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POTENTIAL IMPACTS OF SOLAR ARRAYS ON HIGHWAY ENVIRONMENT, SAFETY AND OPERATIONS

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16. Abstract

The advent of solar energy utilization in highway infrastructure around the country has been increasing in recent years. Right of Ways (ROWs) have several advantages for energy development such as the existing electrical infrastructure aligned with the major highways, a secured boundary, and easy maintenance access. It has been identified by various Departments of Transportation (DOTs) and the Federal Highway Administration (FHWA) that solar array deployment along the ROW is possible after adequate site evaluation and impact study. With higher solar insolation available, CDOT can generate electricity from solar arrays on its ROWs across much of the State of Colorado. Political climate, public cooperation with energy providers, commitment of utility companies and potential impacts are some of the major concerns in successful solar array deployment. The potential impact of photo voltaic (PV) arrays on driver safety, highway operation and maintenance, and the environment are the focus of this research study. Changes in driver's expectations, glare, maintenance practices due to snow drifting along the roadside, and local ecosystems are some of the impacts that are evaluated in this report.

To understand the potential impacts on driver safety, environmental resources, and maintenance operations, case studies are presented from national and international projects. A base line study was performed pertaining to the current ROW's physical characteristics, operational conditions, regulatory requirements and PV array design criteria. Factors associated risk impacts are analyzed qualitatively as well as quantitatively. Mitigation measures are recommended to minimize the undesirable impacts in the planning, design, construction, operation and maintenance of solar array. This document provides guidance for CDOT Management, Project Engineers, Operation and Maintenance personnel and energy generators who are interested in installing and maintaining PV arrays in the CDOT ROW. The following are the main objectives of this project:

- Develop a general model of a solar highway focusing on user safety and maintenance activities
- Study and analyze the impact of highway solar array on driver's safety
- Study and analyze the impact of highway solar array on road maintenance
- Evaluate and assess the impact of the highway solar array on the environment
- Identify and list the critical risk factors in solar array and array deployment and develop risk reduction strategies
- Provide CDOT with a guidance manual that will provide basic considerations and requirements to address CDOT environmental, safety, and operation and maintenance expectations
- Make design and safety guidance recommendations pertaining to highway PV array design, installation, operation and maintenance

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Solar array, right of way, energy provider, environmental, safety, operation and maintenance, impacts, mitigation, risk impacts, glare, snow drifting, decision making tools, NEPA	No restrictions. This document is available to the public through the National Technical Information Service Springfield, VA 22161; www.ntis.govor CDOT's Research Report website http://www.coloradodot.info/programs/research/pdfs

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CDOT Study No. 32.08

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EXECUTIVE SUMMARY

Highway Right of Way (ROW) areas are becoming recognized as potential alternative energy resources in many state Departments of Transportation (DOTs). In an era of limited state DOT budgets, ROW areas can be a source of income to DOTs through alternative energy development, especially in the area of solar energy. State DOTs and private Tollway Authorities have been leasing ROW areas to energy providers to offset carbon footprint emissions or to obtain financial resources through long-term lease agreements. The use of ROWs for solar energy generation has been used extensively in Europe for the past 30 years.

Highway ROW areas have physical and topographical characteristics that complement the generation of solar energy such as: 1) well maintained vegetation 2) ease of access to the solar array facility adjacent to the road 3) electrical transmission lines often follow the ROW alignment, and 4) minimal presence of trees or other objects that can obscure sunlight.

This research study has identified numerous CDOT concerns and potential impacts associated with the leasing of a CDOT ROW to energy providers. The Colorado State University-Pueblo (CSU-P) Team collaborated and coordinated with the following CDOT organizational departments to identify concerns and potential areas of impact:

- Environmental Programs Branch (Wildlife, Water Quality and Sustainability)
- Regional Highway Maintenance
- Right of Way Management and Permits
- Regional Environmental Management
- Regional Transportation Design Engineering
- Headquarters Traffic and Safety Branch

Some of the areas of impact identified by the CSU-P Team are not significant and would not be expected to affect implementation. Others are more potentially significant and for those impact mitigation measures are proposed including proper project siting, administrative controls, proper design criteria, ROW management and engineering controls. The main potential impacts identified in this research study are as follows:

- Snow drift and deposition
- Glare/glint from solar panels
- Water quality management (construction and post construction)
- Driver safety associated with solar array structure collisions
- Driver awareness and expectation
- Access and safety during solar array maintenance

The research team was able to develop decision-making tools that can be used by other DOT Management and energy providers in other sections of the country who wish to develop a solar array on a DOT ROW.

These tools include the following:

- Glint and Glare Hazard Models
- Solar Array Siting Criteria
- Solar Array Impacts and Mitigation
- Solar Array Risk Impact Matrix
- Sequence of CDOT Coordination Actions

IMPLEMENTATION STATEMENT

Currently there is no guidance for DOTs that consider using their ROWs for solar energy generation using ground mounted solar arrays. CDOT recognizes that there are highway, environmental resources, ROW operations and maintenance impacts that need to be identified and mitigated before a solar array is allowed to be built within a CDOT ROW.

This research report provides guidance for CDOT and other DOTs to use their ROWs for solar energy development. This report can lead to the development of a guidance document entitled Standard Considerations and Operating Procedures for Solar Arrays in CDOT ROWs, which is currently under development by CDOT. It is recommended that this report be provided to all CDOT decision makers regarding the consideration of allowing solar arrays to be constructed and maintained within the ROWs for a 20-25 year time period.,. The following representatives should use and implement this report as a main reference document, if CDOT decides to use their ROWs for energy development:

Environmental Management-This report should be a main reference to environmental professionals who will need to coordinate an environmental analysis according to CDOT National Environmental Policy Act (NEPA) procedures and federal regulations. The report will provide CDOT a list of environmental criteria that must be evaluated by an interested energy provider.

Safety Engineering-Engineering controls necessary to address driver safety concerns are provided for reference. Proper solar array siting, orientation and location within and out of the Clear Zone are critical to highway safety.

Highway Maintenance- Highway operation and maintenance impacts and associated mitigation strategies are provided for mowing operations and winter time road maintenance. Snow drifting and deposition concerns are addressed in the report.

ROW Management- This report will provide a broad overview of the impacts associated with all activities within the ROW while implementing solar energy development. This report will be a main reference to ROW management statewide that will provide the information necessary for CDOT officials to ask the right questions and ask for the right feasibility studies prior to solar array design, construction and maintenance.

It is recommended that CDOT explore the use of their ROW for solar energy development. The ROW represents a CDOT resource that can provide financial revenue by leasing land space to energy providers, who can generate the electricity that can be placed on the electrical grid, and/or save energy costs by generating the energy on its own property to power various transportation assets such as maintenance facilities, rest areas, and to light interchanges, etc. Electricity generated from solar energy can help to reduce CDOT's carbon footprint and support the State of Colorado's Climate Action Plan. In addition, implementing Photovoltaic (PV) projects with a good understanding of the associated risk can help CDOT to minimize undesirable impacts and implement good environmental stewardship.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Official
CAD	Computer Aided Design
CALTRANS	California Department of Transportation
CATEX	Categorical Exclusion
CDOT	Colorado Department of Transportation
CDPHE	Colorado Department of Public Health and Environment
CFR	Code of Federal Regulations
CPV	Concentrated Photovoltaic
CRS	Colorado Revised Statute
CSU-P	Colorado State University-Pueblo
DC	Direct Current
DFC	Denver Federal Center
DIA	Denver International Airport
DOT	Department of Transportation
DTD	Division of Transportation Development
EA	Environmental Assessment
FHWA	Federal Highway Administration
GIS	Geographic Information System
GWh	Giga Watt- Hour
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt hour
LED	Light Emitting Diode
MASSCEC	Massachusetts Clean Energy Centre
MASSDEP	Massachusetts Department of Environmental Protection
MASSDOER	Massachusetts Department of Energy Resources
MUTCD	Manual on Uniform Traffic Control Devices
NEPA	National Environmental Policy Act
NREL	National Renewable Energy Laboratory
ODOT	Oregon Department of Transportation
OSHA	Occupational Safety and Health Administration
PV	Photovoltaic
REI	Renewable Energy Installation
ROW	Right of Way
RSDG	Roadside Design Guide
SGHAT	Solar Glare Hazard Analysis Tool
SH	State Highway
T&E Species	Threatened and Endangered Species
TRB	Transportation Research Board
UAP	Utility Accommodation Policy

CHAPTER 1. INTRODUCTION

1.1 Background

The advent of solar energy utilization in highway infrastructure around the country has been increasing in recent years. Colorado is one of several states with a high solar insolation, ranking fifth out of 50 states (Denholm and Margolis, 2007). Effective utilization of photovoltaic (PV) systems located in vacant Right of Way (ROW) areas across the State of Colorado has the potential to produce a significant amount of electricity. The Colorado Department of Transportation's (CDOT) commitment to explore and evaluate the highway ROWs for possible solar array installation is a proactive step. As reported in the "Assessment of Colorado Department of Transportation Rest Areas for Sustainability Improvements and Highway Corridors and Facilities for Alternative Energy Use Project" (Kreminski et al., 2011), CDOT has an estimated 55,500 Giga Watt Hour (GWh)/year of electricity generation capacity associated with solar energy development within the existing ROW areas statewide. Typical spaces available for solar energy generation are rest areas, land outside ROW clear zones, space adjacent to interchanges and CDOT building roof tops. Based on the space availability and site characteristics, road orientation, PV array design and energy capacity, PV arrays could effectively be installed on CDOT property. In addition to the available space, ROWs offer electrical infrastructure corridors (existing transmission lines aligned with the highways), well maintained secure land, and easy access for construction and maintenance. High solar insolation provides an opportunity for CDOT to develop solar arrays across much of the State of Colorado.

The deployment of solar arrays along highway ROWs is relatively new in North America. The Oregon Department of Transportation (ODOT) was the first state department of transportation (DOT) to employ a solar array within its ROWs. In 2008, ODOT initiated the construction of the Solar Highway Project near Portland, Oregon comprised of 594 solar panels, producing about 130,000 kilowatt hour (kWh) annually (Poe and Filosa, 2011). Other state DOTs and various private toll ways have also implemented solar technologies for electricity generation within their ROWs.

Most of the DOTs and the Federal Highway Administration (FHWA) are in agreement that solar array deployment along the ROW is possible after careful site evaluation and impact analysis. Initial feasibility studies and the National Environmental Policy Act (NEPA) are the current evaluation processes. The main potential concerns associated with solar array deployment in the ROW and the main focus of this study include:

- Driver safety
- Highway operation and maintenance
- Environmental impacts

Introducing a large PV array has the potential to change driver expectations, DOT maintenance practices and the overall transportation environment and its dynamics. These and other potential impacts need to be analyzed for safe implementation of PV arrays along highway ROWs.

A team of professionals from academia and engineering (the Team) with substantive knowledge and experience in solar array design, deployment, environmental impacts, highway safety and CDOT ROWs investigated potential impacts associated with solar energy development. This effort created a roadmap for impact analysis and developed a comprehensive decision matrix to aid CDOT in managing ROW energy development. CDOT representatives such as Project Managers, Right of Way Managers, Maintenance Managers and external energy providers can use this knowledge to identify and manage risks associated with PV array deployment. This report contains the following chapters and information:

Chapter 1- Introduction
Chapter 2- PV Array in ROW
Chapter 3- Regulations and Permitting Requirements
Chapter 4- Field Study Findings
Chapter 5- Impacts from PV Array Development
Chapter 6- Mitigation Analysis
Chapter 7- Conclusion and Recommendations

A brief summary is presented in Appendix A that is meant to be a standalone guidance document and a starting point for policy makers and energy providers. CHAPTER 6 presents the mitigation strategies, which might be useful to the project designers and field professionals. For comprehensive understanding of the risk factors and impact understanding, remaining chapters could be referenced. Flat PV arrays are only considered in this research for impact analysis. PV array or solar array is interchangeably used throughout the document.

1.2 Project Objectives

The main goal of this project is to identify critical environmental, safety, operation and maintenance impacts associated with the potential development of PV arrays in CDOT ROWs followed by potential mitigation considerations associated with PV array project planning, design, construction, and operation and maintenance. To study the potential impacts the Team will identified and evaluated the current ROW physical characteristics and operational conditions with consideration of various PV array design criteria and operational variables. Risk factors are identified and mitigation strategies conceptualized to eliminate or reduce potential impacts. The following are the main objectives of this research project:

- Develop a general model of a solar highway focusing on user safety and maintenance activities
- Study and analyze the impact of highway PV array on driver's safety
- Study and analyze the impact of highway PV array on road maintenance and operations
- Evaluate and assess the impact of highway PV array on environmental resources
- Identify and list the critical risk factors in PV array deployment and develop risk reduction strategies
- Provide CDOT a guidance manual that will provide basic considerations and requirements to address CDOT environmental, safety, operation, and maintenance expectations
- Make design and safety guidance recommendations pertaining to highway PV array design, installation, operations and maintenance

1.3 Project Approach

The first step in this research project involved a literature search of PV arrays and related impacts associated with state DOT highway ROWs. National and international projects' experiences as they relate to motorist safety, environmental impacts, and ROW operations and maintenance were studied. The literature search involved the study of reports published by various transportation and energy organizations such as the Transportation Research Board (TRB), National Renewable Energy Laboratory (NREL), the Federal Highway Administration (FHWA), Oregon Department of Transportation (ODOT), CDOT, and other international professional organizations. The NEPA studies and potential impacts from the California Department of Transportation (CALTRANS) were also reviewed.

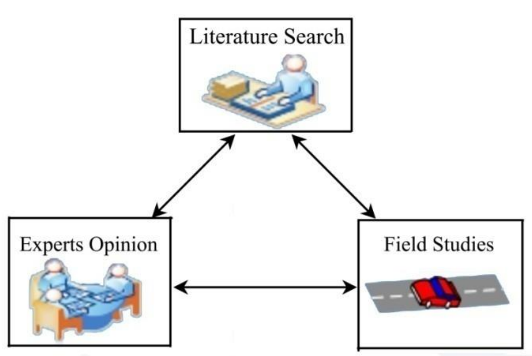
The second step was to study the base line conditions and find potential concerns by conducting a focus group discussion with CDOT functional representatives who are currently involved in highway management activities and whose functional responsibilities would be impacted by the placement of solar array systems in the ROWs such as:

- Highway Maintenance Representatives (Region 1)
- Design Engineers (Region 2)
- Right of Way Managers (Regions 1 and 4)
- Environmental Representatives (Region 1 and Headquarters
- Traffic and Safety Engineers (Headquarters and Region 2)

A conceptual PV array design was developed to facilitate the discussion with CDOT representatives about potential impacts of solar arrays in ROW areas. An open question and answer session followed by an active discussion served to gather information and understand concerns. The Team also coordinated meetings and visits with external CDOT entities that have implemented solar arrays within or near highway ROW areas.

The third step of the research was field study and analysis, which was critical for the collection and evaluation of impact-related data to assess their effects and develop mitigation strategies. The overall research methodology approach is shown in Figure 1.

Figure 1. Research Study Approach Framework

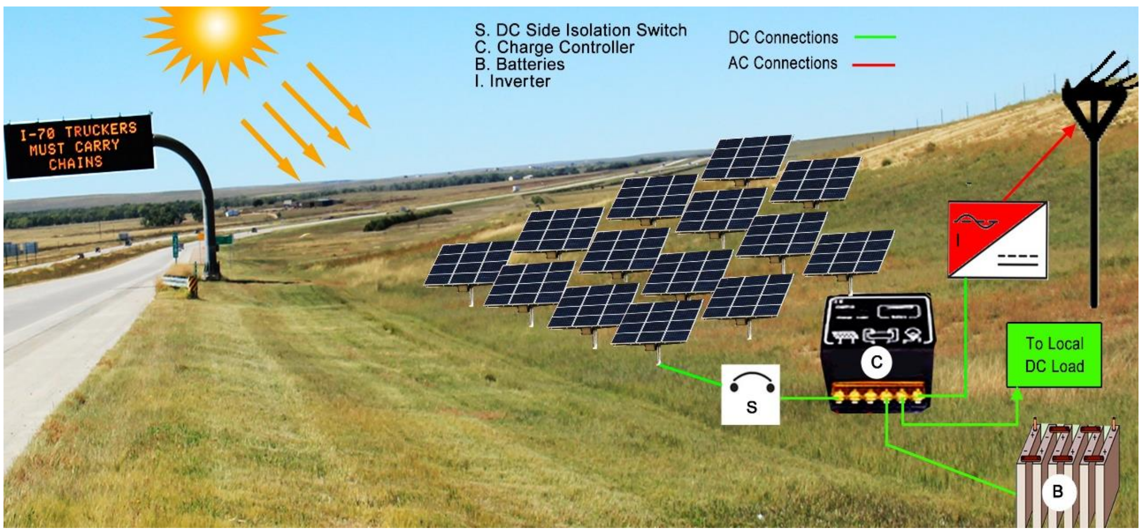


Potential impacts identified in the literature search were examined during the field studies, and the outcomes were verified by the expert opinion and vice versa. The Team performed field studies of conceptual PV array development locations along Interstate 70 (I-70), Interstate 76 (I-76) and Interstate 25 (I-25). This triangular relationship comprising the literature search, expert opinion, and field study served for the validity of the research outcome. An impact matrix (Table 1, Appendix A) was created to quantify impact and analyze the risk level by summarizing the most of the contributory factors. A flowchart was proposed to identify optimum site locations based upon solar efficiencies, safety risk, environmental impacts, highway operations and maintenance activities. The research was conducted in close collaboration with CDOT and the report summarizes the research results, findings, conclusions and guidance recommendations.

1.4 PV Array in ROW - Model

PV arrays use solar cells that consist of layers of semiconducting materials, which convert light energy to electricity. Silicon (single crystalline, multi-crystalline, and amorphous), polycrystalline thin films (copper-indium-diselenide, cadmium telluride, and thin-film silicon) and single crystalline thin film (gallium arsenide) are commonly used materials for solar cells (Mah, 1998). Solar cells are combined into a module, and the modules are connected together to form an array for a practical application of energy generation. A simple model of a PV array in a ROW is presented in Figure 2

Figure 2. Hypothetical Model of PV Array in ROW



A PV panel, charge controller, inverter and transformer are the main components of a PV array. A charge controller helps to regulate the voltage before connecting the power to inverters. The inverter converts the DC electricity coming from the PV into AC, and the transformer consequently steps up the voltage in order to supply the power to the grid. In an off-grid system a battery and local DC load are connected to the charge controller. ROWs constitute varying landscapes with or without a slope. Landscapes and road orientations might help or hinder the PV installation. Locating a PV array next to a road with high-speed vehicles might need extra safety considerations in comparison to a system installed in an isolated location.

CHAPTER 2. PV ARRAY IN ROW

Initially, PV arrays were intended to supply power for temporary needs such as message boards, signage and weather information in remote locations, thus reducing electrical transmission infrastructure costs (TRB, 2011). The simple small modular system did not have noticeable undesirable impacts. However, large scale PV array with an increased size enhances the system complexity as well as potential impacts. This section highlights a few of the PV projects and programs that are implemented nationally and internationally to understand the various constituents of PV arrays and their impacts to transportation.

2.1 Existing PV Array in ROW and Rest Areas

In the United States, DOTs in Oregon, California, Massachusetts, Ohio, Wyoming, Michigan, Texas and Florida are actively deploying PV arrays for power generation. Some of the projects from some of these states are presented below as examples.

Oregon Department of Transportation (ODOT)

ODOT is the leader in tapping solar energy resources within the ROW. As per the State of Oregon Governor's Directive to state agencies for achieving their future energy needs, by using 100% renewable energy, ODOT plans to offset all of their electrical usage via solar and wind energy (Poe and Filosa, 2011). In 2008, ODOT implemented a Solar Highway Project near Portland, Oregon, that comprised 594 solar panels and is currently producing about 130,000 kilowatt hour (kWh) annually (FHWA, 2012). As per conversations with the ODOT Program Manager (Hamilton, 2013), no specific NEPA impact analysis for the solar array development was performed.

In 2013, ODOT performed a site pre-feasibility and impact analysis for the West Linn solar highway project. The feasibility study using a basic NEPA methodology assessed impacts to biological resources, wetland and water quality issues, hazardous materials, noise, visual and aesthetic resources, socioeconomics, geotechnical, archaeological and historical resources, and air quality. Additional resources that could have impacts from a PV array were also investigated such as electromagnetic field effects, wildfire risk potential, social effects such as crime and vandalism, and the potential for glare. None of the risk factors were found to be negatively affected by the PV array. During the feasibility study it was conceptualized that the PV array could be a protective barrier, which could prevent wildfire spreading (Good Company, 2010).

Massachusetts Department of Transportation (MassDOT)

MassDOT in conjunction with the Town of Carver installed a 122 kW PV array along U.S. Route 44 in the State of Massachusetts. An airspace lease (Section 3.3) was granted for the state-owned land by MassDOT with a recurring annual payment, and the electricity generated from the project is being used to support the power demand of a nearby waste water treatment facility in the North Carver Water District. The project is located behind an existing guardrail 65 ft. away from the roadway along an east-west state highway. One of the easement conditions provides DOT a right to reuse the land if needed for future road expansion (Poe and Filosa, 2011).

In December 2012, Massachusetts Department of Energy Resources (MassDOER), in cooperation with Massachusetts Department of Environmental Protection (MassDEP) and the Massachusetts Clean Energy Centre (MassCEC), published a report titled "Clean Energy Results" for the ground mounted solar array. The report was developed to help local decision-makers and community members to investigate the potential impacts from the installation of PV arrays. Most of the impact factors considered such as hazardous material, ambient temperature, noise, glare, electro-magnetic fields and water were concluded not to be affected by PV arrays (Mass.gov, 2012).

