DEPARTMENT OF TRANSPORTATION

Harnessing Solar Energy Through Noise Barriers and Structural Snow Fencing

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Research Report
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16. Abstract (Limit: 250 words)
This research studied the possibility of harnessing solar energy through right-of-way associated structures, such as noise barriers and snow fences. A detailed survey was conducted of the general public, farmers, and utility companies to determine their acceptance of such an initiative. A large percentage of the general public, farmers, and utility companies welcomed the idea of harnessing power using right-of-way associated structures. Furthermore, a detailed structural design for the solar noise barrier and snow fence were created. The effects of the solar panels installed on noise barriers or snow fences in terms of noise reduction, glaring, impact and crash responses, and snow-drift responses were studied, and the potential influence on traffic safety was summarized. To make the generated energy usable, a convenient connection with the power grid through modularized controllers and inverters was developed and tested in a lab setting. It was verified through the lab testing that such a prototype can realize the proposed functionalities very well. Based on the developed system and including cost of materials, construction, and maintenance, a cost-benefit model was created to analyze the possible scenarios for MnDOT to implement such a system and to guide MnDOT in its decision.

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HARNESSING SOLAR ENERGY THROUGH NOISE BARRIERS AND STRUCTURAL SNOW FENCING

FINAL REPORT

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LIST OF ABBREVIATIONS

PV: Photovoltaic
MnDOT: Minnesota Department of Transportation
FHWA: Federal Highway Administration
NCHRP: National Cooperative Highway Research Program
DC: Direct Current
AC: Alternate Current
PVNB: Photovoltaic Noise Barrier
PVSF: Photovoltaic Solar Snow Fence
PP: Payback Period
NPV: Net Present Value
IRR: Internal Rate of Return
NREL: National Renewable Energy Laboratory
EPA: Environmental Protection Agency
PPA: Power Purchase Agreement
O&M: Operation and Maintenance
REC: Renewable Energy Certificate
SES: Solar Energy Standard
BOS: Balance of System
EPC: Engineering, Procurement, and Construction
ITC: Investment Tax Credit
GHG: Greenhouse Gas

EXECUTIVE SUMMARY

In 2019, the Minnesota Department of Transportation implemented more than 135 miles of noise barriers and 10 miles of structural snow fences. These installations were pure expenditure in a sense and cost more than $200 million. Enhancing them through solar integration could provide progress toward MnDOT's goals to support renewable energy and reduce carbon pollution and achieve operational cost savings.

With such an initiative in mind, systematic research was conducted during the past two years and reported in this final report. The entire report is separated into nine chapters that cover the literature review and the surveys as well as the surveys' data analysis about the public's, farmers', and utility companies' acceptance of harnessing solar energy through rights-of-way. Further, the research team designed a solar noise-barrier and snow-fence system using commercial and self-designed brace schemes. The stability and suitable dimensions of the solar highway structures and their detailed connections were provided. Adopting solar noise barriers and snow fences will affect traffic, thus a thorough study of noise reduction was conducted in Chapter 4, with minor degrading of the existing noise barrier expected (2%). Sun glaring can also be an issue when solar panels are installed on noise barriers and snow fences. A lab and numerical model through Solar Glare Hazard Analysis Tool (SGHAT) were conducted. For an entire year in Minnesota, during about 373 minutes, travelers may feel a temporary influence on their driving if they are without protections such as sunglasses. Snow causes many issues for traffic. A systematic, numerical modeling through ANSYS fluent, a numerical analysis software, was conducted. A similar trend was observed with the numerical model compared to the field measurement conducted in the 1990s. The terrain profile's effect was included in the modeling. Trenches or hills change the snow-drifting profiles, to a minor degree, and reduce the snow fence's effectiveness. The durability of the solar highway structure was also evaluated for its impact and collision safety. Low- and high-velocity impacts were conducted on the solar panels. The fragment sizes and their speeds were recorded with a high-resolution digital camera. An analysis of the recorded images shows that the fragments move at a slow speed and in different sizes (typically 1/10 of the original structure), which will not pose safety challenges to the travelers.

With the functionalities of the solar highway systems tested, the next step is to determine how to connect the electricity generated to the power grid. When many solar panels are used, the connection used between the panels is another critical issue that needs to be addressed. In this project, a Gallium Nitride Mosfets-based controller and inverter are designed, which could modularize the solar highway system and enhance its efficiency. Different load scenarios have been used in the lab and ambient settings. The DC voltage generated through the solar panels has been converted to an AC charge and has reached the power-grid level.

Cost-effectiveness is a key concern that could prevent MnDOT from implementing the new technology. A systematic, cost-benefit model is thus created for this purpose and applying the solar system to an existing noise barrier or snow fence or applying it to new construction is also studied. Different times to the breakeven point are calculated. It is shown that most solar highway systems can reach a full profit model in 10-12 years with the potential to shorten the payback period through a power purchase agreement (PPA). Considering the service of highway accessory structures, their useful life cycle is typically 25-30 years, which will create a profitable period of at least 15-20 years.

Key Takeaways

- Through the survey, about 90% of general-public respondents supported the idea of using solar panels on noise barriers along highways, and 84% still supported it even though the noise barrier's appearance would change because of the solar panels' installation.
- Only about half of general-public respondents indicated they would support this project if using solar panels would result in less noise reduction, which shows the general public's concern about this project's potential influence on the barrier's effectiveness.
- Through extensive lab and field experiments and numerical simulations, an integrated solar noise-barrier and snow-fence system has been developed. The modularized Ganfet-based inverter and controller were designed to connect different solar panels and power grids. The prototype has been verified as being able to reach the intended functions and can be connected to power grids.
- The proposed solar noise-barrier or snow-fence system will not affect traffic safety, slightly reduce the noise reduction level (by 2%), have a minimum glaring period (373 minutes a year), and can seamlessly serve the two intended purposes: noise reduction or snow drifting control; and energy production.
- Adding photovoltaic (PV) panels on noise barriers will shorten the payback period of a noise-barrier project, thus making it more cost-effective and attractive.
- Structural snow fences are not typically used in summer, and the installation of PV panels on them will add more value to the structural snow fence. Additionally, photovoltaic snow fence (PVSF) will be good for the environment through the generation and use of renewable energy.
- Considering the PV system as a standalone project, the payback period would be 19-plus or 10-plus years if installed on a 1-mile or 1,000-mile noise barrier, respectively, and 22-plus or 12-plus years if installed on a 1-mile or 1,000-mile snow fence, respectively. A power purchase agreement (PPA) would significantly shorten the payback period in consideration of the key benefits brought through a PPA to MnDOT, including minimal up-front capital costs, lower energy costs, no risk, no upkeep, leveraging available tax credits, and enhancing the value of the property.
- Installing PV panels on 1 mile of NEW noise barriers (considered as a whole project) is not cost-effective unless environmental and societal benefits like the cost of carbon are included in the cost-benefit analysis. This suggests that these types of applications would be a lower priority for the agency.
- Installing PV panels on 1 mile of EXISTING noise barriers (as a whole project) through a PPA would result in minimal up-front costs with nearly zero years of payback. This suggests that these types of applications would be a higher priority for the agency.
- A PPA for PV panels installed on 1 mile of NEW structural snow fences (considered as a whole project) pays back in 4 years, even when environmental and societal benefits are not included in the cost-benefit analysis. This suggests that these types of applications would be a higher priority for the agency.
- A PPA for PV panels installed on 1 mile of EXISTING snow fences (as a whole project) pays back in just 1 year, even when environmental and societal benefits are not included in the cost-benefit analysis. This suggests that these types of applications would be a higher priority for the agency.

- For <u>a 20-foot-tall noise barrier wall</u>, installing standard PV panels (8’ × 4’) on the side facing south with a 45° tilt angle (fixed installation) and 3 layers (1,980 panels per mile) is the most cost-effective design and thus recommended.
- For an 8-foot-tall 50% porosity structural snow fence, installing customized PV panels (12’ × 0.7’) facing south with a 45° tilt angle (fixed installation and 3,520 panels per mile) is the most cost-effective design and thus recommended.
- For PV noise barriers or snow fences, the longer the length, the more cost-effective the project. Therefore, a 1,000-mile PV noise barrier or snow fence project has a shorter payback period and is more cost-effective than a 1-mile project.
- Applying the findings of this research will require collaboration across the agency to understand the technical, regulatory, and environmental aspects of implementation. When the research is implemented, the legal team of MnDOT would need to confirm that selling electricity to a utility is not considered commercial activity on the rights-of-ways (ROW).

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

MnDOT is interested in exploring the possibility of harnessing solar energy from snow fences and sound barriers. Minnesota needs hundreds of noise barriers and thousands of miles of snow fencing. Assume that each solar panel is about 330 W and that 1,000 panels could be integrated into 1 mile of noise barrier or snow fence. Considering that the solar irradiance changes throughout a year, these panels could generate up to 330 kW per mile, which is equivalent to 1,300 kWh of energy per mile per day, on average.

To move forward with this initiative, the research team conducted a series of surveys and created a preliminary design for the system. The surveys were given to the general public, utility companies, and landowners. The results of these surveys were summarized in this report and a preliminary design for the system's structural and electrical components was developed. This project's findings will be submitted to the Minnesota Department of Transportation (MnDOT) and will help with the agency decide whether to implement this technique in the state.

1.2 INITIAL ASSESSMENT OF RESEARCH BENEFITS

1.2.1 Improved Life-cycle Costs

As found on the MnDOT website:
(https://www.dot.state.mn.us/environment/noise/pdf/guidance/faqs.pdf), 135 miles of sound barriers were built before 2016, and in 2019, there were 70 miles of living snow fences along state and federal highways, 30 miles of corn rows or hay bales, and 10 miles of structural fence.

(https://www.mprnews.org/story/2019/02/03/mndot-new-snow-fencing-paying-dividends-this-winter).
If an integrated solar system is added, the material and installation cost is $2.70/watt DC for the residential scale (3-10 kW), $1.83/watt DC for the commercial scale (10 kW-2,000 kW), and $1.06/watt DC for the utility scale (>2,000 kW). If the sellback price is assumed to be $0.08/kwh, the operational and maintenance cost is $12/kW/year, and the payback time is 13.83 years, including the insurance cost, system loss, and a 30% tax credit. Considering the 25-year service life for structural snow fences and sound barriers, it is estimated that the life-cycle costs have improved, reaching a net gain for half of the structures' service life.

1.2.2 Technology

This project developed an integrated energy-harvesting system along roadways, which is a new technology that will produce green energy, will not occupy additional land, and is easy to construct. With these components designed in detail and on record, including the connections, electrical connectors, and controllers and converters, the technology is ready to be implemented and extended to other states.

1.2.3 Safety Improvements

In addition to improved life-cycle costs, enhanced safety, including reduced snowdrift, similar noise reduction as the existing noise barriers, and low-voltage operations through the system's modular configuration, was considered for the project. With better snow control, traffic safety is expected to improve along with the consistent noise reduction that the original noise-barrier and snow-fence system gave.

CHAPTER 2: LITERATURE REVIEWS AND SURVEYS

The Federal Highway Administration (FHWA) has determined that the use of highway right -of-ways (ROWs) to accommodate public-utility facilities is in the public's interest. Many state DOTs already implemented this technique for various projects (FHWA, 2016), such as the I-5/I-205 interchange's solar demonstration project in Oregon, the 115 kW I-280 veteran's glass city skyway bridge in Ohio, and the Massachusetts solar photovoltaic (PV) program. The business model could be adapted to include DOTs leasing the ROW to utility companies or private developers, DOTs hiring contractors to install the energy-harvesting facility and then utilizing the energy produced for transportation lights and other systems, etc. Technically, the highlights of harvesting solar energy through ROWs lie in the connection design for mounting PVs, the electric-circuit integration between panels and with the power grid, and changes brought into the existing highway structures by mounting PVs. For these aspects, the FHWA is the leading agency that makes advances (FHWA, 2016, 2017). State DOTs followed this trend and implemented many demonstration projects (Carder & Barker, 2006; Oregon DOT, 2016). European researchers are also on the forefront of developing such a technique. They have been researching to develop PV noise barriers in England and the Netherlands (Morgan, 2006; Vanhooreweder et al., 2017). Even though the previous research created the foundation for this project, the details of using the existing noise barriers and snow fencing for PVs need to be researched and evaluated comprehensively; items to examine include the connection design and evaluation for mounting PVs on concrete, steel, and wooden posts; the integration of energy harvesting and the structural functions for these systems; the side effects caused by PV mounting; and the ways to utilize the power.

Interviews and surveys were conducted with the general public, utility companies, and landowners. The survey forms used for this study are attached to this report (Appendix A). More than 50 households, 21 utility companies, and 20 landowners were interviewed or surveyed. The households who took the surveys were either familiar with noise-barrier walls or were living in the communities that are adjacent to highways/noise barriers. The 21 utility companies were surveyed with an online form created on Survey Monkey (https://www.surveymonkey.co.uk/r/QQL98F3). The survey for landowners who own farmland that is adjacent to highways (I-94, US-10, 2, and 59) was conducted with phone interviews. The survey results are summarized below, and more details, including comments, can be found in Appendix B. Figures 2.1, 2.2, and 2.3 show the survey results for the general public, utility companies, and landowners, respectively.

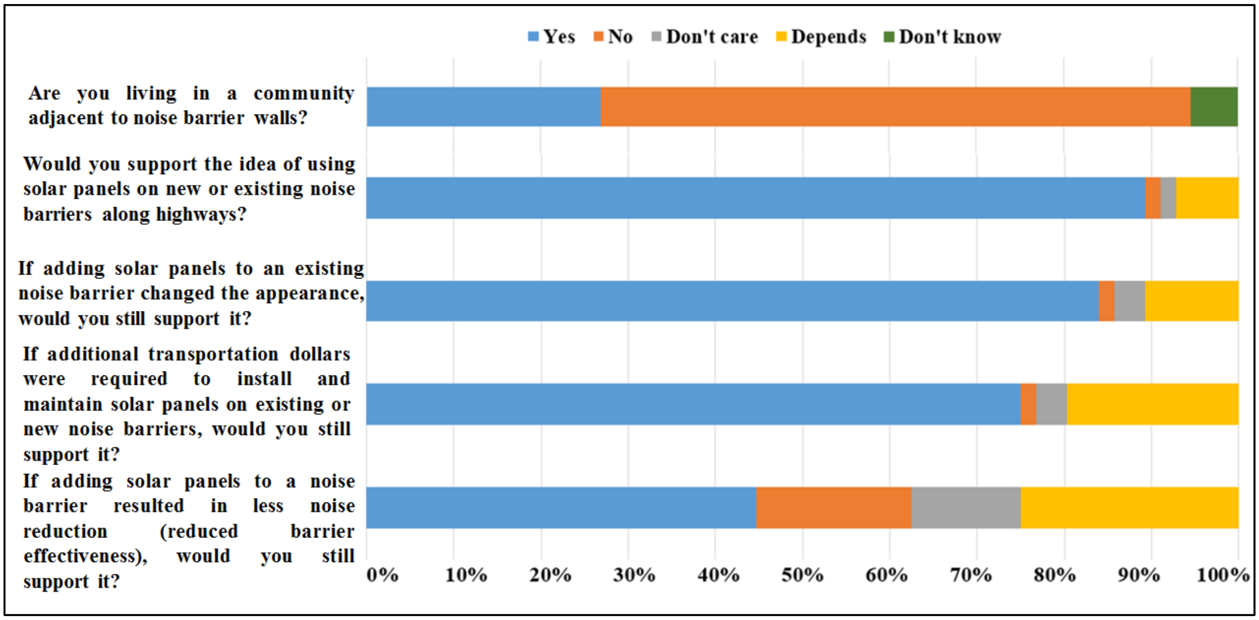


Figure 2.1 Survey results for the general public

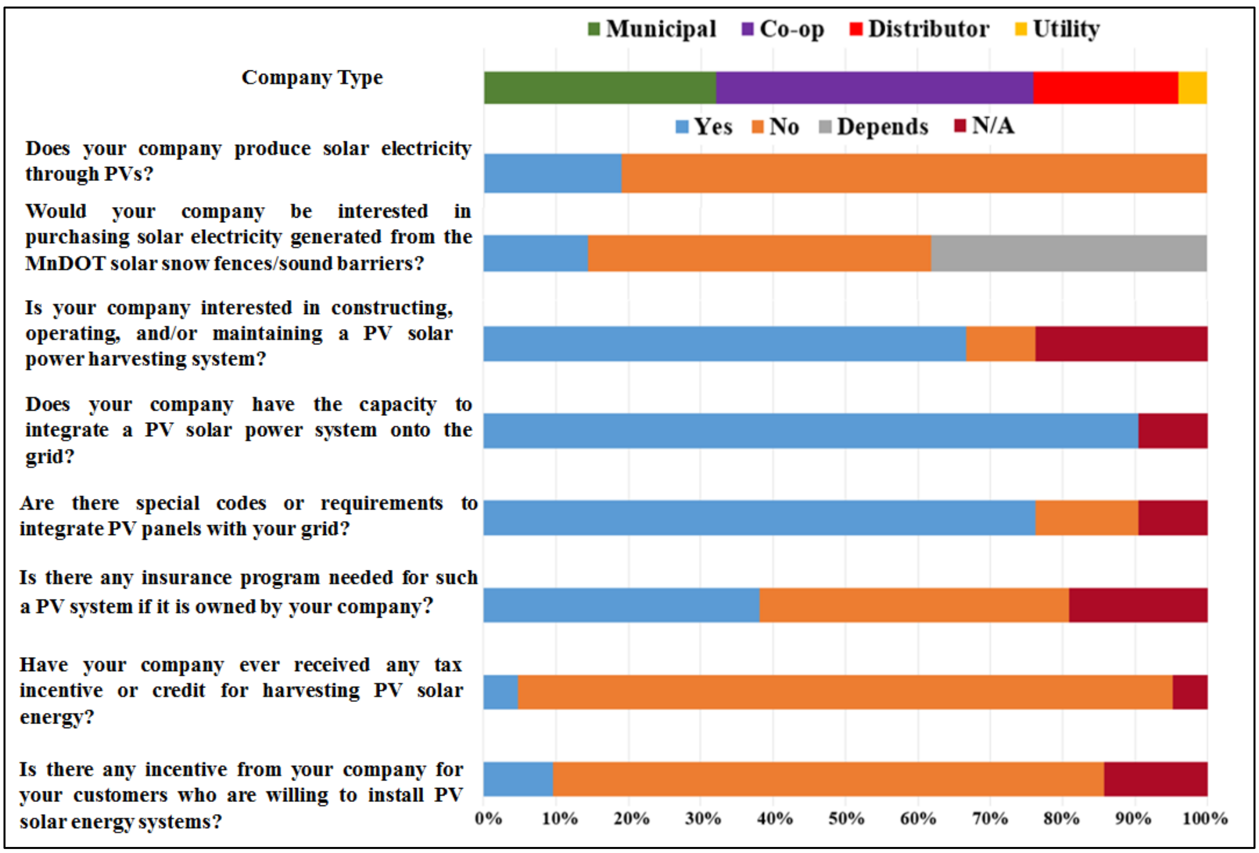


Figure 2.2 Survey results for the utility companies

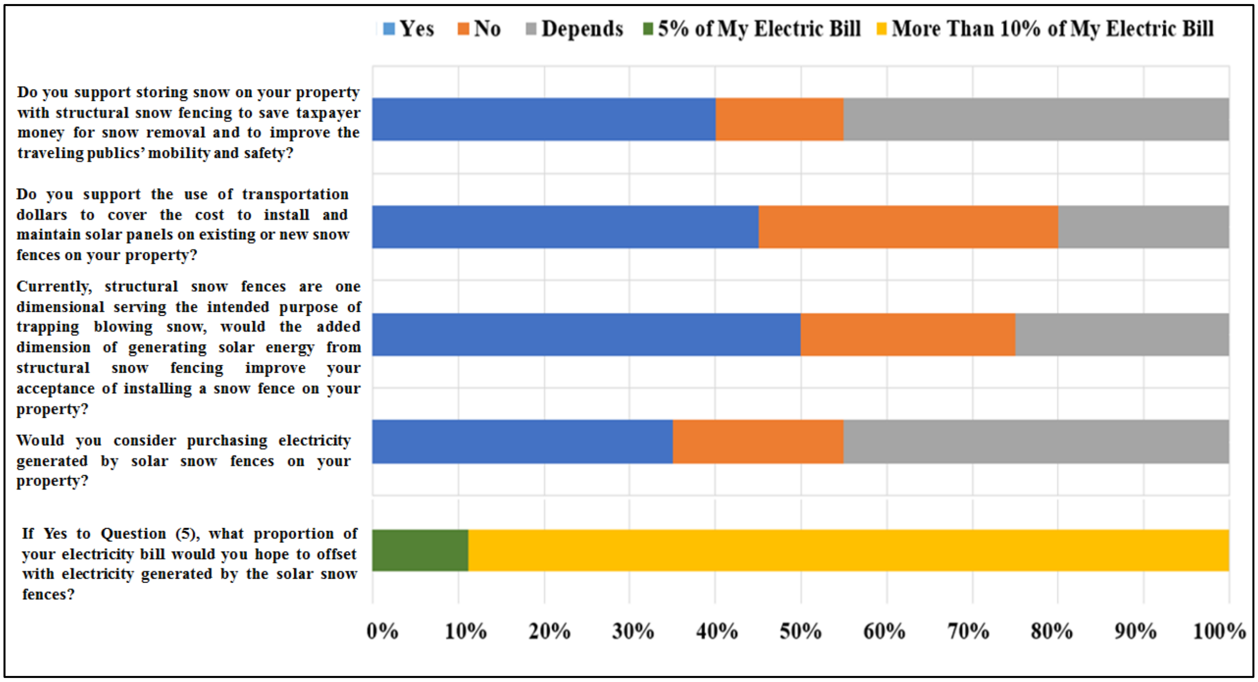


Figure 2.3 Survey results for the farmland owners

As shown in Figure 2.1, about 90% of the general-public respondents supported the idea of using solar panels on noise barriers along highways, and 84% of them still supported it even though the noise barrier's appearance will change because of the solar panels' installation. Seventy-five percent of these respondents supported the use of transportation dollars for the installation and maintenance of solar panels, and the people (about 20% of the total general-public respondents) who did not vote "Yes" but "Depends" indicated the importance and necessity of a cost-and-benefit analysis. However, only about 45% of the respondents indicated that they would support this project if using solar panels would result in less noise reduction, which shows the general public's concern about this project's potential influence on the barrier's effectiveness. This response emphasized the need and importance of an appropriate design, as part of this project, to retain the barrier's effectiveness when adding solar panels to it.

As shown in Figure 2.2, about 44% of the surveyed utility companies were co-ops; 32% were municipal utilities; and 20% were distributors. Most of the surveyed companies (81%) did not produce solar electricity with PV panels. About half of the surveyed companies (48%) were not interested in purchasing solar electricity that is generated from the MnDOT PV panels, and 38% of these utility companies voted "depends" on "price," "size of the PV solar field," "contract and/or agreement with their power suppliers or G&Ts," "Public Utility Regulatory Policies Act (PURPA)," or "MN net metering laws." Therefore, only 14% of them voted "Yes." However, about 67% of the surveyed utility companies were interested in constructing, operating, and/or maintaining a PV solar-power harvesting system, and most of them (90%) indicated that their companies have the capacity to integrate a PV solar-power system onto the grid. From the survey, we can also see that only 5% of the surveyed companies have ever received a tax incentive or credit for harvesting PV solar energy, and most of them (90%) do not provide any incentive to customers who are willing to install PV solar-energy systems.

Figure 2.3 shows the survey results for farmland owners, where 40% of them supported the installation of structural snow fencing on their properties, and 45% said “depends” on “compensation,” “can do it for non-agriculture field,” etc. (See Appendix B for more details.), meaning that 15% of them said “No.”. When asked “Do you support the use of transportation dollars to cover the cost to install and maintain solar panels on existing or new snow fences on your property?”, 45% of the surveyed landowners said “Yes”; 20% of them said “depends” on “size,” “efficiency,” and “if it is profitable”; and 35% said “No.”. Their acceptance of installing snow fences on their property appeared to increase a little bit (from 40% to 50%) due to the added dimension of solar panels on the snow fences. (50% voted “Yes”; 25% voted “Depends”; and 25% said “No.”). When they were asked if they were interested in purchasing the electricity generated by solar snow fences on their property, 35% of them said “Yes,” and about half of them (45%) said “depends” on “cost/price,” “discount,” or “only if it would offset the losses.”

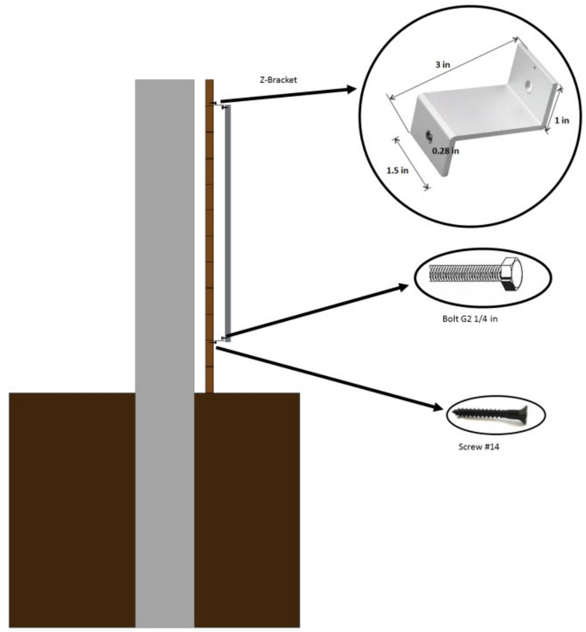
CHAPTER 3: SOLAR SOUND BARRIER AND SNOW FENCE STRUCTURAL DESIGN

3.1 THE SOLAR SOUND BARRIER'S STRUCTURAL DESIGN

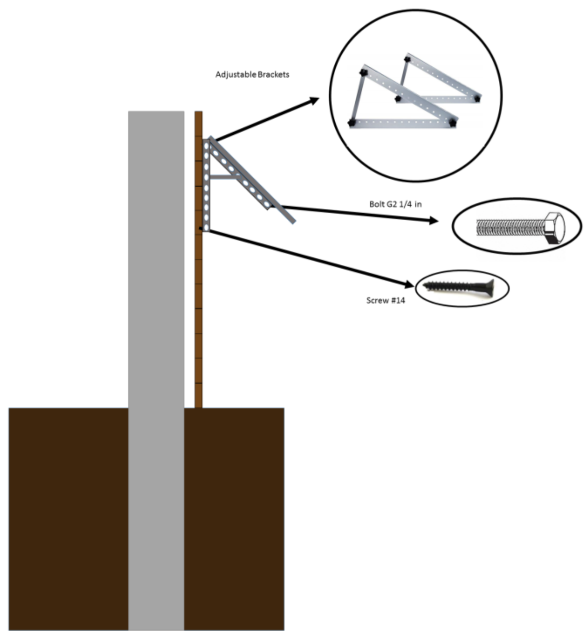
The solar sound barrier's structural design includes panel selection, connector design, post design, and foot design. The loads considered are self-weight of the panels and wind-load. With Minnesota's geographic location, the wind pressure for such a system is 30 psf. The self-weight of each panel (4x8 ft) is estimated to 60 lbs. Based on these loads, the load demand and the capacity for each component in the suggested system is shown in Table 3.1. The configuration for the entire system is shown in Figure 3.1.

Table 3.1 The load demand and the capacity of the suggested system

Noise-barrier component	Product	Vertical load demand	Capacity (or weight)	Lateral load demand	Capacity
Solar panel	Panasonic HIT N330 Watt Mono Solar Panel	--	40.81 lbs	--	50 PSF (2400 Pa)
Bracket	1/8'' thick and 1.5'' wide aluminum, z-shape brackets	--	1000 lbs	--	1000 lbs
Connection between bracket and solar panel	¼'' Grade 2 bolts	15 lbs	1766 lbs	160 lbs	1060 lbs
Connection between bracket and noise-barrier wall panels	#14 screw	15 lbs	715 lbs	160 lbs	429 lbs
Noise-barrier wall panels	2x8	--	--	1920 lb-in	14703 lb-in
Post	12x18 reinforced concrete	--	--	92,000 lb-in	600,000 lb-in
Connection between noise-wall panels and the noise-barrier wall post	Use current MnDOT configuration	--	--	--	--
Connection of the wall post with the foundation	7-ft embedded length	--	--	7680 lb-ft	8733 lb-ft



(a) Vertical-mounted solar-energy harvesting system



(b) Tilt-mounted solar-energy harvesting system

Figure 3.1 Configuration of the suggested, integrated solar sound barrier or snow fence

3.2 COMMERCIAL ON-SHELF CONNECTION FOR A SOLAR NOISE BARRIER OR A SNOW FENCE

Commercial connections are available on the market, and they could be used for solar noise barriers or snow fences. The research team searched the available products and found that the connectors manufactured by Engineered Power Solutions fit the purposes of solar noise barriers or snow fences. The connector and the setup configuration are shown in Figure 3.2. In order to demonstrate the setup's final configuration, a demonstration of the assembly for the solar panels (at NDSU's Structural Lab) is shown in Figure 3.3.

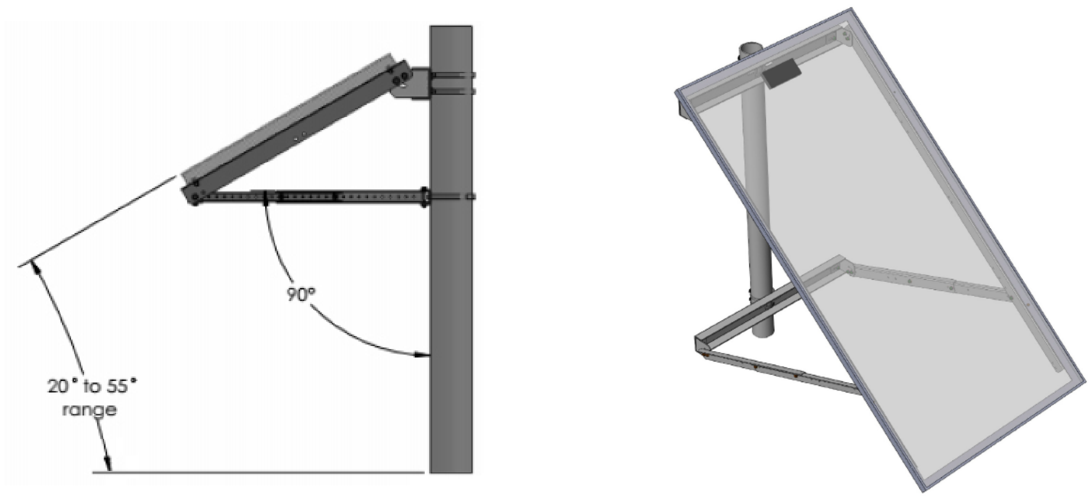


Figure 3.2 Suggested connection and its field setup

Figure 3.3 The assembled solar panels using the suggested connectors

3.3 THE SOLAR SNOW FENCE'S STRUCTURAL DESIGN

For snow fences, PV panels are installed next to each other using pole mounting (Figure 3.4). For snow-drifting purposes, it is better to install the solar panels on the two top rows because the snow accumulation blocks the radiation for the two lower rows. Based on the catalog provided by Engineered Power Solutions, the mounting connection in Figure 3.4 withstands 30 psf (115-mph wind loads) with high-tensile strength and corrosion resistance.

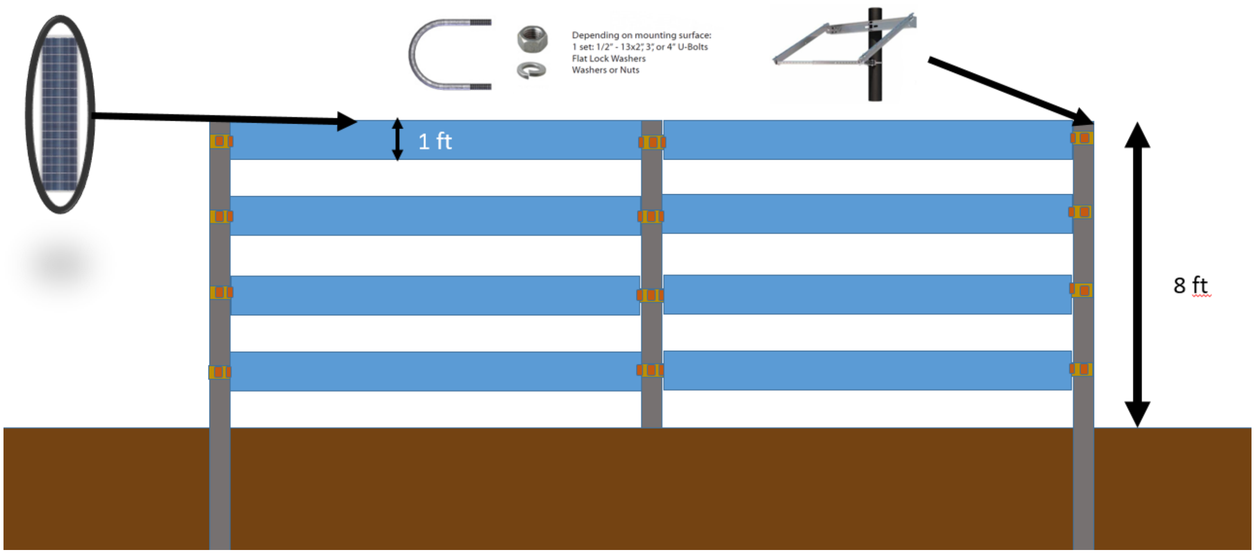


Figure 3.4 Configuration for the integrated snow fence

3.4 SIMPLIFIED CONNECTION FOR SNOW FENCES

For construction convenience, a simplified connection is suggested for the solar snow fences. Considering that vertical loads due to self-weight are 60 lbs and that horizontal loads are 960 lb per panel due to the 30-psf wind load applied to the 4x8 panels, a steel post with side wings is suggested for the solar snow fences as shown in Figures 3.5 and 3.6. For the extended wings coming from the solar panels, a steel plate of A36 1/4x2 is selected. Its shear capacity is 0.9x0.6x36x1/4x2x4=38.88 kips > 0.96 kips. The two wings on the HSS section post could be welded with the same plate size. The bolts are 1/4'' grade-2 bolts, with a tension capacity of 1.77 kips and a shear capacity of 1.07 kips for each one. The screws to the solar panel are #14 screws. There are two screws at each location.
For bolt, the tension and shear capacities are checked:

1. Tension failure: 1.77 kips>120 lb
2. Shear failure: 1.07 kips>8.75 lb

For the connection plates, the following conditions are checked:

1. Tension rupture: P= 0.75x(2-(1/4+1/8)x2) (0.25) (58) =13.59 kips> 8.75 lb
2. Shear rupture: P= 0.6 x (2-(1/4+1/8)x2) (0.25) (58) =10.87 kips >8.75 lb
3. Bearing: P=1.8 x 36 x1/4 x1/4x2=8.10 kips>8.75 lb
4. Tensile yielding: P= 0.9x36 x2 x0.25=16.20 kips > 8.75 lb
5. Tear out: P=0.75x0.6x58x(1/2-(1/4+1/8)*0.5)(1/4)x4=8.16 kips >8.75 lb.

For welds of the extension wings: P=0.75x0.6x60x0.707x2x ¼=9.54 kips > (12.5 x12.5+240 x240) ^ (1/2) = 240.32 lb.
For the bending moment at the post's base: M = 480 x (30''+22'') + 480 x (22'') = 2.960 k-ft<Moment capacity of 2x2x1/4 tube (28.9 k-ft).
In conclusion, the connection design is more than adequate to support the solar panels.

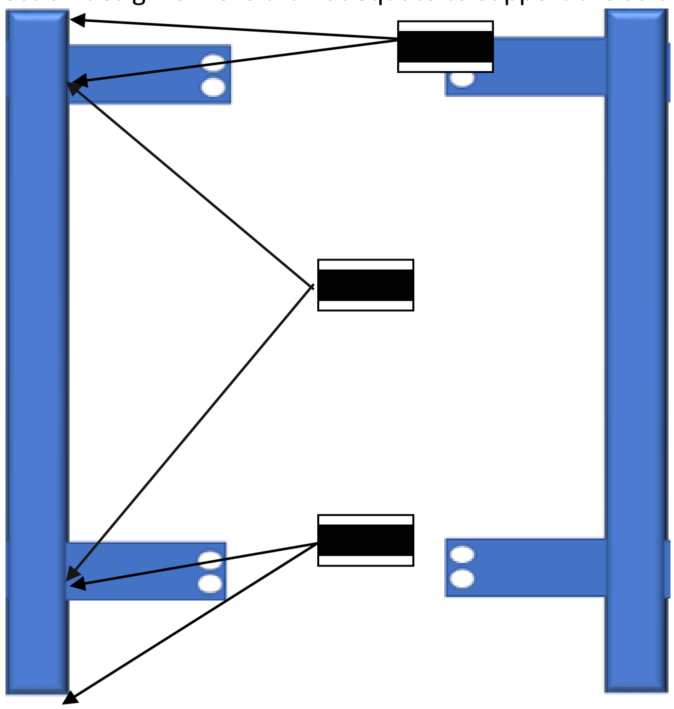


Figure 3.5 Steel post with side wings for solar snow-fence connections

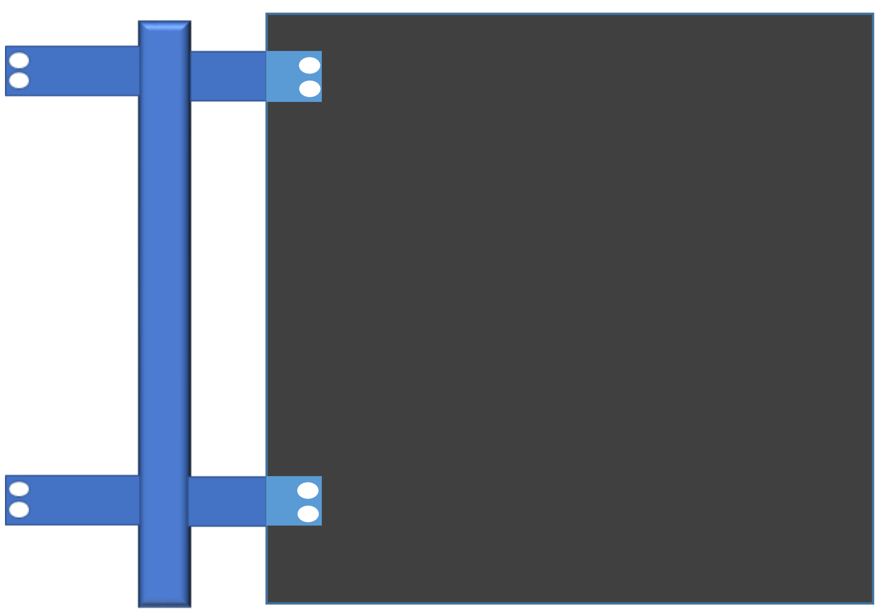


Figure 3.6 Connections between solar panels and the steel post

A prototype of the solar system is set up at NDSU's Structural Lab by using the suggested steel posts and connectors (Figure 3.7). The system is easy to install.

Figure 3.7 Prototype of the solar system using the suggested steel posts and the simplified connectors

CHAPTER 4: SOUND LOSS WITH THE SOLAR SOUND BARRIERS

Insertion loss can be estimated using the model proposed by Kurze and Anderson (1971), which compiles data from many researchers onto a set of equations (Eq. (1) and (2)) for a point source (Figure 4.1).

$$IL = 5dB + 20\log\left(\frac{\sqrt{2\pi N}}{tanh\sqrt{2\pi N}}\right) \quad up\ to\ N = 12.5 \tag{1}$$

$$IL = 20\ dB\ for\ N > 12.5 \tag{2}$$

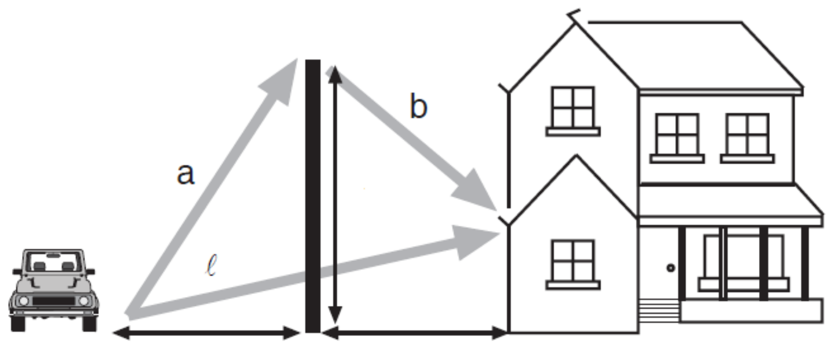


Figure 4.1 Sound-loss calculation diagram

N is defined as the Fresnel number, a non-dimensional measure of how much farther the sound must travel as a result of the barrier. It is calculated with the following equation:

$$N = \frac{(a+b-l)f}{c_o} \quad , \tag{3}$$

where *l* is the original length of the direct path from the source to the receiver, *a* and *b* are the lengths of the two straight-line segments comprising the path, *f* is the sound frequency in Hz (500 Hz), and c_o is the speed of sound propagation in the air (approximately 1,100 ft/sec).

Based on the above-mentioned equations, insertion loss has been calculated and is shown in Table 4.1 for different noise-barrier heights and different distances between the highway and the receiver. L_t is the distance between the noise wall and the nearest tire; L_h is the distance between the noise wall and a house or residential complex; and the window height (W_h) is 4 ft.

Table 4.1 Insertion loss for different noise-barrier locations and heights

(Noise-barrier height = 8 ft)

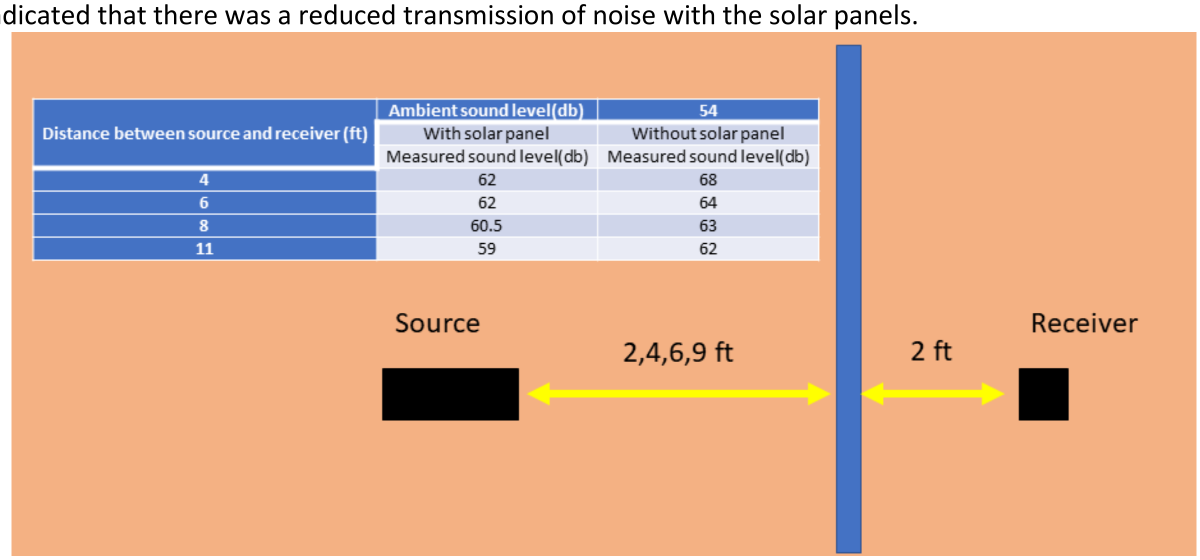
L_t (ft)	L_h (ft)	W_h (ft)	*a* (ft)	*b* (ft)	*l* (ft)	*N*	*IL (dB)*
10	10	4	12.8	10.8	20.4	1.45	14.60
10	15	4	12.8	15.5	25.3	1.37	14.37
10	20	4	12.8	20.4	30.3	1.33	14.26
15	25	4	17	25.3	40.2	0.96	12.88
15	30	4	17	30.3	45.2	0.95	12.82
15	35	4	17	35.2	50.2	0.94	12.78
20	40	4	21.5	40.2	60.1	0.73	11.74

20	*45*	*4*	*21.5*	*45.2*	*65.1*	*0.73*	*11.71*
20	*50*	*4*	*21.5*	*50.2*	*70.1*	*0.72*	*11.68*
25	*55*	*4*	*26.2*	*55.1*	*80.1*	*0.59*	*10.86*
25	*60*	*4*	*26.2*	*60.1*	*85.1*	*0.59*	*10.84*
25	*65*	*4*	*26.2*	*65.1*	*90.1*	*0.58*	*10.83*

From Table 4.1, we can see that the 8-ft noise barrier could reduce the noise level by at least 10 dB, which is quite impressive.

4.1 NOISE-REDUCTION TESTING

A noise-reduction test is conducted in the Structural Lab. The source level is set 3 ft above the ground while the receiver is located 4 ft above the ground to mimic the height of residential windows. The noise source's location is varied, as shown in Figure 4.2, to see the transmission's mitigation effect. From the data collected, we could see that the transmission-mitigation effect exists and has an average inert loss of 3.38 dB. Theoretically, the insert loss is estimated to be 15.65 dB. Due to the solar panel's small size and the Structural Lab's enclosed space, the lab's testing results are not accurate; however, the tests indicated that there was a reduced transmission of noise with the solar panels.



Distance between source and receiver (ft)	Ambient sound level(db)	54
	With solar panel	Without solar panel
	Measured sound level(db)	Measured sound level(db)
4	62	68
6	62	64
8	60.5	63
11	59	62

Figure 4.2 The reduced noise which is transmitted through the solar panels

4.2 NOISE-REDUCTION MODELING

Insertion loss is simulated for a solar noise barrier which is installed along a section of I-94 in Clay County; the simulation was done using the traffic noise modeling software (TNM) recommended by the FHWA. For this purpose, a typical noise barrier with a height of 15 ft and a length of 1 mile is defined in Clay County along the I-94 interstate highway (Figures 4.3 and 4.4). Besides the walls' effect, the solar panels' influence must be considered. This effect can be considered by defining the noise barriers' noise reduction coefficient (NRC). For this project, the NCR for the walls covered by solar panels is assumed to be 0.05, which is equal to the NCR value for glass. For the noise-absorbing concrete, the NCR is assumed to be 0.2. The point which must be emphasized is that the noise reduction or reflection coefficient mostly affects the noise level on the wall's opposite side. Therefore, covering a noise barrier with solar panels does not have much influence on the insertion loss through that barrier.

The main factors for calculating the insertion loss are the barrier's height and the traffic volume. Roadway input includes traffic speed and hourly traffic volumes for each vehicle type. The traffic volume can be obtained by using MNDOT traffic data. For this project, the Automatic Traffic Recorder (ATR) number for February is used. The data for the entire month are shown in Table 4.2, which illustrates the daily traffic volume for each lane (measured in 10,000 traffic volume). In the software, hourly traffic must be defined and could be calculated with the ATR data. Based on the data in Table 4.2, the maximum hourly traffic volume can be considered as 500 for the total vehicles in each lane. The ratio of passenger vehicles to the entire traffic volume is 0.9, and the remaining traffic is considered to be trucks (Table 4.3). The traffic speed is assumed to be 70 mph for all the vehicles. Based on the above-defined model, the simulated results, which were obtained by using the software, are shown in Tables 4.4 and 4.5.

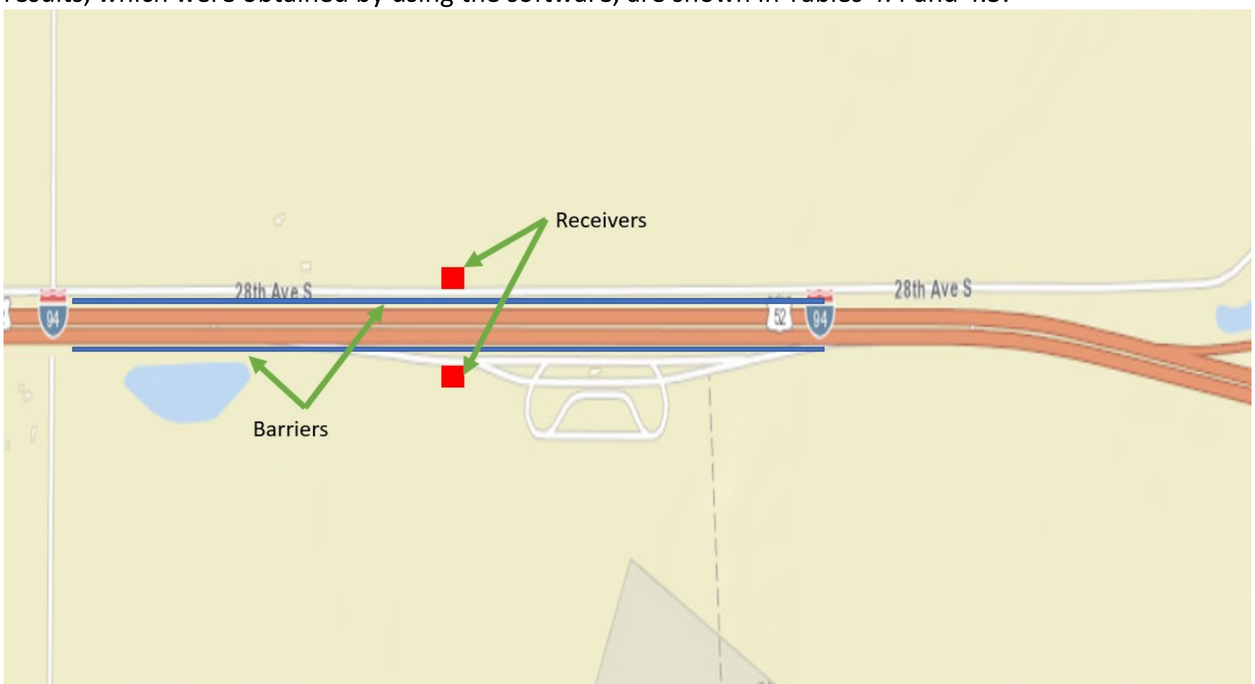


Figure 4.3 Setup of the solar noise-barrier model

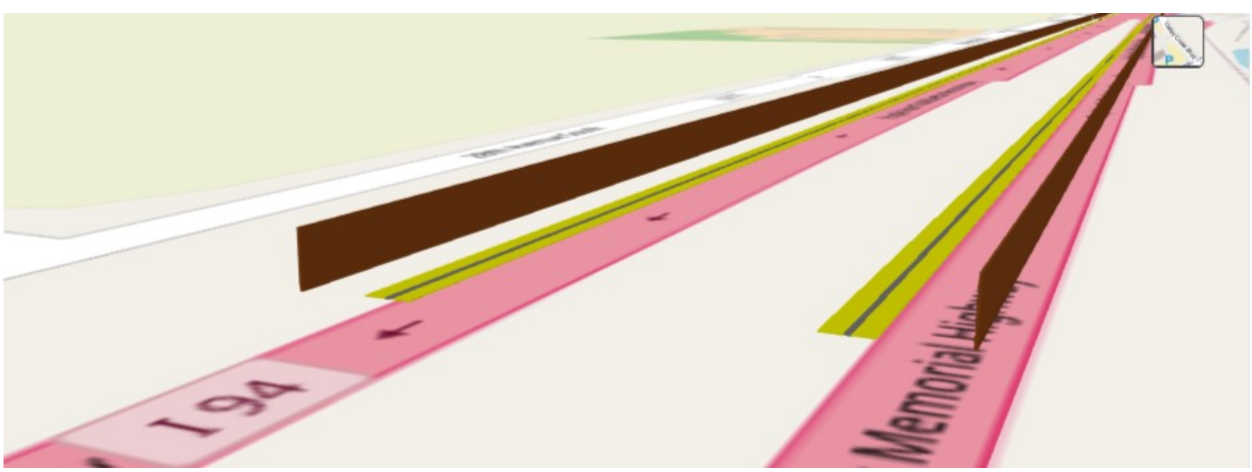


Figure 4.4 Configuration for the barrier, roadway, and traffic

Table 4.2 Monthly traffic at site 149, E OF CSAH11 IN AUDUBON on I-94 in Clay County, February 2020

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
						Date: 01 EB: 25,863 WB: 13,918 Diff: 11,945
Date: 02 EB: 22,109 WB: 11,145 Diff: 10,964	Date: 03 EB: 23,987 WB: 12,328 Diff: 11,659	Date: 04 EB: 25,133 WB: 12,886 Diff: 12,247	Date: 05 EB: 25,289 WB: 13,098 Diff: 12,191	Date: 06 EB: 25,119 WB: 13,167 Diff: 12,952	Date: 07 EB: 31,411 WB: 17,039 Diff: 14,372	Date: 08 EB: 25,582 WB: 13,377 Diff: 12,205
Date: 09 EB: 24,546 WB: 12,850 Diff: 11,696	Date: 10 EB: 25,382 WB: 12,777 Diff: 12,605	Date: 11 EB: 27,036 WB: 14,132 Diff: 12,904	Date: 12 EB: 10,427 WB: 5,410 Diff: 5,017	Date: 13 EB: 26,791 WB: 13,673 Diff: 12,918	Date: 14 EB: 33,446 WB: 18,767 Diff: 14,679	Date: 15 EB: 27,368 WB: 15,269 Diff: 12,099
Date: 16 EB: 26,364 WB: 13,551 Diff: 12,813	Date: 17 EB: 28,941 WB: 14,368 Diff: 14,573	Date: 18 EB: 25,677 WB: 12,858 Diff: 12,819	Date: 19 EB: 25,535 WB: 13,009 Diff: 12,526	Date: 20 EB: 28,025 WB: 14,540 Diff: 13,485	Date: 21 EB: 32,685 WB: 18,131 Diff: 14,554	Date: 22 EB: 26,802 WB: 14,306 Diff: 12,496
Date: 23 EB: 27,599 WB: 14,367 Diff: 13,232	Date: 24 EB: 25,625 WB: 13,008 Diff: 12,617	Date: 25 EB: 24,958 WB: 12,783 Diff: 12,175	Date: 26 EB: 25,721 WB: 13,288 Diff: 12,433	Date: 27 EB: 28,026 WB: 14,492 Diff: 13,534	Date: 28 EB: 33,260 WB: 18,337 Diff: 14,923	Date: 29 EB: 28,007 WB: 15,315 Diff: 12,692

Table 4.3 Hourly traffic in the first three days of February at station 43, westbound on I-94 in Clay County

1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
20	19	23	29	107	261	700	1058	566	426	381	372	373	326	385	470	458	476	241	174	113	79	50	32
30	26	22	30	94	250	699	975	504	438	381	414	392	357	442	483	512	421	243	178	191	138	69	46
29	20	21	34	87	197	657	904	438	470	416	496	445	390	474	552	543	566	337	250	237	155	93	66

Table 4.4 Traffic-noise modeling results for the case with solar noise barriers

Receiver name	Modified traffic-noise levels			
	Without barriers	With barriers		
	Sound level (dB)	Sound level (dB)	Noise reduced (dB)	Goal noise intended (dB)
Receiver 1	72.2	56.1	16.2	8.0
Receiver 2	74.5	56.1	18.4	8.0

Table 4.5 Traffic-noise modeling results for the case with regular, noise-absorbing concrete barriers

Receiver name	Modified traffic-noise levels			
	Without barriers	With barriers		
	Sound level (dB)	Sound level (dB)	Noise reduced (dB)	Goal noise intended (dB)
Receiver 1	72.2	55.9	16.4	8.0
Receiver 2	74.5	55.9	18.6	8.0

From the results in Tables 4.4 and 4.5, we can see that the solar noise barrier reduces the noise level by 16.2 dB and 18.4 dB for the two receiver locations while, for the regular noise barrier, the noise level is reduced by 16.4 dB and 18.6 dB for the two receivers, respectively. Even though solar noise barriers reduce the effectiveness of the current sound-absorbing noise barriers, the effect is negligible.

4.3 NOISE-REDUCTION MODELING FOR A ROAD SEGMENT WITH TWO-WAY TRAFFIC AND A SINGLE SIDE BARRIER ON I-94 IN MOORHEAD

Installing solar panels on noise barriers changes the surface's sound-reflection mechanism. Sometimes, only one side of a sound barrier is installed, and the sound transmission for such a configuration will behavior differently compared to the case in Section 4.2. Moreover, recent practice with sound barriers uses high sound-absorption materials for the sound barrier, which will add another variable to the noise-reduction modeling. Considering the high sound-absorption materials, the values for the sound absorption-coefficient are increased and are shown in Table 4.6. The reflection coefficient for glass (solar panels) is more than the value with concrete. Therefore, installing solar panels on concrete or timber walls negatively affects the noise barrier's performance. Sometimes, reflected sound is amplified and redirected, affecting residential areas due to the single-side barrier installation. To illustrate this issue, the effect of sound reduction for noise barriers covered with solar panels is compared with the existing sound-absorbing noise barrier and the typical concrete noise barrier on a single side by utilizing the Traffic Noise Model (TNM). The assumptions for this simulation are as follows:

- The barrier's height is 4.3 m (almost 14 ft).
- The lengths of the barrier and the road are 400 m.
- The number of vehicles is 500 per hour, and 10% of them are heavy trucks.

Table 4.6 Noise reduction coefficient (NRC)

Material	NRC
Sound-absorbing material	0.9
Concrete block, coarse	0.3-0.4
Glass	0.03-0.05

The TNM model does not consider the single barrier's reflection by itself. A modification for the original model is created to solve this problem. The original noise-reduction model is solved with the superposition of two models: (1) Model 1 with the noise barrier is used to calculate the noise-reduction level behind the barrier. (2) Model 2 with a mirror traffic source, but without the noise barrier, is used to capture the reflected noise level. Model 1 is self-explanatory and can be created with the TNM software. Model 2 adopts a mirror-analysis method because the TNM cannot directly model the amount of noise that reflects off a highway noise barrier. Referring to Figure 4.5, a "mirror" source (imaginary traffic) is placed on the wall's east side. The distance from the mirror source to the wall is the same as the distance from the actual roadway to the wall ("x" and "y"). One mirror roadway should be placed for each actual roadway that is modeled. Thus, in the example shown for Figure 4.6, a mirror northbound roadway is modeled, as is a mirror southbound roadway. Note that, when using the mirror source method, the wall itself is not modeled. Traffic volumes and speeds on the mirror roadway(s) should match the actual roadway(s) times (1- the Noise reduction coefficient (NRC)) because only this portion of the noise will be reflected.

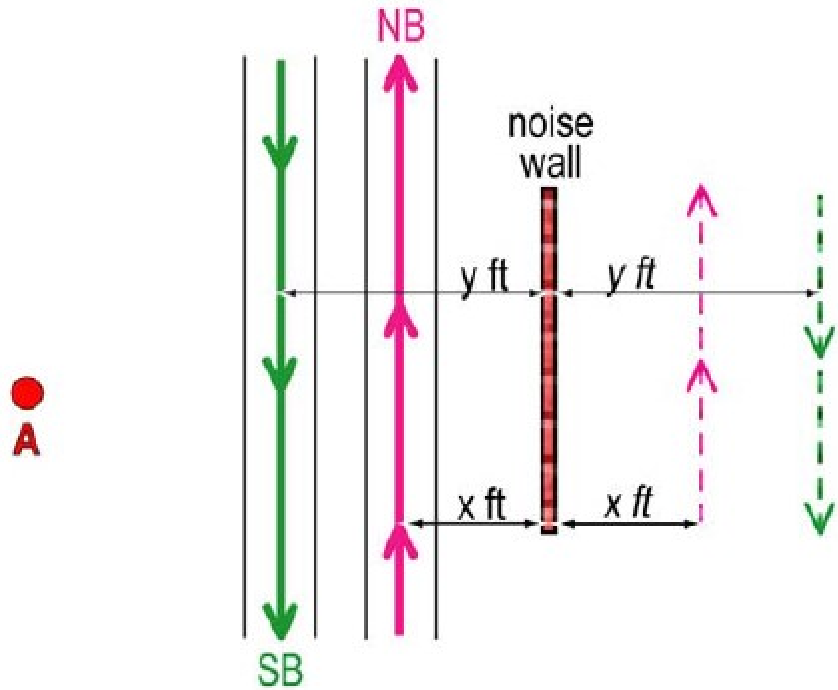


Figure 4.5 Mirror method for single-barrier noise-reflection calculations

The predicted increase for the noise levels at the receivers located opposite a reflective wall will be anywhere from a few tenths of a decibel (dB) to 2 dB. The theoretical maximum increase from doubling a line source's strength is 3 dB, which would occur when a receiver is located opposite an infinitely long, infinitely tall, perfectly reflective wall. Comparison of the relative noise increases in the above two cases proves the method's accuracy.

In all the cases modeled, part of I-94 is selected for the noise-calculation location as shown in Figure 4.6. The calculated noise level is shown in Table 4.7. From the results, we can see that the noise reduction is lessened when mounting solar panels on the noise barriers; however, the level of change is small, about 0.35 dB (0.7%). On the reflection side, a noise barrier with mounted solar panels increases the noise level by 1.0-1.6 dB (2.6%).

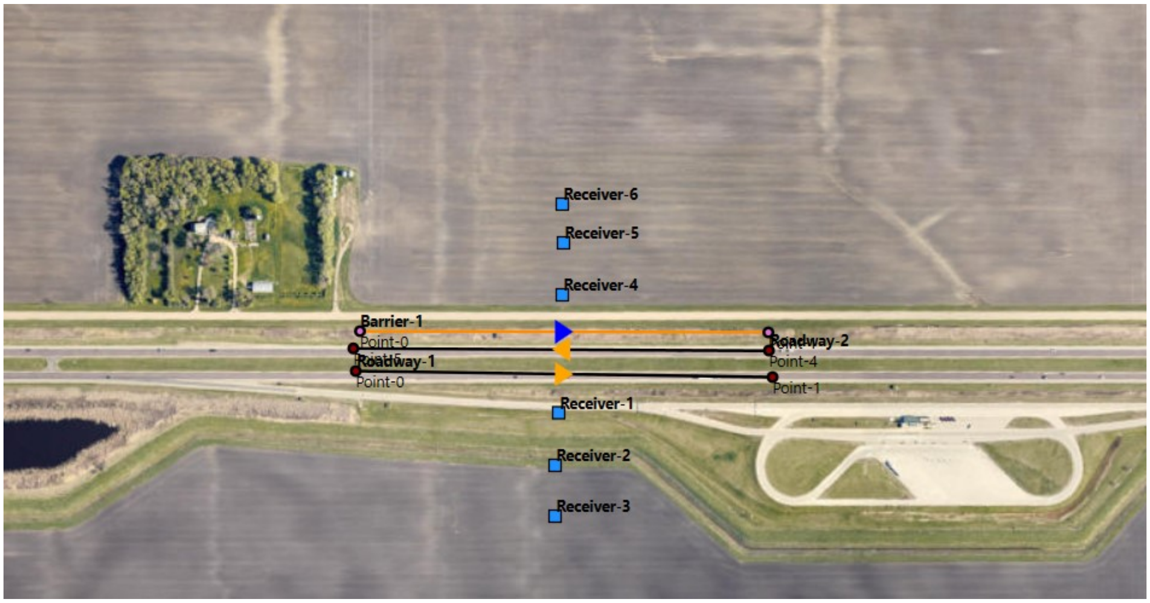


Figure 4.6 Noise barrier and road location (I-94)

Table 4.7 Results for the noise level using the TNM

	Receiver's sound level					
Material	1	2	3	4	5	6
Sound-absorbing material	70.13	65.55	62.70	55.36	52.97	51.72
Concrete block, coarse	70.84	66.57	63.86	55.69	53.23	51.97
Glass	71.14	66.97	64.30	55.79	53.30	52.04

CHAPTER 5: SUNLIGHT-GLARE ANALYSIS OF SOLAR NOISE BARRIERS

5.1 SUNLIGHT-GLARE TEST FOR THE SOLAR PANELS

A sunlight-glare test was conducted at NDSU's Structural Lab. The test setup is shown in Figure 5.1.

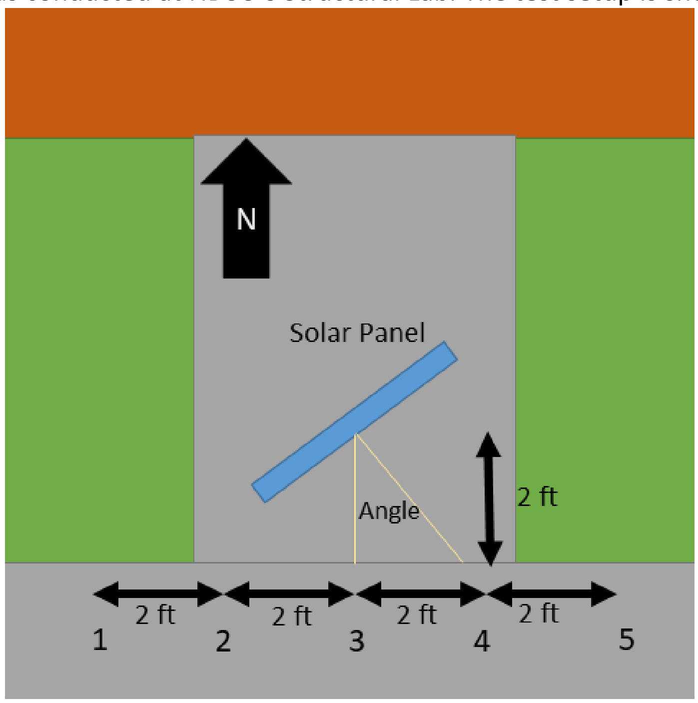


Figure 5.1 Setup for sunlight-glare testing

The intensity of the sunlight's glare was measured at three different times (10:00 AM, noon, and 3:00 PM) on June 25, 2020. The varying light intensity is recorded with an HHC250 light-intensity meter. The measurements are shown in Tables 5.1-5.3, where the light is measured by using the max/min mode right in front of the solar panel's surface. In order to avoid interference, an extension stick was used to scan the light intensity of the solar panel's surface at different measurement points. The quantified sunlight intensity is shown in Figures 5.2-5.4.

