INVESTIGATION OF TRANSPARENT PHOTOVOLTAIC VEHICLE INTEGRATION

by

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To my family, friends, and mentors that have supported me throughout my journeys.

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LIST OF ABBREVIATIONS

AC - Alternating Current
BEV - Battery Electric Vehicle
DC - Direct Current
EV - Electric Vehicle
FCEV - Fuel Cell Electric Vehicle
GHG - Greenhouse gas emissions
GM - General Motors
HEV - Hybrid Electric Vehicle
ICE - Internal Combustion Engine
ICV - Internal Combustion Vehicle
NREL - National Renewable Energy Laboratory
PHEV - Plug-in Hybrid Electric Vehicle
PV - Photovoltaic
SAM - System Advisor Model
SEV - Solar Electric Vehicle
TPV - Transparent Photovoltaic
U.S. - United States

GLOSSARY

Clean Energy	Energy derived from renewable, zero-emissions sources, as well as energy saved through energy efficiency measures (NCSEA, n.d.).
Climate Change	A change in the usual weather found in a place (May, 2017).
Renewable Energy	Energy that is produced by natural resources – such as sunlight, wind, rain, waves, tides, and geothermal heat – that are naturally replenished within a time span of a few years (Lund, 2014).
Sustainable Energy	A form of energy that can be utilized again and again without putting a source in danger of getting depleted, expired, or vanished (Dincer, 2018).

ABSTRACT

The pursuit to combat climate change continues, identifying new methods and technologies for sustainable energy management. Automakers continue developing battery electric vehicles while researchers identify new applications and materials for solar photovoltaics. The continued advancement of technology creates new holes within literature, requiring investigation to understand the unknown.

Photovoltaic vehicle integration gained popularity during the 1970s but did not commercialize due to technology, economics, and other factors. By 2021 the idea resurfaced, showcasing commercial and concept vehicles utilizing photovoltaics. The emergence of new transparent photovoltaics presents additional options for vehicle integration but lacks literature analyzing the energy output and economics. The theoretical analysis investigated transparent photovoltaic replacing a vehicle's windows. The investigation found that transparent photovoltaic vehicle integration generates energy and financial savings. However, due to high system costs and location, the system does not provide a financial payback period like other photovoltaic arrays. Improving cost, location, and other financial parameters create more favorable circumstances for the photovoltaic system. Furthermore, transparent photovoltaics provide energy saving benefits and some return on investment compared to regular glass windows.

CHAPTER 1. INTRODUCTION

Chapter One presents the investigation and purpose of transparent solar photovoltaic (TPV) vehicle integration. Chapter One outlines the investigation's problem, purpose, significance, scope of research, limitations, and delimitations.

The increasing impacts of climate change combine with finite fossil fuel resources continue pushing societies to pursue a sustainable future. Governments continue implementing renewable and sustainable technologies while researchers pursue new methods for clean energy generation including transparent solar photovoltaic (PV) panels. Transparent solar photovoltaics emerged as a new form of clean electricity generation, receiving increased research attention to replace glass within building structures. The replacement provides electricity generation for building consumptions, saving energy costs while reducing greenhouse gas (GHG) emissions from powerplants.

The emergence of transparent photovoltaics created new gaps within academic research and literature, fueling increased investigations for applications. Automobile applications present opportunities for energy generation by replacing windows using transparent photovoltaics. The replacement provides potential electricity generation to recharge batteries or run electrical applications within vehicles. Current literature lacks information analyzing transparent photovoltaics automotive applications, creating a need for investigation.

1.1 Problem

Energy demand continues growing alongside new technology and population increases. Fossil fuels provide energy but use a finite supply that pollutes the environment, affecting earth's climate. Businesses continue pursuing clean energy alternatives from government initiatives to combat climate change and finite fossil fuel resources. However, clean energy faces innovation, infrastructure, education, and cost challenges for adoption within society. Researchers continue to combat challenges while discovering new inventions or innovations that require further investigation for adoption including solar electric vehicles (SEV's).

Solar electric vehicles showcase solar photovoltaic technology integration into battery electric vehicles (BEV's), providing a clean method of transportation. Batteries store energy generated by photovoltaics from the sun for electric propulsion, creating a pollution free transportation method. New transparent photovoltaics emerged on the market as solar windows for building integration and electricity generation. The technology presents potentials for other areas of integration that utilize glass or windows, including vehicles. No research has analyzed the energy generation of transparent photovoltaics within electric vehicles (EV's), creating voids within literature and a need for investigation.

1.2 Purpose

The research investigated the energy generation potential of transparent photovoltaic electric vehicle integration. Battery electric vehicles require grid charging, costing consumers time and money. The integration of transparent photovoltaics within electric vehicles present energy and financial savings opportunities for consumers. Transparent photovoltaics produce free energy each day from sunlight like normal photovoltaics. The free energy generated translates to financial savings compared to purchasing from the grid.

1.3 Significance

Sustainable energy adoption continues growing throughout the energy and transportations sectors from government incentives. Automakers plan to sell only electric vehicles by 2035 (Baldwin, 2021) while power utilities pursue wind and solar energies. Unpredictable wind and solar energy generation present issues for constant demand while battery electric vehicles increase power grid loads. Forms of solar electric vehicles present opportunities to combat unpredictable generation and grid stabilization by storing energy, known as smart grid integration. Solar electric vehicles also generate electricity for daily driving, requiring less grid charging while saving time, money, and greenhouse gas emissions. Photovoltaic electric vehicle integration presents opportunities to decrease electric vehicle life cycle costs while improving adoption, operation, charging, and driving range.

1.4 Research Questions

The investigation answered the research questions, determining energy output of transparent photovoltaic vehicle integration while analyzing associated costs and benefits.

1. How much energy output do transparent photovoltaics generated at a fixed orientation?
2. How much electricity savings do transparent photovoltaic achieved within vehicles?

1.5 Hypothesis

Transparent photovoltaic electric vehicle integration creates energy savings that outweigh the system costs.

1.6 Scope of Research

The scope of research contains two sections: energy and financial analysis. The energy analysis calculates the expected electricity output from fixed transparent photovoltaics at a specific location each year. Efficiency, area, inclination, and orientation assumptions provide analysis parameters to calculate energy generation. Cost assumptions for electricity, transparent photovoltaic panels, and other systems provide financial analysis parameters to determine overall cost savings.

1.7 Cost Benefit Analysis

The financial analysis provides costs for comparing energy savings and benefits. The cost and benefit comparisons determine if transparent photovoltaic vehicle integration provides economic reasons for pursuing future research and adoption.

1.8 Limitations

The research study does not investigate any effects on greenhouse gas emissions for any product involved within the research study. Greenhouse gas emission analysis requires an in-depth life cycle investigation for each product and manufacturing process.

Solar irradiation data for conducting the energy analysis uses recordings from the National Renewable Energy Laboratory (NREL) database at a specific location. The acquired data lists each day and hour from local weather recording stations over one-year. The research study assumes consistent annual weather data every year.

Stationary energy generation occurs at one location, simulating a vehicle parked and facing south. The study does not investigate any effects of stationary charging with grid and solar inputs or dynamic charging while driving. The investigation assumes direct current (DC) electricity and no conversion occurs to alternating current (AC).

The financial analysis does not include taxes, insurance rates, tax credits, energy credits, government incentives, electricity price fluctuations, or demand charges. The financial analysis only investigates the energy cost savings provided by the transparent photovoltaic system. One hundred percent of the energy generated charges the batteries for driving. No equipment replacement, repair, salvage occurred for the study.

1.9 Delimitations

The energy analysis provides data for a one-year investigation. The study uses annual data to project the life cycle energy generation while accounting for system losses. Solar panels experience degradation over time, creating losses and reducing performance. Present worth calculations account for degradation over the entire analysis length. Losses occur from wiring, temperatures, dust, snow, rain, and other parameters. Losses summed as one value and used within the analysis provide a conservative result.

The financial analysis looks at all present and future costs to estimate the system's net present worth. The study conducts a financial analysis using annual energy data calculated from modeling. The energy generation provides annual savings projected throughout the system's life. The financial calculations consider system maintenance and operation costs as well as rates of inflation and interest. The cost for each transparent photovoltaic panel accounts for the balance of system, components, installation, labor, etc., simplified to a fixed value per Watt.

Chapter One summarizes the scope of research for potential financial savings from transparent photovoltaic vehicle integration. Chapter Two details the review of literature regarding photovoltaics and electric vehicle technologies, providing background information on each concept within the study.

CHAPTER 2. REVIEW OF LITERATURE

Chapter Two provides a literature review related to photovoltaic vehicle integration, discussing the history, technologies, and concepts regarding photovoltaic solar panels and electric vehicles.

2.1 Background

During the 1970's oil crisis, engineers proposed photovoltaic electric vehicle integration to combat fossil fuels, known as solar electric vehicles (SEV's) (Connors, 2007; Rizzo, 2010). The SEV housed photovoltaics on every surface, achieving maximum energy output while using batteries to store electricity generated for propulsion (Connors, 2007; Rizzo, 2010). By the 1980s, the United States (U.S.) and Australia hosted solar races to promote and demonstrate SEV concepts (Connors, 2007). Engineers optimized SEV's to reduce energy losses from friction, housing one individual to improve aerodynamics while using lightweight materials (Connors, 2007; Rizzo, 2010). The SEV remains a research and sports project due to cost, feasibility, and practicality (Connors, 2007). However, engineers continued identifying new materials, designs, and manufacturing methods for improving EV and PV technologies (Connors, 2007).

2.2 Solar Energy

The sun provides life-sustaining energy for the earth. Radiant heat creates thermal energy, driving weather patterns, while photons from sunlight provide energy to plants (Boyle, 2004). Plants use thermal and photon energy through photosynthesis to transform energy into life (Lambers et al., 2008). The combination of solar thermal and photon energy provides free, clean energy that benefits all life on earth (Lambers et al., 2008).

Scientists have developed ways of harnessing the sun's direct and indirect energy through renewable technologies (Boyle, 2004; Hodge, 2017). Renewable technologies include wind turbines, water turbines (hydroelectric dams, tidal wave, tidal barrage), solar thermal systems, and solar photovoltaic (PV) systems (Boyle, 2004; Hodge, 2017). Wind and water turbines generate electricity from fluid movement driven by weather patterns, an indirect form of solar energy (Boyle, 2004; Hodge, 2017). Solar thermal systems capture direct radiant energy from the sun using fluids to generate heat or electricity (Boyle, 2004; Hodge, 2017). Solar photovoltaics convert direct sunlight photons into electricity through the photovoltaic effect (Boyle, 2004; Hodge, 2017). Individuals and organizations continue investing in renewable technologies to provide clean energy generation, contributing to a sustainable future (Maycock, 2005).

Renewable technologies differ in cost, size, and usable location (Boyle, 2004; Hodge, 2017). Water and wind turbines require rivers and open land, respectively, accompanied by the infrastructure to produce energy, restricting locations for implementation (Boyle, 2004; Hodge, 2017). Solar thermal systems require mechanical equipment, piping, and maintenance for collecting and transporting energy, varying based on size and location (Evangelisti et al., 2019; Tian & Zhao, 2013). Solar photovoltaics provide simple, scalable electricity generation through photosynthesis for different locations and sizes (Parida et al., 2011). Schreiber & Lucietto (2021) present various solar energy applications in further detail, discussing uses for buildings and industrial applications. The sun provides energy everywhere worldwide, making direct solar energy technologies a popular choice of investment (Vasiliev & Alameh, 2019). Individuals and organizations continue investing in solar photovoltaics due to cost, ease of implementation, and universal usability of electricity (Parida et al., 2011).