Ohio Department of Transportation (Ohio DOT)

The Ohio DOT in conjunction with the University of Toledo deployed a 100 kW solar array in its highway ROW adjacent to the Veteran's Glass City Skyway Bridge in Toledo, Ohio. The electricity generated from the solar array is used to offset the electricity demand associated with a 196 ft. lighted structure on the bridge which has about 384 light-emitting diodes (LED). The 100 kW test array consisting of both rigid and flexible solar panels made in Ohio is used to evaluate and identify problems that might arise from the implementation of PV arrays within the highway ROW (Mehmet Emre et al., 2013).

Sacramento Municipal Utility District, California

The Sacramento Municipal Utility District investigated the development of PV array projects at two potential sites along the Highway 50 corridor within the California Department of Transportation (CALTRANS) ROW (Burleson Consulting, July 2011). The projects envisioned a capacity of 1.4 MW but were not implemented. Flat-plate PV arrays and concentrated photovoltaic (CPV) array technologies were investigated for the two locations (East Sacramento section and Mather Field interchange section). The pre-feasibility and potential impact study concluded that the proposed project would not contribute incrementally to an environmental change or impact when considered in combination with other projects in the area, and therefore the project would not create a significant impact. For certain identified potential impacts, specific mitigation measures were suggested to reduce the impact to a less than significant level.

Michigan Rest Area Applications

In September 2011, the Michigan Department of Transportation (MDOT) awarded a contract to develop and install technology to convert solar energy into electricity at three MDOT rest areas (AASHTO Journal, 2011). Two rest stops in the Upper Peninsula and one in southeast Michigan use three separate, grid-connected solar arrays to lower overall energy costs while demonstrating the feasibility and benefit of photovoltaic energy generation. The project is 100% federally funded with a grant from the U.S. Department of Energy. MDOT will oversee installation of the solar-energy systems along Interstate 75 in St. Ignace, Interstate 94 in Chelsea, and Michigan 28 in Seney. Each project is designed to have a lobby kiosk that will display real-time information about energy savings.

International Solar PV Applications

Internationally, European countries have been deploying PV arrays along the ROW for over thirty years. The approaches to PV array deployment on ROWs are different among the countries, depending upon the nature of the ROW and the type of existing infrastructure. Primarily, PV arrays are deployed on noise barriers alongside highways and on top of automobile tunnels. Noise barriers are principally installed to protect residential or commercial areas exposed to highway noise pollution and provide the ability to generate renewable energy by adding PV panels (see Appendix B).

Relatively lower solar insolation in European countries requires more space for electricity production through PV systems on a large scale. They tend to utilize most of the available spaces; for example, the noise barriers along European motor and railways often stretch over many kilometers and are used for electricity production. Countries such as Germany, Spain, and Italy implemented many solar highway projects called the "Solar Roadways"(European Commission, 2000).

The combination of power generation and noise protection capability makes PV array noise barriers adjacent to the road an attractive option in the highway ROW. PV array could be installed on top of the existing structural support of the noise barrier. Utilizing existing structures lowers the project's overall cost by saving part of the support structure installation costs and time. This cost-saving benefit enables a cost-effective use of solar energy in many locations. See Appendix B for the examples of noise abatement, solar array systems along highways in the Europe.

Germany and Spain are well poised with quantitative tools to analyze potential glare impacts and are equipped with established procedures to enforce the impact remediation measures. In Germany, before PV arrays are installed, glare analysis and the influence of glare on passing drivers is performed and approved by the government authority. Permission will not be granted to install PV array along highways unless the assessment process is complete (Meseberg, 2012). In Germany, any structure within 100 meters (328 feet) of a federal motorway or within 50 meters (164 feet) of certain federal highways requires a permit from the Regional Highway Authority, and nothing can be built within 40 meters (131 feet) in federal motorways and 20 meters (66 feet) in federal highways. The clear zone is 10 meters (33 feet). Within the clear zone PV array projects can be permitted by a special planning procedure depending on individual case review (Persem et al. 2011). This process ensures that there is no influence or increased accident risk for drivers due to PV array glare. The review of existing PV array developments suggest that to avoid any undesirable circumstances resulting from PV array development, an impact study is important that considers factors such as specific technology, geographic locations, road conditions, orientation and local environment.

2.2 ROW PV Resource Potential and Potential Impact Concerns

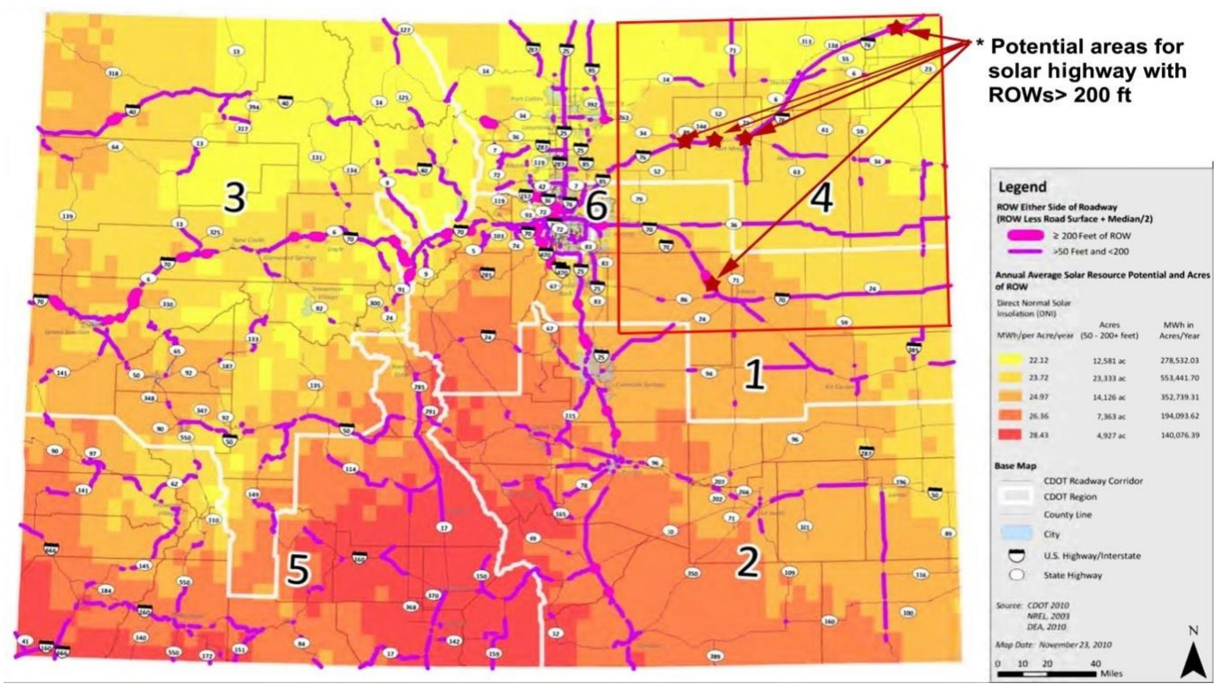
In 2011, The CDOT Division of Transportation Development (DTD) Applied Research and Innovation Branch completed a research project on the availability of alternative energy statewide within the CDOT ROW. The report entitled "Assessment of Colorado Department of Transportation Rest Areas for Sustainable Improvements and Highway Corridors" highlighted the solar energy generation capabilities within the CDOT ROW. The following summarizes the salient aspects of the report to this project:

CDOT maintains 9,144 linear miles of roadway ROW and numerous other properties including rest areas, maintenance yards, remnant parcels and office complexes. Colorado's unique characteristic - more than 300 days of sunshine per year is conducive to alternative energy production from solar array. A resource map was presented in the report for the entire State of Colorado to show the location and distribution of solar resources, giving an estimated theoretical maximum amount of energy from solar for CDOT Rest area, maintenance facilities are some of the assets within or near the ROW that can accommodate ground mounted or roof mounted solar array (Kreminski, 2011). However, the estimates presented in the previous report did not consider specific details such as the size of the clear zone or siting criteria, therefore the actual capacity of the ROW would be different. In addition, spaces on the bridges and noise walls could also be considered as potential areas for PV array installation were not included.

2.3 Baseline Conditions and Concerns

Colorado receives solar insolation in the range of 8.08 to 10.38 GWh/acre/year, with the highest in south and southwestern locations (from the San Luis valley west to Cortez) within CDOT Regions 2 and 5 (NREL, 2009). Previous research studies performed by CDOT indicate that almost the entire CDOT ROW has space available for some kind of PV array installation. Figure 3 shows the levels of insolation and the major highways in the State of Colorado. The areas marked in thicker red lines identify the potential areas for setting up PV array in CDOT ROW that are greater than 200 ft. wide (Kreminski et al., 2011). While it can still be feasible to set up solar array in ROWs with a lesser area, key findings from literature and expert interviews suggest that ROWs with a minimum width of 30 ft. are more appropriate to reduce the impacts, since they provide adequate area for electricity generation while maintaining efficient ROW operation and maintenance actions.

Figure 3. Insolation Levels for Colorado



Based upon the scope of this research project, the area for potential PV array field study locations was focused upon I-70 (east from Denver to the Kansas State line) and Interstate Highway I-76 up to the

Nebraska State Line. Based on the map and the field studies, baseline ROW conditions amenable to solar arrays can be summarized as follows:

- Many areas have ROW width beyond the Clear Zone (30 ft. from the edge of pavement)
- Some areas have greater than 200 ft. of ROW
- Most of the ROWs are in rural settings that might be most desirable for energy development within CDOT ROWs
- Maximum vehicle speed (Interstate) allowed in Colorado is 75 mile per hour (mph)
- A variety of road orientations is available: straight roads in a long stretch of the eastern plains, bends and slopes in the mountains, highways running both east-west and north-south
- Existing PV arrays in and next to highways (presented in CHAPTER 4) but not in CDOT ROWs
- Areas available that have space to accommodate large PV array (2.5 MW and more)

The Team conducted meetings with CDOT at various points during the study and at different CDOT locations such as in CDOT Headquarters, CDOT Maintenance Branches in Limon and Denver in CDOT Region 1, and Region 2. A wide range of solar array ideas, concerns and implementation ideas were obtained from discussions with CDOT representatives about ROW procedures, guidance and permitting processes. The following generally summarizes the main issues identified by CDOT representatives:

- The CDOT Environmental Representatives had potential impact concerns about stormwater management, ecosystems, noxious weeds, prairie dog colonies, bird migration, wildlife migration disruption and the attraction of wildlife to PV arrays.

- The CDOT Safety Engineering Representatives had a concern that a stationary object like a PV array within a ROW (but outside the Clear Zone) might cause driver fatality if the vehicle goes out of control and collides with the array framework/structure. The location of PV arrays either behind the existing guard rail or in isolated places away from the highway is the best. There are engineering approaches that can be used to mitigate potential safety issues such as adding berms, installing cable guard rails or constructing new guardrails alongside the roadway.

- CDOT Traffic Engineers were concerned about traffic flow and lighting systems. Access and egress of maintenance vehicles used to maintain the solar array could challenge the smooth flow of traffic and be a potential safety issue. Signage along the highway will be needed to alert drivers of upcoming maintenance actions to avoid sudden stopping or dramatic slowdowns in traffic speeds.

- CDOT Maintenance Representatives had snow management, and ROW mowing concerns. Maintenance representatives voiced concerns about changing patterns of snow drifting and deposition along the roadway that could result in unsafe, icy conditions to the drivers. The application of chemical deicer (magnesium chloride) could cover the panel surfaces and require additional PV array maintenance. Snow plow blasts from snow clearing could hit or damage the PV panels and structure thus requiring additional PV maintenance. Grass cutting operations could be obstructed by the placement of chain link fencing around the solar arrays.

- The CDOT Right of Way Representatives were concerned about the number of times an energy provider would need to access the PV array. The frequent PV arrays maintenance actions require increased ROW parking and the use of equipment near the roadway that may impact driver and worker safety thus requiring traffic control plans. Visits by low speed maintenance vehicles impacts traffic safety. It is possible that during PV array construction and maintenance actions, a Traffic Control Plan would need to be developed and managed by the solar energy provider and CDOT. It is preferred that solar array access be provided from an adjacent frontage road and not directly off the highway. Detail of focus group discussion is presented in Appendix C.

CHAPTER 3. REGULATIONS AND PERMITTING REQUIREMENTS

Disclaimer: Summary of the existing rules and regulations is presented here as a reference. This is not a comprehensive list; one willing to implement an actual PV project in ROW needs to follow the regulations that are current at the time of project development and needs to coordinate closely with their CDOT Project Manager.

The deployment of PV arrays with an operational life of at least 25 years along the highway ROW is a long-term project and needs to abide by the existing procedures and regulations followed by the DOT in ROW development and long-term management. The requirements that need to be followed by an energy provider during project design, construction, operation and maintenance are presented

3.1 ROW Design Requirements

CDOT has a responsibility for the safe and efficient flow of traffic along highways. Consequently, the safety of drivers and working crews is vital. To help avoid accidents, it is necessary to identify a general design approach for renewable energy installations near the roadway. The Manual on Uniform Traffic Control Devices and FHWA safety guidelines were referenced directly in this research (AASHTO 2011) and the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (RSDG) is a standard for ROW design and management.

3.1.1 AASHTO Definitions

Pertinent AASHTO definitions are as follows:

- The Clear Zone is defined by the RSDG as "the total roadside border area, starting at the edge of the traveled way that is available for an errant driver to stop or regain control of a vehicle. This area might consist of a shoulder, a recoverable slope, and/or a non-recoverable, traversable slope with a clear run-out area at its toe."
- Crash Cushions are systems that mitigate the effects of errant vehicles that strike obstacles, either by smoothly decelerating the vehicle to a stop when hit head-on, or by redirecting the errant vehicle.
- Guardrails which might be flexible or rigid, help guide the off track vehicle back to the road. This type of barrier would protect the driver and help decrease the severity of accidents from head-on collisions with the PV array.
- Lateral offset on the horizontal curve of a road is the space between the road and a line connecting two ends of the curve.
- Breakaways are design features which allow a device such as a sign, luminary, or traffic signal support to yield or separate upon impact. The release mechanism may be slip plane, plastic hinges, fracture elements or a combination of these.

3.1.2 AASHTO Requirements

The National and Industry Standards in the Rules & Regulations Guide require that all DOT agencies adhere to the following:

- "A Guide for Accommodating Utilities within Highway Right-of-Way," AASHTO, October 2005 edition

- “A Policy on the Accommodation of Utilities Within Freeway Right-of-Way,” AASHTO, October 2005 edition
- “Roadside Design Guide”, AASHTO, 4th edition 2011

3.1.2.1 AASHTO RSDG

Applicable RSDG guidance is as follows:

- Most highway agencies provide at least 30 ft. of clear zone (traversable and unobstructed roadside area) for high-volume, high-speed roadways.
- RSDG discusses specific guidance on the location of fixed and/or permanent applications along the roadside.
- Fixed or permanent structures such as PV arrays must be adequately protected from the effects of ambient conditions (e.g. ice and wind loads, temperature) and meet or exceed the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaries and Traffic Signals.
- AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaries and Traffic Signals and NCHRP Report 350 list criteria that a breakaway support will fail in a predictable manner when struck head-on by an 1800 pound vehicle or equivalent, at speeds of 20 mph and 60 mph. Breakaway designs are intended to reduce the severity of an accident rather than to reduce the frequency.

The existing RSDG does not have a direct provision for renewable energy installations; however, these requirements need to be followed in installing a PV array within the ROW.

3.1.2.2 Federal Regulations and Standards

The following includes the Federal regulations and standards that must be followed while accommodating utilities in the Right of Way:

- “Rights of Way,” [Title 23 - Highways] 23 CFR 1.23, April 1, 2008
- “Utility Relocations, Adjustments, and Reimbursement,” 23 CFR Part 645A, April 1, 2008
- “Accommodation of Utilities,” 23 CFR Part 645 B, April 1, 2008
- Air Space Lease 23 CFR 710
- “Transportation of Natural and Other Gas by Pipeline; Minimum Safety Standards,” Hazardous Materials Regulation Board, [Title 49 - Transportation] 49 CFR Part 192, October 1, 2007
- “Transportation of Liquids by Pipeline; Minimum Safety Standards,” Hazardous Materials Regulation Board, 49 CFR Part 195, October 1, 2007

3.1.3 Maintenance and Operations ROW Considerations

Traffic flow, road maintenance, and user safety are the major functional components of highway operation and maintenance. The following is a list of the ROW considerations based on road maintenance and operations:

- Snow removal during winter and mowing during summer are maintenance responsibilities, in addition to repairing pavements and structures (CDOT, 2012). CDOT follows the AASHTO guidelines as applicable.
- For a maximum speed limit of 75 mph on the interstate freeway (GHSA.gov), a 30 foot Clear Zone is critical for drivers to recover control if the vehicle goes off the roadway. Few rigid objects in the Clear Zone help reduce the severity of accidents.
- Lane shift and reduced speed are some of the characteristics of a work zone. Open space for road diversion, maintenance storage, maintenance activity and access roads for maintenance vehicles are desirable for faster road maintenance and better traffic flow (AASHTO, 2011). Traffic Management Plans are often required by CDOT for construction and some maintenance actions occurring within the ROW.

3.2 ROW Environmental Regulations

3.2.1 Environmental Requirements

CDOT's commitment to the protection and preservation of the state environment requires energy providers to comply with federal, state and local environmental regulations and land use requirements in all projects and activities.

Wherever significant adverse social, economic or environmental impacts may result from the ROW work, the utility owner (PV developer in this case) shall comply with applicable Federal, State and local laws, regulations and codes. PV projects shall follow the following environmental regulations:

- Maintain air quality, ("Colorado Air Quality Control Act," Title 25, Article 7, CRS) and minimize noise (25-12-103, CRS for noise control).
- Minimize the generation of hazardous wastes (25-15-101(9), CRS) resulting from operations, take a prompt action to remove/ dispose/ treat any such wastes from ROW, (Title 25, Article 15, CRS). For solar array support structure foundations, proper attention should be taken to avoid any contact with subsurface hazardous waste.
- Maintain stormwater quality during construction and post construction (Title 25, Article 8, CRS), "Protection of Fishing Streams," (Title 33, Article 5, CRS), and maintain temporary erosion and sediment controls (CDOT, 2002).
- Comply with all requirements of an applicable permit and all special conditions by the US Army Corps of Engineers, when impacting wetlands, placing dredged or fill materials in waters of the State of Colorado for utility line crossings or construction.
- Avoid construction or other activity in wetlands unless there is no practicable alternative to such construction or activity and provided that all practicable measures are taken to minimize harm to wetlands which may result from such use.
- Perform advance cultural resource investigations, as necessary for the Department to comply with the "Colorado Historical, Prehistoric and Archaeological Resources Act," Title 24, Article 80, CRS, the

"Colorado Register of Historical Places Act," Title 24, Article 80.1, CRS, and all applicable Federal, State and local agency rules and regulations.

- Require an environmental review under the National Environmental Policy Act

3.2.2 ROW Environmental Guidance

When directed by CDOT, utility company and/or energy provider shall perform advance natural resource investigations in the vicinity of all proposed buried or above-ground installation, as necessary, to comply with the Endangered Species Act of 1973, the Migratory Bird Treaty Act and the Bald and Golden Eagle Protection Act.

Any cultural resource investigation shall be performed by a Colorado permitted archaeologist. Such investigations, and proposed mitigation if any, shall be subject to review and concurrence by the Colorado State Historic Preservation Officer.

As per the Water Quality Control Division (WQCD) of the Colorado Department of Public Health and Environment (CDPHE), the utility owner shall contact CDPHE to obtain a Colorado Discharge Permit System (CDPS) Stormwater Construction Permit applicable to construction site Stormwater runoff, drainage from utility line casings, equipment wash water.

According to NEPA requirements, each action in the highway ROW that is classified as a potential major federal action must comply with NEPA requirements and other relevant environmental regulations. Federal actions are projects that use federal funding, require a federal permit, or require a federal agency's approval. The appropriate NEPA action is determined by the significance of the environmental impact of the project being proposed. Actions in the highway ROW that do not individually or cumulatively have a significant effect on the environment may be covered under a Categorical Exclusion level document (US DOT, 2012).

3.3 Utility Accommodation Policy and Airspace Leasing

The FHWA has developed ROW guidance (23 CFR 710 Subpart D) (FHWA, 2013) for utilities that are appropriate for ROW alternative energy generation, which is summarized in "Renewable Energy Generation in the Highway Right-of-Way" (Volpe, 2013). The installation of renewable energy in the ROW can be carried out in two possible ways, a project that serves "the public" can be accommodated under the DOT's approved Utility Accommodation Policy (UAP) or projects for private or proprietary use needs to be approved under airspace leasing requirements.

In Colorado, CDOT has the authority and responsibility to issue permits for utility accommodations on Interstate and State Highway ROWs that may also include local streets within the local agency jurisdiction. It is the responsibility of all utility owners to obtain any permits from the CDOT prior to performing any utility accommodation work. The State Highway Utility Accommodation Code serves as a guideline for safe, efficient and effective joint utilization of State Highway ROWs for both transportation and utility purposes (CDOT, 2009). The Code establishes a consistent statewide process for accommodating utilities within ROWs to ensure that such accommodations do not adversely affect user safety or otherwise impair the operation, aesthetic quality or maintenance of the transportation facility, or conflict with applicable law.

Concerning the utility accommodation and airspace lease permit procedure, the Federal government requires the NEPA process for the environmental analysis of new project development. It is expected that solar arrays in ROWs will not cause significant impacts; therefore, a costly and time-consuming Environmental Assessment (EA) would not be necessary and a more limited Category Exclusion (CATEX) would be appropriate. An EA may be needed if a very large solar array was being considered for a large corridor and a programmatic environmental approach would be needed by CDOT. Some of the Environmental factors that might be affected directly by the PV array are described here, and need to be assessed under the CDOT NEPA process for solar array. The energy provider will need to coordinate closely with the appropriate regional CDOT Environmental Manager and other environmental representatives regarding potential environmental impacts.

3.4 Existing ROW Leases and Potential Conflict with PV array Development

Before starting the PV Array project, it is necessary to avoid any conflict with existing projects and agreements such as the potential location might already have been leased or there might be another infrastructure planned or in place. CDOT should have its right to reuse the property without any burden if it needs the space for future road expansion.