Table 5.1 Light-intensity measurement for the test at 10:00 AM

Angle (degree)	1st Point (lux)	2nd Point (lux)	3rd Point (lux)	4th Point (lux)	5th Point (lux)
0	14,979	13,470	13,250	11,130	13,210
30	9,400	8,000	8,090	6,350	11,090
45	5,829	7,240	7,730	5,780	8,400
60	7,590	8,190	8,690	10,410	11,180

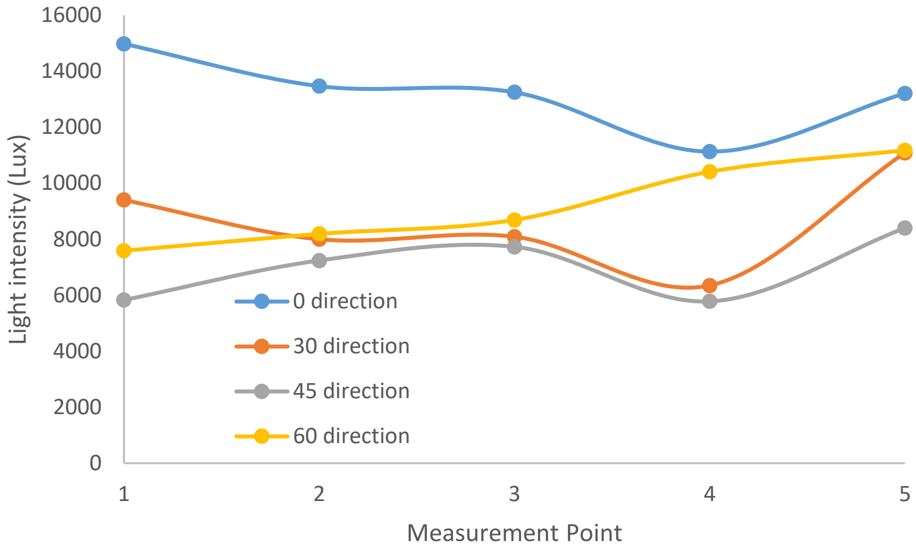


Figure 5.2 Variation of the light intensity with different measurement points and sunlight orientations at 10:00 AM

From Figure 5.2, we can see that the 0° direction has the highest light intensity, which makes senses because direct sunlight has the most-direct effect. The light intensity lessens when the measurement point comes to the middle of the panel; this finding could be due to the solar panels' light absorption. Instead of reflection, the solar panels absorbed most of the energy when the measurement was taken at the middle plane.

Table 5.2 Light-intensity measurement for the noon test

Angle (degree)	1st Point (lux)	2nd Point (lux)	3rd Point (lux)	4th Point (lux)	5th Point (lux)
0	15,640	11,550	10,250	13,440	14,020
30	14,080	14,830	13,670	13,320	14,250
45	11,820	11,750	14,470	14,410	14,140
60	12,640	9,240	10,710	12,390	13,960

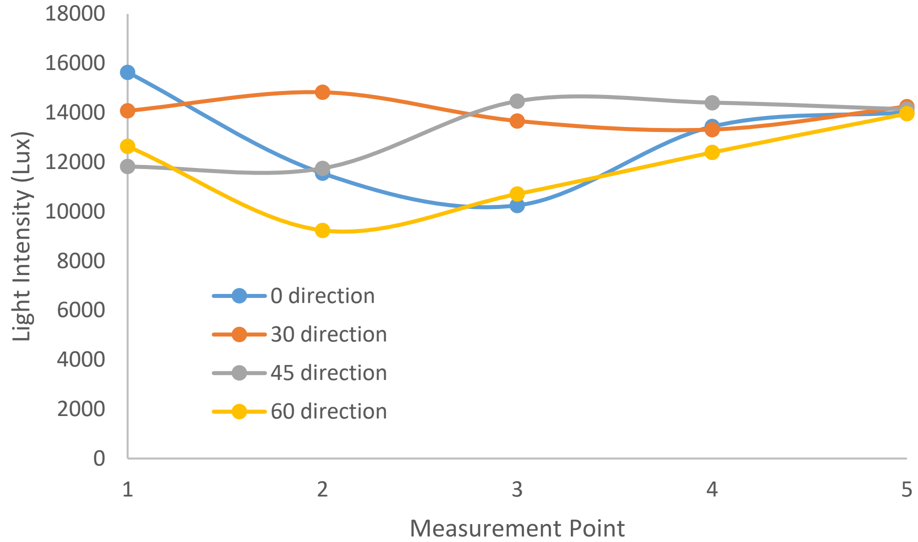


Figure 5.3 Light-intensity variation for different measurement points and sunlight orientations at noon

Table 5.3 Light-intensity measurement for the 3:00 PM test

Angle (degree)	1st Point (lux)	2nd Point (lux)	3rd Point (lux)	4th Point (lux)	5th Point (lux)
0	14,130	14,540	14,000	16,060	15,320
30	13,690	13,550	11,130	15,740	17,550
45	14,280	13,520	11,290	13,340	14,090
60	14,240	12,500	11,290	13,750	16,200

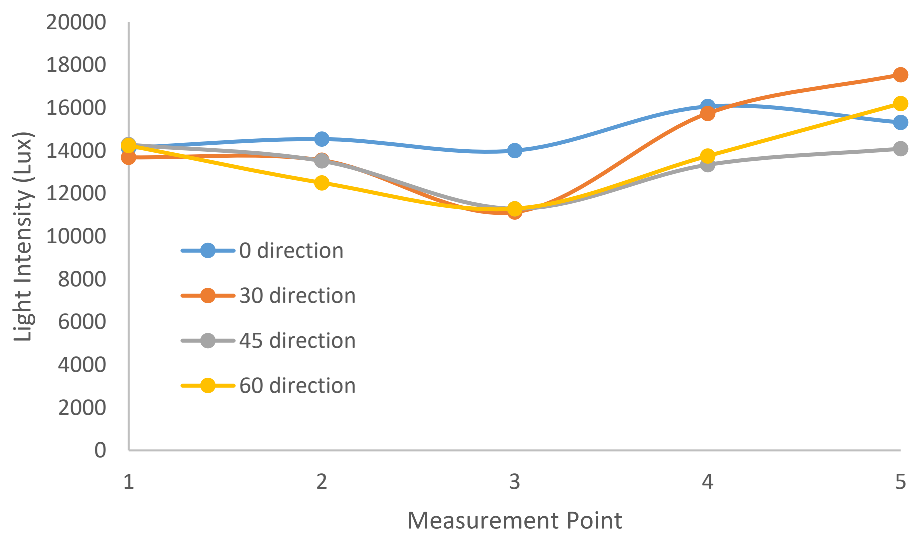


Figure 5.4 Light-intensity variation for different measurement points and sunlight orientations at 3:00 PM

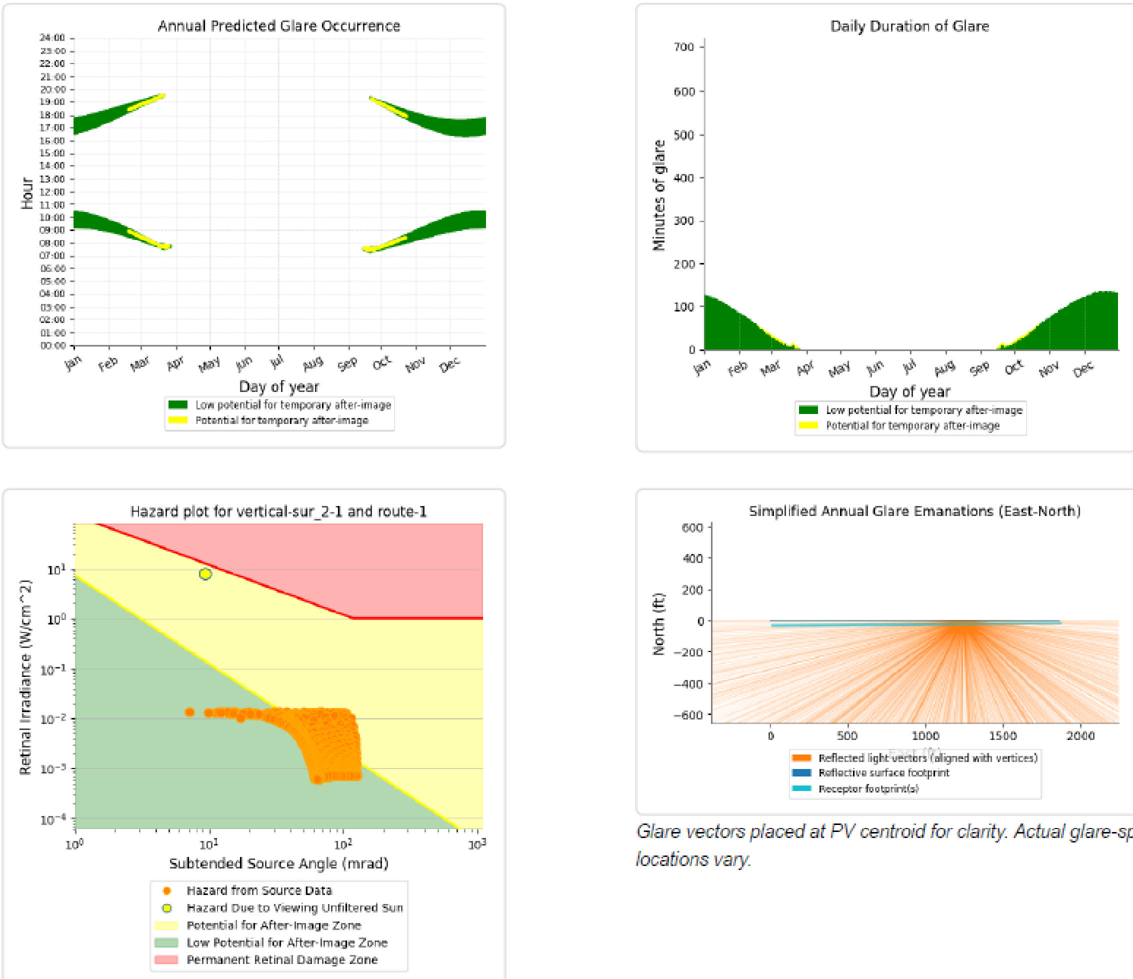
When comparing these plots, it is consistently seen that the light intensity is less when the measurement points come to the panel's middle. Moreover, the sunlight intensity is higher when the time is around noon or in the afternoon, which is reasonable for solar activities in the Minnesota and North Dakota region.

5.2 SUNLIGHT-GLARE MODELING FOR THE SAME SECTION OF I-94 IN CLAY COUNTY

Sunlight glaring was simulated for a solar noise barrier that was assumed to be installed along a section of I-94 in Clay County, the same section as in the noise reduction modeling; this task was completed by using the solar glare hazard analysis tool (SGHAT) developed by Sandia National Laboratories. For this purpose, a typical solar noise barrier with a height of 15 ft and a length of 1 mile was selected in Clay County; this barrier was along the I-94 interstate highway (Figure 5.5). The solar glare was analyzed every 4 minutes. The receiver's location was placed at 3 ft, close to the driver's eye elevation, with a view angle of 12.1^{o}.

Figure 5.5 The section of I-94 used for the solar-glare analysis

The simulation results are shown in Figure 5.6. We can see that, for a majority of the time (99.9%), the solar light will not cause any potential damage to the drivers. In a 1-year period, only 373 minutes could cause temporary after-damage without any personal protection equipment, such as sunglasses.



Glare vectors placed at PV centroid for clarity. Actual glare-spot locations vary.

Figure 5.6 The SGHAT-analysis results of the solar noise barrier along I-94 in Clay County

CHAPTER 6: SNOW-DRIFT MODELING WITH A SOLAR SNOW FENCE

During the initial stages of a drift's growth, the snow particles that pass through a porous barrier encounter a zone of diminished winds, an area which extends downwind for a distance equal to 7 H (Figure 6.1). Most particles that reach the ground within this region come to rest and form a lens-shaped drift. This drift becomes thicker in the middle as deposition continues. The lens-shaped deposit continues until the airflow cannot follow the curvature. At this stage, the flow separates from the surface. The resulting snow pile extends the effective sheltered region to 12 H to 15 H downwind. This area is where most snow is deposited until the fence is about 75% full. The formation of the slip face and the circulation zone characterize the second stage of drift growth. The circulation zone extends downwind for a distance equal to 6-7 times the height of the slip face. During this second stage of development, the flow adds significant resistance to the approaching wind. This promotes snow deposition on the drift's nose and reduces surface winds within the circulation zone. As a result, with light to moderate winds, the trapping efficiency can be greater than the initial trapping efficiency at the onset of accumulation.

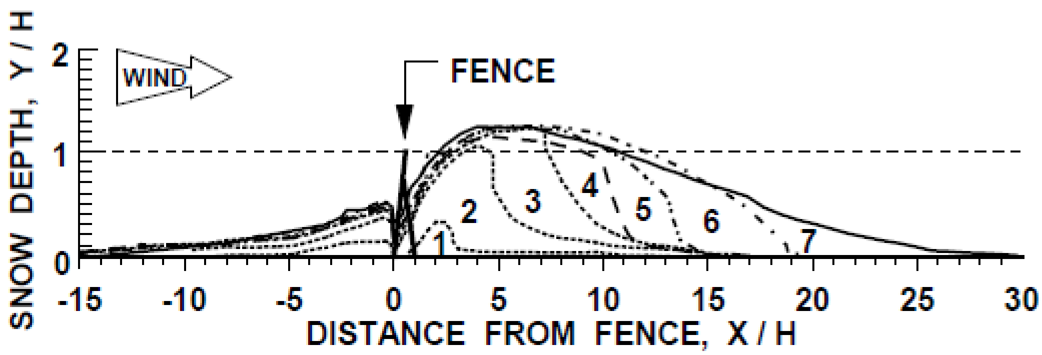


Figure 6.1 Cross-section of the snow drift formed with a 50% porous, horizontal-board fence (Constantinescu et al., 2015)

6.1 SNOW-DRIFT MODELING FOR A FLAT GROUND SURFACE

Modeling the snow accumulation for a snow fence was conducted. Based on the reference above, the height of the domain was considered to be more than two times the fence's height (8 ft.). The porosity of the snow fence was equal to 50%, and the ratio of the bottom gap to the fence's height was 12.5%. For the sake of an accelerated model analysis, the volume fraction of the snow in the air was chosen as 50%. The maximum inlet wind speed in the domain was 20 m/s (45 mph), and the wind profile obeyed the power law. The distributions of the velocity magnitude for the model (Figure 6.2) and the reference report (Figure 6.3) are shown in Figures 6.2, 6.3, and 6.8.

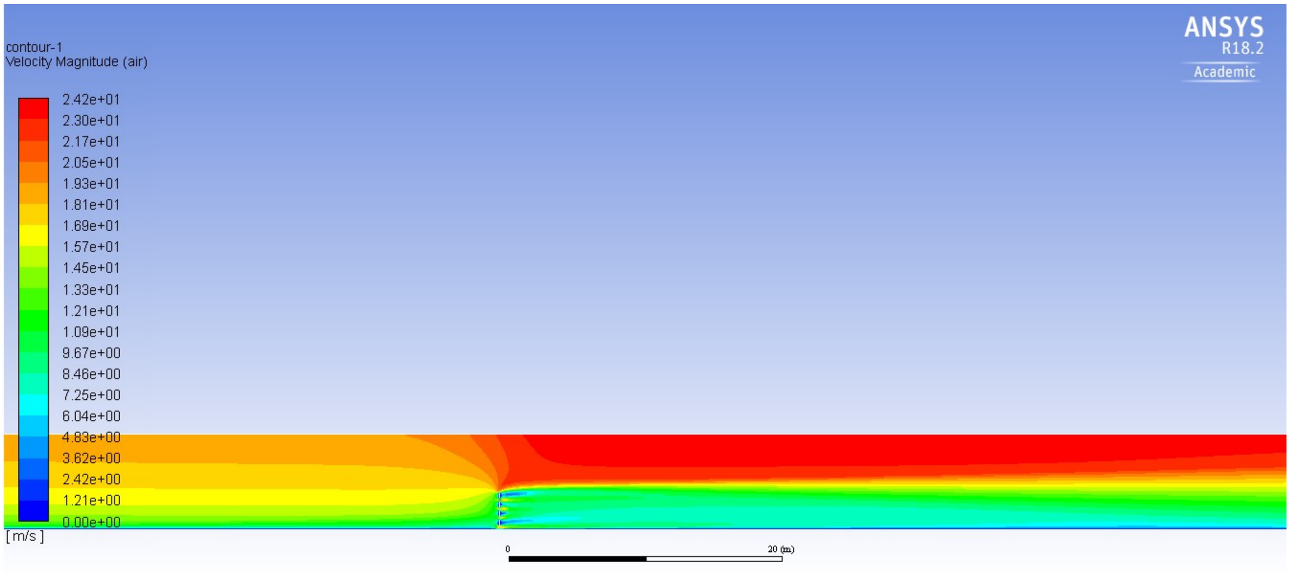


Figure 6.2 Distribution of the velocity magnitude for the model (50% porosity, Gap/H=12.5%)

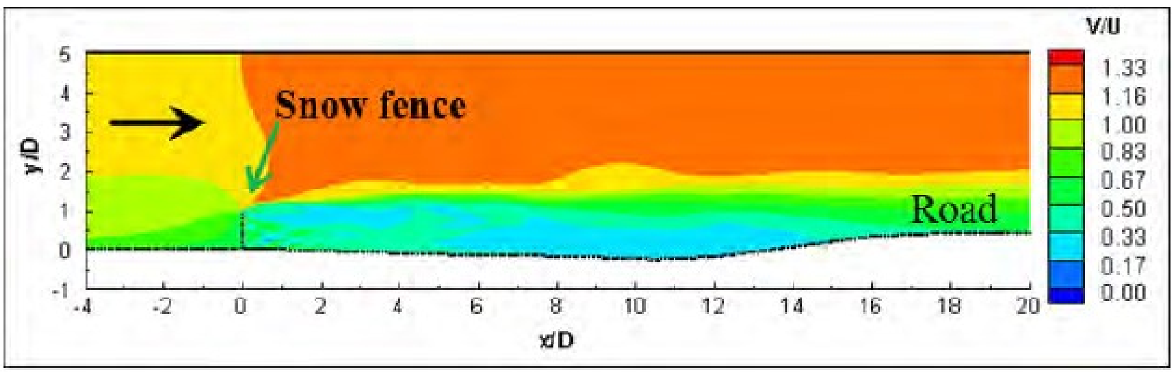


Figure 6.3 Distribution of the velocity magnitude for the reference report (50% porosity, Gap/H=8%) (Constantinescu et al., 2015)

Snow accumulation is also compared and is shown in Figures 6.4-6.7 for different simulation times. From Figures 6.4-6.6, we can see that the snow-drift results are reasonable.

During the early stages of accumulation, the snow begins to pile up close to the ground because there are no slip conditions on the ground. Figure 6.5 illustrates that the snow depth close to the fence and at the bottom gap has increased. Also, there is an observable highest point in the downwind area for the snow's profile. In the final stages of accumulation, the height of the snow profile remains constant, and the profile's length continues to grow (Figure 6.6). In the final stage (Figure 6.7), the shape does not change. At this stage of accumulation, neither the height nor the length of the profile grows.

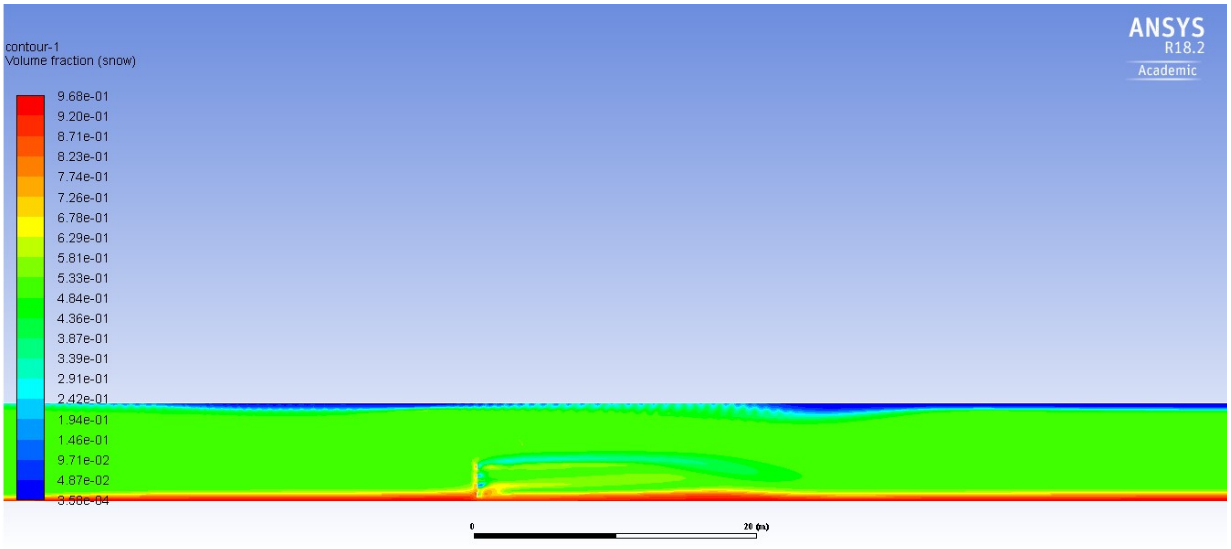


Figure 6.4 Early stage of snow accumulation for the model

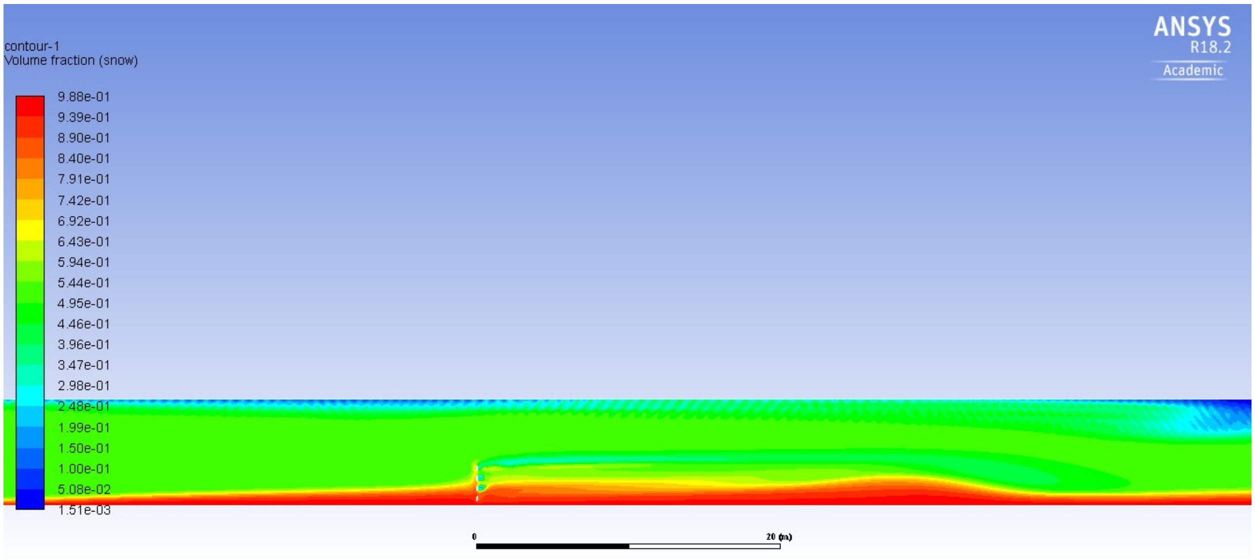


Figure 6.5 Snow accumulation when the drift starts to lengthen downwind

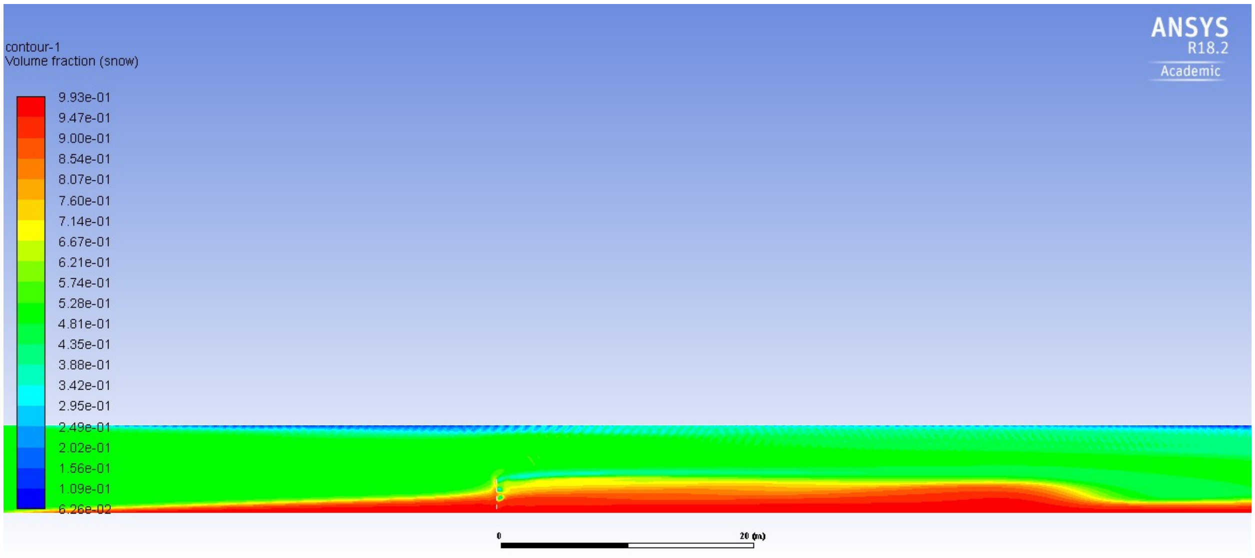


Figure 6.6 The drift grows until it reaches the equilibrium profile

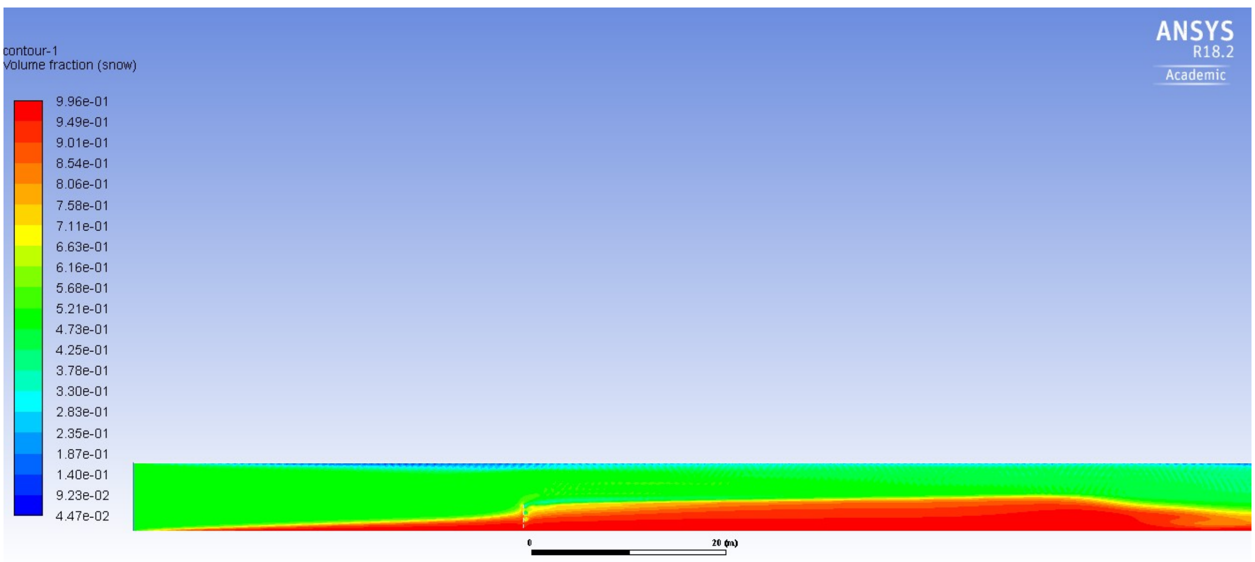


Figure 6.7 The drift's equilibrium profile

A comparison is made between the wind velocity's distribution for the snow-fence model at different locations and the accumulated snow profiles as shown in Figure 6.8 and Table 6.1, respectively. From Figure 6.8, we can see that the actual wind-velocity distribution along the elevation is very much captured by the numerical model, except at the ground level, due to the difference between the nonslip boundary in the numerical model and the sensor's measurement location. Table 6.1 shows that the numerical snow-drift model accurately simulated the snow-drift height and its length extension when compared to the empirical ratios found in Tabler (2003).

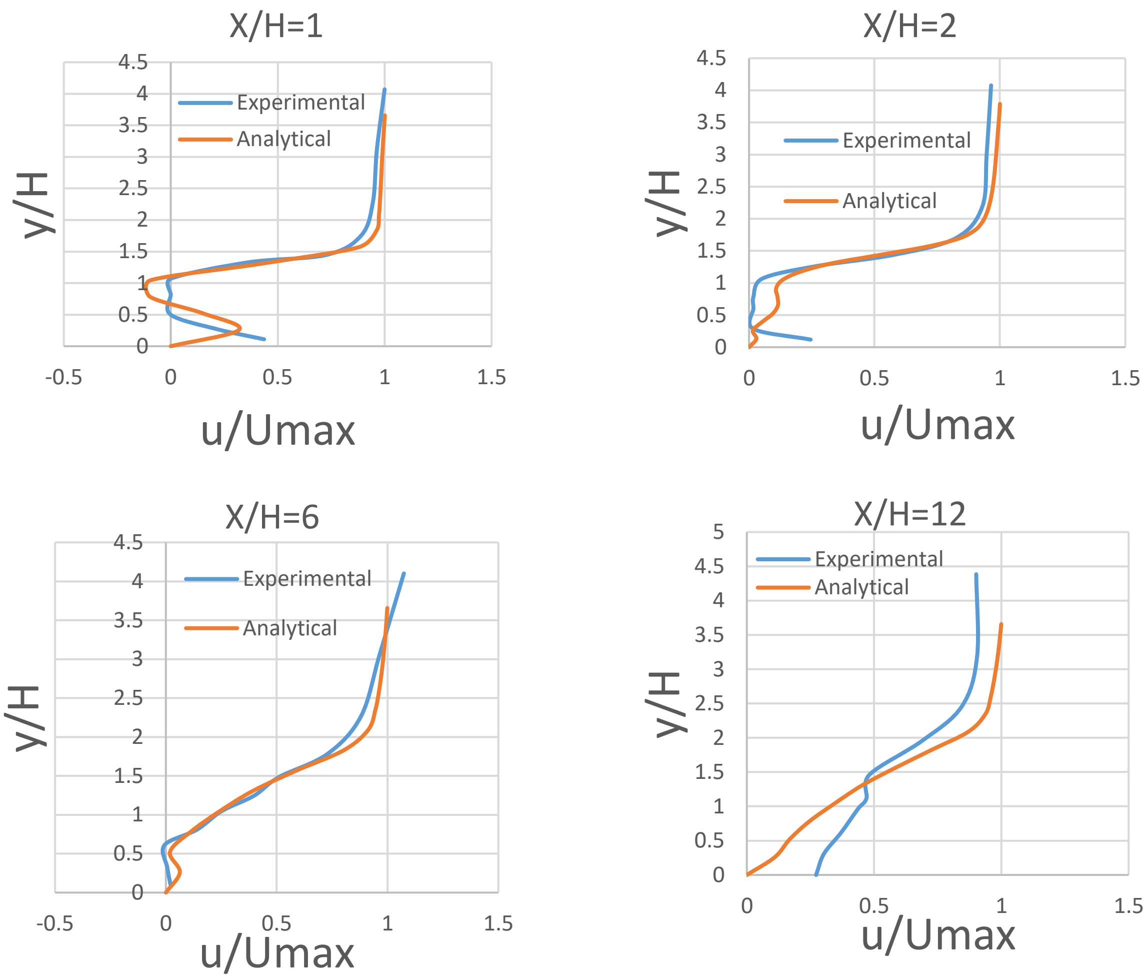


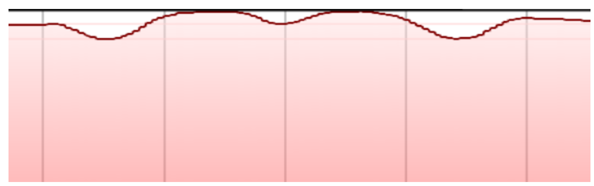
Figure 6.8 Comparison of the normalized velocity in the simulation to the normalized velocity in the reference (Tabler, 2003) for different points beyond the fence; X = distance from the fence, H = fence height, y = elevation from the ground, u = velocity, and Umax = maximum velocity at the location

Table 6.1 Snow-profile parameters for the last stage of accumulation

Ratio of the Maximum Drift Length to the Fence Height in the Simulation (L/H)	30.3
Ratio of the Maximum Drift Length to the Fence Height in the Reference (L/H)	35
Ratio of the Maximum Depth of the Snow Profile to the Fence Height in the Simulation	1.42
Ratio of the Maximum Depth of the Snow Profile to the Fence Height in Reference	1.2

6.2 SNOW-DRIFT MODELING OVER ACTUAL GROUND TERRAIN

Most snow fences are built along roadways with ditches, which will affect the snow piles during drift. For this project, one location on I-94 between Fargo and Minneapolis was chosen for the analysis. The road's profile was measured using Google Earth Pro (Figure 6.9). The snow fence's distance from the road was chosen as 35 times the fence's height (Tabler, 2003). In the computational fluid dynamics (CFD) model, the height of the domain is chosen to be more than two times of the fence's height (8 ft). For the sake of accelerated analysis, the volume fraction of the snow in the air is chosen as 20%. The inlet's wind velocity is defined based on the power-law profile where the velocity at a height of 10 m is equal to 20 m/s.



b) Extracted ground profile

a) The profile in Google Earth Pro

c) The 2D ground profile model and mesh in ANSYS

Figure 6.9 The road's profile

Snow accumulation is shown for the structural snow fence with two different ground profiles (Figures 6.10 and 6.11). A comparison of the snow accumulation for the two cases with the snow accumulation profile on flat ground is shown in Figure 6.12. As seen in Figure 6.9, considering the ditches along the snow fence causes a reduction of the snow-accumulation profile in the region close to the fence. At early stages of accumulation, the snow begins to pile up close to the ground because there are no slip conditions on the ground. Also, there is an observable highest point in the snow profile's downwind area. In the final stages of accumulation (as we can see in Figures 6.10 and 6.11), the snow profile's height remains constant, and the profile's length stops growing.

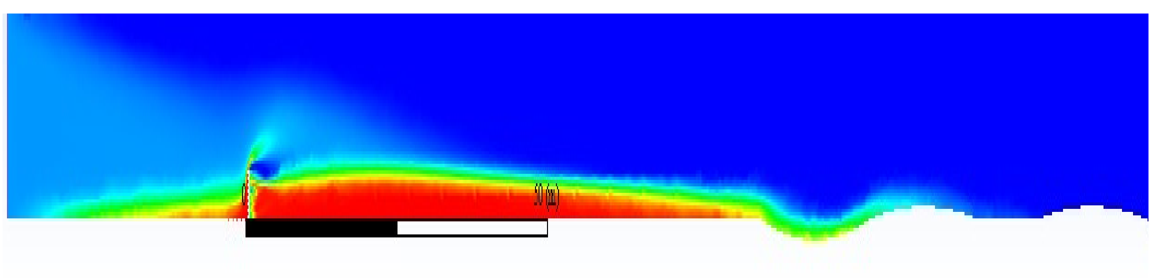


Figure 6.10 Equilibrium drift profile with the actual ground profile measured using Google Earth (Typical profile)

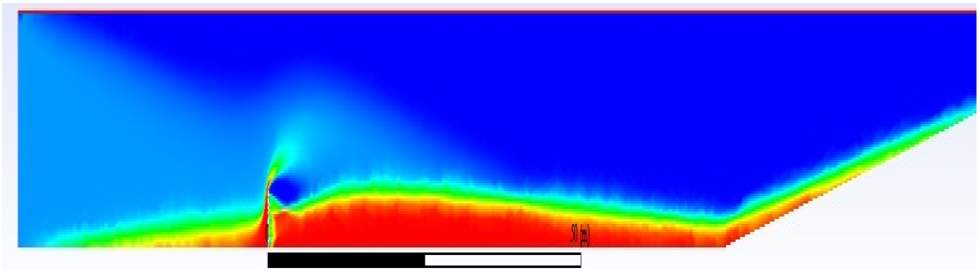


Figure 6.11 Equilibrium drift profile with an imaginary, uphill ground profile (Exaggerated profile)

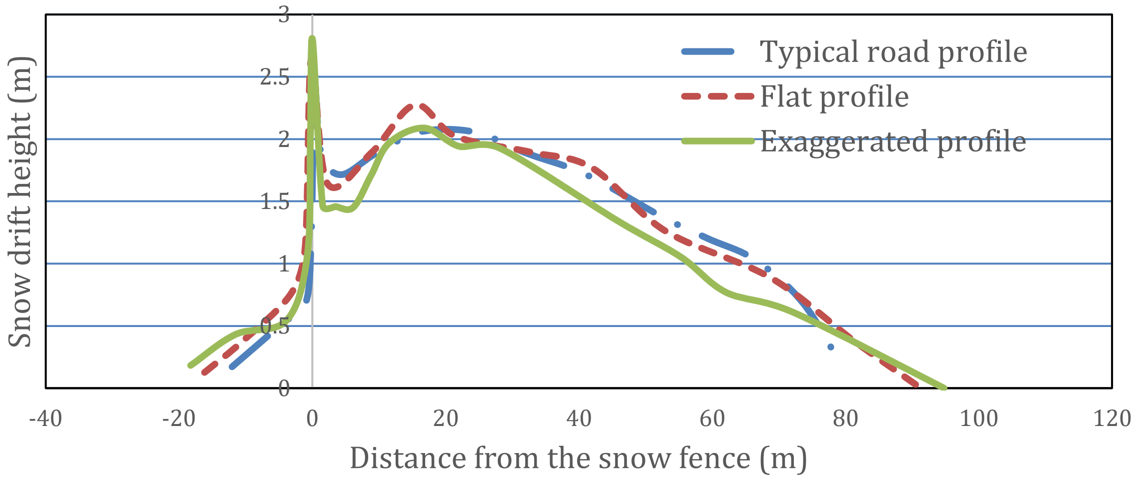


Figure 6.12 Comparison for different drift profiles with a snow fence

CHAPTER 7: IMPACT TESTING FOR THE SUGGESTED SOLAR PANELS ON A HIGHWAY SYSTEM

7.1 DROP-WEIGHT TESTING RESULTS

In order to evaluate effect of broken solar panels on the traffic safety due to impacts and collisions, a steel tube was dropped 6 ft above the solar panel. The tube's length and weight were 11 3/8 inch and 640 grams, respectively. The steel tube's outer diameter was 2 1/8 inch, and its thickness was 1/8 inch. The tested solar panel was 18x6x1/8 inch in dimension and was simply supported along the short edge. A high-speed camera with a frame rate of 120 frames per second was used to record this test. The captured video was converted to images which were then analyzed using the ImageJ software to obtain the sizes and speeds. Figure 7.1 shows the traced segments in the camera view. The scale factor between the images' dimensions and the real displacement is 0.0178 inch per pixel. Table 7.1 shows the sizes and the speeds for each segment generated during the impact test.

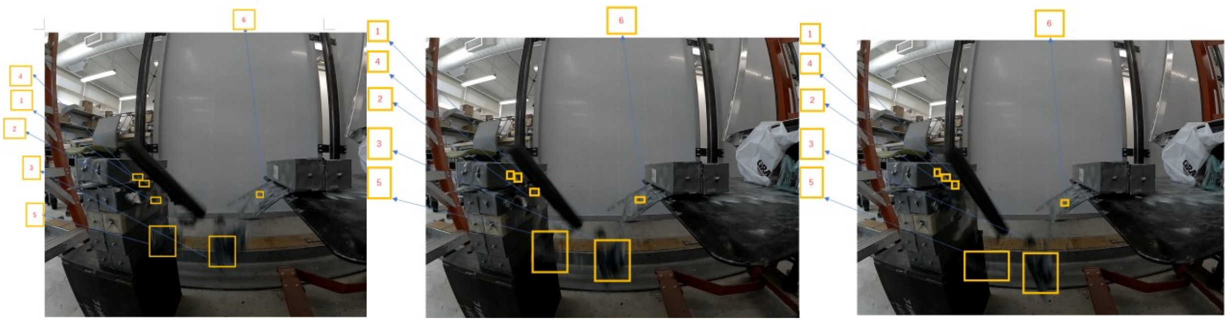


Figure 7.1 Images captured during the steel tube's impact test

Table 7.1 Sizes and speeds of the solar-panel segments after impact

Segment	1		2		3		4		5		6	
L (Length), W (Width)	L	W	L	W	L	W	L	W	L	W	L	W
Size (pixel)	15	12	11	12	105	67	8	12	109	79	9	8
Size (inch)	0.27	0.21	0.20	0.21	1.88	1.20	0.14	0.21	1.95	1.39	0.16	0.14
Speed (in./s)	19.2		21.7		78.3		18.4		51.3		19.4	

From Table 7.1, most segments of the solar panel have less speed: 19.2 inch/s, 21.7 inch/s, 18.4 inch/s, and 19.4 inch/s, respectively. However, some large segments have higher speeds of 78.3 inch/s and 51.3 inch/s, moving with the projectile (at a speed of 235.9 inch/s). These speeds are low in magnitude (less than 4.0 mph) and will not cause human safety concerns (Ashton & Mackay, 1979).

7.2 HIGH-SPEED, GAS-GUN IMPACT-TESTING RESULTS

A high-speed impact test was also conducted with the gas-gun setup shown in Figure 7.2. The projectile has a mass of 16.37 g and a speed of 70 m/s, which injects an energy of 40.109 J into the system. The specimen for the high-speed testing has dimensions of 6x6x1/8 inch with fixed supports along the edges. After the impact, the solar panel is broken into pieces as shown in Figure 7.2(c).

Figure 7.2 High-speed impact-test setup and the solar panel's broken pieces after the impact

CHAPTER 8: ELECTRICAL CONTROLLER AND INVERTER DESIGN

8.1 THE ELECTRICAL CONTROLLER'S DESIGN

The solar noise barrier and snow fence system adopts a new inverter topology called a solid-state transformer (SST). In the system, a group of 12 power transistors is used to construct a power-mode switch module. The inverter's voltage and current sensors send information to the controller, and the controller's processor produces appropriate output signals to control the power transistors' states. Therefore, the controller has the ability to read the sensor outputs from the main module in order to prevent unstable operation (Figure 8.1).

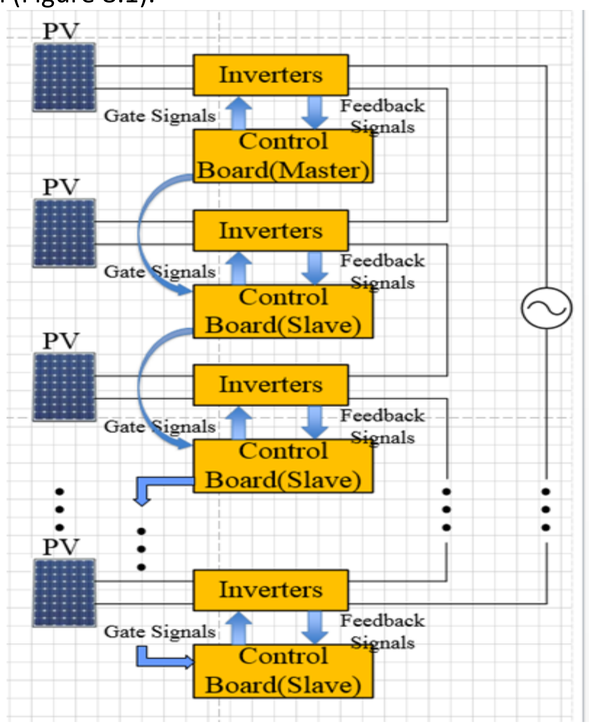


Figure 8.1 The diagram of the controller

There are several considerations for the safe implementation of power systems. The most important one is direct accessibility for the technicians. In the event of emergencies, the entire system should be accessible in order to quickly disable it. The modules must be isolated so that a problem with one module does not affect other modules in the chain. Due to the high-frequency isolation transformer design inside each inverter module, only low-voltage DC (30~50 V) and low-voltage AC (36 V) are generated within each module, preventing potential electrocution even when the PV panel is disconnected and damaged from an accident. This feature gives an input-parallel, output-series connection as seen in Figure 8.1.

In the event of vehicle accidents, there are potential hazards with roadside PVs; Through the proposed module inverter and controller system, human can only be in contact with low-voltage DC on the PV side, which prevents high-voltage human exposure. It is important that the controller has a built-in function to read the output voltage and the current, which can rapidly turn the output off when such dangerous conditions are present.

Fault conditions can be resolved by using a hardware interruption. When a fault is detected in one module, the chain is broken. An external hardware trigger immediately halts the software's programmed function and sends a signal to the next controller, triggering the next hardware interruption. The modules need to be reset by a technician. This procedure prevents the entire system from energizing the line again. In practice, the entire process happens in a matter of milliseconds.

The control board's first revision requires research about the design of circuit boards for signal integrity, different forms of isolation, and the functions of the F28335 Series Digital Signal Processor (DSP). A 3D rendering of the controller is given in Figure 8.2, which incorporates Texas Instruments' Control Card Evaluation Board for the F28335 DSP via the dock (Figure 8.2).

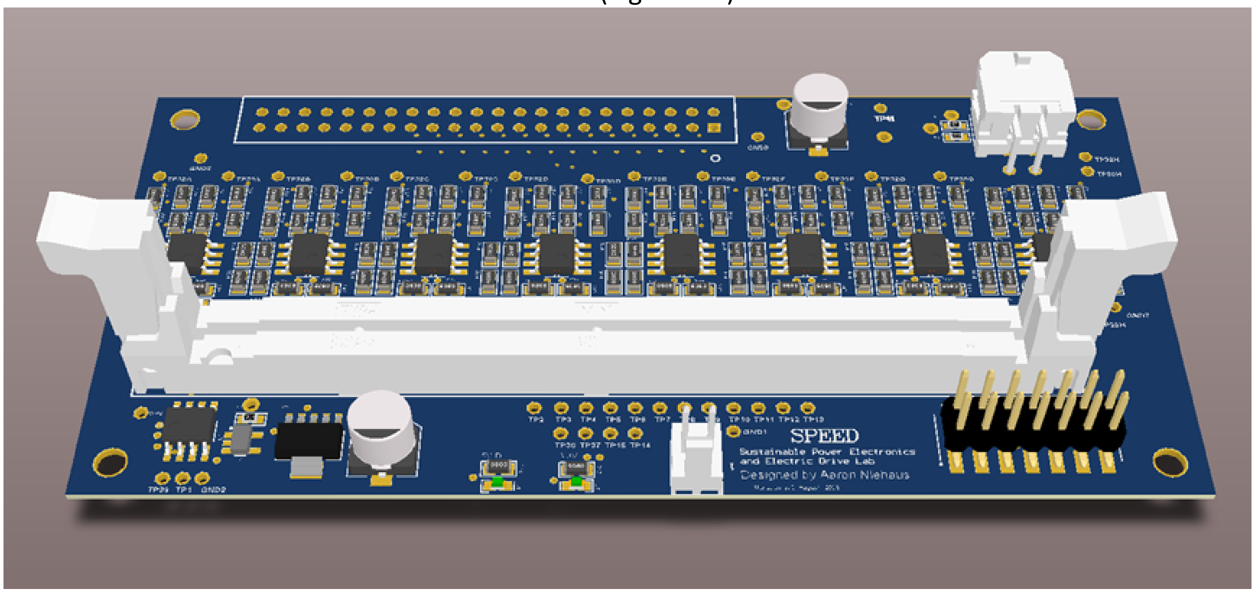


Figure 8.2 The control card evaluation board

8.2 VALIDATION AND PROTOTYPE TESTING

The controller's pulse-width modulation (PWM) outputs were first tested for a phase delay along the traces. With 50-ohm loads on the controller's output, delays around 4 nanoseconds were recorded (Figure 8.3), which was negligible for our application. A picture of the testing setup can be seen in Figure 8.4.

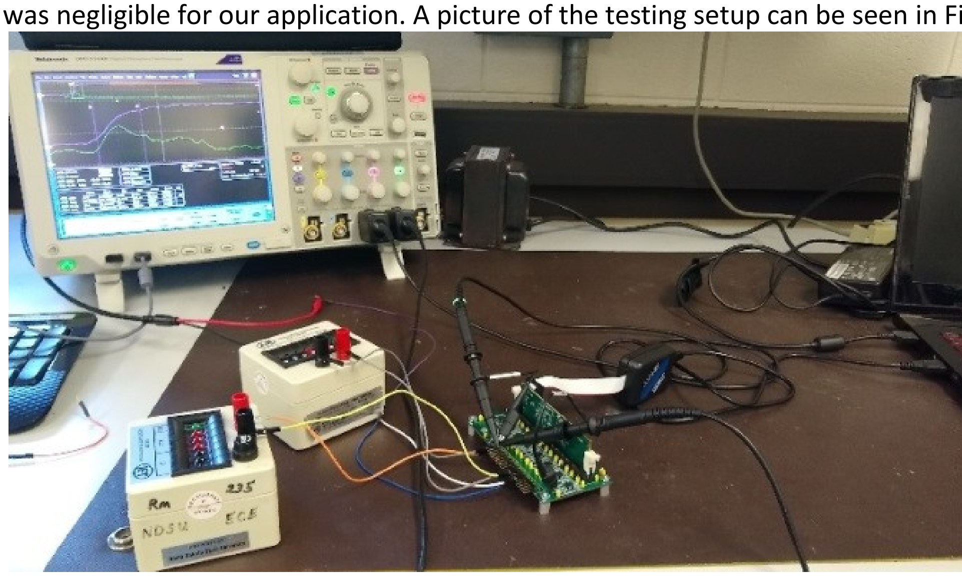


Figure 8.3 Test setup for the controller's validation

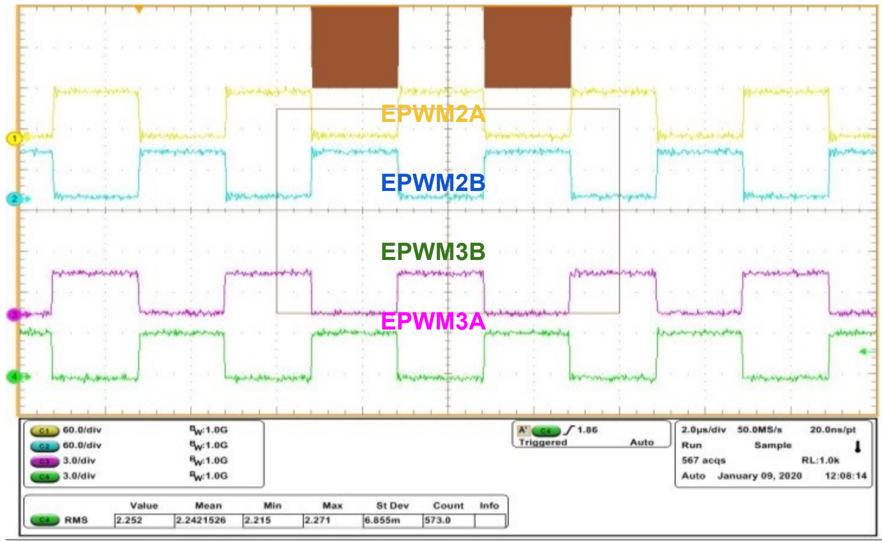


Figure 8.4 Test results for the 250-kHz PWM

The 250-kHz PWM signals were generated in complementary pairs in the software and were probed with an oscilloscope. One sample includes signals 2A, 2B, 3A, and 3B (Figure 8.4). Figure 8.4 demonstrates the inverse coupling of the A and B signals, which is essential for the inverter to function properly.

Signal pairs 5A and 5B (Figure 8.5) demonstrated the variable PWM. In EPWM5 and EPWM6, the PWM signals were quickly modulated to form a 60-Hz period. This PWM signal was smoothed to simulate the grid output (Figure 8.6).

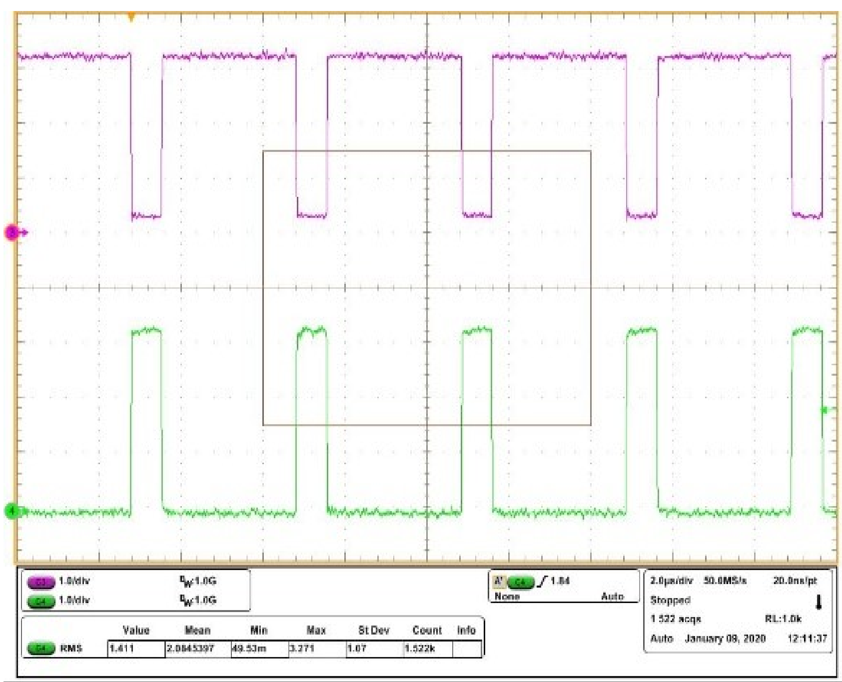


Figure 8.5 Test setup for variable PWM

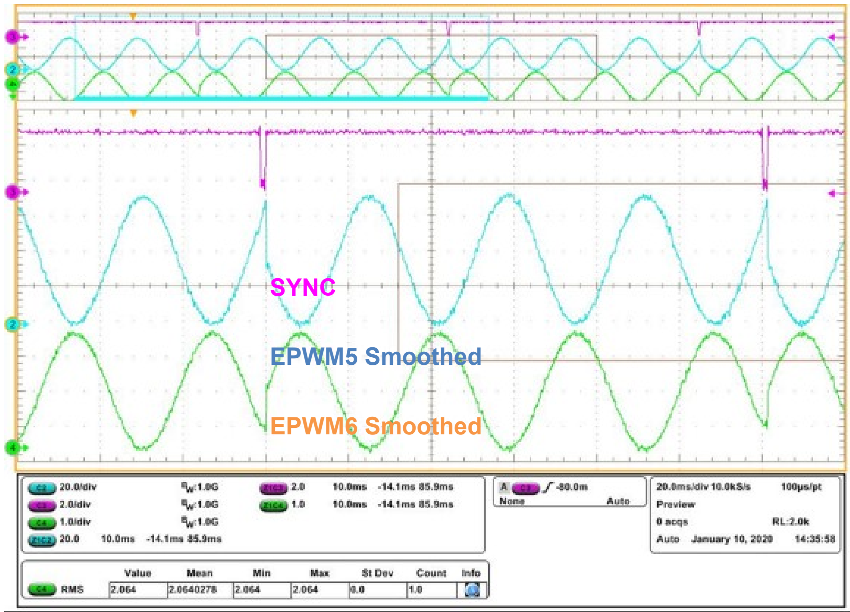


Figure 8.6 The obtained, modulated 60-Hz grid output

A third signal, sync, is used to reset the sine wave to align the output with the power grid. The master controller's output is a 60-Hz pulse, and slave controllers reset themselves whenever this signal is received. The sync pulse is forwarded to the next module in the chain. If no signal is given for 3 continuous power cycles (50 milliseconds), the controller assumes that it is the master and generates its own signal. This simple chain allows for versatility in the event that one controller is disabled.

A potential problem with this solution is its dependency on the sync chain. In future revisions, this sync signal will be replaced with a Controller Area Network (CAN) bus, some form of master arbitration, or sensor feedback from the power grid. The signals are intentionally given out of time in this example to demonstrate the sync signal's role. In a practical setting, the sync would pulse at 60 Hz, and EPWM5 and EPWM6 would be continuous sine waves.

The Analog to Digital Converter (ADC) module was debugged. Values from the 16 ADCs are constantly fed into a mathematical transform which calculates the corresponding analog value. These analog values are stored in a global array. In this way, the controller will know different currents and voltages to disable when the PV is disconnected.

8.3 THE ELECTRICAL INVERTER'S DESIGN

The inverter topology is composed of 3 parts and is shown in Figure 8.7. The first part is the DC/DC circuit which converts solar energy into electrical energy. Because the PV panel's output-voltage varies, it is necessary to adopt a DC/DC circuit to keep the PV panel's voltage constant, which could potentially achieve the Maximum Power Point Track of the inverter in future work. The second part is an isolated circuit named the LLC circuit. Through a solid state transformer, T_1, the LLC circuit can isolate the PV panel's side voltage and the load side's voltage for safety purposes. Moreover, the secondary side voltage must be float because four converters are connected in series. The third part is a full-bridge inverter which converts DC voltage to AC voltage for the load. The output AC voltage's root mean square for each inverter is around 28 V.

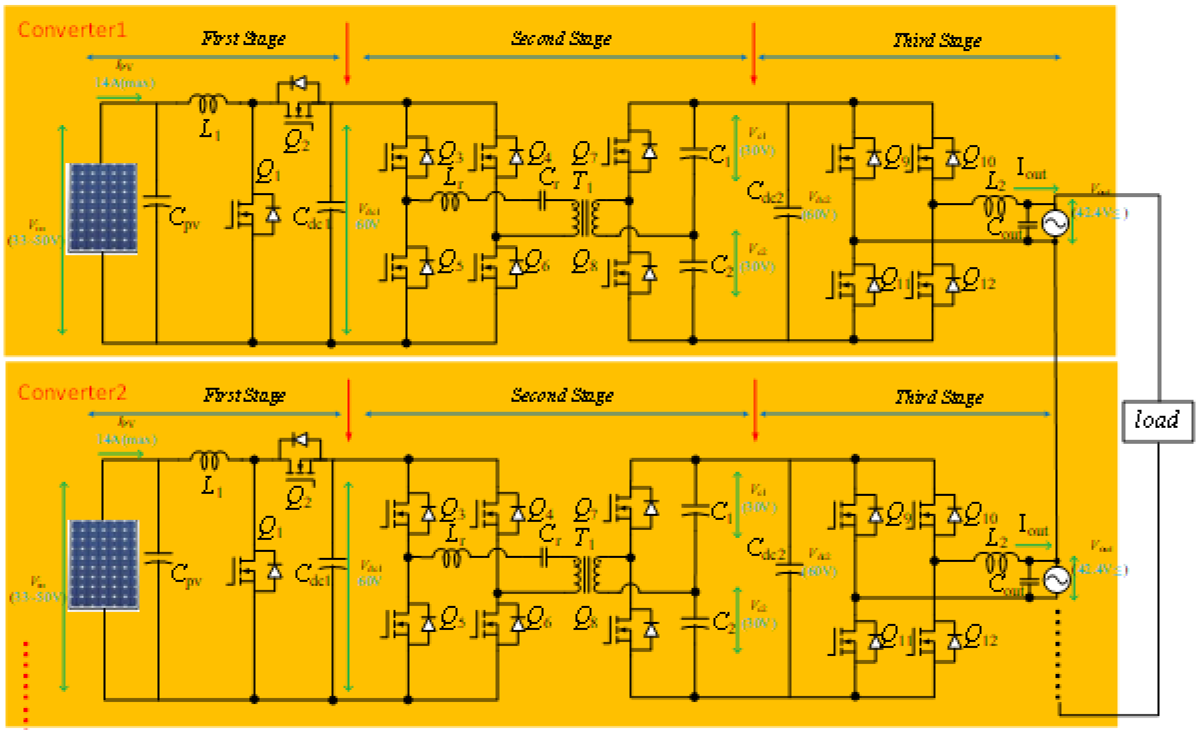


Figure 8.7 Inverter circuit

Gallium Nitride Mosfets are utilized for the inverter circuit because of their small volume and high switch-speed characteristic. Moreover, due to the small power loss with a Gallium Nitride Mosfet, the heat sink can be saved for a higher power-density printed circuit board (PCB) board.

In normal circumstances, every inverter works at 28 V. When 4 inverters are in a series, the output voltage is around 110 V. If one PV panel is broken or removed from the system, the rest of inverters can still work normally. At that time, each inverter will work at 36 V. The PV panel's voltage as well as the inverter's output voltage and current are detected by the controller. If one of the PV panels is removed, the controller will immediately send an interrupt signal to other inverters in order to remind them to adjust their output voltage. With this method, the entire system's output voltage will stay at 110 V/AC all the time.

8.4 VALIDATION AND PROTOTYPE TESTING

A series of simulations were conducted to validate the circuit design. Figure 8.8 shows the simulation results for one inverter (the left side) and the entire system (the right side). The PV panel's output-voltage ripples are around 0.4 V, and its output-current ripples are around 2 A. Each inverter's output voltage is around 28 V/AC.

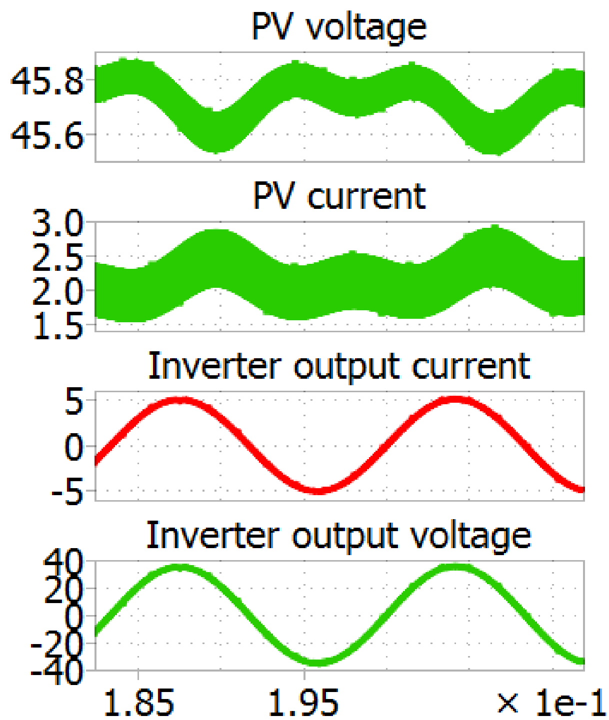


Figure 8.8 Simulation results for one inverter (left) & the entire system (right)

The simulation results for four inverters in series are shown on the right of Figure 8.8. The system's output voltage is 110 V/AC. When one PV panel is removed, each inverter's output voltage will change from 28 V/AC to 36 V/AC, keeping the system's output voltage at 110 V/AC. Output-voltage overshoot will happen at this time, which can be avoided by optimizing the DSP's control strategy. A 3D rendering of the inverter's control board is shown in Figure 8.9, and the detailed inverter board is shown in Figure 8.10.