2.3 Photovoltaic Solar Panels

Alexandre Edmond Becquerel observed the photovoltaic effect in 1839 using an electrode solution to convert sunlight into electricity (Goetzberger et al., 2003; Green, 1990). Other scientists followed Becquerel’s research, improving the technology and creating the first solar cell in 1883 with a one percent efficiency (Green, 1990; Hodge, 2017). Photovoltaic research continued over time and increased during the space race between the U.S. and Soviet Union after World War II (Green, 1990; Hodge, 2017). By 1954, researchers at Bell Laboratories discovered the monocrystalline silicon photovoltaic solar cell that dominated the market for years (Goetzberger & Hebling, 2000; Loferski, 1993). Researchers continued investigating photovoltaic technologies for performance or cost improvements, leading to new materials, manufacturing methods, and terrestrial application adoption (Goetzberger & Hebling, 2000; Green, 1990; Loferski, 1993).

2.4 How Photovoltaics Work

Solar photovoltaic cells consist of semiconductor materials to produce electricity, a positive p-type and a negative n-type (Goetzberger et al., 2003). The n-type materials are charged with extra valence electrons while p-type materials have valence electrons removed, referred to as holes (Greacen, 1991). The n-type material is placed on top of the p-type, creating an electric field at the junction (Goetzberger et al., 2003). The pn junction causes a depletion region where extra valence electrons fill atom holes missing electrons (Goetzberger et al., 2003). As sunlight hits the n-type material, photons penetrate to the depletion region, freeing electrons by breaking the material bandgap energy (Greacen, 1991). Freed electrons flow toward the n-type material while atoms missing electrons flow to the p-type material as shown by Figure 2.1 (Greacen, 1991). Energy flows from the n-type material to the p-type through an external electrical circuit connection, creating usable power (Greacen, 1991). Semiconductor material properties determine the valence electron bandgap energy and the associated power output of each photovoltaic solar cell along with assembly (Kazmerski, 2006).

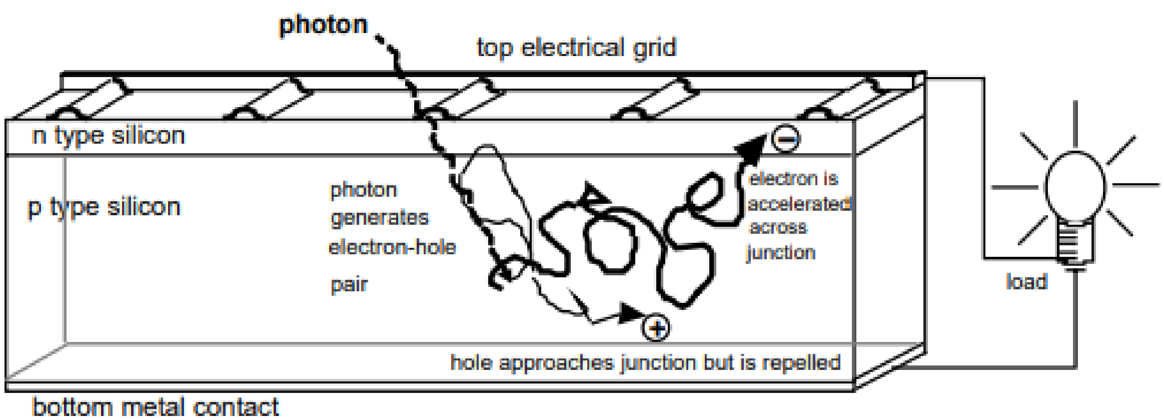

Figure 2.1: Schematic of a photovoltaic solar cell (Greacen, 1991)

Module assembly consists of materials that provide junctions, support, insulation, and protection, affecting photovoltaic performance (Goetzberger et al., 2003; Kazmerski, 2006). Multiple pn junctions produce different performances by using three or more semiconductor wafer materials as shown by Figure 2.2 (Kazmerski, 2006). Material properties and assembly within a single photovoltaic cell assembly determine the performance output of multiple junction cells (Kazmerski, 2006). Solar photovoltaic modules use multiple cells through series and parallel electrical connections to obtain a desired voltage and current outputs (Kazmerski, 2006). Concentration devices also affect performance by directing additional sunlight to a module, improving energy output (Kazmerski, 2006). Module electrical connections, materials, and other devices determine the overall performance of each solar photovoltaic panel.

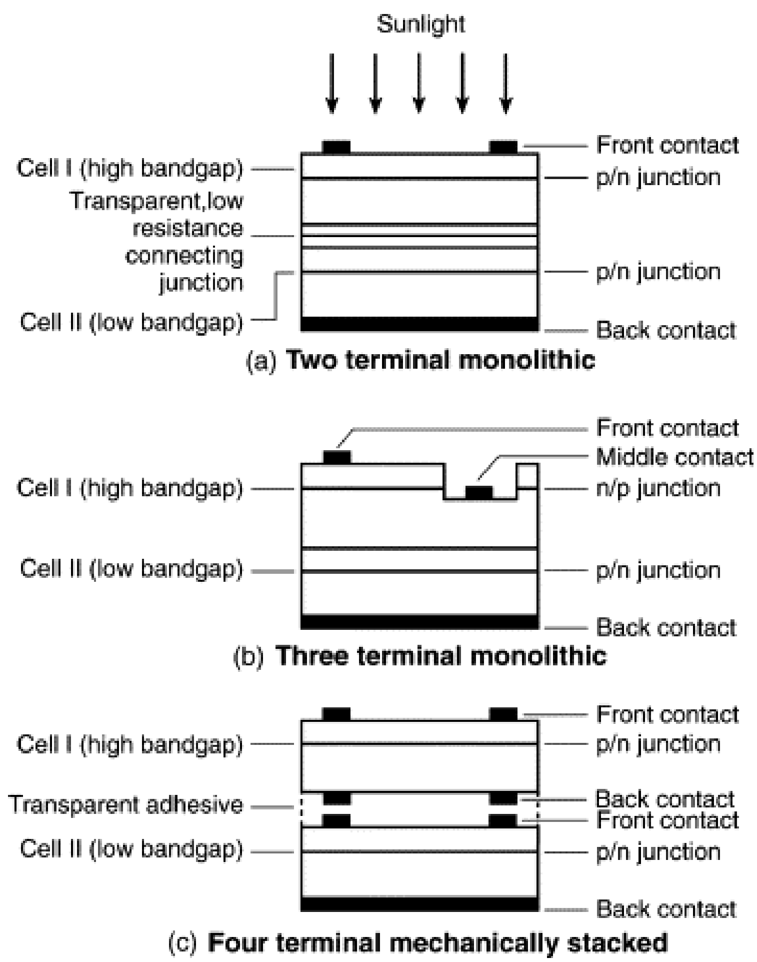

Figure 2.2: Cross section of multiple junction solar cells (Kazmerski, 2006)

2.5 Photovoltaic Materials

Tyagi et al. (2013) divide solar photovoltaic materials into five categories: crystalline silicon, thin-film, organic/polymer, hybrid photovoltaic, and dye-sensitized. Tyagi et al. (2013)

categorize monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), and gallium arsenide (GaAs) as crystalline silicon materials. All three compositions provide the highest efficiencies of photovoltaic materials, however, GaAs does not contain silicon (Tyagi et al., 2013). Thin-films use amorphous silicon, cadmium telluride, and other semiconductor materials to create photovoltaic cells that provide different performances (Tyagi et al., 2013). Emerging photovoltaic materials include organics, polymer, and dye-sensitized compositions that hold less than one percent of market shares combine as material development continues (Tyagi et al., 2013). Researchers continue to develop thin-films, organics, polymer, and dye-sensitized materials to overcome challenges for adoption (Parida et al., 2011; Polman et al., 2016; Tyagi et al., 2013).

Hybrid solar cells combine crystalline and non-crystallin materials, broadening photovoltaic applications (Parida et al., 2011; Tyagi et al., 2013). Researchers continue studying the potential of hybrid cell compositions and applications including photovoltaic materials on glass (Goetzberger et al., 2003). Clear thin-film solar cells applied to glass create a hybrid cell technology known as transparent photovoltaics (T.P.V.'s) (Goetzberger et al., 2003). The properties of transparent thin-film photovoltaics depend on manufacturer, application requirements, and potential integration within buildings and vehicles (Fathi et al., 2017; Goetzberger et al., 2003).

2.6 Photovoltaic Manufacturing

Manufacturing methods and discoveries contributed to photovoltaic cost and performance improvements. Silica sand melted into a crucible creates crystalline silicon material while removing impurities (Goetzberger et al., 2003). A seed crystal dipping process into the molten silicon produces pure mono-Si material from the chemical reaction (Goetzberger et al., 2003). The seed crystal rotates while being dipped multiple times until reaching the desired cylinder diameter (Goetzberger et al., 2003). Goetzberger et al. (2003) discuss techniques to obtain pure mono-Si material in further detail, stressing the energy requirements and refinement of the processes (Goetzberger et al., 2003).

Researchers developed block casting methods for producing poly-Si material, reducing cost and energy consumption compared to mono-Si (Goetzberger et al., 2003). Poly-Si has lower material efficiencies than mono-Si, however, the block shape reduces the performance differences at module levels (Goetzberger et al., 2003). Square poly-Si wafers utilize more area compared to circular mono-Si cells within rectangular module assemblies, evening the performance (Goetzberger et al., 2003).

Thin-film technologies require the melting of molten semiconductor material and extraction through dies to create solar cells (Goetzberger et al., 2003). Lasers cut thin-film materials to desired shapes and sizes, avoiding material losses from sawing (Goetzberger & Hebling, 2000). The shape and structure of thin-film cells vary based on application and material requirements such as transparent photovoltaics (Takeoka et al., 1993). Transparent photovoltaics use clear or semitransparent thin-film solar cells attached to glass windows for generating electricity (Fathi et al., 2017; Goetzberger et al., 2003; Takeoka et al., 1993). The films are attached to the interior face or four edges of a window depending on application requirements to produce energy (Fathi et al., 2017; Goetzberger et al., 2003; Takeoka et al., 1993). Other transparent photovoltaics also use embedded microstructures to deflect and refract light passing through glass, affecting performance output (Traverse et al., 2017; Vasiliev & Alameh, 2019)

Goetzberger et al. (2003) present multiple methods for creating and modifying photovoltaic wafer structures based on material and requirements. Manufacturers use diamond wire to cut thin crystalline silicon wafers from blocks and cylinders for module use (Goetzberger et al., 2003). The cutting process increases costs and losses for mono-Si and poly-Si materials (Goetzberger et al., 2003). Inkjet and plasma cutting provides additional methods for producing solar cells or texturing grooves (Kazmerski, 2006). Material texturing increases surface area for light absorption, improving energy generation from a two to three-dimensional space (Goetzberger et al., 2003). Material recrystallization also improves material grain structure, similar to heat treating metals, affecting performance (Goetzberger et al., 2003).

This paper focuses on mono-Si, poly-Si, thin-films, and transparent photovoltaics. Further investigations of organic, polymer, and dye-sensitized is not be investigated.

2.7 Photovoltaic Performance

Photovoltaic performance depends on location, orientation, weather, terrain, module assembly, and equipment (Parida et al., 2011; Tyagi et al., 2013; Zehner, 2012). Solar irradiance and weather patterns vary worldwide, influencing the energy output of photovoltaic modules (Darhmaoui & Lahjouji, 2013; George & Maxwell, 1999; Inman et al., 2013; Parida et al., 2011;

Tyagi et al., 2013). Greater irradiance intensity and exposure for photovoltaic arrays produce larger energy outputs of DC electricity (George & Maxwell, 1999). However, outdoor temperatures, weather, organic materials, and terrain also impact solar cell performance (Tyagi et al., 2013; Zehner, 2012). Dust, snow, trees, buildings, and other objects impede sunlight absorption, reducing the overall performance (Tyagi et al., 2013; Zehner, 2012). Higher outdoor temperatures also reduce efficiency, causing cells to heat up outside optimal levels (Tyagi et al., 2013). Temperatures, weather patterns, and organic matter all degrade photovoltaic materials, reducing performance over time (Zehner, 2012). Lower outdoor temperatures with clear skies provide the optimal conditions for achieving the maximum energy output from a solar photovoltaic cell (Tyagi et al., 2013).