CHAPTER 4. SOLAR ARRAY FIELD VISITS

In Colorado, many PV arrays have been installed in recent years. PV arrays installed on or near the ROW by various investors were selected for this research study. The orientations of the panels, site design, system capacity, configurations and maintenance as well as related impacts were studied during the field study visits.

4.1 CSU-P Solar Array

CSU-P is the first public university in Colorado to deploy a PV array to offset its energy demand by installing a ground mounted flat PV array in a utility scale (with 1.2MW capacity on 3.4 acres of land). CSU-P has monitored the environmental and other general impacts of the PV array in the surrounding area since its inception in 2008. The PV array is located on the northeast corner of the campus away from the campus traffic and activity area. There were initial concerns that glare and view shed distractions would affect the viewing of sporting events at the adjacent stadium. Based upon monitoring and public feedback, no problems associated with glare were encountered; however, the impact of glare or any other distractions might be different under roadside conditions.

Beyond glare, another concern of any PV array project is its implications to the wildlife and their habitat. The CSU-P project location is surrounded by a wildlife area and is adjacent to a wildlife preserve. Encountering coyote and other wildlife on the preserve is very common, but no wildlife impacts have been observed. There were initial concerns about PV performance related to rodents building their nests underneath or around the panels which might have resulted in damaged wires from animal chewing. No such incidents have been observed since its installation in 2008.

Maintenance requirements of the system are minimal, which might be due to a relatively clean campus environment. However, it is possible that frequency of maintenance requirements might be higher in the highway ROW due to the air particulates from tail pipe emission of motor vehicles and dust deposition by the wind blowing from a desert’s dry open space. In addition, chemical deicing residue and/or splashes from the high speeding vehicles during rainy and snowy days can spoil the panel surface and/or corrode the structure.

4.2 E-470 Toll Road

E-470 is a toll road on the east side of Denver connecting the north and south sides of the metropolitan area. The privately owned highway provides easy access to Denver International Airport (DIA) from the metropolitan area. In 2012, PV arrays were installed in 22 sites along a 17-mile stretch of the toll road from 64th Avenue to Gartrell Road. The 708 kilo watt (kW) system supplies one-third of the operational power need of the toll road.

Figure 4 shows a PV array used to supply power to the traffic lights on Smoky Hill Road adjacent to E-470. The PV panels are installed on the slope alongside the exit ramp. The pole support structure is used for a standalone array in a group of twelve panels. Panels are orientated toward the south to avoid shading from each other during morning and afternoon sun. The energy investors on E-470 won the “Social Responsibility President's Award” in 2013 (IBTTA, 2013).

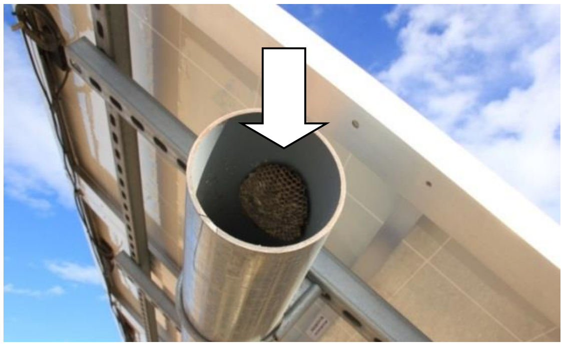
Figure 4. Solar Array on E-470

4.3 Denver International Airport (DIA)

DIA installed PV arrays adjacent to Pena Boulevard near the Terminal Building in 2011. DIA has both tracking as well as fixed PV array installed facing south. The DIA staff engineer pointed out that the tracking systems exhibit malfunctioning due to weather conditions. This has primarily been observed at subzero temperatures during winter months which freezes the liquid in the hydraulic equipment thus limiting the performance of the tracking system. The DIA PV array is privately owned and has no financial relationship with DIA operations. One of the main impacts noted was corrosion of the array structural framework, which might be due to deicing chemicals or emissions from vehicle tail pipes.

The array is approximately 90 feet away from the main Pena Boulevard guardrail near the East/West Terminal split. More reflection was noticed from the array frame than from the panels. The DIA project used recycled concrete on the "floor" of the array system, and it was noted that some noxious weed control is necessary. No bird issues associated with the solar array system have been recorded. Figure 5 shows the presence of a wasp nest in some of the structure pipes used for support structures which could present a safety issue to the maintenance crew.

Figure 5.Wasp Nest in Support Structure



4.4 Northwest Parkway

The Northwest Parkway, located in the northwestern portion of the Denver metropolitan area, signed a 20-year power purchase agreement with an energy provider (Soltura Energy Capital) to use their ROW for energy generation. Installed in 2011, the solar array within the Northwest Parkway's ROW is comprised of seven individual systems that generate 63 kW of electricity. A separate contractor (Bella Energy) was responsible for the construction and ongoing maintenance. The following highlights the discussion and field observations with the Northwest Parkway Lead Engineer (Mark Shotkoski):

- The solar panels were facing in a southerly direction along the tollway, orienting parallel to the highway.
- There is approximately 35 ft. distance between the shoulder edge and the closest panel.
- The efficiency of the panels does not significantly improve much after panel washing and was discontinued.
- No deicer impacts have been noted on the solar array structure.
- Coordination with the city of Broomfield was needed for prairie dog colony impacts.
- No snow drifting and depositional impacts on the roadway surface were observed.
- Solar panel angles are between 18-24 degrees, and no glare impacts have been noted by the engineer and the traveling customers.
- It is important to place end caps on metal cylindrical structural framework to prevent insect nests.
- A geotechnical study was performed for the ground mounted structure design and construction.
- Erosion control during construction was required by the City of Broomfield.
- Fences were used to protect the PV array from theft (as shown in Figure 6); razor wire was not used due to aesthetics.

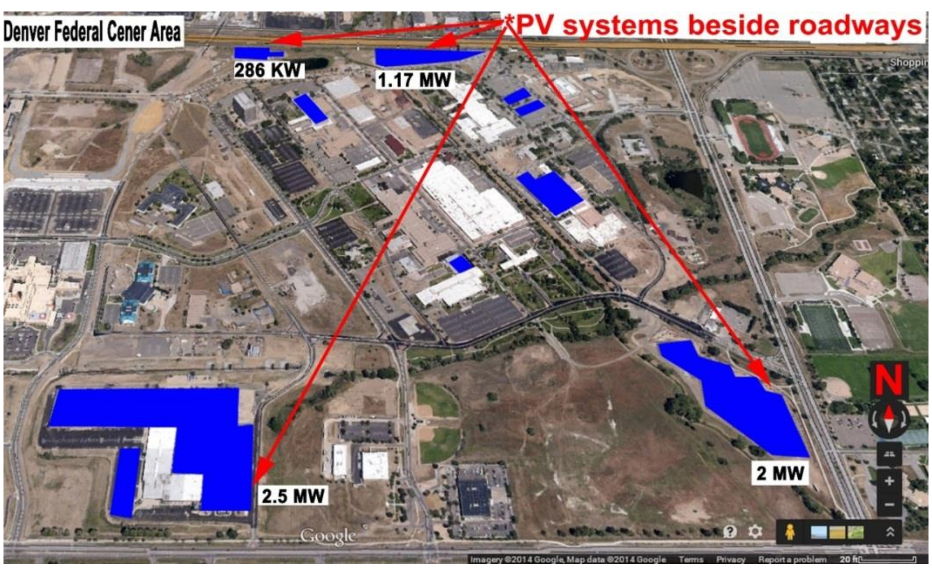
Figure 6. PV Array with Fence

4.5 Denver Federal Center (DFC)

The DFC installed an 8 MW direct current (DC) solar array in 2008, which provides approximately 17% of the DFC's electrical needs annually. A computer-based system operation and maintenance program is in place that monitors energy production and overall operations of the system (corrosion, contamination, electric short and leakage, etc.). The following highlights the discussion and field observations with the DFC Lead Engineer:

- The PV development was done under NEPA Categorical Exclusion and no major impacts were identified.
- Some array panels were located adjacent to US 6 in close proximity to the ROW fencing (see Figure 7) and no driver complaints were received.
- Panel cleaning is not performed since self-cleaning by rain or snow precipitation seems to be providing the cleaning function.
- The panels are not very reflective and may not produce any glare effect, but glare was observed from the frames of the system.
- Most of the DFC site has fences surrounding the array system with continuous area security; therefore, no theft or vandalism has been was reported so far.
- Evidence of panel breakage was observed in some of the visited sites. The major causes of panel breakage have been either due to manufacturer's defect, panel mishandling during panel installation, or lawn mowing during which small rocks/pebbles break the panels upon impact.
- Noxious weeds are a problem under and near the solar panels; active re-vegetation was not performed immediately after construction.

Figure 7. Denver Federal Center PV Arrays



As shown in Figure 7, four PV array sites are located beside roadways; consequently, due to adjacency to roadways, inevitable impacts on motorists such as glare may cause driver distraction. For illustration, a PV array sited near the bridge adjacent to highway US-6 is shown in Figure 8. Glare from the PV array adjacent to the bridge could pose risks to motorists. A driver distracted by the PV array could lose vehicle control in an immediate narrowed road and hit the guard rail of the bridge. Panels are supported in aluminum square channels with a truss structure, as shown in Figure 9. The ground below the panels contains grass, which might need mowing once or twice a year.

Figure 8. DFC Solar Array Near Bridge

Figure 9. DFC Support Structure Example

4.6 Air Force Academy

A 6 MW ground- or pole-mounted system is installed in 32.4 acres located on the north side of Colorado Springs, Colorado, adjacent to I-25. The energy company Sunpower has installed more than 19,000 PV modules in this array system which has been in operation since 2011 (AASHE, 2011) (Winkle, 2010). It is observed that the public has encountered some inconvenience from this system and commented on the project website. CDOT maintenance staff also reported an increase in snow accumulation on the road potentially due to the enhance snow drifting and shade. The PV array layout is shown in Figure 10.

Figure 10. PV Array on the Air Force Academy (Baillie Amber, 2012)

4.7 Community-Owned Solar Garden (off I-25 MP, 135.5 near Fountain)

The Community Solar Garden near Fountain, Colorado was built in 2013 by Clean Energy Collective (CEC) consisting of 2,210 solar panels in 8.67 acres of land. The 500 kW system is oriented at a tilt angle of 40 degree south-facing. El Paso County has granted a special permit in a variance of their land development code. They require planning of landscape, hazardous material handling, mowing and weed control, opaque fencing toward the neighborhood side, and drainage **(**Clean Energy Collective, 2013**).** Figure 11 shows the PV solar garden, which is adjacent to the highway. This site was used as a model for a glare analysis, which will be presented in Section (5.4.1).

Figure 11. Community Solar Garden Adjacent to I-25

For more information on the field visits regarding the site conditions, physical characteristics and modeling variables, and expert interviews, see Appendix E.

CHAPTER 5. IMPACTS OF ROW PV ARRAY

PV technology is relatively safe and is implemented with few impacts. However, installing, constructing, operating and maintaining PVs in ROWs might pose unique impacts as discussed in the previous chapters. In this chapter, potential impact within the ROW will be grouped under three categories: 1) driver safety, 2) road maintenance and 3) environmental impacts.

5.1 Driver Safety Impacts

Drivers have certain expectations while driving on a freeway. Adequate sight distance, proper signage, smooth traffic flow, limited distractions, smooth road conditions, well-disciplined fellow drivers and well-managed ROWs are desirable and expected. Installing PV arrays within ROWs may compromise these expectations and can introduce other undesirable experiences. Some of the undesirable factors for driver's safety identified in this research are presented here.

5.1.1 Driver Distraction

Driving requires full attention to control the vehicle and respond to the changes in traffic dynamics such as approaching a slower vehicle, maneuvering in a curve on the road, providing space for merging vehicles, etc. To perform these tasks a constant coordination between eye, mind, and body is essential. Any distractions that take a driver's attention away from the road for a few seconds could lead to an accident. Driver distraction is one of the major causes of vehicle crashes, which could be caused by visual (eyes off the road), cognitive (mind off the road), and manual (hands off the steering wheel) malfunction (CA.gov, 2011). Eighty percent of crashes and 65% of near-crashes involve some form of driver distraction that occurs within three seconds before the vehicle crash. Looking at an object or event outside of the vehicle is one of the principal actions that cause distracted driving which leads to vehicle crashes (NHTSA and VTTI, 2006).

The US Department of Transportation's National Highway Traffic Safety Administration (NHTSA) reported 33,561 highway deaths in 2012, which is an increase of 1,082 from the previous year. The number of fatalities caused by distraction-related crashes decreased slightly from 3,360 to 3,328 in the same year, while the number of injuries increased to 421,000 people from 387,000, a 9% increase for 2012 (NHTSA, 2013). Most of the DOTs have set goals to decrease these incidents, and PV array deployment should not impede their goal. The unexpected view of a PV array may catch the sudden attention of drivers while approaching a PV array site and contribute to drivers' distraction; however this potential impact is not significant and can be easily mitigated by signage or proper placement of the arrays.

5.1.2 Fixed Structure Within/Near the Clear Zone

A fixed structure near the road increases as the risk of accidents and driver fatalities. Introducing a stationary object next to a high-speed roadway is unsafe as a car deviating from the road may hit the stationary object resulting in fatal accidents due to the higher momentum of the speeding car. A fixed structure solar array may increase driver fatalities or injuries if introduced within the clear zone without barrier protection or adequate distance.

In addition, the PV array may block animal migration or daily routes. The trapped animals can become confused and run into traffic. Similarly, introduction of a PV array in ROWs might alter mowing and other maintenance activities; the change in maintenance activity could compromise the driver's safety. Crashes due to road maintenance equipment and wild animals accounts for around 0.29% and 14.54% of total accidents respectively in 2011 (CDOT, 2011).

5.1.3 Light Reflection- Glint and Glare

Glint is defined as a temporary flash of light, while glare is defined as a continuous source of excessive reflected radiance. Solar glare causes nearly two hundred fatalities and thousands of accidents involving motor vehicles on average each year. The impacts of glare from PV array installations can range from discomfort to disability (Clifford, 2013).

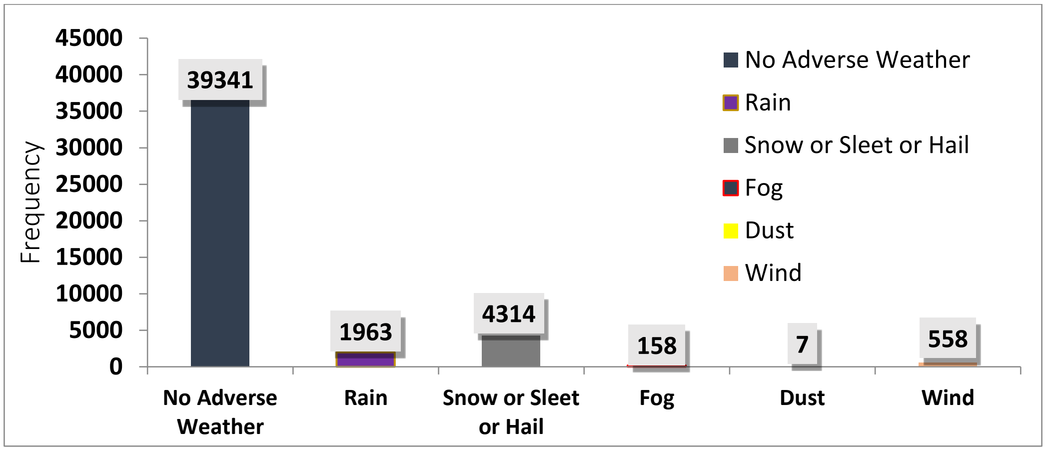
Albedo is the unit of the measure of reflectivity, which is the ratio of solar radiation across the visible and invisible light spectrum reflected by a surface. Albedo varies between zero (surfaces that reflect no light) to one (a mirror-like surface that reflects all incoming light). The mono-crystalline silicon wafers which are the basic building block of most PV modules absorb up to 70% of the sun's solar radiation in the visible light spectrum (Good-Company, 2011). Solar panels with a single anti-reflective coating have an 0.10 albedo (sand: 0.15-0.45, agricultural vegetation: 0.18 - 0.25) (Budikova, May 8, 2010). This suggests that the solar panels have a lower reflectivity than the prevailing ground cover area; agricultural crops, etc. (see Table 3, Appendix F, for detailed list).

PV cells are encapsulated and covered with a transparent cover film. These protective layers reduce the amount of reflected light from photovoltaic modules. Most solar panels are now designed with at least one anti-reflective layer and some panels have multiple layers. A PV array does not significantly alter the site's current amount of reflected indirect sunlight; however, their orientation may create glare or glint at certain viewing points in certain daylight conditions. PV arrays have a potential of flash blindness, which can cause temporary vision impairment. A high-speed driver with temporary vision impairment might lose vehicle control, resulting in a crash.

5.1.4 Snow Drifting

Snow deposition on the highway is a major concern to the CDOT Maintenance. The installation of a PV array along the highway ROW might affect the existing snow drifting and depositional patterns thereby increasing ice and snow build up on the roadway making the road more slippery. Ice on the roads lowers tire gripping and causes loss in vehicle control. Car pile-ups and collision incidents are high during winter. Icy road conditions slow down the flow of traffic for safe driving and increase the travel time. In addition, PV arrays may alter the natural wind flow; the wind may bring more snow flurries to the road causing visibility problems to drivers. Accident rates in Colorado in 2011 due to different weather conditions are shown in Figure 12.

Figure 12. 2011 State Highway Crashes due to Weather Condition in Colorado



As shown in Figure 12, state highway crashes in snowy weather conditions are approximately 9.3% of the total road accidents; the highest in comparison to other weather conditions in Colorado (CDOT, 2011). To better understand snow drifting behavior and impacts, estimating the snow accumulation season is vital.

Snow accumulation season is the period of drift growth that begins with the first blowing snow event that causes drifts to persist through winter, and it ends when snow drifts reach maximum volume for winter. The snow accumulation season is delimited by dates when the average air temperature reaches 0°C, as computed using mean monthly temperatures (Tabler, 1994a). Snow drifting depends upon the snow mass flux, concentration, height, and wind velocity. Snow impact analysis is presented later (Section 5.4.2).

5.2 Road Maintenance Impacts

Road maintenance activities include but are not limited to mowing during summer, snow plowing during winter, maintenance of drainages, repairing of pavement, fixing and building fences and road structures. The ROW serves as a buffer between the traveled way and adjacent private property (CDOT, 1979). The ROW maintenance approach used by CDOT depends on the location of the highway (rural or urban) and the land use sharing the border with the ROW.

A PV array might have an impact on road maintenance as the array framework and associated security fencing might alter the mowing operations within the ROW. Mechanized equipment is used to perform mowing operations along the ROW, and separate standards are used for urban and rural highways. The grasses on the ROW are usually maintained at a height between three inches and six inches in the urban areas, while mowing along rural highways are maintained at a height between four inches and ten inches in all areas of the ROW starting from the pavement edge (CDOT, 1979). The mowing operation is carried out at least once a year or otherwise when necessary. The presence of a PV array will limit the movement of the mechanized equipment thereby limiting large-scale mowing operations. Snow plowing is done for snow removal, which normally deposits the snow alongside the road within the ROW. There may not be enough space to deposit the snow (if the array security fence is closer to the road), as the space is occupied by the PV array.

5.3 Environmental Impact Analysis

5.3.1 Wildlife and Habitat

Installation of a PV array on the ROW may limit wildlife movement, including migration of deer, antelope, and elk. Long continuous sections of PV array, especially with the security fencing, may present a significant barrier. Sensitive terrestrial environments such as the short grass prairie ecosystem, for which CDOT has a 20-year biological mitigation program, may be impacted. The introduction of noxious weeds caused by ground disruption during construction at the project site might invade the native ecosystems.

The main impact to wildlife and habitat stems from the land use footprint used by the PV array. The vegetation of the site may be altered and the soil may become exposed to erosion during and after solar array construction. It is possible that trees and shrubs may need to be removed to provide adequate solar array exposure, altering wildlife habitat or removing natural snow barriers. Hiding spots, preying strategy and food availability has the potential of being affected, and thus the habitat conditions of the land may be altered. Therefore, it is necessary to avoid placing array systems in known animal migration routes or wherever threatened and endangered (T&E) species may be encountered. An initial site assessment of potential solar array installation sites should be carried out to avoid or reduce impacts.

5.3.2 Water Resources

Impacts to geo-hydrological resources include topsoil erosion, increase of sediment load to receiving streams and the need for increased stormwater management. Concentrated stormwater flows may result from rainstorm/snowmelt events running off the solar array panels that can cause localized erosion, vegetation impacts and water quality problems. Removal of vegetation increases runoff to streams from rainfall and snowmelt. Thus, precautions should be taken in the removal of vegetation at a PV array site. The establishment of native vegetation under the PV array panels should be encouraged to prevent erosion, soil transport and introduction of noxious weeds. Placement of arrays should be avoided within 50 feet from surface water systems. Stormwater should be managed according to CDOT specifications and CDPHE stormwater permit regulations.

A site feasibility study of the ODOT West Linn solar highway project proposed to arrange the PV array in rows and establish twenty-foot vegetated strips in between panel rows to allow stormwater infiltration. Shallow bio-swales along each row were proposed in the project. Excess stormwater not absorbed by the vegetated strips will be directed into the bio-swales which in turn are directed into a proposed ditch. The study concluded that the proposed stormwater management will improve drainage flows in the project site (Company, 2010). As an alternative, it is possible that gravel bedding could be used below the array systems to support infiltration of stormwater runoff depending upon site conditions.

5.3.3 Hazardous Waste

After a PV array's useful operational life, PV cells should be recycled to prevent the introduction of materials into the environment such as cadmium, arsenic, and silica particles contained within the cells. Any mishandling of PV panels during installation and maintenance of PV modules can cause damage to cells and expose the toxic chemicals into the air, which can hurt the public and environment during long-term exposure. For example, inhalation of silica dust ($0.3 mg/m^3$) over long periods of time (> 8hrs) can lead to silicosis, a disease that causes scar tissue in the lungs and respiratory decline (OSHA, 2002).