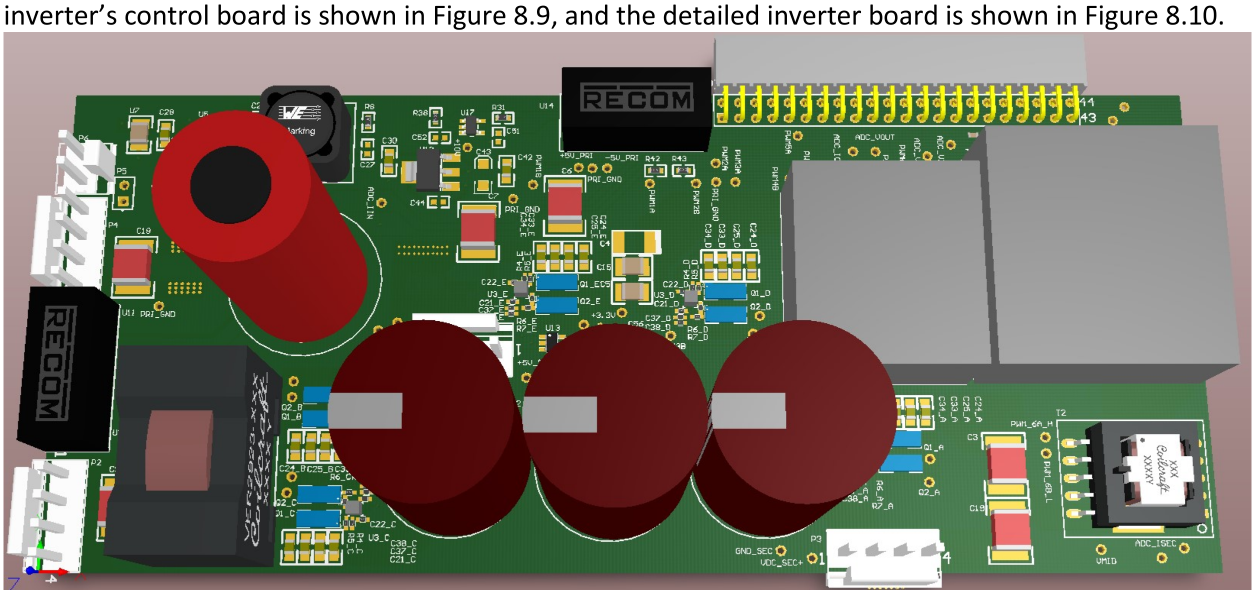


Figure 8.9 A 3D model of the main inverter's control board

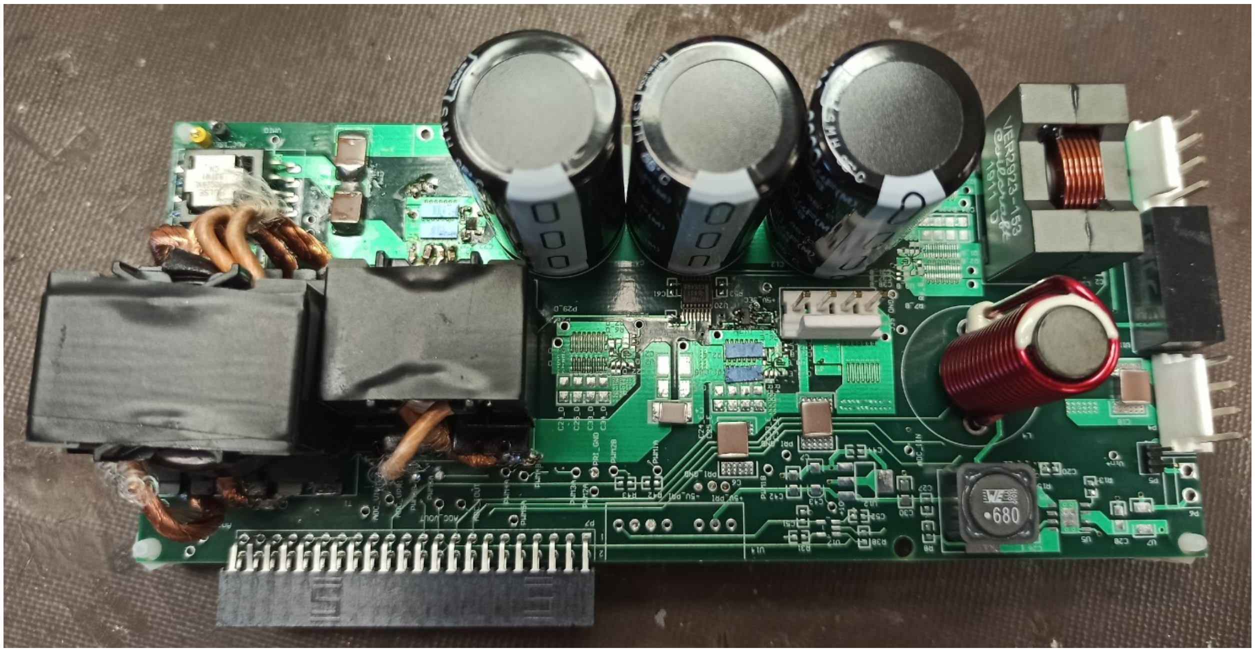


Figure 8.10 A 3D model of the inverter's board

8.5 DEBUGGING THE ELECTRICAL INVERTERS

Every inverter connects with a control board as shown in Figure 8.11. The control board is responsible for signal processing. Like the ADC, the PWM drives and sends synchronization signals. The power board is responsible for energy conversion and transfer. The board aims to convert DC voltage to AC voltage. The power board has 3 stages. The first stage is a DC/DC circuit that converts solar energy to electrical energy. The second stage is an isolated topology called the LLC circuit. The LLC circuit can separate the PV panel side and the output side for safety purposes. The third stage is a full-bridge circuit which can convert DC voltage to AC voltage for a load. Figure 8.11 shows the prototype for a single inverter and the experiment's platform.

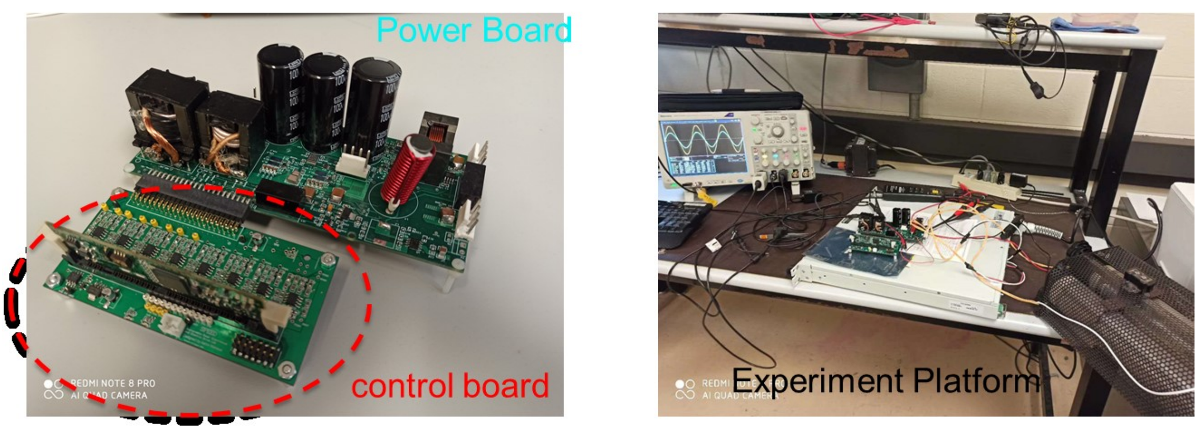


Figure 8.11 The prototype and the experiment's platform

8.5.1 Single-Inverter Experimental Result

In order to make the entire system work, it is necessary to make the single inverter work first. The single-inverter experiment includes two components: the steady-state experiment and the soft-start test. The DC power supply is used to produce a steady voltage input. The soft-start experiment verifies whether the single inverter can start gradually without damage caused by a current or a voltage overshoot.

8.5.1.1 Single-Inverter, Steady-State Experiment

The single-inverter, steady-state experiment is completed in three steps. The first step is to verify every stage separately, and in this way, it is easier to check the defects and correct them. The second step is to debug the first and second stages together, and then debug the second and third stages together. The third step is to debug the single inverter as a completed device.

The first stage's experimental waveform is shown in Figure 8.12. The pink waveform in the left figure is V_{in}, and its value is 30 V, which is produced by the DC power source. The yellow waveform in the left figure is I_{out1}, and its RMS value is around 2.5 A. The blue waveform in the left figure is V_{dc1}, and its value is around 60 V. The output power is around 150 watts.

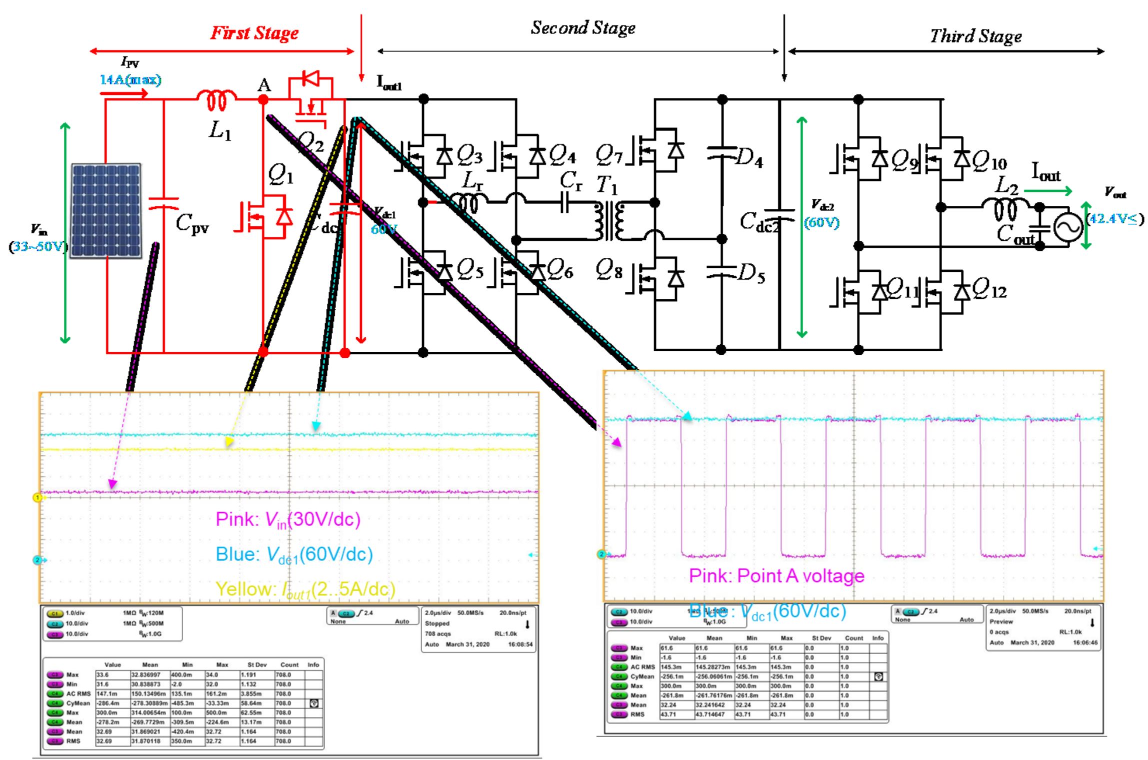


Figure 8.12 The first stage's experimental waveform

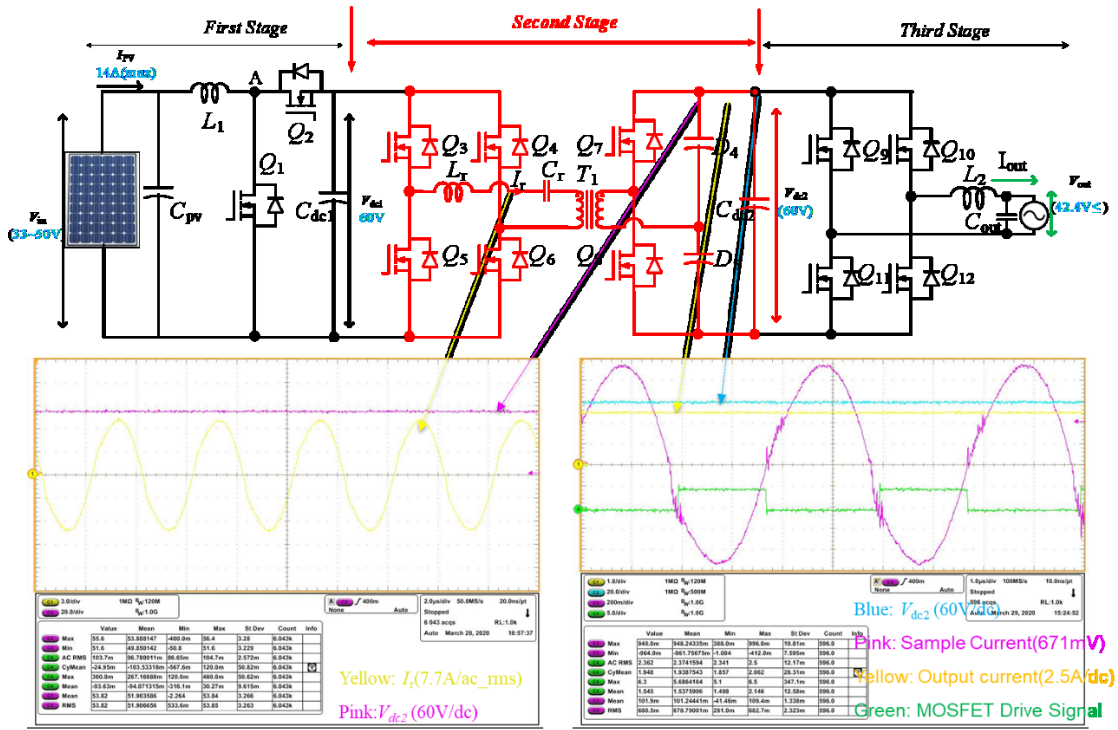


Figure 8.13 The second stage's experimental waveform

The second stage's experimental waveform is shown in Figure 8.13. V_{dc1} is 60 V and is produced by the DC power source. The blue waveform in the right figure is V_{dc2}, and its value is around 60 V. The yellow waveform in the right figure is the second stage's output current, and its RMS value is around 2.5 A. The output power is around 150 watts.

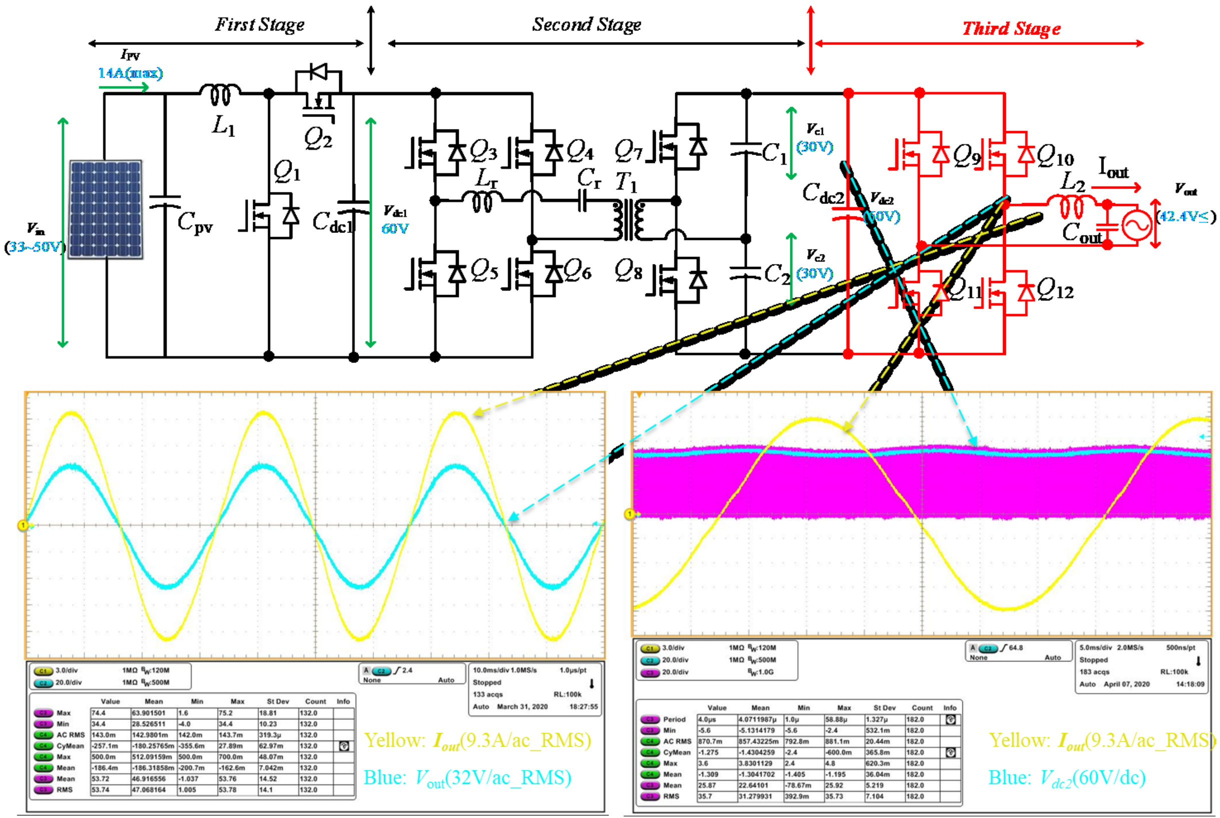


Figure 8.14 The third stage's experimental waveform

The third stage's experimental waveform is shown in Figure 8.14. The blue waveform in the right figure is V_{dc2}, and its value is 60 V that is produced by the DC power source. The yellow waveform in the left figure is I_{out}, and its RMS value is around 9.3 A. The blue waveform in the left figure is V_{out}, and its RMS value is around 32 V. The output's power is around 300 watts.

The second-stage and third-stage joint-experiment waveform is shown in Figure 8.15. The blue waveform is V_{dc1}, and its value is 60 V that is produced by a DC power source. The yellow waveform is I_{out}, and its RMS value is around 9.3 A. The blue waveform is V_{out}, and its RMS value is around 32 V. The output's power is around 300 watts.

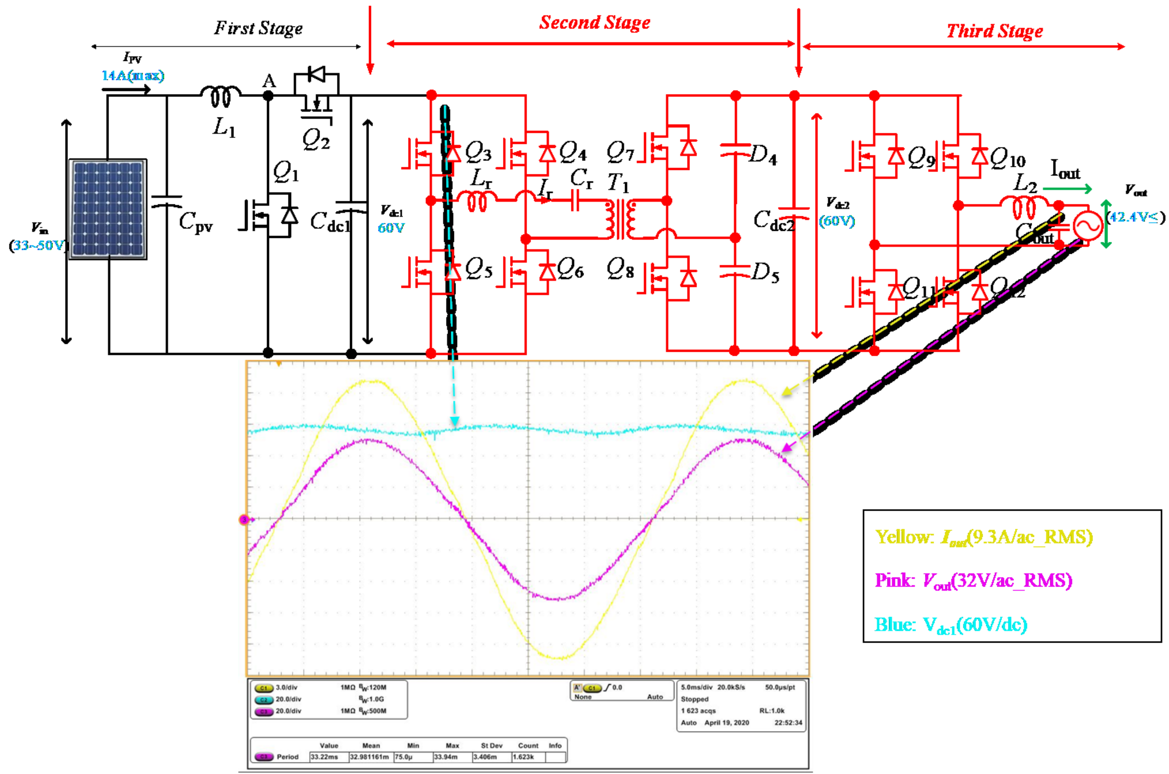


Figure 8.15 The second and third stage's joint-experiment waveform

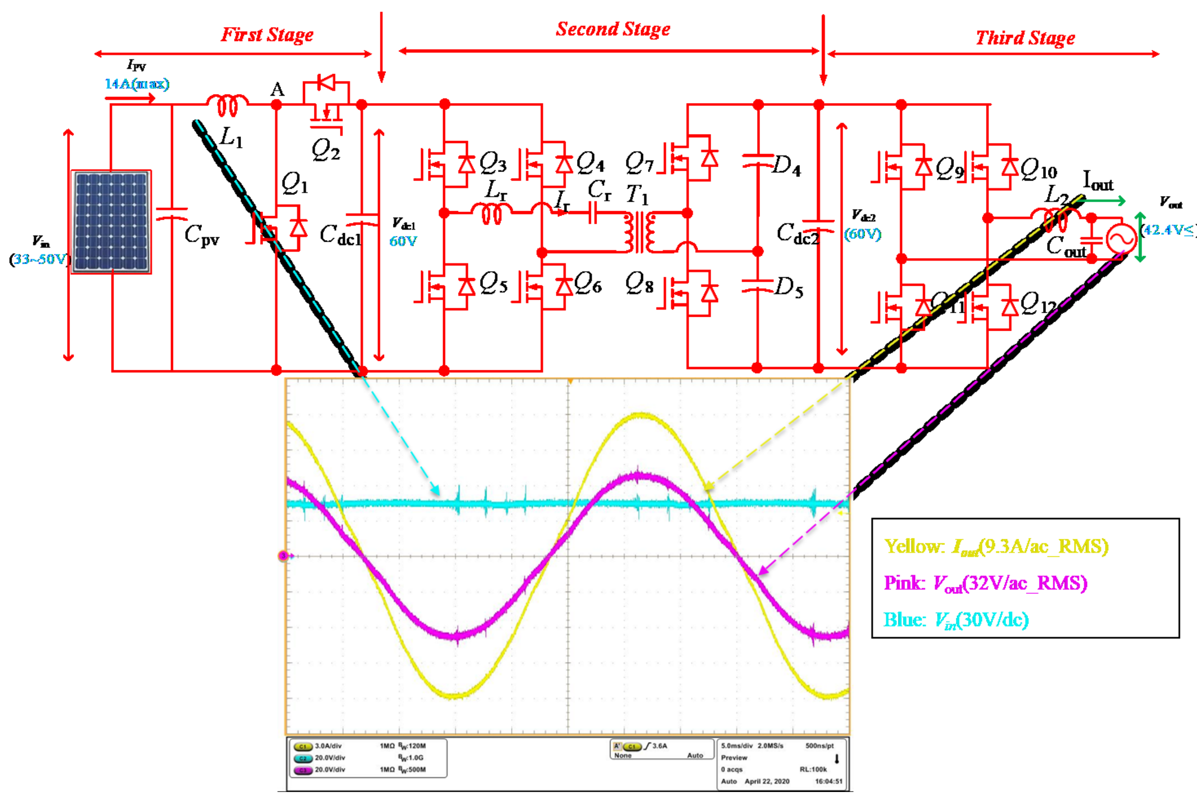


Figure 8.16 The entire single-inverter experimental waveform

The entire inverter experiment's waveform is shown in Figure 8.16. The blue waveform is V_{in}, and its value is 30 V that is produced by a DC power source. The yellow waveform is I_{out}, and its RMS value is around 9.3 A. The red waveform is V_{out}, and its RMS value is around 32 V. The entire inverter's output power is around 300 watts.

The highest temperature rise on the power board is usually from the transformer and power mosfet, and is a very important index for the inverter's working stability. If the mosfet temperature is too high, the inverter's life will decrease dramatically. Figure 8.17 utilizes an infrared thermometer and shows the entire power board's temperature distribution with 300 watts of power. Gallium Nitride Mosfets Q_9~Q_{12} show the highest working temperature, around 70°C, which is an acceptable value.

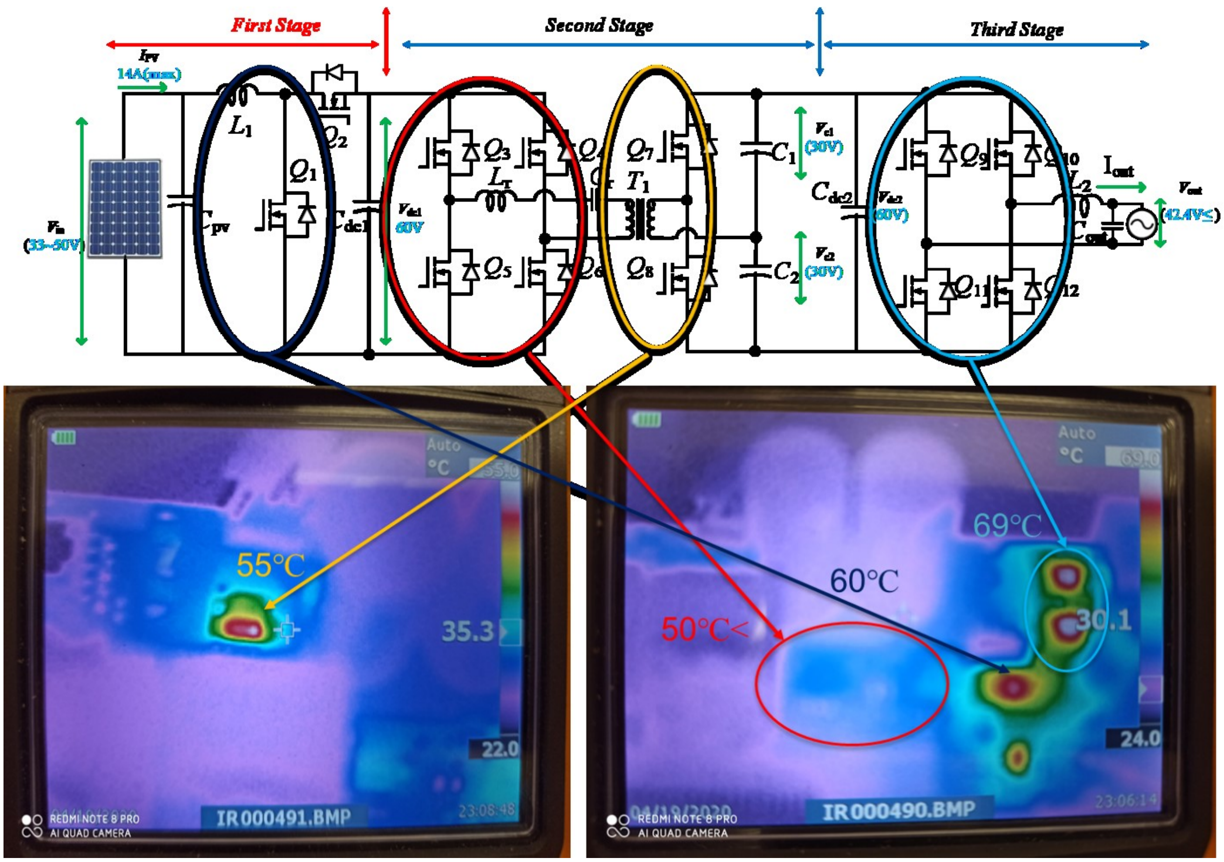


Figure 8.17 the single inverter's temperature distribution with 300 watts

8.5.1.2 Single-Inverter, Soft-Start Experiment

A soft start is very important because it can avoid the current or a voltage overshoot that may damage devices. For example, when an inverter connects to the DC power source by closing the air breaker, the resonance between the DC power source's capacitor and the wire inductor will cause a very high voltage spike. In this situation, the inverter must stay closed until the spike disappears; otherwise, it is very easy to break the inverter.

Figure 8.18 shows the soft-start procedure when the inverter starts to work. Step 1 is to wait until the input voltage, V_{in}, is steady. Steps 2 and 3 aim to gradually increase the second stage's voltage, V_{dc2}, until it equals the input voltage, V_{in}. Otherwise, the current overshoot will damage Q_3~Q_6. Step 4 is to increase the V_{dc2} from V_{in} to 60 V, and step 5 is to keep the output voltage, V_{out}, stable.

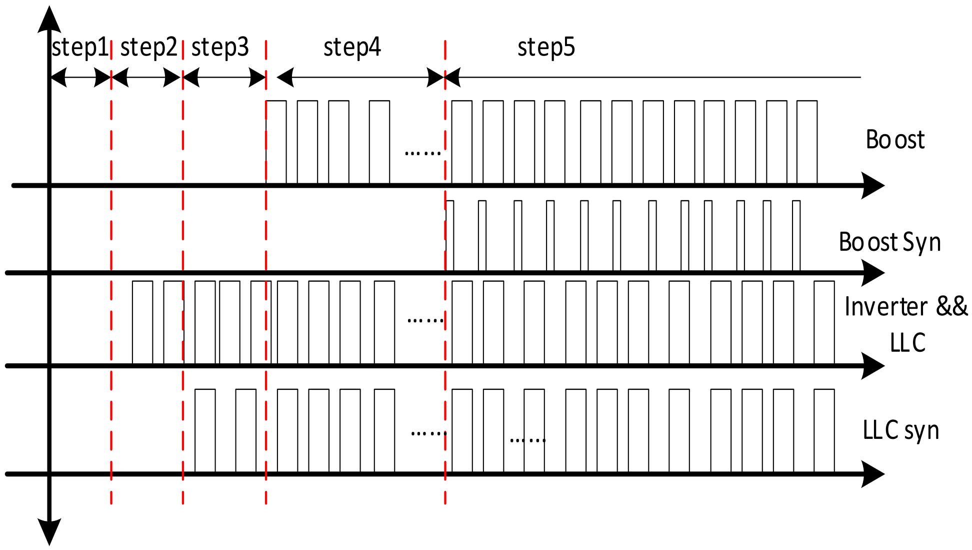


Figure 8.18 Soft-start procedure

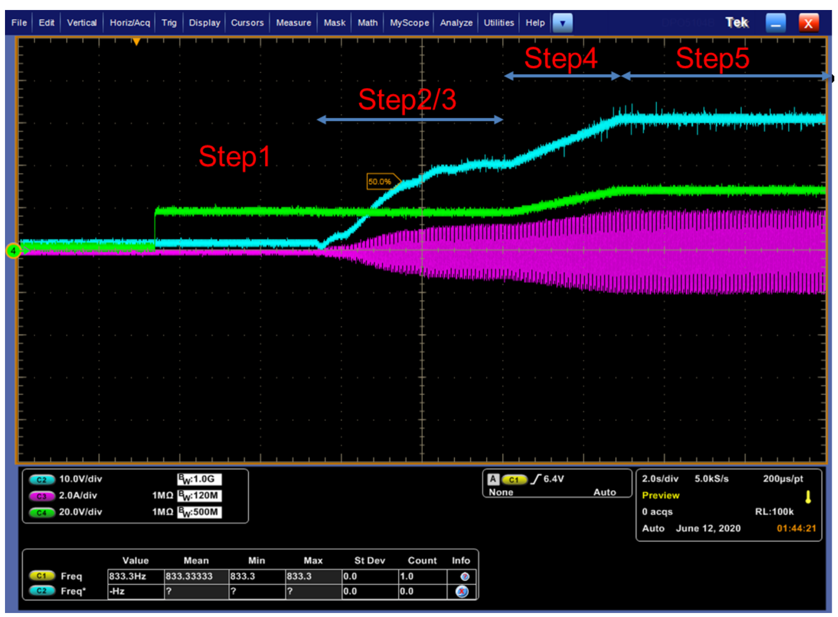


Figure 8.19 Single-inverter, soft-start experiment's waveform

Figure 8.19 shows the single-inverter, soft-start experiment's waveform. The green waveform is the input voltage, V_{in}. The blue waveform is the second stage's waveform, V_{dc2}. The pink waveform is the output voltage, V_{out}. There is no voltage spike observed in Figure 8.19, which proves the soft-start procedure's feasibility.

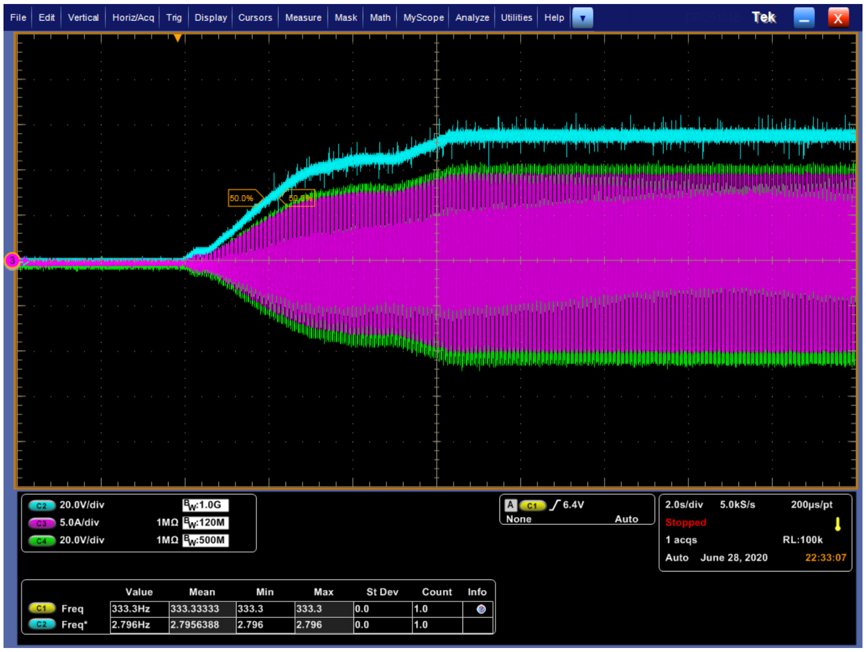


Figure 8.20 Single-inverter, soft-start experiment's waveform at 250 watts/45 V V_{in}

Figure 8.20 shows the soft-start procedure with 250 watts. The input voltage, V_{in}, is 45 V. The green waveform is the output voltage, V_{out}, and its RMS value is around 36 V. The blue waveform is the second-stage waveform, V_{dc2}, and its value is set as 60 V. The pink waveform is the output current, I_{out}, and its RMS value is around 6.9 A.

8.5.2 Multiple-Inverter Connection and Experimental Results

For a solar noise barrier or snow-fence system, connections between multiple inverters are needed. A two-inverter-in-series experiment is conducted, and its results are shown in Figure 8.21.

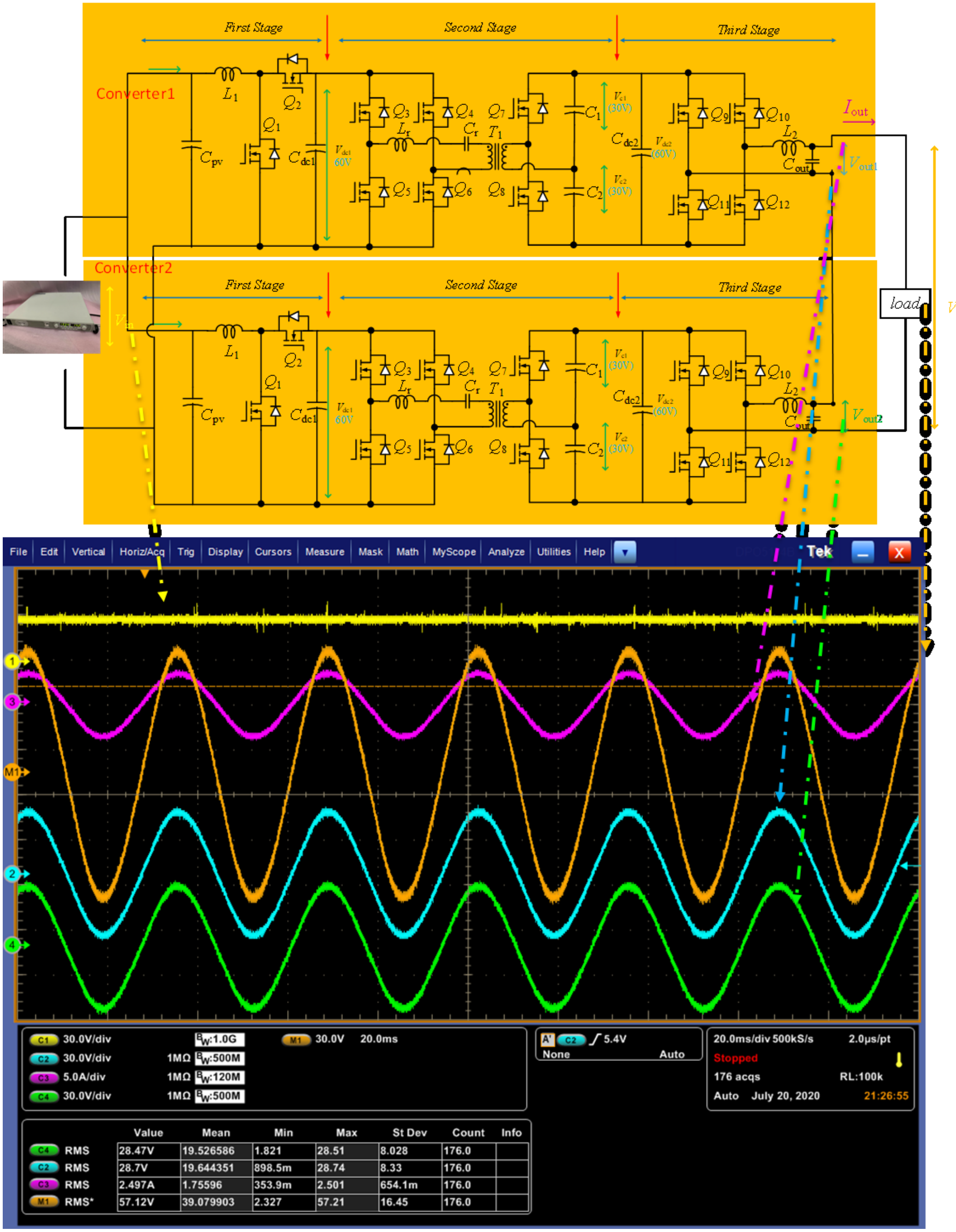


Figure 8.21 Two-inverter-in-series topology and its experimental result

Figure 8.21 shows the two-inverter-in-series topology and its experimental result. A DC power source is used to replace the solar panels in order to supply the two inverters, and the load is assumed to be resistors. The blue and green lines represent converter1 and converter2's output voltage separately, which are around 28.5 V/rms. The pink line is the output current, which is around 2.5 A/rms. The yellow line is the input voltage, which is 30 V. The brown line is the total output voltage, V_g, which is around 57.12 V.

8.5.3 Three-Inverter Connection and Experimental Result

8.5.3.1 Connecting Three Inverters in a Series

Figure 8.22 shows a three-inverter-in-series prototype's experimental platform. A DC power source is used to replace the solar panel in order to supply the three inverters, and the load is provided through a resistor. Three inverter-output ports are connected in a series to increase the total output's voltage. The experiment's result when using solar panels for the inputs is shown in the next section.

Figure 8.23 shows the three-inverter-in-series topology and its experimental result. The blue, green, and yellow lines are converter1, converter2, and converter3's output voltage, respectively. The pink line is the current's output. The brown line is total voltage output, V_g, which is around 60 V/rms.

8.5.3.2 One Inverter Bypassed with a Three-Inverter-in-Series Situation

Figure 8.24 shows the experiment's results when inverter #3 is bypassed or disabled with a three-inverter-in-series situation. The blue and green lines are converter1 and converter2's output voltage separately. The pink line is the current's output. The brown line is the total voltage output, V_g, which is still around 60 V/rms.

When inverter #3 is bypassed, Ganfet Q_{1C}~Q_{10C} are turned off while Ganfet Q_{11C}~Q_{12C} are still on. The output's current will flow through inverter #3 by Q_{11C}~Q_{12C} as well as inductor L_{2C}. With this method, the output's current can continuously flow through the load because the closed output-current loop is always established. The experiment's result proves that, when one inverter is bypassed/disabled, the rest of the inverters can still produce the same AC voltage. This technology apparently improves the robustness of the entire system; moreover, which can decrease the maintenance cost for the entire photovoltaic power system.

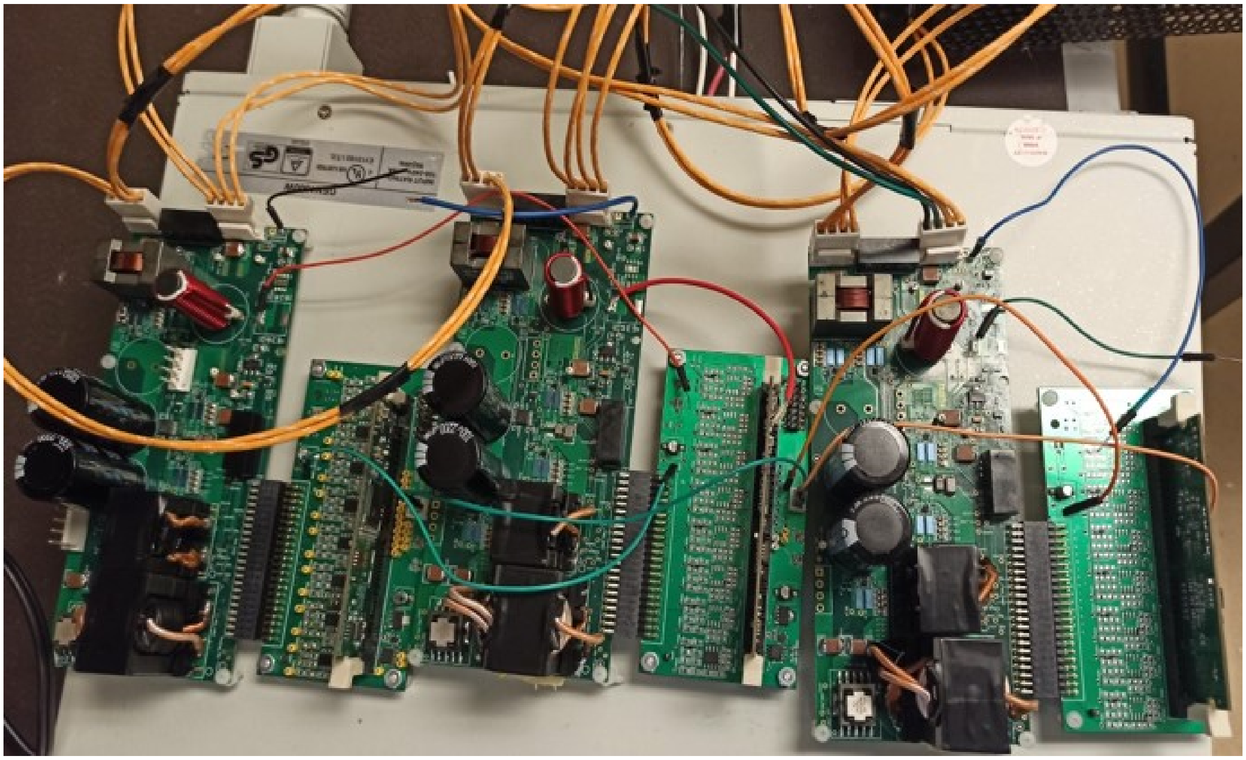


Figure 8.22 The three-inverter-in-series prototype's experimental platform

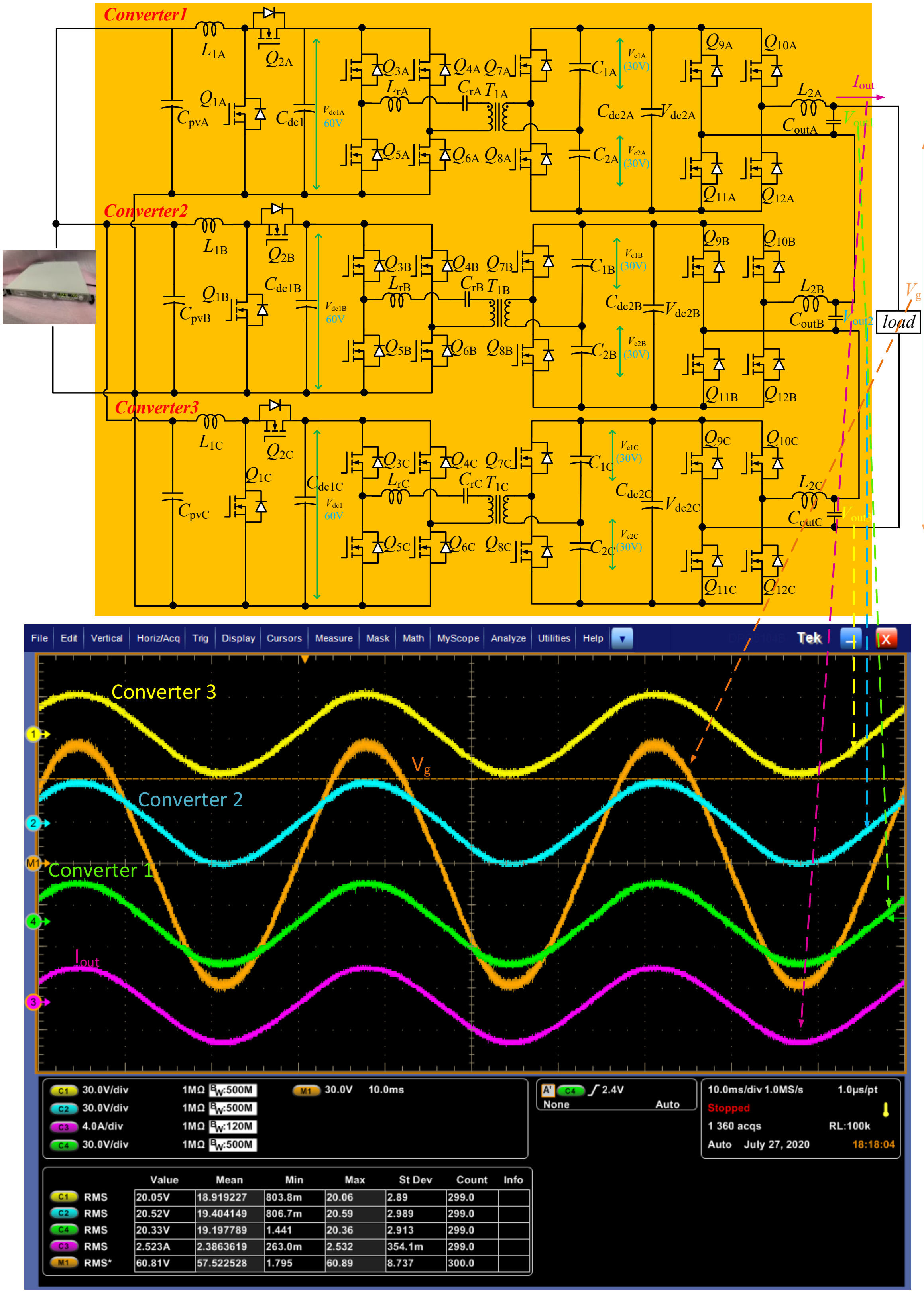


Figure 8.23 Three-inverter-in-series topology and experimental results

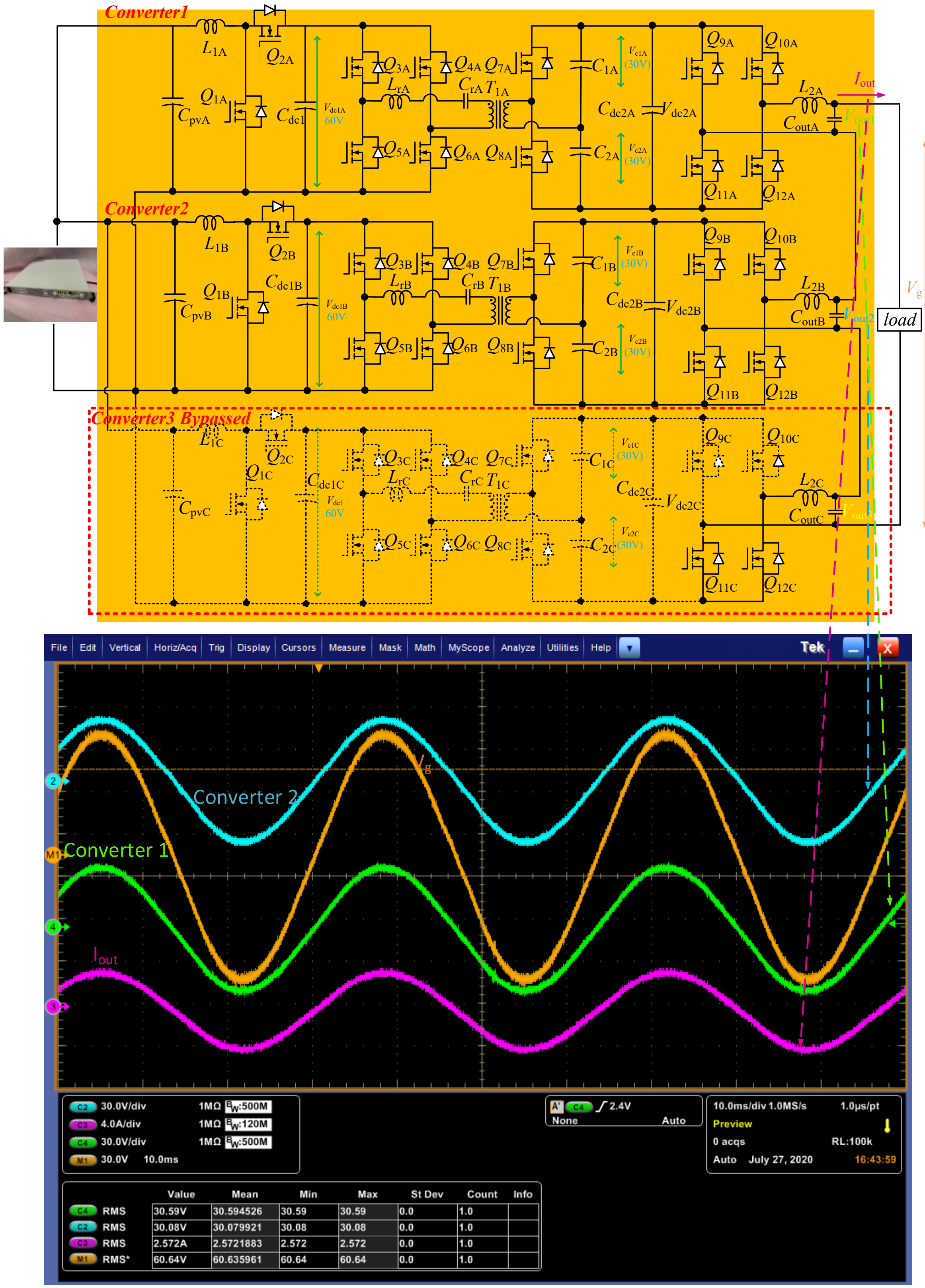


Figure 8.24 Inverter #3 bypassed with a three-inverter-in-series situation

8.6 PROTOTYPE FOR THE SOLAR HIGHWAY SYSTEM

A prototype for the solar highway system was built at NDSU's Structural Lab. The setup is shown in Figure 8.25.

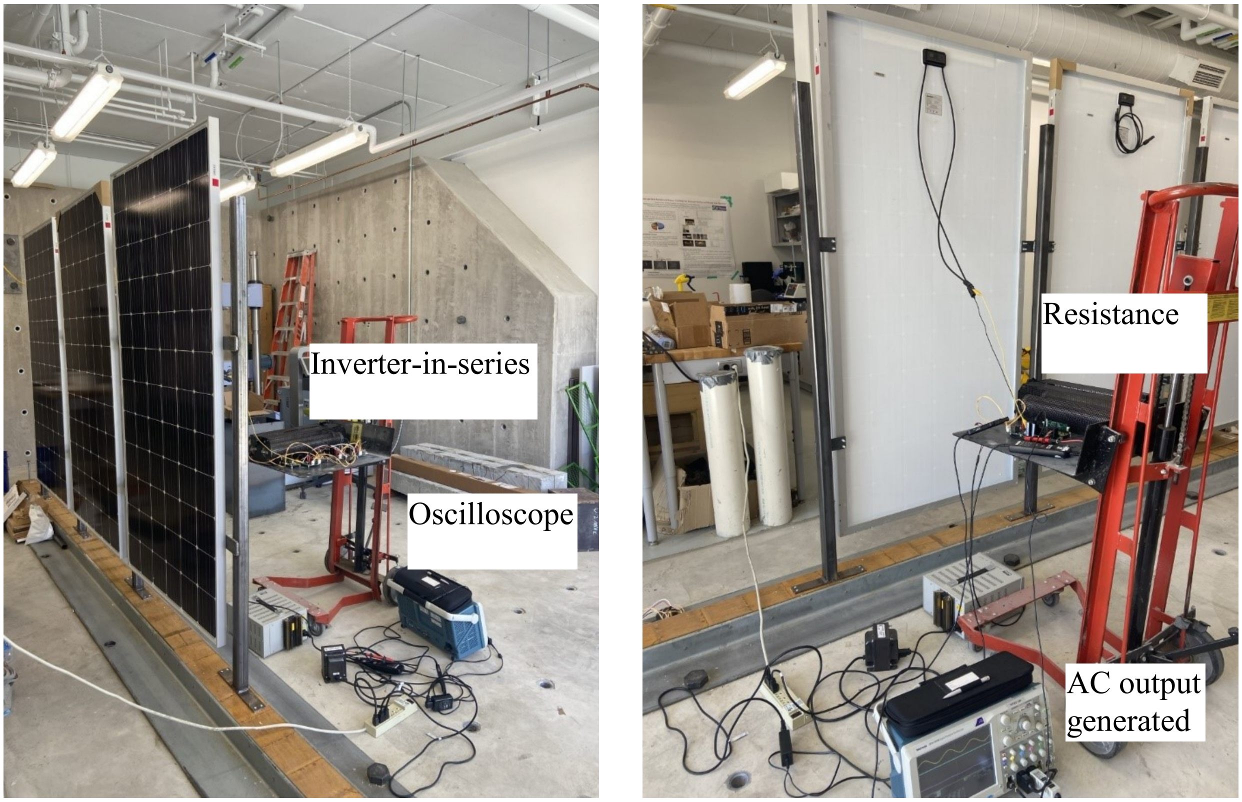


Figure 8.25 Prototype for the solar highway system

As seen in Figure 8.25(a), multiple solar panels and their individual inverters and controllers could be connected in a series. From Figure 8.25(b), we can see that the AC output is generated on the oscilloscope, which verifies the design and its connection with the solar panels.

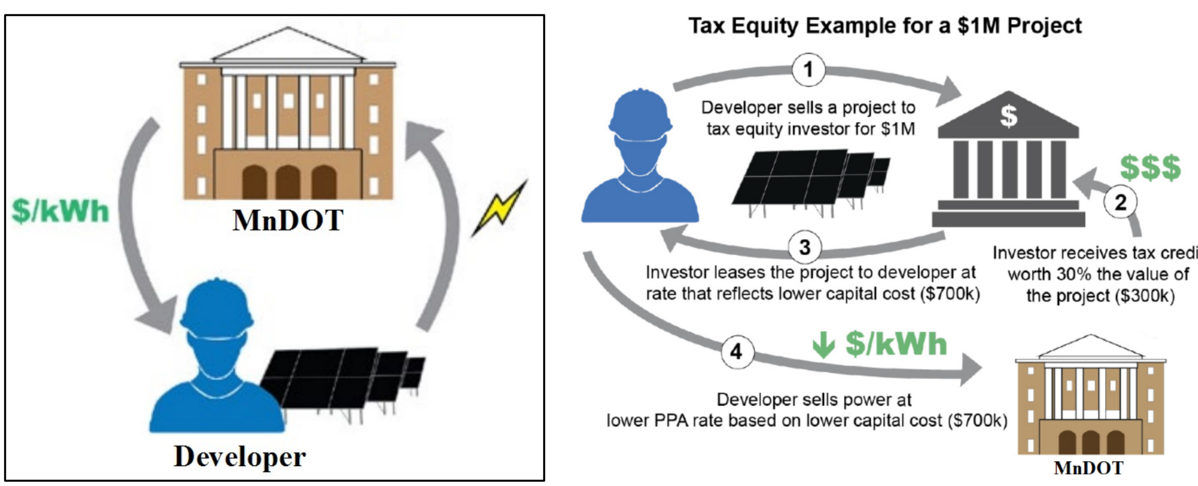
In order to measure the system's efficiency, one solar panel was deployed outside the Structural Lab and was tested for its capability to utilize ambient sunlight (Figure 8.26). From Figure 8.26(a), we can see that the solar panel could be adjusted for its incline angle and efficiency. In Figure 8.26(b), an AC voltage of 27 volts is generated from the single panel, and the output capacity reaches 120 watts. This system could be optimized and reach its designated capacity at 375 watts if the resistance load's maximum is adjusted.

Figure 8.26 Testing the solar highway system with ambient sunlight

CHAPTER 9: COST-BENEFIT ANALYSIS OF THE SOLAR HIGHWAY SYSTEM

The cost-benefit analysis includes material, labor, and recycling/disposal costs for the installation and maintenance of the PV noise barriers and PV snow fences. The benefits include the collected solar energy, i.e., the economic benefit when the generated energy is used by MnDOT facilities with the intention of reducing electricity bills and/or generating revenue for MnDOT by selling the generated power to utility companies. The environmental benefits are also tracked, including the reduced use of fossil fuels to generate the same amount of electrical energy, as well as the associated reduction of greenhouse-gas emissions, the noise reduction due to the use of noise barriers from benefited receptors, the reduction of salt usage for snow and ice control, and the reduction of operations for snow and ice removal. The monetary values of these environmental benefits are reflected in the cost-benefit analysis, and the possible increase for the operation and/or maintenance costs of the snow fences and noise barriers due to the installation and use of solar panels is taken into account. Additionally, the difference between MnDOT's direct ownership and a third-party ownership of the PV system through a Power Purchase Agreement (PPA) is identified and evaluated.

A PPA is a financial mechanism that allows MnDOT to accrue the benefits of solar power without owning the system. In a PPA, a solar project's developer procures, builds, operates, and maintains the solar system while MnDOT buys power from the developer at a negotiated rate (Figure 9.1(a); NREL, 2016a). A PPA also allows MnDOT to benefit indirectly from tax incentives through lower electricity prices by using tax equity, considering that MnDOT, generally, does not pay taxes. (Figure 9.1(b) shows how PPA works for a $1M project). Figure 9.2 shows the averaged 2015 PPA rates for power systems that are between 100 kW and 5 MW, by state and region, across the U.S.



(a) (b)

Figure 9.1 A PPA's financial mechanism (NREL, 2016a)

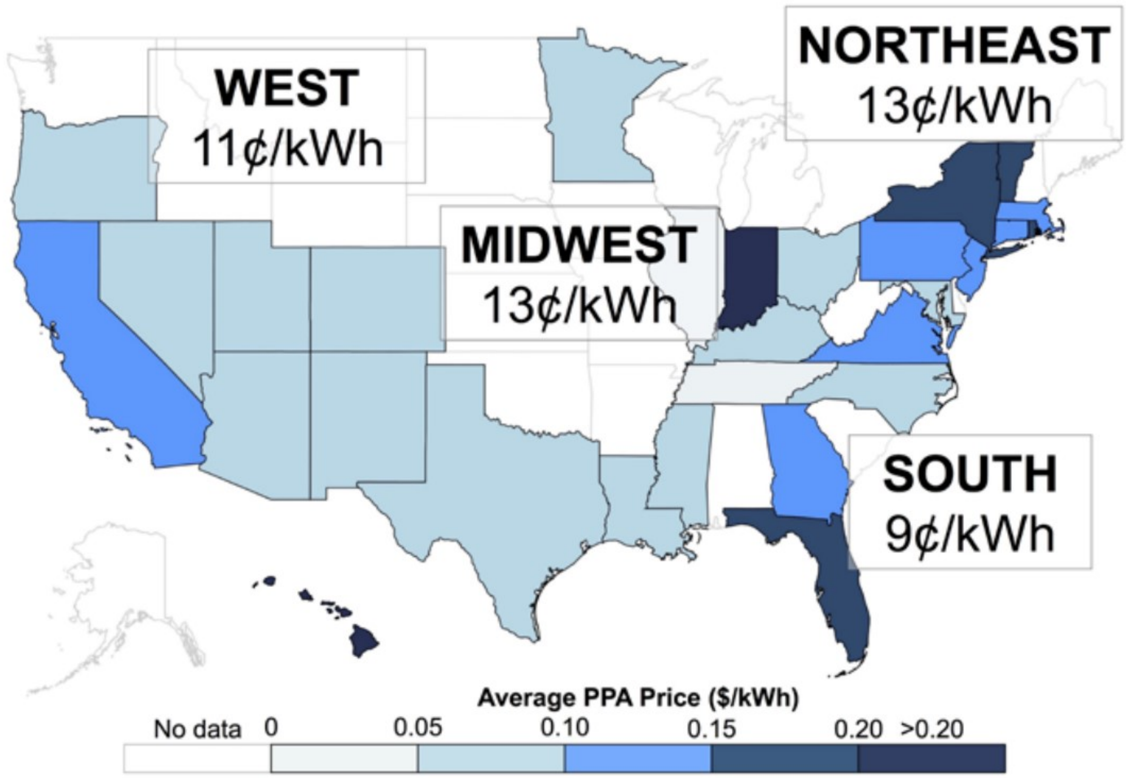


Figure 9.2 Average rates for solar-powered systems that are between 100 kW and 5 MW (NREL, 2016a)

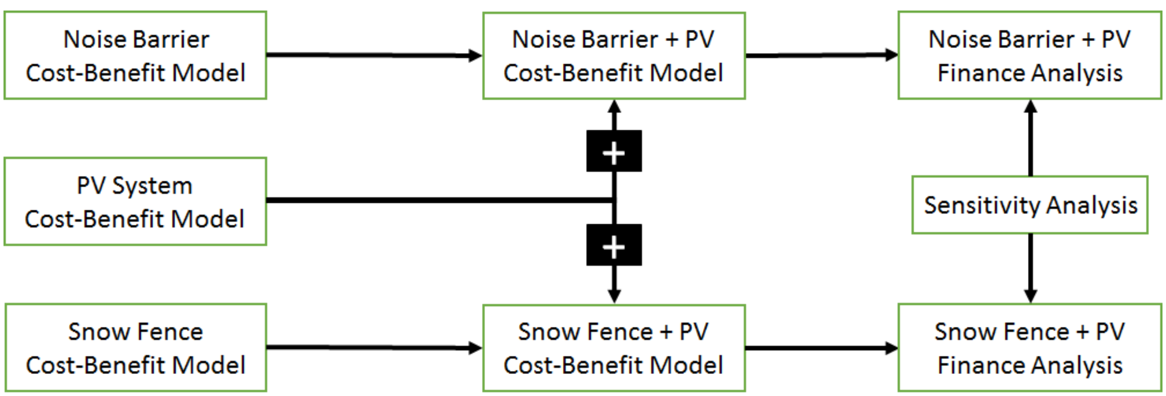


Figure 9.3 The approach to estimate the system's total costs and benefits

9.1 THE COST-BENEFIT MODEL'S DEVELOPMENT

A comprehensive cost-benefit model consists of three sub-models: the models for the noise barriers, the snow fences, and the PV system. The three models were developed separately, and then, model integrations (Section 9.2) were conducted, depending on whether the PV system was installed on the noise-barrier walls or snow fences, as shown in Figure 9.3. Once the models were established and integrated, a sensitivity analysis was conducted (Section 9.3) in order to find the most sensitive (critical) parameters and to evaluate their potential effects on the results. The development of the three models is described in the following sections.

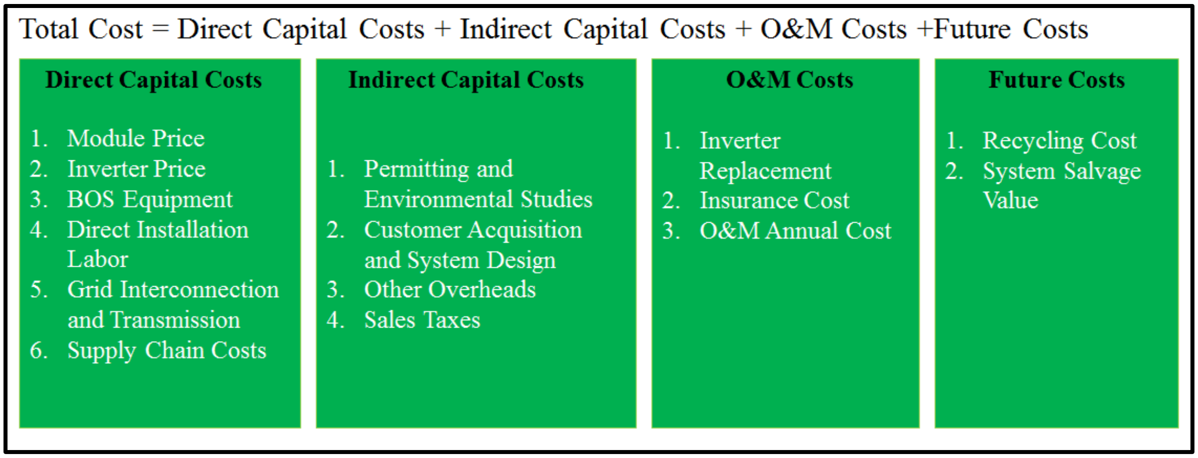


Figure 9.4 Total cost of the PV system

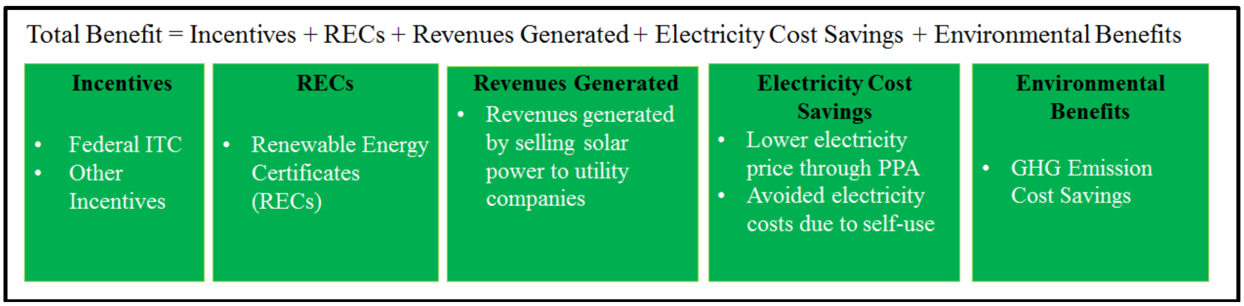


Figure 9.5 Total benefit of the PV system

9.1.1 Model for the PV System

In the cost-benefit model for the PV system, the total cost includes the direct capital cost, the indirect capital cost, the operation and maintenance (O&M) cost, and the future cost of the PV system, as shown in Figure 9.4; the total benefits include the solar energy collected, e.g., the economic benefit when the energy is used to power facilities with the intention of reducing electricity bills and/or to generate revenue for MnDOT by selling the generated power to utility companies (Figure 9.5). The environmental benefits' monetary values, e.g., the reduced use of fossil fuels to generate the same amount of electrical energy and/or the associated reduction of greenhouse-gas emissions, were also included. Incentives from federal/state/local governments and/or utility companies, such as the federal solar investment tax credit (ITC; TruNorth Solar), were considered, too. Renewable Energy Certificates (RECs) can also be considered as an additional benefit for the project, if applicable; through the Minnesota Renewable Energy Standard (RES) program, MnDOT can sell the RECs to utility companies (MnDOC, 2019). For example, the RES requires that Xcel Energy obtain 25% of its Minnesota retail sales from renewables, and all other utilities are subject to the RES requirements to obtain 17% of their Minnesota retail sales from renewables. Additionally, in 2013, a Solar Energy Standard (SES) was established, which sets a goal for public utilities, including Minnesota Power, Ottertail Power Company, and Xcel Energy, to obtain at least 1.5% of their total Minnesota retail sales from solar energy by the end of 2020 and 10% by 2030 (MnDOC, 2019).

