf.

California Department of Fish and Game. 2009a. Mojave Desert Overview. Retrieved from http://www.dfg.ca.gov/wildlife/WAP/region-mojave.html.

California Department of Fish and Game. 2009b. “State and Federally listed endangered and threatened animals of California”. State of California, The Resources Agency, Department of Fish and Game, Biogeographic Data Branch, California Natural Diversity Database.

California Energy Commission. (2008a). “Renewable Energy Transmission Initiative (RETI)”. Retrieved from http://www.energy.ca.gov/reti/index.html

California Energy Commission. (2008b). “Victorville 2 hybrid power project: Application for certification” (CEC Docket No. 07-AFC-01). Sacramento, CA: U.S. Government Printing Office. Retrieved from www.energy.ca.gov/sitingcases/victorville2/index.html

Chew, R.H. and Chew, A.E. 1965. The primary productivity of a desert-shrub (Larrea tridentate) community. Ecological Monographs, 35: 355-375.

Cotell, C.M., J.A. Sprague, and Smidt, Jr., F.A. (Eds.) 2004. ASM Handbook. *Surface Engineering*, Vol.5, 44-47.

Environmental Protection Agency. 2008. “Proposal-Integrated Gasification Combined Cycle (IGCC)”. Retrieved from http://www.epa.gov/environmentaltechnology/etc_at_propigcc.html

Herbst, D. 2006. “Salinity Controls on Trophic Interactions Among Invertebrates and algae of Solar Evaporation Ponds in the Mojave Desert and Relation to Shorebird Foraging and Selenium Risk”. *Wetlands, 26*(2), 475-485.

Houghton, R. A. 2005. "The contemporary carbon cycle". In William H Schlesinger (editor), *Biogeochemistry* (pp. 473–513). Amsterdam: Elsevier Science.

Hudson, G. 2008. “Mega Solar: the World’s 13 Biggest Solar Thermal Energy Project”. Retrieved from http://ecoworldly.com/2008/04/12/mega-solar-the-worlds-13-biggest-solar-thermal-energy-projects/

Huenneke, L.H. and Schlesinger, W.H. 2006. Patterns of net primary production in Chihuahuan Desert ecosystems. In: Structure and Function of a Chihuahuan Desert Ecosystem: The Jornada Basin Long-Term Ecological Research Site (eds Havastad KM, Huenneke LF, Schlesinger WH), pp. 232-246. Oxford University Press, Oxford.

IPCC. 2007. "Climate Change 2007: Synthesis Report". Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Janzen, H.H. 2004. "Carbon cycling in earth systems—a soil science perspective". *Agriculture Ecosystems & Environment, 104 (3),* 399–417.

Kearney, D., B. Kelly, U. Herrmann, R. Cable, J. Pacheco, R. Mahoney, H. Price, D. Blake, P. Nava, and N. Potrovitza. 2003. Engineering aspects of a molten salt heat transfer fluid in a trough solar field. Energy, 29 (5-6), 861-870.

Lal, R. 2004. "Carbon Sequestration in Dryland Ecosystems". *Environmental Management* 33(4), 528-544.

Maloney, P. (2008, Sept. 23). "Solar projects draw new opposition." *The New York Times* Retrieved from http://www.nytimes.com/

Marquis, A.L. 2008. "Solar Rush: California's Solar Boom Threatens the Very Places it's Meant to Protect". *National Parks*, Winter, 16-19.

Mieszkowski, K. 2009. "The Tortoise and the Sun". Retrieved from http://www.salon.com/env/feature/2009/01/22/desert_tortoises/print.html.

Mills, D. 2004. "Advances in Solar Thermal Electricity Technology". *Solar Energy* 76(1-3), 19-31.

Monroe, R. 2008. "Lake Mead could be dry by 2021". Retrieved February 16, 2009 from http://ucsdnews.ucsd.edu/newsrel/science/02-08LakeMead.asp

National Renewable Energy Laboratory. 2006. Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California (Report No. AEK-5-55036-01). Overland Park, KS: Stoddard & Abiencunas. Retrieved from www.ceert.org/reports_pdf/Concentrating_Solar_May2006.pdf

Owen, A. 2004. "Environmental Externalities, Market Distortions and the Economics of Renewable Energy Technologies". *The Energy Journal* 25(3):127-156.

Quaschning, V. 2004. "Technical And Economical System Comparison of Photovoltaic and Concentrating Solar Thermal Power Systems Depending On Annual Global Irradiation". *Solar Energy* (77), 171-178.

Ruether J., Ramezan, M., Baldash, P. 2004. “Greenhouse Gas Emissions from Coal Gasification Power Generation Systems”. *Journal of Infrastructure Systems.*

Schlesinger, W.H., Belnap, J., and Marion, G. 2009. “On Carbon Sequestration in Desert Ecosystems”. *Global Change Biology*, Vol.9999(9999).

Schlesinger, W.H. 1997. *Biogeochemistry an Analysis of Global Change.* Academic Press, New York.

Schlesinger, W and Jones, 1984. The comparative importance of overland runoff and mean annual rainfall to shrub communities of the Mojave Desert. Botanical Gazette, 145, 116-124.

Solel. 2007. “Ten Facts about Solar Thermal Power”. Retrieved from http://www.solel.com/faq/

Sovacool, B.K., and Cooper, C. 2007. “The hidden costs of state renewable portfolio standards (RPS)”. *Buffalo Environmental Law Journal* 15(1), 1-17.

Stirling Energy Systems. 2009. “Solar One”. Retrieved from http://stirlingenergy.com/projects/solar-one.asp

Stone, R. 2008. “Have Desert Researchers Discovered a Hidden Loop in the Carbon Cycle?” *Science*, Vol.320 (5882), 1409-1410.

Whittaker, R.H. and Niering, W.A. 1975. Vegetation of the Santa Cataline Mountains, Arizona. V. Biomass, production, and diversity along the elevation gradient. Ecology. 56: 771-790.

Wohlfahrt, G., Fenstermaker, L.F., and Arnone III, J.A. 2008. “Large Annual Net Ecosystem CO_2 Uptake of a Mojave Desert Ecosystem”. *Global Change Biology*, Vol.14, 1475-1487.

Xie, J., E Yan Li, E.Cuixia Zhai, E. Chenhua Li, and E. Zhongdong Lan. 2009. “CO_2 Absorption by Alkaline Soils and its Implication to the Global Carbon Cycle”. *Environmental Geology*, Vol.56, 953–961.