5.3.4 Fire Potential

The fire hazard potential of ground-mounted PV infrastructural materials (e.g., phosphine, diborane, cadmium), and their improper disposal, presents an additional challenge to minimizing the environmental impacts of a solar array (Hernandez et al., 2014). Fire hazard due to electric arcing associated with loose wiring connections, short circuits due to animal chewing and external stimuli might be a challenge. The State of Colorado has a range of arid to semiarid regions with a record number of wildfire incidents every year. Defensible space around a PV array can help protect the array from forest fires as well as protecting the forest from igniting if the solar array system catches fire. This is particularly true in light of the dramatic increases in the frequency and intensity of wild land fires in arid and semiarid regions (Hernandez et al., 2014).

5.3.5 Noxious Weeds

Construction of a PV array project, as with any construction, might bring noxious weeds into the project area. Machinery, vehicles, people, livestock, wildlife, wind and water can all transport seeds from existing infected areas to new sites. Once established, noxious weeds aggressively invade adjacent areas. Consequently, these foreign plants have no natural constraints to keep them in balance with the native ecosystems and they quickly overtake and replace indigenous plants and dominate entire landscapes. Various rules and regulations are established by the State of Colorado and counties to deal manage noxious weeds.

By reducing the land's ability to sustain native vegetation and water resources, noxious weeds deprive wildlife from food, water and habitat. These weeds can cause health problems in humans and domestic animals. Some weeds that are non-noxious may still cause problems. For example during windy weather conditions, tumbleweeds blown away by wind, create "tumbleweed blizzards" on the highway interfering with traffic by creating a nuisance to drivers. Accumulation of these plants upon the PV array might increase the maintenance need of the ROW.

5.3.6 Microclimate Change

Solar panels have low reflectivity and convert a fraction of insolation into heat, which leads to a microclimate change, raising temperature locally in the surrounding environment. The rise of temperature is caused by the infrared component of solar radiation. The surface of a PV module may attain a temperature up to 70˚ C which is significantly higher than the ambient temperature and results in heating the surrounding air (Chiabrando et al., 2009). The microclimate impacts are not likely to be an issue for most ROW PV arrays, but it might be experienced in large-scale PV arrays installed in urban areas and in areas with high insolation levels such as deserts.

5.3.7 Noise

Noise is defined as an unwanted sound which interferes with or disrupts normal activities. Long-term exposure to high levels of noise causes hearing loss. The individual human response to environmental noise is based on the sensitivity of the individual, along with the type and time of noise.

The scattered noise of a ground mounted PV array comes from the inverter and transformer. The inverters and transformers make a humming sound during operation for generation of electricity in the daytime. The sound of transformers and inverters is inaudible at 50 to 150 feet from the boundary of the arrays (Mass.gov, 2012). Noise impacts can be mitigated using enclosures, shielding and placement of the sound-generating equipment on-site. Siting of noise-generating equipment is critical as the sound impact can be reduced by half by doubling the distance to the receptor. In some areas both in the U.S. and Canada, sound impact analysis is required as part of the permitting process for large PV arrays. For example, in the Province of Ontario, Canada, any project greater than 12 MW is required to perform a sound impact analysis (Ontario, 2009). However, the noise level of a PV array will not be higher than the traffic noise.

5.4 Modeling and Analysis

From the literature search impact study, it is evident that glare and snow drifting are the critical factors that need to be considered when implementing a PV array system. Conceptual site assessments and/or the NEPA process should model potential sites for glare and snow drift analysis. To help understand these impacts, glare modeling was completed at a potential future PV array site and at an existing PV array site.

5.4.1 Glare Analysis

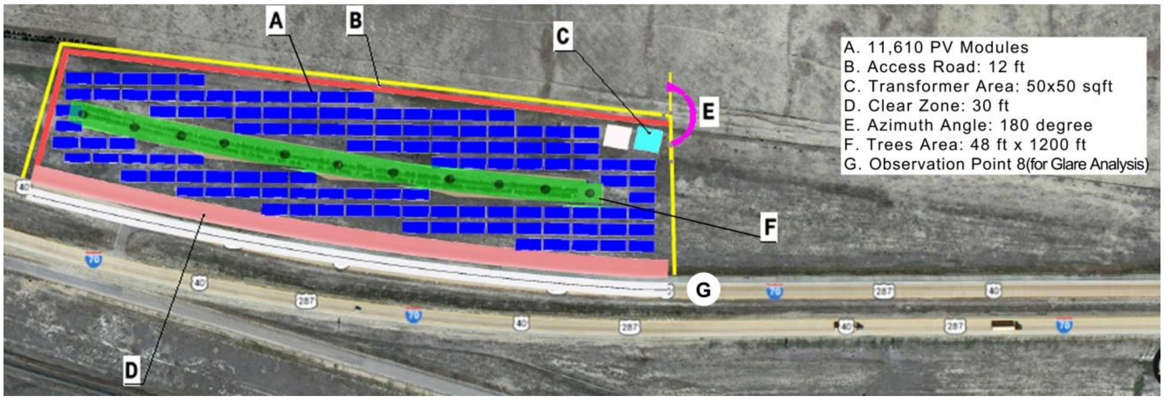
<u>Site 1: I-70 West of Limon, Colorado (Mile Post 358.2)</u>

This project study area is located west of Limon, Colorado at mile post 358.2 along I-70 and is on the north side of the interstate. The available ROW space is 328 feet wide from the edge of the shoulder and approximately 1100 feet long. Two rows of small trees (10-15 feet high) were observed at the middle of the ROW. Infrastructure for stormwater drainage and irrigation was present and grass covered the entire project study site area. Animal bones and snake skins on the ground indicates the presence of wildlife in the vicinity. Varieties of plants such as barley were seen to be growing with a large presence of insects such as locusts and bugs. The ROW also had a large amount of trash from the driving motorists. The barbed wire fence at an approximate height of 3-3.5 feet above ground level was used as a ROW boundary. Low-lying ROW land was observed in comparison to the elevation of the highway, which might help to avoid snow deposition and snow drifting on the highway.

Modeling a Conceptual Solar Array

A hypothetical solar array installed on the north side of I-70 facing south, presents a probability of reflection from the panels to the road that could impact passing by motorists. The site is modeled using a 11,610 fixed-tilt PV solar array having an estimated power capacity of 2.5 MW. A glare modeling analysis was performed to assess the potential impact of the PV array layout as shown in Figure 13.

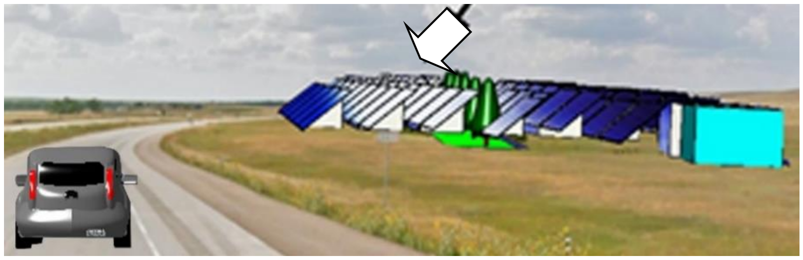
Figure 13. Conceptual Solar Array (Limon, Colorado)



As shown in Figure 13, a 30 ft. width from the edge of pavement was kept for the Clear Zone. South facing panels are installed in multiple rows aligning east-west with space provided for existing trees in the middle. The amount of glare and the resulting ocular hazard depends upon the intensity of the light (retinal irradiance) (W/cm^2) and viewing angle (subtended angle). Retinal irradiance (W/cm^2) is the solar flux entering the eye and reaching the retina which is a function of irradiance at the cornea (front of eye). The subtended angle is the size of glare source divided by distance from the observer (9.3 mrad (milliradian) for sun). In case of PV, the subtended angle is the ratio of the distance between the observer and the PV array and glare size (size of glare from PV or frame). As the car (driver) moves with respect to the PV array, glare starts from a certain point and increases to its peak. With the change in position of the moving car the glare will decrease and disappear after some time (glare: zero to highest and highest to zero). Solar receivers produce more diffuse reflections with lower solar intensities but greater subtended angles. Therefore, the potential impact of different retinal irradiances is defined as a function of subtended angle and is dependent upon the distances. The glare impact commonly expressed as ocular hazard has three levels: 1) normal brightness, 2) potential of flash blindness, and 3) potential for permanent eye damage. The minimal retinal irradiance value that can cause flash blindness is 0.01 – 0.1 W/cm^2. The visual recovery times would be between 4-12 seconds depending on the solar irradiance (ranging from 7-11 W/m^2) at the eye (Clifford, 2010). Detail information on flash blindness potential is presented in Appendix E.

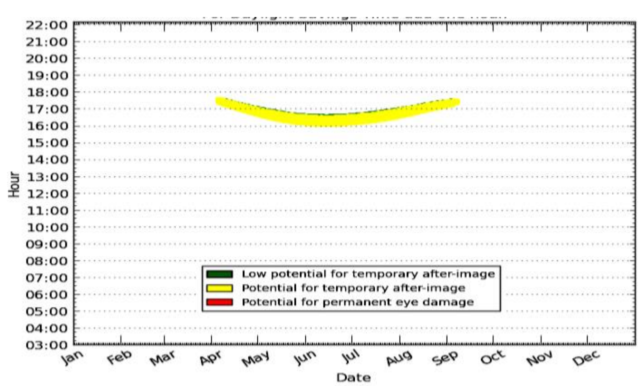
To estimate the amount of glare severity and occurrence time, a three dimensional geometrical model of the conceptual array system and site characteristics was created as shown in Figure 14.

Figure 14. Glare Occurrence Rendering of Site 1



As shown in Figure 14, the white color represents the glare from the panels to the driver. The south facing panels could create glare to motorists on I-70. To determine the time and duration of glare occurrence, a glare analysis was conducted using the Solar Glare Hazard Analysis Tool (SGHAT) (see Appendix E). The SGHAT employs an interactive Google Map where the user can locate a site, draw an outline of the proposed PV array and specify observer locations or paths. Latitude, longitude and elevation are automatically recorded through the Google interface, providing necessary information of sun position and distances. The results are presented in a plot that specifies the duration of glare occurrence with color codes indicating the level of ocular hazard. A series of observation points were selected along the road to estimate the amount of glare to a driver passing by. Intensity and duration of the glare from one of the observation points is shown in Figure 15.

Figure 15. Glare Analysis Result for Observation Point G (or 8)



As shown in Figure 15, hours of the day are on the y-axis and months of a year are on the x-axis. The yellow highlighted area represents the presence of glare with a potential for temporary after image. Glare is predicted to be visible from G (Figure 13) during the evenings (4:00-6:00 PM) from April to September for 40-60 minutes duration. The glare is visible from the 3,600 foot road segment; for an individual driver driving at a speed of 75 mph it takes 33 seconds to travel this distance. This is a very long exposure duration compared to the 0.15-second standard used in the ocular hazard analysis.

Another observation point displays similar glare in the morning hours (see Appendix F). This analysis suggests that the site has a potential of glare impacts to drivers heading east during the morning hours and heading west during the evening hours of the day.

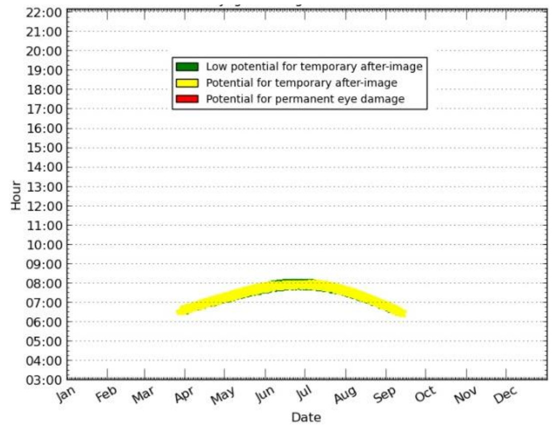
Modeling of an Existing PV Array

<u>Site-2: Community-owned solar array south of Colorado Springs (I-25 Mile point 134.5)</u>

This project study area is located south of Colorado Springs, Colorado at mile post 134.5 near I-25 ROW on the east side of the interstate. The site is next to a power substation in a wide land space near the ROW. The site with a model of array orientation is shown in Figure 16 and resulting glares in Figure 17.

Figure 16. Observation Points of Glare Analysis

Figure 17. Glare Occurrence Plot



Yellow color code in glare occurance plot in Figure 17 suggests presence of glare from I-25 (from observation point 3 beside the array) from the month of April to September. It is noteworthy that all observation points (1, 2,3) receive glare, but based on the road direction, the driver's direct view does not align with the observation direction used in this analysis. Drivers normally concentrate on the road, and the glare away from the direct view might have minimal impact. Rendering of possible glare on the panel surface is shown in Figure 18.

Figure 18. Glare Rendering

5.4.2 Snow Drifting Analysis

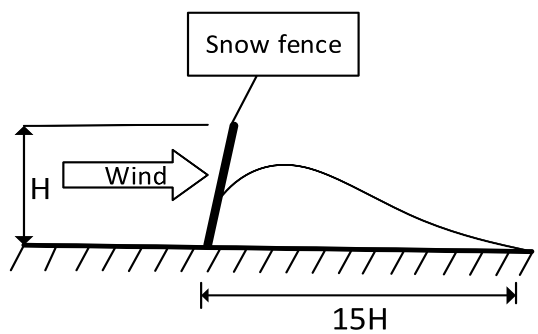
Colorado receives multiple snow storms during the winter months every year. Snowy road condition is a major concern for winter road maintenance. The I-70 and I-76 corridors are very susceptible to high winds and snow drifting during the winter and spring months; highway closures are not uncommon along these corridors. Additions of solar arrays could accelerate or slow down snow deposition on the road. Any additional snow deposition caused by a PV array is undesirable for driver safety and road maintenance.

A model for snow drifting and the potential of snow accumulation on the highway is proposed by Tabler (Tabler, 1994b). In Colorado (eastern plains) wider diurnal temperatures melt snow away and reduces the probability of snow accumulation from one storm to the next. The following equation could be used to locate setback distance (distance of the fence from the edge of the road) based on the height of the snow fence to stop the snow drifting to the road.

$$\boldsymbol{S = 15H} \qquad \text{Equation 1}$$

As shown in equation 1, H is the height of the snow fence and S is the setback distance for snow accumulation (fetch distance) from the fence. A schematic of snow deposition pattern in a snow fence is shown in Figure 19.

Figure 19. First Stage of Snow Drifting



As shown in Figure 19, most of the snow accumulates within a few feet of the fence and slowly trails off. Depending upon the height of the fence and its distance from the road, the amount of snow that reaches the road could be determined. For example, if a solar panel support structure has a height of 10 feet the fetch distance (S) is 150 feet assuming the panel will act as a snow fence (having a porosity of 0.5). For Site-1 as described previously with a ROW width of 328 ft., there is enough space to install the panels away from the required fetch distance of 150 ft. to settle down the snow. This suggests that if a PV array is installed at this site, it will not contribute to highway snow drifting. However, snow modeling of each potential site is necessary to understand the snow drifting behavior of that location.

CHAPTER 6. MITIGATION ANALYSIS

Many studies have shown that PV arrays produce significant environmental impacts no greater than those produced by typical road projects or similar PV projects installed elsewhere. However, careful planning and mitigation strategies need to be devised to reduce undesirable consequences as the severity of incidents in the PV array is significantly higher in the ROW environment than in projects located in isolated areas. Siting criteria, selection process, and system placement are key mitigation measures.

6.1 Site Selection and Design Criteria Mitigation

Approximately one-third of vehicle crashes in the USA are attributed to roadway factors or roadway and human interaction. Almost 3% of vehicle crashes in the USA are attributed to roadway factors alone whereas almost 30% of accidents are attributed jointly to human and roadway factors (AASHTO, 2010). The existing problem of roadway and human interaction in accidents might be worsened by the presence of PV arrays along the road side. Distraction, glare, snow drift, road, and weather conditions are all factors that might contribute to an increase in vehicle crashes if PV arrays are installed along roads. This section discusses mitigation strategies applicable for the installation of PV arrays within the ROW to minimize any impact to driver safety, the road environment, and road maintenance and operations.

Solar arrays should be installed only in spacious ROWs that can accommodate a PV array while providing sufficient clear zone distance. A minimum of 30 feet of width on the ROW is desirable for the clear zone (AASHTO, 2011). If a solar array is installed within the clear zone, it should be located behind an existing guardrail structure. This provides the opportunity to install a PV array without changing the road dynamics. Guardrails should be placed according to AASHTO and CDOT requirements and specifications. In addition, the security fence should be designed to help absorb car collisions and prevent the panels and materials from entering the road due to high winds or extreme weather. The materials and color of the fence should be selected to match with the natural landscape.

Proper solar array siting is critical for preventing or significantly reducing the environmental, safety, operations, and maintenance impact of the solar array on the roadway. Location and installation criteria include but are not limited to orientation, layout, and support structure (see Table 2 for Solar Array Siting Criteria).

Land Topography

In the process of choosing a location to set up a ground-mounted PV array, the topography and size of the available land should be taken into consideration. A ground-mounted PV array should be installed on fixed land (less than 5% slope), and the project area should be consistent with land use planning. The project site should have southern exposure, and should not be located in areas within designated floodplains, wetland areas, or protected stream corridors. It is preferable to site a PV array close to an existing electrical grid to reduce the cost of electrical connections, transmission, and transmission-related trenching impacts. If possible, solar arrays should be placed on the downwind side of the roadway to avoid snow drift.

Orientation

In the northern hemisphere, PV modules are ideally oriented to the south. The tilt angle for the PV array can vary from 15-24 degrees based on the site location. A step structure is best for optimal performance with minimal shading. It is recommended that the arrays be set up parallel to an east-west highway and perpendicular to a north-south highway to avoid direct exposure of the PV array to drivers.

Panel Spacing

A well-designed solar array needs clear and unobstructed access to the sun rays from about 9 a.m. to 3 p.m. throughout the year. PV arrays are adversely affected by shading; even small shadows such as the shadow of a single branch of a leafless tree can significantly reduce the output power of a solar module. It is also recommended that the PV site be kept free of vegetation to avoid any kind of attraction (food, nest, etc.) for animals. Array spacing using a proper packing factor, the ratio of available space to used space (1.5 to 2.5 is recommended), between the array groups and string rows helps in reducing shade and enhancing power generation, as well as providing easy access for maintenance and cleaning.

PV Structure

The PV support structure is another important design criterion. The PV support structures must be adequate to support the PV modules mounted on them; must be able to accommodate ice, snow, and wind loads; and must have the capacity to withstand the temperatures to which they are exposed. During installation, dissimilar metals (such as steel and aluminum) should be isolated from one another using non-conductive shims, washers, and other methods. Corrosion resistant aluminum is a recommended material for support structures; however, aluminum should not be in direct contact with concrete due to corrosion potential. Hot dip galvanized steel, paint, or coated steel support material could be considered in low corrosive environments. Breakaway type support structures should be used for the rows closest to the roadway to minimize the impact of potential vehicle collisions with the PV array.

6.2 Safety Impact Mitigation

Glare and Distraction

In the State of Massachusetts, placing signage along the road to warn the traveling public about an upcoming solar array was identified as a plausible solution for reducing the distraction impact of PV array sites.

However, there have been no research studies that confirm that the existence of solar arrays along the ROW causes significant driver distraction.

Temporary blindness or impaired vision due to glare from the panels and support structures could be avoided by using low reflective panels and orienting the panels in such a way that the reflected light will not interfere with drivers' vision. Anti-reflective coatings, glass texturing, blinds, and screens are some of the methods used by PV panel manufacturers to reduce light reflection from the PV array surface. Textured glass and antireflective coatings can reduce the near-normal specular reflectance of PV modules to ~1 to 2 percent. The reduced reflectance and the increased scatter of the reflected beam can reduce the retinal irradiance and potential for ocular hazards. Proper design and siting might be effective in mitigating solar glare issues; with consideration of the array's size, orientation, optical properties and location relative to key observation points. To assist with proper design and siting, solar developers have tools which could be used to model and approximate glare and ocular hazards. For example, SGHAT is web-based software that analyzes the intensity of glare in a specified location. TRIVIUM is another software tool used in similar applications in Europe.

Snow Drift and Deposition

In order to mitigate the impact of snow drift, it is important to avoid placement of a PV array system in areas susceptible to high snow drift, or the array system should be installed on the leeward side of the roadway whenever possible. Snow fences have been used over the years to mitigate snow drift problems; however, it is important to consider the setback distance from the highway, orientation, height and porosity of the snow fence. From research conducted by the Strategic Highway Research Program (Tabler, 1991) on snow management, snow fences too close to the highway can increase the amount of snow deposited on the road. During winter, in snowy conditions, snow tends to accumulate on the leeward side of the snow fence. At the first stage of snow drift, snow is deposited to a distance 15 times the height of the snow fence. When the drift builds up, snow accumulates to a distance of 20 times the height of the snow fence; then the wind profile becomes smooth until it gets to about 35 times the height of the snow fence. However, a distance of 15 times the height of the array fence (15H) could be used to locate the outer boundary of the PV array system if the snow accumulated during the first storm cycle on the downwind side of the fence melts away before the next storm and so on. The combined effect of the boundary snow fence and the solar array structure might be effective in reducing snow drift. Two types of fences are commonly used: live (rows of corn, tree, etc.) and mechanical (man-made structures of wood, steel or plastic).

Wind velocity is another determining factor for potential snow transport direction. For the common north-north west (NNW) wind direction in the eastern plains of Colorado, the prevailing snow transport direction was calculated to be 233° azimuth (measured from north) for the site used in this study (mile post 358.2, I-70 Limon, Colorado). This suggests that the snow drift is in the same direction as the predominant wind direction. Site-specific information and personal knowledge from CDOT maintenance personnel could be used by the energy provider to conduct detailed quantitative analysis and mitigation.

Solar Array-Vehicle Collisions

The solar array structural framework is considered a roadside obstacle that presents a potential risk to drivers. It is possible that a car could lose control, go past the shoulder area, enter the Clear Zone, and then crash into the solar array structure. A solar array presents a significant risk to drivers on a 70-75 mph speed limit road.