To develop the cost-benefit model of the PV system, several important factors are considered:

- Factor 1: the system's scale/size (i.e., the system's capacity in terms of kW), which is determined by the number of PV panels to be installed on the snow fences/noise barriers for a 1-mile or 1,000-mile long stretch;
- Factor 2: who has ownership, i.e., direct MnDOT ownership or third-party ownership through a PPA;
- Factor 3: how the generated electrical power is used, i.e., sell it to a utility company or self-use it by MnDOT for existing facilities, such as amenities at highway rest areas or street lights;
- Factor 4: if environmental and/or social benefits are monetarily quantified and included in the analysis? Some of the environmental/social benefits, i.e., the possible reduction of greenhouse-gas emissions, are difficult for MnDOT to monetize and use them directly in order to offset the costs.
- Factor 5: if incentive(s) is(are) included? The current incentive programs may change in the future when/after MnDOT initiates the project.

Table 9.1 shows these critical factors as well as how they are used in the model.

Table 9.1 Critical factors considered for the PV cost-benefit model

Factor #	Description	Variation
1	System scale/size	1 mile or 1,000 miles
2	Ownership	Owned by MnDOT or a 3rd party via a PPA
3	How to use the generated electricity?	Selling to a utility or self-used
4	If including environmental and/or social benefits?	Included or not included
5	If including incentive(s)?	Included or not included

Given the five critical factors, possible changes for the model are shown in Table 9.2, where 10 different case scenarios are considered. Other conditions and assumptions used to develop the PV cost-benefit model are summarized in Tables 9.3, 9.4, 9.5, and 9.6.

Table 9.2 Case Scenarios

Factor	Case 1	Case 3	Case 5	Case 7	Case 9
1	Miles (1 or 1,000)	Miles (1 or 1,000)	Miles (1 or 1,000)	Miles (1 or 1,000)	Miles (1 or 1,000)
2	Owned by MnDOT	Owned by MnDOT	Owned by MnDOT	Owned by MnDOT	3rd party via PPA
3	Sell to Utility	Sell to Utility	Self-Used	Self-Used	Solar PPA
4	Not Included	Not Included	Not Included	Not Included	Not Included
5	Not Included	Included	Not Included	Included	N/A
Factor	**Case 2**	**Case 4**	**Case 6**	**Case 8**	**Case 10**
1	Miles (1 or 1,000)	Miles (1 or 1,000)	Miles (1 or 1,000)	Miles (1 or 1,000)	Miles (1 or 1,000)
2	Owned by MnDOT	Owned by MnDOT	Owned by MnDOT	Owned by MnDOT	3rd party via PPA
3	Sell to Utility	Sell to Utility	Self-Used	Self-Used	Solar PPA

4	Included	Included	Included	Included	Included
5	Not Included	Included	Not Included	Included	N/A

Table 9.3 PV panel information for noise barriers

PV Panel Information for Noise Barriers		Comments/Notes
Panel Capacity [Watt]	375	ReneSola SPM (SLP) 375 (Figure 9.6) JC375S-24/Abpw
Panel Length [feet]	6.42	Given by the manufacturer
Panel Width [feet]	3.25	Given by the manufacturer
Number of Panels per 1 Mile*	2,640	Four-layer vertical installation on noise barriers (Figure 9.7)
Number of Panels per 1,000 Miles*	2,640,000	Number of panels per 1 Mile × 1,000
Degradation Rate [%]	0.8	(NREL, 2012)
Module Type	Standard	-
Array Type*	Fixed/Adjustable	-
System Losses* [%]	14.08	(Pvwatts)
Tilt* [deg]	90	Vertical installation as shown in Figure 9.7
Azimuth [deg]	180	Facing South
Inverter Efficiency [%]	96	(Pvwatts)
Latitude	46.89° N	Assume that the PV panels are installed along US-10 in Moorhead, MN
Longitude	96.78° W	
Annual AC Energy Output: 1 Mile* [kWh]	990,979	Calculated by using the online PVWatts Calculator developed by NREL (Pvwatts)
Annual AC Energy Output: 1,000 Miles* [kWh]	990,979,440	
Metric Tons of CO2 Equivalent/year: 1 Mile	701	Calculated by using the EPA Greenhouse Gas Equivalencies Calculator (National Average) (U.S. EPA)
Metric Tons of CO2 Equivalent/year: 1,000 Mile	700,662	

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.4 PV panel information for snow fences

PV Panel Information for Snow Fences		Comments/Notes
Panel Capacity* [Watt]	100	Customized PV panel to fit the snow fences as shown in Figure 9.8
Panel Length [feet]	12.0	Same size as the snow-fence rail of an 8-foot-tall, 50% porosity fence

Panel Width* [feet]	0.5	Same size as the snow-fence rail of an 8-foot-tall, 50% porosity fence
Number of Panels per 1 Mile*	3,520	Eight customized panels (0.5×12 ft) per section, installed vertically on snow fences (Figure 9.8)
Number of Panels per 1,000 Miles*	3,520,000	Number of panels per 1 mile × 1,000
Degradation Rate [%]	0.8	(NREL, 2012)
Module Type	Customized	-
Array Type	Fixed	Not adjustable to not influence the original function and effectiveness of the snow fences
System Losses [%]	14.08	(Pvwatts)
Tilt* [deg]	90	Vertical installation as shown in Figure 9.8
Azimuth [deg]	180	Facing South
Inverter Efficiency [%]	96	(Pvwatts)
Latitude	46.89° N	Assume that the PV panels are installed along US-10 in Moorhead, MN
Longitude	96.78° W	
Annual AC Energy Output: 1 Mile* [kWh]	352,348	Calculated by using the online PV Watts Calculator developed by NREL (Pvwatts)
Annual AC Energy Output: 1,000 Miles* [kWh]	352,348,000	
Metric Tons of CO2 Equivalent/year: 1 Mile	249	Calculated by using the EPA Greenhouse Gas Equivalencies Calculator (National Average) (U.S. EPA)
Metric Tons of CO2 Equivalent/year: 1,000 Mile	249,045	

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.5 Cost information for the PV system

PV System's Cost Information		Comments/Notes
Direct Capital Costs		
Module Price* [$/W]	$0.65/$0.40 $0.85/$0.60	Standard PV: $0.65/W for 1-mile noise barriers (NREL, 2016b) Standard PV: $0.40/W for 1,000-mile noise barriers (NREL, 2016b) Customized PV: $0.85/W for 1-mile snow fences (Alibaba, 2020) Customized PV: $0.60/W for 1,000-mile snow fences (Alibaba, 2020)
Inverter Price [$/W]	$0.15/$0.10	$0.15/W for 1-mile noise barriers/snow fences (NREL, 2016b)

		$0.10/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Balance-of-System (BOS) Equipment [$/W]	$0.35/$0.25	$0.35/W for 1-mile noise barriers/snow fences (NREL, 2016b) $0.25/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Direct Installation Labor [$/W]	$0.20/$0.10	$0.20/W for 1-mile noise barriers/snow fences (NREL, 2016b) $0.10/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Grid Interconnection and Transmission [$/W]	$0.05/$0.03	$0.05/W for 1-mile noise barriers/snow fences (NREL, 2016b) $0.03/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Supply Chain Costs [% of the total material cost]	10%	(NREL, 2018a)
Total Direct Capital Costs [$/W]	$1.52/$0.96 $1.74/$1.18	Standard PV: $1.52/W for 1-mile noise barriers Standard PV: $0.96/W for 1,000-mile noise barriers Customized PV: $1.74/W for 1-mile snow fences Customized PV: $1.18/W for 1,000-mile snow fences
Indirect Capital Costs		
Permitting and Environmental Studies [$/W]	$0.05/$0.03	$0.05/W for 1-mile noise barriers/snow fences (NREL, 2016b) $0.03/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Customer Acquisition and System Design [$/W]	$0.05/$0.02	$0.05/W for 1-mile noise barriers/snow fences (NREL, 2016b) $0.02/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Other Overheads [$/W]	$0.20/$0.10	$0.20/W for 1-mile noise barriers/snow fences (NREL, 2016b) $0.10/W for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Sales Taxes* [%]	6.875%	(Taxmaps)
Total Indirect Capital Costs [$/W]	$0.38/$0.21	$0.38/W for 1-mile noise barriers/snow fences $0.21/W for 1,000-mile noise barriers/snow fences
O&M Costs		
Inverter Lifetime [Years]	13	(NREL, 2016b)
Inverter Replacement [$/W]	$0.09/$0.06	$0.09/W for 1-mile noise barriers/snow fences (NREL, 2018a)

		$0.06/W for 1,000-mile noise barriers/snow fences (NREL, 2018a)
Insurance Cost by Capacity [$/kW-yr]	$5.00/$3.00	$5.00/kW for 1-mile noise barriers/snow fences (Enbar et al., 2016) $3.00/kW for 1,000-mile noise barriers/snow fences (Enbar et al., 2016)
O&M Annual Cost by Capacity [$/kW-yr]	$10.00/$7.00	$10.00/kW for 1-mile noise barriers/snow fences (NREL, 2016b) $7.00/kW for 1,000-mile noise barriers/snow fences (NREL, 2016b)
Total O&M Costs [$/W]	$0.38/$0.25	$0.38/W for 1-mile noise barriers/snow fences $0.25/W for 1,000-mile noise barriers/snow fences
Future Costs		
Recycling Cost [$/W]	$0.17	(Fthenakis , 2000)
System Salvage Value [% of Capital Cost]	15%	(Guney & Onat, 2010)
Financial Parameters		
PV System's Lifetime [Year]	25	(ReneSola, 2015)
Real Discount Rate* [%/yr]	0.35%	(Executive Office of the President, 2020)
Federal Income Tax Rate [%]	0.00%	Confirmed by MnDOT
State Income Tax Rate [%]	0.00%	Confirmed by MnDOT
Electricity Utility Price Paid by MnDOT* [$/kWh]	$0.12	According to the utility costs provided by MnDOT
Li-ion Standalone Storage System Cost (For Self-Use)		
Duration [hr]	2	-
Li-ion Battery Cost [$/kWh]	$209.00	About $0.42/W (NREL, 2018b)
Battery's Central Inverter [$/W]	$0.07	(NREL, 2018b)
Structural BOS [$/W]	$0.03	(NREL, 2018b)
Electrical BOS [$/W]	$0.10	(NREL, 2018b)
Installation Labor & Equipment [$/W]	$0.07	(NREL, 2018b)
EPC Overhead [$/W]	$0.03	(NREL, 2018b)
Land Acquisition [$/W]	$0.01	(NREL, 2018b)
Permitting Fee [$/W]	$0.01	(NREL, 2018b)

Interconnection Fee [$/W]	$0.03	(NREL, 2018b)
Contingency [$/W]	$0.02	(NREL, 2018b)
Developer Overhead [$/W]	$0.02	(NREL, 2018b)
EPC/Developer Net Profit [$/W]	$0.04	(NREL, 2018b)
PV Cost Summary		
PV for 1-Mile Noise Barriers [$/W]	$1.89/$2.79	System Size: 990 kW $1.89/W for selling power to a utility company $2.79/W for self-use (including battery costs)
PV for 1,000-Mile Noise Barriers [$/W]	$1.16/$2.05	System Size: 990 MW $1.16/W for selling power to a utility company $2.05/W for self-use (including battery costs)
PV for 1-Mile Snow Fences [$/W]	$2.13/$3.02	System Size: 352 kW $2.13/W for selling power to a utility company $3.02/W for self-use (including battery costs)
PV for 1,000-Mile Snow Fences [$/W]	$1.39/$2.29	System Size: 352 MW $1.39/W for selling power to a utility company $2.29/W for self-use (including battery costs)

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.6 Benefit information for the PV system

PV System's Benefit Information		Comments/Notes
Federal ITC or other incentives *	10.00%	(U.S. DOE, 2019)
RECs* [$/REC or $/MWh]	$0.65	(MnDOC, 2019)
Price to sell back to a utility company* [$/kWh]	$0.11	According to the survey responses from utility companies conducted for Task 2
PPA for 3rd-party ownership* [$/kWh]	$0.10	(NREL, 2016a) or Figure 9.2
Bituminous Coal [Per Short Ton]		
Heating Value [MMBtu]	24.93	(U.S. EPA, 2014)
1 kWh to Btu	3,412	(U.S. EIA)
Electricity Output [kWh]	7306.57	(U.S. EPA, 2014)
kg CO_2	2,325	(U.S. EPA, 2014)
g CH4	274	(U.S. EPA, 2014)
g N2O	40	(U.S. EPA, 2014)
Greenhouse gas (GHG) Emission Cost Savings		
Per metric ton CO_2	$42.00	(U.S. EPA, 2017)
Per metric ton CH4	$1,200.00	(U.S. EPA, 2017)
Per metric ton N2O	$15,000.00	(U.S. EPA, 2017)
GHG Emission Ratio (Coal/Solar)	8.37	(Fan, 2014)

*A parameter to be considered for the sensitivity analysis in Section 9.3

Figure 9.6 shows the PV panels that were considered for the cost-benefit analysis, and Figures 9.7 and 9.8 illustrate the installation of the PV panels on a 20-foot-tall noise-barrier wall and an 8-foot-tall 50% porosity snow fence, respectively. As shown, the PV panels are installed vertically by attaching them to the noise-barrier wall with four layers, which allows for the installation of 2,640 panels on an 1 mile long noise-barrier wall. For the snow fences, rails are replaced with customized PV panels that have the same dimension as the rail, i.e., 12 × 0.5 ft, and are installed vertically to ensure that the original function of the snow fences is not affected.

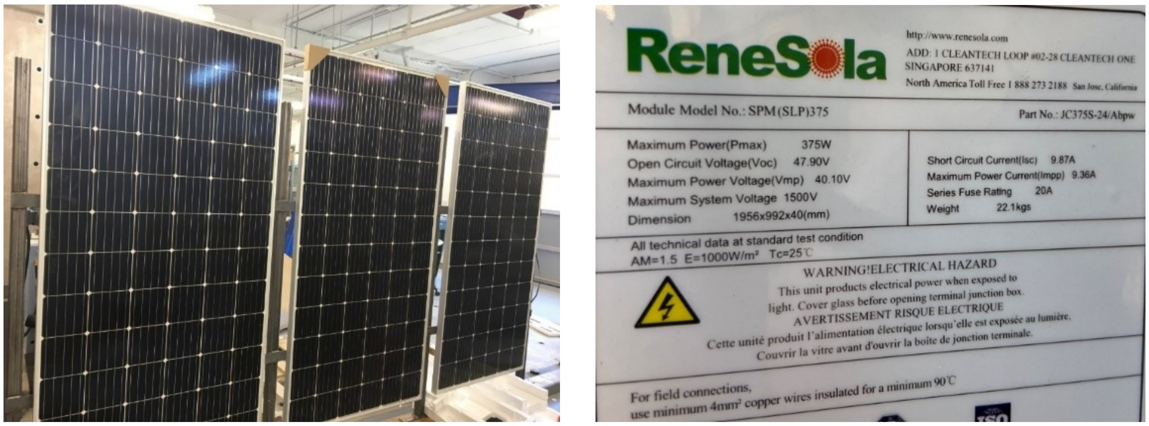


Figure 9.6 ReneSola SPM (SLP) 375 Panel

Three different methods were used to compare the case scenarios (Table 9.2) in order to make financial decisions**:** ***Payback Period (PP), Net Present Value (NPV),*** and ***Internal Rate of Return (IRR)***. Tables 9.7 and 9.8 summarize the analysis results for the PV panel systems which will be installed on noise barriers (Table 9.7) and snow fences (Table 9.8), respectively. The results are slightly different for these two tables, which is mainly caused by the distinct capital costs of the PV panels that will be installed on noise barriers or snow fences, as shown in Tables 9.3 and 9.4.

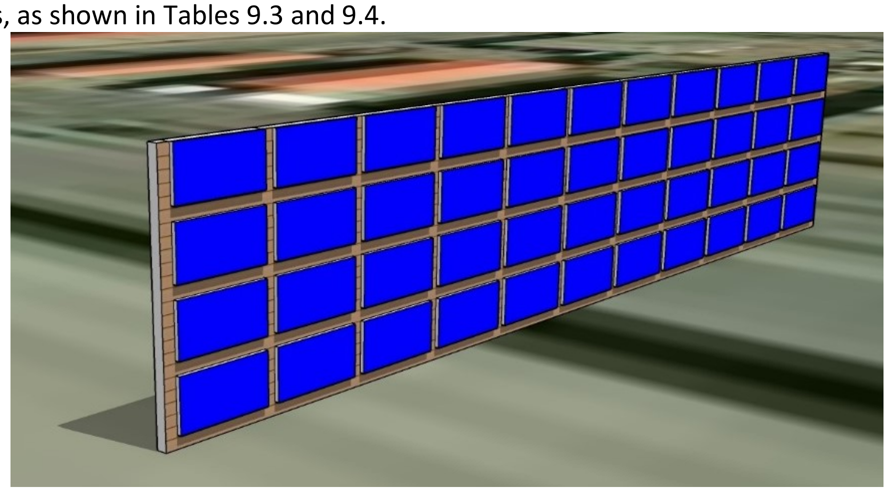


Figure 9.7 PV panels installed on the noise-barrier walls

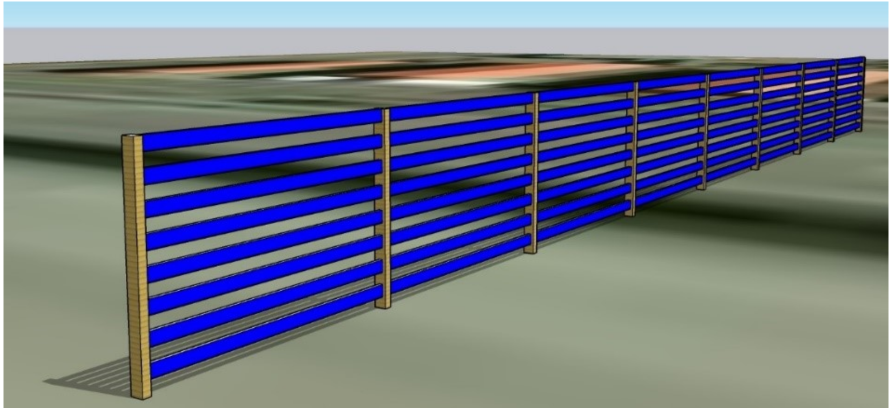


Figure 9.8 PV panels installed on the snow fences

Table 9.7 Results for the PV cost-benefit analysis (for noise barriers)

For 1 Mile						For 1,000 Miles				
Case Scenario	NPV	PP (Yr)	IRR	Rank		Case Scenario	NPV	PP (Yr)	IRR	Rank
Case 10	$687,538.53	NA	NA	1		Case 4	$1,218,766,493.10	10	8.49%	1
Case 4	$450,924.12	19	2.46%	2		Case 2	$1,104,239,653.59	11	7.17%	2
Case 9	$431,330.60	NA	NA	3		Case 3	$948,540,315.21	12	6.95%	3
Case 2	$263,609.94	21	1.49%	4		Case 1	$834,013,475.69	14	5.72%	4
Case 3	$180,697.95	22	1.23%	5		Case 10	$687,538,532.05	NA	NA	5
Case 1	$(6,616.24)	>25	0.32%	6		Case 8	$634,881,804.90	18	3.05%	6
Case 8	$(132,960.56)	>25	-0.11%	7		Case 6	$431,516,077.89	20	2.05%	7
Case 7	$(403,186.74)	>25	-1.09%	8		Case 9	$431,330,598.61	NA	NA	8
Case 6	$(409,113.64)	>25	-0.95%	9		Case 7	$364,655,627.01	20	1.96%	9
Case 5	$(679,339.82)	>25	-1.90%	10		Case 5	$161,289,900.00	22	1.01%	10

Table 9.8 Results for the PV cost-benefit analysis (for snow fences)

For 1 Mile						For 1,000 Miles				
Case Scenario	NPV	PP (Yr)	IRR	Rank		Case Scenario	NPV	PP (Yr)	IRR	Rank
Case 10	$244,458.09	NA	NA	1		Case 4	$368,999,891.16	12	6.30%	1
Case 9	$153,361.96	NA	NA	2		Case 2	$320,059,309.75	14	5.13%	2
Case 4	$95,953.13	22	1.49%	3		Case 3	$272,919,492.30	15	4.93%	3
Case 2	$21,124.53	24	0.58%	4		Case 10	$244,458,093.97	NA	NA	4
Case 3	$(127.27)	>25	0.35%	5		Case 1	$223,978,910.89	16	3.83%	5
Case 1	$(74,955.87)	>25	-0.51%	6		Case 8	$161,396,430.55	20	2.11%	6
Case 8	$(111,650.33)	>25	-0.65%	7		Case 9	$153,361,958.78	NA	NA	7
Case 7	$(207,730.73)	>25	-1.58%	8		Case 6	$80,868,689.14	22	1.17%	8
Case 6	$(218,066.09)	>25	-1.46%	9		Case 7	$65,316,031.69	22	1.09%	9

Case 5	$(314,146.49)	>25	-2.36%	10		Case 5	$(15,211,709.72)	>25	0.19%	10

9.1.2 Model for Noise Barriers

In the analysis, the noise-barrier model was established based on the information provided by MnDOT as well as resources found online (FHWA; VTPI, 2016; MnDOT(a); Morgan et al. 2001). Table 9.9 shows the cost information for the noise barriers used in the analysis, and Table 9.10 shows the benefit information. Table 9.11 summarizes the analysis results for 1-mile and 1,000-mile noise-barrier walls. In the analysis, no significant changes were made between the 1-mile and 1,000-mile noise barrier walls for the cash-flow calculations since noise barriers are typically not continuous (installed separately based on miles) and thus the potential cost reduction due to the lower wholesale price is negligible.

Table 9.9 Cost information for the noise barriers

Noise-Barrier Cost Information		Comments/Notes
Average Height [feet]	20	As shown in Figure 9.7
Project Length [mile]*	1 or 1,000	-
Primary Construction Material*	Concrete	-
Installation & Material Costs* [$/sq ft]	$36.00	Provided by MnDOT
Disposal cost [$/sq ft]	$5.00	Provided by MnDOT
Maintenance Cost [$/sq ft-Year]	$0.00	Provided by MnDOT
Sales Taxes* [%]	6.875%	(Taxmaps)
Real Discount Rate* (%)	0.35%	(Executive Office of the President, 2020)

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.10 Benefit information for the noise barriers

Noise-Barrier Benefit Information		Comments/Notes
# of Benefited Receptors per Mile*	51	Determined to make zero NPV for the noise barriers (Worst Case): See Table 9.11
Cost-Effectiveness Value per Benefited Receptor	$78,500	Provided by MnDOT

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.11 Results for the Noise barrier's cost-benefit analysis

Miles	Payback	NPV	IRR
1 Mile	30	$(7,410.12)	0.34%
1,000 Miles	30	$(7,410,123.13)	0.34%

As shown in Table 9.10, the number of benefited receptors per mile would vary, but the minimum number (51 as shown) can be determined when the cost of a noise wall and its cost-effectiveness value per benefited receptor ($78,500/Receptor) are known. As suggested by MnDOT, this number was determined by setting the NPV and/or IRR equal to (or in this case close to) zero, as shown in Table 9.11, meaning that the annual cash flows for the costs and benefits are balanced in the analysis period. This approach allows MnDOT to understand how the costs and benefits of the PV panel system affect the final analysis when combining the two cash flows together through model integration (Section 9.2). In addition, the number of benefited receptors per mile is considered to be a critical parameter for the sensitivity analysis (Section 9.3), where this number is increased to see how it affects the result.

9.1.3 Model for Snow Fences

Like the noise barriers, the structural snow-fence model was also developed based on the information provided by MnDOT. Table 9.12 shows the cost information for the snow fences used in the analysis, and Table 9.13 shows the benefit information. Table 9.14 summarizes the results for 1-mile and 1,000-mile snow fences. In the analysis, no significant changes were made between 1-mile and 1,000-mile snow fences for the cash flows, since structural snow fences are typically not continuous (installed separately on the basis of miles) and thus the potential cost reduction due to the lower wholesale price is negligible.

Table 9.12 Cost information for the structural snow fences

Structural Snow-Fence Cost Information		Comments/Notes
Unit Hight [feet]	8	As shown in Figure 9.8
Unit Length [mile]*	1 or 1,000	-
Install & Material Costs* [$/foot]	$72.10	Provided by MnDOT
Land Cost [$/linear foot/year]*	$1.00	Rental cost (Provided by MnDOT)
O&M Cost [$/mile-Year]	$3,000.00	Provided by MnDOT
Property Tax*	$0	Lease: Paid by landowners
Recycling Cost [$/foot]	$0.25	(Ernie's Wagon)
Real Discount Rate* [%]	0.35%	(Executive Office of the President, 2020)

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.13 Benefit information for the structural snow fences

Structural Snow-Fence Benefit Information		Comments/Notes
Drifting Savings* [$/mile-Year]	$34,486.03	Agency cost savings with drifting-snow events: Determined from a document given by MnDOT
Blow Ice Savings* [$/mile-Year]	10,207.09	Agency cost savings with blowing snow and ice events: Determined from a document given by MnDOT
Avoided Crashes* [$/mile-Year]	29,638.00	Cost savings from fatal, injury, and property-damage crashes: Determined from a document given by MnDOT
Avoided Travel Time* [$/mile-Year]	12,826.93	Savings caused by travel-time reductions due to improved road conditions: Determined from a document given by MnDOT
Avoided Carbon Emissions* [$/mile-Year]	$241.40	Cost savings from reduced carbon emissions from the agency's equipment: Determined from a document given by MnDOT
Salvage Value [$/foot]	$0.09	For steel poles (Scrapmonster)

*A parameter to be considered for the sensitivity analysis in Section 9.3

Table 9.14 Results for the now fence's cost-benefit analysis

Miles	Payback	NPV	IRR
1 Mile	4	$1,936,541.62	25.32%
1,000 Miles	4	$1,936,541,615.22	25.32%

9.2 MODEL INTEGRATION

Integrating the developed models for PV panels, noise barriers, and snow fences was done by using the method shown in Figure 9.3.

9.2.1 Model Integration Between the PV Panels and Noise Barriers

The costs and benefits of the PV panels and noise barriers incurred in the same year are integrated through mathematical addition, assuming that the mutual influence between the two cash flows is negligible. Table 9.15 summarizes the cost-benefit analysis for this integrated model when installing PV panels on a new noise-barrier wall, where the PV panels and noise-barrier walls are built together, thus they are analyzed with the integrated cash flow. When installing PV panels on an existing noise-barrier wall, the cash flow for the PV panels (not including the noise barriers) is used for the analysis (because the mutual influence is ignored); the results are found in Table 9.7.

Table 9.15 Results of the cost-benefit analysis for PV panels installed on a new noise-barrier wall

For 1 Mile						For 1,000 Miles				
Case Scenario	NPV	PP (Yr)	IRR	Rank		Case Scenario	NPV	PP (Yr)	IRR	Rank
Case 10	$75,056.02	25	0.50%	1		Case 4	$606,283,984.43	22	1.33%	1
Case 4	$(161,558.39)	>25	0.11%	2		Case 2	$491,757,144.92	23	1.13%	2
Case 9	$(181,151.91)	>25	-0.03%	3		Case 3	$336,057,806.54	23	0.90%	3
Case 2	$(348,872.57)	>25	-0.15%	4		Case 1	$221,530,967.02	24	0.71%	4
Case 3	$(431,784.56)	>25	-0.30%	5		Case 10	$75,056,023.38	25	0.50%	5
Case 1	$(619,098.75)	>25	-0.56%	6		Case 8	$22,399,296.24	>25	0.38%	6
Case 8	$(745,443.07)	>25	-0.64%	7		Case 6	$(180,966,430.78)	>25	0.10%	7
Case 7	(1,015,669.25)	>25	-1.02%	8		Case 9	$(181,151,910.06)	>25	-0.03%	8
Case 6	(1,021,596.15)	>25	-0.97%	9		Case 7	$(247,826,881.66)	>25	-0.01%	9
Case 5	(1,291,822.33)	>25	-1.34%	10		Case 5	$(451,192,608.67)	>25	-0.29%	10

As shown in Table 9.15, when integrating these two cash flows together, the results are significantly influenced by the cash flow of the noise barriers (compared with Table 9.7) because the capital cost for the noise barriers is much higher than the cost for the PV system. For example, noise barriers account for about 67% (for 1-mile noise barriers) or 77% (for 1,000-mile noise barriers) of the total capital cost.

Table 9.16 Results of the cost-benefit analysis for customized PV panels installed on new snow fences

For 1 Mile						For 1,000 Miles				
Case Scenario	NPV	PP (Yr)	IRR	Rank		Case Scenario	NPV	PP (Yr)	IRR	Rank

Case 10	$1,823,048.67	4	28.79%	1		Case 4	$1,947,590,469.07	7	14.96%	1
Case 9	$1,731,952.54	4	27.48%	2		Case 2	$1,898,649,887.66	7	13.91%	2
Case 4	$1,674,543.71	9	10.58%	3		Case 3	$1,851,510,070.21	7	14.34%	3
Case 2	$1,599,715.11	10	9.61%	4		Case 10	$1,823,048,671.88	4	28.79%	4
Case 3	$1,578,463.31	10	10.08%	5		Case 1	$1,802,569,488.80	8	13.32%	5
Case 1	$1,503,634.71	10	9.13%	6		Case 9	$1,731,952,536.68	4	27.48%	6
Case 8	$1,466,940.25	11	7.73%	7		Case 8	$1,739,987,008.45	9	10.51%	7
Case 7	$1,370,859.85	12	7.31%	8		Case 6	$1,659,459,267.04	10	9.52%	8
Case 6	$1,360,524.49	12	6.81%	9		Case 7	$1,643,906,609.59	10	10.03%	9
Case 5	$1,264,444.09	13	6.41%	10		Case 5	$1,563,378,868.19	10	9.06%	10

Table 9.17 Results of the cost-benefit analysis for customized PV panels installed on existing snow fences

For 1 Mile						For 1,000 Miles				
Case Scenario	NPV	PP (Yr)	IRR	Rank		Case Scenario	NPV	PP (Yr)	IRR	Rank
Case 10	$2,127,768.03	1	1213.5%	1		Case 4	$2,252,309,829.07	4	26.09%	1
Case 9	$2,036,671.90	1	1157.3%	2		Case 2	$2,203,369,247.66	5	23.43%	2
Case 4	$1,979,263.07	6	16.42%	3		Case 3	$2,156,229,430.21	4	25.10%	3
Case 2	$1,904,434.47	7	14.60%	4		Case 10	$2,127,768,031.88	1	1213.5%	4
Case 3	$1,883,182.67	7	15.75%	5		Case 1	$2,107,288,848.80	5	22.54%	5
Case 1	$1,808,354.07	7	13.98%	6		Case 8	$2,044,706,368.45	7	15.93%	6
Case 8	$1,771,659.61	9	11.28%	7		Case 9	$2,036,671,896.68	1	1157.3%	7
Case 7	$1,675,579.21	9	10.77%	8		Case 6	$1,964,178,627.04	7	14.15%	8
Case 6	$1,665,243.85	10	9.85%	9		Case 7	$1,948,625,969.59	7	15.30%	9
Case 5	$1,569,163.45	10	9.37%	10		Case 5	$1,868,098,228.19	8	13.57%	10

9.2.2 Model Integration Between PV Panels and Structural Snow Fences

Similarly, the cash flows for the PV panels and the structural snow fences are integrated mathematically by adding the corresponding costs and benefits which are incurred in the same year together, but with the exception that the snow-fence rails are replaced with the customized PV panels as shown in Figure 9.8. The panels have the same dimension as the rail, i.e., 12 × 0.5 feet, thus the cost of the snow-fence rails, which accounts for about 18% of the total fencing cost, was removed from the integrated cash flow; instead, the cost of the customized PV panels was included to reflect the mutual influence when combining PV panels and snow fences.

Table 9.16 summarizes the cost-benefit analysis of this integrated model for the new installation of both PV panels and snow fences. Installing the customized PV panels on the existing structural snow fences is still considered; the result is shown in Table 9.17. In this case, the replacement cost (materials and labor) for the customized PV panels and the recycling costs for the snow-fence rails (polyethylene) are considered.

As shown in Tables 9.16 and 9.17, when integrating these two cash flows, the results are primarily influenced by the cash flow for the snow fences (compared with Table 9.8) due to the significant benefit of using snow fences (as shown in Table 9.13), even though snow fences only account for about 29% (for 1-mile snow fences) or 39% (for 1,000-mile snow fences) of the total capital cost (including the PV system). Structural snow fences are typically installed on farmland along highways, and MnDOT has two methods to obtain permission from a private landowner to install snow fences: 1) purchasing the property through an easement or 2) leasing farmland. Therefore, a cost-benefit analysis, from a landowner/farmer's perspective, was conducted to obtain information about the installation and use of snow fences with/without PV panels. In the analysis, the costs (Table 9.18) included the yield loss for agriculture, property taxes if the land was leased to MnDOT, and the cost for the PV system if it was owned by the landowners. The benefits (Table 9.18) included the rental payments from MnDOT (if the land was leased) or the income from selling the land to MnDOT (if land was purchased), and the income from selling the generated electrical power to the utility companies if the PV system was owned by the landowners. Breakeven points were also determined to look at how much MnDOT will pay (for leasing or purchasing farmland) in order to balance between the income and expenditures for landowners/farmers.

Table 9.18 Cost information from a landowner's perspective

Cost Information		**Comments/Notes**
Land Width [feet]	25	A 25-foot width of property is needed to install and to maintain the structural snow fences.
Land Length [mile]*	1	For 1 mile of snow fencing (typically about ¼ mile per landowner).
Land Area [acre]	3.03	Width × Length
Property Market Value [$/Acre]	$5,241	Average value in Minnesota (AcreValue)
Property Tax [%]	1.5%/2%	○ Land is considered as Commercial/Industrial/Public Utility Use • 1.5% if market value ≤ $150K (MN House Research, 2019) • 2.0% if market value >$150K (MN House Research, 2019) ○ State General Property Tax: 36% (MN Department of Revenue) ○ Total Local Tax Rate: 100% (Clay County MN) ○ Total Market Value Tax Rate: 0.19% (Clay County MN) ○ Zero property tax if land owned by MnDOT (All numbers were confirmed with Nancy Gunderson, Clay County Assessor)
Farm-Product Price Index	161.50	For the year of 2019. (MnDOT(b))
Farm-Product Profit [$/Acre]	$271.66	(MnDOT(c))
Cost Due to PV System	See Table 9.5	-
Benefit Information		**Comments/Notes**

Income Due to Land (Leased or Purchased)	$1.00/linear foot/yr $10,000/acre	$1.00/linear foot: The land's rental rate $10,000/acre: The land's purchase price
Income Due to PV System	See Table 9.6	-

Table 9.19 shows the NPV for landowners who either lease or sell farmland to MnDOT. As shown, from the landowner's point of view, leasing land to MnDOT that will pay $1.00/linear foot/year is more cost-effective than selling the land at a price of $10,000/acre during the 25-year analysis period. Landowners will reach the breakeven point to lease the land at $0.22/linear foot/year or to sell the land for about $7,110/acre to MnDOT. Please note, other inconveniences for the landowners/farmers due to the installation of snow fences were not considered because the issues are difficult to determine and to quantify.

Table 9.19 Analysis result from a landowner's perspective (without PV panels)

	NPV	Breakeven
Lease Land	$ 107,366.74*	Land rental rate: $0.22/linear foot/year
Purchase Land	$8,759.38**	Land purchase fee: $7,109.40/acre

*Other inconveniences for landowners are not considered

**The landowners' original expenditure to purchase the land was not included with the analysis because the purchase could have occurred many years ago and, thus, be difficult to determine

Table 9.20 Analysis result from a landowner's perspective (with PV panels)

Case	PP	NPV	IRR	Breakeven
Lease land to MnDOT + Invest in the PV system				
Case 1	24	$32,400.25	0.70%	$0.77/linear foot/year
Case 2	21	$128,480.64	1.70%	$0.07/linear foot/year
Case 3	21	$107,228.85	1.61%	$0.22/linear foot/year
Case 4	19	$203,309.24	2.65%	$0/linear foot/year
Sell land to MnDOT + Invest in the PV system				
Case 1	>25	$ (66,197.35)	-0.42%	$31,847.31/acre
Case 2	24	$29,883.05	0.68%	$137.58/acre
Case 3	25	$8,631.25	0.46%	$7,151.41/acre
Case 4	21	$104,711.65	1.61%	$0/acre

If the installed PV system is financed and owned by landowners/farmers who will lease or sell farmland to MnDOT and then sell the generated electrical power to utility companies (Cases 1-4), the analysis results, including NPV, PP, IRR, and breakeven points, are shown in Table 9.20. The payback period is 19 years or 21 years for landowners if both the environmental benefits and the incentives are considered and included with the analysis (Case 4), which will result in a higher NPV and IRR compared to the other cases. As shown, $0/linear foot/yr or $0/acre means that this case (Case 4) will reach a breakeven point without any compensation from MnDOT. However, environmental benefits are typically difficult to monetize and to use directly (unlike the real "money" that is utilized by landowners/farmers). Therefore, Case 3, where only the incentives are considered and included, would be more realistic for the landowners/farmers.

9.3 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted with the developed models for PV noise barriers and PV snow fences, respectively, in order to find the critical parameters that significantly affect the analysis. Then, the effects of these parameters on the results, in terms of PP, NPV, and IRR, were quantified. Another objective of the sensitivity analysis was to ensure that all possible situations were considered and covered in the study. The parameters studied with the sensitivity analysis are indicated in Tables 9.3, 9.4, 9.5, 9.6, 9.9, 9.10, 9.12, and 9.13 (with an asterisk "*") and are summarized in Table 9.21.

Table 9.21 Parameters studied

Parameter Index	PV System Parameters for Noise Barriers	Used in Baseline Model	Varying Ranges and Notes
PVNB - 1	Number of Panels/Mile	2,640	1,980 or 2,640: Three layers or four layers as shown in Appendix C
PVNB - 2	Array Type	Fixed	Fixed or Adjustable: The tilt angle can be adjusted manually (based on a labor cost of $25/hr with 220 hrs per mile per time for 2 times per year: assuming that 1 person needs 5 minutes to adjust 1 panel)
PVNB - 3	System Losses* [%]	14.08	• 14.08% for vertical and 45° installation with three layers (1,980 panels/mile) • 25% for 45° installation with four layers (2,640 panels/mile): Considering that some of the lower panels would be partially shaded by the upper ones as shown in the simulation results (Appendix C)
PVNB - 4	Tilt [deg]	90	45 or 90 as shown in Appendix C
PVNB - 5	Orientation [deg]	180	90, 180, or 270: Corresponding to different orientations, i.e., East, South, and West
PVNB - 6	Sales Taxes [%]	6.875%	0%~6.875%: Sales Tax is included or not
PVNB - 7	Real Discount Rate [%/yr]	0.35%	0%, 0.35%, 1%, or 3%: The influence of COVID-19 is included or not
PVNB - 8	Electricity Utility Price Paid by MnDOT [$/kWh]	0.12	0.10, 0.12, or 0.14: According to the utility costs provided by MnDOT for its rest areas and/or street lights
PVNB - 9	Price to Sell Back to Utility Company [$/kWh]	0.11	0.11, 0.09, 0.07 or 0.03: Considering that the price may vary among utility companies (https://greatriverenergy.com/making-electricity/purpa-qualifying-facilities/)
PVNB - 10	PPA Pricing [$/kWh]	0.10	Changed by -10%, -20%, or -30%: Considering that the PPA rate may vary among solar developers
PVNB - 11	Federal ITC and Other Incentives	10%	0%, 5%, 10%, or 22%: Considering that the ITC or other incentives may vary year after year (Fan, 2014)
PVNB - 12	RECs	$0.65	$0.20, $0.65, and $1.10 per REC: Considering that utility companies may purchase the RECs to meet RES compliance (MnDOC, 2019)

PVNB - 13	Noise Barrier Type	Concrete	Concrete ($36/sf) or Wood ($25.6/sf): Provided by MnDOT
PVNB - 14	# of Benefited Receptors per Mile*	51	51, 60, or 70: Considering the various effects if the number of benefited receptors per mile increases
PVNB - 15	Module Price of PV System [$/W]	$0.65/$0.40	Changed by ±25% or ±50%: Considering the existence of uncertainties and the possible variations of PV-system costs in the future as the further development of solar technology
PVNB - 16	Self-Consumption Utilization Rate [%]	100%	50% or 75%: Considering the limited battery capacity when the generated power is self-used by MnDOT, meaning that 25% or 50% of the electrical power generated would be either discarded or sold to utility companies. 100% implies that all the electrical power generated will be used by MnDOT facilities, such as for street lights and/or rest areas.
PVNB - 17	Noise-Barrier Wall Length [mile]	1 or 1000	1, 25, 50, 100, 300, 500, or 1000: To see the effect of noise barrier wall length on the result
Parameter Index	**PV System Parameters for Snow Fences**	**Used in Baseline Model**	**Varying Range and Notes**
PVSF - 1	Panel Width [feet]	0.5	0.5 ft with vertical installation 0.7 ft with 45^{o} installation: To ensure that the panel's horizontal projection has a dimension of 12 ft × 0.5 ft (Appendix D)
PVSF - 2	Tilt [deg]	90	45 or 90: Fixed installation and the tilt angle cannot be adjusted manually (Appendix D)
PVSF - 3	Orientation [deg]	180	90, 180, or 270: Corresponding to different orientations, i.e., East, South, and West
PVSF - 4	Sales Taxes [%]	6.875%	0%~6.875%: Sales Tax is included or not
PVSF - 5	Real Discount Rate [%/yr]	0.35%	0%, 0.35%, 1%, or 3%: The influence of COVID-19 is included or not
PVSF - 6	Electricity Utility Price Paid by MnDOT [$/kWh]	0.12	0.10, 0.12, or 0.14: According to the utility costs provided by MnDOT for its rest areas and/or street lights
PVSF - 7	Price to Sell Back to Utility Company [$/kWh]	0.11	0.11, 0.09, 0.07, or 0.03: Considering that the price may vary among utility companies (https://greatriverenergy.com/making-electricity/purpa-qualifying-facilities/)
PVSF - 8	PPA Pricing [$/kWh]	0.10	Changed by -10%, -20%, or -30%: Considering that the PPA rate may vary among solar developers
PVSF - 9	Federal ITC and Other Incentives	10%	0%, 5%, 10%, or 22%: Considering that the ITC or other incentives may vary year after year (Fan, 2014)
PVSF - 10	RECs	$0.65	$0.20, $0.65, and $1.10 per REC: Considering that utility companies may purchase the RECs to meet RES compliance (MnDOC, 2019)
PVSF - 11	Snow Fence Leased or Owned	Leased	Leased ($1.00/linear foot/yr) or Owned ($10,000/acre)
PVSF - 12	Snow Fence Benefit (Drifting, Blow ice, Avoided crashes, Travel Time, and Carbon Emissions)	See Table 9.13	Reduced by 25% or 50%: Considering that the severity of the blowing-snow problem area with regards to the frequency and severity of crashes, the highway's traffic volume, and the number of resources spent on materials/labor/equipment to keep the highway open may vary from site to site.
PVSF - 13	Module Price of PV System [$/W]	$0.85/$0.60	Changed by ±25% or ±50%: Considering the existence of uncertainties and the possible variations of PV-system costs in the future with the further development of solar technology
PVSF - 14	Self-Consumption Utilization Rate [%]	100%	50% or 75%: Considering the limited battery capacity when the generated power is self-used by MnDOT, meaning that

			25% or 50% of the generated electrical power would either be discarded or sold to utility companies. 100% implies that all the generated electrical power would be used by MnDOT facilities, such as for street lights and/or rest areas.
PVSF - 15	Snow-Fence Length [mile]	1 or 1000	1, 25, 50, 100, 300, 500, or 1000: To see the effect of the snow fence's length on the result

Figure 9.9 shows the curves which were used to reflect the price variation for the PV system with the increased length from 1 to 1,000 miles (PVNB-17 or PVSF-15), i.e., from \$2.13/W to \$1.39/W for PV snow fences and from \$1.89/W to \$1.16/W for PV noise barriers, as shown in Table 9.5.

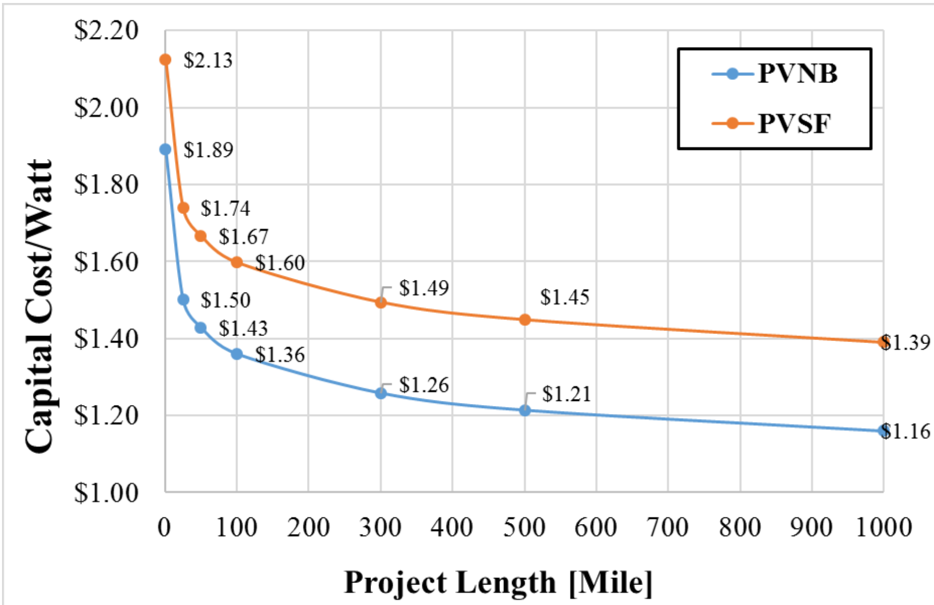
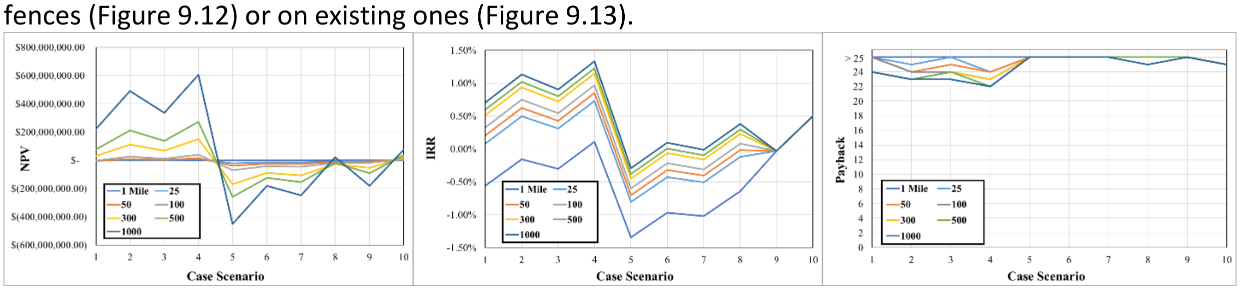


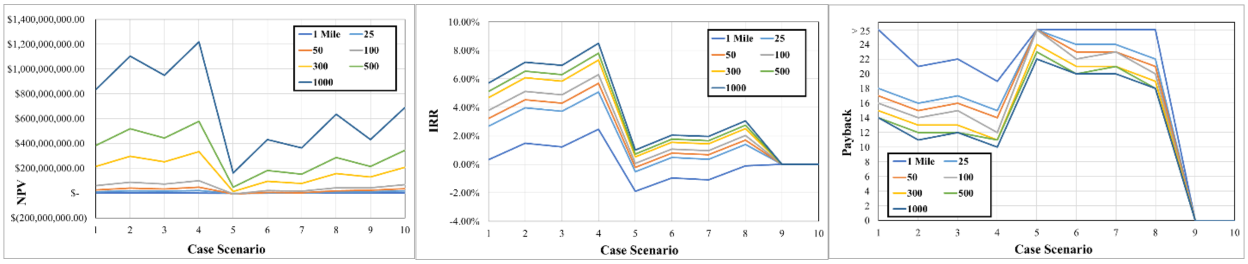
Figure 9.9 Price variation for the PV capital cost when changing the length between 1 and 1,000 miles

Figures 9.10 and 9.11 show the results for the sensitivity analysis of PVNB-17 for the PV panels installed on new noise-barrier walls (Figure 9.10) or on existing ones (Figure 9.11), where (a) represents the NPV results, (b) represents the IRR results, and (c) represents the PP results. Similar results can be found in Figures 9.12 and 9.13 for the sensitivity analysis of PVSF-15 for the PV panels installed on the new snow fences (Figure 9.12) or on existing ones (Figure 9.13).



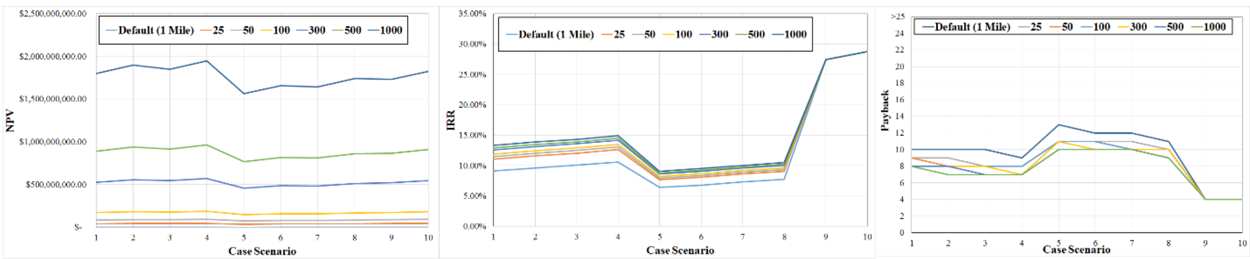
(a) (b) (c)

Figure 9.10 NPV, IRR, and PP with various PVNB lengths (PVNB-17) for new noise barriers



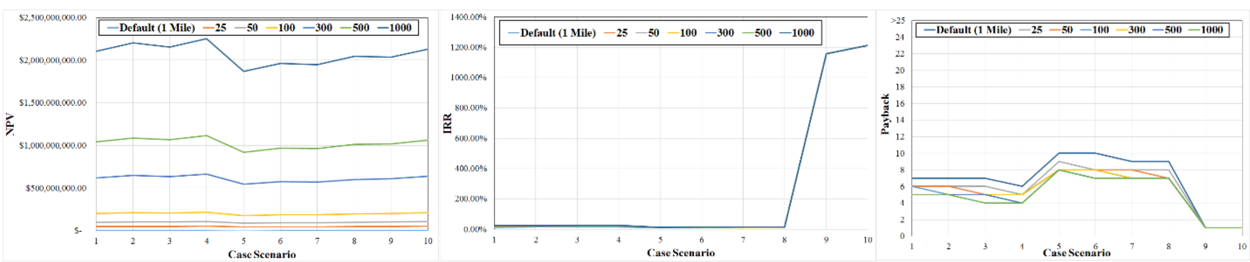
(a) (b) (c)

Figure 9.11 NPV, IRR, and PP with various PVNB lengths (PVNB-17) for existing noise barriers



(a) (b) (c)

Figure 9.12 NPV, IRR, and PP with various PVSF lengths (PVSF-15) for new snow fences



(a) (b) (c)

Figure 9.13 NPV, IRR, and PP with various PVSF lengths (PVSF-15) for existing snow fences

Other sensitivity-analysis results are shown in Appendix E (noise barriers) and F (snow fences), where each figure demonstrates the potential effects of the parameters described in Table 9.21 for the 10 case scenarios (Table 9.2) on the NPV, IRR, and PP values.

9.4 RESULTS AND DISCUSSIONS FOR THE COST-BENEFIT ANALYSIS

The arithmetic means for these sensitivity-analysis results (NPV, PP, and IRR) of each case (from 1 ~ 10) are shown in Appendix G, which demonstrates the possible variation ranges for these results, subject to changes for these critical parameters as listed in Table 9.21.

In summary, the results are as follows:

- For PV noise barriers, the analysis (NPV, PP, and IRR) shows that the addition of PV panels will help to increase the NPV and IRR while reducing the PP of a noise-barrier project, thus making PVNB more cost-effective.
- Structural snow fences are not typically used in the summer, and the installation of PV panels on them will add more value to the structural snow fence. Additionally, PVSF will be good for the environment through the generation and use of renewable energy.
- It is not cost-effective for MnDOT to self-use the generated electrical power due to the high capital costs (battery costs).
- The 1,000-mile PV noise barriers or PV snow fences are more cost-effective than the 1-mile PV noise barriers or PV snow fences due to a lower capital cost and increased power generation.
- Shorter PPs can be achieved with 3rd-party ownership of the PV system (Case 9 or 10), i.e., through a PPA, compared to the other cases where MnDOT owns the system.
- For 1-mile noise barriers or snow fences, it is cost-effective for MnDOT to not own the PV system. In other words, a PPA is a better choice for MnDOT, allowing a solar developer to own the PV system.
- For 1,000-mile noise barriers or snow fences, it is cost-effective for MnDOT to have direct ownership of the PV system and to sell the generated electrical power back to utilities, in which case a higher NPV can be achieved with a decent PP (as indicated in Tables 9.7, 9.8, 9.14, 9.15, and 9.16 as well as Appendix G), especially for PV snow fences (Tables 9.15 and 9.16), even though a shorter PP can be achieved with a PPA (Case 9 or 10).
- Higher NPVs with shorter PPs can be achieved by installing PV panels on existing noise barriers or snow fences than new ones, as shown in Appendix G.
- For PV noise barriers, wood walls are more cost-effective than concrete walls.
- For PV noise barriers, increasing the number of benefited receptors from 51 to 70 per mile reduces the payback period by 4~6 years.
- For PV snow fences, increasing the real discount rate (PVSF-5) from 0.35% to 3.0% increases the payback period by 0-3 years, and decreasing the selling price (PVSF-7) from $0.11/KWh to $0.03/KWh increases the payback period by 1-4 years.
- For PV noise barriers, increasing the real discount rate (PVNB-7) from 0.35% to 3.0% or decreasing the selling price (PVNB-9) from $0.11/KWh to $0.03/KWh increases the payback period by at least 5 years.
- For PV noise barriers, the cost-benefit comparison for the four cases listed below is as follows: *Case A is more cost-effective than Case B that has similar cost-effectiveness with Case C while Case C is more cost-effective than Case D*.
    - <u>Case A</u>: installing panels with a 45^{o} tilt angle (fixed) and 3 layers (1,980 per mile), as shown in Figure 9.14-a
    - <u>Case B:</u> installing panels with a 45^{o} tilt angle (fixed) and 4 layers (2,640 per mile), as shown in Figure 9.14-b
    - <u>Case C:</u> installing panels on adjustable mounts with 45^{o} (Figure 9.14-b) ~ 90^{o} (Figure 9.14-c) tilt angles and 4 layers (2,640 per mile)

- Case D: installing panels with a 90° tilt angle (fixed) and 4 layers (2,640 per mile), as shown in Figure 9.14-c

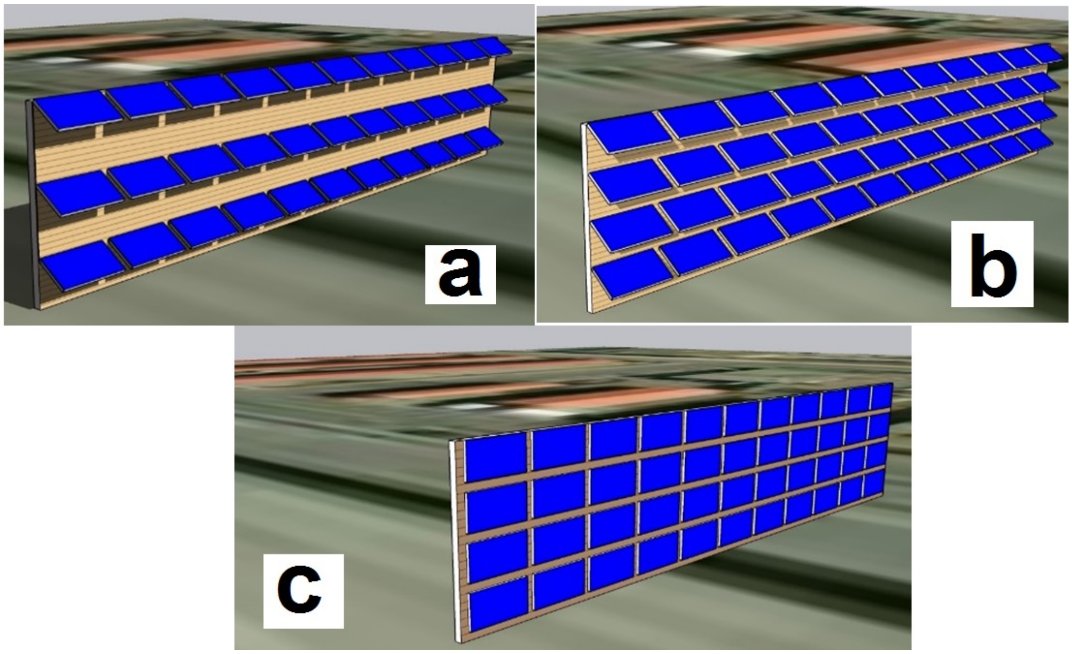


Figure 9.14 PVNB demonstration (a: PV panels with a 45° tilt angle (fixed) and 3 layers; b: PV panels with a 45° tilt angle (fixed) and 4 layers; c: PV panels with a 90° tilt angle (fixed) and 4 layers)

- For PV snow fences, the cost-benefit comparison between the two cases listed below is that *Case A is more cost-effective than Case B.*
  - Case A: installing panels with a 45o tilt angle and a size of 12 × 0.7 ft (fixed), as shown in Figures 9.15-a and 9.16.
  - Case B: installing panels with a 90° tilt angle and a size of 12 × 0.5 ft (fixed), as shown in Figures 9.15-b and 9.16.

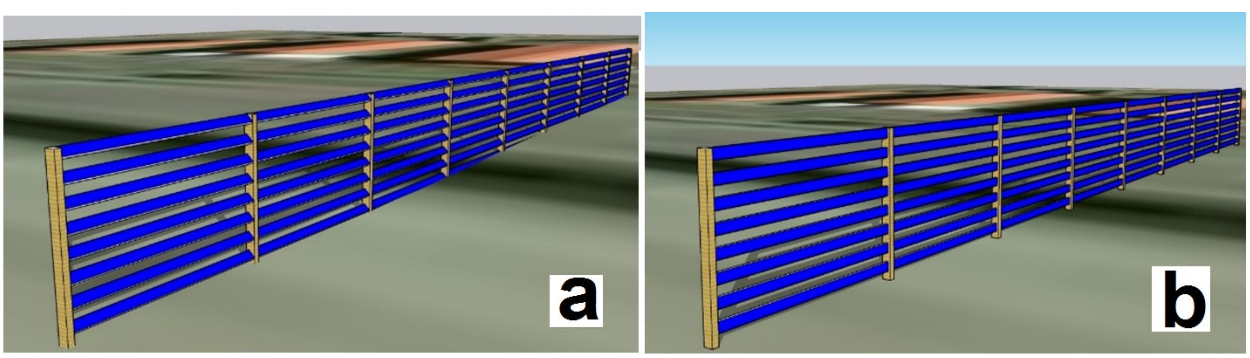


Figure 9.15 PVSF demonstration (a: PV panels with a 45° tilt angle and a size of 12 × 0.7 ft (fixed); b: PV panels with a 90° tilt angle and a size of 12 × 0.5 ft (fixed))

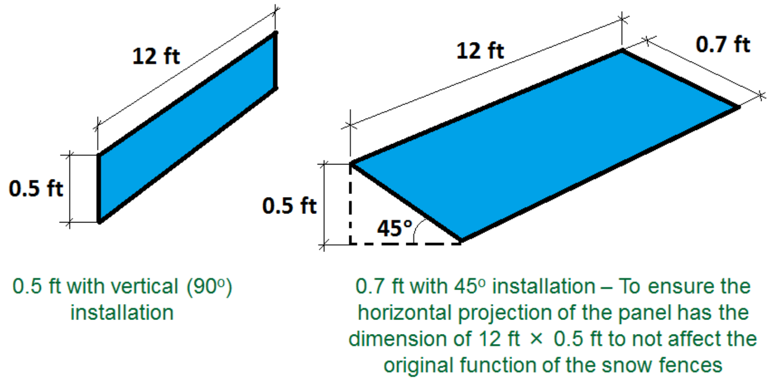


Figure 9.16 Vertical (90°) vs 45° Installation for PVSF

- For PV noise barriers or snow fences, the cost-benefit comparison among the seven cases with various noise-barrier wall/snow-fencing lengths (1; 25; 50; 100; 300; 500; and 1,000 miles) demonstrates that *the longer the length is, the more cost-effective the structure is.*
- For PV noise barriers or snow fences, the cost-benefit comparison for the three cases listed below is as follows: *Case A is more cost-effective than Case B that has similar cost-effectiveness with Case C.*
    - Case A: installing panels with an orientation of 180 ° (facing south), as shown in Figure 9.17-a
    - Case B: installing panels with an orientation of 90 ° (facing east), as shown in Figure 9.17-b
    - Case C: installing panels with an orientation of 270 ° (facing west), as shown in Figure 9.17-c

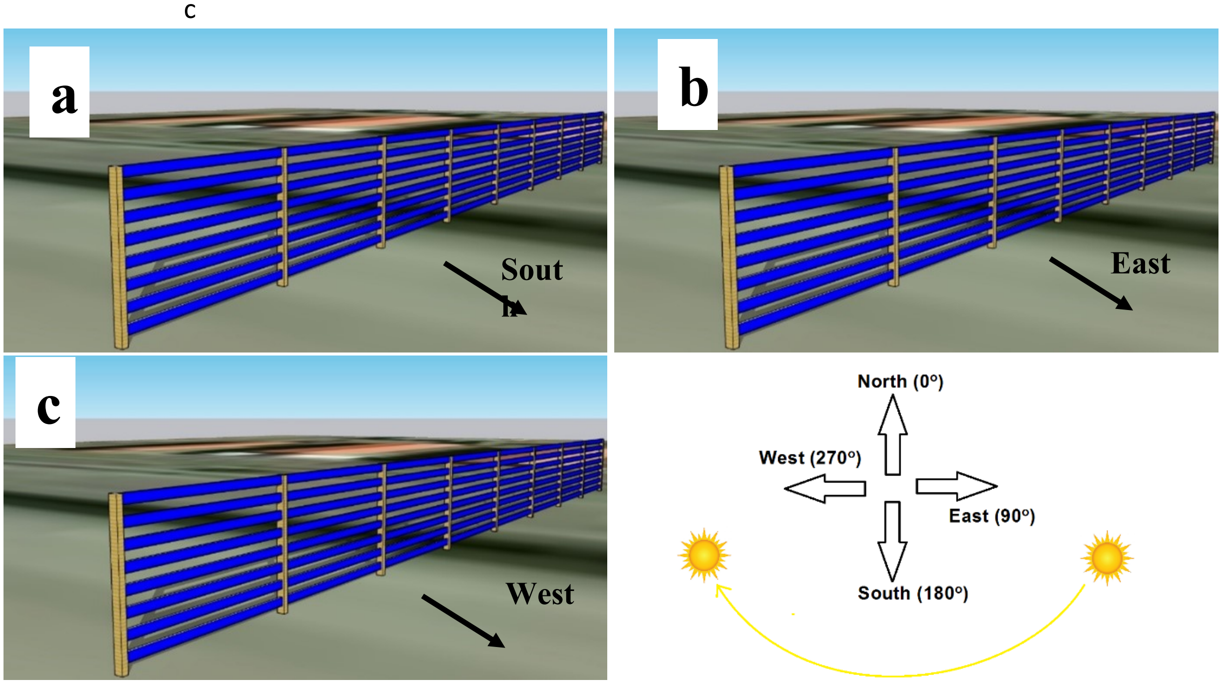


Figure 9.17 PV panels with different orientations on snow fences (similar conclusions were drawn for PVNBs) (a: PV panels with an orientation of 180° (facing south); b: PV panels with an orientation of 90° (facing east); c: PV panels with an orientation of 270° (facing west))

- From the landowner/farmer's perspective, leasing land to MnDOT, which will pay $1.00/linear foot/year, is more cost-effective than selling land at a price of $10,000/acre during the 25-year analysis period. Landowners/farmers will reach a breakeven point to lease the land at $0.22/linear foot/year or to sell the land for about $7,110/acre to MnDOT that will then install structural snow fences or PVSF on it.
- If the installed PV system is financed and owned by landowners/farmers who will otherwise lease or sell farmland to MnDOT and then sell the generated electrical power to utility companies, the analysis results are summarized below.
  - The payback period is between 19 and 24 years for landowners if leasing farmland to MnDOT and between 21 and 25+ years if selling farmland to MnDOT.
  - Landowners will reach a breakeven point in 19 years (if leasing land) or 21 years (if selling land) without any compensation from MnDOT, if environmental benefits can be monetized along with incentives and used directly to offset the project costs.