The configuration, size, and efficiency of a solar cell, module, or array contribute to performance outputs (Parida et al., 2011). Ideal arrangement minimizes energy losses while utilizing the maximum area within a module for creating electricity (Goetzberger et al., 2003). Photovoltaic panels create DC electricity that is converted to AC for travel across power lines and uses within society (Fathabadi, 2017; Ochoa & Harrison, 2010). To minimize losses, energy generation, conversion, and distribution require equipment optimization throughout all processes (Ochoa & Harrison, 2010).

Each photovoltaic module uses a fixed or tracking platform that affects performance (Hammad et al., 2017; Huld et al., 2008). Fixed platforms constrain panels to a specific orientation (known as azimuth or γ) and inclination (known as tilt or β) (Darhmaoui & Lahjouji, 2013; Khan et al., 2020). Rules of thumb require panels to face perpendicular to the equator at an inclination (β) equal to the location latitude (Darhmaoui & Lahjouji, 2013; Khan et al., 2020). The rules of thumb provide optimal annual energy generation, utilizing both summer and winter sun orientations (Darhmaoui & Lahjouji, 2013; Khan et al., 2020). Panels require shallower inclination angles (β) for greater summer energy generation due to the sun’s high sky location (Darhmaoui & Lahjouji, 2013). Winter optimization requires steeper inclination angles (β) due to the sun’s low sky location (Darhmaoui & Lahjouji, 2013). Individuals on occasion bias panel orientation to generate optimal energy output for specific seasons (Khan et al., 2020). Biasing panel orientation depends on demand such as increase heating and energy needs during Winter.

Tracking systems increase energy generation and optimization for all seasons by changing a panel’s orientation and angle relative to the sun (Dolara et al., 2012; Hammad et al., 2017; Huld et al., 2008). Tracking systems consist of one-axis and two-axis setups that use sensors, motors, and rotating mounts to obtain the maximum energy output (Dolara et al., 2012; Hammad et al., 2017; Huld et al., 2008). One-axis tracking changes the orientation or inclination of panels each day to improve energy output (Dolara et al., 2012). Two-axis tracking adjusts orientation and inclination for maintaining perpendicular normality to the sun, providing optimal energy generation (Hammad et al., 2017; Huld et al., 2008). Two-axis tracking provides the optimal annual energy output, however, location and economics determine mounting systems and adoption (Hammad et al., 2017).

2.8 Photovoltaic Market Adoption

The adoption of photovoltaics continues as renewable energy technology costs decrease while producing free, zero-emission electricity (Maycock, 2005). The space race of the cold war pushed researchers to identify methods for reducing cost while improving performance (Hodge, 2017; Loferski, 1993). A commercial solar photovoltaic panel in 1955 cost $1785 per Watt compared to $2 in 2018 (Fu et al., 2018; Hodge, 2017). As performance improved and cost decreased, individuals began to implement photovoltaics for terrestrial application (Green, 1990).

Governments aided photovoltaic implementation by providing subsidies, low-interest loans, and other incentives to reduce upfront costs (Goetzberger et al., 2003; Kazmerski, 2006; Maycock, 2005). Public education and awareness further increased the adoption of photovoltaic technology for terrestrial applications (Kazmerski, 2006). Companies continue installing photovoltaic arrays on buildings, uninhabited lands, vehicles, and other infrastructure to save money on electricity expenses (Kurokawa et al., 2009; Lagorse et al., 2009; Rizzo, 2010; Sreenath et al., 2020). The overall savings occur over time and depend on the modules chosen for installation.

Mono-Si and poly-Si cells dominate 90 percent of photovoltaic market shares combine, achieving 25 and 20 percent peak cell efficiencies, respectively (Polman et al., 2016). Other materials fail to compete against crystalline silicon materials due to high efficiencies and low cost (Polman et al., 2016). Poly-Si leads mono-Si market shares 65 to 35 percent, respectively, due to lower cost and comparable module efficiency (Polman et al., 2016). GaAs produce the highest efficiencies, setting a record at 47 percent, but cost more than either crystalline silicon material (Geisz et al., 2020; Tyagi et al., 2013). Thin-films hold the third-largest market share of solar photovoltaics, achieving lower efficiencies than crystalline silicon at less cost (Tyagi et al., 2013).

Transparent photovoltaic (TPV) concepts appeared during the 1970s oil crisis as researchers searched for alternative forms of energy generation (Debije & Verbunt, 2012). Researchers continued to identify improvements for TPV’s, achieving better cost and performance (Fathi et al., 2017; Goldschmidt, 2018; Takeoka et al., 1993; Traverse et al., 2017; Vasiliev & Alameh, 2019). Material improvements led researchers to investigate TPV applications for building and vehicle integration to generate clean energy (Fathi et al., 2017; Miyazaki et al., 2005; Saleem et al., 2020; Takeoka et al., 1993). Transparent photovoltaic tint varies based on requirements, generating sunlight while improving heating or cooling loads within buildings (Fathi et al., 2017; Traverse et al., 2017; Vasiliev & Alameh, 2019). However, cost and economics continue slowing market adoption of TPV’s. Transparent photovoltaics cost two to four times more than traditional crystalline silicon panels (Extance, 2018; William, 2021). The new technological emergence and combined use of glass material contribute to the higher cost of the technology (Extance, 2018; William, 2021). Comparing the combined cost of photovoltaics and glass as one entity provides a better metric for economic comparison. As time progresses, research and development continue to innovate photovoltaic technology and improve market adoption. Increasing market adoption of photovoltaic technology relies on overcoming challenges to improve savings, performance, and reliance.

2.9 Photovoltaic Reliability Challenges

Renewable energies rely on weather patterns such as wind, rain, and sunlight to generate energy (Inman et al., 2013; Yang et al., 2018). Unpredictable weather patterns make renewable energy integration difficult, requiring fossil fuel generation to meet demands when unavailable. (Inman et al., 2013; Tuohy et al., 2015; Yang et al., 2018). Unpredictable energy generation also creates changes in electricity load on the grid, requiring load balancing (Inman et al., 2013; Tuohy et al., 2015). Solar forecasting and energy storage present solutions for improving the integration of photovoltaics and other renewable technologies (Keck et al., 2019; Tuohy et al., 2015).

2.9.1 Photovoltaic Solar Forecasting

Solar forecasting uses sensors, models, and historical data to predict weather patterns (Inman et al., 2013; Tuohy et al., 2015; Yang et al., 2018). Several methods for solar forecasting exist to identify renewable energy availability (Inman et al., 2013; Tuohy et al., 2015; Yang et al., 2018). Forecasting identifies energy availability and determines when other forms of electricity generation are needed to meet society's demands (Inman et al., 2013). Improvements in solar forecasting methods provide better understanding and knowledge for renewable energy integration to meet demands while providing clean electricity generation (Tuohy et al., 2015; Yang et al., 2018). Solar forecasting combine with energy storage improves the reliability and adoption of renewable energy technologies to balance demand and grid loading (Inman et al., 2013; Keck et al., 2019).

2.9.2 Photovoltaic Energy Storage

Energy storage provides solutions for renewable energy reliability issues (Keck et al., 2019). A photovoltaic panel requires sunlight to create energy instantaneously from solar photons (Greacen, 1991). Every location on Earth experiences sunlight, varying based on location, terrain, and annual weather patterns (George & Maxwell, 1999). When sunlight is unavailable, energy storage provides demand requirements while balancing grid loads (Connors, 2007; Inman et al., 2013; Rajeev et al., 2009). Australia uses 100 MW of Tesla batteries combined with renewable energy to provide clean electricity generation and storage (Keck et al., 2019; Lu et al., 2017). The batteries provide constant electricity and grid balancing, creating an effective, economical clean energy system (Keck et al., 2019; Lu et al., 2017). Battery electric vehicles combine with photovoltaic technologies present additional solutions for energy generation and storage through smart grid integration concepts (Fathabadi, 2017; Mwasilu et al., 2014).

2.10 Electric Vehicles

Robert Henderson created the first battery-powered electric carriage during the 1830s (Saleem et al., 2020; Yong et al., 2015). Throughout the 1800s, researchers made improvements to battery electric vehicle (BEV) technology, identifying rechargeable lead-acid batteries and high-efficiency DC motors (Yong et al., 2015). By the 1900s, electric, gasoline, and steam powered vehicles competed within the automotive market (Kirsch, 2000; Rajashekara, 2013; Situ, 2009). The BEV dominated the automotive market in the early 1900s due to better performance (Kirsch, 2000; Rajashekara, 2013; Saleem et al., 2020; Situ, 2009; Yong et al., 2015). By the 1930s, internal combustion vehicles (ICV) surpassed BEV's after achieving performance improvements (Kirsch, 2000; Rajashekara, 2013; Saleem et al., 2020; Situ, 2009; Yong et al., 2015). The BEV lacked reliable infrastructure and driving range compared to ICV's, reducing popularity while motivating research improvements (Situ, 2009; Yong et al., 2015).

Researchers continued experimenting with different forms of energy propulsion and storage systems until the 1970s oil crisis (Rajashekara, 2013). The oil crisis brought BEV's and other alternative fuel vehicle ideas into the spotlight for a brief period until cheap gasoline prices returned (Kowalewicz & Wojtyniak, 2005). General Motors (GM) introduced the EV1 in 1996, an electric vehicle capable of 100 miles of driving range and speeds of 80 miles per hour (Johnson, 1999; Kirsch, 2000; Situ, 2009). Other automakers soon followed GM by developing electric vehicles aided by fund programs from the U.S. Department of Energy (Situ, 2009).

2.11 Adoption of Electric Vehicle Technology

Government incentives pushed companies, researchers, and consumers to identify and adopt alternative energy vehicles (Sun et al., 2019). Toyota introduced the Prius in 1997, a hybrid electric vehicle (HEV) that led to a declining interest in pure BEV's (Rajashekara, 2013). The HEV improved fuel economy by optimizing efficiency between electric motor and internal combustion engine (ICE) operations, reducing GHG emissions (Arshad & Ashraf, 2020; Zhou et al., 2015). Honda followed Toyota, introducing the Insight in 2000, beginning BEV technology trends for consumer vehicles (Situ, 2009). Trends and incentives for electric vehicles led to new technological discoveries and emerging companies (Wesseling et al., 2014).

Tesla Motors emerged as a pure BEV manufacturer, releasing the Roadster in 2003 (Rajashekara, 2013). The Roadster used lithium-ion batteries, providing a range of 200 miles while achieving speeds of 125 mph (Rajashekara, 2013). Other automakers began producing new HEV's and alternative fuel vehicles by 2008, increasing market competition (Situ, 2009). Honda introduced the Clarity as the first commercial hydrogen fuel cell electric vehicle (FCEV's) (Ajanovic & Haas, 2020). The Clarity used hydrogen to generate electricity through fuel cells and power electric motors (Ajanovic & Haas, 2020). The FCEV remains a small share of the automotive market due to infrastructure, cost, and safety concerns (Ajanovic & Haas, 2020). Automakers continued developing HEV's and EV's with GM releasing the Volt, the first plug-in hybrid electric vehicle (PHEV) (Situ, 2009). The Volt allowed operation using pure electric mode or hybrid driving (Situ, 2009). The Volt allowed owners to recharge vehicle batteries from the electric grid like a pure BEV while utilizing HEV technology (Situ, 2009). Automakers continue producing HEV, PHEV, and BEV vehicles as the world pursues a sustainable future (Cano et al., 2018; Rajashekara, 2013). Competition and demand continue to sustain developments of EV technology within the transportation industry and motorsports (Wesseling et al., 2014).

Motorsport competitions continue implementing and transitioning to EV technology to improve performance (Schoeggl et al., 2012). Formula 1 began using hybrid technology in 2009, providing better performance (Schoeggl et al., 2012). The progression of EV technology continues into other motorsports competitions including rallycross, GT3, and LMP (Schoeggl et al., 2012). The Fédération Internationale de l'Automobile (F.I.A.) introduced Formula E in 2013 to promote pure electric vehicle racing while increasing research and development (Schoeggl et al., 2012). Motorsports push researchers to identify new technological advantages to obtain a competitive edge and improve performance (Schoeggl et al., 2012; Wesseling et al., 2014). Performance improvement discovered within motorsport permeate into consumer vehicles, leading to greater efficiencies and technological adoption (Doi et al., 1998).