There are several mitigating approaches that can address this safety concern and reduce the potential impact. The AAHSTO has established guidelines and engineering strategies to address roadside obstacles for culverts, inlets and trees that are applicable to solar array frameworks (AASHTO, 2011). A barrier on the roadside is itself an obstacle which might be hit; therefore, a barrier should only be installed when it is clear that the result of a vehicle striking the barrier will be less severe than the result of that vehicle hitting the unshielded object (the solar array framework). The optimal solution for barrier type protection becomes less evident as the distance between the obstruction and the roadway increases.

The AASHTO Roadside Design Guide (4th Edition, 2011) identifies several strategies that allow planners to avoid fixed obstacles in the ROW and within the Clear Zone Area. These strategies include using flexible barrier systems that include the following:

Low-tension cables use a combination of low cable tension and weak posts to redirect impacting vehicles and produce large deflections. Advantages of low-tension cable include low cost, effective vehicle containment and redirection over a wide range of vehicle sizes. The open cable design is advantageous in the wintertime because snow drift and deposition is minimized. Depending upon the ROW conditions, high-tension cable that is normally used in medians can be used to protect solar array structures. It is possible that the tension cable systems can be placed within the Clear Zone area to maintain driver expectations, which reduces driver shy-line offset that results in driver slowing or lane changes due to unexpected visual conditions.

Existing guardrails could be used to guard the solar array from driver impact. The solar array framework could be located behind existing guardrails that are protecting other obstacles such as ditches, box culverts, etc. However, it is possible that existing guardrails are not long enough to protect drivers from a long array system or they are protecting areas like ravines that could not accommodate a solar array.

Breakaway solar array frames and security fencing could be used to protect drivers much like light pole designs do. No research could be found about design criteria or specifications for breakaway solar array frames. This is a potential area for future ROW research.

W-Beam and modified W-Beam guardrails (weak post) could be constructed within the clear zone or near the edge of the traveled way. These guardrails have posts that are very weak and are spaced far apart. This results in large lateral deflections and redirection of vehicles.

Ironwood aesthetic guardrails use the weak post concept. Wooden timbers are used as cross beams to provide an aesthetic look.

There are other barrier types of approaches to shield arrays from errant vehicles. Crash cushions like those normally used at the ends of median barriers could be installed. Berms could be constructed to shield and divert vehicles away from array structures.

The major factors that should be considered for the placement of barriers include the following:

- Lateral offset from the edge of traveled way
- Barrier to obstacle separation
- Terrain effects
- Flare rate
- Length of need
- Grading for terminals
- Aesthetics
- Cost

It is recommended that the energy provider work closely with the CDOT Safety Engineers in the selection and placement of barriers within the ROW and clear zone.

6.3 Road Maintenance and Operation Mitigation

Solar array installation on the ROW might impact the operation and maintenance of the highway. Array systems can affect the normal depositional patterns of snow and increase the buildup of ice and snow on the roadway. Array systems might also interfere with normal mowing operations within the ROW. In some locations tumbleweed accumulation along the array security fence will affect ROW aesthetics, potentially affect array performance and require frequent removal.

It is recognized that mechanical mowing operations would be potentially impacted from the placement of the solar array and the associated security fencing. Large mowing operations would not be able to mow close to the security fencing, which would allow weeds to grow and proliferate.

To address the mowing impact, the energy provider should be responsible for mowing within and just outside of the solar array security fencing. The energy provider will need to coordinate with CDOT ROW and Maintenance representatives to perform mowing activities and coordinate ROW access.

The energy contractor should also be responsible for the control of noxious weeds. Noxious weed growth can be initiated by ground disturbance associated with construction sites or may grow under arrays over time. It is recommended that the energy contractor be responsible for monitoring and controlling noxious weeds according to the CDOT Noxious Weed Plan.

6.4 Environmental Impact Mitigation

Solar PV projects along the CDOT ROW will probably have an environmental impact similar to that of other PVs deployed with other DOTs where the NEPA process has been followed for impact evaluation. Under an NEPA impact and mitigation approach, environmental areas of interest will include biological resources, endangered species, wetland and water quality issues, noise, visual and aesthetic considerations, socioeconomics, geotechnical concerns, air quality, and archaeological, historical, and cultural resources. Applicable state and local land use regulations as well as hazardous material content and handling need to be considered. The following section discusses the environmental impact and mitigation strategies for the deployment of PV arrays along the highway ROW. Table 2 (Appendix A) contains a Solar Array Impact and Mitigation table that identifies risk factors, potential impact, and mitigation actions through administrative, design criteria and siting actions.

6.5 Risk-Based Impact Analysis

In order to determine the total risk imposed by a factor, the severity (threat) of possible accidents and the likelihood of such incidents must be taken into account. A mathematical model called the Risk-Based Impact Matrix (Impact Matrix) was developed for the project by incorporating risk factors, severity, and probability of occurrence. This risk-based approach was adopted from the basic Failure Mode and Affect Analysis methodology (American Society of Quality, 2014).

The Impact Matrix uses the quantifiable measurement of various ROW factors that are potentially impacted by the PV array within and outside the ROW. Risk factors are identified based on research literature, field study, and expert opinion. Impact is assessed in terms of its effect on driver safety, environmental losses, ROW operations and maintenance, and the surrounding community or organization.

The severity of a risk factor is determined based on its harmfulness to the receptor. To choose the most appropriate domain for the identified risk, the severity of risk used for the project is assessed on a scale of 1 to 10 and is used to develop an impact score, which is expressed as follows:

$$\boldsymbol{Severity} = \begin{bmatrix} \mathbf{10} \quad (\boldsymbol{fatal}) \\ \mathbf{8}\ (\boldsymbol{permanent\ damage}) \\ \mathbf{4}\ (\boldsymbol{temporary\ damage}) \\ \mathbf{1} \quad (\boldsymbol{unnoticeable}) \end{bmatrix} \qquad \textbf{Equation 2}$$

As shown in Equation 2, the severity factors range from 1-10; within a safety context, a severity level of 2 is nearly unnoticeable, and a severity of 10 is fatal, including personal death or irreparable damage to the ecosystem. Numbers between 8 and 4 represent unrecoverable injury (permanent damage) and recoverable bodily injury (temporary damage), respectively. If any factors impose a severity of 8 or higher, a mitigation measure should be considered.

The frequency of harmful incidents expressed as probability of occurrence is another risk-assessment criterion. As shown in Equation 3, the probability of an occurrence is determined based on the number of possible incidents within 25 years, which is the life cycle of a typical PV array.

$$\boldsymbol{Probability\ of\ occurrence} = \frac{\boldsymbol{Total\ \ number\ of\ incident\ hours}}{\boldsymbol{Total\ project\ life\ (hours)}}\ \boldsymbol{x10} \qquad \textbf{Equation 3}$$

Probability of occurrence is given in a range from 1-10; a value is determined based on quantitative probability when data is available, or best professional judgment when data is scarce. It is essentially the probability that a given event may occur within a given timeframe. For example, the overall project life of the solar array is assumed to be 25 years. If glare is detected 3 hours every day for two months a year, (3 hours x 30 days x 2 months x 25 years/213,600 hours) the resulting probability of occurrence of is 0.2. Mathematically, 0.2 on a scale of 10 is a relatively small number, but if the glare were to cause vehicle collisions 2 percent of the time, the impact could be severe, considering the volume of cars on the road. Thus professional judgment should be used when evaluating the probability of incident occurrence and the DOT's goal of reducing incidents (based on statistics) should be considered.

Some risk factors are time-sensitive (time of day, seasonal, etc.); others are constant throughout the year. For non-time sensitive factors, which are either critical by nature or mandated by law, a very high probability of occurrence needs to be assigned.

Incident severity and probability of occurrence are used in the Impact Matrix to calculate the Total Risk Score of a given risk factor. As shown in Equation 4, the total risk score is the product of the severity and probability of occurrence. The product of the two variables represents the potential cascading effects of a risk factor and also provides a basis for comparison.

$$\boldsymbol{Total\ Risk\ Score = Severity * Probability\ of\ Occurrence}\ (\%) \qquad \textbf{Equation 4}$$

Depending on the Total Risk Score, a greater or lesser degree of action must be taken to mitigate each risk factor. Table 1 shows Total Risk Score, associated risk level, and a description of recommended actions. Typical mitigation approaches recommended by the CSU-P Team are based on literature assessments, engineering best practices, field studies, CDOT interviews, and computer models.

Table 1. Total Risk Score and General Recommendations

Total Risk Score	Risk Level	Recommendation
80-100	Danger	Avoid the site or significant mitigation action
50-80	High Threat	Mitigation action or detailed planning should be included to avoid a catastrophe event.
10-50	Medium Threat	Mitigation measures should potentially be included into the PV array design plans.
1-10	Low Threat	Limited mitigation action

As mentioned earlier, Total Risk Score values are calculated by finding the product of the severity and probability of occurrence of an incident caused by an individual factor. The range of Total Risk is from 1 to 100, with 1 being the lowest. Total Risk in the range of 1 to 10 is considered insignificantly low; 10 to 50 is considered moderate risk; 50 to 80 is considered high potential risk; and 80-100 is significant risk. Risk factors having a total score between 50 and 80 should be addressed with mitigating measures while factors having total risk scores higher than 80 might force the moving of the site or the development of a comprehensive mitigation measure. An Impact Matrix with a list of risk factors and their potential impact is given in (Appendix A) to identify, quantify and compare potential risks. The Impact Matrix Table can be used as a site-specific tool for ROW solar array assessment that provides a generalized risk evaluation of the safety, operation and maintenance, and environmental risk factors.

Based on the risk analysis of model areas along I-70, I-76 and I-25 using the Impact Matrix the following major risk factors associated with construction and operation of solar arrays in the DOT ROW have been identified:

- Snow drift and deposition
- Glare/glint from solar panels
- Water quality management (construction and post construction)
- Noxious weed control
- Driver safety associated with solar array structure collisions
- Driver awareness and expectation
- Access permitting and safety during solar array maintenance
- Wildlife attraction, migration and habitat
- Grass mowing operations
- Snowplow blast during snow removal operations

Some of the factors are inter-related, and others can cause multiple problems. For example, drifting snow may cause maintenance problems and also pose a threat to drivers. A systematic process analyzing the impact of major risk factors will guide the site selection process and enable planners to select appropriate mitigation measures. Mitigation strategies to address these high risk factors can be found in Table 2 (Appendix A).

In the Impact Matrix, risk factors are quantified, which will allow CDOT to move beyond vague, general statements and base impact conclusions on credible numbers. During the decision making process this will help to determine the optimal trade-off between risk factors and the impact of mitigation. The Matrix could also be used when comparing the economic benefits of a project with impact and mitigation costs (safety, maintenance, and environment). This Risk Impact Matrix is an important tool that will aid CDOT in managing their ROW when a solar array is constructed and maintained. Table 3 and Figure 1 in Appendix A provide a working example of an Impact Matrix and a Flow Process Diagram that identifies potential impact and mitigation strategies for several risk factors.

6.6 Solar Array Site Selection and Evaluation Process

Planners developing solar arrays must take into consideration the requirements of site-related safety and PV technology in addition to environmental and operational factors. Although economic considerations are important for site selection, available space and impact factors should also be used in the site selection process to identify high risk factors and mitigate the impact of the system. The most effective approach for impact mitigation is the proper siting of the solar array. The following are major CDOT ROW site location factors that need to be considered by the energy provider:

- Evaluate the capacity of solar energy generation from a proposed site in order to estimate the available scale of a ROW solar array and analyze the impact of the system based on an estimated scale. CDOT's Road Map (Kreminski et al., 2011) and the NREL PVWatts software can be used to locate the site and calculate the energy potential and scale of the proposed project (NREL); this software was used in this study.
- Consider geographical parameters related to energy production that are included in the site evaluation process listed in Table 2 below.
- Model the site for analysis using computer-aided design (CAD) software.

To take into account the various solar array design requirements and environmental, safety, and operational demands, a list of siting criteria was developed and presented in Table 2. One of the most efficient ways to identify potential locations is to use a Geographic Information System analysis. CDOT possesses numerous types of data layers that can aid in initial siting; however, ROW boundary data is not currently available electronically. Criteria associated with permitting, site-specific considerations, and preliminary site selection screening are also needed. This is an important tool that can be used by CDOT and the energy provider in selecting optimal locations within the ROW.

Table 2. Solar Array Siting Criteria

Siting Criteria
Project must be in CDOT-owned right of way
Area available beyond clear zone at least 30 ft. from edge of travel lane shoulders
Project site is vacant or undeveloped coordinate respective agencies for existing underground utilities (if any)
Project site is at least 5 acres
Project area has 24/7 year round access from paved or gravel roadway
Project area within 1/2 mile of existing electricity grid
Project site has less than 5% slope
Project site has southern exposure
Project site is not within designated floodplains, wetland areas or protected stream corridors
Project area is not within or adjacent to threatened and endangered species flora or fauna
Project area is not within designated local, state or federal scenic corridors or protected view sheds
Project area is within the Statewide Transportation Improvement Program
Project area is consistent with land use planning
Project area is not within or adjacent to public parks or recreational areas (safety and vandalism) check with other related institutions if they are interested and coordinate accordingly
Permitting and Site Specific Criteria Considerations
Coordinate with CDOT Regions for NEPA requirements (Form 128 Categorical Exclusion depends on the size, or permitting) procedure will depend whether airspace lease or UAP is being pursued

Ensure that project area does not have known cultural or historical artifacts
Perform Total Solar Resource Fraction Analysis (has at least 95% total solar resource fraction)
Perform view shed analysis
Develop Stormwater Management Plan and Construction Stormwater Permit (greater that one acre)
Develop permanent Stormwater Best Management Practice
Perform Utility Connection Assessment
Perform Threatened and Endangered Species Assessment
Perform Cultural and Archaeological Resource Assessment
Identify local government permitting
Conduct public outreach and education
Evaluate temporary construction noise impact (residential areas)
Evaluate overall project site, utility and road access available to project for duration of use/agreement
Survey if the project site has 3-phase power or capability
Has fiber optic connectivity for security and data transmission
Does not conflict with future transportation planning (25 years)
Analyze slopes and soils for Geotechnical feasibility
perform Residential Glint/Glare Analysis
perform Driver Glint/Glare Analysis
make sure project does not disproportionately impact minority or low income populations
Preliminary Site Screening Criteria
Solar energy generation potential
Current and future land uses or transportation uses
Land requirements (3.5 acres per megawatt generation)
Access to the electric grid
Access and safety
Threatened and Endangered Species Habitat
Sensitive Wetlands and Surface Water Systems
Project area does not have known hazardous materials or waste via an Initial Site Assessment (ISA), ISA, Phase I, and/or Phase II Hazardous Waste Assessment

6.7 Solar Array Development

The development of a solar array involves an understanding of the impact of the array on highway safety, operations, maintenance, and environmental resources. It also involves an understanding of the required sequence of events that are driven by CDOT policy, management expectations, and federal regulations. Table 3 provides a sequence of actions that will aid CDOT and energy providers in the coordination and eventual implementation of solar arrays in the ROW.

Table 3. Sequence of Coordination Actions for Solar Array Implementation on ROW

1. Contact Primary CDOT Representatives Right of Way Manager Alternative Energy Coordinator (once designated)

2. Review Solar Impact Guidance Document/Report
    - Review siting criteria
    - Review potential impacts and mitigation strategies
3. Identify and visit potential sites for initial feasibility study
    - Communication with CDOT
    - Coordinate with ROW for access permit
4. Identify potential impacts, mitigation strategies and overall site risk
5. Identify ROW permit strategy
    - Air Lease
    - Utility
    - Other
6. Coordinate meeting(s) with CDOT representatives to gain project acceptance
    - Safety
    - Operation and Maintenance
    - Environmental
    - Geotechnical
    - Right of Way Management
    - Alternative Energy Coordinator
    - FHWA (as necessary according to permit)
7. Coordinate NEPA Analysis with CDOT and FHWA
    - Obtain approved Categorical Exclusion as required
8. Coordinate with CDOT on Draft/Final Designs
    - Obtain CDOT approval
9. Develop Construction Plan and Schedule
    - Geotechnical studies
    - Obtain CDOT approval
    - Develop operations and management plan
    - Develop system decommissioning plan
10. Construct Solar Array
    - Coordinate with ROW Management
    - Traffic Operations Management Plan
    - Environmental and Stormwater Management and permitting
    - Mitigation development
11. Maintain Solar Array
    - Coordinate with ROW Management for Access Permits
    - Monitor system performance and security
    - Vegetation and Stormwater management
12. Decommission Solar Array
    - ROW Management Coordination
13. Recycle solar array

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

It is possible to use the ROW for solar energy development with minimal safety, maintenance and environmental impact. State DOTs and private toll way authorities have been leasing ROW areas to energy providers to generate electricity, offset carbon footprints, and obtain financial resources through long-term lease agreements. The use of ROW for solar energy generation has been used extensively in Europe for the past 30 years.

Currently, no general guidance document is available for DOTs who are considering using their ROWs for solar energy generation using ground-mounted solar arrays, although some DOTs and private owners have installed PV arrays near the road using a special approval process.

Highway ROW areas have physical and topographical characteristics that complement the generation of solar energy for the following reasons: 1) vegetation is well maintained by operation and maintenance professionals, 2) there is easy access to the area, 3) roads generally follow electrical utility lines, 4) there is a general absence of trees or objects that can obscure sunlight and 5) there is an abundance of non-developed land in both rural and urban areas. However, the total solar capacity of ROWs might be much less than the one presented in the previous studies.

Concerns of different functional groups within CDOT were discussed and areas of potential impact associated with using ROWs for energy generation were identified. Most areas of impact are not significant, and a few of them can be mitigated through proper project siting, administrative controls, proper design criteria, ROW management controls, and engineering controls. The major potential areas of impact identified in this research study are as follows:

- Snow drift and deposition
- Glare/glint from solar panels
- Water quality management (construction and post construction)
- Noxious weed control
- Driver safety associated with solar array structure collisions
- Driver awareness and expectation
- Access permitting and safety during solar array maintenance
- Wildlife attraction, migration, and habitat
- Grass mowing operations
- Snowplow blast during snow removal operations

An Impact Matrix was developed to quantitatively assess the impact of different factors. In addition, several decision-making tools that can be used by CDOT and energy providers who wish to develop a solar array on DOT ROWs were provided. These tools include the following:

- Glint and Glare Hazard Models
- Solar Array Siting Criteria
- Solar Array Impact and Mitigation
- Sequence of CDOT Coordination Actions

7.2 Recommendations

This research report provides guidance for CDOT and other DOTs to use their ROWs for solar energy development. It is recommended that this report be provided to all CDOT representatives who are decision makers in allowing solar arrays to be constructed and maintained within the ROWs. The following CDOT representatives should use this as a main reference document:

Environmental Management-This report should be a main reference to environmental professionals who will need to coordinate an environmental analysis according to CDOT NEPA procedures and federal regulations. The report will provide CDOT a list of environmental criteria that must be evaluated by an energy provider.

Safety Engineering-Engineering controls necessary to address driver safety concerns are provided for reference. Proper solar array siting, orientation and location within the Clear Zone are critical to highway safety.

Highway Maintenance-Highway operation and maintenance impact and mitigation strategies are provided for mowing operations and winter road maintenance. Snow drift and deposition concerns are addressed in the report.

ROW Management-This report will provide a broad overview of the impact associated with all solar energy development activities within the ROW. This report will be a main reference for ROW management statewide and will provide the information necessary for CDOT officials to ask the right questions and ask for the right feasibility studies prior to solar array design, construction and maintenance.

It is recommended that CDOT explore the use of ROWs for solar energy development. The ROW represents a resource that can provide CDOT financial revenue by leasing ROWs to energy providers or using the solar energy to power maintenance facilities, rest areas, and light interchanges. CDOT could decide to use the generated solar energy to reduce their carbon footprint by using carbon offsets. This approach would be consistent with the State of Colorado's Climate Action Plan.

It is recommended that this final report be submitted to FHWA and AASHTO in order to establish a framework for a DOT Solar Array Guidance Document or a Standard Operating Procedure. This standardization in how to effectively and efficiently use highway ROWs for solar energy generation will set the stage to reduce greenhouse gas emissions and create potential carbon offset approaches nationwide.

7.3 Future Study

In the Impact Matrix, the probability of occurrences and severity scales are still estimates. The probability of occurrence is based on time and distance of the system from the road as well as probability of similar incidents recorded in the existing literature.

Severity is based on professional best guess in reference to existing incidents. To improve the matrix and produce more precise scores a physical experimental study or simulation in a virtual model could be performed in the future. Data collected from these experiments after simulating risk factors will reliably quantify their severity and enable the creation of a more specific model.

During the field study, it was found that some of the spaces identified as potential solar resource areas in the previous studies (Kreminski et al., 2011) did not have suitable topography and land space. To determine the practical solar capacity considering allowable clear zone, road orientation, wind and snow drift direction and factors sensitive to environmental and archeological concerns, a review study needs to be performed.

The model referenced for snow drift analysis in this study does not encompass the semi-arid climatic conditions of Colorado and may not reflect the true results. For example, the snow accumulation is based on the snow season, which is based on the average temperature of the region. With a significant diurnal temperature difference in Colorado, the average temperature might not be effective to address the day/night temperature variations. For a more reliable snow drift model, experiments need to be conducted locally to account for dominant factors such as wind direction, road orientation, temperature variability, average snow accumulation, etc.

In summary, recommended topics for additional study are as follows:

- Snow drift modeling
- Driver awareness studies, urban public awareness and acceptance studies
- Solar panel utilization for noise walls
- GIS study to identify optimum locations for PV arrays statewide

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Appendix A: Guidance for ROW Solar Array Placement Operations and Maintenance

1.0 Introduction

The purpose of this guidance document is to provide CDOT representatives and energy providers a concise, easy to follow reference on potential areas of impact to consider when planning the placement of a solar array in the CDOT right-of-way (ROW). Currently there are no CDOT or national FHWA guidelines or standard operating procedures regarding identification of areas of impact and development of mitigation strategies to address these areas.