Additionally, the potential effects of rules, regulations, policies, insurance, the utility company's interconnection requirements, and/or tax credits/incentives, as well as the potential solar developers available in Minnesota for the project are discussed in Table 9.22.

Table 9.22 Other considerations/factors for the project

Rules, Regulations, and Policies	• Electrical permits are required for solar PV systems (Minnesota Department of Labor and Industry, 2019). • Work on large plants must comply with the Minnesota State Building Code (Minnesota Statutes section 216E.10). Large electric-power-generating plants are defined as 50,000 KW or greater in capacity by Minnesota Statute 216E. They can include solar PV-collection sites in multiple locations if all sites are constructed within 12 months of each other, and are owned and funded as a single project. These cases do not include the electric-power generator plants that are owned and operated by a public utility (Minnesota Department of Labor and Industry, 2019). • Utility Accommodation: The FHWA has determined that using a highway ROW to accommodate public-utility facilities is in the public's interest. To the extent that these facilities serve "the public," they can be accommodated under the DOT's approved Utility Accommodation Policy (UAP). If utilizing such facilities serves a private or proprietary interest, the use would have to be approved under the ROW-use agreement requirements (23 CFR 710 Subpart D). Thus, the distinction between public or private use, which is defined by state statute, determines which regulations apply (FHWA, 2016). • Control of Access to the Interstate: The FHWA retains all approval rights to control access to the interstate system (23 CFR 620.203h). A DOT is required to obtain the FHWA's written approval when access to the interstate system is added or modified. Both temporary and permanent modification of access control for transportation and non-transportation purposes requires FHWA approval (FHWA, 2016). • Use and Occupancy Permit: Renewable-energy facilities on the highway ROW require a Use and Occupancy Agreement (23 CFR 645.213). The permit must reference the state's DOT standards and include the following information: a description of the facility's type, size, and location; an

	adequate drawing that shows the existing/proposed facility, ROW lines, control of access limits, and approved access points; the extent of liability and responsibilities for future adjustments; and the action to be taken for non-compliance (FHWA, 2016). • National Environmental Policy Act (NEPA): Under federal law, the NEPA applies to any proposed action or transportation project where federal funds or assistance will be used at some phase of project development or where federal permits or approvals are required. FHWA approval of ROW Use Agreements or access control constitutes a federal action, thus requiring that the NEPA procedures be followed (FHWA, 2016). • Subpart B: Accommodation of Utilities of the Electronic Code of Federal Regulations, Title 23, Chapter I, Subchapter G, Part 645 (Office of the Federal Register (OFR) and the Government Publishing Office). • Prohibition of Commercial Establishments in the ROW (Minn. Statute 160.08) • Asked by NDSU: "Is there any policy/regulation in MNDOT to allow/against selling the electricity generated by the solar system near highways to utility companies to generate revenue/profit?" Answered by James Zigman (MnDOT): "We do not have any regulations against solar systems located off the MnDOT ROW. We do treat their lines as private utility lines until they connect with the public electric grid. As a private line, they are only allowed to cross our right of ways and not be installed parallel within the right of way." "Our Utility Accommodation Policy does not define energy-generating facilities, such as solar, as a utility, and as such, they are not able to be permitted to be installed within our right of way as a utility. Energy-generation facilities may be allowed to occupy a portion of a trunk highway right of way in some instances through a lease agreement, depending upon the nature of the trunk highway right of way and MnDOT's ownership interest of the right of way. " Asked by NDSU: "The PV panels would be installed on the existing facilities (not on the ground), such as structural snow fences and noise barrier walls, which are owned by MnDOT. Does this matter?" Answered by James Zigman (MnDOT): "If they are located within trunk highway right of way, the second paragraph of my initial response would apply. We would still not have any restrictions on the facilities regarding the selling of the electricity." • When the research is implemented, the legal team of MnDOT may need to confirm that selling electricity to a utility is not considered commercial activity on the ROW.
Insurance	Most large PV systems require liability and property insurance, and many developers may opt to add policies such as environmental-risk insurance (NREL, 2010). • General liability covers policyholders for death or injury to persons or for damage to property owned by third parties. • Property-risk insurance covers 'damage to or loss of policyholders' property. While the manufacturer's warranty will provide some limited defect coverage, the system owner usually purchases property insurance to protect against risks not covered by the warranty or to extend the coverage period.

	• Environmental-damage coverage indemnifies system owners of the risk of either environmental damage done by their development or pre-existing damage on the development site. Developers estimate the annual insurance cost to be around 0.25% of the project's total installation cost; the amount could be as high as 0.5% annually in areas where extreme weather events are likely (NREL, 2010).
Interconnection	• Interconnection Standards: "Interconnection" refers to the physical linking of an energy generator to the larger electric grid. Assuming that a renewable energy system will be connected to the electricity grid, local electric utilities manage that interconnection (FHWA, 2016). • Information from Xcel Energy: Xcel Energy is required to follow Minnesota's statewide Distributed Energy Resources Interconnection Process (MN DIP) for all solar interconnections (https://www.xcelenergy.com/working_with_us/how_to_interconnect)
Tax Credits/Incentives	• The investment tax credit (ITC) and the production tax credit (PTC) both provide tax relief to a renewable-energy developer in an amount that depends on the program available, which for solar projects has been the ITC. Under the ITC, the IRS approves a tax credit that is equal to 30% of the project's total cost. The tax credit can be claimed when filing federal income taxes subsequent to the project going into service. The tax credit's value may be sold to other private entities which have a tax interest and see an economic advantage to partnering on the project. With the tax credit, the private entity never receives cash to help pay for a project but, rather, receives a credit on the payments due, thereby producing a net positive on the company's balance sheet (Federal Aviation Administration, 2018). • A source to examine when searching for policies and incentives by state is as follows: https://programs.dsireusa.org/system/program?fromSir=0&state=MN
Sales, Income, or Property Taxes	• Solar equipment has an exemption from state sales tax; The tax exemption would need to be vetted/confirmed whether it applies to MnDOT and its contractors as well as the general public. https://www.revisor.mn.gov/statutes/cite/297A.67 (From Tiffany Dagon of MnDOT) • Farmland, if used to place snow fences, will be considered as Commercial/Industrial/Public Utility use, instead of its original intended use, when landowners pay property taxes if the land is leased to MnDOT (From Nancy Gunderson, Clay County Assessor). • No property taxes will be paid if MnDOT purchases and owns farmland to install snow fences (From Nancy Gunderson, Clay County Assessor). • Asked by NDSU: "If MnDOT owns the solar project, does MnDOT need to pay the income tax when selling the electricity generated to utility companies?" Answered by Siri Simons (MnDOT): "No, MnDOT does not need to pay income tax on the revenue."
Potential solar developers for PPA in Minnesota	• Great River Energy (763-445-5000, www.greatriverenergy.com) • Cedar Creek Energy (1-800-834-3378, https://cedarcreekenergy.com/commercial-solar-energy-panels-minnesota/power-purchase-agreements/) • AMERESCO (612-315-6930, https://www.ameresco.com/contact-us/) • Northern States Power Company (Xcel) (612-330-5500, www.xcelenergy.com)

	• US-Solar (MN) (David Watts, 612-294-6978, marketing@us-solar.com, https://www.us-solar.com/contact.html) • Minnesota Power (ALLETE) (Amy Rutledge, 218-723-7400) • Otter Tail Power Company (218-739-8200) • Marshall Solar, LLC (218-739-8200, marshallsolarproject@gmail.com, https://mn.gov/eera/web/project/626/) • Allco & Ecos Energy (651-268-2053, info@allcous.com, https://allcous.com/)
Other considerations about PPA	Information provided by the Cedar Creek Energy: • The PPA contract term is flexible, but usually ranges from 15-25 years. • A sample PPA document can be found at https://www.seia.org/sites/default/files/inline-files/SEIA%20C%2BI%20PPA%20v2.0.pdf • RECs are typically owned by the developer/investor. • The net metering cap is 40 kW, and a project with 40kW or greater will have a lower energy selling price (around $0.02~0.03/kWh). • PPA price varies project by project but is negotiable. • The location of the project matters depending on how for the system to connect to the grid. • Newly developed panels and/or system (for PVSF) will increase the uncertainties, and the solar developer will work with MnDOT and NDSU to evaluate the project first before proceeding any further.

CHAPTER 10: CONCLUSIONS

Through literatures review, public survey, lab experiments, and numerical modeling, a comprehensive study is performed to evaluate the feasibility of harnessing solar energy through noise barriers and structural snow fences. The research conclusions of the project are summarized in the following key findings:

i. Based on the survey results, about 90% of general-public respondents supported the idea of using solar panels on noise barriers along highways, and 84% still supported it even though the noise barrier's appearance would change because of the solar panels' installation.
ii. Only about half of general-public respondents indicated they would support this project if using solar panels would result in less noise reduction, which shows the general public's concern about this project's potential influence on the barrier's effectiveness.
iii. Through extensive lab and field experiments and numerical simulations, an integrated solar noise-barrier and snow-fence system has been developed. The modularized Ganfet-based inverter and controller were designed to connect different solar panels and power grids. The prototype has been verified as being able to reach the intended functions and can be connected to power grids.
iv. The proposed solar noise-barrier or snow-fence system will not affect traffic safety, slightly reduce the noise reduction level (by 2%), have a minimum glaring period (373 minutes a year), and can seamlessly serve the two intended purposes: noise reduction or snow drifting control; and energy production.
v. Adding photovoltaic (PV) panels on noise barriers will shorten the payback period of a noise-barrier project, thus making it more cost-effective and attractive.
vi. Structural snow fences are not typically used in summer, and the installation of PV panels on them will add more value to the structural snow fence. Additionally, photovoltaic snow fence (PVSF) will be good for the environment through the generation and use of renewable energy.
vii. Considering the PV system as a standalone project, the payback period would be 19-plus or 10-plus years if installed on a 1-mile or 1,000-mile noise barrier, respectively, and 22-plus or 12-plus years if installed on a 1-mile or 1,000-mile snow fence, respectively. A power purchase agreement (PPA) would significantly shorten the payback period in consideration of the key benefits brought through a PPA to MnDOT, including minimal up-front capital costs, lower energy costs, no risk, no upkeep, leveraging available tax credits, and enhancing the value of the property.
viii. Installing PV panels on 1 mile of NEW noise barriers (considered as a whole project) is not cost-effective unless environmental and societal benefits like the cost of carbon are included in the cost-benefit analysis.
ix. Installing PV panels on 1 mile of EXISTING noise barriers (as a whole project) through a PPA would result in minimal up-front costs with nearly zero years of payback.
x. A PPA for PV panels installed on 1 mile of NEW structural snow fences (considered as a whole project) pays back in 4 years, even when environmental and societal benefits are not included in the cost-benefit analysis.
xi. A PPA for PV panels installed on 1 mile of EXISTING snow fences (as a whole project) pays back in just 1 year, even when environmental and societal benefits are not included in the cost-benefit analysis.
xii. For a 20-foot-tall noise barrier wall, the most cost-effective design is to install standard PV panels (8' × 4') on the side facing south with a 45° tilt angle (fixed installation). 3 layers (1,980 panels per mile) is recommended.

xiii. For an 8-foot-tall 50% porosity structural snow fence, the most cost-effective design is to install customized PV panels (12’ × 0.7’) facing south with a 45° tilt angle (fixed installation and 3,520 panels per mile).

xiv. For PV noise barriers or snow fences, the longer the length, the more cost-effective the project. Therefore, a 1,000-mile PV noise barrier or snow fence project has a shorter payback period and is more cost-effective than a 1-mile project.

Applying the findings of this research will require collaboration across the agency to understand the technical, regulatory, and environmental aspects of implementation. When the research is implemented, the legal team of MnDOT would need to confirm that selling electricity to a utility is not considered commercial activity on the rights-of-ways (ROW).

REFERENCES

1. Federal Highway Administration. (2016). FHWA-HEP-16-052, *Renewable energy generation in the highway rights-of-way.* Washington, DC: FHWA.
2. Federal Highway Administration. (2017). FHWA-HEP-17-088, *Highway renewable energy: photovoltaic noise barriers*. Washington, DC: FHWA.
3. Oregon DOT. (2016). *Solar highway program: From concept to reality: A guidebook for departments of transportation to develop solar photovoltaic systems in the highway rights-of-way*.Salem, OR: Oregon DOT.
4. Carder, D. R. & Barker, K. J. (2006). *M27 trial of highway noise barriers as solar energy generators*, TRL limited report PPR178. Transport Research Laboratory (Great Britain), Great Britain Highways Agency.
5. Morgan, P.A. (2006). *Photovoltaic noise barriers: Scope for demonstration schemes on London's main roads,* TRL limited report PPR128. Transport Research Laboratory (Great Britain), Greater London Highways Agency.
6. Vanhooreweder, B., Marcocci, S.,& De Leo, M., (2017). *State of the art in managing road traffic noise: Noise barriers*. Conference of European Directors of Roads, Brussels, Belgium.
7. Klingner, R. E., McNerney, M. T.,& Busch-Vishniac, I. J. (2003). *Design guide for highway noise barriers*, No. 1471-1474. Austin, TX: Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin.
8. Tabler, R. D. (2003). *Controlling blowing and drifting snow with snow fences and road design,* No. NCHRP Project 20-7 (147). The National Academies, The American Association of State Highway and Transportation Officials.
9. Constantinescu, G., Muste, M., & Basnet, K. (2015). *Optimization of snow drifting mitigation and control methods for Iowa conditions*, TR-626 Report. Ames, IA: Iowa State Department of Transportation.
10. ETSC. (1995). *Reducing traffic injuries resulting from excess and inappropriate speed*. Brussels, European Transport Safety Council.
11. NREL. (2016a). *Using Power Purchase Agreements for Solar Deployment at Universities.* Retrieved from https://www.nrel.gov/docs/gen/fy16/65567.pdf
12. TruNorth Solar. (n.d.). *Federal solar investment tax credit (ITC)*. Retrieved from https://www.trunorthsolar.com/incentives/#:~:text=In%202020%2C%20the%20tax%20credit,will%20end%20in%20January%202023.
13. Minnesota Department of Commerce (MnDOC), Division of Energy Resources. (2019). *Minnesota Renewable Energy Standard: Utility Compliance*. Retrieved from https://www.leg.mn.gov/docs/2019/mandated/190330.pdf
14. NREL. (2012) *Photovoltaic Degradation Rates – An Analytical Review.* Retrieved from https://www.nrel.gov/docs/fy12osti/51664.pdf
15. Pvwatts. (n.d.). *Pvwatts Calculator*. Retrieved from https://pvwatts.nrel.gov/pvwatts.php
16. U.S. Environmental Protection Agency (EPA). (n.d.). *Greenhouse Gas Equivalencies Calculator*. Retrieved from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
17. NREL. (2016b). *The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs.* Retrieved from https://www.nrel.gov/docs/fy16osti/65872.pdf

18. Alibaba. (2020). *Manufacturer 100W Flexible Solar Panel*. Retrieved from https://www.alibaba.com/product-detail/China-manufacturer-100w-flexible-solar-panel_62042402589.html?spm=a2700.7724857.normalList.60.37f454d1CDX4Ed
19. NREL. (2018a). *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018.* Retrieved from https://www.nrel.gov/docs/fy19osti/72399.pdf
20. Taxmaps. (n.d.). *Arcgis web application*. Retrieved from https://taxmaps.state.mn.us/salestax/
21. Enbar, N., Weng, D., & Klise, G. T. (2016). Budgeting for Solar PV Plant Operations & Maintenance: Practices and Pricing (No. SAND-2016-0649R). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).
22. Fthenakis, V. M. (2000). *End-of-life management and recycling of PV modules*. Energy Policy, 28(14), 1051-1058.
23. Guney, I., & Onat, N. (2010). *Cost calculation algorithm for photovoltaic systems*. Retrieved from https://www.intechopen.com/books/paths-to-sustainable-energy/cost-calculation-algorithm-for-photovoltaic-systems.
24. ReneSola. (2015). *ReneSola Limited Warranty Terms for PV Modules*. Retrieved from https://servicemy.solar/wp-content/uploads/warranty_documents/Renesola-Module-Warranty-2016.pdf
25. Executive Office of the President. (2019). *2020 Discount Rates for OMB Circular No. A-94*. Retrieved from https://www.whitehouse.gov/wp-content/uploads/2019/12/M-20-07.pdf
26. NREL. (2018b) *2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark*. Retrieved from https://www.nrel.gov/docs/fy19osti/71714.pdf
27. U.S. Department of Energy (DOE). (2019). *Investment Tax Credit Requirements for Privately Owned Solar Photovoltaic Systems on Federal Sites*. Retrieved from https://www.energy.gov/sites/prod/files/2019/08/f65/investment-tax-credit.pdf
28. U.S. Environmental Protection Agency (EPA). (2014). *Emission Factors for Greenhouse Gas Inventories*. Retrieved from https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf
29. U.S. Energy Information Administration (EIA). (n.d.) *EIA - Independent statistics and analysis*. Retrieved from https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php
30. U.S. Environmental Protection Agency (EPA). (2017, January 9). *The social cost of carbon*. Retrieved from https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html
31. Fan, J. (2014). *Life cycle assessment and life cycle cost of photovoltaic panels on Lake Street Parking Garage* (Doctoral dissertation, Colorado State University).
32. FHWA. (n.d.) *Noise Barrier Inventory Tool*. Retrieved from https://www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/inventory_tool/index.cfm#results
33. VTPI. (2016) *Transportation Cost and Benefit Analysis Techniques, Estimates and Implications*. Retrieved from https://www.vtpi.org/tca/
34. MnDOT(a). (n.d.) *Roadway Data – Fun Facts*. https://www.dot.state.mn.us/roadway/data/fun-facts.html
35. Morgan, S.M., Kay, D.H.,& Bodapati, S.N. (2001). *Study of noise barrier life-cycle costing*. Journal of Transportation Engineering, *127*(3), 230-236.

36. Ernie's Wagon. (n.d.). *Fence removal service*. Retrieved from https://www.ernieswagon.com/fence-removal/
37. Scrapmonster. (n.d.). *Steel scrap prices USA, UK, China, India, current scrap steel price*. Retrieved from https://www.scrapmonster.com/scrap-prices/category/Steel/300/1/1
38. AcreValue. (n.d.). *AcreValue web application*. Retrieved from https://www.acrevalue.com/map/MN/?lat=46.521455&lng=-93.36421&zoom=5
39. MN House Research. (2019). *Property Tax 101: Property Tax Variation by Property Type*. Retrieved from https://www.house.leg.state.mn.us/hrd/pubs/ss/ssptvart.pdf
40. MN Department of Revenue. (n.d.). *State General Property Tax*. Retrieved from https://www.revenue.state.mn.us/state-general-property-tax#:~:text=The%20final%20commercial%2Dindustrial%20state,taxes%20payable%202021%20is%2017.306%25
41. Clay County MN. (n.d.). *Tax Capacities & Rates*. Retrieved from https://claycountymn.gov/163/Tax-Capacities-Rates
42. MnDOT(b). (n.d.). *Living Snow Fences – Control Blowing and Drifting Snow*. Retrieved from http://www.dot.state.mn.us/environment/livingsnowfence/forms.html
43. MnDOT(c). (n.d.). *Example – MnDOT's Blowing Snow Control Annual Payment*. Retrieved from https://www.dot.state.mn.us/environment/livingsnowfence/pdf/payment-sched-example.pdf
44. Minnesota Department of Labor and Industry. (2019). *Solar photovoltaic system and the state building code*. Retrieved from https://www.dli.mn.gov/sites/default/files/pdf/fs_code_solar.pdf
45. Federal Aviation Administration. (2018). *Technical guidance for evaluating selected solar technologies on airports.* Retrieved from https://www.faa.gov/airports/environmental/policy_guidance/media/FAA-Airport-Solar-Guide-2018.pdf
46. FHWA. (2016). *Renewable energy generation in the highway right-of-way*. Retrieved from https://www.fhwa.dot.gov/real_estate/publications/row/fhwahep16052.pdf
47. NREL. (2010). *Insuring solar photovoltaics changes and possible solutions*. Retrieved from https://www.nrel.gov/docs/fy10osti/46932.pdf
48. Office of the Federal Register (OFR) and the Government Publishing Office. (n.d.). *Electronic code of federal regulations*. Retrieved from https://www.ecfr.gov/cgi-bin/text-idx?SID=3c25c40ead77be4e7bf7442e1ea6518b&mc=true&node=pt23.1.645&rgn=div5#sp23.1.645.b
49. Kurze, U.J., & Anderson G.S. (1971). *Sound attenuation by barriers*. *Applied Acoustics, 4*(1), 35-53
50. Ashton, S. J., & Mackay, G.M. (1979). *Some characteristics of the population who suffer trauma as pedestrians when hit by cars and some resulting implications*. Proceedings of the 4th IRCOBI conference, Gothenburg.

APPENDIX A: SURVEY FORMS

Questionnaire for Land Owners

For the research study supported by Minnesota Department of Transportation (MnDOT)

➢ **Solar Energy Participation Interest*** (More descriptions regarding the MnDOT project are attached, which we would appreciate your feedback on.)

(1) Do you support storing snow on your property with structural snow fencing to save taxpayer money for snow removal and to improve the traveling publics' mobility and safety?	YES / NO (please specify why not) / Depends (please specify) Or other comments about this question:
(2) Do you support the use of transportation dollars to cover the cost to install and maintain solar panels on existing or new snow fences on your property?	YES / NO (please specify why not) / Depends (please specify) Or other comments about this question:
(3) Currently, structural snow fences are one dimensional serving the intended purpose of trapping blowing snow, would the added dimension of generating solar energy from structural snow fencing improve your acceptance of installing a snow fence on your property?	YES / NO (please specify why not) / Depends (please specify) Or other comments about this question:
(4) If Yes to Question (2) or (3), how would you like to be compensated and what incentives would you need for the use of your land?	
(5) Would you consider purchasing electricity generated by solar snow fences on your property?**	YES / NO (please specify why not) / Depends (please specify) Or other comments about this question:
(6) If Yes to Question (5), what proportion of your electricity bill would you hope to offset with electricity generated by the solar snow fences?	(A) 0% of my electric bill (B) 5% of my electric bill (C) 10% of my electric bill (D) More than 10% of my electric bill (Please circle one) Or other comments about this question:

*All the data provided are maintained in confidence and only used for the study purposes

**This survey is only intended to ask for your perspective, and does not constitute, nor should it be understood as, legal agreement.

Do you have any questions or comments for us? If so, please list them below.

Should you have any questions, please don't hesitate to contact us: Yao Yu at yao.yu@ndsu.edu or 701-231-8822.

For research team use only		
1. Today's Date:	2. Signature:	3. Notes/Comments:

Questionnaire for General Public

For the research study supported by Minnesota Department of Transportation (MnDOT)

➢ **<u>Solar Energy Participation Interest*</u>** (More descriptions regarding the MnDOT project are attached, which we would appreciate your feedback on.)

(1) Are you living in a community adjacent to noise barrier walls?	YES / NO / Don't Know
(2) Would you support the idea of using solar panels on new or existing noise barriers along highways?	YES / NO / Don't Care / Depends (please specify)
(3) If adding solar panels to an existing noise barrier changed the appearance, would you still support it?	YES / NO / Don't Care / Depends (please specify)
(4) If additional transportation dollars were required to install and maintain solar panels on existing or new noise barriers, would you still support it?	YES / NO / Don't Care / Depends (please specify)
(5) If adding solar panels to a noise barrier resulted in less noise reduction (reduced barrier effectiveness), would you still support it?	YES / NO / Don't Care / Depends (please specify)

*All the data provided are maintained in confidence and only used for the study purposes

Do you have any questions or comments for us? If so, please list them below.

Should you have any questions, please don't hesitate to contact us: Yao Yu at yao.yu@ndsu.edu or 701-231-8822.

For research team use only		
1. Today's Date:	2. Signature:	3. Notes/Comments:

Questionnaire for Utility Companies

For the research study supported by Minnesota Department of Transportation (MnDOT)

➢ **Company Information***

Company Type	Power provider / Distributor / Co-op (Please specify)

➢ **Solar Energy Participation Information*** (MnDOT is studying the potential for harvesting solar electricity along highways. These solar panels are intended to be installed along the sound barriers and snow fences. Additional information about this project is attached at the end, which we would appreciate your feedback on.)

Does your company produce solar electricity through PVs?	YES / NO / Don't Know
If Yes above, how much does it cost for producing solar electricity, at $x.xx/kwh or $x,xx/kw (the overall cost)?	
If your company sells solar electricity, how much does it cost per kWh for commercial customers?	
If you provided a solar electricity rate above, how does that vary from the standard commercial electricity rate?	
Would your company be interested in purchasing solar electricity generated from the MnDOT solar snow fences/sound barriers?**	YES / NO / Depends (please specify)
If Yes above, how much is your company interested in purchasing the solar electricity, at $x.xx/kwh?	

➢ **Capacity Evaluation***

Is your company interested in constructing, operating, and/or maintaining a PV solar power harvesting system?**	YES / NO / NA
Does your company have the capacity to integrate a PV solar power system onto the grid?	YES / NO / NA
Are there special codes or requirements to integrate PV panels with your grid?	YES / NO / NA
If Yes above, what are the code(s) or requirements, such as code title? Please specify.	

Is there any insurance program needed for such a PV system if it is owned by your company?	YES / NO / NA
If Yes above, what is the insurance program or rate you are aware of?	

Have your company ever received any tax incentive or credit for harvesting PV solar energy?	YES / NO / NA
If Yes above, how much incentive/credits did your company receive so far?	

Is there any incentive from your company for your customers who are willing to install PV solar energy systems?	YES / NO / NA
If Yes above, what is the incentive(s)?	

*All the data provided are maintained in confidence and only used for the study purposes
**This survey is only intended to ask for your perspective, and does not constitute, nor should it be understood as, legal agreement.

Do you have any questions or comments for us? If so, please list them below.

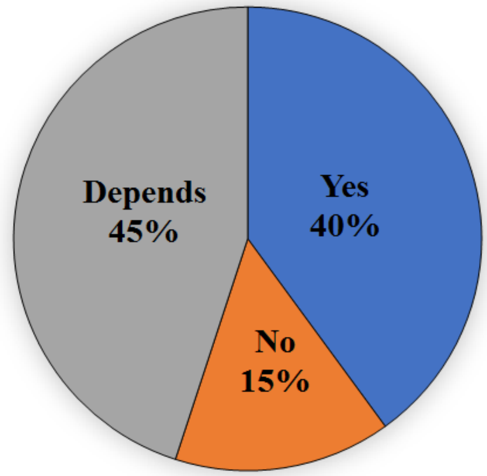
Should you have any questions, please don't hesitate to contact us: Yao Yu at yao.yu@ndsu.edu or 701-231-8822.

For research team use only		
1. Today's Date:	2. Signature:	3. Notes/Comments:

APPENDIX B: DETAILED SURVEY RESULTS

For Landowners

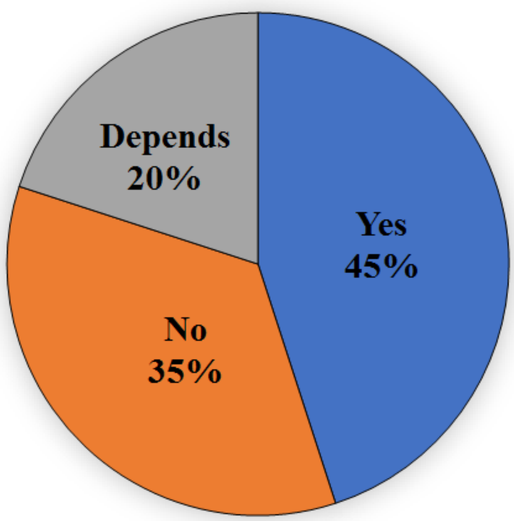
Land Owners Q1
Do you support storing snow on your property with structural snow fencing to save taxpayer money for snow removal and to improve the traveling publics' mobility and safety?



Comments:
- Yes: Don't have any currently
- Yes: If someone else installs, yes
- Yes: Usually comes from the north
- No: Would take our farmland
- NO: Doesn't have room for it
- Depends: Didn't have a choice
- Depends: Compensation
- Depends: Heavy land, problem for the land as far as farming
- Depends: Depends on compensation
- Depends: Doesn't make sense on their side of the highway
- Depends: Will do it for non-agriculture field
- Depends: Hard to get into field in the spring
- Depends: Trees/bush would be perfect
- Depends: Probably

Yes	No	Depends	Total
8	3	9	20

Land Owners Q2
Do you support the use of transportation dollars to cover the cost to install and maintain solar panels on existing or new snow fences on your property?

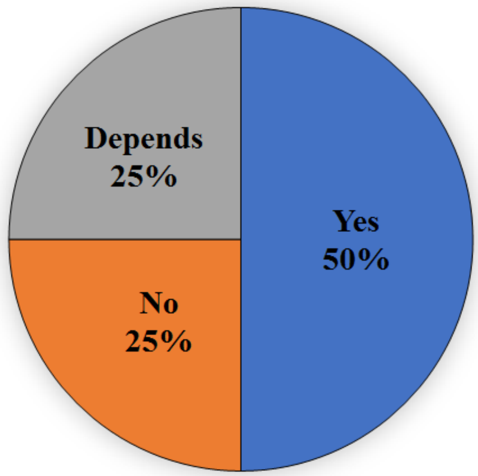


- **Comments:**
- Yes: As long as it doesn't increase taxes
- No: Space reasons; permanent
- No: Bridges are more of a concern
- No: Not interested
- No: Doesn't want fences on property
- No: Not in favor of solar panels due to oil and gas being more efficient
- No: Depends on type of land that can sustain snow, where would the money come from
- Depends: Doesn't make sense for their property due to forests
- Depends: Depends on size
- Depends: Depends if it is profitable
- Depends: Efficiency and the gains-money

Yes	No	Depends	Total
9	7	4	20

Land Owners Q3

Currently, structural snow fences are one dimensional serving the intended purpose of trapping blowing snow, would the added dimension of generating solar energy from structural snow fencing improve your acceptance of installing a snow fence on your property?



Comments:

- ❖ No: Not in favor of solar panels due to oil and gas being more efficient
- ❖ No: Doesn't have room for it
- ❖ No: Not enough return, would have to be large for a return
- ❖ No: Same reason as before - space reasons
- ❖ Depends: Not really for MN
- ❖ Depends: How will the electrical work?
- ❖ Depends: Depends if new snow fences are being built on his property
- ❖ Depends: Depends on amount of electricity
- ❖ Depends: Wiring factors

Yes	No	Depends	Total
10	5	5	20

Land Owners Q4

If Yes to Question (2) or (3), how would you like to be compensated and what incentives would you need for the use of your land?

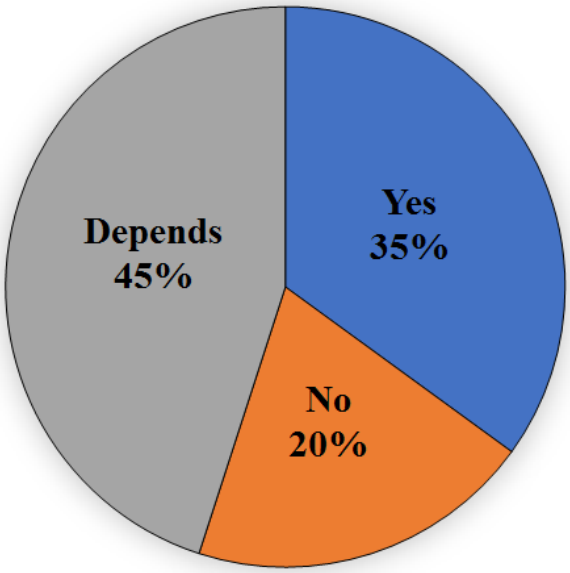
Comments:

- ❖ Money for the property being used.
- ❖ Money for lost rented land
- ❖ More
- ❖ Not sure, cash farm
- ❖ Not ready to put a hammer but want
- ❖ Doesn't apply due to not having room for snow fences
- ❖ Don't know
- ❖ Can't answer, but husband can
- ❖ Money
- ❖ Cost share program/money
- ❖ Doesn't know a number but money
- ❖ Money- Similar to other solar farms

Total
12

Land Owners Q5

Would you consider purchasing electricity generated by solar snow fences on your property?



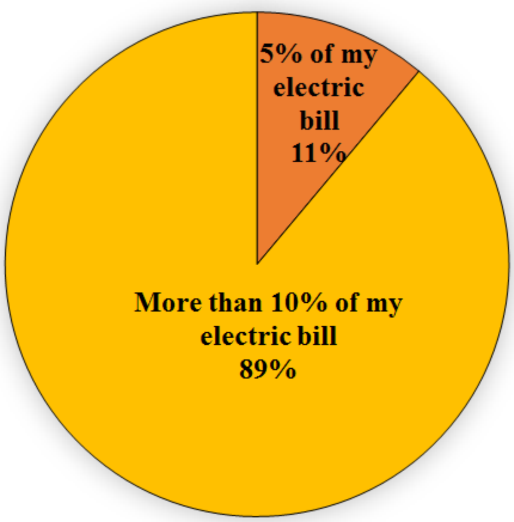
Comments:

- ❖ Yes: If doesn't exceed other rates
- ❖ Yes: Not if it costs more than now
- ❖ No: Doesn't use much electricity
- ❖ No: Live too far away
- ❖ Depends: If at significant discount
- ❖ Depends: Cost?
- ❖ Depends: If reasonable cost
- ❖ Depends: Free power from his land
- ❖ Depends: Co-op would purchase it
- ❖ Depends: If saves more in long run
- ❖ Depends: Depends on the cost of the electricity
- ❖ Depends: Not an option he currently has
- ❖ Depends: Only if it would offset losses

Yes	No	Depends	Total
7	4	9	20

Land Owners Q6

If Yes to Question (5), what proportion of your electricity bill would you hope to offset with electricity generated by the solar snow fences?



Comments:

- ❖ More than 10% of my electric bill: As much as available
- ❖ More than 10% of my electric bill: As much as available
- ❖ More than 10% of my electric bill: As much as available
- ❖ More than 10% of my electric bill: As much as available
- ❖ More than 10% of my electric bill: As much as available
- ❖ Doesn't matter as long as it doesn't cost more

0% of my electric bill	5% of my electric bill	10% of my electric bill	More than 10% of my electric bill
0	1	0	8

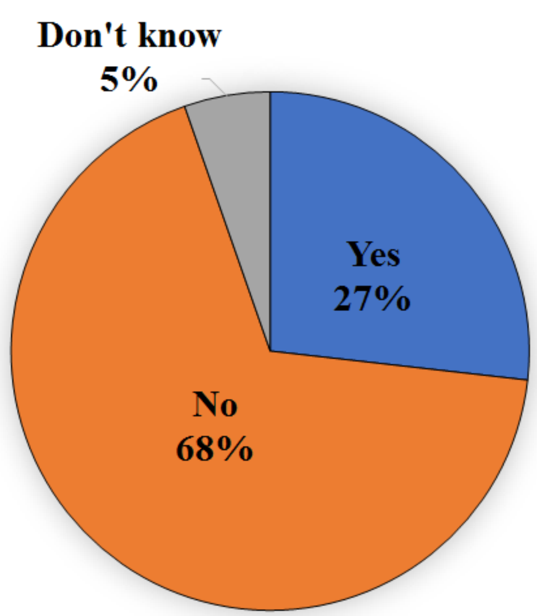
Land Owners Q7
Do you have any questions or comments for us? If so, please list them below.

Comments:
- The added value of solar panels is great.
- Interesting, worth a study; Would there be an extra charge for the alternative energy?
- It's a great idea, just doesn't work on my property
- Snow Fences make it harder to farm; Land is always behind on production; Benefits travel; What would a storage system look like?

Total
4

For General Public

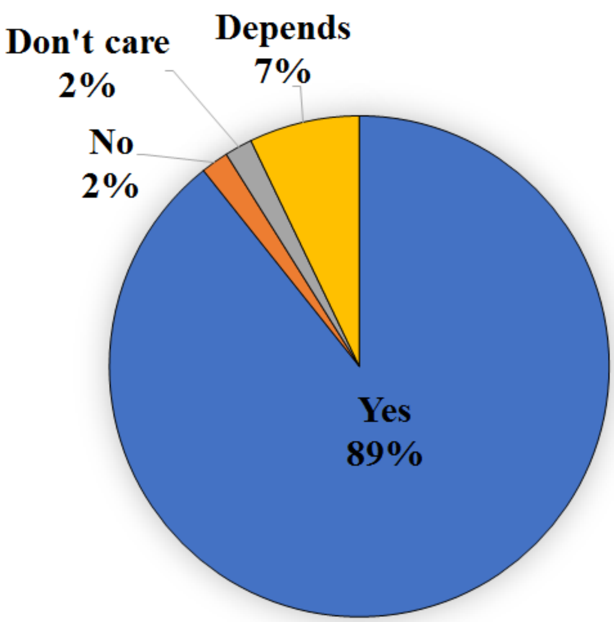
General Public Q1
Are you living in a community adjacent to noise barrier walls?



Yes	No	Don't know	Total
15	38	3	56

General Public Q2

Would you support the idea of using solar panels on new or existing noise barriers along highways?



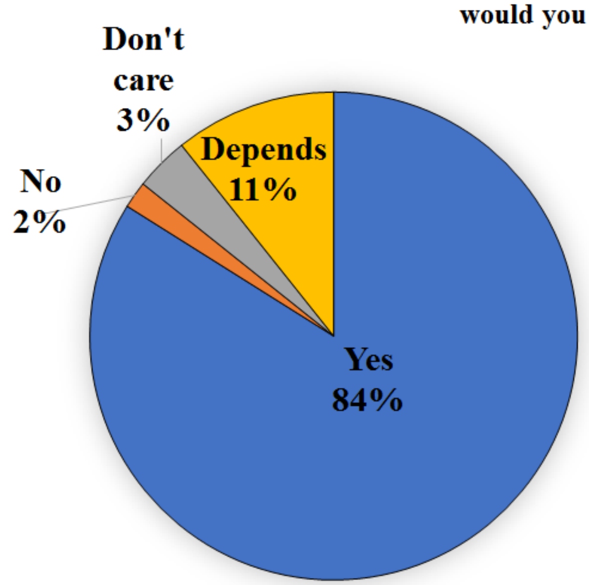
Comments:

- Depends: There needs to be a long-term ROI that is positive on this project to make it worth it.
- Depends: Is it reasonable cost effective? How much maintenance? Will it be a greater eye sore?
- Depends: On how the LED headlights would reflect off of these panels during night driving.
- Depends: Are they economically viable?

Yes	No	Don't Care	Depends	Total
50	1	1	4	56

General Public Q3

If adding solar panels to an existing noise barrier changed the appearance, would you still support it?



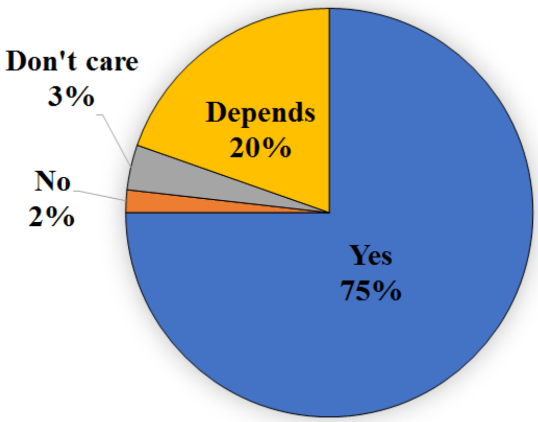
Comments:

- Depends: People live by these - so it must look ok.
- Depends: I would hope for thoughtful consideration of appearance & maintenance.
- Depends: I would want to make sure the panels would not reflect sunlight that would be problematic for drivers.
- Depends: Aesthetics are important to the people who live near and travel by them frequently.
- Depends: No one wants to be driving through a post-apocalyptic looking movie, and Fargo looks grim enough all winter without it.
- Depends: Only if these would not be distracting to drivers.

Yes	No	Don't Care	Depends	Total
47	1	2	6	56

General Public Q4

If additional transportation dollars were required to install and maintain solar panels on existing or new noise barriers, would you still support it?



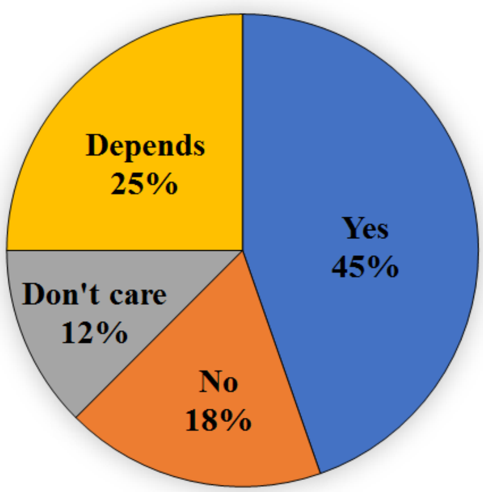
Comments:

- Depends: Cost/benefits
- Depends: It would need cost/benefit analysis
- Depends: Cost/benefits
- Depends: Cost not too prohibitive
- Depends: The financial return on the captured sunlight as energy (thereby reducing electrical costs to our community as a whole that is greater than the investment of the solar panels) must be positive and provide some amount for repairs and replacement cost. If the numbers show it, and the numbers are disseminated to the community for viewing, then I would be interested in supporting it.
- Depends: Who will benefit from the electricity generated by the solar panels? It would not be fair to double dip!
- Depends: If it's reasonably cost effective and not a terrible eye sore then yes. I was sent this as a pastor of our church. We would offer our roof also as a place for solar panels.
- Depends: Would the solar panels generate enough electricity to pay back the cost? If so, I would support it.
- Depends: On the cost and how much energy they would capture.
- Depends: I am concerned about the money needed to maintain current roadways and where money for this would come from.
- Depends: If it will pay itself off, yes

Yes	No	Don't Care	Depends	Total
42	1	2	11	56

General Public Q5

If adding solar panels to a noise barrier resulted in less noise reduction (reduced barrier effectiveness), would you still support it?



Comments:

- Depends: If noise sensitive locations like schools, hospitals or parks are affected, I would advocate for other location
- Depends: Maybe - cost/benefits
- Depends: It seems ok to us, but I don't live near the freeway and would not be impacted
- Depends: I'd need to know how much the effectiveness is impaired
- Depends: How much less?
- Depends: Depends on if the people that are affected by the noise cave
- Depends: On how much, I don't live near one, I would not want to have a different situation to others
- Depends: Depending on the answer to #4, yes, I would. However, I am not directly next to the barrier, and so have less of a vested interest in the noise reduction vs ROI of this renewable energy.
- Depends: It would depend on how much it changed the effectiveness.
- Depends: Would want to know how significant a change it was
- Depends: How much change?
- Depends: If it is significant then no. Defeats the purpose of the barrier. But if it is minimal - then yes. The benefit of the solar would be worth it.

Yes	No	Don't Care	Depends	Total
25	10	7	14	56

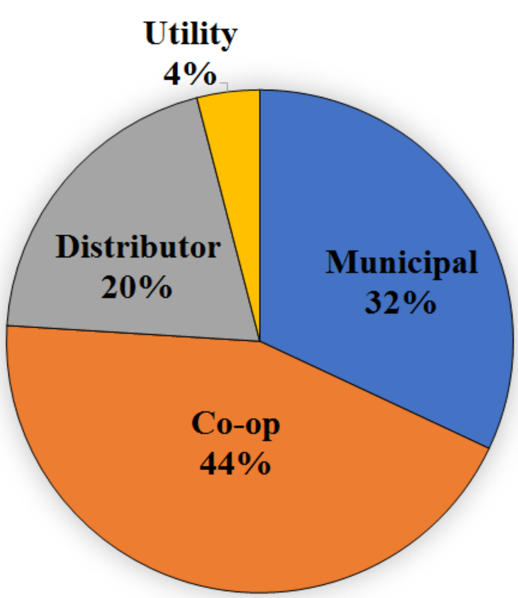
General Public Q6
Do you have any questions or comments for us? If so, please list them below.

Comments:

- Good idea!
- Moorhead can make another statement.
- If the solar panels generate enough, perhaps that could be used to expand the program
- Sounds like a great idea & use of space!
- Great idea!
- Anything we can do to be better humans engaged in healing your environment is vital to be supported.
- Please put together financial numbers of this project and send them to the respondents of the survey, as well as the Moorhead community that they may see what the feasibility on this, if it gets to that point.
- The more solar panels the better. Immediate action is demanded to combat the climate crisis. This is one tiny step in the direction of a sustainable future.
- I am responding as a member of a church which was included because of a nearby sound wall. The Church is a half-mile from a MNDOT highway, and about 50 miles from a highway with a sound barrier.
- We live approximately 100 miles from the nearest known noise barrier.
- This is a good idea.
- I am for solar panels wherever we can get them. I love seeing them on rooftops/carports.
- Who would be receiving the energy benefits?
- Who gets the energy?
- a. Who pays for this? b. Didn't the people buying this property know it would be noisy? c. How is the money generated from these panels spent? d. Does the money go to the State so it can be spent of anything they want? e. I was a little child when the State of Ohio built the freeway and charged us by the mile for using it. The structure was to be turned over to the state when it was paid for. I am now 86 and it still hasn't turned over. Are you really serious?

For Utility Companies

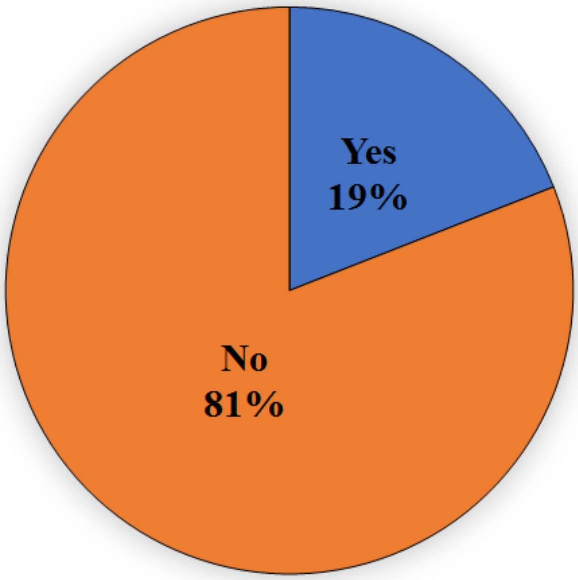
Utility Companies Q1
Company Type



Municipal	Co-op	Distributor	Utility	Total*
8	11	5	1	25

*25 replies by 21 Companies

Utility Companies Q2
Does your company produce solar electricity through PVs?



Comments:
- Yes (Small solar panel)

Yes	No	Total
4	17	21

Utility Companies Q3
If Yes above, how much does it cost for producing solar electricity, at $x.xx/kwh or $x,xx/kw (the overall cost)?

Comments:
- $0.045 per KWH
- Not real sure.
- We have a very small solar unit
- We are investigating a couple of system at this time.
- Doesn't really track it

Total
5

Utility Companies Q4
If your company sells solar electricity, how much does it cost per kWh for commercial customers?

Comments:

- ❖ We do not sell solar energy directly to our customers, it is a part of our power providers mix We do provide a clean energy rate at $0 .005
- ❖ $0.025
- ❖ An additional $0.005 per kWh above there normal rate.
- ❖ Do not sell solar specifically. We sell renewable energy credits (green tags) for $1 per kWh. this is in addition to normal price of their electricity.
- ❖ Solar is part of our generation and transmission (G&T) provider's portfolio, sales are not direct
- ❖ We don't sell solar energy to our customers, but they are credited with whatever energy is produced by the solar modules they own in our community solar garden.
- ❖ Any solar we produce or purchase is rolled into our cost of service to our customer.

Total
7

Utility Companies Q5
If you provided a solar electricity rate above, how does that vary from the standard commercial electricity rate?

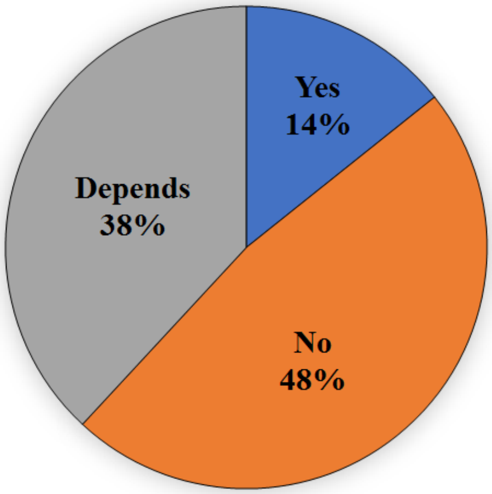
Comments:

- ❖ $0.0839
- ❖ An additional $0.005 per kWh above there normal rate.
- ❖ The credit above is at the same rate as for selling electricity to that customer class.
- ❖ Minnesota law requires net metering for installations less than 40 kW.
- ❖ If you are referring to a rate where the customer can purchase 100% solar energy, we do not have such a rate.

Total
5

Utility Companies Q6

Would your company be interested in purchasing solar electricity generated from the MnDOT solar snow fences/sound barriers?



Comments:

- Depends: Price
- Depends: we'd follow the existing PURPA (Public Utility Regulatory Policies Act) and net metering rules
- Depends: We cannot purchase power that is not generated within the City limits of our community. Per our Power agreement with our power supplier.
- Depends: It would depend on the size of the PV solar field.
- Depends: We are unable to purchase energy from anyone other than our members due to our contract which requires that we purchase all of our energy from our power supplier. Our power supplier may be interested and we would be happy to facilitate a discussion between MnDOT and our power supplier.
- Depends: Contractually we purchase 95% of energy needs from our G&T, the 5% option is up for negotiation. We would be interested to compare the cost of output to something we would need to construct
- Depending on the contract the Co-op has with its G&T. No all Co-ops have the opportunity to purchase electricity outside of the contract they have with their G&T.
- Depends: If arrays were less than 40 kw, MLEC would purchase under MN net metering laws. If 40 kw and larger, the rate would be negotiated with Great River Energy.
- Yes: By law they need to purchase it

Yes	No	Depends	Total
3	10	8	21

Utility Companies Q7

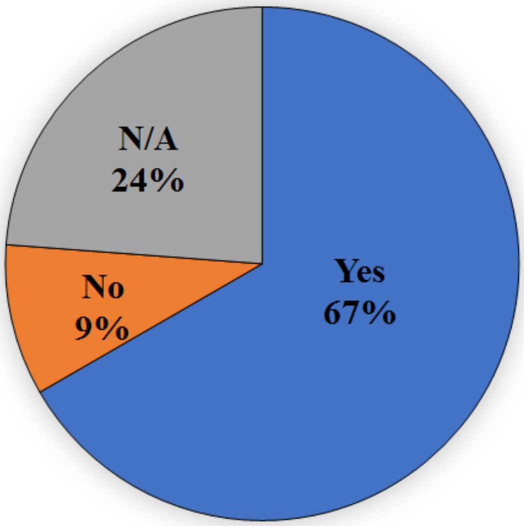
If Yes above, how much is your company interested in purchasing the solar electricity, at $x.xx/kwh?

Comments:

- Varies. Cost depends on large scale output costs, would have to have a better understanding on the amount of output.
- $0.04/kWh
- 1.9 cents per kwh.
- The rate we would purchase solar at depends on the size of the solar system. If the unit is under 40 kW and considered a net metered unit, we pay around $0.08/ kWh. If it is over 40 kW the price would be $0.0238/kWh
- $0.11/kwh
- If under 40 kw, we would purchase solar at $.11875/kwh
- State rules/laws rate

Total
7

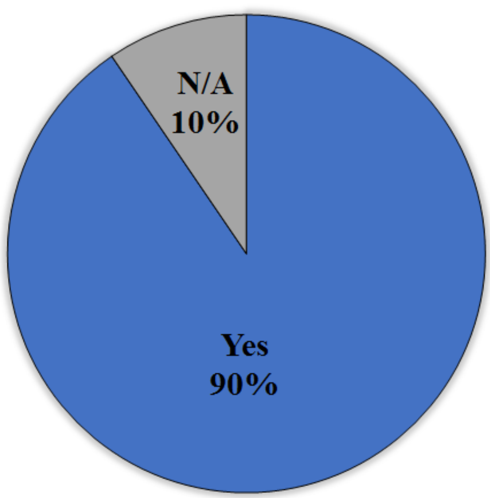
Utility Companies Q8
Is your company interested in constructing, operating, and/or maintaining a PV solar power harvesting system?



Comments:
- N/A (Must be a member of co-op)
- N/A (Depends what size)

Yes	No	N/A	Total
14	2	5	21

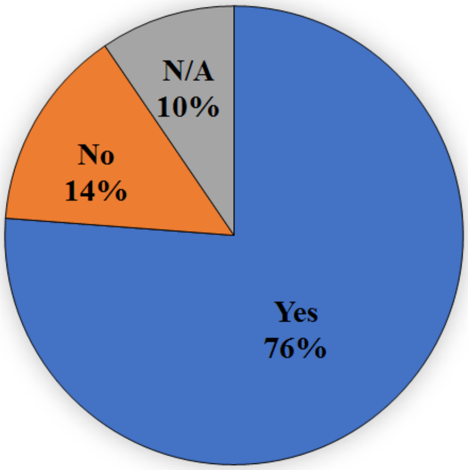
Utility Companies Q9
Does your company have the capacity to integrate a PV solar power system onto the grid?



Comments:
- N/A (Depends what size)

Yes	No	N/A	Total
19	0	2	21

Utility Companies Q10
Are there special codes or requirements to integrate PV panels with your grid?

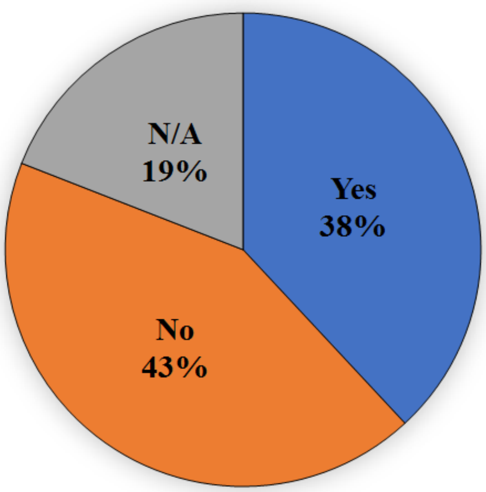


Comments:

- Yes: Not sure exactly, but there are a variety of codes that govern this area.
- Yes: There is a process through our adopted cogeneration policy/rules which adheres to the state of Minnesota's guidelines for interconnection of solar panels
- Yes: We follow the Municipal Distributed Energy Resource Interconnection process. (M-MIP)
- Yes: Needs to meet all applicable NESC, NEC and IEEE standards.
- Yes: Anything with output rating at or above 40 kW is not considered a small-scale installation and is subject to different guidelines than many of our member installed solar systems. We are not able to collect any government incentives as a cooperative, need a partner in investment
- Yes: Inverters must get their timing signal from the carrier wave on the power line. Thus if there is a power outage then the solar inverter goes off-line as well. This is a safety measure to prevent putting power on the grid when linemen think the line is dead.
- Yes: We follow the State of MN Distributed Energy Resources Interconnection Process. (MN DIP)
- Yes: C-MIP process
- Yes: The State of Minnesota has established a standard interconnection procedure and technical guidelines that interconnecting customers need to abide by.
- Yes: Different politics through MN
- Yes: National electric safety code, UL1741, IEEE154.

Yes	No	N/A	Total
16	3	2	21

Utility Companies Q11
Is there any insurance program needed for such a PV system if it is owned by your company?

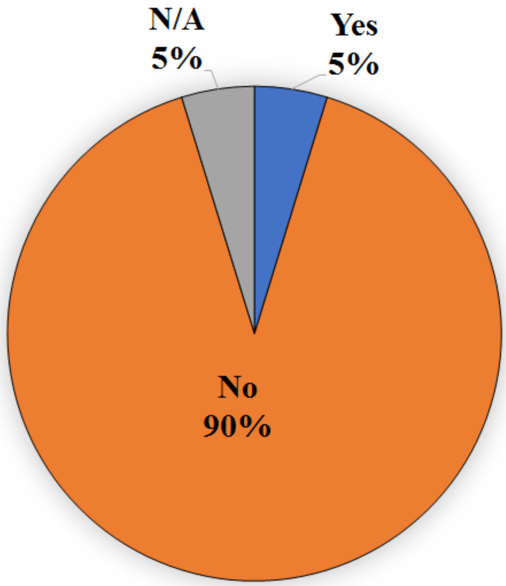


Comments:

- Yes: I'm unsure what the specific insurance is needed.
- Yes: There is a minimum of liability insurance required to connect to the grid. This would all be fleshed out during contract negotiations for the purchase of the power.
- Yes: Insurance requirements are based on size of generation system, minimum $300,000
- Yes: See section 5.10 of the MN DIP for specifics, but in general: <40 kW - $300,000 >40 to 250 kW - $1,000,000 >250 to 5 MW $2,000,000
- Yes: Minimum $300,000 liability limit
- Bases On size $300,000 is minimum

Yes	No	N/A	Total
8	9	4	21

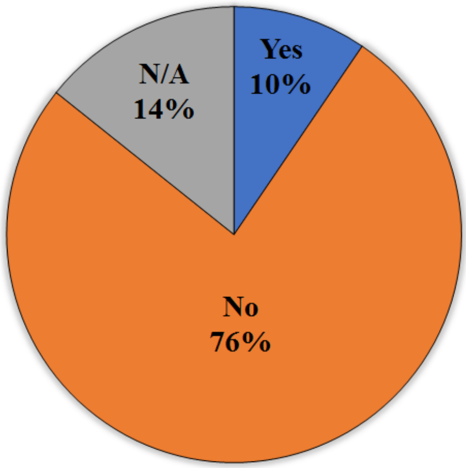
Utility Companies Q12
Have your company ever received any tax incentive or credit for harvesting PV solar energy?



Yes	No	N/A	Total
1	19	1	21

Utility Companies Q13

Is there any incentive from your company for your customers who are willing to install PV solar energy systems?



Comments:

- ❖ No: Nothing above the ARCER, rate paid to those that over generate energy in a given month
- ❖ Yes: Required net metering rate. No other incentives.
- ❖ Yes: Buy back power from customer with PV systems.
- ❖ Yes: Reimbursed for energy product at standard rate

Yes	No	N/A	Total
2	16	3	21

Utility Companies Q14

Do you have any questions or comments for us? If so, please list them below.