2.12 Electric Vehicle Performance

Electric vehicle technologies improve vehicle performance for motorsports and consumer vehicles (Arshad & Ashraf, 2020; Schoeggl et al., 2012; Zhou et al., 2015). Electric motors achieve greater efficiencies than ICE's, transforming more potential energy into kinetic (Ma et al., 2012). Engineers design electric motors to fit various shapes and sizes, allowing installation within ICE configurations or distribution to each wheel (Ganta, 2020). Motor wheel distribution reduces energy losses from transfer throughout the vehicle while providing improved balance and handling (Ganta, 2020). Electric motors also provide regenerative braking and brake steering, further improving performance (Ganta, 2020; Kumar, 2020; Subramaniyam et al., 2018; Yong et al., 2015).

Electric motors require little maintenance while achieving wide speed ranges, power outputs, low noise, and high torque densities (Rajashekara, 2013). The power output depends on the voltage and current required to meet design goals (Gnaciński et al., 2019). Power results from the combination of voltage and current (Gnaciński et al., 2019). Current defines the speed of electricity while voltage provides the energy potential (Gnaciński et al., 2019). Current generates energy losses that increase with electricity speed, requiring a need to improve performance (Gnaciński et al., 2019). Researchers identified high voltage motors as a solution to reduce current requirements while providing the same power output and improving efficiency (Jung, 2017). Researchers continue to investigate performance improvements for increasing EV adoption while reducing cost and overcoming other challenges.

2.13 Electric Vehicle Challenges

The electric vehicle faces several challenges for consumer adoption including driving range, cost, infrastructure, and education. All vehicles rely on energy storage for propulsion while providing capabilities for traveling from direct infrastructure connections. Space and weight capacities limit storage and driving range for all vehicles, ICV's and BEV's. The ICV uses fuel tanks while BEV's use rechargeable batteries, providing more driving range potential once either is refilled (Cano et al., 2018). Improvements in battery technology led to the adoption of lithium-ion technology, replacing lead-acid batteries (Connors, 2007). Lithium-ion provides better energy density, increasing capacity and range at a higher cost (Cano et al., 2018). However, charging infrastructure and speed pose challenges for electric vehicle driving range and adoption.

2.13.1 Driving Range Challenges

Installed infrastructure provides convenient refueling for ICV's, allowing long-distance travel (Hardman et al., 2018). Charging infrastructure for BEV's continues to grow but is inadequate for distant travel (Hardman et al., 2018). Individuals must plan for long journeys by identifying charging stations to prevent becoming stranded, known as range anxiety (Cano et al., 2018). Researchers surveyed consumers regarding BEV's, concluding over fifty percent of drivers require 175 miles of driving range for adoption (Cano et al., 2018). Range anxiety prevents consumers from purchasing BEV’s along with increased charging times compared to ICV’s (Cano et al., 2018). Battery electric vehicles take longer to recharge than filling a gas tank, reducing convenience and ease compared to ICV’s (Ganta, 2020; Hardman et al., 2018; Sivasankar et al., 2020).

Tesla installed a network of supercharging stations along the U.S. interstates, improving travel and charging time for Tesla vehicles (Stringham et al., 2015). However, charging stations cost more compared to home charging, reducing savings when compared. Other automaker vehicles also require different charging stations and connections due to Tesla’s exclusive plug configuration (Yong et al., 2015). Furthermore, supercharging degrades battery life, requiring earlier replacement and increased cost (Shirk & Wishart, 2015). Electric vehicle infrastructure combine with cost and education present further challenges for large-scale consumer adoption.

2.13.2 Cost and Education Challenges

New battery electric vehicles cost $15,000 more than ICV’s and $4,000 more over a vehicle’s life cycle according to Aguirre et al. (2012). The exact cost difference depends on the specific vehicle comparison but remains a hurdle for consumer adoption along with education and awareness (Aguirre et al., 2012; Hardman et al., 2018). Interested consumers lead to greater awareness of battery electric vehicle technology and the associated benefits (Hardman et al., 2018). Researchers continue investigating new technologies to increase safety, energy storage, driving range, and charging time while reducing cost. In 2021, GM and Ford pledged to invest 27 and 29 billion dollars, respectively, for EV research (Baldwin, 2021). The higher cost, increased refueling times, smaller infrastructure, and driving range make battery electric vehicles less desirable by consumers (Wesseling et al., 2014). Inventors and innovators continue pushing improvement, identifying new charging and energy storage concepts.

Ganta (2020) discusses a battery rental program as another source of quick charging, increasing driving range. Honda researched techniques for dynamic charging through contact and non-contact methods, increasing vehicle range (Tajima et al., 2017). Solar electric vehicle concepts demonstrate dynamic vehicle charging possibilities for increasing driving range from photovoltaic electricity generation. New electric vehicle charging concepts require research, investment, and cooperation from governments and industry for adaptation and adoption.

2.14 Solar Electric Vehicles

The oil crisis of the 1970s led to increased research for alternative vehicle propulsion technology (Connors, 2007; Rizzo, 2010). The emergence of photovoltaic technology combined with known battery electric vehicle technology sparked the solar electric vehicle idea (Connors, 2007; Rizzo, 2010). The SEV relies on battery storage, dynamic electricity generation from solar photovoltaic frame integration, and grid charging to power vehicle propulsion (Connors, 2007; Rizzo, 2010). Researchers and governments promoted SEV race competitions to increase technology awareness, holding competitions in the U.S. and Australia that became known as solar races (Connors, 2007; Rizzo, 2010). The SEV idea never commercialized after cheap oil returned, remaining at a sport and research level (Connors, 2007; Rizzo, 2010).

Mangu et al. (2010) developed a solar electric vehicle that achieved 75 mph and 75 miles of range using a five-kilowatt-hour battery pack. Delft University created solar electric vehicles using 6 m^2 of solar panels for the solar races (Rizzo, 2010). The university designs showcased solar electric vehicle possibilities but unrealistic use as consumer vehicles due to design. Western Washington University later developed the Viking 23, improving potential consumer usability compared to previous solar electric vehicles (Rizzo, 2010). Researchers continue investigating solar electric vehicle concepts to achieve consumer-friendly vehicles.

Ahmed et al. (2014) presented a two-seater SEV design for urban commuting, discussing the cost-effectiveness and pollution reduction potential. Mohammadi (2018) researched and designed a SEV suitable for all environments to work without the electric grid on or off-road. Saleem et al. (2020) investigated photovoltaic integration on every surface of an electric-powered bus, improving driving range and charging time. Researchers continue to investigate concepts of photovoltaic integration for electric vehicles to achieve a sustainable future.

2.14.1 Photovoltaic Automotive Applications

Takeoka et al. (1993) investigated the integration of transparent photovoltaics on a car’s sunroof, showing potential for integration among other glass surfaces. However, the transparent photovoltaic presented by Takeoka et al. (1993) used dark, opaque solar cells, reducing visibility. Government laws limit window tint to provide visibility and safety. Rizzo (2010) presents consumer vehicle photovoltaic integration including a Toyota Prius and Fiat Phylla that powered electronic applications. Volkswagen, Hyundai, and Fisker Automotive also provided concepts for photovoltaic integration that have commercialized into consumer vehicles (Mohammadi, 2018; Muoio, 2016; Templeton, 2019). Solar photovoltaics provides clean energy generation for remote locations and mobility operations when sunlight is available (Connors, 2007; Inman et al., 2013; Rajeev et al., 2009). Photovoltaic electric vehicle integration presents dynamic charging opportunities, providing power for vehicle applications and improving driving range while saving money (Mohammadi, 2018; Rizzo, 2010; Saleem et al., 2020). Photovoltaic vehicle integration can also improve electricity grid loading and balancing, serving as generators while reducing power plant demands (Fathabadi, 2017; Mohammadi, 2018). Researchers continue to investigate and analyze new designs while automakers present new electric vehicle concepts. Aptera emerged as a solar electric vehicle company, releasing its first vehicle in 2021 (Kaplan, 2021). The Aptera achieved a top speed of 110 mph, can provide 45 miles of charging range each day (Kaplan, 2021).

2.15 Financial Assessment of E.V. and P.V. Technologies

Photovoltaic and electric vehicle technologies present solutions for providing financial savings over time (Aguirre et al., 2012; Dumortier et al., 2015; Good et al., 2015; Miyazaki et al., 2005; Mousa et al., 2019). Photovoltaic systems cost an average of $2 per Watt, including manufacturing, transportation, and installation (Fu et al., 2018; Polman et al., 2016). After installation, photovoltaics generate clean, free energy from the sun, saving money over time (Kannan et al., 2006). The energy savings add up to the total system cost over time, known as payback period (Kannan et al., 2006). The payback period varies depending on weather, location, system, and utility purchase price of electricity (Knapp & Jester, 2000). Owners continue to save money on electricity bills after reaching payback until the system's end of life (Kannan et al., 2006). Photovoltaics have some disposal value for recycling at the end of life, creating additional monetary and GHG savings (Tyagi et al., 2013).

The average battery electric vehicle costs more than internal combustion vehicles, however, the vehicles chosen for comparison determine actual financial savings (Aguirre et al., 2012; Dumortier et al., 2015). Battery electric vehicles require less maintenance while electricity is cheaper per mile than gasoline, creating financial savings over a vehicle's life cycle (Aguirre et al., 2012; Dumortier et al., 2015). At the end of life, battery electric vehicles possess recyclable technologies and materials, creating salvage value while further improving financial savings.

The combination of photovoltaic electric vehicle integration presents opportunities for increasing financial savings. The photovoltaic panels provide free electricity that powers the vehicle's movements. While researchers have investigated photovoltaic integration on electric vehicles, no research has investigated a vehicle replacing all glass with transparent photovoltaics. A vehicle using transparent photovoltaics as glass is investigated to determine the amount of energy generation from an automobile and associated benefits.

CHAPTER 3. RESEARCH METHODOLOGY

The research methodology consists of two main sections: energy and financial analyses. The energy analysis uses software, data, equations, and estimates to model an expected photovoltaic system output. The financial analysis uses the energy output, estimates, and equations to determine costs and savings. Each area focuses on different data and background information covered within each section. The results of both analyses provide the expected energy output and financial savings of the photovoltaic system under investigation. Appendix D lists the process for achieving the results using Appendices A, B, and C and E.

3.1 Reliable

The methodology adheres to accepted practices for conducting technical and financial analyses. The energy analysis uses assumptions, equations, and data obtained from peer reviewed articles, books, and databases to provide accurate, reliable, and valid results (Dobos, 2014; Duffie & Beckman, 2013). Equations include the Liu and Jordan model for calculating the solar irradiance experienced by a fixed surface (Berrizbeitia et al., 2020; Duffie & Beckman, 2013; LeBaron & Dirmhirn, 1983). The Liu and Jordan model provides methods to calculate solar irradiance while accounting for altitude and sunlight diffusion through clouds (Berrizbeitia et al., 2020; Duffie & Beckman, 2013; LeBaron & Dirmhirn, 1983). Researchers use the Liu and Jordan model to study solar irradiance of photovoltaic systems across the globe (da Silva et al., 2019; Kazem et al., 2013; Mondol et al., 2008).

The financial analysis uses engineering economic practices from published and reviewed sources for determining the time value of money of the system (Duffie & Beckman, 2013). Following the research methodology provides result replication and reliability for each analysis and process.

3.2 Validity

The National Renewable Energy Lab (NREL) System Advisor Model (SAM) (*SAM Downloads*, n.d.) provides methods for comparing energy and financial analyses results (Dobos, 2014). Researchers at NREL conducts investigations throughout all fields of renewable energy, publishing peer reviewed articles detailing energy equations and financial analysis of systems. Employees at NREL created SAM for public use, allowing individuals to model energy systems based on published and reviewed equations (Dobos, 2014).