This research report provides guidance for CDOT and other DOTs to follow when using their ROWs for solar energy development. It is recommended that this report be provided to all CDOT representatives who are decision makers regarding the construction and maintenance of solar arrays within the ROW. The following CDOT representatives should use this guidance document and the mail research report as a main reference document for solar array implementation:

- Environmental Management-This report should be a main reference to environmental professionals who will need to coordinate an environmental analysis according to CDOT NEPA procedures and federal regulations. The report provides CDOT with a list of environmental criteria that must be evaluated by an energy provider prior to implementation of a solar array within the ROW.
- Safety Engineering-Engineering controls necessary to address driver safety concerns are provided for reference. Proper solar array siting, orientation and location within the clear zone are critical to highway safety.
- Highway Maintenance- Highway operation and maintenance impact and mitigation strategies are provided for mowing operations and winter road maintenance. Snow drifting and deposition concerns are addressed in the report.
- ROW Management- This report will provide a broad overview of the impact associated with all solar energy development activities within the ROW. This report will be a main reference for ROW management statewide and will provide the information necessary for CDOT officials to ask the right questions and ask for the right feasibility studies prior to solar array design, construction and maintenance.

The guidance document will aid in the development of efficient array location and feasibility studies, NEPA environmental studies, solar array design and maintenance, and decommission activities. This guidance document is intended to provide CDOT and the energy providers information for consideration and is not formal CDOT policy at this time. This guidance document contains the following tools and tables:

- Solar Array Siting Criteria
- Solar Array Risk Impact Matrix
- Solar Array Impact and Mitigation Table
- Sequence of Coordination Actions for Solar Array Implementation on CDOT ROW

2.0 Solar Array Siting Criteria

Planners developing solar arrays must take into consideration the requirements of PV technology in addition to environmental, operational, and safety factors. Although economic considerations are important for site selection, available space and impact factors should also be used in the site selection process to identify high risk factors and mitigate the impact of the system. The most effective approach for impact mitigation is the proper siting of the solar array. The following are major CDOT ROW site location factors that need to be considered by the energy provider:

- The capacity of solar energy generation from a proposed site in order to estimate the available scale of the ROW solar array and evaluate the impact of the array based on an estimated scale.
- Geographical parameters related to energy production; The National Renewable Energy Laboratory's (NREL) PVWatts Software can be used as a tool to help locate potential sites and calculate the energy potential and scale of the project (NREL).

To take into account the various solar array design requirements and environmental, safety, and operational demands, a list of siting criteria was developed and presented in Table 1. One of the most efficient ways to identify potential locations is to use a Geographic Information System analysis. CDOT possesses numerous types of data layers that can aid in initial siting. Table 1 provides suggested criteria associated with GIS Siting, Permitting and Site Specific Considerations and Preliminary Site Selection Screening. This Table is an important tool that can be used by CDOT and the energy provider in selecting optimal locations within the CDOT ROW.

3.0 Solar Array Risk Impact Matrix

From the literature and field study it is clear that solar arrays offer tremendous benefits to energy developers and/or CDOT with some impact on driver safety, CDOT maintenance, and environmental resources. The Risk Impact Matrix (Table 16) was developed by the CSU-P Team to identify, quantify and compare potential risks. This Risk Impact Matrix will help CDOT to manage the ROW if and when a solar array is constructed and maintained within the ROW. The Risk Impact Matrix lists risk factors in the first column and provides a description of the potential CDOT impact of those risks in the second column. These risk factors were identified through a review of the literature and through conversations with professionals including CDOT representatives and solar array experts.

Total Risk - contains risk factor values that are calculated based on the product of severity and probability of occurrences of an individual factor (see below). The maximum range for total risk is 1-100 with 1 being the lowest total risk value. Total risk in the range of 1 to 10 is considered low to insignificant; 10 to 50 is considered moderate risk; 50 to 80 is considered significant risk requiring mitigation measures; 80 to 100 is high risk requiring comprehensive mitigation from the very beginning of project consideration through implementation.

Severity Factor - defines the severity of the potential human, operational, or environmental impact. The severity factors range from 1-10 in which one is unnoticeably small and insignificant and 10 represents a potential loss of human life or major impact to an environmentally sensitive area that may result in regulatory fines.

Probability of Occurrence - defines the probability of occurrence of a negative event based upon a qualitative range from 0-10. This factor is estimated based on quantitative probability when data is available and best professional judgment when data is scarce. It is essentially the probability that a given event may occur within a given timeframe. For example, the overall project life of the solar array is assumed to be 25 years. If glare is detected 3 hours every day for two months a year (3 hours x 30 day x 2 month x 25 years/213,600 hours) the resulting probability of occurrence of 0.2.

Some risk factors are time sensitive while others are not. For non-time sensitive factors, which are either critical by nature or are imposed by law, a very high probability of occurrence will be assigned based upon best professional judgment and information gained from research.

Table 1 is a Risk Impact Matrix that provides a generalized risk assessment for solar array implementation within a highway ROW. The risk assessment is based upon conversations with CDOT representatives and outside experts and information gained from a literature review. The severity factor and the probability of occurrence in this matrix is a mixture of best professional judgment and mathematical estimates based on available data. It is recognized that severity factors and probability of occurrence may differ based on CDOT regions and site conditions. This Risk Impact Matrix will give CDOT representatives and management, along with the energy provider, an idea of the risk factors that should be considered when installing solar arrays on highway ROW areas.

Table 1. General Risk Impact Matrix

Risk Factor	CDOT Potential Impacts	Total Risk Score	Severity Factor	Probability of Occurrence	CDOT Concern
Safety					
Glare and Glint	Sunlight reflecting off of the solar panels may affect driver safety along roadways by short periods of intense light impacting driver sight.				Yes
Driver Awareness	Solar array may catch the sudden attention of drivers along interstates and state highways. This change in driver expectation may be a safety issue.				Yes
Worker Safety	Construction and Operation & Maintenance representatives may be at risk when working within the right of way area or may create a potential risk to drivers/ visitors.				Yes
Collision Safety	Solar array can increase driver fatalities or injuries by the introduction of a new non-moveable structures within the Clear Zone Area.				Yes
Solar Array Structure Integrity	Solar array panels and overall structure could be damaged by high winds and materials may potentially enter the roadway area thus causing a safety issue.				Yes
Solar Array Security	Solar arrays may be attractive to theft within the right of way.				No

Risk Factor	CDOT Potential Impacts	Total Risk Score	Severity Factor	Probability of Occurrence	CDOT Concern
Fire Potential	Loss of electrical connection integrity could result in electrical arcing or other actions that could cause fire that could spread along the right of way and affect the safety of drivers.				No
Biting Insects	Stinging or biting insects may nest within the solar array structure.				No
Extreme Weather Conditions	Extreme weather conditions such as hail, high winds, tornados and lightening may impact solar array operations or require additional maintenance and right of way presence.				Yes
Solar Array Maintenance and Access	Solar array construction and maintenance vehicles that access the solar areas from the roadway shoulder may cause a safety concern to traffic and worker safety via parked equipment along the shoulder and right of way.				Yes
Operation and Maintenance					
Snow Drifting and Deposition	Solar array could affect existing snow drifting and depositional pattern conditions thus increasing ice and snow build up on the roadway.				Yes
Tumbleweed Accumulation	Tumbleweed accumulation along the array security fencing may impact right of way aesthetics and increase maintenance efforts for removal.				Yes
Chemical Deicing Agents	Magnesium chloride application onto the roadway may drift onto solar array panels and create rust and electrical connection problems. This would lead to increased solar array maintenance activities on the CDOT ROW.				Yes
Right of Way Mowing	Array system fencing will require an alteration in mowing operations outside the array fencing area, restricted mowing in the clear zone in some areas for habitat reasons, and maintenance concerns about mowing near security fencing.				Yes
Environmental					
Tree Removal	Tree removal from construction activities along the roadway can impact local wildlife, aesthetics, and carbon sequestration.				Yes
Threatened and Endangered Species (T&E)	Solar array construction, operation, and maintenance may disrupt T&E plant and animal species.				Yes
Wildlife Attraction	Solar array panels may provide shelter for birds and rodents and may attract large animals that could impact bird and animal migration.				Yes

Risk Factor	CDOT Potential Impacts	Total Risk Score	Severity Factor	Probability of Occurrence	CDOT Concern
Generation of Micro-Climate from Solar Collection	The collection of solar radiation can cause an increase in temperature in the surrounding area and create localized heating and micro-habitat changes.				No
Post Construction Stormwater Management	Concentrated stormwater flows due to rain and melting snow running off of solar array panels may cause localized erosion, damage to vegetation, and water quality problems.				Yes
Construction Stormwater Management	A CDPS Stormwater Permit is required from CDPHE and CDOT Erosion Control Specifications must be followed. Best management practices must be used to reduce soil erosion and sediment transport into surface waters.				Yes
Habitat Impact	Location of solar array may impact sensitive terrestrial environments such as short grass prairie ecosystems.				Yes
Prairie Dog Colonies	Construction of solar array can impact and disrupt prairie dog colonies, which are protected by municipalities and CDOT.				Yes
Noxious Weeds	Ground disruption may cause the introduction of noxious weeds that can create ecological and aesthetic issues.				Yes
National Environmental Policy Act Compliance	Large corridor type projects may require expensive and time-consuming environmental assessments (NEPA).				Yes
Natural Hazards	Placement of solar array on steep slopes or potential landslide areas may cause soil shifting and sloughing that may impact the right of way.				No
Hazardous Waste	Buried tanks of hazardous waste materials may be encountered during the construction of solar arrays and electrical system trenching.				No
Migratory Bird Treaty Act	Construction, operation and maintenance of solar arrays and associated electrical connection trenching may impact migratory birds according the Migratory Bird Treaty Act.				Yes
Right of Way Landowners Other than CDOT	Solar array placement may not be consistent with right of way owners' management plans or meet aesthetic criteria (e.g. US Forest Service).				Yes
Project Decommissioning and Site Restoration	The removal of the solar array after project completion can cause erosion and disrupt existing vegetation.				No

Risk Factor	CDOT Potential Impacts	Total Risk Score	Severity Factor	Probability of Occurrence	CDOT Concern
Glare (Including Solar Arrays on Land Adjacent to CDOT Right of Way)	Potential glare and glint may impact driver vision.				Yes

Table 2. Solar Array Impact and Mitigation Table

Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
Safety						
Glare and Glint	Sunlight reflecting off of the solar panels may affect drivers' eyesight.	Yes		Design	Maintain angle of panels at 18°- 40°. Use anti-reflective panels and dull polishing on structures.	Although solar panels are designed to absorb light as opposed to reflecting light, this study has shown glint/glare impacts from arrays on drivers. Mitigation required after site specific glare analysis.
				Siting	Place arrays that do not affect driver sight distance near curves or hill areas. Locate array system on the lee side of highway.	
Driver Awareness	Solar array may catch the sudden attention of drivers along highways. This change in driver expectation may be a safety issue.	Yes		Admin	Place signage along the road warning the traveling public about upcoming solar array.	CDOT Safety Engineers were concerned about this potential impact affecting safety; signage could be used to alert drivers about upcoming solar array.
Worker and Driver Safety	Construction, Operation & Maintenance representatives are at risk working within the ROW area or pose a risk to drivers/ visitors.	Yes		Admin	Prepare Site Safety and Health Plan and conduct tailgate safety meetings; reference CDOT Procedural Directive 80.1 or equivalent; develop Traffic Operation Management Plan for driver awareness and safety.	
Collision Safety	Solar array can increase driver fatalities or injuries by the introduction of a new non-moveable structure within the clear zone area.	Yes		Design	Guardrail placed according to AASHTO requirements; guardrail can be cable or solid aluminum. Incorporate berms to deflect oncoming vehicles from solar arrays. Solar arrays will be protected by chain link fencing for security purposes; design security fencing to absorb car collisions away from solar arrays.	Need to work with CDOT Safety Engineers about mitigation and design criteria to protect array and drivers. CDOT Safety Engineering Meeting; AASHTO
				Admin	The solar arrays' distance from the roadway could be increased beyond the 30 foot clear zone. Break away type materials that will maintain the structural integrity of the array system can be used.	
				Siting	Look for right of way areas with already existing guardrails, barriers or berms within the Clear Zone Area. Select areas with wide right of way areas that can accommodate the largest possible Clear Zone Area.	
Solar Array Structure Integrity	Solar array panels and overall structures could be damaged by high winds and materials may enter the	No		Design	Chain link security fencing designed to contain potential flying panels and materials.	Sacramento Municipal Utility District & Caltrans

Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
	roadway area, causing a safety issue.					
Solar Array Security	Solar arrays may be attractive to theft within the right of way.	No		Design	Chain link fencing should surround the solar array and be at least 8 ft. high with barbed or razor wire on top. The solar panels may be installed closer to the ground making access to the fasteners and wiring more difficult for thieves.	Oregon DOT used razor wire for security purposes without incidents. Mass DOT experienced the loss of solar panels from right of way due to theft. Personal Conversation with Oregon DOT and Mass DOT.
Fire Potential	Loss of electrical connection could result in arcing and cause fire along the ROW affecting safety of drivers.	No		Admin	Keep vegetation cut by mowing within and near security fencing.	Ensure wiring connections are insulated against arcing; check electrical connections during routine maintenance.
Biting Insects	Stinging or biting insects may nest within the solar array structure.	No		Admin	Incorporate insect bites into field safety plan.	Identified as an unexpected maintenance safety issue at ODOT. Personal conversation with ODOT.
				Design	Structures and open pipe in the solar array should be closed by welding or by covering with plastic lids that suit design criteria.	
Extreme Weather Conditions	Extreme weather conditions such as hail, high winds, tornados and lightening may impact solar array operations or require additional maintenance and right of way presence.	Yes		Admin	Prepare Site Safety and Health Plan and conduct tailgate safety meetings; reference CDOT Procedural Directive 80.1 or equivalent; develop Traffic Operation Management Plan for driver awareness and safety, if needed.	
				Design	Ensure solar array structure can support extreme wind loads from wind storms.	
Solar Array Maintenance and Access	Solar array construction and maintenance vehicles that access the solar areas from the roadway shoulder may cause a safety concern to traffic and worker safety via parked equipment along the shoulder and right of way.	Yes		Admin	The construction project will need to coordinate with CDOT Maintenance and ROW Representatives about traffic control procedures that include signage and perhaps cones. There may be time restrictions or lane closures. Determine if access is possible from adjacent frontage roads. Contractor will need to coordinate with Regional Right of Way permitting representatives to determine if a Traffic Control Plan is needed. Contractor should develop worker safety plan and follow CDOT safety directives.	
				Design	Design solar array that promote efficient maintenance actions	
Operation and Maintenance						

Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
Snow Drifting and Deposition	Solar array could affect existing snow drifting and depositional pattern conditions thus increasing ice and snow build up on the roadway.	Yes		Design	For a particular height of a snow fence the accumulated snow gets collected over a distance of 15 times the fence height. Only beyond this length should the system be located from the solar array's fence.	No increase in snow drifting or deposition has been noted on US 6, E-470 or Northwest Parkway due to solar arrays. No research; only observational from US 6, E-470 and Northwest Parkway, Oregon DOT.
				Siting	Place solar arrays on the leeward (downwind) side of the roadway. Avoid array placement in known high snow drifting area. Calculate array distance from roadway using snow mechanics calculations (reference).	
Tumbleweed Accumulation	Tumbleweed accumulation along the array security fencing may impact right of way aesthetics and increase maintenance efforts for removal.	Yes		Admin	Remove accumulated tumbleweed as part of routine right of way maintenance.	
Chemical Deicing Agents	Magnesium chloride application onto the roadway may drift onto solar array panels and create rust and electrical connection problems. This would lead to increased solar array maintenance activities on the CDOT ROW.	Yes		Design	Structural materials should be made of corrosive resistant stainless steel or other corrosive resistant materials. Electrical connections should be secure and covered with connectors to prevent deicing agent corrosion.	Noted at DIA that framework near the roadway was corroding. No magnesium chloride residues noted at Federal Center and Northwest Parkway.
Right of Way Mowing	Array system fencing will require an alteration in mowing operations outside the array fencing area, restricted mowing in the clear zone in some areas for habitat reasons, and maintenance concerns about mowing near security fencing.	Yes		Admin	Coordinate mowing expectation with CDOT right of way and maintenance representatives; mowing in clear zone is avoided 20 ft. from shoulder edge in short grass prairie ecosystems.	CDOT Maintenance mentioned that energy developer would need to mow around the array area and fencing although there are restrictions that need to be worked out. Ensure vegetation growth does not impact solar panel performance due to vegetative height.
Environmental						
Tree Removal	Tree removal from construction activities along the roadway can impact local	No		Admin	Mitigate trees at a 1:1 or 1:2 ratio according to CDOT specifications and/or CDOT Region policy.	CALTRANS

Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
	wildlife, aesthetics, and carbon sequestration.			Siting	Avoid placement of arrays in mature tree areas.	
Threatened and Endangered Species (T&E)	Solar array construction, operation, and maintenance may disrupt T&E plant and animal species.	Yes		Admin	Perform an initial assessment of the area to ensure avoidance of T&E species such as burrowing owls and sensitive plant species; coordinate with CDOT Wildlife representatives and NEPA Coordinator.	Coordinate with regional representatives to avoid sensitive ecosystems when siting array system. Northwest Parkway, Oregon DOT
				Siting	Avoid placement of solar arrays in known T&E areas.	
Wildlife Attraction	Solar array panels may provide shelter for birds and rodents and may attract large animals. This might impact bird and animal migration.	Yes		Design	Construct security fencing to discourage large animal sheltering.	Discussions with other solar operators have not experienced bird, rodent or large animal problems and impacts.
				Siting	Avoid placing solar arrays in known animal migration routes; review road kill database to identify potential migration routes.	
Generation of Micro-Climate from Solar Collection	The collection of solar radiation can cause an increase in temperature in the surrounding area and create localized heating and micro-habitat changes.	No		Siting	Locate solar array away from sensitive vegetation and wildlife.	Not expected to be a concern in a CDOT ROW; more appropriate for large scale solar array.
Construction Erosion Control	Soil disruption from solar array construction, cable trenching, and substation establishment may cause sediment to enter local surface water systems.	Yes		Admin	Develop Stormwater Management Plan according to CDOT specifications and obtain CDPHE Construction Stormwater Management Permit.	Stormwater quality management is a very sensitive compliance issue for CDOT. CDOT Specifications; CDPHE Stormwater Regulations.
				Design	Design solar array with the smallest possible disruption footprint. Use CDOT approved erosion control best management practices (BMPs) during construction. Re-vegetation plan and associated BMPs must be developed and implemented; height of solar array should allow sunlight to reach underlying vegetation	
				Siting	Avoid array placement within 100 ft. from surface water systems.	
Post Construction Stormwater Management	Concentrated stormwater flows due to rain and melting snow running off of solar array panels may cause localized erosion, damage to vegetation, and water quality problems.	Yes		Admin	Manage concentrated flows coming off solar panel surfaces to avoid erosion. Established native vegetation under solar array panels to prevent erosion and soil transport; promote use of runoff infiltration practices, rock berms or native vegetative BMPs; routine maintenance must be performed BMPs	Assumed that contractor will be required to perform the BMP maintenance within CDOT right of way

Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
				Design	Use vegetation, erosion control matting, gravel material and/or vegetation to prevent soil erosion and transport. Designs should incorporate CDOT approved best management practices.	
Habitat Impact	Location of solar array may impact sensitive terrestrial environments such as short grass prairie ecosystems.	Yes		Siting	Avoid sensitive ecosystems when siting array systems; anticipate potential mitigation banking requirements and potential costs.	Coordinate with regional representatives to avoid or mitigate sensitive ecosystems when siting array systems.
Prairie Dog Colonies	Construction of array systems can impact and disrupt prairie dog colonies.	No		Admin	May need to notify and obtain permit from local municipality and follow CDOT prairie dog guidance.	Regulatory issue with sensitivity in certain municipalities. Northwest Parkway
				Siting	Avoid solar array placement in or near prairie dog colonies whenever possible.	
Noxious Weeds	Ground disruption may cause the introduction of noxious weeds that can create ecological and aesthetic issues.	Yes		Design	Follow CDOT specifications where noxious free-certified materials are used for erosion control. Plant native grass species in disrupted areas. Monitor vegetation growth during solar array and right of way maintenance. May need to develop a Noxious Weed Plan if developing a large array system. Reference CDOT specifications 217.03 and 217.03; reference CDOT Integrated Noxious Weed Management Plan requirements.	CDOT Green Book Specifications
National Environme ntal Policy Act (NEPA) Complianc e	Large corridor type projects may require expensive and time-consuming environmental assessments.	Yes		Admin	Keep projects within a smaller scope so a categorical exclusion can be used to avoid environmental assessments. CDOT develop programmatic agreements with FHWA and other affected agencies to streamline NEPA process.	Although not a project risk factor this is a management consideration that could significantly impact the feasibility of a project; determine if programmatic agreements are in place among agencies.
Natural Hazards	Placement of solar array on steep slopes or potential landslide areas may cause soil shifting and sloughing that may impact the right of way.	Yes		Siting	Avoid placement of solar array on steep slopes greater than 3:1; perform a geotechnical evaluation on slope and soil type.	The Slope side ratio of 3:1 from the road way helps in panel operation and maintenance. Northwest Parkway
Hazardous Waste	Subsurface hazardous waste material may be encountered during the construction of solar arrays and electrical system trenching.	No		Admin	Perform a Phase I Environmental Assessment to determine potential of hazardous materials/waste; conduct Phase II Assessment if there is a high potential for buried waste; reference CDOT Specifications 250.	ODOT