Comments:

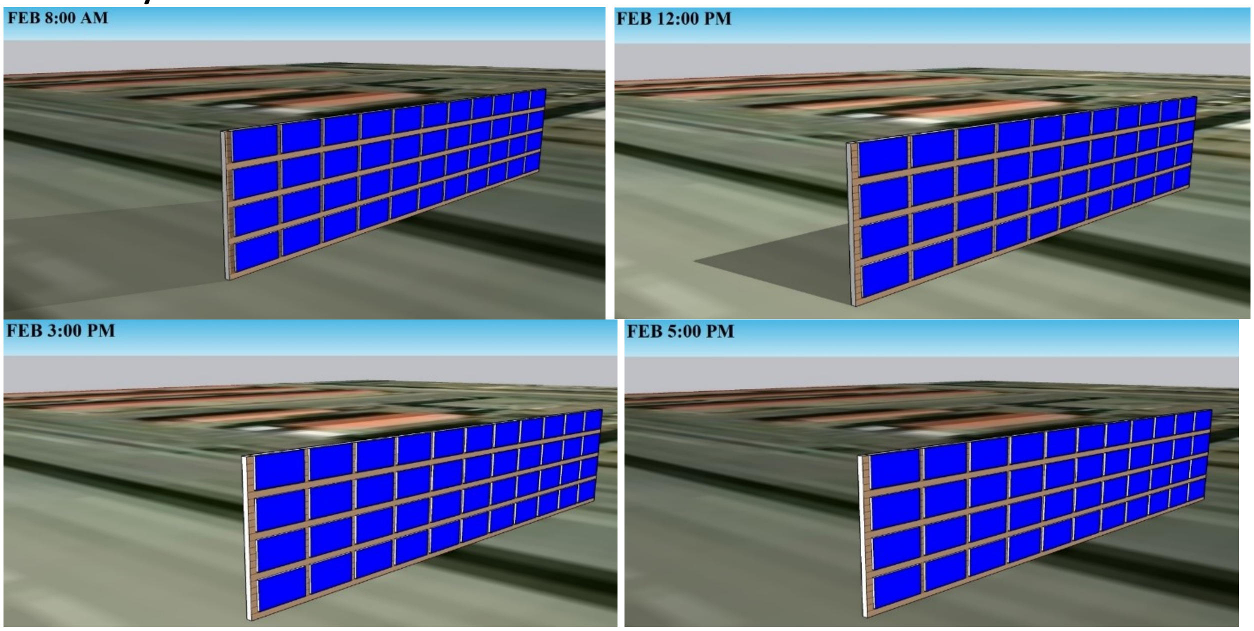
- ❖ Thank you for including rural electric cooperatives, interested to hear more about the progress of the project
- ❖ Project does not make economic sense. Maintenance alone to keep snow off would be overburden

Total
3

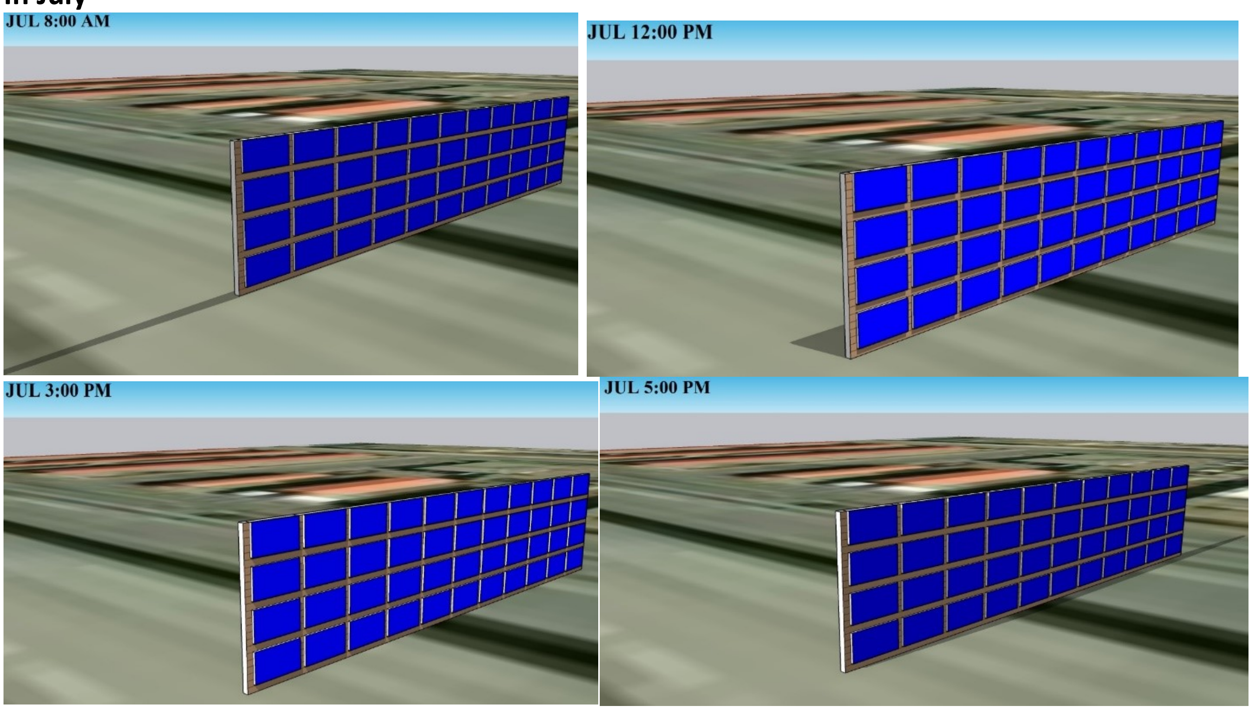
APPENDIX C: PVNB PANELS WITH DIFFERENT TILT ANGLES

Four-layer installation of PV panels on noise barriers with 90o tilt angle (vertical)

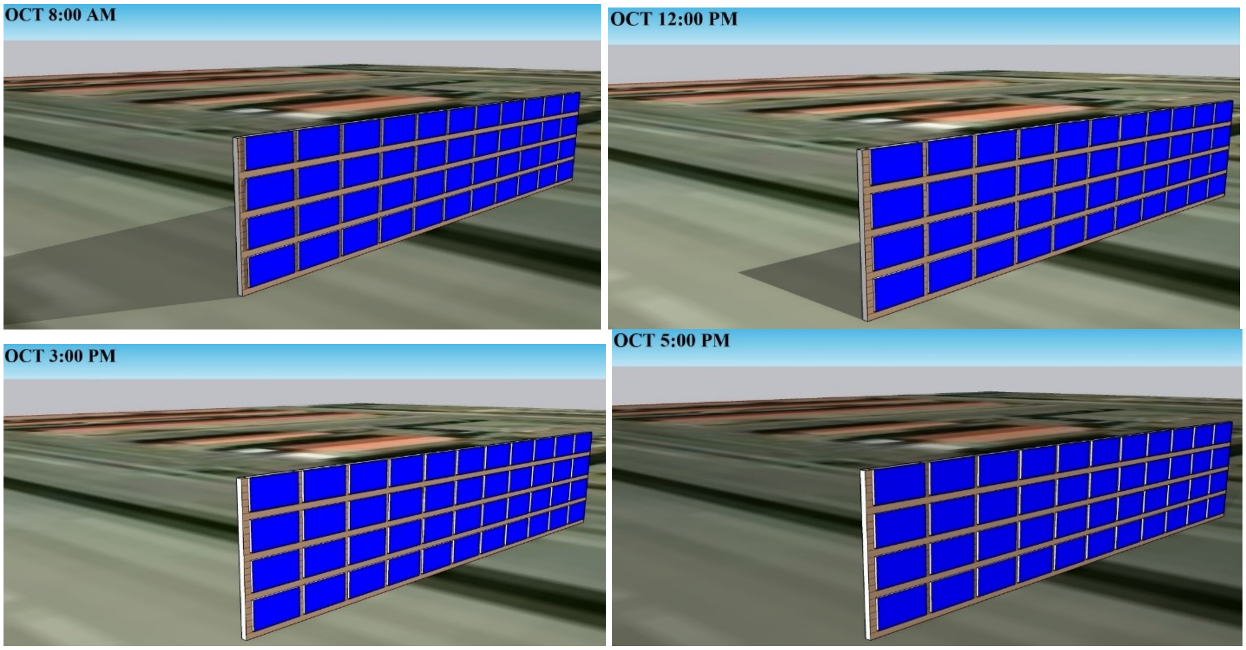
In February



In July

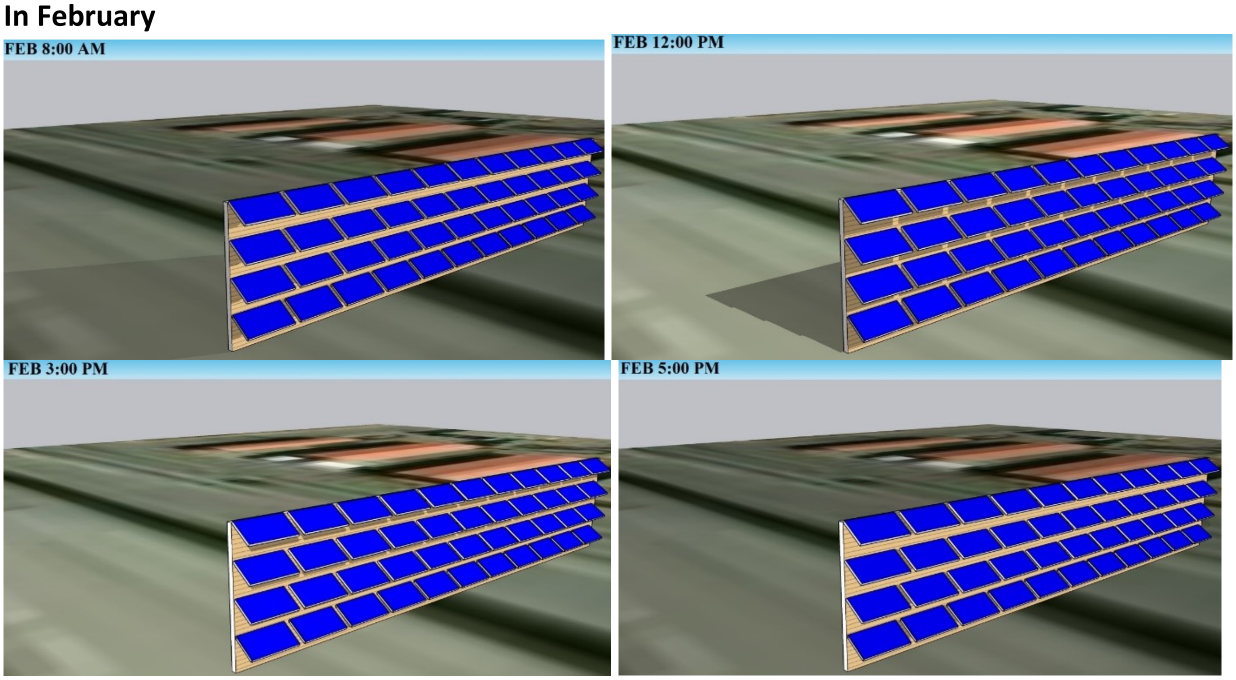


In October

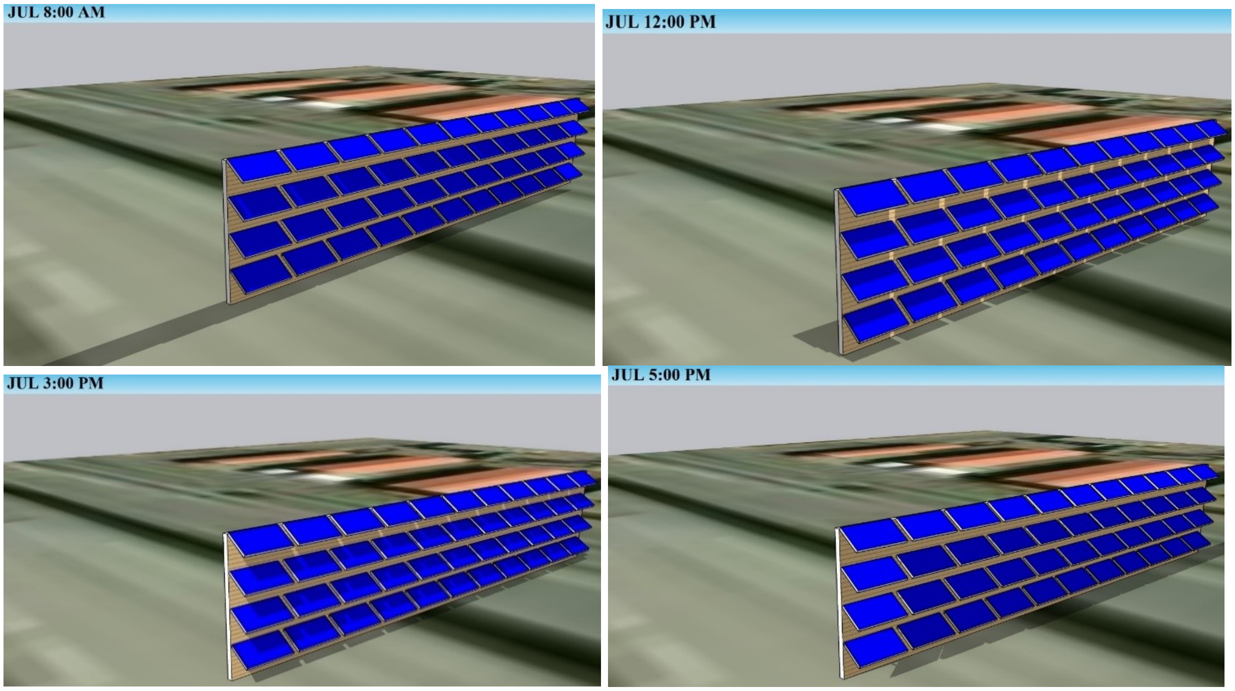


Four-layer installation of PV panels on noise barriers with 45o tilt angle

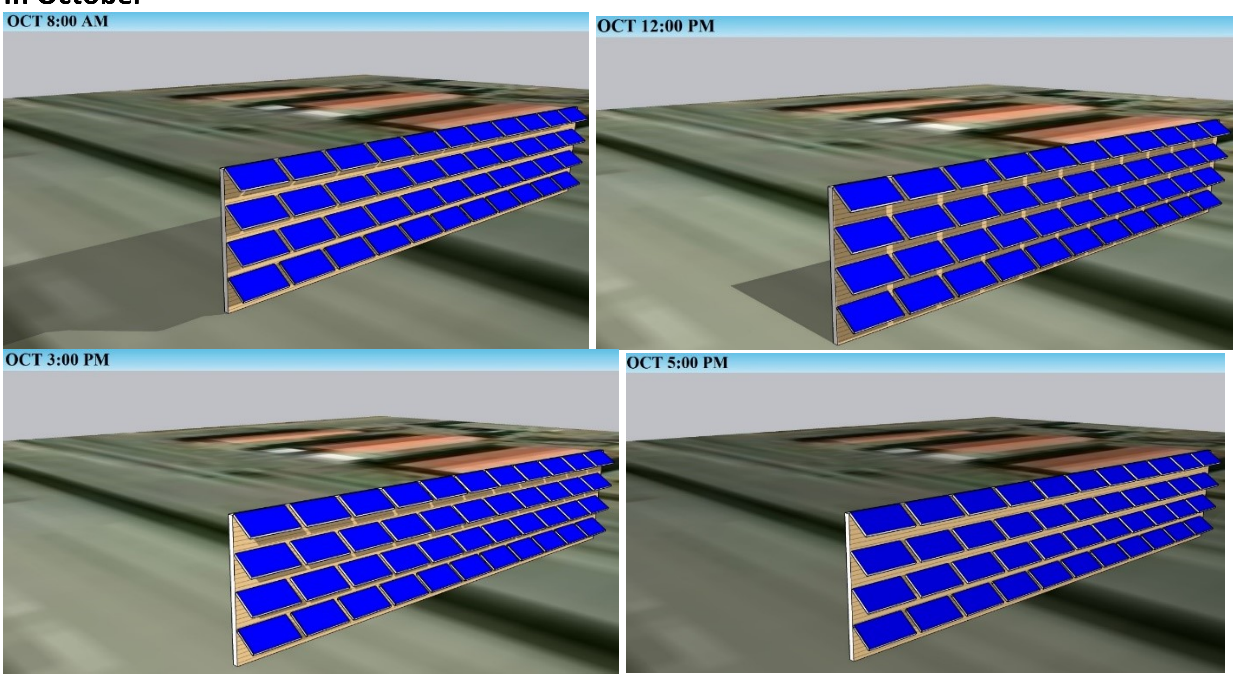
In February



In July

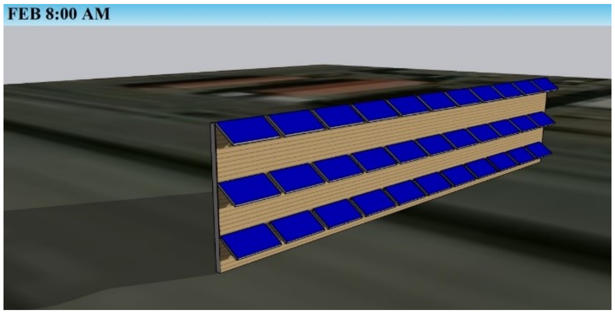


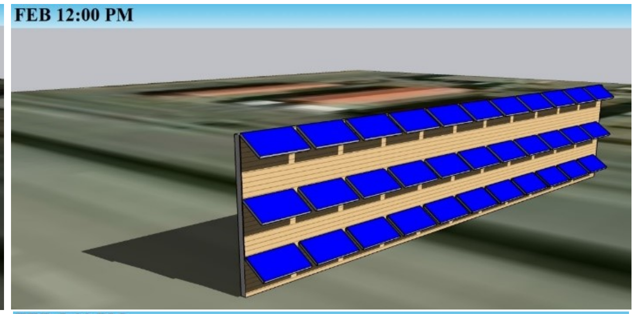
In October

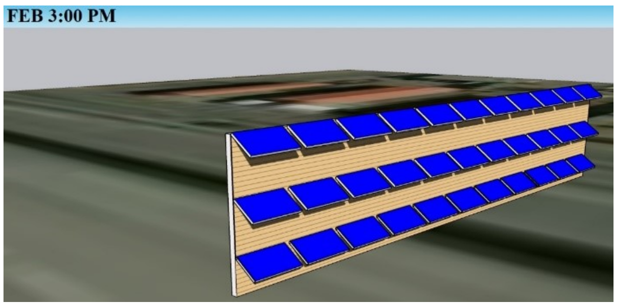


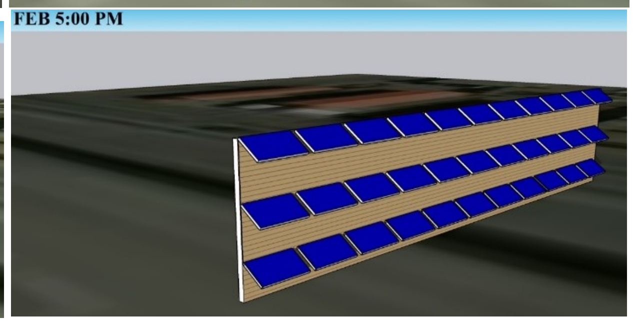
Three-layer installation of PV panels on noise barriers with 45° tilt angle

In February

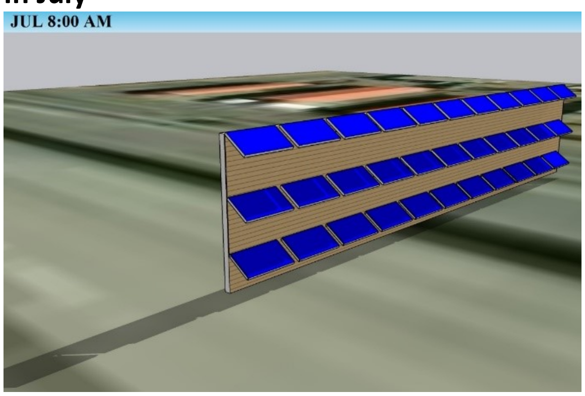


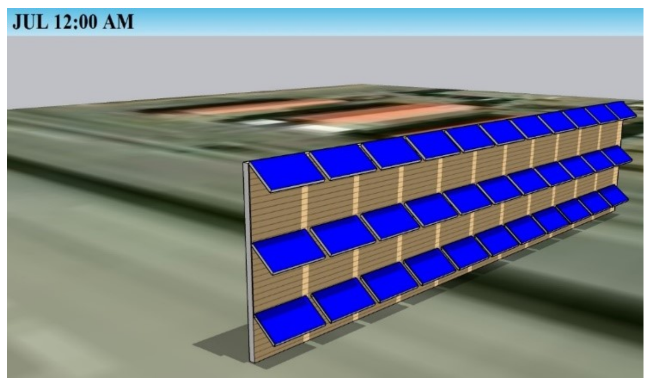


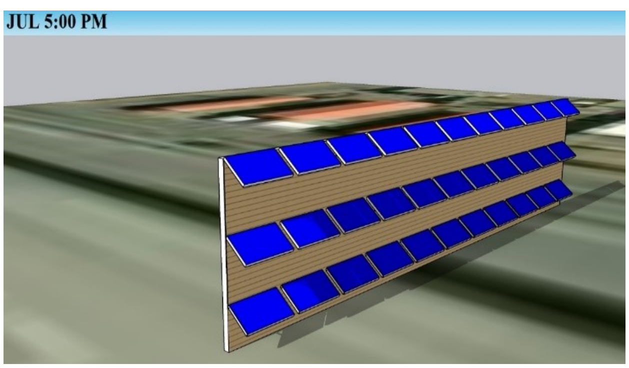


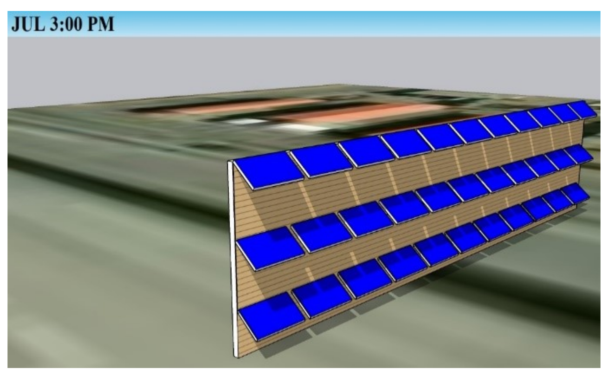


In July

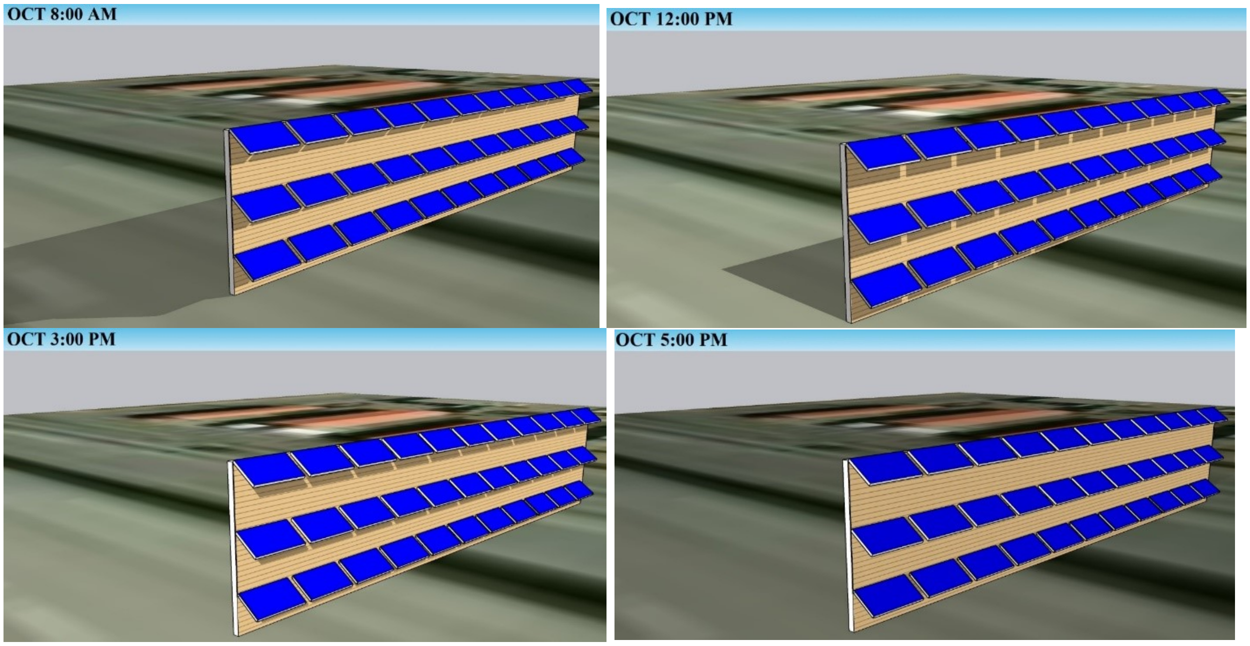








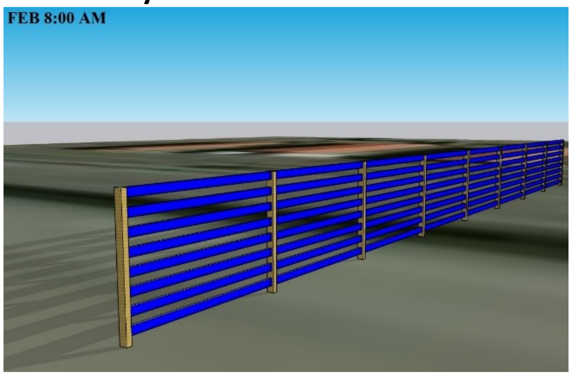
In October

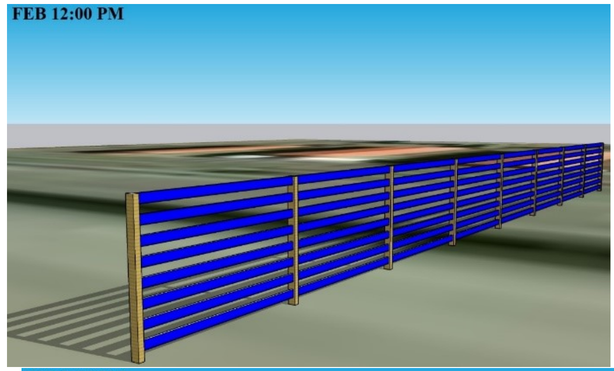

OCT 8:00 AM
OCT 12:00 PM
OCT 3:00 PM
OCT 5:00 PM

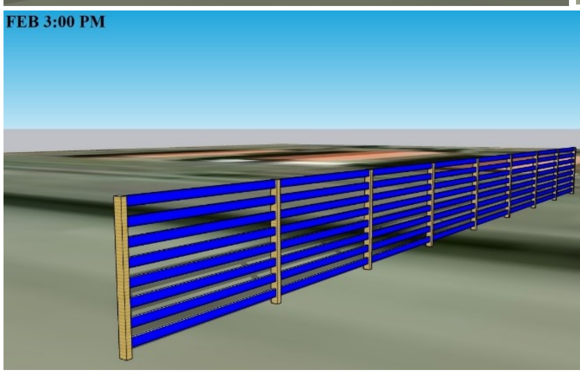
APPENDIX D: PVSF WITH DIFFERENT TILT ANGLES

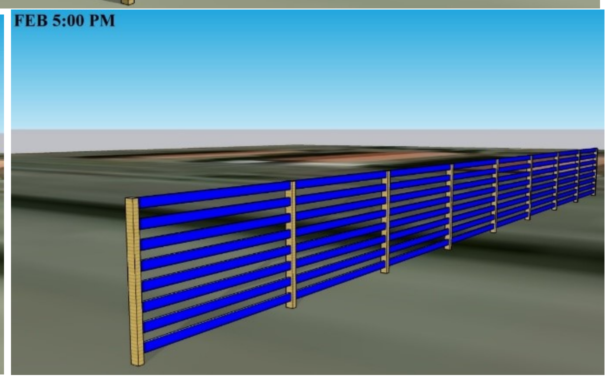
PV panels on snow fences with 90º tilt angle (vertical)

In February

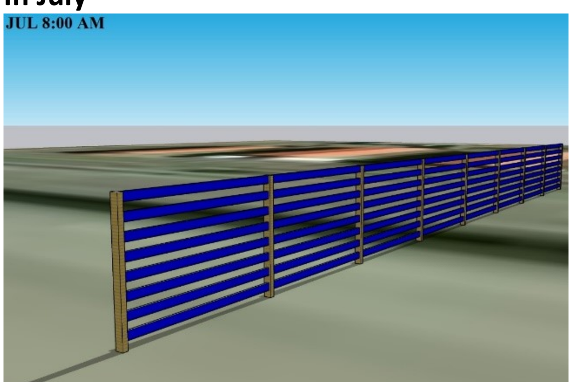


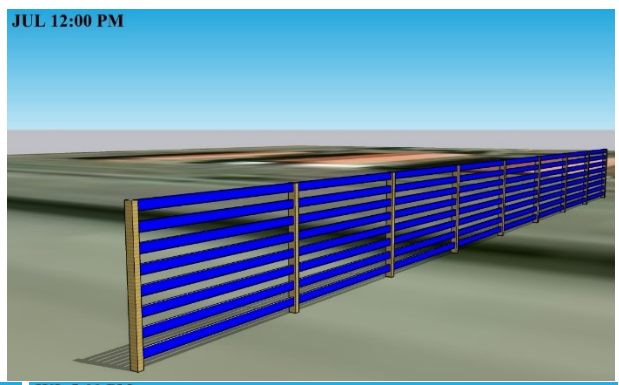


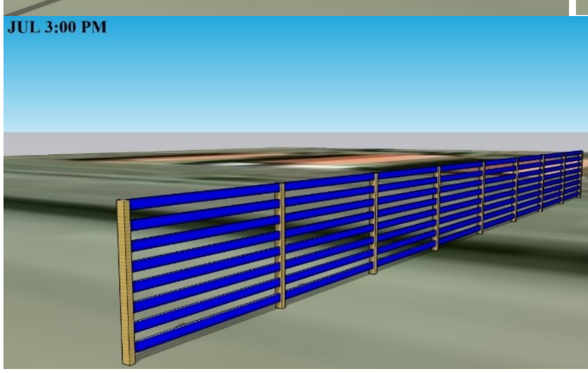


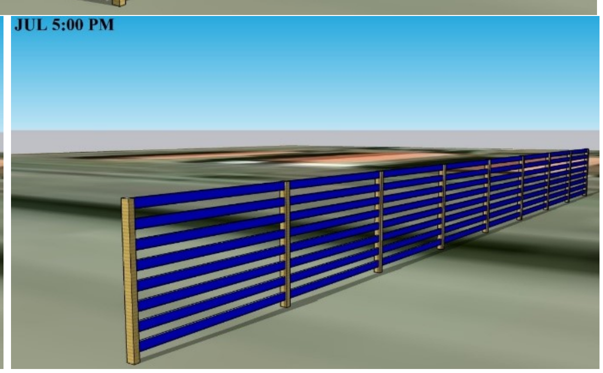


In July

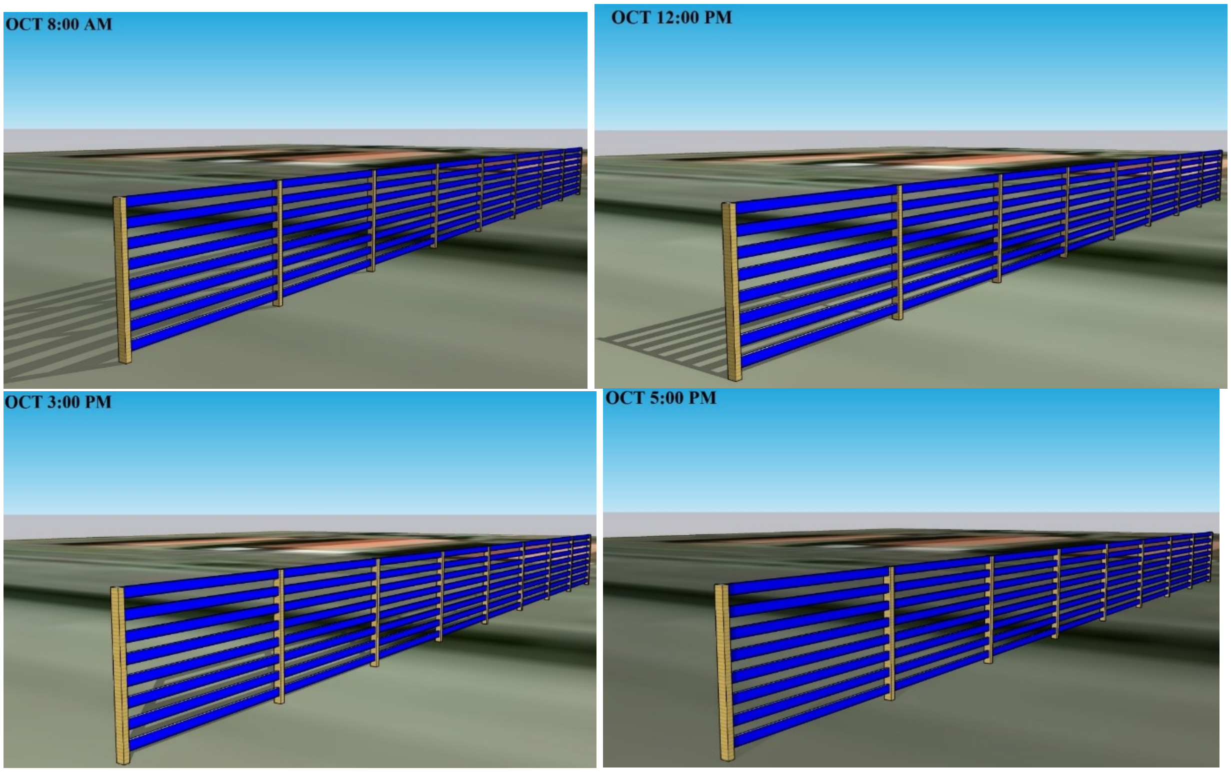




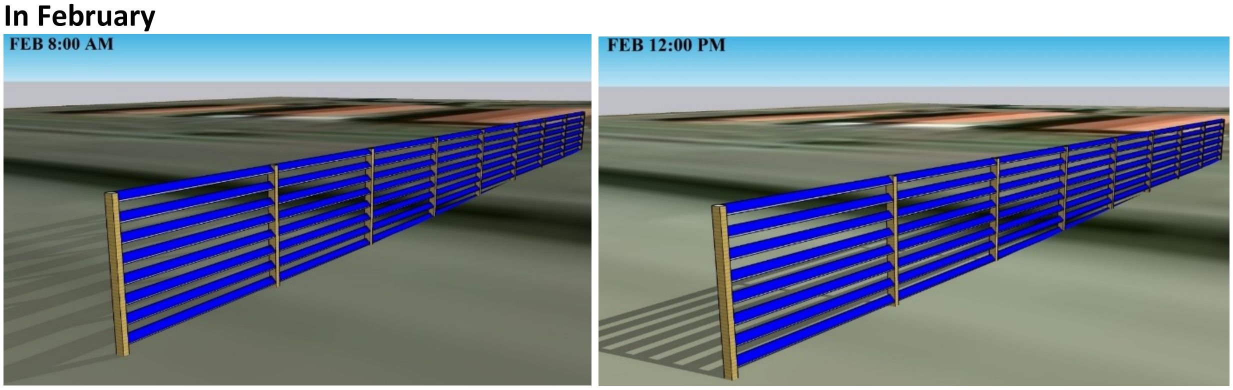


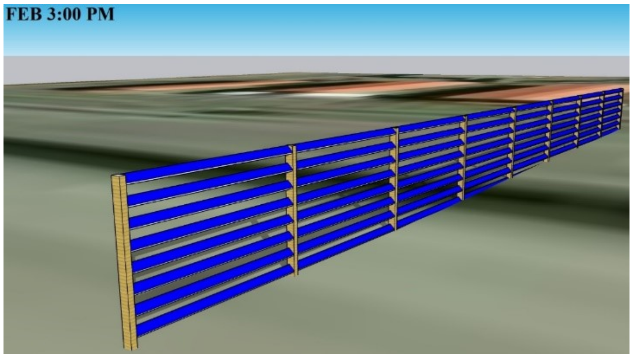


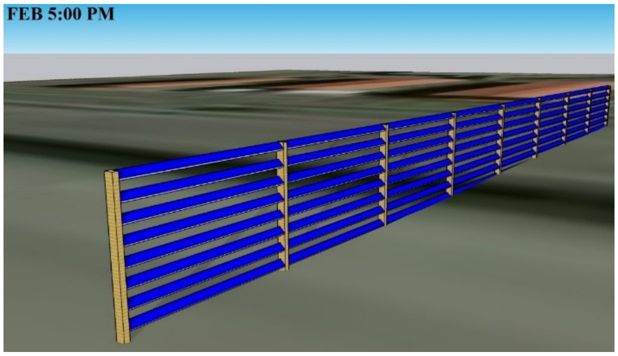
In October



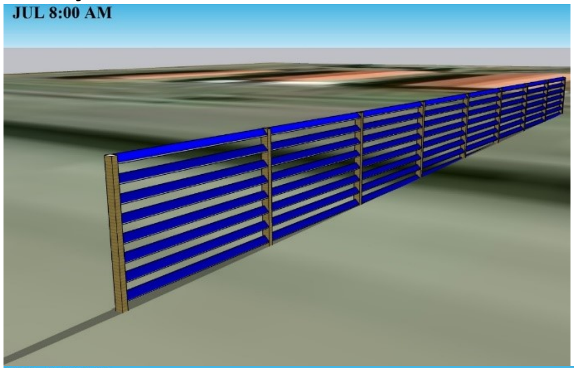
PV panels on snow fences with 45º tilt angle
In February

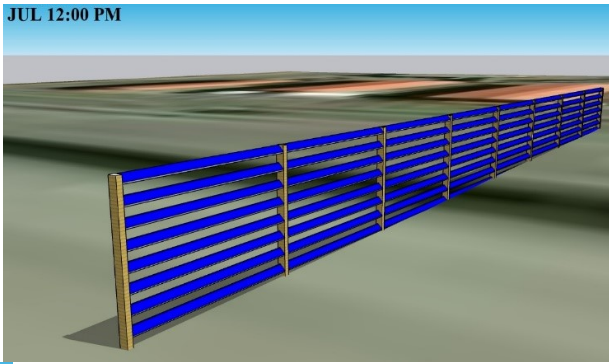


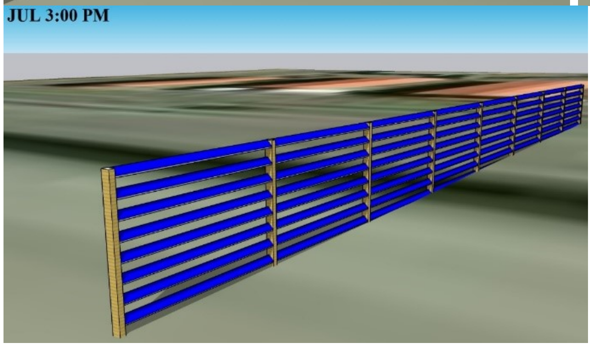


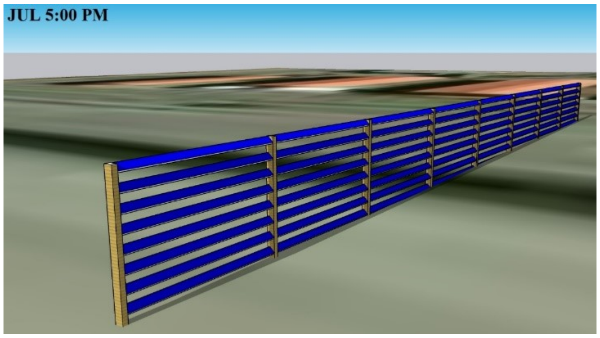


In July

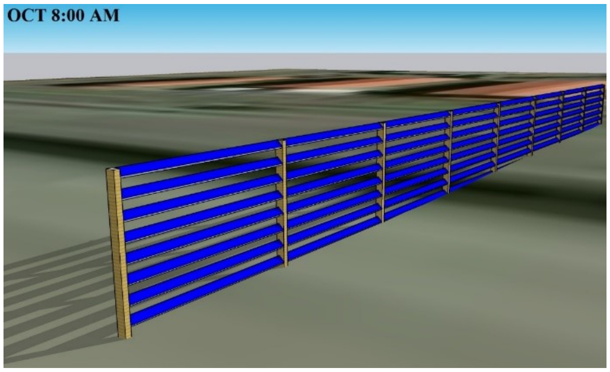


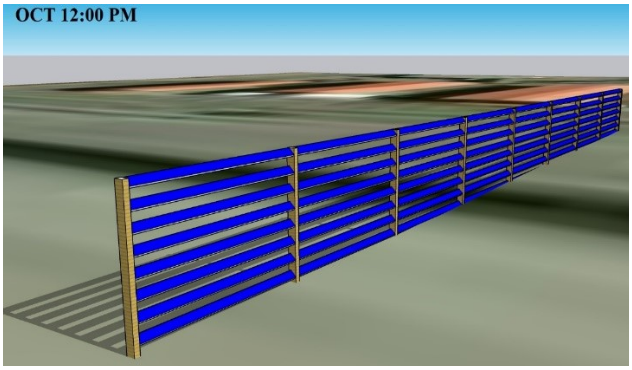


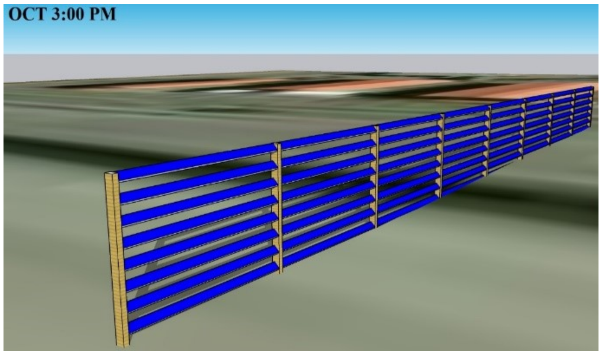
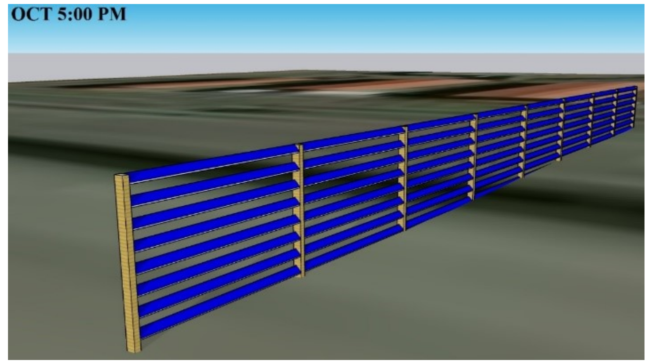




In October





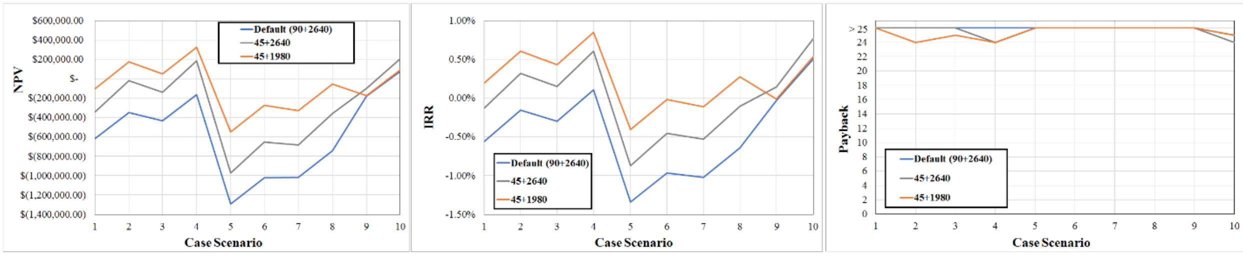

OCT 3:00 PM

OCT 5:00 PM

APPENDIX E: SENSITIVITY ANALYSIS RESULTS FOR PVNB

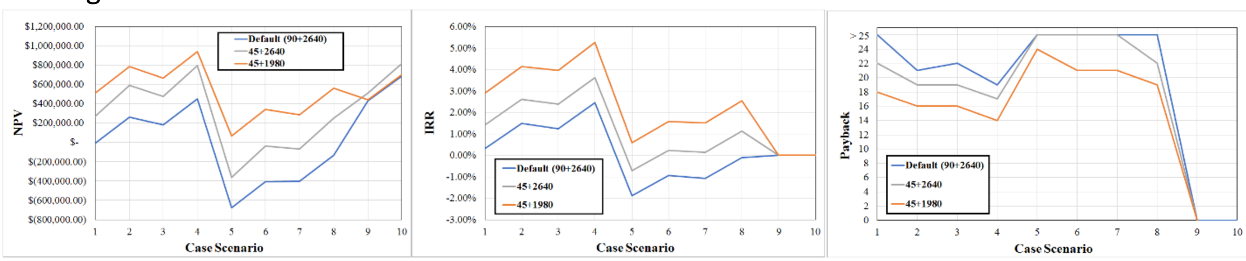
1-Mile PVNB

PVNB – 1, 3, 4

New PVNB

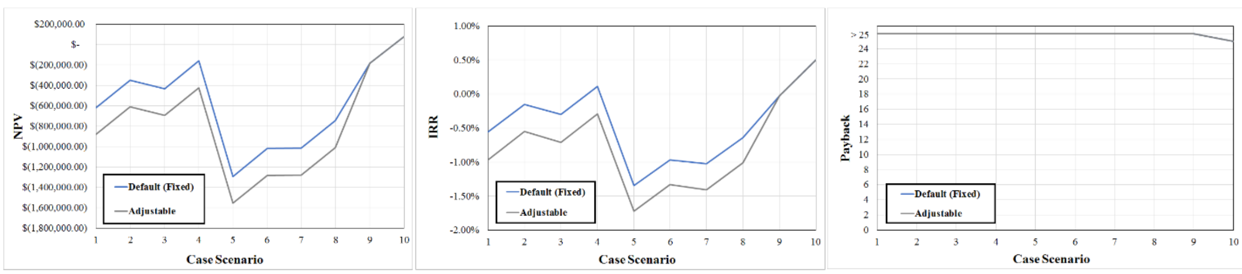


Existing PVNB

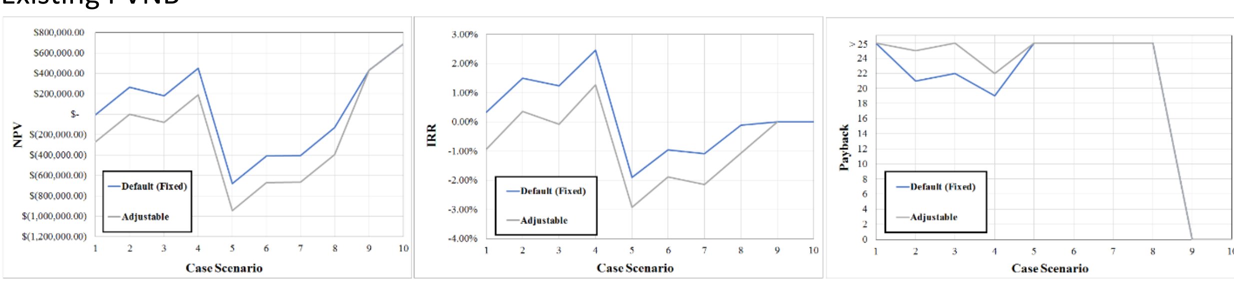


PVNB – 2

New PVNB

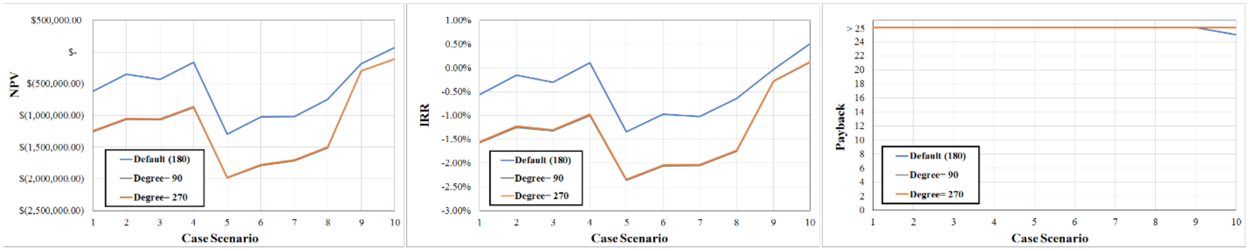


Existing PVNB

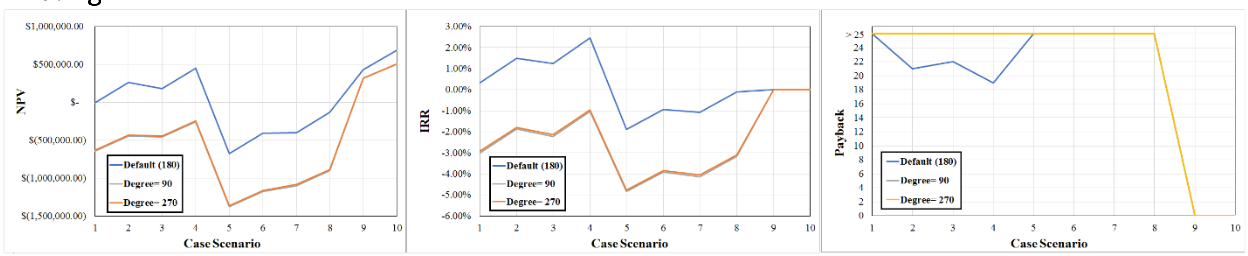


PVNB – 5

New PVNB

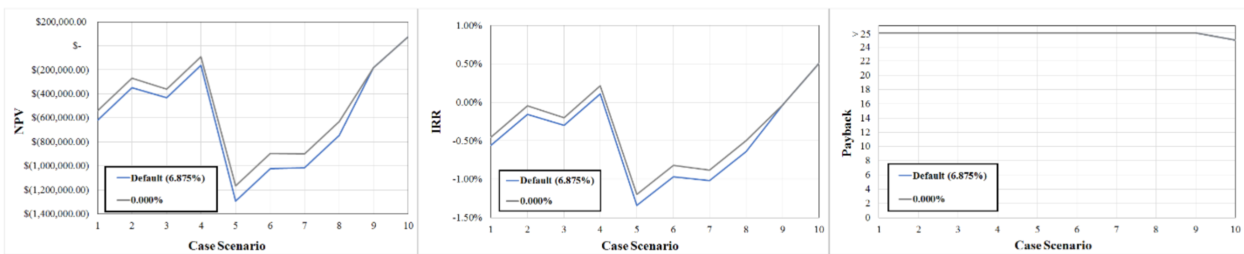


Existing PVNB

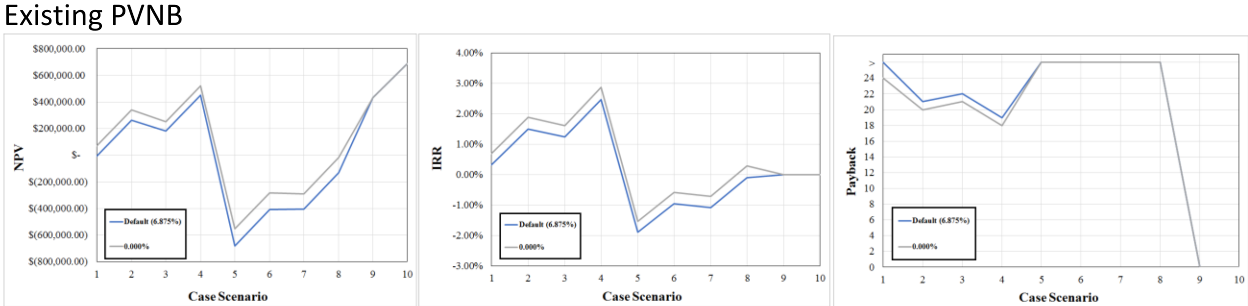


PVNB – 6

New PVNB

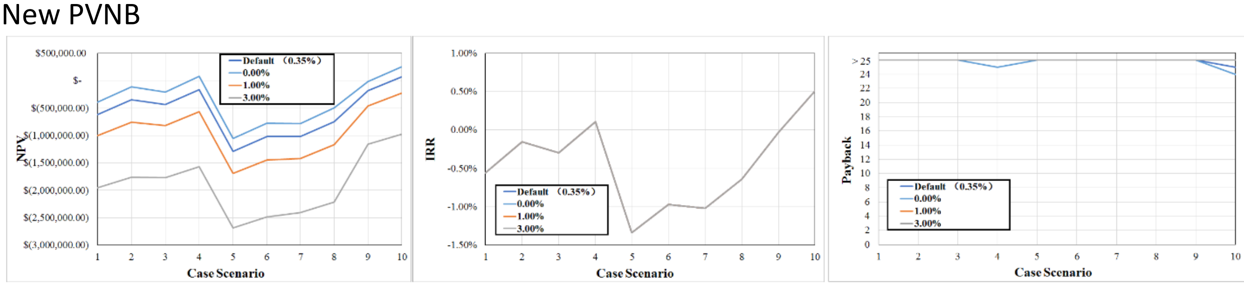


Existing PVNB

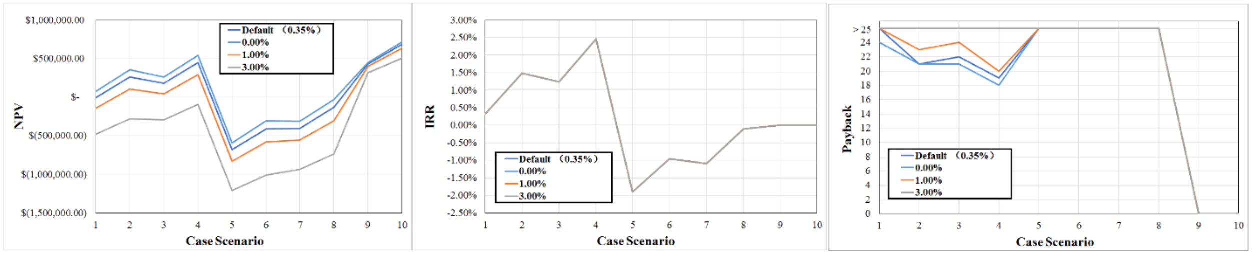


PVNB – 7

New PVNB

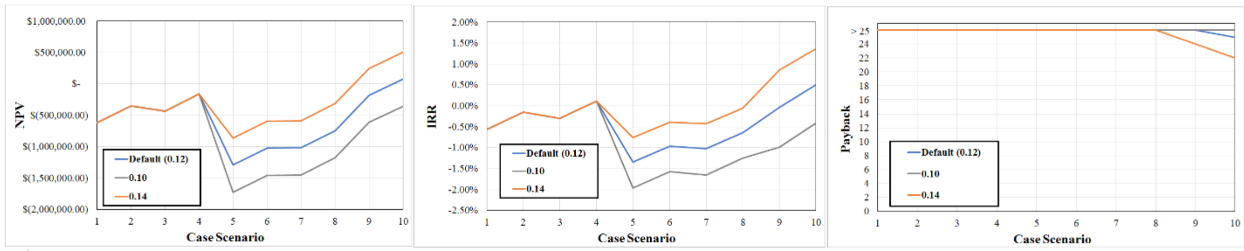


Existing PVNB

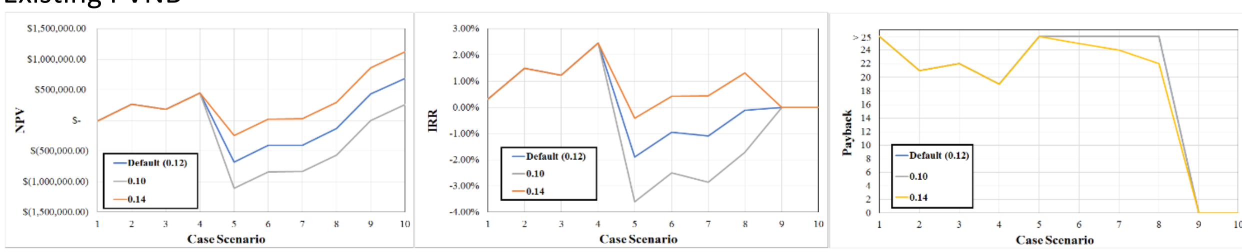


PVNB – 8

New PVNB

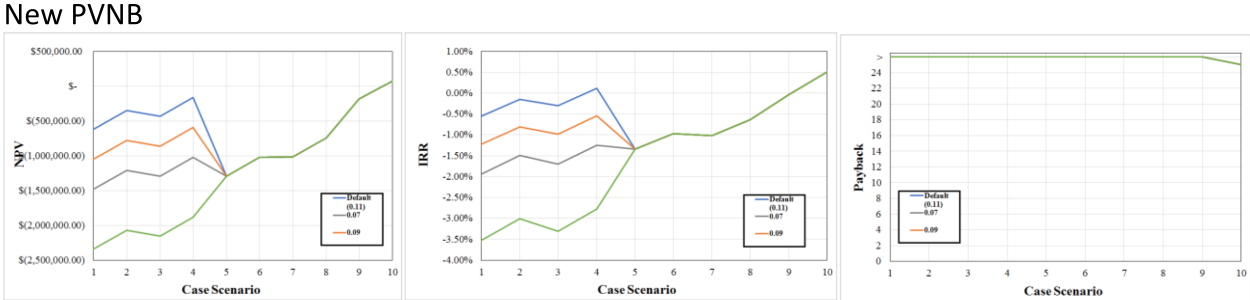


Existing PVNB

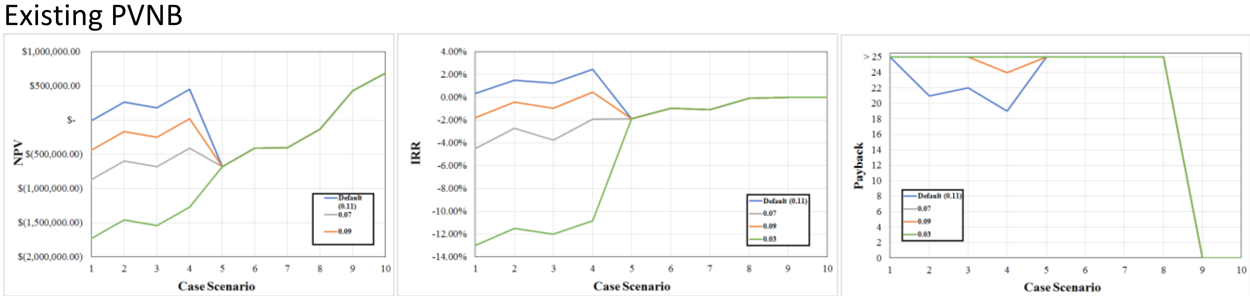


PVNB – 9

New PVNB

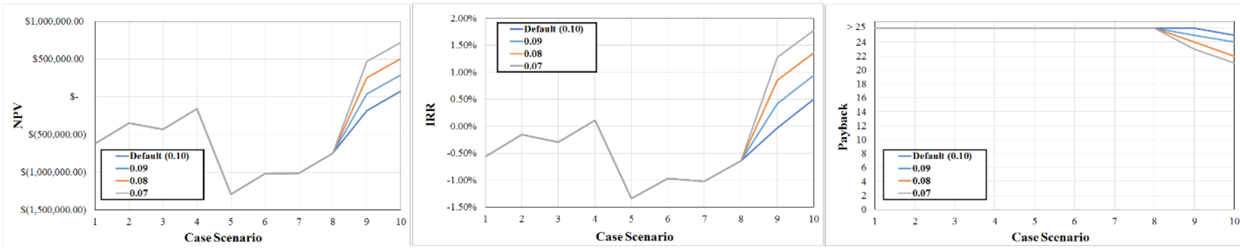


Existing PVNB

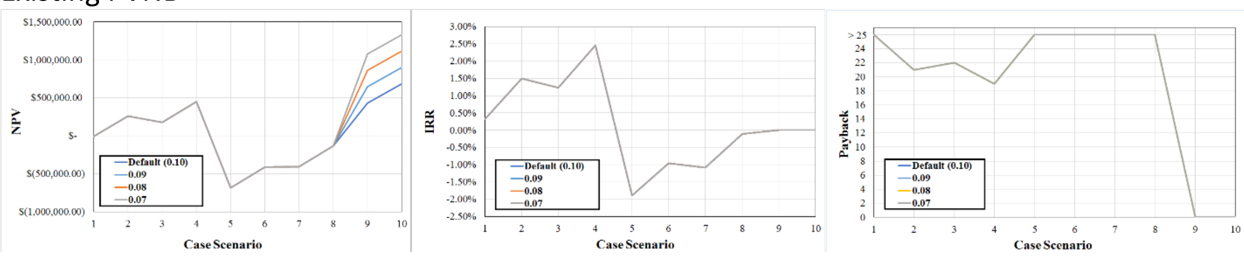


PVNB – 10

New PVNB

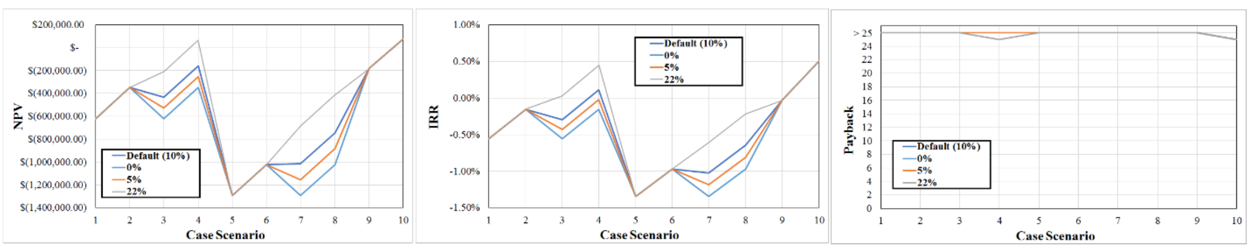


Existing PVNB

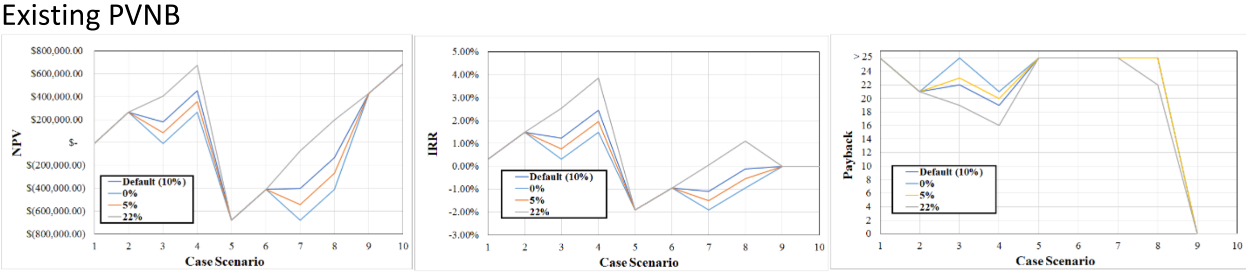


PVNB – 11

New PVNB

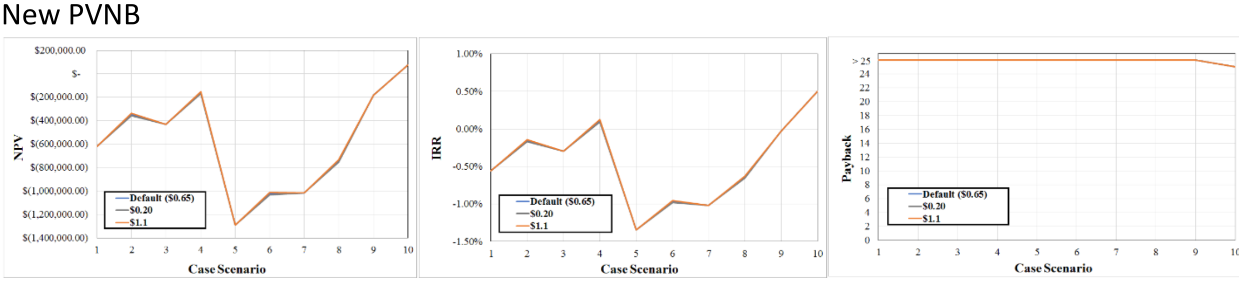


Existing PVNB

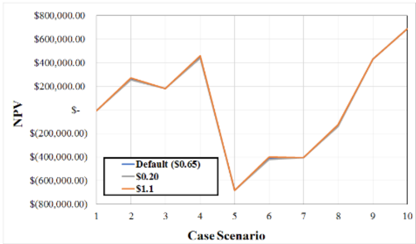


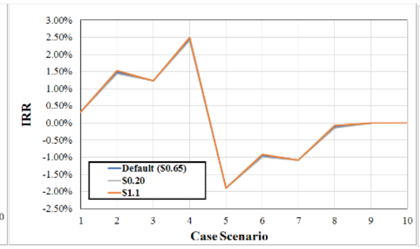
PVNB – 12

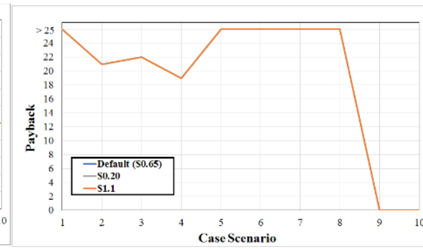
New PVNB



Existing PVNB

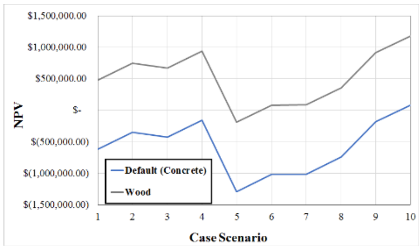


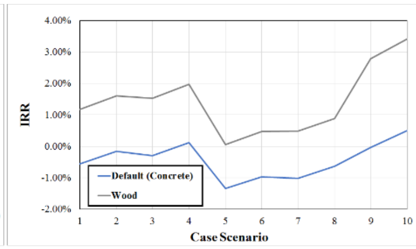


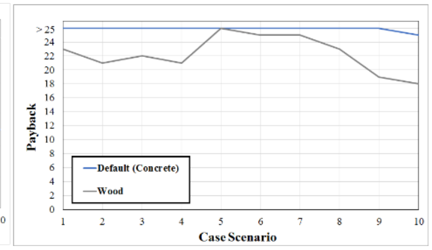


PVNB – 13

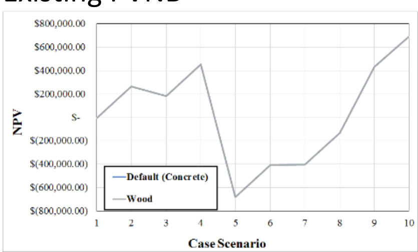
New PVNB

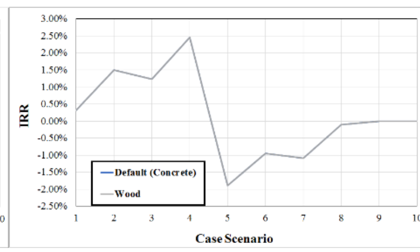


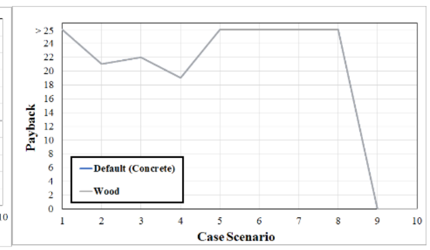




Existing PVNB

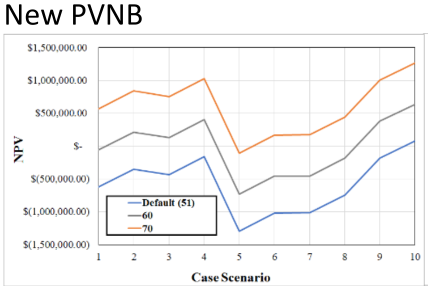


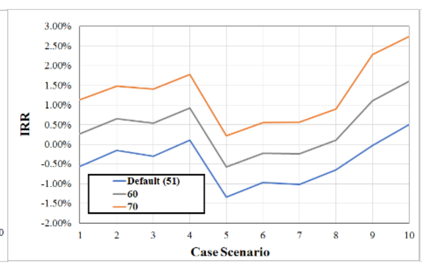


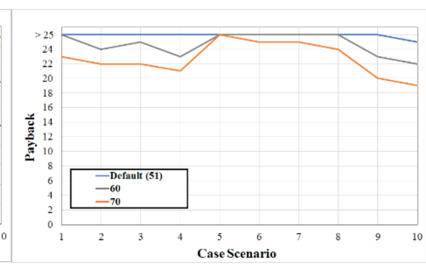


PVNB – 14

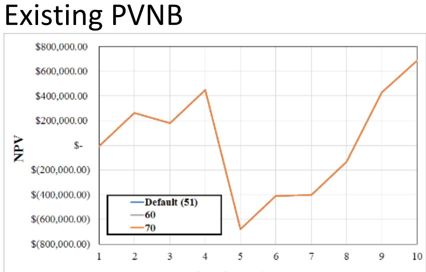
New PVNB

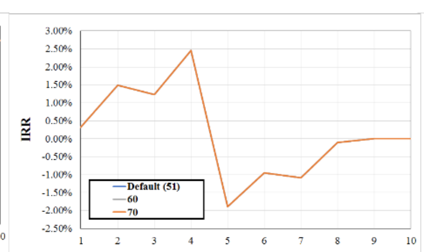


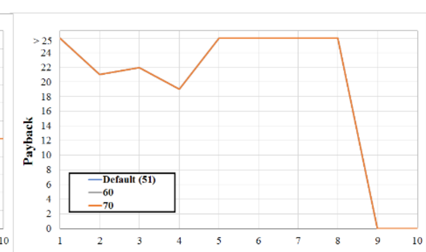




Existing PVNB

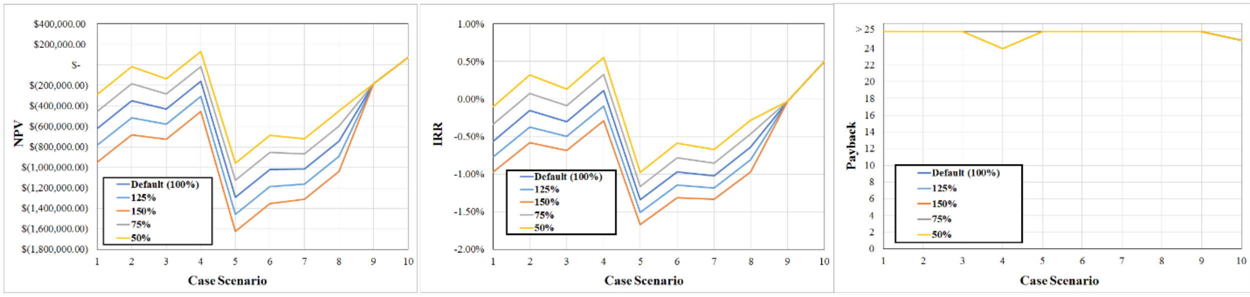




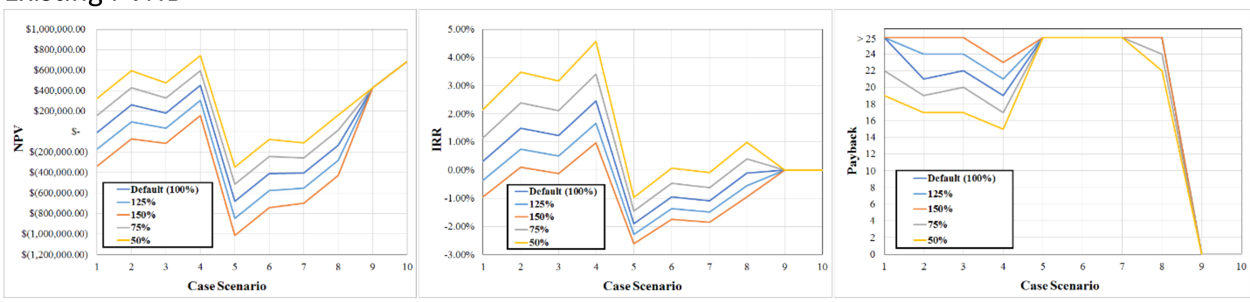


PVNB – 15

New PVNB

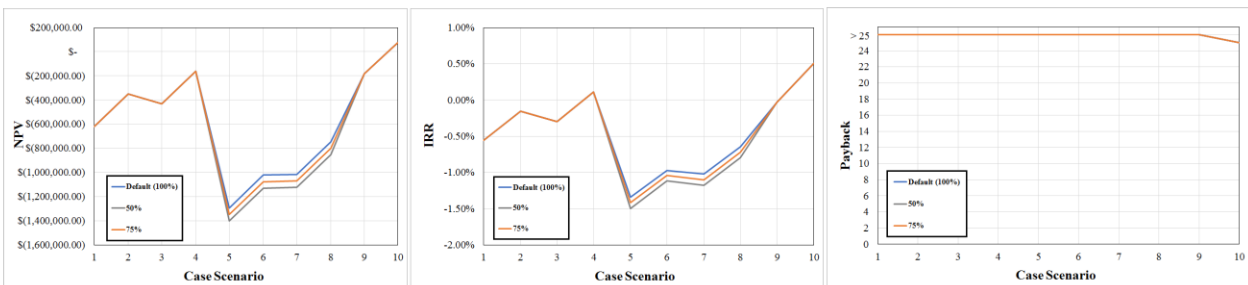


Existing PVNB



PVNB – 16

New PVNB



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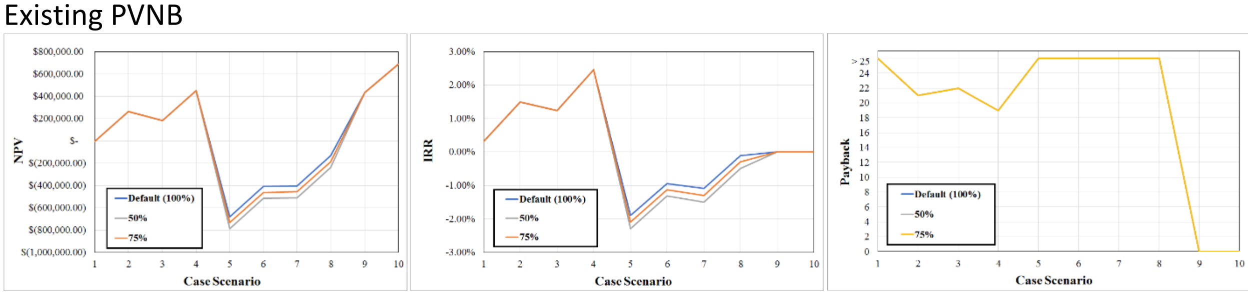
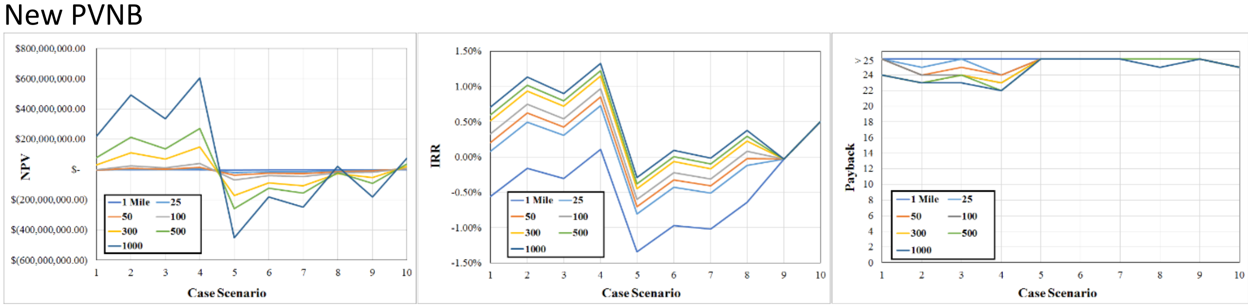
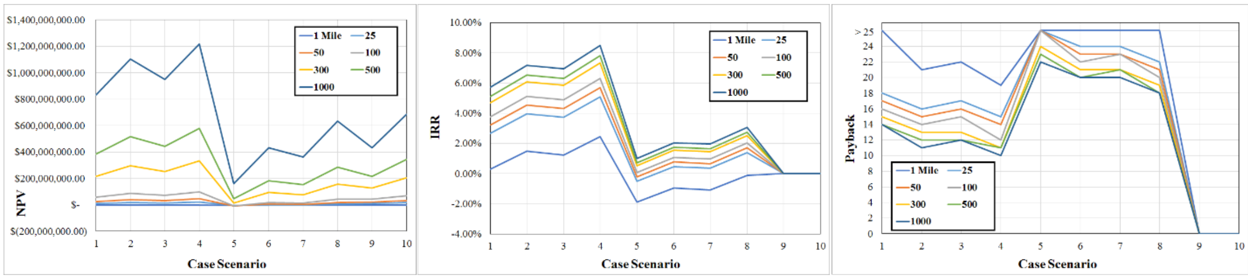