The financial assessment uses energy calculations to determine financial savings. The financial analysis follows time value of money engineering economics equations to calculate cost and savings while providing accurate results. The financial analysis uses assumed values of interest, inflation, and discount rate needed to determine financial costs and savings provided. The calculation values from both energy and financial analysis studies are compared to NREL's SAM values to ensure accuracy (Dobos, 2014; Duffie & Beckman, 2013).

3.3 Energy Analysis

The energy analysis consists of two subsections, data gathering and modeling. Data gathering identifies values and estimates from literature and databases to conduct the energy modeling analysis. Modeling utilizes the gathered data within computer calculation software to obtain an energy output from transparent photovoltaics.

3.3.1 Data Gathering

Solar irradiation location data, equations, and estimates provide methods for calculating the system's energy output. Solar irradiation provides energy for the photovoltaic system while estimates provide parameters for obtaining results. Both solar irradiation and system estimates provide necessary information for determining a solar array's output based on technical engineering practices (Berrizbeitia et al., 2020; Duffie & Beckman, 2013; LeBaron & Dirmhirn, 1983).

The area, efficiency, orientation, and inclination of each transparent photovoltaic solar panel affects energy output, requiring conservative estimates to reflect realistic performance. Estimate values derived from the literature review provide reliable results that reflect a real-world output.

The location for analysis requires historical solar irradiation data gathered from a reliable source. The SAM software provided by NREL houses a database of typical meteorological year (TMY) data at a specific location, including solar irradiance, temperature, and humidity.

Irradiance, temperature, and humidity all affect solar cell performance. SAM provides TMY data that investigators export into a .CSV spreadsheet for calculations. The spreadsheet provides data for calculations to estimate solar photovoltaic energy output at specific locations. Appendix E shows a brief example of the TMY data spreadsheet formatted for the analysis.

3.3.2 Energy Modeling

The energy modeling uses scientific equations to estimate the expected energy output of each panel (Duffie & Beckman, 2013). Using the gathered data within the equations provides an estimated energy output for each hour. Multiple iterations of calculations provide an estimated energy output over a specific length of time. The solar irradiation data obtained from SAM provides only one year of TMY data for analysis, limiting iterations quantity. As time progresses, degradation causes energy output to decrease, reducing energy savings and salvage value over time. Accounting for degradation provides realistic values for financial calculations.

MATLAB conducts the mathematical calculations using known equations, solar irradiation data, and assumptions to obtain the expected energy output for a single year (*MATLAB*, n.d.). MATLAB provides methods for the calculation and implementation of large data sets. Solar energy equations 1 through 10 listed by Duffie and Beckman (2013) provide methods for estimating the system's energy output. Researchers use the equations to estimate and validate real world results or compare to other solar irradiance models (Berrizbeitia et al., 2020; da Silva et al., 2019; Duffie & Beckman, Kazem et al., 2013; 2013; LeBaron & Dirmhirn, 1983; Mondol et al., 2008). Equations 1 through 10, listed below, provide energy analysis results for the investigation. Degradation calculations use the present worth equation 11 to account for annual exponential energy losses.

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$$\text{Solar Time} = \text{Standard Time} + \frac{4*(L_{st}-L_{loc})}{60} + \frac{E}{60} \qquad (1)$$

<u>Where:</u>

Solar Time – suns position relative to the study location

Standard Time - local time without daylight savings correction

L_{st} = Longitude of Standard Time Zone

L_{loc} = Longitude of Location

$$E = 9.87*\sin(2*B)-7.53*\cos(B)-1.5*\sin(B) \quad (2)$$

$$B = 360*(n-81)/365 \quad (3)$$

n = day of the year

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (4)$$

<u>Where:</u>

$$\cos\theta = \sin(\delta)*\sin(\phi)*\cos(\beta) - \sin(\delta)*\cos(\phi)*\sin(\beta)*\cos(\gamma) + \cos(\phi)*\cos(\delta)*\cos(\beta)*\cos(\omega) + \cos(\gamma)*\sin(\phi)*\cos(\delta)*\sin(\beta)*\cos(\omega) + \sin(\gamma)*\cos(\delta)*\sin(\beta)*\sin(\omega) \quad (5)$$

$$\cos\theta_z = \cos(\phi) * \cos(\delta) * \cos(\omega) + \sin(\phi) * \sin(\delta) \quad (6)$$

$\delta = 23.45\sin(360\left(\frac{284+n}{365}\right))$ solar declination (7)

β = panel inclination (tilt angle)

ω = 15*(Solar Time – 12) hour angle (8)

ϕ = latitude

γ = orientation (azimuth)

$$I_T = I_b R_b + I_{d,iso}(\frac{1+\cos(\beta)}{2}) + \rho_g I(\frac{1-\cos(\beta)}{2}) \quad (9)$$

<u>Where:</u>

I_T = total irradiance incidence on a surface

I_b = beam irradiance obtained from TMY data (DNI)

I = total irradiance normal to the earth obtained from TMY data (GHI)

$I_{d,iso} = I - I_B$ Horizontal diffused irradiance (10)

ρ_g = ground reflectance (coverage) ratio

Present Worth: $PW_N(A) = \frac{A(1+i)^{N-1}}{(1+d)^N}$ (11)

3.4 Financial Analysis

The financial analysis requires multiple estimates and calculated values to determine costs and savings. Information from the review of literature and energy analysis provides values for conducting cost calculations. Financial savings depend on system cost, economic rates, salvage value, and maintenance costs over the length of the analysis.

The calculated electricity output determines the amount of energy savings provided by the PV system. The free electricity charges the vehicle's batteries, saving money equal to local electricity rates, i.e., every kWh of electricity generated saves \$0.15. The energy output provides cost savings by reducing charging needs from the electricity grid.

A time value of money assessment using rate and cost estimates determines the economic feasibility of the system. The analysis uses equations derive from common engineering economic practices to estimate financial costs and savings (Duffie & Beckman, 2013). Equations 12 and 13 provide present worth factor calculations required for equations 14, 15, and 16.

Present Worth Factor: $PWF(N, i, d) = \frac{1}{d-i}(1 - (\frac{1+i}{1+d})^N)$ when $i \neq d$ (12)

$PWF(N, i, d) = \frac{N}{1+i}$ when $i = d$ (13)

Where:

N = length of analysis in years

A = Annual cost or energy

i = inflation rate

d = discount rate

Life Cycle Savings (LCS): $LCS = P_1C_E - P_2C_s$ (14)

Where:

$P_1 = PWF(N, i, d)$ Present Worth Factor of future energy payments (15)

C_E = the total cost of energy from the first year after the system is installed

C_S = the total cost of the installed system

P_2 = present worth factor of future costs associated with owning the system

$$P_2 = D + (1-D)\frac{PWF(N_1,0,d)}{PWF(N_L,0,m)} + M_s PWF(N_L, 0, m) \quad (16)$$

Where:

D = ratio of down payment over initial cost

N_L = Length of loan in years

N_1 = Minimum between N_L and N

m = annual interest rate of loan

M_s = system maintenance cost per year as a fraction over the initial system cost

CHAPTER 4. RESULTS

The results display both MATLAB (Version R2020a) and SAM (Version 2020.11.29) analysis methods for comparison and validation. The MATLAB analysis uses all equations from Chapter Three to calculate the energy output and financial costs. The SAM software uses embedded equations within the PVWatts for calculating energy output and financial costs (Dobos, 2014). SAM provides an option to download the data with equations as an excel spreadsheet for in-depth investigation. Both SAM and MATLAB use the same estimates with minor differences since each uses different calculation methods (Dobos, 2014; Duffie & Beckman, 2013).

4.1 Assumptions

The MATLAB calculations require educated estimate values to determine energy output and financial costs. The MATLAB model also uses equations that require solar panel orientation values between -180 and 180 degrees for North (-180 or 180), South (0), East (-90), and West (90), differing from PVWatts. Both calculation methods require location data, module information, and financial parameters. APPENDIX A lists all assumptions used for MATLAB calculations conducted using the code displayed under APPENDIX C.

The PVWatts distributed residential calculator provides a valid method for determining and comparing the system under investigation. PVWatts provides a simple method for calculating annual energy output, expected performance over time, and financial performance. All calculations use embedded equations within the software that require estimated and assumed values (Dobos, 2014). APPENDIX B listed the estimated values used within PVWatts. PVWatts requires more inputs for calculations compared to MATLAB calculations. Minor differences include orientation angles (0 degrees North), real versus nominal discount rate, and other factors given within APPENDIX B.

Four transparent photovoltaic solar panels replace a vehicle's windows with assumed areas, inclinations, and orientations. Obtaining each panel’s energy output and financial costs required four calculations using each program, changing energy and financial parameters. The study investigates West Lafayette, Indiana as starting location due to the temperate climate. The vehicle faces south as shown by Figure 4.1, indicating the orientation of each transparent photovoltaic panel given within Appendices A and B. Appendix D provides the process for achieving the results using appendices A, B, and C. Appendix A lists the assumptions for MATLAB calculations. Appendix B lists the estimates for PVWatts calculations. Appendix C provides the MATLAB code used for calculations.

Figure 4.1: Vehicle and photovoltaic orientation

The front windshield faces south towards the sun and provides a larger surface for energy generation. The rear windshield faces north while the driver and passenger side windows face east and west, respectively.

4.2 Results

Table 4.1 lists MATLAB results from each orientation, size, and inclination. The estimates provided by Appendix A and equations from Appendix C generate the results listed within Table 4.1. All annual energy results include values with and without system and environmental losses. The results also list each individual panel's annual energy output, system cost, and overall life cycle savings. Annual energy output with losses provides realistic values for calculating the Life Cycle Savings (LCS), also known as Net Present Value.

Table 4.1: MATLAB results for each transparent photovoltaic panel

MATLAB	North	East	South	West
Area (m^2)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Gamma] (degrees)	180	-90	0	90
Inclination [Beta] (degrees)	30	75	30	75
Annual Energy without losses (kWh)	108	71	171	72
Annual Energy with losses (kWh)	87	57	138	58
System Cost ($)	800	600	800	600
LCS ($)	-932	-706	-890	-705

The south facing solar panel produces the most energy followed by north, west, and east. The area, inclination, orientation, and energy losses all impact the systems life cycle savings. Figures 4.2 and 4.3 provide graphic representation of the results from Table 4.1 for comparison.