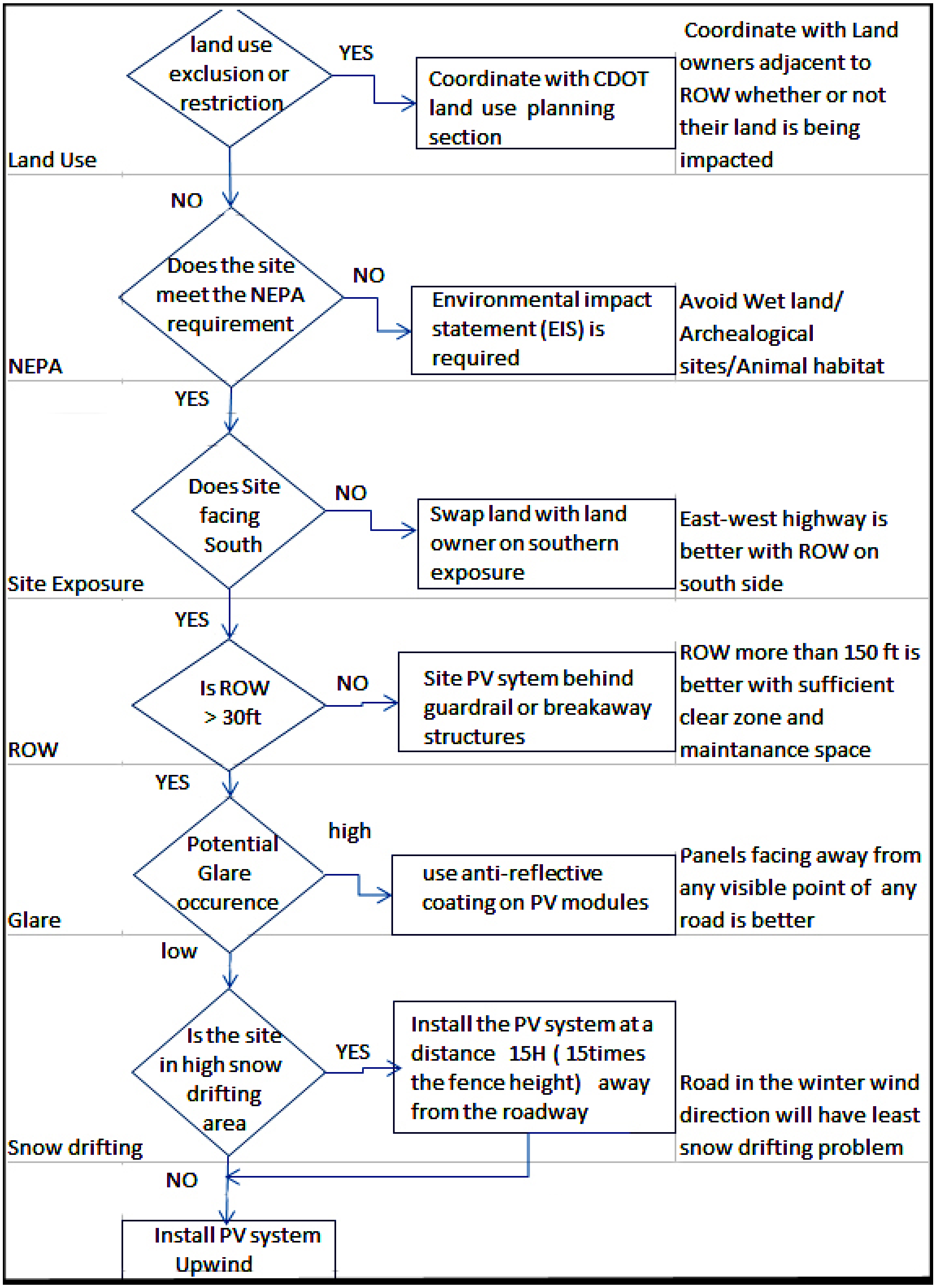
Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
				Siting	Avoid potential hazardous waste areas; however, use of previously disturbed areas (brownfield areas) can safely accommodate solar array construction and trenching activities.	
Migratory Bird Treaty Act	Construction, operation and maintenance of solar arrays and associated electrical connection trenching may impact migratory birds according the Migratory Bird Treaty Act.	Yes		Admin	If construction activities would occur during the nesting season (April -August), reconstruction surveys for the presence of special-status bird species or any nesting bird species shall be conducted by a qualified biologist within 500 ft. of proposed array construction areas. If any other nest sites of bird species protected under the Migratory Bird Treaty Act (MBTA) are observed within the vicinity of the project site, then the project will be modified and/or delayed as necessary to avoid direct take of identified nest, eggs, and/or young.	Not a known impact from other DOTs or solar array owners regarding bird attraction during operation and maintenance.
Project Decommissioning and Site Restoration	The removal of the solar array after project completion can cause erosion and disrupt existing vegetation.	No		Admin	Require that a project decommissioning and site restoration plan is developed and approved by CDOT.	This plan could be included in the Stormwater Management Plan.
Community/Social						
Glare and Glint	Glint and glare can have visual or aesthetic impact on local homeowners and communities.	No		Admin	Conduct outreach with local community or receptors before final design and construction. Glint and glare modeling and analysis should be performed to address visual impact to the local community if this is deemed a concern.	Noted by Caltrans and ODOT as not a major risk issue.
				Design	Access panel orientation and angle relative to visual receptors.	
				Siting	Avoid placing solar array within urban areas or areas with potential visual receptors if possible.	
Adjacent Landowner	Solar arrays may cause changes in vegetation and impact the livelihood of adjacent landowners.	Yes				Consultation required.

Impacts				Mitigation Measure		Remarks
Risk Factor	**CDOT Potential Impacts**	**CDOT Concern**	**Risk**	**Criteria**	**Actions**	**Comments/ Reference**
Context Sensitivity and Communit y Acceptance	Solar array planners should minimize conflict with the local environment and social context; solar arrays should fit the local surroundings and land use requirements.	No		Admin	Develop a community education and outreach plan that includes direct interaction with affected residents. Conduct public meeting(s) as necessary to discuss public concerns, Address public concerns by altering design if possible.	State of Massachusetts DOT experienced community dissatisfaction with solar array systems within local communities; CALTRANS experienced pubic concerns about aesthetics and glare. CALTRANS
Right of Way Landowner s other than CDOT (USFS)	Solar array placement may not be consistent with right of way owners' management plans or meet aesthetic criteria.	Yes		Admin	Coordinate with landowners and understand aesthetic requirements, design criteria, and potential permitting.	Areas of concern are in the mountain areas where USFS owns the right of way.
				Siting	Avoid placing solar arrays on USFS or other agency property.	

Table 3. Generalized Solar Array Risk Impact Matrix (Working Example)

Risk Factor	Risk Score	Severity	Probability of Occurrence (%)	Time of Occurrences			Comments
				hours	days	months	
Safety							
Glare and Glint	48	8	6	1	30	4	Software analysis (3% of accidents is high)
Driver Awareness	10	2	5	12	30	12	Always
Worker Safety	46	5	3	8	10	1	Road maintenance need
Collision safety	50	5	10				ROW accidents AASTHO
Structure Integrity	50	5	10	24	30	12	Always
Array Security	20	2	10	24	30	12	Always
Fire Potential	6	3	2	6	10	3	Fire danger period
Biting Insects	4	2	2	8	2	3	Seasonal
Extreme Weather	10	5	2	6	2	4	Seasonal
Array Maintenance and Access	50	10	5	8	2	2	PV maintenance need
Operation and Maintenance							
Snow drifting	40	10	4	24	7	4	Windy snowy days
Tumbleweed Accumulation	15	5	3	24	10	4	Seasonal
Deicing Agents	12	3	4	24	10	4	Winter snowy days
Right of Way Mowing	50	10	5	8	1	4	Mowing need
Environmental							
Tree Removal	20	10	2	8	1	1	Once a year
Threatened and Endangered Species (T&E)	100	10	10				Regulatory
Wildlife Attraction	80	10	8	24	30	2	Nesting or reproduction
Micro-Climate change	10	5	2	12	30	4	Summer days
Post Construction Stormwater Management	45	9	5	24	5	4	Seasonal
Construction Stormwater Management	35	5	7	24	6	1	Installation stage
Habitat Impact	100	10	10	24	30	12	Always
Prairie Dog Colonies	100	10	10				Always
Noxious Weeds	40	8	4	8	10	4	Seasonal
National Environmental Policy Act Compliance	100	10	10				Regulatory
Natural Hazards	30	10	3	10	2	4	Rarely
Hazardous Waste	50	5	10				Rarely
Migratory Bird Treaty Act	100	10	10				Regulatory
Other Landowners	10	10	10				Always
Decommissioning and Site Restoration	64	8	8	24	30	1	Once in a project life
Adjacent Land Owner	60	60	10				Always

Figure 1. Flow Chart for PV Array Development



Appendix B European Solar Highways

Rated Capacity	Location, Country	Description	Year of Completion
2.65 MW	**Aschaffenburg,** Germany	Solar park Aschaffenburg, noise barrier A3	2009
1 MW	**Töging am Inn,** Germany	Noise barrier A94	2007
833 kW	**Oppeano** (Verona), Italy	Noise barrier along S.S. 434 "Transpolesana"	2010
730 kW	**Maranod'Isera** (Trento), Italy	Noise barrier along A22 Brenner Motorway	2009
600 kW	**Freising** (Munich), Germany	Noise barrier along A92 motorway	2009
365 kW	**Freiburg,** Germany	Noise barrier along B31	2006
283 kW	**Bürstadt,** Germany,	Noise barrier along B57	2010
180 kW	**Vaterstetten,** Germany	400 m long noise barrier along railway tracks	2004
123 kW	**Melide,** Switzerland	Noise barrier along Gothard motorway	2007
101 kW	**Gleisdorf,** Austria	Noise barrier along A2 motorway near Graz	2001
100 kW	**Domat/Ems,** Switzerland	World's first photovoltaic noise barrier along the A13	1989
100 kW	**Giebenaach,**Switzerland	Noise barrier along the A2 motorway	1995
90 kW	**Biessenhofen**(Bayern), Germany	Nestle facility, noise barrier	2010
80 kW	**Safenwil,** Switzerland	Noise barrier along the A1 motorway	2001
40 kW & 20 kW	**Saarbrücken,** Germany	Noise barrier along A620 motorway Saarbrücken – Gündingen	1995
53 kW	**Emden,** Germany	Noise barrier along the A31 motorway	2003
40 kW	**Seewalchen,** Austria	Noise barrier along A1 motorway near Salzburg	1992
30 kW	**Ammersee,** Germany	Noise barrier along A96 München-Lindau motorway	1997
30 kW	**Rellingen,** Germany	Noise barrier along the A23 motorway	1992
28 kW	**Großbettlingen,** Germany	PV array "Stoiadler III" mounted on noise barrier in Großbettlingen	2006
24 kW	**Melbourne,** Australia	Tullamarine-Calder Interchange, adjacent to Essendon Airport, Melbourne	2007
12 kW	**Münsingen,** Switzerland	Bifacial PV noise barrier along the railway tracks.	2008
10 kW	**Zürich – Aubrugg,** Switzerland	First bifacial photovoltaic noise barrier along the A1 motorway.	1997
9.6 kW	**Zürich – Walliselen,** Switzerland	First photovoltaic noise barrier along the railway tracks.	1998

Figure 1. PV Arrays in Noise Barrier

Appendix C: Summary of Focus Group Discussion

The following is a list of concerns regarding solar highway impact discussed during the focus group and study panel meetings:

Safety

- Glare is an issue for north-south roads; not just the panels but the frames; perhaps fixed versus tracked panels may cause more glare; angle modification could be performed after installation if deemed a concern and glare screens implemented.
- The clear zone distance is not fixed but rather is dependent upon variables such as speed limit, slope, road curves and best professional judgment.
- There is a recovery zone that may be within or outside of the clear zone area.
- If arrays are within the clear zone, guardrails and breakaway structures need to be considered.
- Placing solar arrays near a 70 -75 mph interstate may represent a high risk concern; fixed objects within the right of way may cause fatalities. Guardrail is a fixed object that represents a risk; the placement of guardrail to prevent solar array and vehicle impact is not necessarily the best approach.
- It is preferred that solar arrays use already existing guardrails instead of installing new guardrails.
- No need for breakaway structures if arrays are outside the clear zone (more than 30 ft from travel way line).
- If construction of arrays require a lane closure, there may be time/seasonal restrictions imposed by CDOT.
- Solar array signage could be considered to avoid driver distraction.
- Check animal-car collisions database for high wildlife areas; avoid these areas for placement.
- There could be flight path restrictions in some right of way areas; check FAA.
- Be aware of electrical wiring and connection corrosion due to magnesium chloride road application and dispersion; corrosion of framework may also occur.
- Program should be aware of and consider using land not within right of way but use adjacent land owned by the State of Colorado or federal government.
- I-70 East an ideal location due to orientation and right of way areas.
- Installing arrays within the state highway right of way would be easier than on federal interstate system.
- Longitudinal projects greater than 500 ft. require FHWA approval on Interstate Systems.
- Consider using breakaway solar array support structures to reduce collision severity.
- Consider using a Jersey Barrier(s) near solar array to potentially deflect out-of-control vehicles away from array systems.
- Communicate with Safety Engineers who review all CDOT projects for safety and consult with experts on issues like snow drift, glare, etc.
- CDOT management will need to justify the additional risk.
- The crash-worthiness of the solar array is a concern; the array system should minimize the impact of out-of control moving vehicles.
- There will need to be a safety right of way training for solar array maintenance and construction employees.
- It is not known if adding solar arrays statistically increases the risk of accidents or fatalities; acceptable risk levels are not well-defined by CDOT.
- E-470 is already using solar arrays in their right of way.
- Be aware that some right of way land is not owned by CDOT.

- Design considerations need to address high wind and snow loads.
- Colorado State Forest Service should be contacted about snow drift and deposition along right of way based on living snow fence applications.
- The safety engineering group would like to be included in the review of the draft document.
- No concerns noted about rest areas or noise wall applications.

Right of Way Maintenance and Permitting

- Snow blowers could throw snow as far as 150-200 ft. from the road; array systems could be hit by snow blowing; not a usual occurrence in the plains area (like I-70 East).
- Concerns about mowing near the solar array chain link security fencing by CDOT tractors; owners of array systems should "hand mow" grass near fencing.
- Wind generally blows from north to south in Colorado and snow drift and removal is a concern.
- Maintenance areas and rest areas are good places for solar arrays.
- Access to arrays for maintenance should be from a frontage road instead of directly off the interstate.
- CDOT Right of Way Access Permits are for temporary (construction) and permanent access (maintenance) from regional right of way permit departments; obtain permits and restrictions on CDOT Website; Form 1233 and ROW management permit 037.
- Interstate highway systems prohibit mowing by outside parties; only CDOT maintenance workers allowed to cut grass on the interstate.

Maintenance Activities:

- Third party does the major construction; CDOT does the maintenance.
- Maintain highway from CDOR ROW fence to fence.
- Fence construction and repair, ditch repair, tumbleweed removal, and mowing 2-5 times a year.
- Snowplowing depends upon the amount of snowfall and duration of the snowy season (0-20 times/ year).
- Winter road maintenance snow removal strategy is to plow away snow and let road catch more snow.
- Typical snow direction in the Limon area is NNW to SSE.
- Snow blowing and spray system in the Denver area might be an issue.
- No heated structures in Colorado.
- All salts are chlorine based not bio or any other fancy types.
- Common deicers used for melting the snow are magnesium chloride, Straight Salt, Salt and Sand, and Ice Slicer.

Issues on chemicals:

- Currently, no major ground water contamination recorded, but new MS-4 rule might change this situation.
- Railroad complaint: the traffic signal short circuits on secondary roads (2-3 time per year). MgCl gets onto track carried by vehicle tires and shorting the copper plates on the track joint.
- Snow is removed using plow only (no blowing).

Potential Solar Installation Issues:

- Anything standing 3-4 ft from ground causes snow drifts and tumbleweed accumulation, which could back up to road.
- Access Road: No access possible from the freeway.
- Off-ramp double-back (take a ramp and use service road) might be the best possible option.
- Generally speaking, installing anything on ROW is not a good idea, even billboards are on land owners' property. CDOT's property use is restricted.

- Cost of replacement might be an issue.
- Traffic volume is going up and unforeseen situations might happen in the future.
- If necessary, panels installed farther away may be better.

Traffic engineering:

- Area covers a large portion of Colorado consisting of four-lane and two-lane highways with a 2-4 ft. shoulder (12 ft. lanes) and a recovery zone with a slope of 15-30 ft. from the white line.
- There should be enough (at least 30 ft.) recovery zone off the road in case a vehicle loses control for any reason.
- Provide some guide way out if a vehicle gets into the obstruction (panels).
- The obstruction object (panels) should be breakable, and the panel structure should break first before it hurts the vehicle in case of an accidental hit.
- Many rest areas are closed; closed rest areas might be the best location for PV array development.
- Safety zone and array placement should account for future road expansion.

Environmental

- Wildlife may be attracted by the glare from solar panels.
- Impact to the Migratory Bird Treaty by birds nesting in the solar frames or by ground nesting birds (like borrowing owls).
- Grass treatment for bird migration could be impacted; no mowing of grass within 22 ft. of the edge of pavement unless previously approved by CDOT.
- Project specific/site specific solar arrays will require a NEPA analysis. It is expected that a Categorical Exclusion (Cat Ex) would be used. The Form 128 along with other reports or requirements may be required by CDOT.
- Stormwater Management Plan will be required by CDOT.
- Change in vegetation allowing noxious weeds will occur; a Noxious Weed Plan will be required.
- Shading factor for re-vegetation under panels is a consideration.
- If using a corridor-based approach, Environmental Assessment may be required due to environmental uncertainties along the corridor.
- Would need to consider the landowners (like the US Forest Service) who may own the right of way in certain locations within the state.
- Watershed organizations may need to be made aware of the array systems if within a Stormwater MS4 area.
- Community property owners' acceptance is a concern in urban areas.
- Soil disturbance and re-establishment is an issue during construction and post construction periods.

Others

- Ensure solar arrays do not preclude future activities or transportation planning.
- Community aesthetics and view shed impacts could be an issue in some locations.
- Leasing land to investors may be in direct competition with private land owners.

Appendix D: Summary of External CDOT Communication

Summary of Volpe Institute Meeting

Meeting Date: January 8, 2013
Resource person(s): Carson Poe, Gina Filosa

- Not many states are looking into solar applications in their right of ways to date; Colorado and Arizona have shown interest in a Phase II Pilot Study with FHWA/Volpe Institute.
- NEPA-Categorical Exclusion seems to be the norm for solar arrays projects in right of ways.
- Santa Clara used a corridor approach that used an Environmental Assessment (It looks like it was done for California CEQA Program), which may not be applicable to Colorado; however, the methods and findings (e.g. for glare) are probably useful.
- **Santa Clara County**: www.dot.ca.gov/dist4/documents/solar_highways_draft_is_mnd_110706_circulation.pdf.
- Massachusetts DOT had the Carver Project that used solar arrays with a municipal stakeholder.
- **Carver, MA article**: www.wickedlocal.com/carver/news/x1851400221/Carver-Route-44-solar-array-restored-security-heightened#axzz2HPbdU5ok.
- Glint and glare issues are common but do not seem to be significant; see Santa Clara's report mentioned above; MIT is coming out with a new glare report for the FAA.
- Visual impact is a potential impact from a community perspective.
- No data on increased accidents due to solar arrays noted by Volpe Institute.
- No known snow impact data associated with solar arrays; Ohio and Massachusetts may have some data on their limited array installations.
- T&E habitat could be an issue related to tree and vegetation removal; select degraded or altered sites for array siting and avoid undisturbed areas.
- No bird migration or nesting issues noted to date.
- Driver expectation and distraction studies were done by University of Nebraska on small solar project (LED) in Lincoln; this is the only known research study on driver distraction.
- Oregon has good criteria using a GIS approach to find potential sites for solar array installations; could be modified for better site selection.
- Security an issue; Mass DOT lost a large number of panels due to theft.

Summary of Oregon Department of Transportation Meeting

Meeting Date: January 8, 2013
Resource person(s): Allison Hamilton (ODOT-Solar Program Manager)

- Mowing by ODOT in the right of way is not an issue with ODOT maintenance; area cut 3-4 times a year.
- No safety issues as long as systems are outside the Clear Zone.
- No bird attraction noted.
- Bees were a problem; solar array structure and pipe with opening without a cap; bees established nest inside piping.

- Although ODOT did an environmental clearance (modified a previous project's environmental NEPA clearance) the solar investor did their own environmental due diligence.
- Negotiations were needed to settle what NEPA requirements were needed for future research type projects; FHWA or DOE NEPA guidelines. The FHWA NEPA process was decided upon for future research projects.
- Community pushback on solar panel arrays at one project area was experienced by ODOT and the community tried to drive the project into an Environmental Assessment due to glare issues. The community was not successful in this attempt.
- ODOT used razor wire on top of security fencing; there were limited aesthetic concerns.
- Visit the ODOT web site; click on the West Linn link for community pushback information.
- Local consulting firm did glare study no significant impacts determined.
- Solar panels designed to absorb and not reflect light.
- No data on snow drift impact from arrays known; TerraLogic will keep in touch with ODOT about this future issue for ODOT.
- TerraLogic should contact DIA about any snow drift studies or observations.
- Rest areas are a good place for solar panels; good public relations and acreage (see Baldock Rest Area).
- Keep the information exchange going between CDOT and ODOT.

Appendix E: Field Study Reports

Summary of Denver International Airport (DIA) Meeting

Date: January 28, 2013/9:30-11:00

Resource person(s): Ed Keegan

- The two megawatt solar array developed in 2008 near the DIA terminal is not owned by DIA but by Sun Edison; DIA will take over the solar array in the next few years (2014).
- Sun Edison sells power to Excel and pays DIA a lease fee.
- The system tracks east to west and is a flat single axis tracking system (that does not operate well in winter) according to Keegan.
- Bottom frame is about 3 ft. off the ground and the top is approximately 6 ft.
- Closest array is approximately 90 ft. from main Pena Boulevard guardrail near the East/West Terminal split
- Noticed more reflection from the array frame and not the panels.
- DIA used recycled concrete for the "floor" of the array system; some weed control is necessary.
- Hydraulic fluid used for tracking hydraulics system (vegetable oil).
- No bird issues associated with the panels.
- DIA is losing money on the solar array investment to date; expected energy costs to increase before the economic downturn.
- If solar arrays do not feed into an existing meter there is an average incremental rate cost which is not cost effective.
- Solar arrays near the fuel farm area hook into an existing meter which is cost effective.
- Cannot have greater than 120% of the normal load into a meter for alternative energy.
- Great public relations mechanism for DIA.
- Use solar arrays to advertise carbon footprint reduction although DIA does not use the solar power (public relations).
- Dust and access are important issues during construction.
- Tracking system framing uses concrete piers that extend 15-20 ft.
- Bees hide and develop nests inside the array support structure pipe.