PVNB – 17

New PVNB



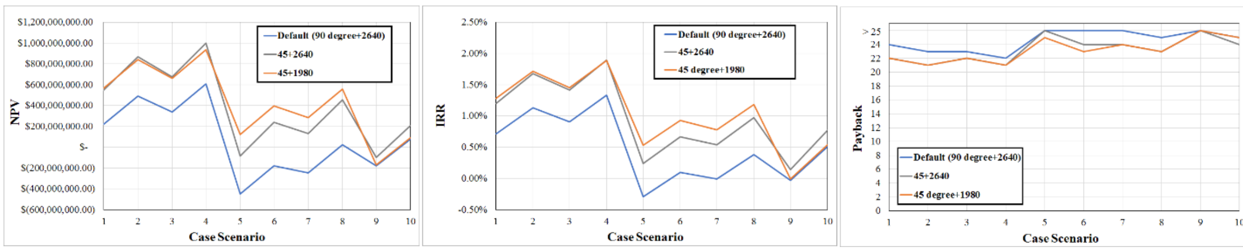
Existing PVNB



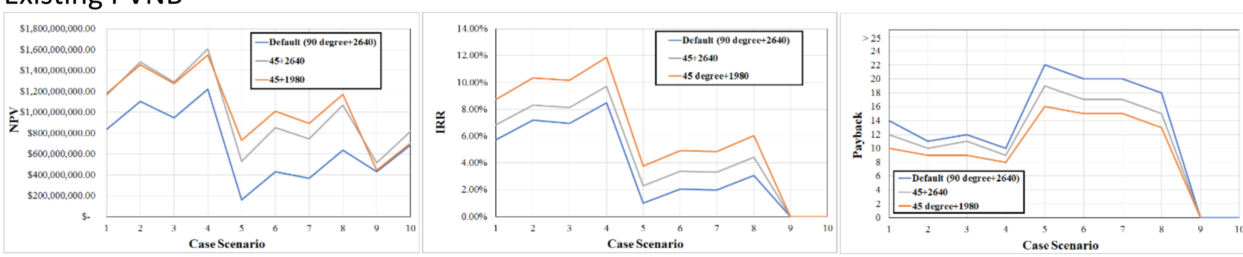
1000-Mile PVNB

PVNB – 1, 3, 4

New PVNB

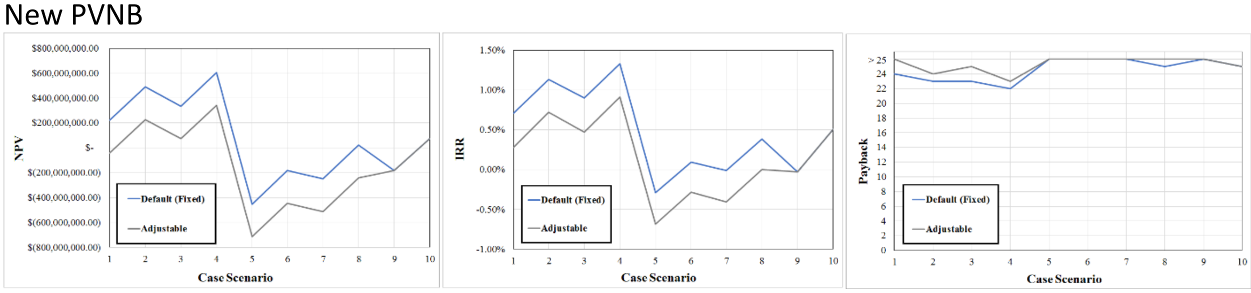


Existing PVNB

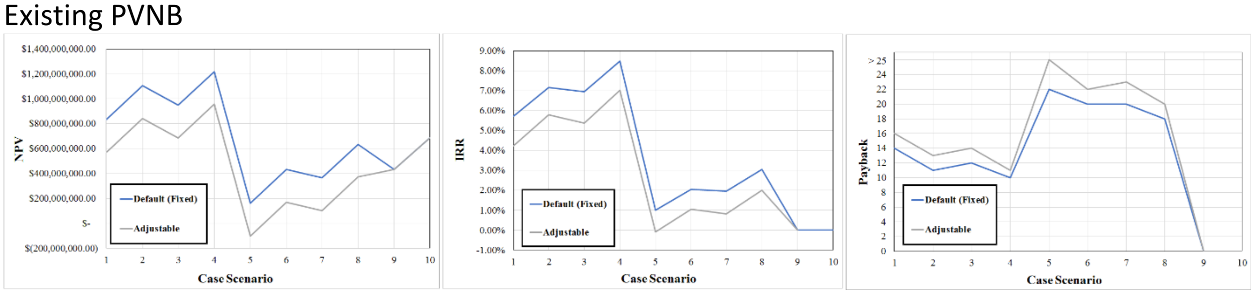


PVNB – 2

New PVNB

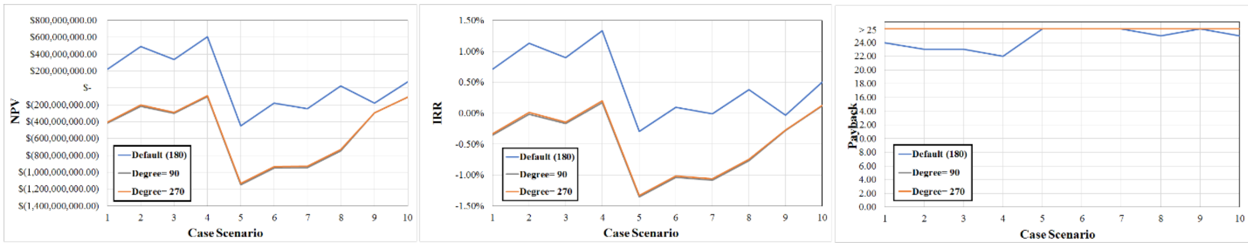


Existing PVNB

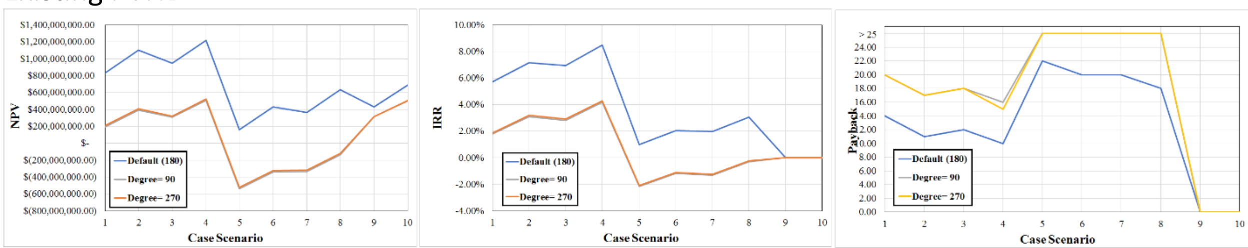


PVNB – 5

New PVNB

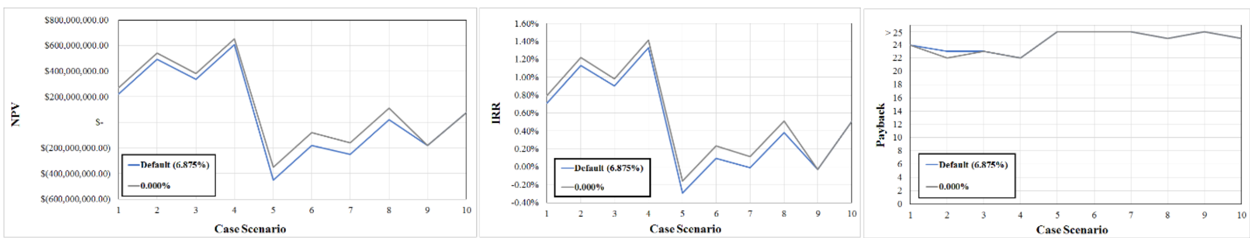


Existing PVNB

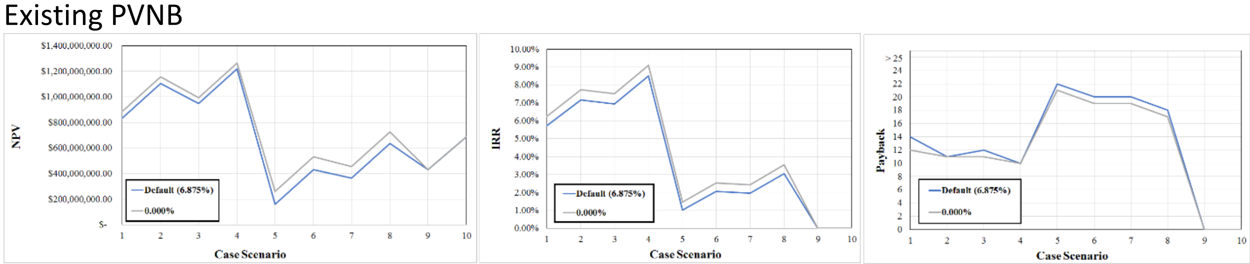


PVNB – 6

New PVNB

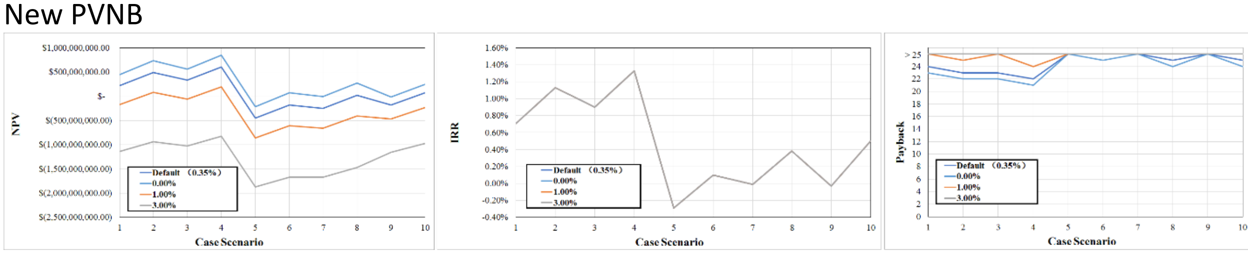


Existing PVNB

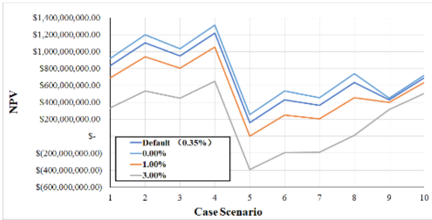


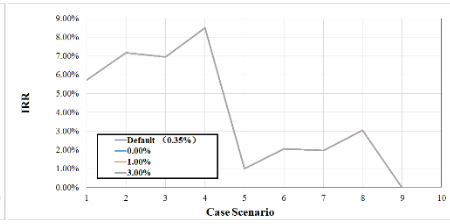
PVNB – 7

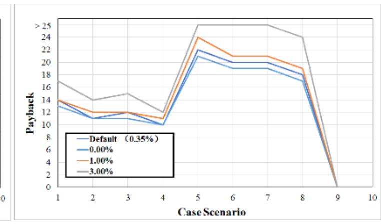
New PVNB



Existing PVNB

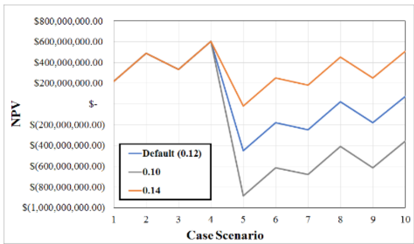


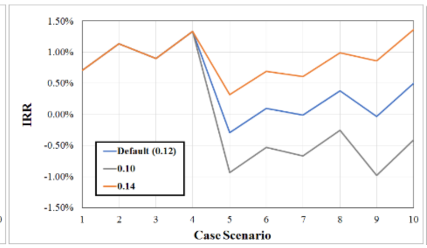


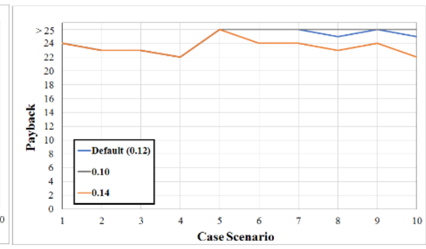


PVNB – 8

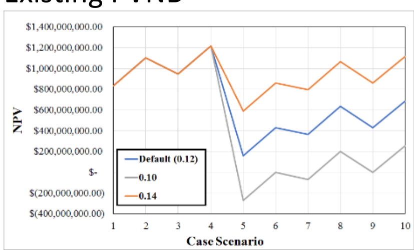
New PVNB

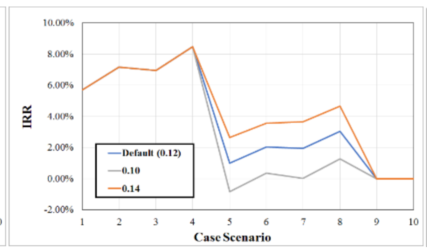


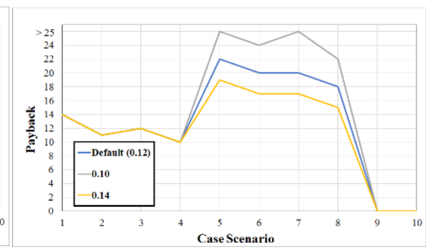




Existing PVNB

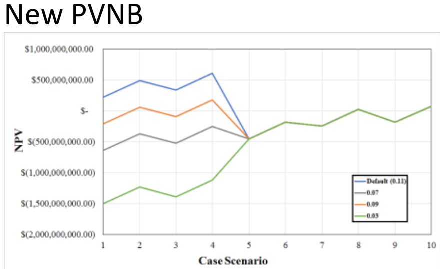


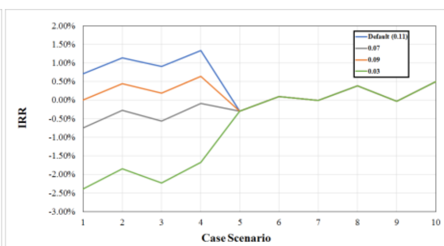


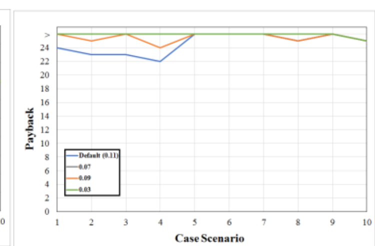


PVNB – 9

New PVNB







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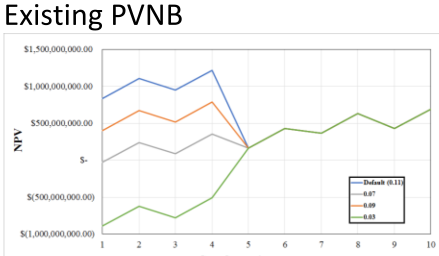
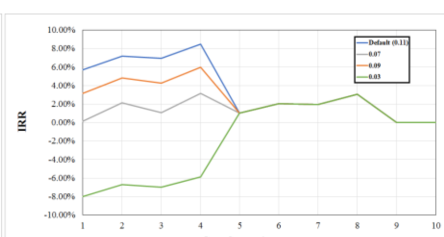
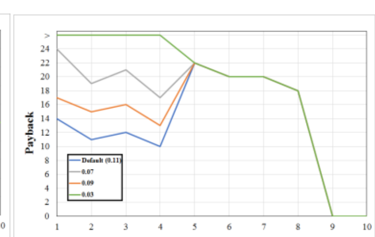
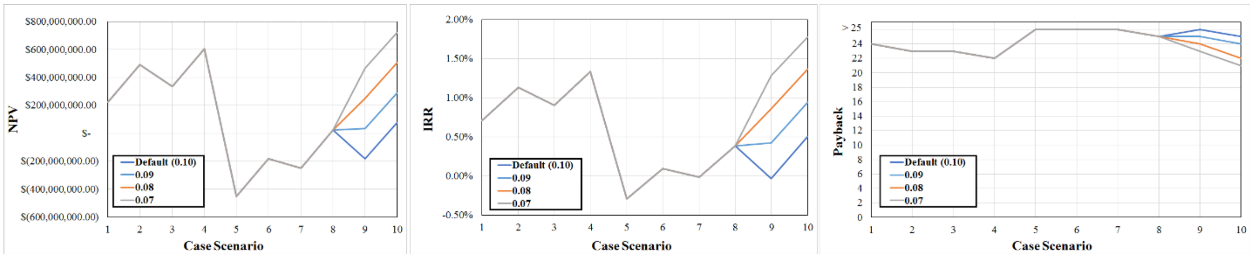






PVNB – 10

New PVNB



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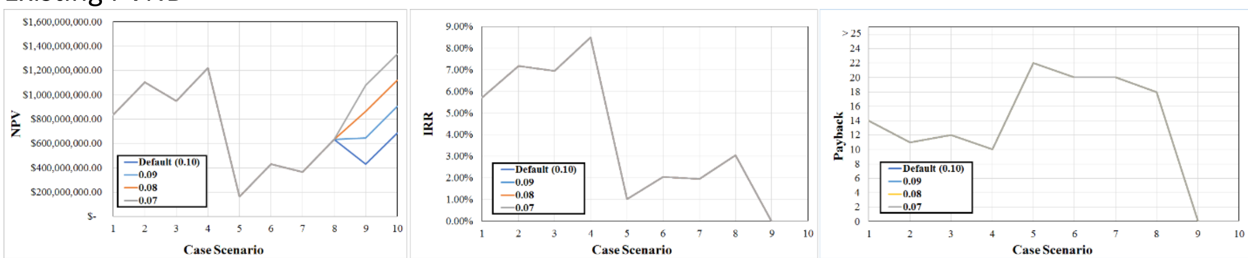

PVNB – 11

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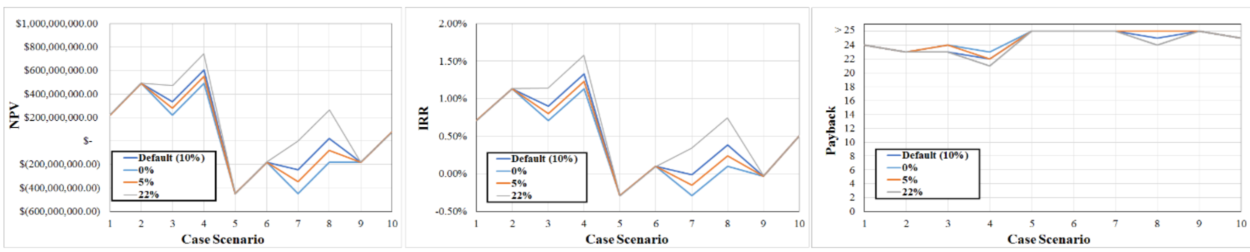
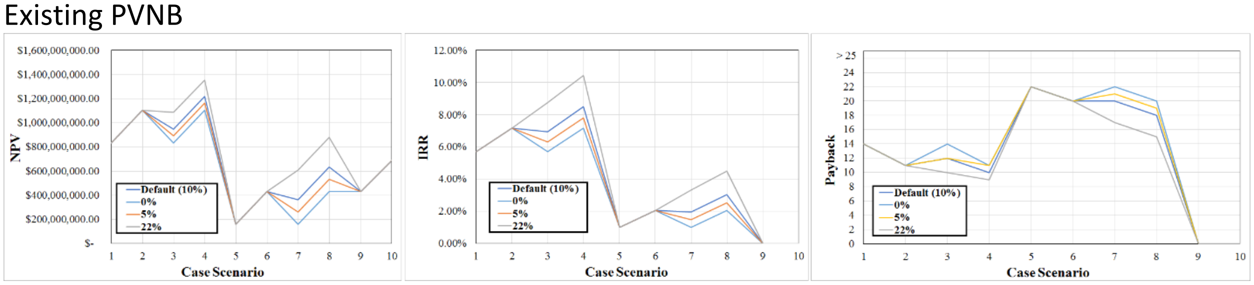
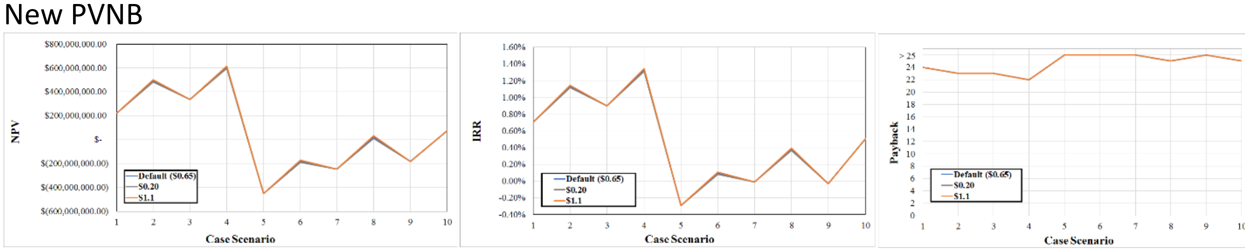


Existing PVNB

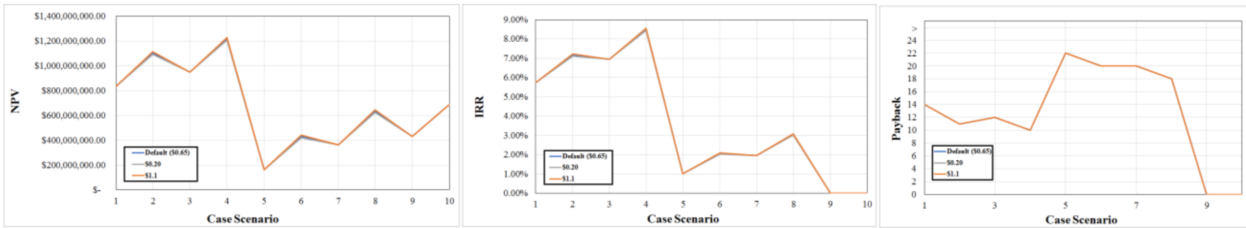


PVNB – 12

New PVNB

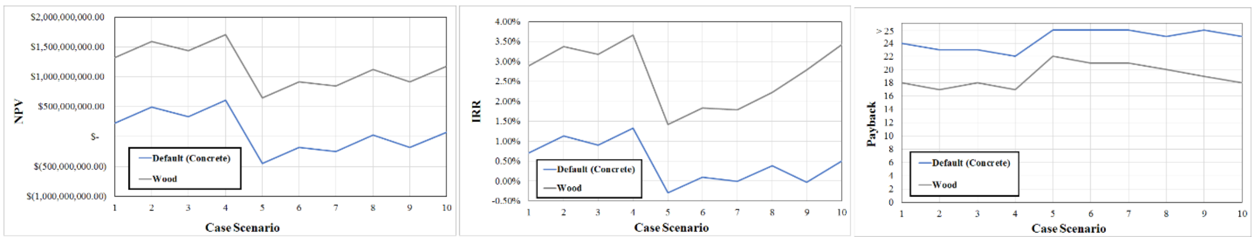


Existing PVNB



PVNB – 13

New PVNB



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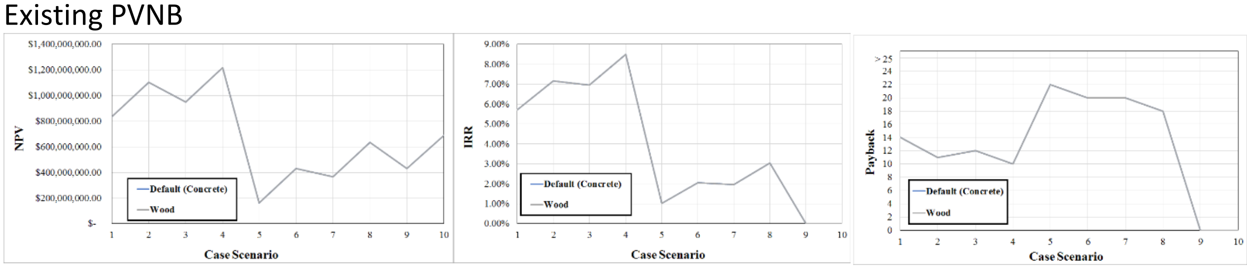
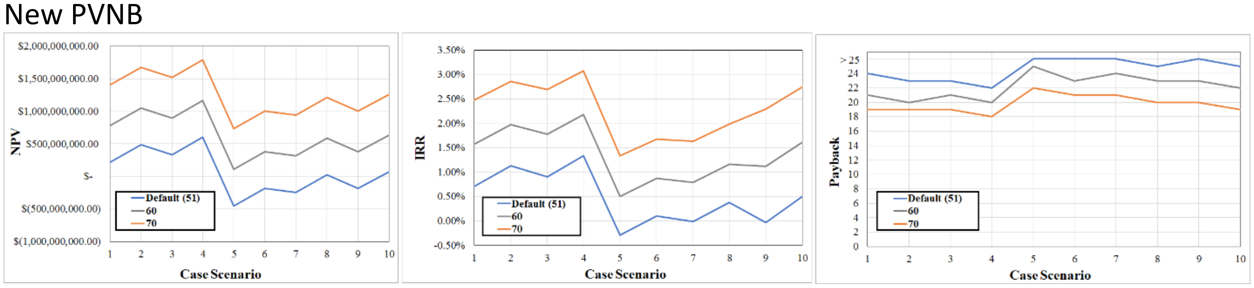


PVNB – 14

New PVNB



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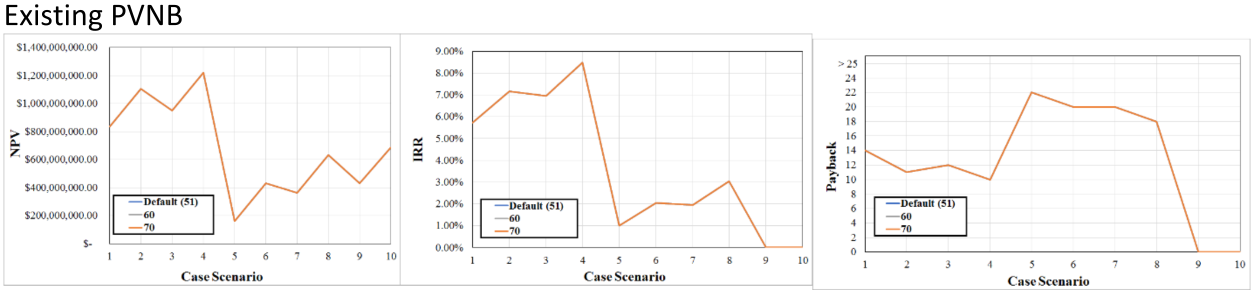

PVNB – 15

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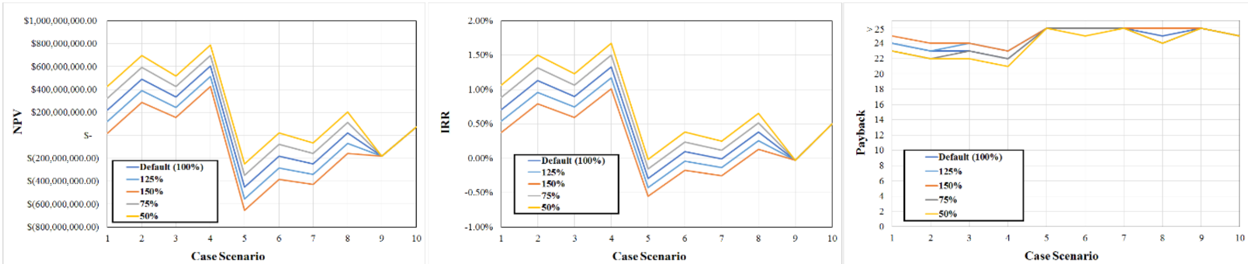

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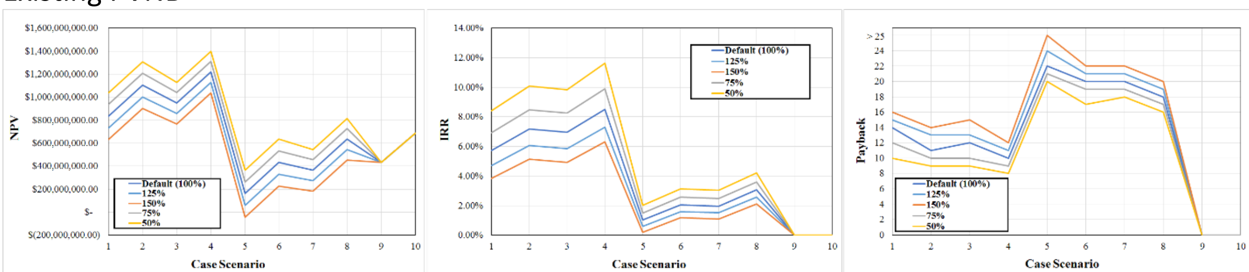
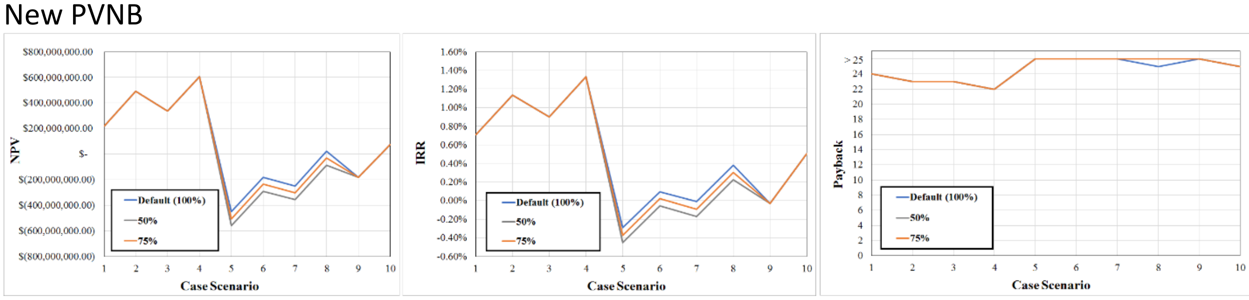


PVNB – 16

New PVNB



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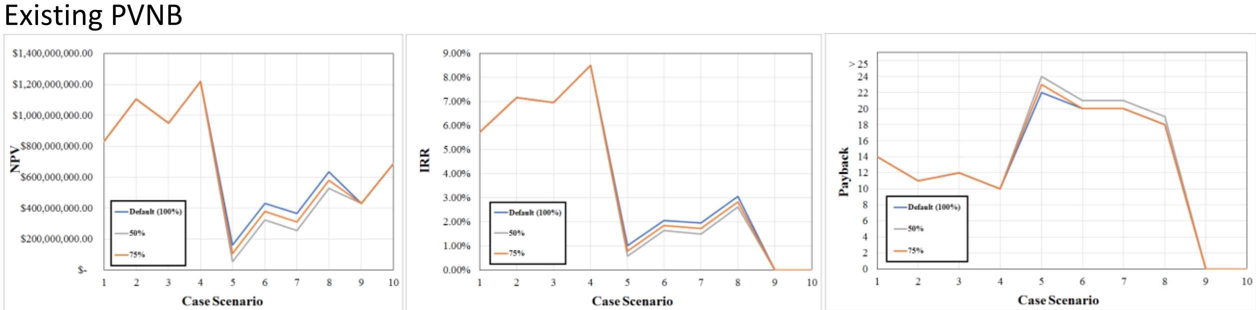
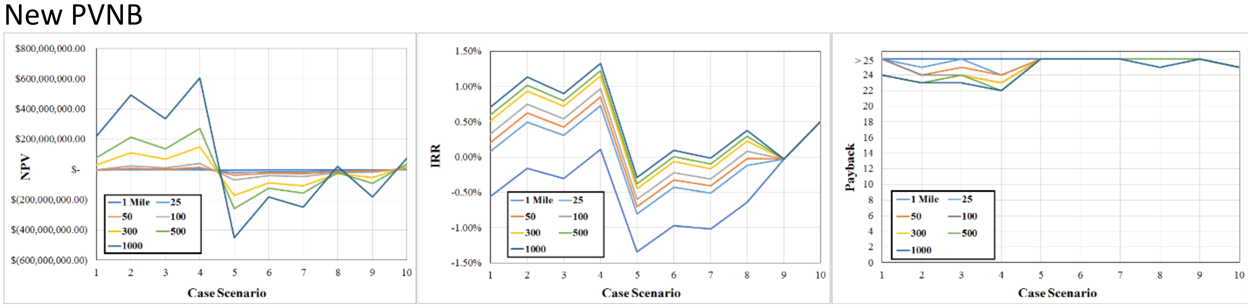


PVNB – 17

New PVNB



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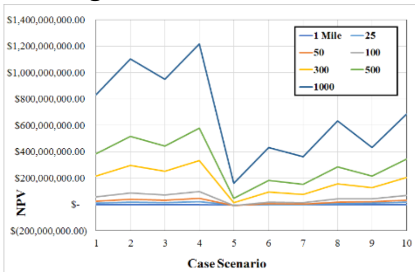
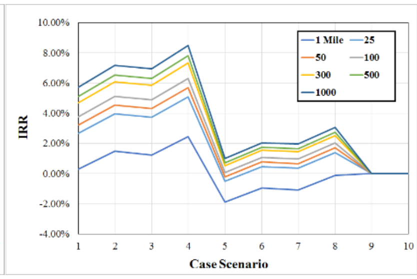
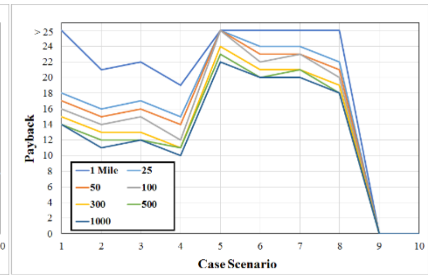




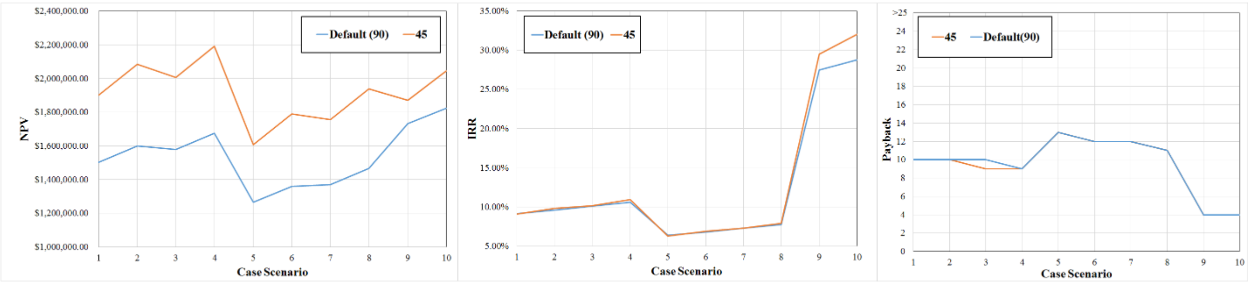


APPENDIX F: SENSITIVITY ANALYSIS RESULTS FOR PVSF

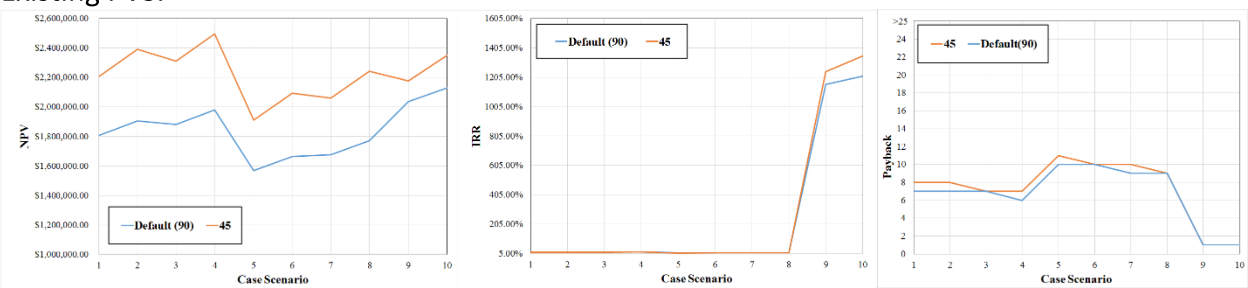
1-Mile PVSF

PVSF – 1,2

New PVSF

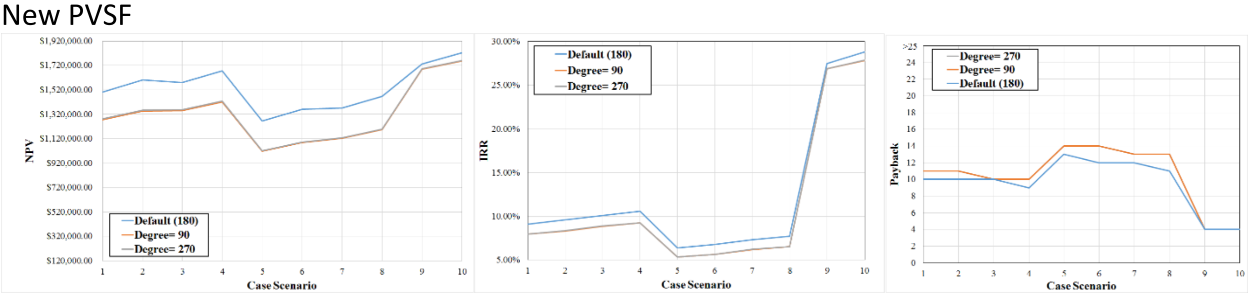


Existing PVSF

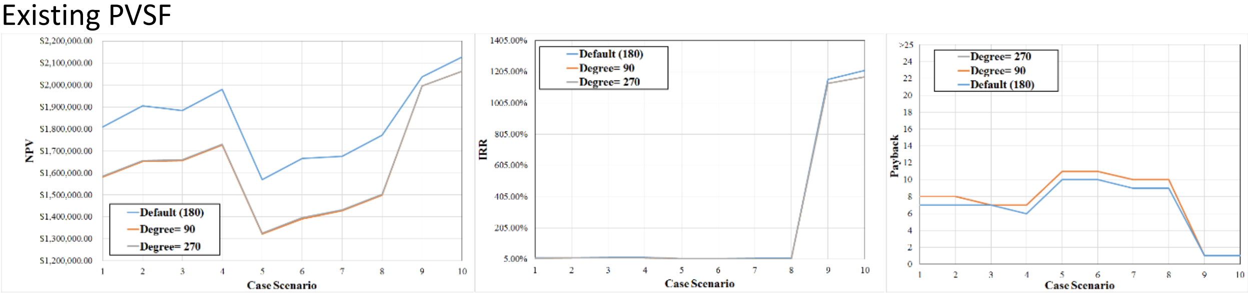


PVSF – 3

New PVSF

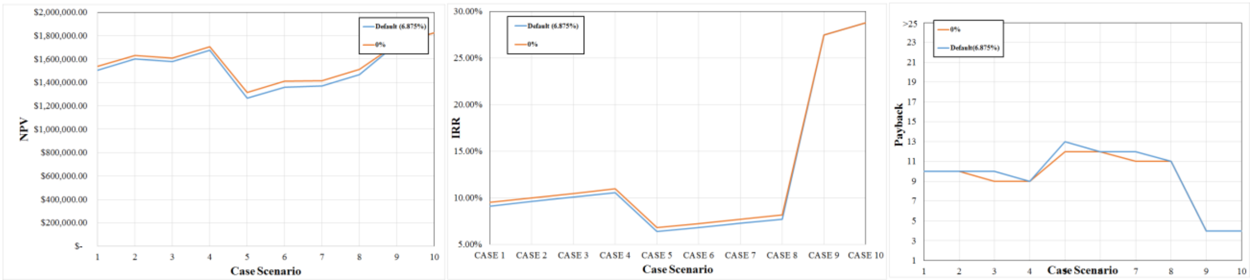


Existing PVSF

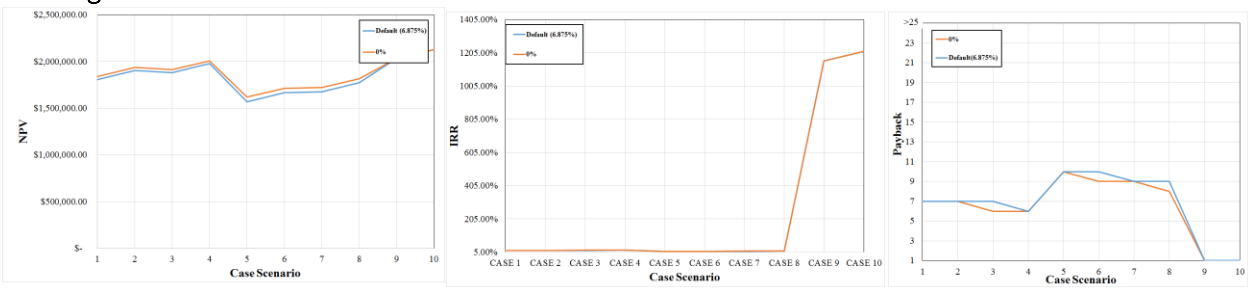


PVSF – 4

New PVSF

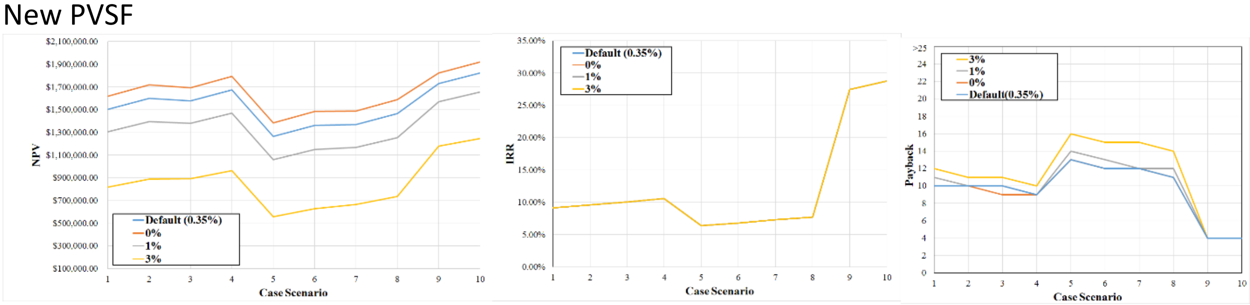


Existing PVSF

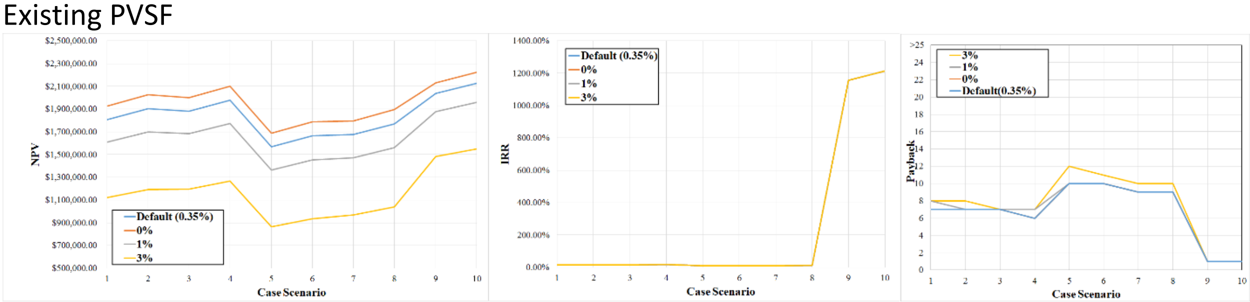


PVSF – 5

New PVSF

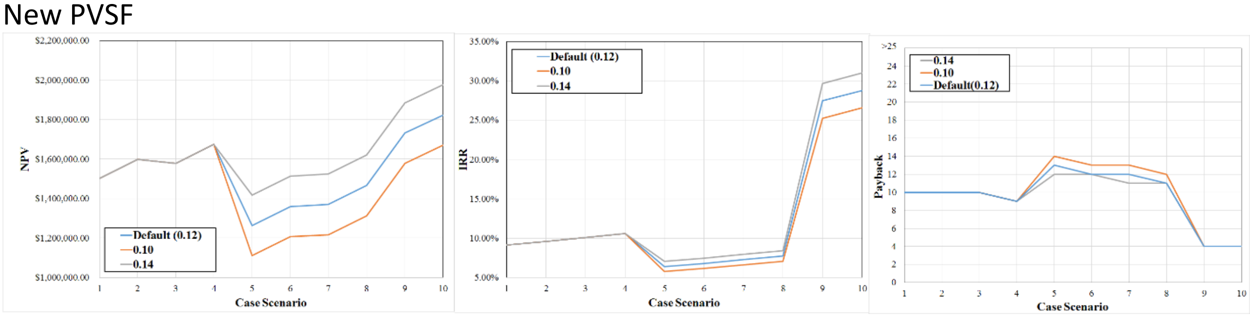


Existing PVSF

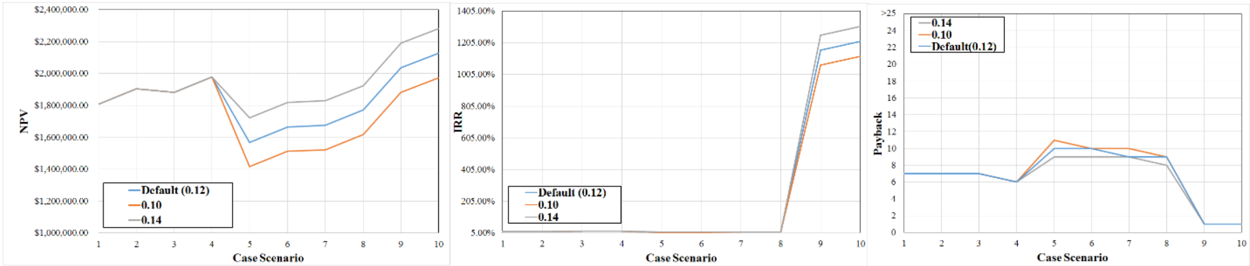


PVSF – 6

New PVSF

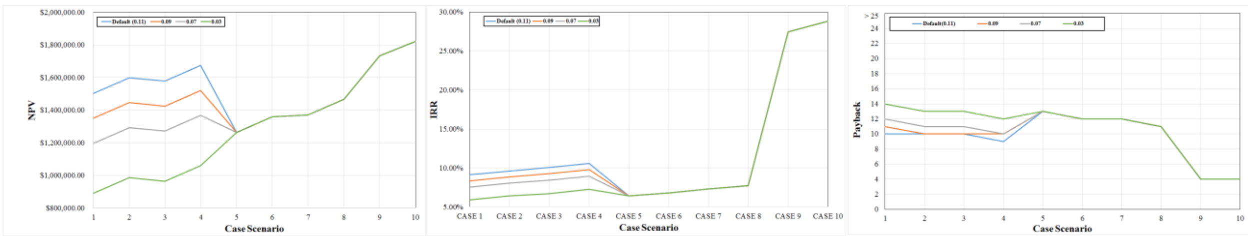


Existing PVSF

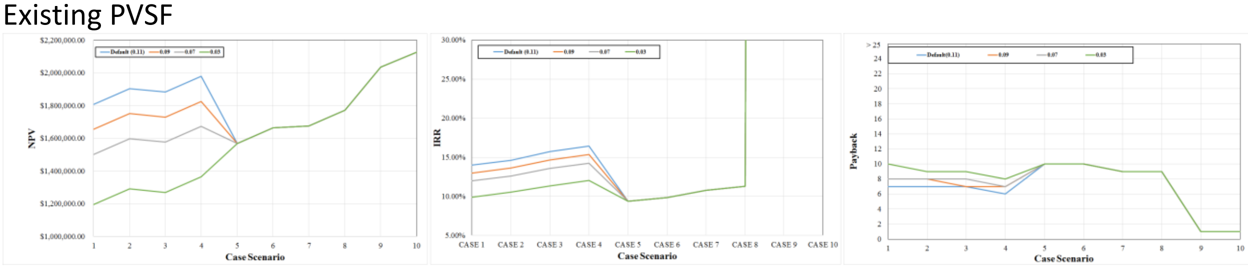


PVSF – 7

New PVSF

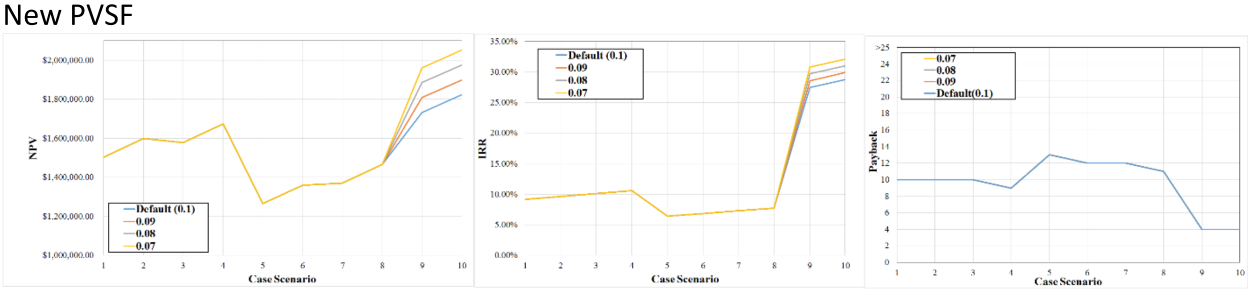


Existing PVSF

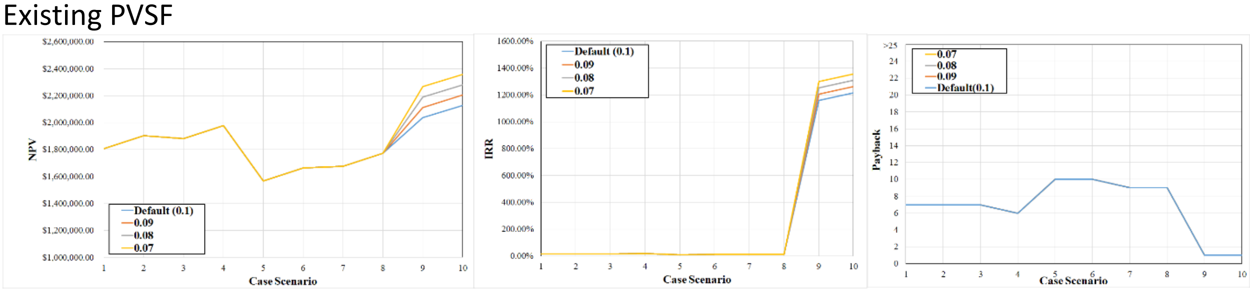


PVSF – 8

New PVSF

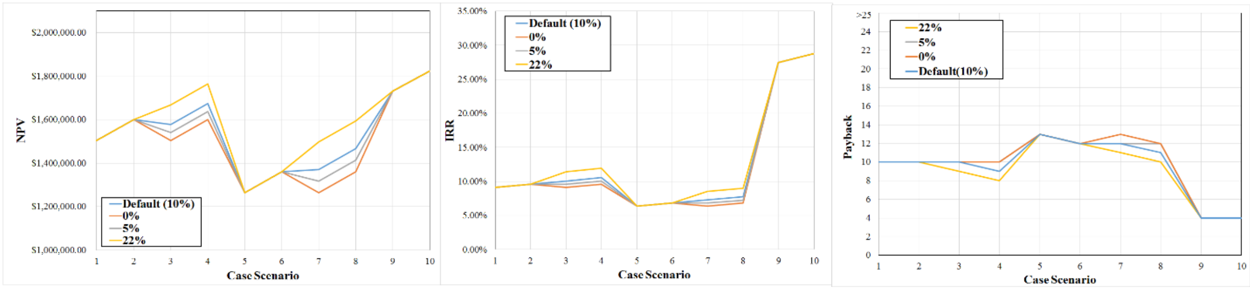


Existing PVSF

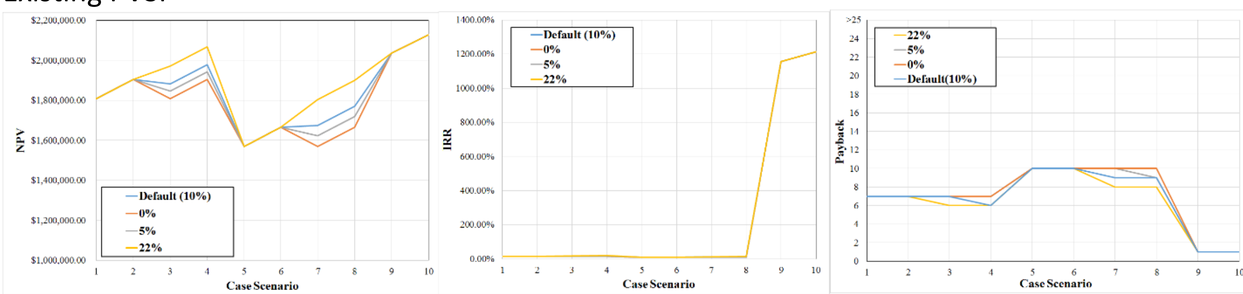


PVSF – 9

New PVSF

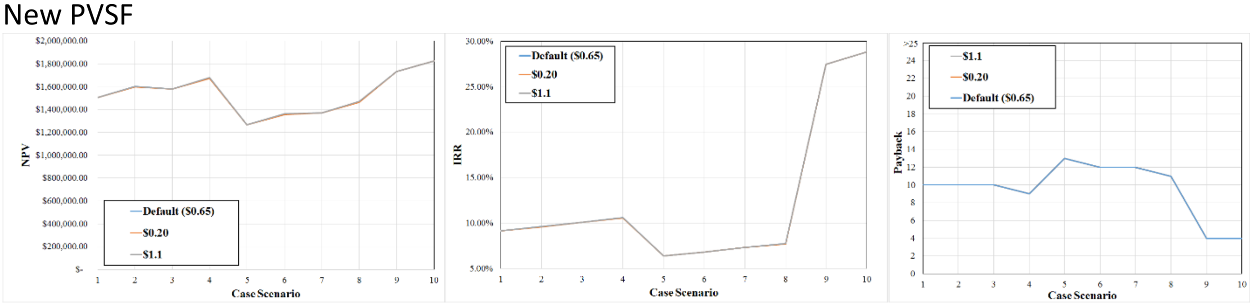


Existing PVSF

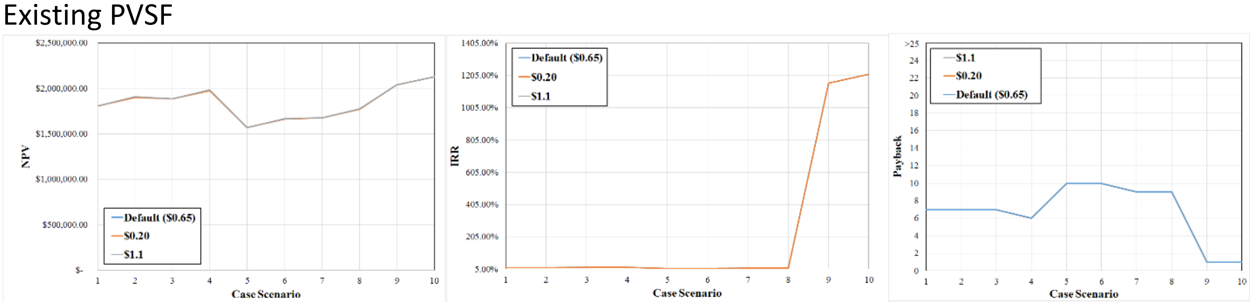


PVSF – 10

New PVSF

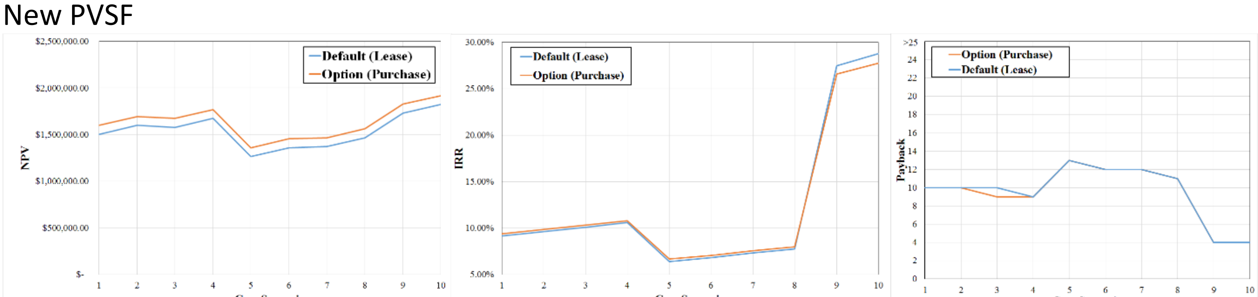


Existing PVSF

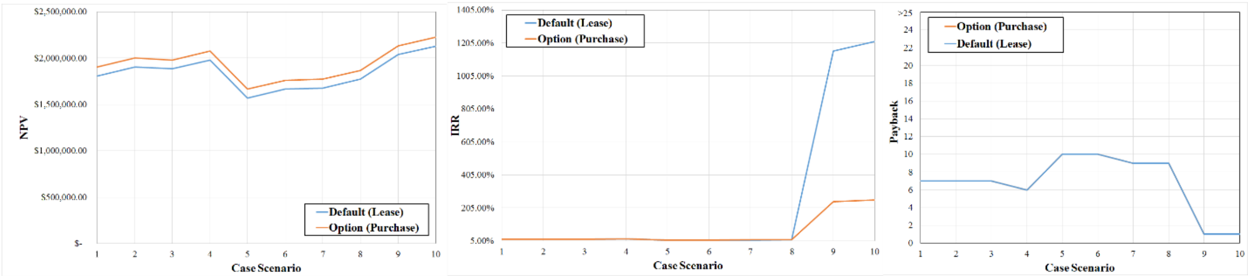


PVSF – 11

New PVSF

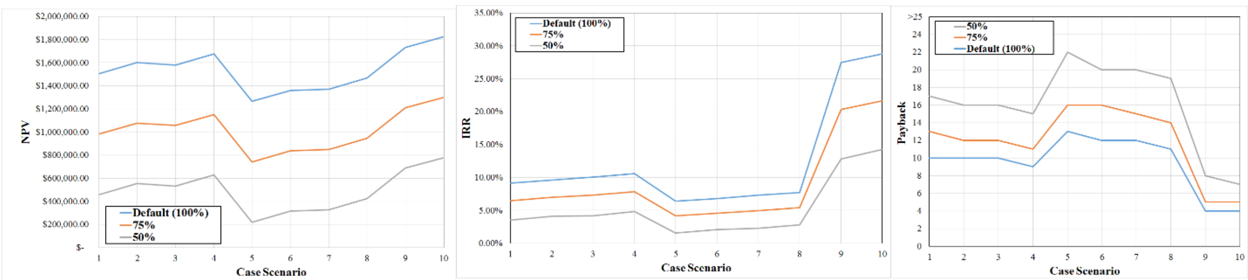


Existing PVSF

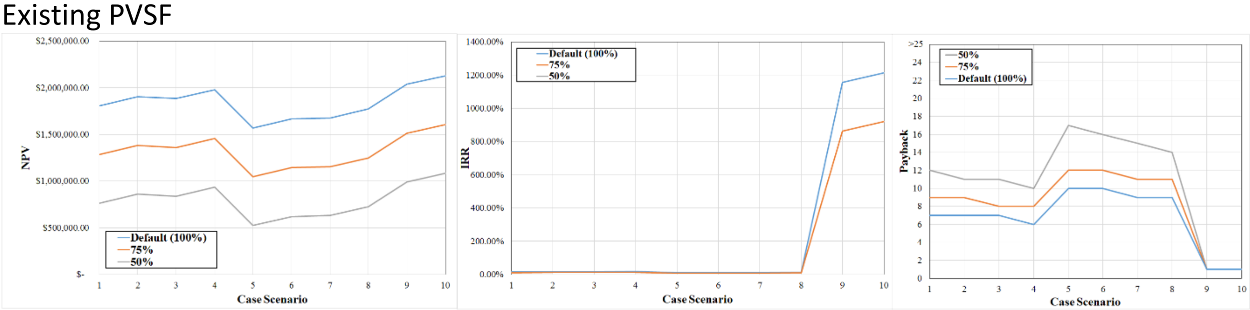


PVSF – 12

New PVSF

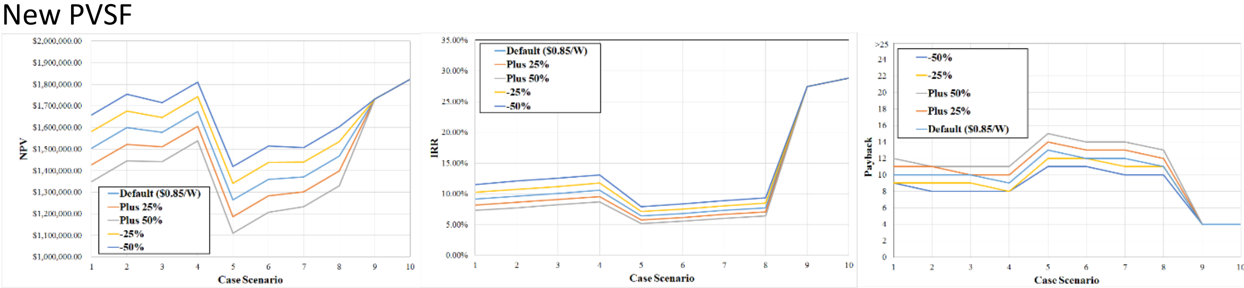


Existing PVSF

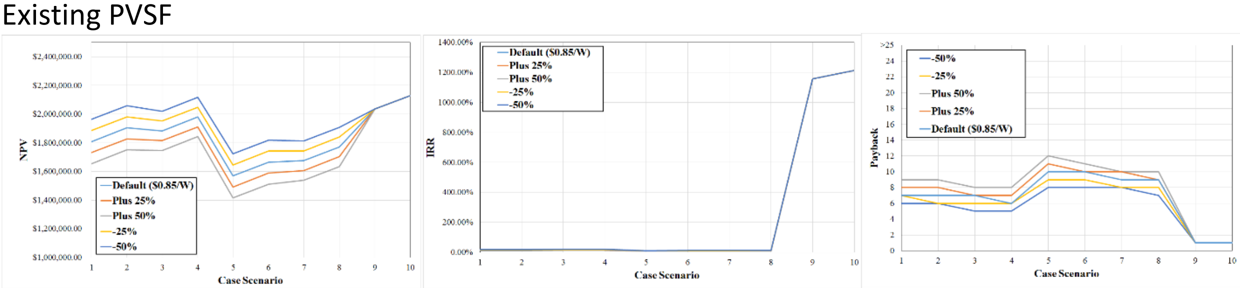


PVSF – 13

New PVSF

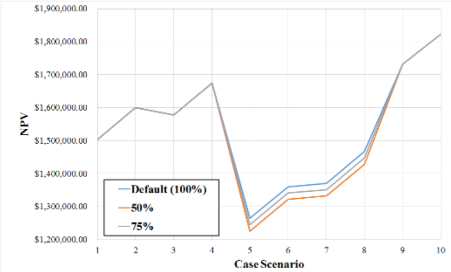


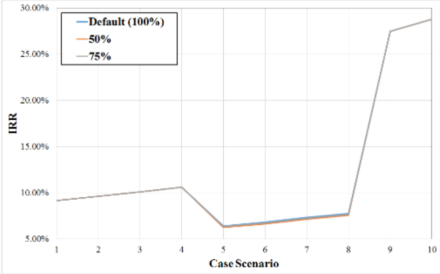
Existing PVSF

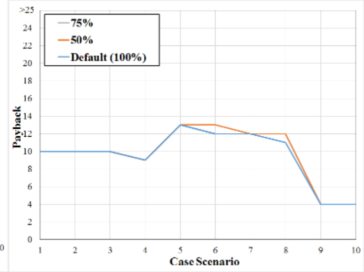


PVSF – 14

New PVSF







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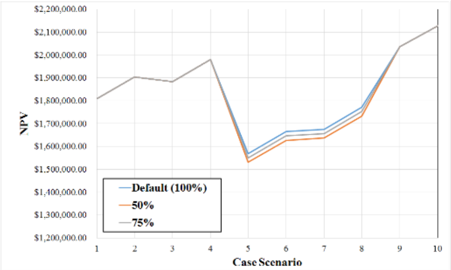