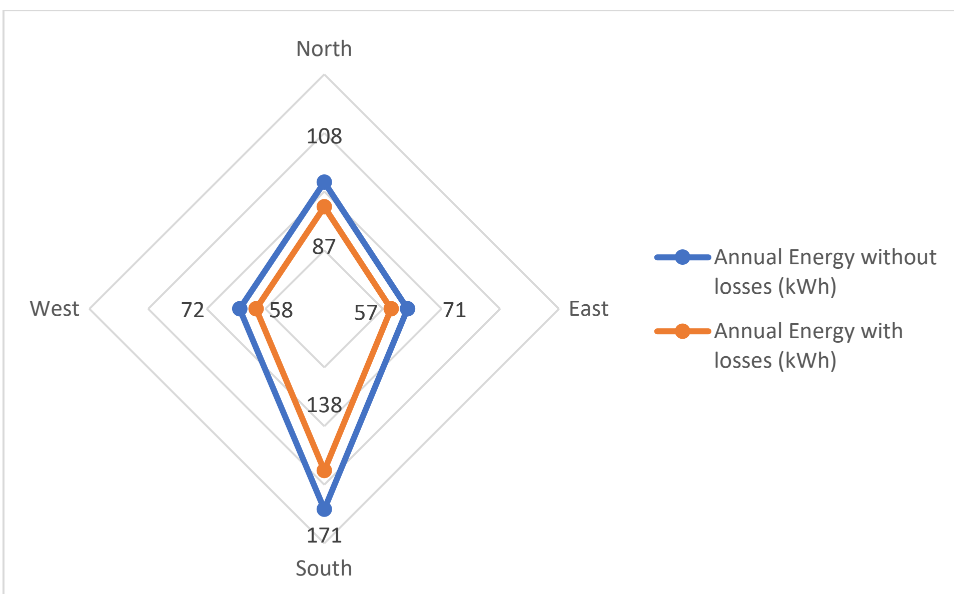

Figure 4.2: MATLAB Annual Energy Output

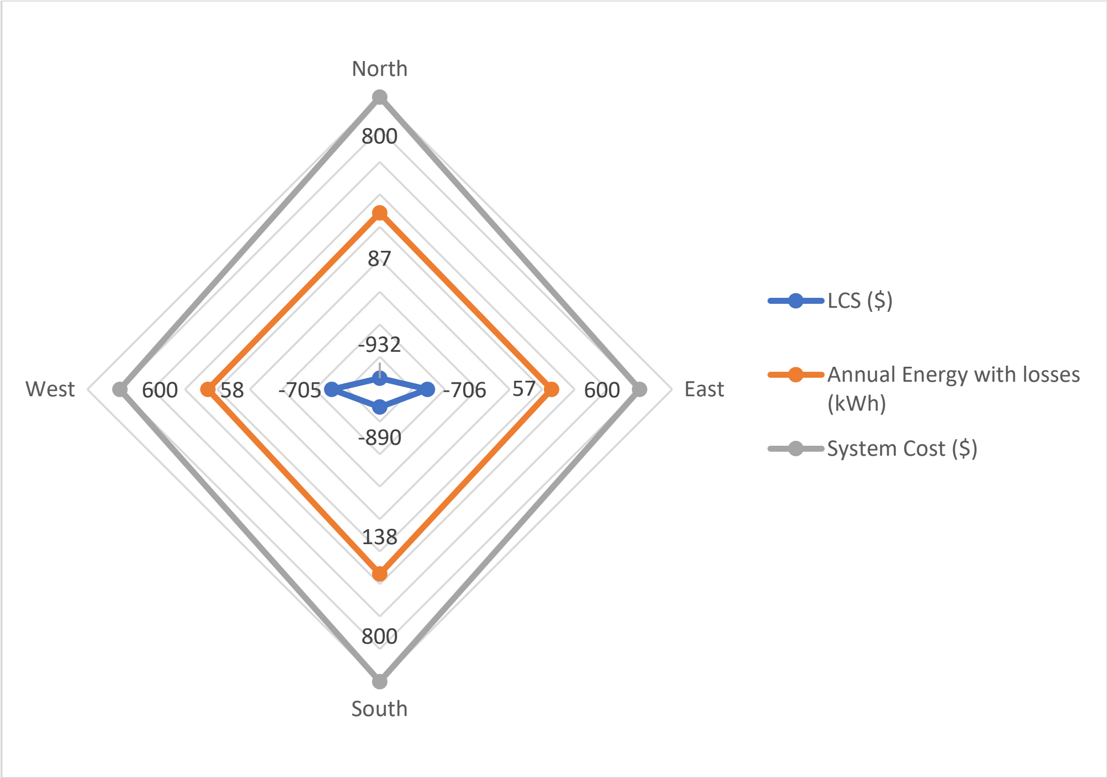

Figure 4.3: MATLAB Annual Energy Output vs Life Cycle Savings and System Cost

Energy losses impact output as shown by Figure 4.2. Each panel experiences the same amount of energy losses, reducing output each year. The reduction in energy output impacts the financial savings over time as shown by Figure 4.3. Both northern and southern panels cost the same using the same area and inclination. However, the southern panel produces more energy due to the orientation relative to the sun. Eastern and western panels produce the least amount of energy due to smaller area, orientation, and inclination. However, the eastern and western facing panels produce the best life cycle savings. The two panels use smaller areas, reducing overall system cost and impacting life cycle savings (LCS).

The investigation also studied the impact of energy generation each month for one single year. The MATLAB equations from Appendix C also provide each month's energy output for comparison as shown by Figure 4.4.

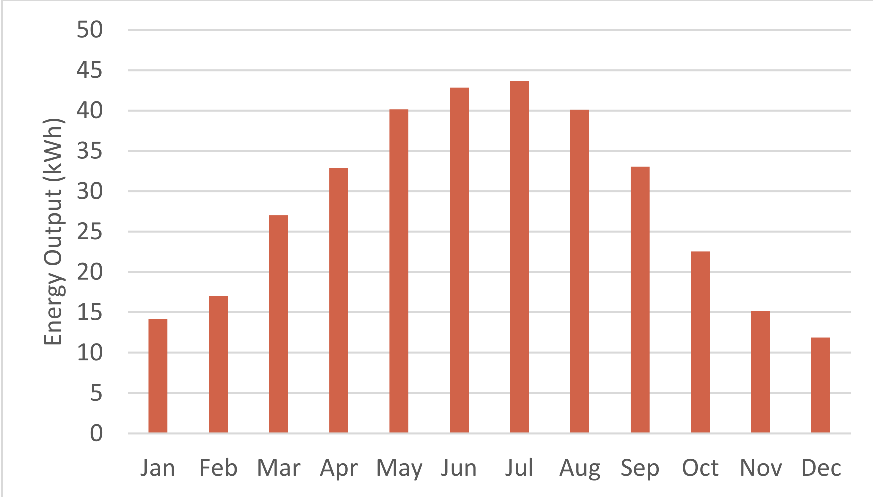

Figure 4.4: MATLAB Monthly Energy Output

Figure 4.4 above shows how energy production changes by month, achieving the greatest generation during July. Longer, less cloudy days occur during the summer months, providing more energy output. Less sunny days and daylight during winter months provides the least potential for energy generation. Producing more energy from the sun requires less electricity from the grid to be purchased, creating more savings.

Table 4.2 lists PVWatts results from SAM including each panel's size, orientation, and inclination. Assumptions under Appendix B provide the results for comparing PVWatts and MATLAB.

Table 4.2: PVWatts results for each transparent photovoltaic panel

PVWatts	North	East	South	West
Area (m^2)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Azimuth] (degrees)	0	90	180	270
Inclination [Tilt] (degrees)	30	75	30	75
Annual Energy without losses (kWh)	95	74	168	75
Annual Energy with losses (kWh)	81	63	143	64
System Cost ($)	800	600	800	600
LCS ($)	-917	-686	-861	-685

Table 4.2 using PVWatts provides similar results compared to Table 4.1. The values from Table 4.2 support the analysis results obtained using MATLAB and the associated energy analysis equations. Figure 4.5 shows a comparison between both MATLAB and PVWatts methods to provide a better graphical representation.

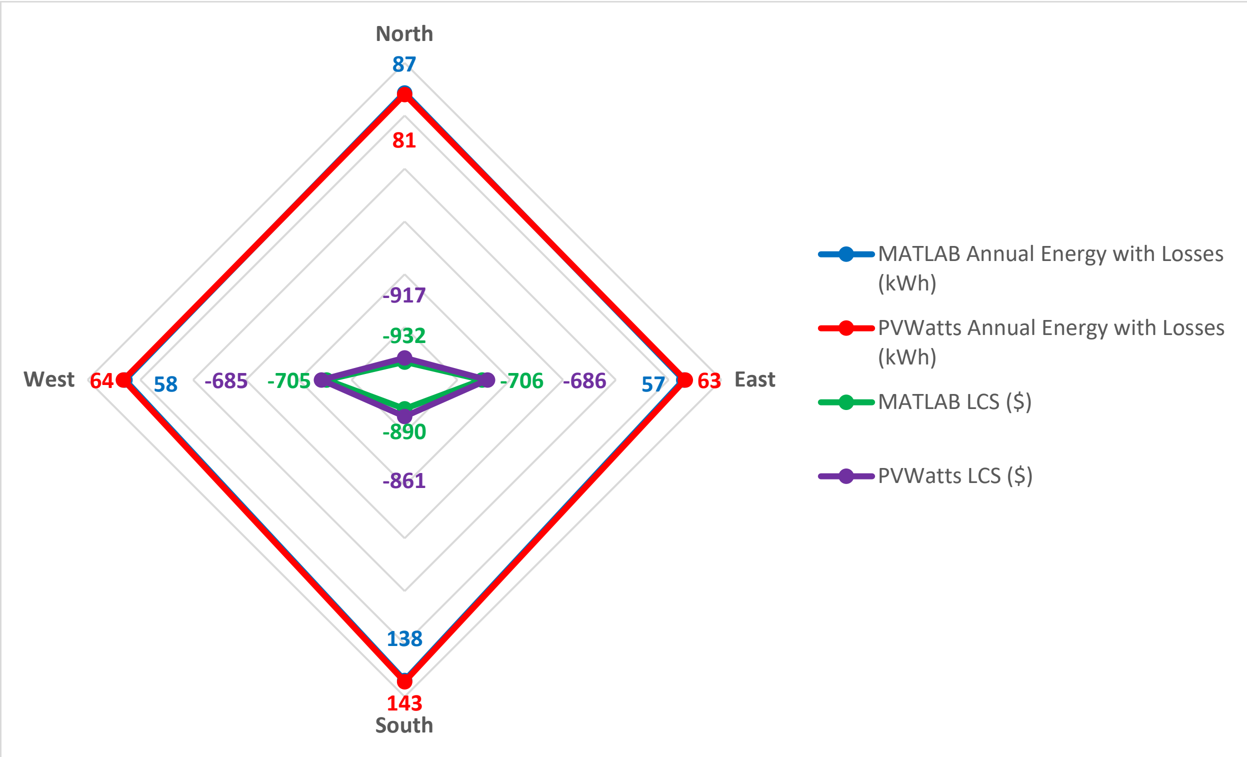

Figure 4.5: MATLAB vs. PVWatts comparison

The MATLAB life cycle savings method brings both annual and single values to the present for financial calculations. The MATLAB method uses the present worth of annual degradation of the entire analysis period, providing the average annual energy output. The present worth calculation conducted using MATLAB creates a lower energy output value compared to PVWatts with losses in year one. The PVWatts method conducts a cash flow analysis for each year, accounting for all losses and degradation. The two calculation methods create a negligible difference for calculating financial savings and annual energy output.

MATLAB uses the Jordan and Lui model to calculate total solar irradiation and energy output for each panel (Duffie & Beckman, 2013). PVWatts calculates the annual energy output using the methods detailed by Dobos (2014) with similar solar irradiance data. The two methods take different approaches but provide similar results. Researchers use both methods to check and support investigations regarding solar photovoltaic systems (Blair et al., 2013; Cameron et al., 2008; da Silva et al., 2019; Kazem et al., 2013; Mondol et al., 2008; ur Rehman et al., 2020). PVWatts uses the same parameters as MATLAB for the analysis to obtain the values within Table 4.2. Figure 4.5 demonstrates similar energy outputs and life cycle savings for both methods. Each result from MATLAB differed from PVWatts within an acceptable margin of error. PVWatts results shown by Table 4.2 support the MATLAB investigation methods, prompting further analysis by changing financial assumptions.

Table 4.3 demonstrates the effects of module cost on life cycle savings. Table 4.3 uses a module cost of $2 per Watt compared to $8 from Tables 4.1 and 4.2.

Table 4.3: MATLAB results for each panel using $2/W and $0.12/kWh

MATLAB	North	East	South	West
Area (m^2)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Gamma] (degrees)	180	-90	0	90
Inclination [Beta] (degrees)	30	75	30	75
Annual Energy without losses (kWh)	108	71	171	72
Annual Energy with losses (kWh)	87	57	138	58
System Cost ($)	200	150	200	150
LCS ($)	-179	-141	-137	-140

Changing the system cost impacts life cycle savings for each panel. The lower system cost improves life cycle savings while reducing the difference between each panel. Table 4.4 takes the process a step further, using $2 per Watt module cost and increasing electricity costs to $0.25 per kWh and $0.38 per kWh. The additional column under Table 4.4 lists the sum of the life savings for all four orientations to find a total life cycle savings greater than zero. Figure 4.6 demonstrates the process for achieving a breakeven point using the results from Table 4.4 and the effects of changing financial parameters.