Woods Allee (DIA Solar Manager)

- Glare issues were considered and investigated; no impact from panel glare.
- FAA guidance Advisory Circular at www.FAA.gov; currently under review by FAA.
- No impact associated with snow drift with current orientation.
- Rock and fabric used near terminal arrays with limited success; other arrays will use a native seed mix developed by CSU.
- No bird issues noted.

The North West Parkway, 3701 Broomfield, Colorado 80023

Date: 12th December 2012

Resource person(s): Mark Shotkoski, Director of Engineering & Maintenance

North West Parkway (NWP) maintains the highway and has a lease agreement for 99 years. The commercial operation date of the highway was started in 2003 and has been in operation for the past 9 years. They are setting up Wind and Solar energy projects along the ROW for renewable clean energy. Xcel Energy is the power supplier and has offered a rebate to NW parkway energy for clean energy generation to power the roadway lighting, deck lights, traffic lights, etc. Solar Plants on the NWP ROW have been in place since June 2011 and have been operating for the past 1.5 years.

Figure 1. North West Parkway PV array in ROW

Figure 2. Fencing for Security

- 7 Sites had been identified for the installation of Solar PV arrays.
- Each system generates 10 KW totaling 63 KW of clean energy generated from all 7 sites.
- NWP's ROW is 350 ft. wide along both sides.
- The clear zone considered for suitable set up of the PV plant is 30 ft. from the shoulder of the highway. The shoulder edge to the panel distance was set-up at approximately 35 ft. distance.
- A building permit for suitable construction out of the clear zone was obtained from the local county.
- Slopes were set-up on the identified sides of the PV array for easy installation. The slope side ratio was approximately 3:1 maximum from the road way. The slopes also help NWP in cleaning the panels easily during O&M.

Operation & Maintenance: NWP's O&M on the solar panel is almost zero.

- No operation and maintenance has been performed to date.
- Advisable O&M practice: Water>>Brush>>Water. Wash the panels with water to remove the dirt/dust in the panels followed by a light brush for thorough cleaning and then wash with water again. It was observed that the efficiency of the panels did not improve after the panel wash.
- Web based systems and software are available to check and record for daily energy production.
- There was one instance where local rodents chewed the conduit which then had to be repaired or replaced.
- Use of conduit is advisable for underground cable.

Ice Removal:

Chemical deicers are being used to remove the ice from the highway. Magnesium chloride (MgCl) and a combination of salt and sand (Ice Slicer) are the main chemicals used. The salt causes pulverization and the sand adds traction to remove the ice and make the highway safe for operation. There might be a chance of splash from another vehicle, which can cause corrosion on the components underneath the vehicle.

- PV array set up :
  - Simple construction.
  - 24 inch diameter holes were dug to place the aluminum supporting structures.
  - The distance between the panels to the safety fence is approximately 10 ft. It is advisable to keep more space in the front for easy cleaning purposes and less in the back.
  - Inverters are placed below the PV panels.
  - Underground cables were used to connect them to the adjacent meters.
- Geotechnical Study: A geo-tech study was being done on every site before the plant was set up.
- Tilting Angle: The tilting angle was approximately set up at 18 – 24 degrees based on the location.
- Shadow/Glare Effect:
  - No glare/shadow effect has been observed from the solar panels.
  - It was observed that there are better glare effects from the aluminum sign boards than the solar panels.
  - It is advisable to set up PV arrays along ROWs that do not have bends on the highway.
  - Panels along the Parallel Roads help.
- Underground fibers and pipelines are present along the highway. Some of these are perpendicular to the road. An irrigation line is present for water supply.
- A well is present inside NWP's premises to supply the water for its own consumption.
- The front portion of the panel is approximately 5 ft. from the ground and the back portion of the panel is approximately 10ft. from the ground. These distances vary from site to site based on the tilting angle.
- Snow Drift:
  - Accumulated snow on top of the panels melts over a period of time.
  - A few snow fences have been placed along the ROW to prevent snow drift.
  - Setting up of the snow fence has prevented the snow from drifting substantially.
  - The ROW fence is made up of woven wire of black plastic material. The fence has a grid pattern with holes with a diameter of approximately one inch.
  - Chain-link fences are not recommended.
- Typical wind direction is north-west.
- There was no evidence of any micro-climate formation.
- There was no presence of noxious weeds. The ROW landscaping maintenance is done once a year.
- There has been no animal concentration around the panels as the PV array is fence protected.
- Traffic Control: Suitable warning signs have been placed at all suitable /required locations.

Recommendations:

- Setting up solar arrays along I-25 would be difficult. The terrain is flat; arrays would block driver vision and negatively impact safety. A bumpy or curvy road surface would be preferable because it would allow the driver to view obstacles when they arise.
- Always advisable to set up the panels facing south.

- Placing the panels along a north-south highway would be inefficient and a step structure would be required for an ideal plant.
- It is advisable to set up the plant along an east-west highway.
- It is advisable to set up the plant parallel to the highway.
- It is advisable to connect the generated power to the grid.

Solar Array at the Denver Federal Centre, Denver, Colorado

Resource person(s): Mr. Douglas B. Porter, Regional Chief Engineer, G.S.A

- The site visited was a fixed PV solar array of capacity 1.17 MW in a 7 acre spear area that gave 14-15% efficiency. The contract was signed with Xcel Energy in Jan 2008 for the credit benefit of having renewable energy.
- After a competitive bidding process Sun Edison received the $6.9 million contract.
- The solar array is aligned east-west with panels facing south.
- The site had equipment like noise buffers that had to be removed. The ground had to be cleaned before starting construction.
- A geotechnical analysis was performed at each proposed site for the solar array. While doing the geotechnical analysis, the corrosive effect was also taken into consideration.
- The plant currently produces approximately 13500 V. A total of 7-8 strings are connected together through 1 combiner box.
- Plants consist of approximately 6000 solar PV panels connected via 16 strings through 54 lines into two inverters. The site had weeds that had to be removed. A temporary irrigation system was used to remove those weeds. It is suggested to use recycled concrete in the plant area to avoid weed disturbance. Weeds are removed once a year.
- The DFC solar panel operates better in the morning than in the afternoon (because of the clearer sky). Panels are inclined at 20° slope. As per the solar operator's design, the 20° slope was suggested as the optimum inclination at which the snow melts and slides from the panel. While the most optimum angle would be 40° slope, the change in efficiency would vary by only approximately 5%.
- DFC recommends that no additional O&M is required for the snow shedding in the solar panels. As the day progresses, the panels warm up which causes the snow to shed by itself. The ideal maintenance for removing snow would be using snow scrapers with long handles. This would require a considerable labor cost and also would require a place to dump the snow. Presently there is no space available along the PV array for the snow to slide.
- The concentration of power generation should be on the panel on the top row compared to the bottom. As the top row would have the most snow shed, it would start generating power more quickly compared to the bottom row, which would not be in operation even if one panel from the row has snow deposits as the panels are connected in series.
- The inverters are of 500 Kw capacity and are connected to booster transformers (step up transformers) to from 200 V DC to 1300 V AC.
- Scheduled maintenance takes place twice a year (cost of cleaning $8000).
- A check list is being maintained by the DFC for the operation and maintenance of the inverters. All the inverters have a timing device that automatically switches OFF at night as they draw unnecessary power.
- Rodents have not been observed in the solar array.

- Presence of bird droppings are on a few solar panels.

Figure 3. Presence of bird's waste on PV module

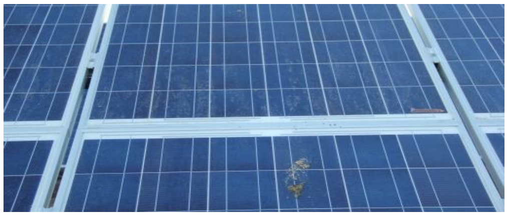


Figure 4. Signage for guide

- As Colorado receives rainfall at least twice a year, the rain is sufficient to clean the panels.
- Since the DFC is a federally protected area, no theft has taken place to date.
- It was observed that the panels are not very reflective and do not cause any glare effect. Thereby the panels along the highway do not have any impact with the highway.
- Maintenance was outsourced by DFC to the local electrical maintenance company. They deploy 2 personnel (1 Electrician + 1 Helper) for 2 days to take care of all electrical concerns.
- Each string has sufficient space to allow a single vehicle to move between the array rows. Vehicles are generally used for transformer replacement and washing the panels.
- While the support structures are mostly aluminum, GI support can also be used (aluminum is highly recommended).
- Hail storms caused disturbance in the adjacent trees but no serious damage was done to the solar panels.
- A few circumstances of panel breakage were reported. The major cause of breakages were manufacture defect, damage incurred during panel installation, or small rocks and pebbles that hit the panels during lawn mowing. Lawn mowing is to be avoided in the solar panel site. It was also suggested that due to contraction and expansion at the joints/screw area of the panels, cracks may form. In the case of breakages, they are replaced by spare panels.
- No pesticides have been sprayed in the soil at the solar site.

Recommendations:

- It is highly recommended that the industry decide on the plant design rather than CDOT recommending what design is desired. Solar operators are aware of the latest design and can have the liberty to alter the design to suit their needs and be in line with the budget.
- Safety standards are to also be figured by the solar operator which should be in line with ASS.

Appendix F: Solar Glare Hazard Analysis

This section provides supplemental information pertaining to glare analysis. Information on albedo is presented first, which is followed by supplemental glare analysis. Table 1 presents the albedo of common reflective surfaces at different angles (Burleson-Consulting-Inc., July 2011).

Table 1. Albedo Chart (Materials Reflectivity)

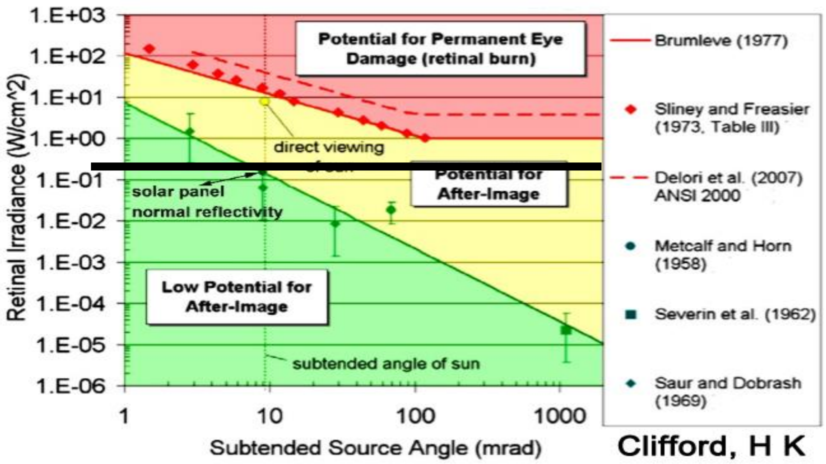
Common Relflective Surfaces		Incident Angle in Degrees						
		0	15	30	45	60	75	90
Material Reflectivity (% of sun's brightness)	Steel	37%	39%	46%	57%	70%	83%	94%
	Fresh Snow	35%	37%	44%	54%	67%	79%	90%
	Ocean Ice	27%	29%	34%	42%	52%	62%	70%
	New Concrete	21%	23%	27%	33%	41%	48%	55%
	Desert Sand	16%	17%	20%	24%	30%	35%	40%
	Green Grass	10%	10%	12%	15%	19%	22%	25%
	Standard Glass	8%	9%	11%	13%	16%	19%	22%
	Plexiglass	8%	9%	10%	12%	15%	18%	21%
	Plastic	7%	7%	9%	11%	13%	16%	18%
	Decidious Trees	7%	7%	9%	11%	13%	16%	18%
	Bare Soil	7%	7%	8%	10%	13%	15%	17%
	Conifer Forest	6%	6%	7%	9%	11%	13%	15%
	Worn Asphalt	5%	5%	6%	7%	9%	11%	12%
	Solar Glass	4%	4%	5%	6%	8%	9%	10%
	Sloar Glass with Anti reflective coating	2%	3%	3%	4%	5%	6%	6%
	Fresh Asphalt	2%	2%	2%	2%	3%	4%	4%

Glare Impact Level:

The reflected light can be characterized as a combination of specular (mirror-like) and diffuse (scattered) reflections. Generally, smooth surfaces such as mirrors and smooth glass produce more specular reflections with greater intensity, which cause larger retinal irradiances and smaller subtended angles. Retinal irradiance (W/cm2) is the solar flux entering the eye and reaching the retina. The subtended angle is the size of glare source divided by distance from the observer. The subtended angle of sun is constant 9.3 mrad and varies for PV array with the respect to the distance of the observer. Impact of retinal irradiance and subtended angle to vision impairment is shown in Figure1.

As shown in Figure 1, the green region depicts a low potential for after-image. Practically, in the green region we experience only diffuse reflection. When the subtended angle increases, the safe retinal irradiance threshold decreases. When the driver approaches the source of the glare (PV array) he or she will be exposed to an increased glare hazard because the shorter distance to the source increases the subtended angle. In the yellow region, a high retinal irradiance may cause a temporary after-image (direct viewing of sun is 10 W/cm^2). For a given retinal irradiance, smaller subtended angles yield smaller after-images, and the potential impact is less. With higher irradiance, the potential of glare is large and may cause permanent eye damage from retinal burn (red region). Note: expose time for this study is 0.15 seconds.

Figure 1. Potential Retinal Irradiance Impacts of as a Function of Subtended Source Angle



The normal reflectivity of a solar panel is 4% of sun's brightness (10W/cm^2 at subtended source angle 9.3mrad) equals to 0.4 W/cm^2, which falls under the green hazard potential. Therefore, the driver will most likely experience only diffuse reflection of solar panel surfaces which is not considered a specular hazardous reflection.

1. Photovoltaic System Model and Projected Impacts (I-70, Limon, Colorado)

Capacity determination is the starting point to model the project site and analyze glare. Available land area is shown in Figure 2 with site dimensions as marked by the black line overlaid on a background of a Google map using 200 ft. scale resolution (computed by CATIA).

Figure 20. Site measurements

Depending on module efficiency, the power generation capacity of a given land area might be different. Panel sizes and their rated capacity are given in table below. Total available area excluding trees and clear zone is 6.3 acres (274757.4 ft^2).

Table 2. PV Module Specification

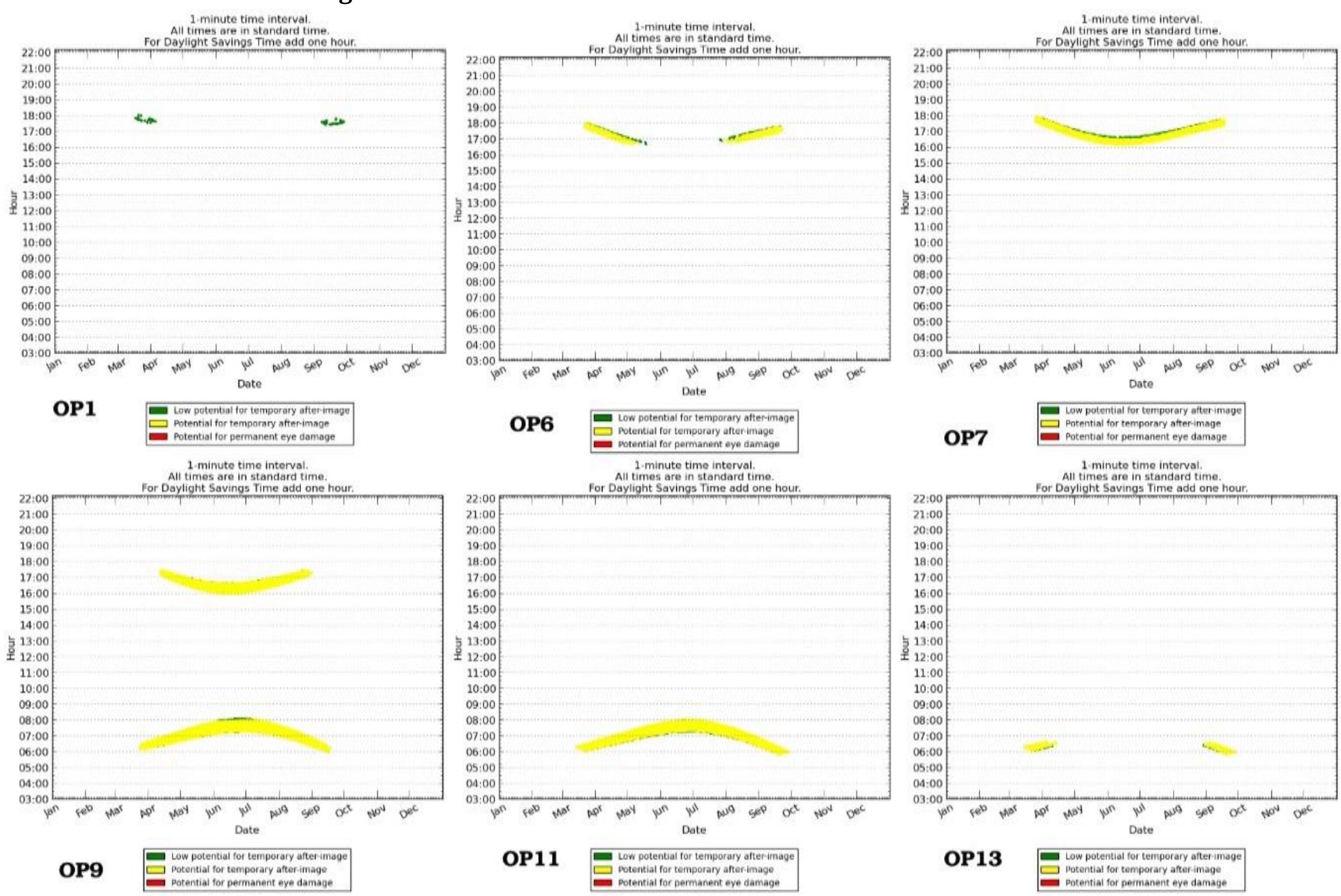
Model	HIT Power 220A (VBHN220AA01)
Rated Power (P max)	220 W (Efficiency = 17.4%)
Module Area	13.56 ft^2
Dimensions (L x W x H)	62.2x31.4x1.8 in (5.18x2.62x0.15 ft)

The theoretical DC power capacity is 4.4 MW; with the packing factor (1.75) the practical capacity is 2.5 MW. Number of PV modules: 274757.4 ft^2/ (1.75x 13.56 ft^2**)** = 11610.

Glare Modeling

For glare analysis at an observation point, the driver's eye was considered to be at a height of 6 ft. above ground. Figure 3 presents the Glare Occurrence Plot for different observation points of site-1 with three representative colors as follows:

Figure 3. Glare Occurrence Plot for Observation Points



As shown in Figure 3, glare does not start until observation point 6. At point 6, there is a small amount of glare which increases at points 7-11, then decreases. The glare result is summarized in Table 3.

Table 3. Glare analysis results

Observation	Side	Distance from the site(ft)	Ocular Impact	Date of Occurrence	Hour of Occuerence	Maximum Duration(min)	Days
OP1	East	6000	Low	Mar.15-30 / Sep.15-30	17 - 18	15	30
OP2	East	4800	Low	Mar.15-30 / Sep.15-30	17 - 18	15	30
OP3	East	3600	Medium	Mar.15-Apr.10 / Sep.1-30	17 - 18	30	55
OP4	East	2000	Medium	Mar.15-Apr.20 / Aug.20-Sep.30	17 - 18	30	75
OP5	East	1500	Medium	Mar.15-May.5 / Aug.15-Sep.31	16.30-18	45	95
OP6	East	1000	Medium	Apr.1 - Sep.10	16-18	45	160
OP7	East	500	Medium	Apr.1 - Sep.15	16-17.30	45	165
OP8	Middle	0	Medium	Mar.25 - Sep.20	6-8 / 16-17.30	60	175
OP9	Middle	0	Medium	Mar.15 - Sep. 30	6-8 / 16-16.45	120	195
OP10	Middle	0	Medium	Mar.15 - Sep.30	6 - 8	60	195
OP11	Middle	0	Medium	Mar.15 - Sep.30	6 - 7.30	45	195
OP12	West	500	Medium	Mar.15-Apr.15/Sep.1-30	6 - 6.45	30	60
OP13	West	1000	Medium	Mar.15-30 / Sep.15-30	6 - 6.30	15	30
OP14	West	1500	Medium	Mar.15-20/ Sep.15-20	6 - 6.30	15	10
OP15	West	2000	Medium	Mar.15-20/ Sep.15-20	6 - 6.30	15	10
OP16	West	2500	No Glare				
OP17	West	3000	No Glare				
OP18	West	3500	No Glare				

Glare impacts

As shown in Table 2, the glare is visible in the evening hours from observation points 3 to 9. A driver will experience glare along this segment of road. The impact of glare might be different if the exposure time is longer than the standard exposure time (0.15s) used in the ocular hazard graph.

2. Site visit: I-76 Fort Morgan

According to CDOT ROW GIS map, three sites along I-76 were identified in Fort Morgan having ROW space more than 200 ft.

Figure 4. Three Sites at I-76 near Fort Morgan

Observations:

1. Sites 1 and 3 have triangular shape but the maximum distance from the roadway is 140 ft.
2. Site 2 has a maximum 120 ft. width ROW distance from the roadway.
3. This ROW has a slope of 30 degrees beside roadway

During the field visit, it was found that the actual ROW is less than 200 ft., and the landscape is not suitable for PV array placement with the presence of trees and slopes. No further modeling and analysis was performed.