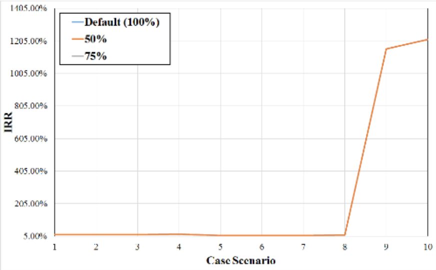

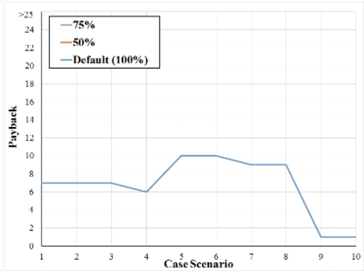

PVSF – 15

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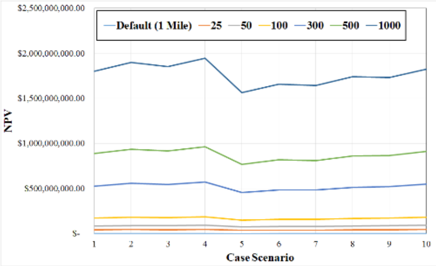

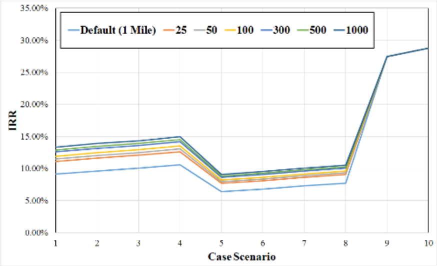

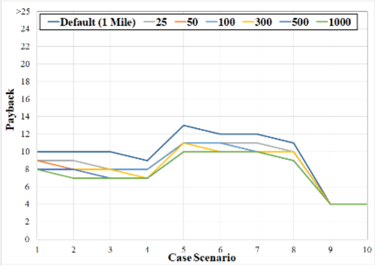

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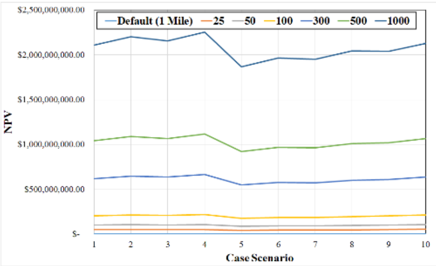

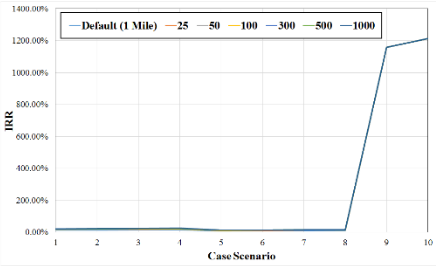

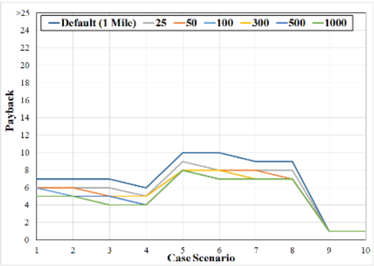

1000-Mile PVSF

PVSF – 1,2

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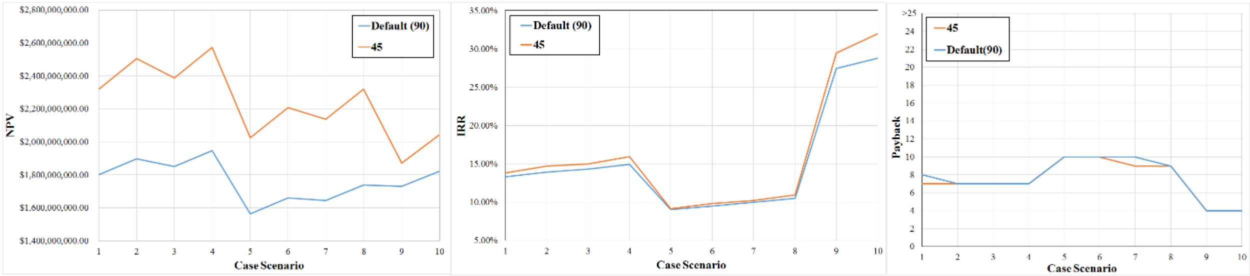

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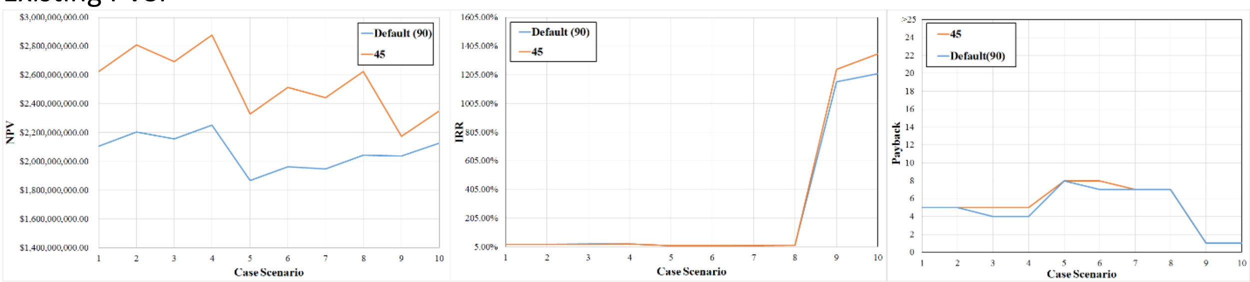

PVSF – 3

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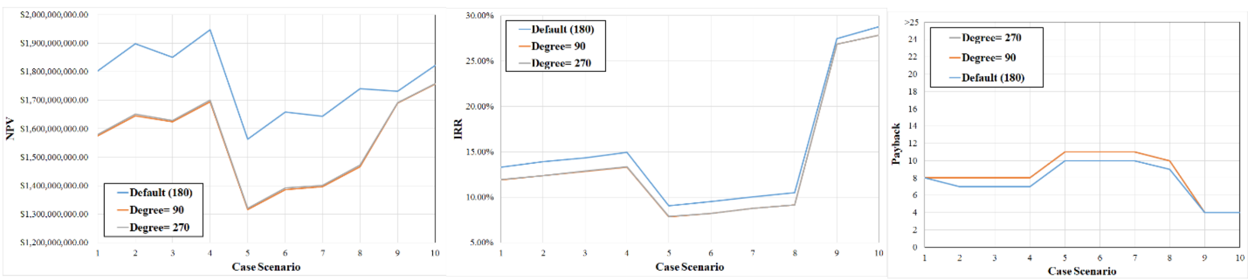

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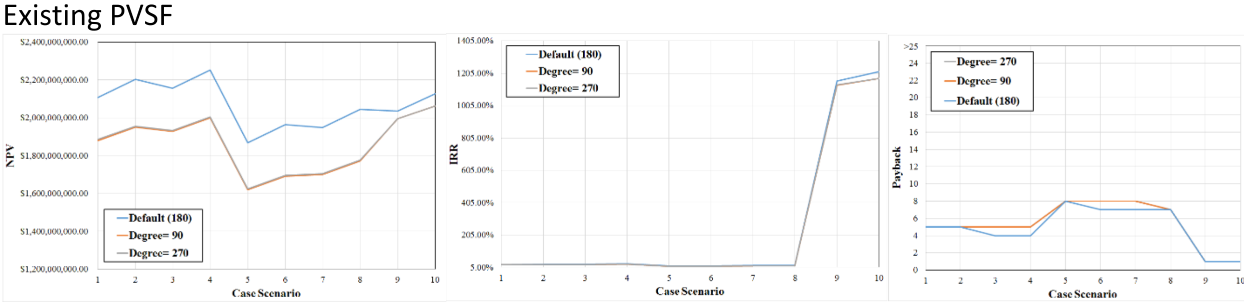

PVSF – 4

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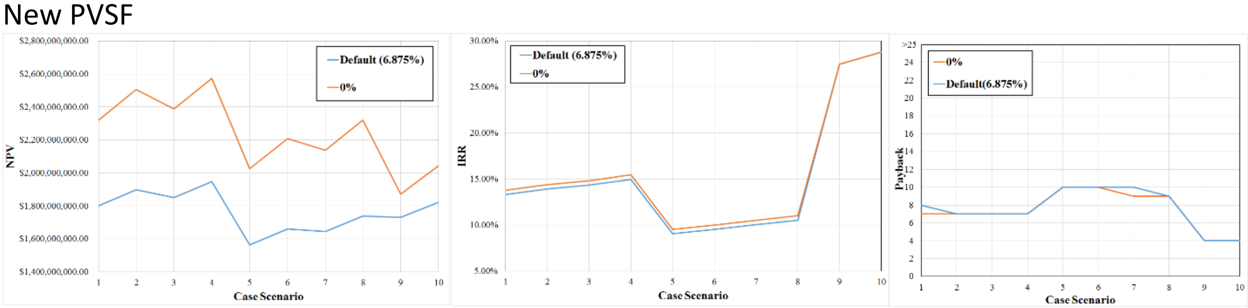

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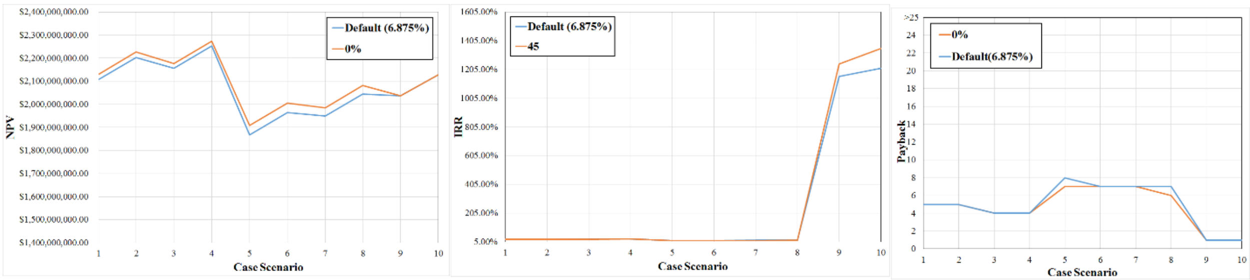

PVSF – 5

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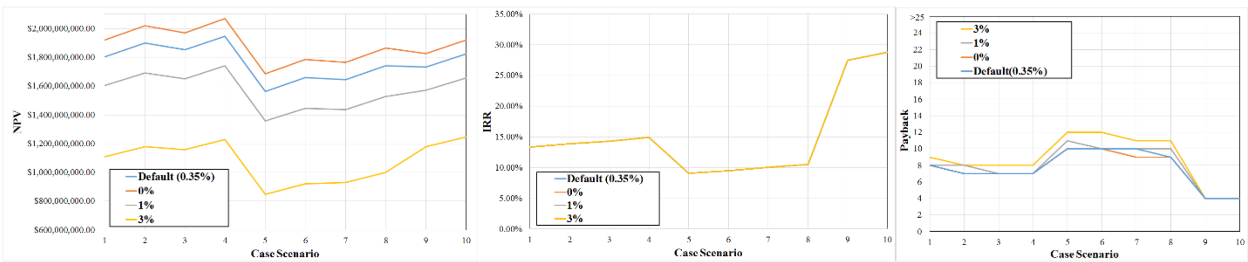

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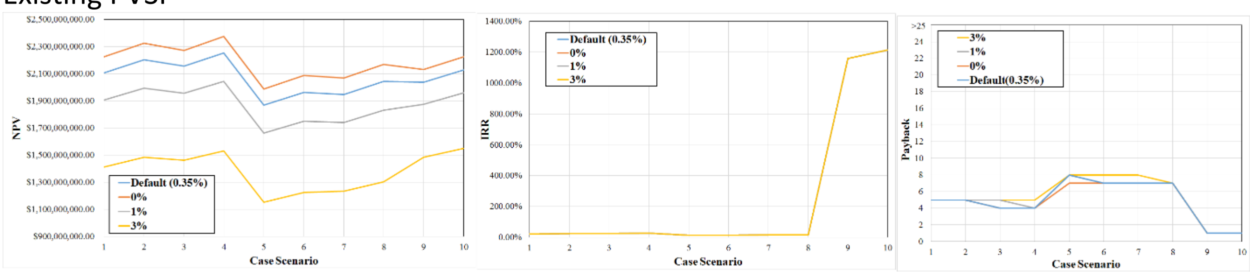

PVSF – 6

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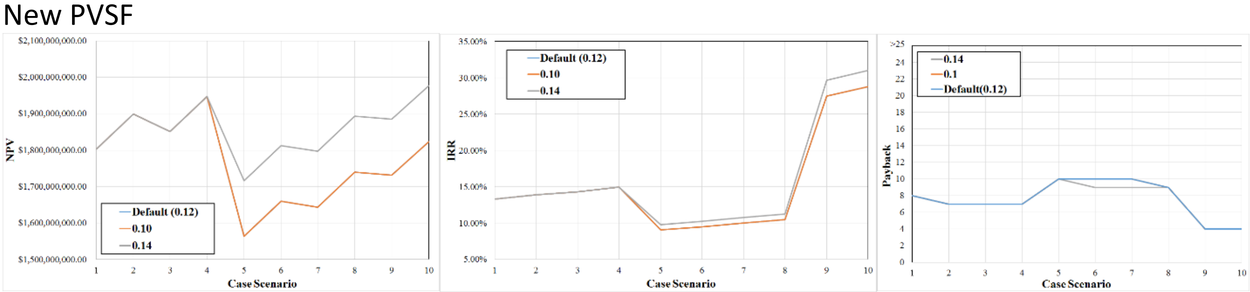

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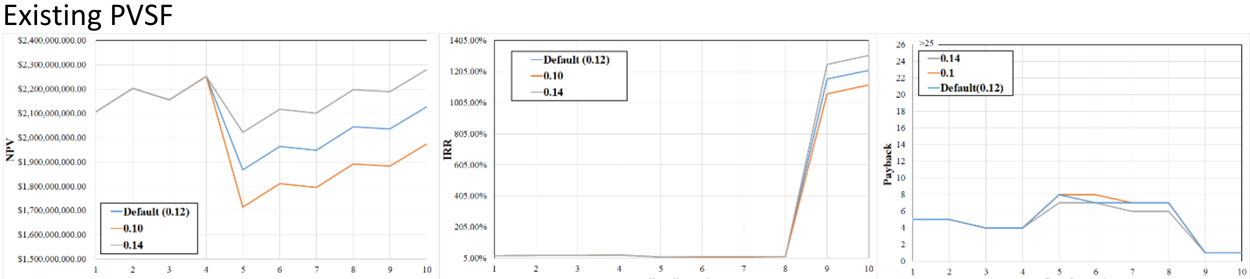

PVSF – 7

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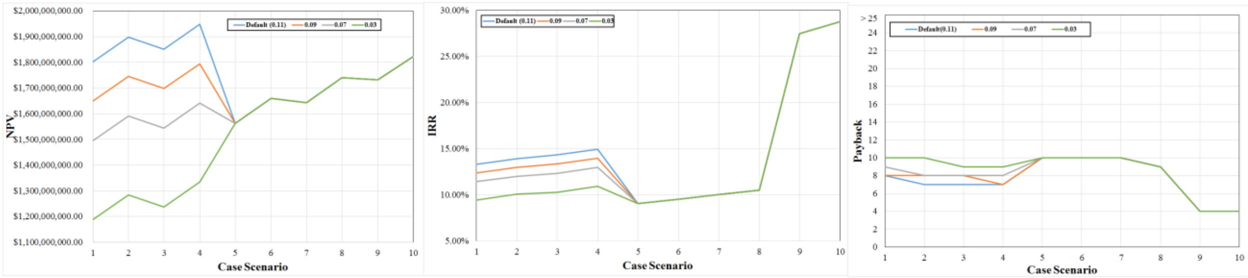

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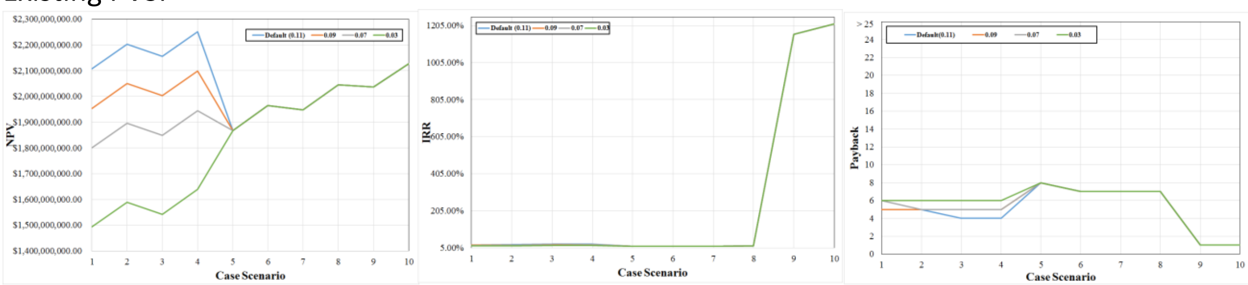

PVSF – 8

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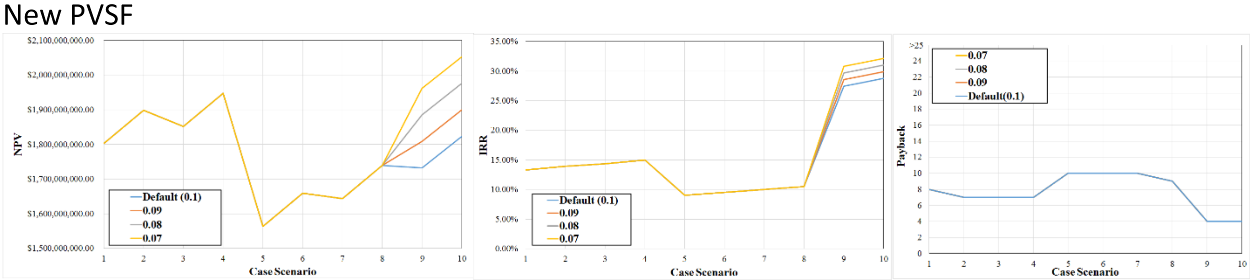

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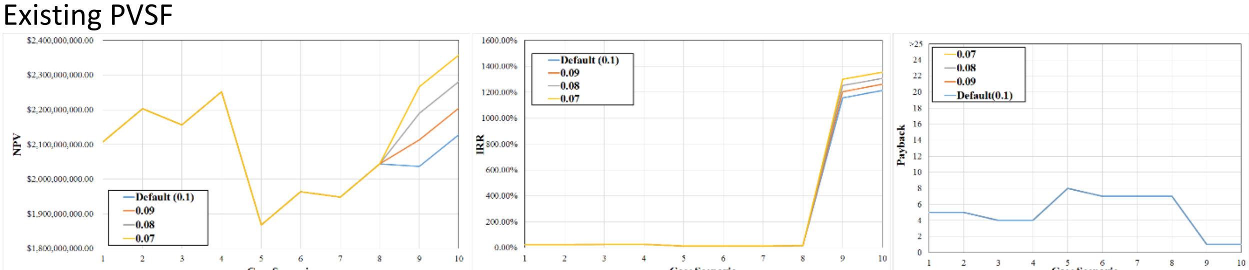

PVSF – 9

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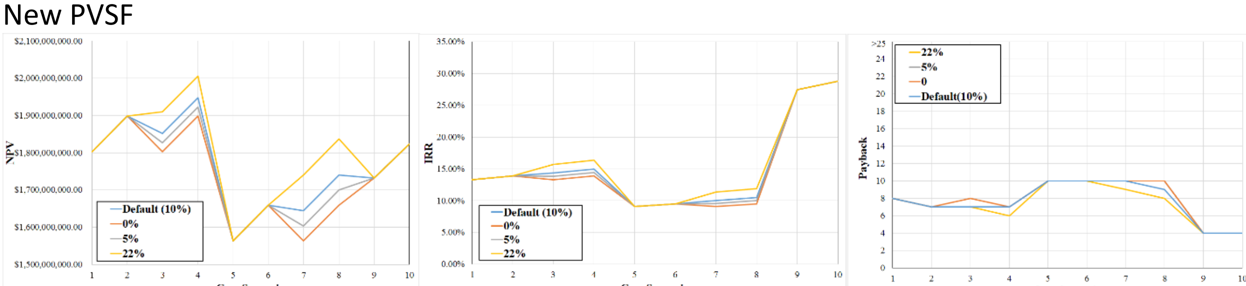

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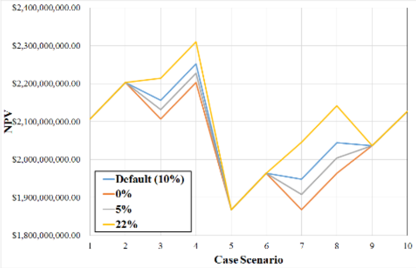

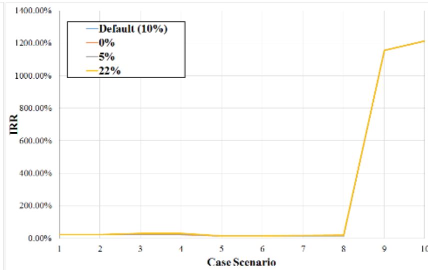

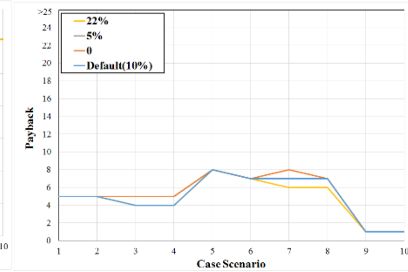

PVSF – 10

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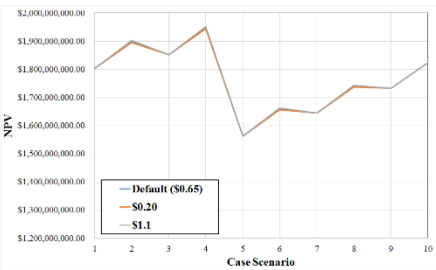

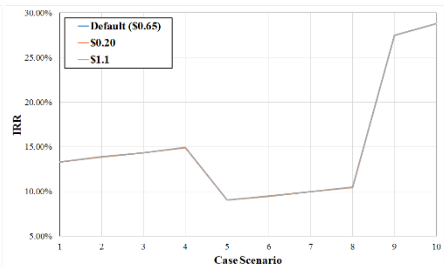

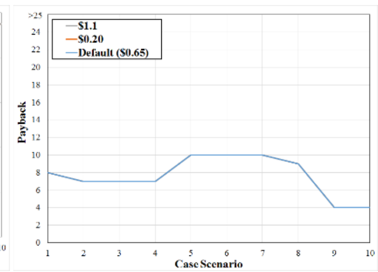

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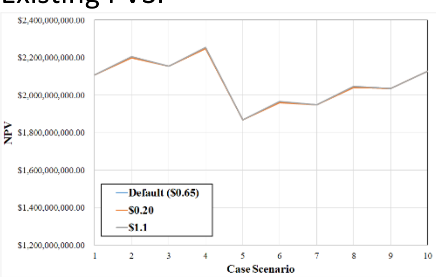

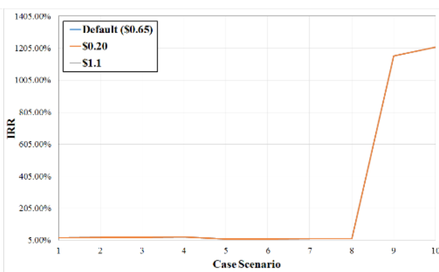

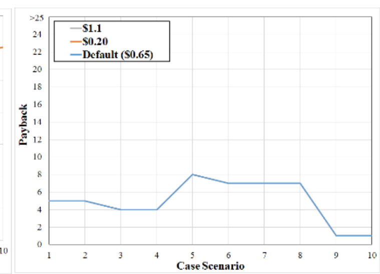

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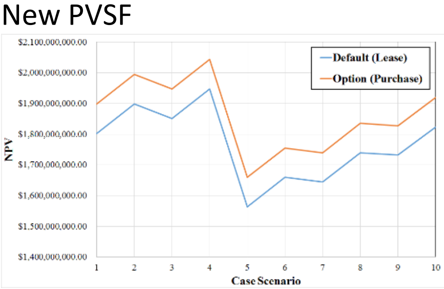

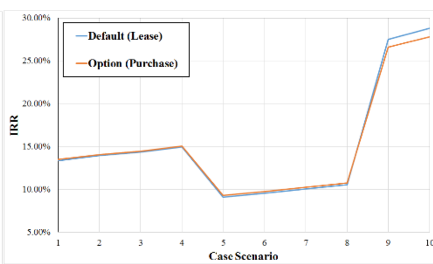

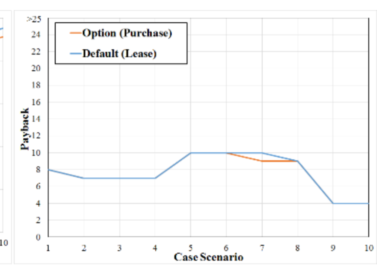

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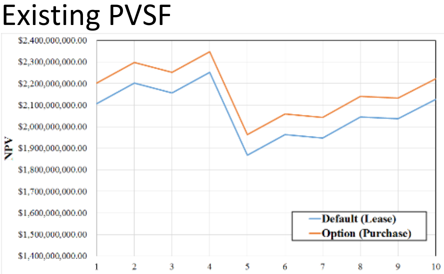

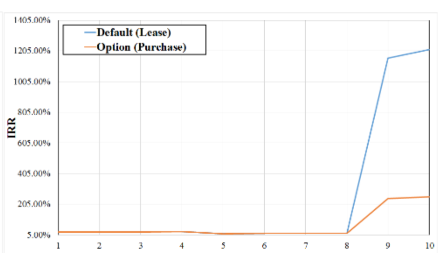

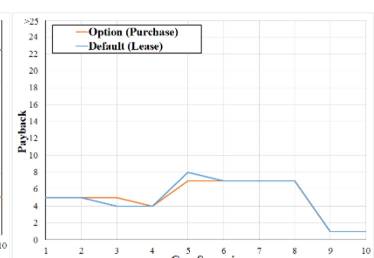

PVSF – 12

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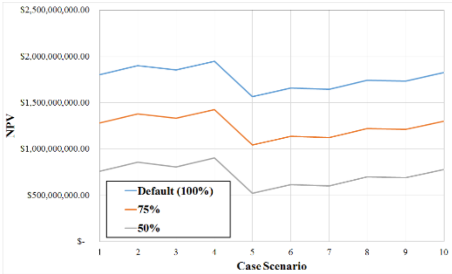

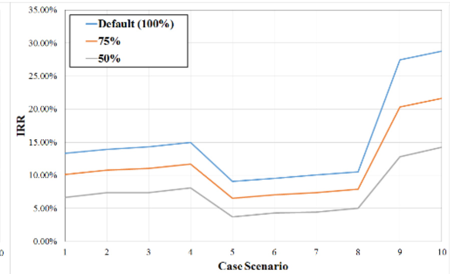

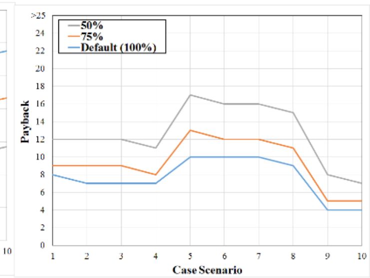

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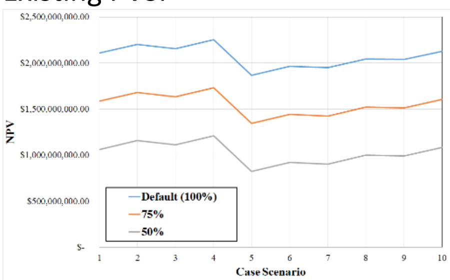

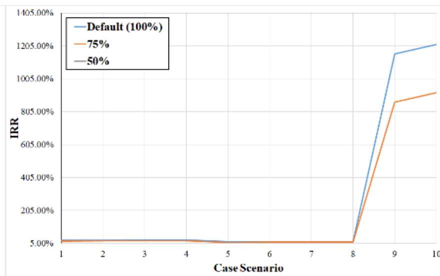

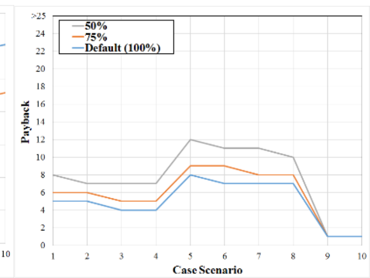

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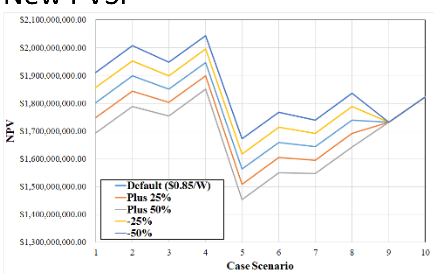

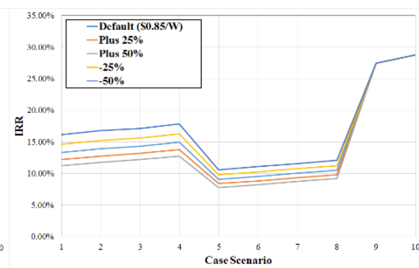

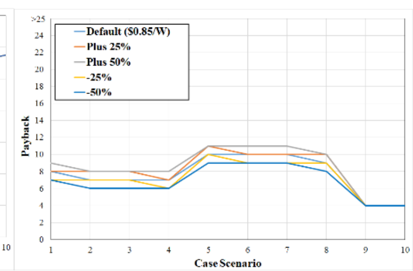

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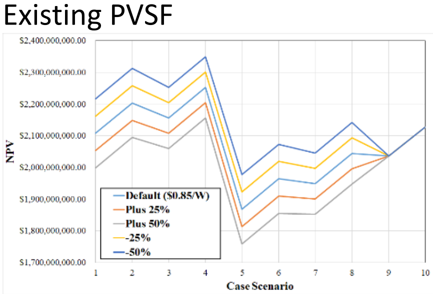

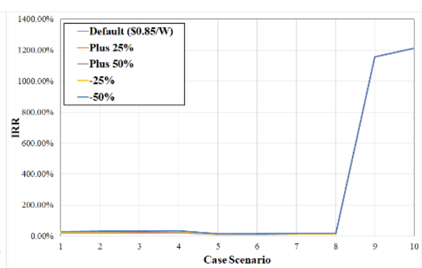

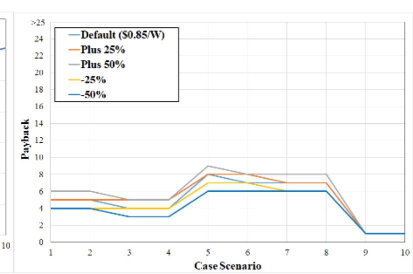

PVSF – 14

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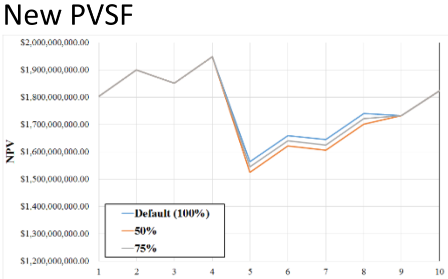

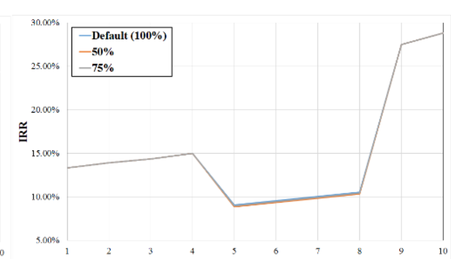

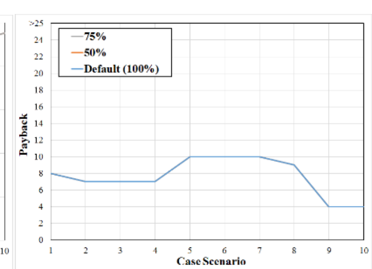

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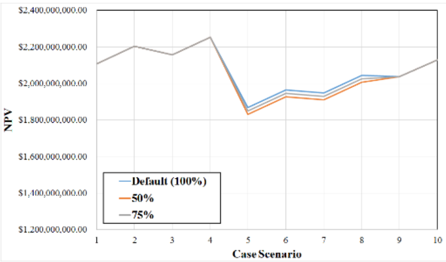

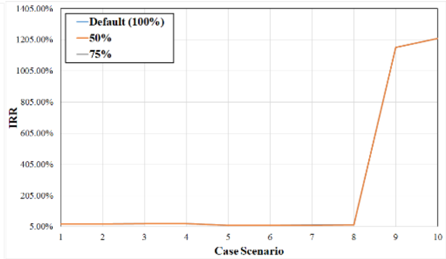

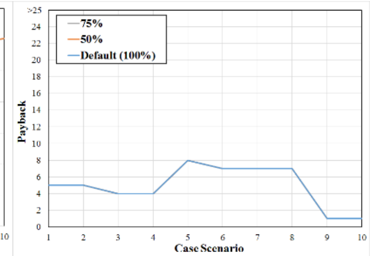

PVSF – 15

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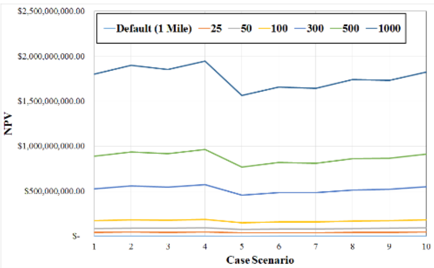

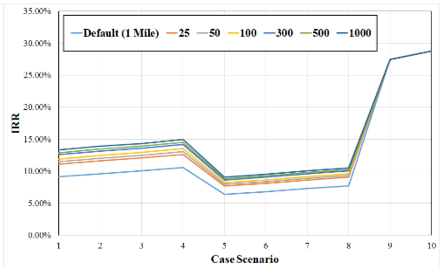

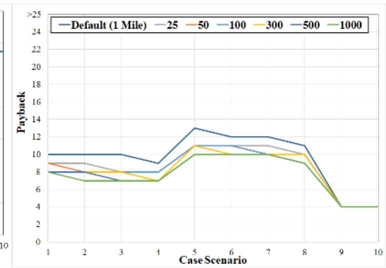

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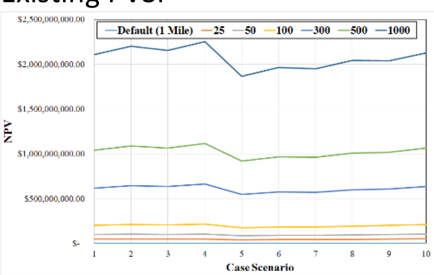

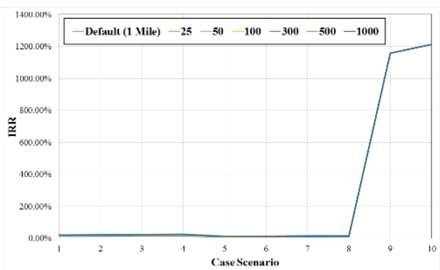

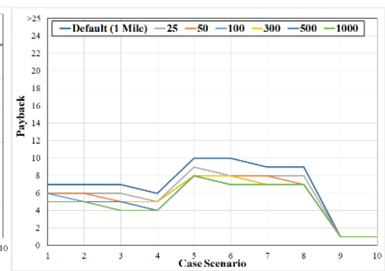

APPENDIX G: ARITHMETIC MEANS OF SENSITIVITY ANALYSIS RESULTS

CASE 1	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ (70,669.20)	0.24%	>25	$ (1,731,938.64)	$ 510,558.11	-4.51%	2.91%	18	>25
1 Mile PVNB (New)	$ (641,356.15)	-0.55%	>25	$ (2,344,421.15)	$ 569,003.84	-3.53%	1.17%	23	>25
PV for 1,000 Mile NB (New)	$ 765,577,675.76	5.51%	14	$ (891,308,918.73)	$1,178,215,694.81	0.12%	8.72%	10	>25
1,000 Mile PVNB (New)	$ 194,890,728.16	0.72%	24	$(1,503,791,427.40)	$1,409,633,561.83	-2.39%	2.90%	18	>25
PV for 1 Mile NB (Existing)	$ (70,669.20)	0.24%	>25	$ (1,731,938.64)	$ 510,558.11	-4.51%	2.91%	18	>25
1 Mile PVNB (Existing)	$ (70,669.20)	0.24%	>25	$ (1,731,938.64)	$ 510,558.11	-4.51%	2.91%	18	>25
PV for 1,000 Mile NB (Existing)	$ 765,577,675.76	5.51%	14	$ (891,308,918.73)	$1,178,215,694.81	0.12%	8.72%	10	>25
1,000 Mile PVNB (Existing)	$ 765,577,675.76	5.51%	14	$ (891,308,918.73)	$1,178,215,694.81	0.12%	8.72%	10	>25
PV for 1 Mile SF (New)	$ (102,985.12)	-0.67%	>25	$ (688,403.70)	$ 323,608.76	-4.95%	2.72%	19	>25
1 Mile PVSF (New)	$ 1,430,167.83	8.80%	11	$ 459,321.81	$ 1,902,199.34	3.49%	11.53%	9	17
PV for 1,000 Mile SF (New)	$ 198,023,728.03	3.56%	17	$ (389,468,924.21)	$ 742,117,450.04	-1.21%	7.73%	11	>25
1,000 Mile PVSF (New)	$1,731,176,681.40	12.95%	8	$ 758,256,590.33	$2,320,708,027.95	6.68%	16.12%	7	12
PV for 1 Mile SF (Existing)	$ 1,734,887.19	13.36%	7	$ 764,041.17	$ 2,206,918.70	7.02%	18.74%	6	12
1 Mile PVSF (Existing)	$ 1,734,887.19	13.36%	7	$ 764,041.17	$ 2,206,918.70	7.02%	18.74%	6	12
PV for 1,000 Mile SF(Existing)	$2,035,896,041.40	21.99%	5	$ 1,062,975,950.33	$2,625,427,387.95	13.04%	30.26%	4	8
1,000 Mile PVSF (Existing)	$2,035,896,041.40	21.99%	5	$ 1,062,975,950.33	$2,625,427,387.95	13.04%	30.26%	4	8

CASE 2	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ 199,058.79	1.16%	21	$ (1,461,712.46)	$ 786,777.02	-11.51%	4.15%	16	>25
1 Mile PVNB (New)	$ (371,628.16)	-0.14%	>25	$ (2,074,194.97)	$ 839,230.02	-3.01%	1.61%	21	>25
PV for 1,000 Mile NB (New)	$1,035,305,663.61	6.81%	12	$ (621,082,740.84)	$1,481,509,792.33	-6.72%	10.33%	9	>25
1,000 Mile PVNB (New)	$ 464,618,716.01	1.15%	23	$(1,233,565,249.51)	$1,679,859,739.73	-1.85%	3.37%	17	>25
PV for 1 Mile NB (Existing)	$ 199,058.79	1.16%	21	$ (1,461,712.46)	$ 786,777.02	-11.51%	4.15%	16	>25
1 Mile PVNB (Existing)	$ 199,058.79	1.16%	21	$ (1,461,712.46)	$ 786,777.02	-11.51%	4.15%	16	>25
PV for 1,000 Mile NB (Existing)	$1,035,305,663.61	6.81%	12	$ (621,082,740.84)	$1,481,509,792.33	-6.72%	10.33%	9	>25
1,000 Mile PVNB (Existing)	$1,035,305,663.61	6.81%	12	$ (621,082,740.84)	$1,481,509,792.33	-6.72%	10.33%	9	>25
PV for 1 Mile SF (New)	$ (6,733.19)	0.18%	24	$ (592,323.30)	$ 506,936.27	-10.56%	3.92%	16	>25
1 Mile PVSF (New)	$ 1,526,419.76	9.29%	10	$ 555,402.21	$ 2,085,526.85	4.08%	12.08%	8	16
PV for 1,000 Mile SF (New)	$ 294,275,663.38	4.69%	15	$ (293,388,525.35)	$ 925,444,963.60	-7.05%	9.24%	10	>25
1,000 Mile PVSF (New)	$1,827,428,616.75	13.54%	7	$ 854,336,989.19	$2,504,035,541.50	7.37%	16.80%	6	12
PV for 1 Mile SF (Existing)	$ 1,831,139.12	14.20%	7	$ 860,121.57	$ 2,390,246.21	7.74%	19.51%	6	11
1 Mile PVSF (Existing)	$ 1,831,139.12	14.20%	7	$ 860,121.57	$ 2,390,246.21	7.74%	19.51%	6	11
PV for 1,000 Mile SF(Existing)	$2,132,147,976.75	22.88%	5	$ 1,159,056,349.19	$2,808,754,901.50	14.00%	31.43%	4	7
1,000 Mile PVSF (Existing)	$2,132,147,976.75	22.88%	5	$ 1,159,056,349.19	$2,808,754,901.50	14.00%	31.43%	4	7

CASE 3	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ 114,730.11	1.13%	22	$ (1,544,624.45)	$ 664,060.71	-3.76%	3.95%	16	>25
1 Mile PVNB (New)	$ (455,956.84)	-0.29%	>25	$ (2,157,106.96)	$ 756,318.03	-3.31%	1.52%	22	>25
PV for 1,000 Mile NB (New)	$ 878,990,928.05	6.71%	13	$ (776,782,079.22)	$1,286,950,696.65	1.08%	10.15%	9	>25
1,000 Mile PVNB (New)	$ 308,303,980.45	0.91%	23	$(1,389,264,587.89)	$1,524,160,401.35	-2.23%	3.18%	18	>25
PV for 1 Mile NB (Existing)	$ 114,730.11	1.13%	22	$ (1,544,624.45)	$ 664,060.71	-3.76%	3.95%	16	>25
1 Mile PVNB (Existing)	$ 114,730.11	1.13%	22	$ (1,544,624.45)	$ 664,060.71	-3.76%	3.95%	16	>25
PV for 1,000 Mile NB (Existing)	$ 878,990,928.05	6.71%	13	$ (776,782,079.22)	$1,286,950,696.65	1.08%	10.15%	9	>25
1,000 Mile PVNB (Existing)	$ 878,990,928.05	6.71%	13	$ (776,782,079.22)	$1,286,950,696.65	1.08%	10.15%	9	>25
PV for 1 Mile SF (New)	$ (28,115.64)	0.16%	>25	$ (613,575.10)	$ 428,368.80	-4.25%	3.73%	17	>25
1 Mile PVSF (New)	$ 1,505,037.31	9.74%	10	$ 534,150.41	$ 2,006,959.38	4.20%	12.52%	8	16
PV for 1,000 Mile SF (New)	$ 246,984,811.85	4.63%	16	$ (340,528,342.80)	$ 810,634,264.02	-0.34%	9.08%	10	>25
1,000 Mile PVSF (New)	$1,780,137,765.22	13.94%	7	$ 807,197,171.74	$2,389,224,841.92	7.41%	17.14%	6	12
PV for 1 Mile SF (Existing)	$ 1,809,756.67	15.06%	7	$ 838,869.77	$ 2,311,678.74	8.26%	20.94%	5	11
1 Mile PVSF (Existing)	$ 1,809,756.67	15.06%	7	$ 838,869.77	$ 2,311,678.74	8.26%	20.94%	5	11
PV for 1,000 Mile SF(Existing)	$2,084,857,125.22	24.50%	4	$ 1,111,916,531.74	$2,693,944,201.92	14.74%	33.61%	3	7
1,000 Mile PVSF (Existing)	$2,084,857,125.22	24.50%	4	$ 1,111,916,531.74	$2,693,944,201.92	14.74%	33.61%	3	7

CASE 4	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ 422,159.37	2.41%	19	$ (411,737.07)	$ 940,279.62	-1.93%	5.25%	14	>25
1 Mile PVNB (New)	$ (147,577.67)	0.19%	>25	$ (1,570,901.58)	$ 1,026,544.21	-1.25%	1.97%	21	>25
PV for 1,000 Mile NB (New)	$1,186,338,798.11	8.44%	10	$ 356,105,295.89	$1,608,434,530.37	3.15%	11.87%	8	17
1,000 Mile PVNB (New)	$ 616,601,749.63	1.41%	22	$ (827,054,078.96)	$1,794,386,579.24	-0.09%	3.66%	17	>25
PV for 1 Mile NB (Existing)	$ 422,159.37	2.41%	19	$ (411,737.07)	$ 940,279.62	-1.93%	5.25%	14	>25
1 Mile PVNB (Existing)	$ 422,159.37	2.41%	19	$ (411,737.07)	$ 940,279.62	-1.93%	5.25%	14	>25
PV for 1,000 Mile NB (Existing)	$1,186,338,798.11	8.44%	10	$ 356,105,295.89	$1,608,434,530.37	3.15%	11.87%	8	17
1,000 Mile PVNB (Existing)	$1,186,338,798.11	8.44%	10	$ 356,105,295.89	$1,608,434,530.37	3.15%	11.87%	8	17
PV for 1 Mile SF (New)	$ 68,136.30	1.07%	22	$ (517,494.70)	$ 611,696.31	-9.97%	5.00%	15	>25
1 Mile PVSF (New)	$ 1,601,289.25	10.25%	9	$ 630,230.81	$ 2,190,286.89	4.81%	13.10%	8	15
PV for 1,000 Mile SF (New)	$ 343,236,747.19	5.85%	13	$ (244,447,943.94)	$ 993,961,777.57	-6.30%	10.70%	9	>25
1,000 Mile PVSF (New)	$1,876,389,700.57	14.56%	7	$ 903,277,570.60	$2,572,552,355.48	8.13%	17.85%	6	11
PV for 1 Mile SF (Existing)	$ 1,906,008.61	15.99%	6	$ 934,950.17	$ 2,495,006.25	9.03%	21.79%	5	10
1 Mile PVSF (Existing)	$ 1,906,008.61	15.99%	6	$ 934,950.17	$ 2,495,006.25	9.03%	21.79%	5	10
PV for 1,000 Mile SF(Existing)	$2,193,432,857.53	25.62%	4	$ 1,207,996,930.60	$2,877,271,715.48	15.78%	34.91%	3	7
1,000 Mile PVSF (Existing)	$2,181,109,060.57	25.49%	4	$ 1,207,996,930.60	$2,877,271,715.48	15.78%	34.91%	3	7

CASE 5	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ (674,152.18)	-1.84%	>25	$ (1,208,974.23)	$ 64,714.51	-3.61%	0.59%	24	>25
1 Mile PVNB (New)	$ (1,243,889.23)	-1.23%	>25	$ (2,686,789.67)	$ (103,719.73)	-1.96%	0.22%	>25	>25
PV for 1,000 Mile NB (New)	$ 161,995,087.49	1.08%	22	$ (392,339,383.48)	$ 732,372,088.22	-0.84%	3.77%	16	>25
1,000 Mile PVNB (New)	$ (407,741,960.99)	-0.18%	>25	$(1,870,154,824.08)	$ 736,909,986.14	-0.94%	1.42%	22	>25
PV for 1 Mile NB (Existing)	$ (674,152.18)	-1.84%	>25	$ (1,208,974.23)	$ 64,714.51	-3.61%	0.59%	24	>25
1 Mile PVNB (Existing)	$ (674,152.18)	-1.84%	>25	$ (1,208,974.23)	$ 64,714.51	-3.61%	0.59%	24	>25
PV for 1,000 Mile NB (Existing)	$ 161,995,087.49	1.08%	22	$ (392,339,383.48)	$ 732,372,088.22	-0.84%	3.77%	16	>25
1,000 Mile PVNB (Existing)	$ 161,995,087.49	1.08%	22	$ (392,339,383.48)	$ 732,372,088.22	-0.84%	3.77%	16	>25
PV for 1 Mile SF (New)	$ (321,882.18)	-2.41%	>25	$ (561,856.72)	$ 27,700.71	-5.13%	0.50%	25	>25
1 Mile PVSF (New)	$ 1,211,270.78	6.22%	13	$ 220,131.19	$ 1,606,291.29	1.58%	7.93%	11	22
PV for 1,000 Mile SF (New)	$ (20,873,325.45)	0.13%	>25	$ (262,921,945.53)	$ 446,209,397.08	-2.78%	3.34%	17	>25
1,000 Mile PVSF (New)	$1,515,687,671.45	8.87%	10	$ 519,065,969.71	$2,024,799,974.98	3.72%	10.58%	9	17
PV for 1 Mile SF (Existing)	$ 1,515,990.14	9.15%	10	$ 524,850.55	$ 1,911,010.65	3.86%	11.79%	8	17
1 Mile PVSF (Existing)	$ 1,515,990.14	9.15%	10	$ 524,850.55	$ 1,911,010.65	3.86%	11.79%	8	17
PV for 1,000 Mile SF(Existing)	$1,816,998,987.92	13.31%	8	$ 823,785,329.71	$2,329,519,334.98	7.07%	16.36%	6	12
1,000 Mile PVSF (Existing)	$1,816,998,987.92	13.31%	8	$ 823,785,329.71	$2,329,519,334.98	7.07%	16.36%	6	12

CASE 6	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ (404,435.52)	-0.88%	>25	$ (1,009,947.98)	$ 340,933.42	-2.50%	1.58%	21	>25
1 Mile PVNB (New)	$ (974,172.56)	-0.86%	>25	$ (2,487,763.42)	$ 166,506.45	-1.57%	0.55%	25	>25
PV for 1,000 Mile NB (New)	$ 431,711,752.85	2.13%	20	$ (193,313,130.45)	$1,008,590,998.15	0.35%	4.90%	15	>25
1,000 Mile PVNB (New)	$ (138,025,295.64)	0.21%	>25	$(1,671,128,571.05)	$1,007,136,164.03	-0.53%	1.84%	21	>25
PV for 1 Mile NB (Existing)	$ (404,435.52)	-0.88%	>25	$ (1,009,947.98)	$ 340,933.42	-2.50%	1.58%	21	>25
1 Mile PVNB (Existing)	$ (404,435.52)	-0.88%	>25	$ (1,009,947.98)	$ 340,933.42	-2.50%	1.58%	21	>25
PV for 1,000 Mile NB (Existing)	$ 431,711,752.85	2.13%	20	$ (193,313,130.45)	$1,008,590,998.15	0.35%	4.90%	15	>25
1,000 Mile PVNB (Existing)	$ 431,711,752.85	2.13%	20	$ (193,313,130.45)	$1,008,590,998.15	0.35%	4.90%	15	>25
PV for 1 Mile SF (New)	$ (225,630.24)	-1.51%	>25	$ (491,641.17)	$ 211,028.22	-4.26%	1.47%	22	>25
1 Mile PVSF (New)	$ 1,307,522.71	6.63%	13	$ 316,211.59	$ 1,789,618.80	2.09%	8.37%	11	20
PV for 1,000 Mile SF (New)	$ 75,378,609.89	1.12%	22	$ (192,706,390.05)	$ 629,536,910.63	-1.85%	4.43%	15	>25
1,000 Mile PVSF (New)	$1,611,939,606.80	9.33%	10	$ 615,146,368.57	$2,208,127,488.54	4.28%	11.08%	9	16
PV for 1 Mile SF (Existing)	$ 1,612,242.07	9.63%	10	$ 620,930.95	$ 2,094,338.16	4.44%	12.33%	8	16
1 Mile PVSF (Existing)	$ 1,612,242.07	9.63%	10	$ 620,930.95	$ 2,094,338.16	4.44%	12.33%	8	16
PV for 1,000 Mile SF(Existing)	$1,913,250,923.27	13.89%	7	$ 919,865,728.57	$2,512,846,848.54	7.75%	17.03%	6	11
1,000 Mile PVSF (Existing)	$1,913,250,923.27	13.89%	7	$ 919,865,728.57	$2,512,846,848.54	7.75%	17.03%	6	11

CASE 7	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ (401,179.06)	-1.03%	>25	$ (932,821.15)	$ 284,846.27	-2.86%	1.50%	21	>25
1 Mile PVNB (New)	$ (970,916.11)	-0.91%	>25	$ (2,410,636.59)	$ 172,433.34	-1.65%	0.57%	25	>25
PV for 1,000 Mile NB (New)	$ 363,000,366.76	2.03%	20	$ (188,973,656.46)	$ 894,194,807.37	0.03%	4.85%	15	>25
1,000 Mile PVNB (New)	$ (206,736,681.72)	0.10%	>25	$(1,666,789,097.06)	$ 940,275,713.15	-0.66%	1.79%	21	>25
PV for 1 Mile NB (Existing)	$ (401,179.06)	-1.03%	>25	$ (932,821.15)	$ 284,846.27	-2.86%	1.50%	21	>25
1 Mile PVNB (Existing)	$ (401,179.06)	-1.03%	>25	$ (932,821.15)	$ 284,846.27	-2.86%	1.50%	21	>25
PV for 1,000 Mile NB (Existing)	$ 363,000,366.76	2.03%	20	$ (188,973,656.46)	$ 894,194,807.37	0.03%	4.85%	15	>25
1,000 Mile PVNB (Existing)	$ 363,000,366.76	2.03%	20	$ (188,973,656.46)	$ 894,194,807.37	0.03%	4.85%	15	>25
PV for 1 Mile SF (New)	$ (215,393.95)	-1.64%	>25	$ (455,440.96)	$ 176,682.77	-4.44%	1.40%	22	>25
1 Mile PVSF (New)	$ 1,317,759.00	7.12%	12	$ 326,546.95	$ 1,755,273.35	2.29%	8.87%	10	20
PV for 1,000 Mile SF (New)	$ 59,706,499.61	1.03%	22	$ (182,394,204.13)	$ 558,948,235.05	-1.99%	4.40%	16	>25
1,000 Mile PVSF (New)	$1,596,267,496.51	9.83%	10	$ 599,593,711.12	$2,137,538,812.95	4.45%	11.58%	9	16
PV for 1 Mile SF (Existing)	$ 1,622,478.36	10.53%	9	$ 631,266.31	$ 2,059,992.71	4.90%	13.38%	8	15
1 Mile PVSF (Existing)	$ 1,622,478.36	10.53%	9	$ 631,266.31	$ 2,059,992.71	4.90%	13.38%	8	15
PV for 1,000 Mile SF(Existing)	$1,897,578,812.98	15.02%	7	$ 904,313,071.12	$2,442,258,172.95	8.32%	18.34%	6	11
1,000 Mile PVSF (Existing)	$1,897,578,812.98	15.02%	7	$ 904,313,071.12	$2,442,258,172.95	8.32%	18.34%	6	11

CASE 8	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ (131,462.39)	-0.04%	>25	$ (733,794.90)	$ 561,065.18	-1.71%	2.54%	19	>25
1 Mile PVNB (New)	$ (701,199.44)	-0.53%	>25	$ (2,211,610.34)	$ 442,659.52	-1.25%	0.90%	23	>25
PV for 1,000 Mile NB (New)	$ 632,717,032.12	3.13%	18	$ 10,052,596.56	$1,170,413,717.31	1.27%	6.05%	13	24
1,000 Mile PVNB (New)	$ 62,979,983.63	0.50%	25	$(1,467,762,844.04)	$1,210,501,891.05	-0.25%	2.23%	20	>25
PV for 1 Mile NB (Existing)	$ (131,462.39)	-0.04%	>25	$ (733,794.90)	$ 561,065.18	-1.71%	2.54%	19	>25
1 Mile PVNB (Existing)	$ (131,462.39)	-0.04%	>25	$ (733,794.90)	$ 561,065.18	-1.71%	2.54%	19	>25
PV for 1,000 Mile NB (Existing)	$ 632,717,032.12	3.13%	18	$ 10,052,596.56	$1,170,413,717.31	1.27%	6.05%	13	24
1,000 Mile PVNB (Existing)	$ 632,717,032.12	3.13%	18	$ 10,052,596.56	$1,170,413,717.31	1.27%	6.05%	13	24
PV for 1 Mile SF (New)	$ (119,142.02)	-0.70%	>25	$ (385,225.41)	$ 360,010.29	-3.54%	2.41%	19	>25
1 Mile PVSF (New)	$ 1,414,010.94	7.54%	12	$ 422,627.35	$ 1,938,600.86	2.81%	9.33%	10	19
PV for 1,000 Mile SF (New)	$ 155,958,434.95	2.06%	20	$ (112,178,648.64)	$ 742,275,748.60	-1.03%	5.55%	14	>25
1,000 Mile PVSF (New)	$1,692,519,431.86	10.32%	9	$ 695,674,109.98	$2,320,866,326.51	5.04%	12.11%	8	15
PV for 1 Mile SF (Existing)	$ 1,718,730.30	11.04%	9	$ 727,346.71	$ 2,243,320.22	5.52%	13.96%	7	14
1 Mile PVSF (Existing)	$ 1,718,730.30	11.04%	9	$ 727,346.71	$ 2,243,320.22	5.52%	13.96%	7	14
PV for 1,000 Mile SF(Existing)	$1,993,830,748.33	15.65%	7	$ 1,000,393,469.98	$2,625,585,686.51	9.04%	19.07%	6	10
1,000 Mile PVSF (Existing)	$1,993,830,748.33	15.65%	7	$ 1,000,393,469.98	$2,625,585,686.51	9.04%	19.07%	6	10

CASE 9	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ 459,926.23	-	-	$ -	$ 1,078,326.50	-	-	-	-
1 Mile PVNB (New)	$ (109,810.82)	0.18%	>25	$ (1,160,133.00)	$ 1,006,950.68	-0.98%	2.79%	19	>25
PV for 1,000 Mile NB (New)	$ 459,926,227.48	-	-	$ -	$1,078,326,496.52	-	-	-	-
1,000 Mile PVNB (New)	$ (109,810,821.00)	0.18%	>25	$(1,160,132,995.75)	$1,006,950,684.75	-0.98%	2.79%	19	>25
PV for 1 Mile NB (Existing)	$ 459,926.23	-	-	$ -	$ 1,078,326.50	-	-	-	-
1 Mile PVNB (Existing)	$ 459,926.23	-	-	$ -	$ 1,078,326.50	-	-	-	-
PV for 1,000 Mile NB (Existing)	$ 459,926,227.48	-	-	$ -	$1,078,326,496.52	-	-	-	-
1,000 Mile PVNB (Existing)	$ 459,926,227.48	-	-	$ -	$1,078,326,496.52	-	-	-	-
PV for 1 Mile SF (New)	$ 163,859.89	-	-	$ -	$ 383,404.90	-	-	-	-
1 Mile PVSF (New)	$ 1,697,012.85	27.14%	4	$ 687,639.64	$ 1,961,995.47	12.83%	30.81%	4	8
PV for 1,000 Mile SF (New)	$ 163,859,893.09	-	-	$ -	$ 383,404,896.94	-	-	-	-
1,000 Mile PVSF (New)	$1,700,420,889.99	27.19%	4	$ 687,639,638.21	$1,961,995,474.84	12.83%	30.81%	4	8
PV for 1 Mile SF (Existing)	$ 2,001,732.21	1124.50%	1	$ 992,359.00	$ 2,266,714.83	570.26%	1299.17%	1	1
1 Mile PVSF (Existing)	$ 2,001,732.21	1124.50%	1	$ 992,359.00	$ 2,266,714.83	570.26%	1299.17%	1	1
PV for 1,000 Mile SF(Existing)	$2,001,732,206.46	1124.50%	1	$ 992,358,998.21	$2,266,714,834.84	570.26%	1299.17%	1	1
1,000 Mile PVSF (Existing)	$2,001,732,206.46	1124.50%	1	$ 992,358,998.21	$2,266,714,834.84	570.26%	1299.17%	1	1

CASE 10	NPV	IRR	Payback	NPV		IRR		Payback	
	Average	Average	Average	N-Min	N-Max	I-Min	I-Max	P-Min	P-Max
PV for 1 Mile NB (New)	$ 715,651.08	-	-	$ 256,207.93	$ 1,334,534.43	-	-	-	-
1 Mile PVNB (New)	$ 145,914.03	0.71%	24	$ (971,431.42)	$ 1,263,158.62	-0.41%	3.42%	18	>25
PV for 1,000 Mile NB (New)	$ 715,651,079.84	-	-	$ 256,207,933.44	$1,334,534,429.96	-	-	-	-
1,000 Mile PVNB (New)	$ 145,914,031.35	0.71%	24	$ (971,431,422.18)	$1,263,158,618.19	-0.41%	3.42%	18	>25
PV for 1 Mile NB (Existing)	$ 715,651.08	-	-	$ 256,207.93	$ 1,334,534.43	-	-	-	-
1 Mile PVNB (Existing)	$ 715,651.08	-	-	$ 256,207.93	$ 1,334,534.43	-	-	-	-
PV for 1,000 Mile NB (Existing)	$ 715,651,079.84	-	-	$ 256,207,933.44	$1,334,534,429.96	-	-	-	-
1,000 Mile PVNB (Existing)	$ 715,651,079.84	-	-	$ 256,207,933.44	$1,334,534,429.96	-	-	-	-
PV for 1 Mile SF (New)	$ 255,118.67	-	-	$ 91,096.14	$ 474,501.03	-	-	-	-
1 Mile PVSF (New)	$ 1,788,271.62	28.47%	4	$ 778,735.77	$ 2,053,091.61	14.25%	32.13%	4	7
PV for 1,000 Mile SF (New)	$ 255,118,666.16	-	-	$ 91,096,135.20	$ 474,501,032.14	-	-	-	-
1,000 Mile PVSF (New)	$1,791,679,663.06	28.52%	4	$ 778,735,773.41	$2,053,091,610.04	14.25%	32.13%	4	7
PV for 1 Mile SF (Existing)	$ 2,092,990.98	1180.14%	1	$ 1,083,455.13	$ 2,357,810.97	626.41%	1355.35%	1	1
1 Mile PVSF (Existing)	$ 2,092,990.98	1180.14%	1	$ 1,083,455.13	$ 2,357,810.97	626.41%	1355.35%	1	1
PV for 1,000 Mile SF(Existing)	$2,092,990,979.53	1180.14%	1	$ 1,083,455,133.41	$2,357,810,970.04	626.41%	1355.35%	1	1
1,000 Mile PVSF (Existing)	$2,092,990,979.53	1180.14%	1	$ 1,083,455,133.41	$2,357,810,970.04	626.41%	1355.35%	1	1