Table 4.4: MATLAB life cycle savings comparison using different financial estimates

LCS parameters	North	East	South	West	Total
$8/W, $0.12/kWh	-932	-706	-890	-705	-3233
$2/W, $0.12/kWh	-179	-141	-137	-140	-597
$2/W, $0.25/kWh	-101	-90	-13	-88	-292
$2/W, $0.38/kWh	-23	-39	110	-37	11

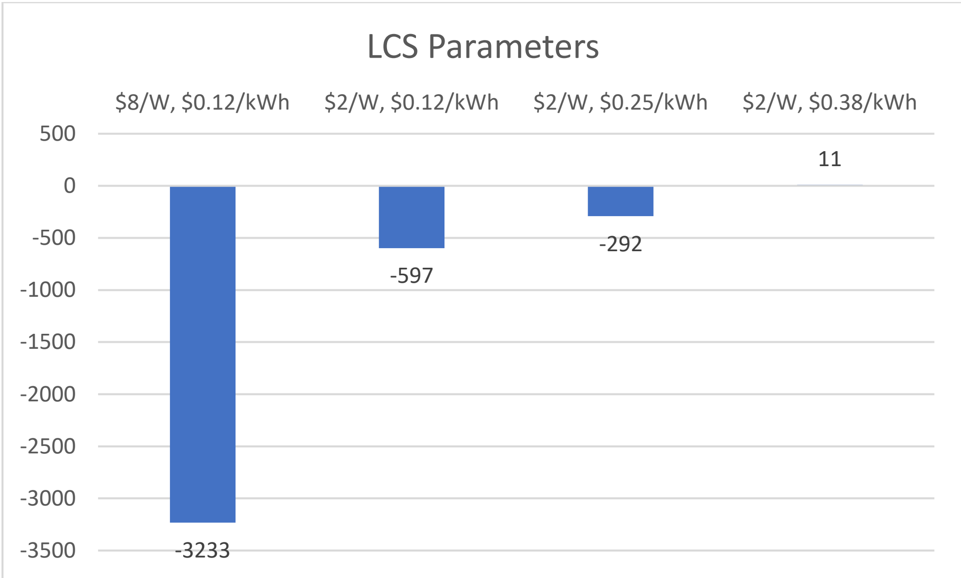

Figure 4.6: Changing financial parameters to achieve a breakeven scenario.

Tables 4.3 and 4.4 provide results from changing financial parameters, lower system costs while improving life cycle savings. Lower system costs and higher electricity rates provide additional life cycle savings by generating free electricity from the sun, creating financial benefits. Figure 4.6 provides a graphical representation of achieving a break even point for the system. The system costs must decrease while electricity costs increase to achieve a more favorable outcome.

4.3 Discussion of Results

Figures 4.2, 4.3, and 4.5 demonstrates that transparent photovoltaics produce energy at all four orientations using different areas and inclinations. The energy output of each panel differs, generating the most from the south facing orientation as expected. The north facing panel produces the second largest output followed by the west and east. The north panel takes advantage of sunlight all day compared to east and west. East and west orientations take advantage of only half the days sunlight, limiting energy output. Inclination, orientation, and area all play a role in capturing energy as discussed within Chapter Two.

Energy losses also impact performance as shown by Figure 4.2. Less energy produced from the system reduces savings as demonstrated by Figure 4.3. Both north and south facing systems cost the same, however, the northern system produces less energy, reducing life cycle savings. East and west facing panels result in near identical cost, energy output, and LCS as shown by Figure 4.3. East and west facing panels also provide the best life cycle cost savings with the least amount of energy produced using an $8 per Watt estimate. After changing costs to $2 per Watt, the differences decreased. The smaller panel size reduces system costs, a major factor in life cycle savings.

Table 4.4 demonstrates that all four panels with different orientations, inclinations, and areas result in negative life cycle savings except for one scenario. Given the correct cost, estimates, and conditions, transparent photovoltaics provide a payback scenario for vehicle integration. While the scenarios result in negative life cycle savings, photovoltaics still provide energy and some return on investment. Compare the cost and return on investment of transparent photovoltaics to regular automotive windows, and the situation presents potential economic feasibility.

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The study analyzed four transparent photovoltaic mimicking vehicle integration, replacing glass windows. The analysis assumed four large transparent photovoltaics with fixed orientations, inclinations, and areas, simulating a parked vehicle. The investigation analyzed annual energy output and life cycle savings of each panel to determine economic feasibility. The study found that using transparent photovoltaics for vehicle integration does not provide a payback period based on present estimates and location. The life cycle savings from the analysis resulted in negative values, indicating the energy savings benefits do not outweigh the current system costs. However, the system does provide annual energy savings, providing potential benefits for owners and the environment. Furthermore, transparent photovoltaics provide potential life cycle savings when compared to regular glass windows and costs are equal.

5.1 Recommendations

Reconduct the analysis to investigate improvements that provide greater energy output and life cycle savings. Improving energy output leads to favorable economics for photovoltaics. Reducing energy losses, providing larger solar irradiation, adjusting orientations or inclinations, and increasing efficiencies present opportunities for improving the output of photovoltaic systems. Improving energy losses occur by optimizing wiring and equipment combine with proper maintenance for operation. Assume fewer losses occur to yield larger energy outputs and provide greater financial savings.

Conduct the analysis at a sunnier location to investigate energy and financial gains. Larger amounts of solar irradiation generate greater energy and financial savings. Adjusting inclination and orientation present additional opportunities for increasing energy output but become difficult when using vehicle integration. However, vehicles have different designs making the idea possible. Increasing solar panel efficiencies captures more energy, presenting more potential financial improvements.

Reconduct the analysis to account for tax credits, salvage value, electricity charges, and other financial factors. Taking advantage of federal and state tax credits or renewable initiatives provides rebates for reducing system costs, improving life cycle savings. Using additional electricity charges such as demand, surge, and more increase costs, also improving life cycle savings. Reducing maintenance and operation cost by caring for the systems also improve life cycle savings. Proper care may provide salvage value at the end of a vehicle's life. The solar panels can be salvaged and sold for reuse within other vehicles or applications. Accounting for salvage value within the financial analysis provides additional life cycle savings.

Other charging method investigations present additional opportunities for increasing the adoption and integration of transparent photovoltaics within vehicles. Simultaneous grid and solar charging present opportunities to decrease charging time, improving electric vehicle convenience. Dynamic charging while driving also increases electric vehicle convenience, increasing distance. Both charging methods and smart grid integration for energy storage and tax credits present additional investigation opportunities for affecting costs, savings, and adoption.

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APPENDIX A. MATLAB ASSUMPTION

Energy Assumptions

Location: West Lafayette, Indiana (40.45N, -86.9W)

Eastern Time Zone Longitude -75W

Module Efficiency = 10%

Ground Reflectance Ratio = 0.2

MATLAB	Front Window (South)	Passenger Side (West)	Rear Window (North)	Drivers Side (East)
Area (m^2)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation (degrees)	0	90	180	-90
Inclination (degrees)	30	75	30	75

**System Size = 1 kW/m^2 * efficiency * Area*

Total system losses to soil, shading, snow, wiring, etc. equal 15%

Degradation = 0.5% each year

Financial Assumptions

System cost (Module, inverter, etc.) = $8/W

Fixed Annual Maintenance Cost = 5% of system cost

Maintenance Escalation Rate = 3%

Standard loan

Down Payment = 0% of initial cost

Loan term = 5 years

Interest rate = 4%

Analysis Period = 10 years

Inflation Rate = 3%

Nominal Discount Rate of 10%

Electricity Escalation = 3%

Electricity Rate = 0.12 $/kWh

APPENDIX B. PVWATTS ASSUMPTION

Energy Assumptions

Location: West Lafayette, Indiana

DC to AC Ratio: 1 (no AC used)

Inverter Efficiency: 99.5% (highest allowed, no AC used, only DC for this application)

Module Type: Thin Film (10% efficiency)

Ground Coverage Ratio = 0.2

Array Type: Fixed open rack

	South	West	North	East
Area (m^2)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Azimuth] (degrees)	180	270	0	90
Inclination [Tilt] (degrees)	30	75	30	75

*System Size = 1 kW/m^2 * efficiency * Area*

Total system losses to soil, shading, snow, wiring, etc. equal 15%

Grid limits not used

Degradation = 0.5%

See APPENDIX A for Financial Assumptions

Additional Financial Assumptions Needed for PVWatts:

Debt fraction = 100% (Down Payment = 0% of initial cost)

Real Discount Rate 6.8 (Nominal Discount Rate of 10% with inflation of 3%)

No Project Tax, Insurance Rates, or Salvage Value

No Tax Deductibles, Tax Credits, Direct Cash Incentives, etc.

Net Energy Metering

No Fixed Charges, Minimum Charges, or Monthly Charges

No Load growth rate

APPENDIX C. MATLAB CODE

Two sections of code provided the energy output and financial cost of each collector. The first set of code includes the majority of calculations for solving the energy output and financial costs. The first set of code relies on a solar irradiation data table that must be imported into the program. The second set creates a present worth financial calculation function used for the first set of code.

ENERGY AND FINANCIAL CALCULATIONS

```
%Solar Irradiance Analysis

%Energy Assumptions
Beta = 30;            %Inclination of solar collector in Degrees
Gamma = 0;            %Orientation relative to the equator
area = 1;             %Area of collector [m^2]
Phi = 40.45;          %Latitude of location in degrees
L_loc = 86.9;         %Longitude of location in degrees
L_st = 75;            %Longitudinal location of Time Zone
Rho_g = 0.2;          %Ground reflectance/coverage ratio
Peak_irr = 1000;      %Solar PV irradiation during testing (W/m^2)
PV_eff = 0.1;         %Solar PV panel efficiency
Energy_total = 0;     %Variable for calculating total energy output
deg = 0.005;          %Degradation rate of system over life
losses = 0.15;        %Annual system losses from wiring, snow, soiling, etc.

%Financial Assumptions
N = 10;               %Length of Analysis
Cost_e = 0.38;        %Cost of electricity in $/kWh
PV_cost = 2;          %Cost of PV's in $/W
d_pay = 0.0;          %Down payment ratio of PV array
d = 0.10;             %Discount rate
L_n = 5;              %Loan length
L_i = 0.04;           %Loan interest Rate
i_e = 0.03;           %Annual electricity inflation rate
m_initial = 0.05;     %Annual maintenance as a percentage of initial cost
m_inflating = 0.03; %Annual maintenance inflation rate


m1=0;                 %Month 1 variable
m2=0;                 %Month 2 variable
m3=0;                 %Month 3 variable
m4=0;                 %Month 4 variable
m5=0;                 %Month 5 variable
m6=0;                 %Month 6 variable
m7=0;                 %Month 7 variable
m8=0;                 %Month 8 variable
m9=0;                 %Month 9 variable
m10=0;                %Month 10 variable
```

```
m11=0;              %Month 11 variable
m12=0;              %Month 12 variable

%Calculating total irradiance experienced by an fixed, inclined surface
for run = 1:8760        %For loop to calculate each hours for 1 year
n = tmydata.Day(run);   %Reading data from TMY table to determine day
m = tmydata.Month(run); %Reading data from TMY table to determine month
if (m > 1)              %Adjusting day value n to correct time of year
    if (m == 2)
       n = n + 31 ;     %February
    end
    if (m == 3)
       n = n + 59 ;     %March
    end
    if (m == 4)
       n = n + 90;      %April
    end
    if (m == 5)
       n = n + 120 ;    %May
    end
    if (m == 6)
       n = n + 151 ;    %June
    end
    if (m == 7)
       n = n + 181 ;    %July
    end
    if (m == 8)
       n = n + 212 ;    %August
    end
    if (m == 9)
       n = n + 243 ;    %September
    end
    if (m == 10)
       n = n + 273 ;    %October
    end
    if (m == 11)
       n = n + 304 ;    %November
    end
     if (m == 12)
       n = n + 334 ;    %December
    end
end

StandardTime = tmydata.Hour(run)+ 0.5;                      %Calculating mid-
hour time for TMY data integrated over a one hour period
B = 360*(n-81)/365;                                         %Day equation
E = (9.87*sind(2*B))-(7.53*cosd(B))-(1.5*sind(B));          %Time equation
SolarTime = StandardTime + (4 *(L_st-L_loc)/60) + (E/60);   %Calculating
solar time, i.e. the suns location in the sky, like a sun dial
Delta = 23.45*sind((360*(284+n)/365));                      %Solar
declination calculation in degrees
Omega = 15*(SolarTime - 12);                                %suns location in
the sky in degrees
Theta = acosd((sind(Delta)*sind(Phi)*cosd(Beta))...         %Calculating
theta in degrees
    - (sind(Delta)*cosd(Phi)*sind(Beta)*cosd(Gamma))...
```

```
    + (cosd(Delta)*cosd(Phi)*cosd(Beta)*cosd(Omega))...
    + (cosd(Delta)*sind(Phi)*sind(Beta)*cosd(Gamma)*cosd(Omega))...
    + (cosd(Delta)*sind(Beta)*sind(Gamma)*sind(Omega)));

Theta_z =
acosd(((cosd(Phi)*cosd(Delta)*cosd(Omega))+(sind(Phi)*sind(Delta)))); %Calcul
ating Theta Z in degrees
R_b = cosd(Theta)/cosd(Theta_z);           %Beam Ratio calculation
G_b = tmydata.DNI(run)* cosd(Theta_z) ;    %Bean irradiation integrated over
1 hour from TMY data
G =  tmydata.GHI(run);                     %Total horizontal radiation
integrated over 1 hour from TMY daya
G_d = G - G_b;                             %Calculating diffused radiation
integrated over 1 hour
G_t = (G_b *R_b) + (G_d*((1+cosd(Beta))/2)) + (Rho_g*G*((1-
cosd(Beta))/2)); %Calculating total irradiation over 1 hour in Watts hour/m^2

 if (G_t <= 0)
     G_t = 0;       %Irradiation results cannot be negative
 end

 %Logging Data into the TMY data table. Requires creating columns
 tmydata.n(run) = n;
 tmydata.B(run) = B;
 tmydata.E(run) = E;
 tmydata.SolarTime(run) = SolarTime;
 tmydata.Delta(run) = Delta;
 tmydata.Omega(run) = Omega;
 tmydata.Theta(run) = Theta;
 tmydata.ThetaZ(run) = Theta_z;
 tmydata.Rb(run) = R_b;
 tmydata.Gb(run) = G_b;
 tmydata.G(run) = G;
 tmydata.Gt(run) = G_t;

Energy_Out = PV_eff*G_t*area;           %Calculating energy output in Watts
hours
tmydata.EnergyOut(run) = Energy_Out;    %Logging energy output into the TMY
data table

PW_Energy = ((Energy_Out*(1^(N-1)))/((1+deg)^N)) * (1-losses);    %Present
worth of energy with degradation over life and annual losses in Watts hours


%Calculating energy output for each month
if (m==1)
    m1 = m1 + PW_Energy;    %January energy output in Watt-hours
end
if (m == 2)
m2 = m2 + PW_Energy;        %February
end
  if (m == 3)
      m3 = m3 + PW_Energy;  %March
    end
    if (m == 4)
```

```
      m4 = m4 + PW_Energy;  %April
    end
    if (m == 5)
       m5=m5 + PW_Energy;   %May
    end
    if (m == 6)
       m6=m6+ PW_Energy;    %June
    end
    if (m == 7)
      m7=m7 + PW_Energy;    %July
    end
    if (m == 8)
       m8=m8 + PW_Energy;   %August
    end
    if (m == 9)
       m9=m9 + PW_Energy;   %September
    end
    if (m == 10)
       m10=m10 + PW_Energy; %October
    end
    if (m == 11)
       m11=m11 + PW_Energy; %November
    end
     if (m == 12)
       m12=m12 + PW_Energy; %December
    end

Energy_total = (Energy_total + Energy_Out); %Summing the total annual energy
in Watt hour
end
%End of iterations to calculate total irradiance

Annual_Energy = Energy_total/1000;  %Calculating Average Annual Solar Energy
Captures, no losses in kilowatt hours
PW_Annual_Energy = ((Annual_Energy*(1^(N-1)))/((1+deg)^N)) * (1-
losses);    %Present Worth of Annual Energy with degredation over life and
annual losses in kilowatt hours


%Determining Size and Cost of PV Array
PV_Watts = Peak_irr *PV_eff * area;     %PV Array Size in Watts
PV_cost_total = PV_Watts * PV_cost;     %Total Cost of PV Array
PV_d_pay = PV_cost_total * d_pay;       %Down Payment of PV Array

%Calculating the annual maintenance cost as a percent of the PV array cost
M_cost_initial = m_initial * PV_cost_total;

%Total System Cost with Loan
C_S_Loan = PV_cost_total + M_cost_initial - PV_d_pay;

%Cost of annual saved electricity at each location
Cost_Sav_E = PW_Annual_Energy * Cost_e;

%P1 Present Worth Factor for Energy Cost
P_1 = pwf_function(N,i_e,d);
```

```
%P2 Present Worth Factor for System Cost
N_1 = min(L_n, N);                          %Calculating N_1
Principle_payment = ((1-
d_pay)*(pwf_function(N_1,0,d)/pwf_function(L_n,0,L_i)));    %Calculating
principle payment factor
Maintenance =
(m_initial*pwf_function(N,m_inflating,d));                             %Calcul
ating maintenance factor
P_2_Loan = d_pay + Principle_payment  +
Maintenance;                                    %Calculating P2

%Calculating the Life Cycle Cost of Solar PV Array using a loan
LCC_Solar_Loan = P_2_Loan * C_S_Loan;

%Calculating the life cycle cost of Electricity
LCC_e = Cost_Sav_E * P_1;

%Calculating the life cycle savings of the system
LCS_Loan = LCC_e - LCC_Solar_Loan ;
```

PRESENT WORTH FACTOR FUNCTION

```
 function [pwf] = pwf_function(N,i,d)
%Present Worth Factor Calculations
if (i==d)
    pwf = N/(1+i);
else
   pwf = (1/(d-i))*(1-((1+i)/(1+d))^N);
end

end
```

APPENDIX D. CALCULATION PROCESS

Energy Analysis: Data Gathering

The estimates and equations used from Appendices A, B, and C analyzes a single scenario to obtain results. To analyze a change in area, inclination, etc. requires additional iteration of the entire calculation set from Appendix C.	Order from Left to right and top to bottom			
Energy Analysis				
Data Gathering				
Identify a Location				
Determine the locations longitude and latitude (Phi)				
Determine the locations time zone longitude				
Download TMY data				
Requires 1 year or more listing every hour, day, month for GHI and DNI irradiance, temperature, and humidity				
Format TMY data for use within MATLAB listing columns focusing on day, month, hour, DNI and GHI.				
Estimate the solar array parameters				
Area				
Inclination (tilt/Beta)				
Orientation (azimuth/Gamma)				
Efficiency				
Estimate ground coverage/reflectance at the location				
Estimate degradation and energy losses				

Energy Analysis: Energy Modeling

The estimates and equations used from Appendices A, B, and C analyzes a single scenario to obtain results. To analyze a change in area, inclination, etc. requires additional iteration of the entire calculation set from Appendix C.	Order from Left to right and top to bottom				
Energy Analysis					
Energy Modeling					
Calculate Solar Time using equations 1 to 3, TMY day and time, and longitudinal estimates					
Calculate B using the day from TMY data					
Calculate E using B					
Calculate Solar Time using TMY time and longitudinal estimates					
Calculate Beam Ratio using equations 4 to 8					
Calculate Delta using day from TMY data					
Calculate Omega using the Solar Time					
Calculate Theta using Phi, Beta, Gamma, Delta, and Omega					
Calculate Theta Z using Phi, Delta, and Omega					
Calculate Beam Ratio using Theta and Theta Z					
Calculate the total irradiance experienced by a fixed, incline surface using equation 9 and 10, beam ratio, ground reflectance, Beta, TMY GHI and DNI data					
Calculate horizontal diffused irradiance					
Calculate total irradiance					
Calculate the annual energy generated using total irradiance, area, efficiency					
Calculate the present worth of annual energy, accounting for losses and degradation					

Financial Analysis

The estimates and equations used from Appendices A, B, and C analyzes a single scenario to obtain results. To analyze a change in area, inclination, etc. requires additional iteration of the entire calculation set from Appendix C.	Order from Left to right and top to bottom							
Financial Analysis								
Estimate Financial Parameters								
Loan Type, Length, and Interest Rate								
Analysis Length, Inflation Rate, and Discount Rate								
PV system cost in $/Watt that include installation, labor, etc.								
Down payment percentage								
Maintenance cost as a percentage of PV array cost								
Inflation/Escalation rates for electricity and maintenance								
Electricity Rate								
Calculate array size in Watts using area, efficiency, and 1000 W/m^2 testing standard								
Calculate PV array cost by multiplying the array size in Watts by estimated PV system cost in Watts/m^2								
Calculate down payment as a percentage pf PV array cost								
Calculate annual maintenance costs as a percentage pf PV array cost								
Calculate total system costs by adding maintenance and PV array costs and subtracting the down payment								
Calculate the Annual electricity savings by multiply the present worth annual energy by the electricity rate								
Calculating Life cycle costs using equations 12 to 16.								
Calculate P1 factor using Equation15 with 12 or 13.								
Calculate P2 using equation 16 with 12 or 13.								
Calculate Life Cycle Cost of the system using total system cost and P2								
Calculate Life Cycle Cost of Energy Savings using annual electricity savings and P1								
Calculate Life Cycle Savings by subtracting the life cycle cost of the system from the life cycle cost of energy savings								

APPENDIX E. TMY DATA EXAMPLE

Year	Month	Day	Hour	Minute	DNI	DHI	GHI	Temperature	n	B	E	SolarTime
2000	1	1	24	30	0	0	0	0	0	0	0	0
2000	1	1	1	30	0	0	0	0	0	0	0	0
2000	1	1	2	30	0	0	0	-1	0	0	0	0
2000	1	1	3	30	0	0	0	-1	0	0	0	0
2000	1	1	4	30	0	0	0	-1	0	0	0	0
2000	1	1	5	30	0	0	0	-1	0	0	0	0
2000	1	1	6	30	0	0	0	-1	0	0	0	0
2000	1	1	7	30	0	0	0	-1	0	0	0	0
2000	1	1	8	30	297	15	27	0	0	0	0	0
2000	1	1	9	30	668	43	172	1	0	0	0	0
2000	1	1	10	30	800	58	313	3	0	0	0	0
2000	1	1	11	30	866	65	415	5	0	0	0	0
2000	1	1	12	30	381	169	338	7	0	0	0	0
2000	1	1	13	30	878	71	455	8	0	0	0	0
2000	1	1	14	30	831	69	387	7	0	0	0	0
2000	1	1	15	30	720	63	268	5	0	0	0	0
2000	1	1	16	30	43	56	63	3	0	0	0	0
2000	1	1	17	30	0	0	0	3	0	0	0	0
2000	1	1	18	30	0	0	0	3	0	0	0	0
2000	1	1	19	30	0	0	0	4	0	0	0	0
2000	1	1	20	30	0	0	0	5	0	0	0	0
2000	1	1	21	30	0	0	0	5	0	0	0	0
2000	1	1	22	30	0	0	0	5	0	0	0	0
2000	1	1	23	30	0	0	0	5	0	0	0	0
2000	1	2	24	30	0	0	0	6	0	0	0	0

*Shaded columns are added for logging data and investigation to ensure correct calculations.