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Master Thesis

The Potential of Solar Photovoltaic Systems Integrated into Building Roofs with Open-Source GIS Techniques. A Case Study of Portland, Oregon

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Abstract

The following study investigates the technical feasibility of integrating solar photovoltaic systems within residential rooftops and discusses a case study concerning Portland, Oregon. This research employs free and open-source Geographic Information System techniques to carry out an extensive analysis. It considers the integration of various building characteristics and data on solar irradiance to determine highly apt rooftops for generating energy from the sun, estimating the amount probably produced. Regression analysis is focused on the relationship between building attributes and energy consumption to find the controlling factors of residential electricity use. In addition, the given study calculates the Solar Suitability Index-SSI and the Solar Capacity Index-SCI at a census tract level within the study area, hence enabling the comparison of the potential of solar energy production with the local demand for electricity. The findings particularly highlight the economic and environmental benefits from the diffusion of rooftop PV systems contributing to energy sustainability but also develop a useful base of insights for a set of policy recommendations focused on the widespread adoption of solar energy in urban contexts. These results therefore set a premise for strategies that could potentially enable the growth of urban solar infrastructure, in turn offering energy efficiency and a transition toward renewable sources of energy.

Keywords: Solar Photovoltaic (PV) Systems, Geographic Information System (GIS), Urban Energy Planning, GHG Emissions Reduction

Acknowledgments

From 2021 to 2024, my journey of studying in Italy has been the most beautiful chapter of my life. In my younger years, I believed the future held countless paths waiting to be explored. Yet, as I look back now, I see only a single, straight road—a road shaped by each step I took, leading me to where I stand today. I once thought there was always time for everything, but time has flown by. Though I part with a heart full of reluctance, I am deeply grateful for all that has been.

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To my dearest, Mr. Guan, thank you for standing by my side, resonating with my every rhythm, and embracing my emotions. Your love is my confidence and my faith, my wings and my sunshine. To whether every unknown storm hand in hand with you is my greatest blessing and joy.

To my friends, I am fortunate to have met you. Life is a vast ocean, and I am grateful that we have shared the same vessel on this journey. The laughter and tears, surprises and regrets, late nights and early mornings we've shared are treasures etched deeply in my memory. Thank you for your trust and support throughout.

May we all, in the ever-changing tides of life, remember the tears of joy and passion of our youth, and may we journey toward bright and promising futures.

Finally, I dedicate this to my sincere and fearless 26-year-old self.

Table of Contents

List of Figures

List of Tables

CHAPTER ONE

1 Introduction

1.1 Background and Context

1.1.1 Urban Development and Climate Change

According to the Global Energy Efficient Cities Initiative launched by the United Nations Environment Programme in 2012, more than half of the world's population now lives in cities and uses more than 80% of the world's energy. It is predicted that the proportion of people living in cities will reach 80% by 2050. Cities account for 3% of the world's land area, generate 80% of GDP, consume 75% of natural resources, emit 60-80% of the world's carbon dioxide, and produce 50% of the world's waste. Therefore, energy conservation, carbon emission reduction and low-carbon urban development are the top priorities for curbing global warming(UNEP, 2012).

Climate change has already affected natural and human systems on Earth, posing significant challenges to human survival and development. The burning of fossil fuels, large-scale industrial pollution, and deforestation, among other human activities, have weakened the Earth's ability to restore the carbon cycle balance, leading to changes in global average temperatures. The phenomena of global warming, such as the increase in atmospheric and ocean temperatures, reduction in snow and ice, rise in sea levels, and increased concentrations of greenhouse gases, have become indisputable facts. The research findings of the Intergovernmental Panel on Climate Change (IPCC) (Figures 1-1) show that rapid increase in global net anthropogenic GHG emissions; increase in global surface temperature as annual anomalies from an 1850-1900 baseline and indicate an increase of around 1.1°C since 1850-1900(IPCC, 2023).

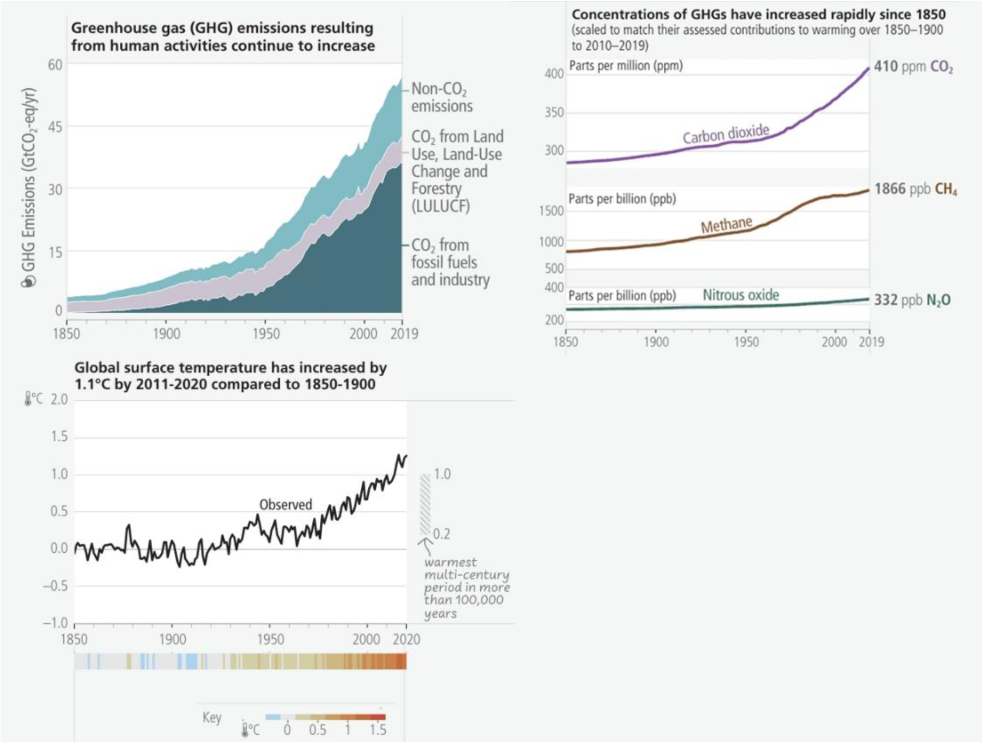

Figure 1-1 Study of IPCC 2023 (Source: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf)

Especially since the Industrial Revolution, anthropogenic greenhouse gas emissions have significantly increased, with about half of human-induced CO_2 emissions occurring in the last 40 years between 1750 and 2011, and CO_2 emissions from fossil fuel combustion and industrial processes accounting for 78% of total greenhouse gas emissions. Environmental politicians have constructed a scientific relationship between human activities and global warming, placing CO_2 emissions and climate warming in the context of human activities and their destructive impact. China's rapid economic development and urbanization process will inevitably lead to increased energy consumption and total CO_2 emissions.

1.1.2 Study of Energy Development

Energy, the Oxford Dictionary defines energy as "a resource that can provide power, such as to produce heat or drive machines." Based on the criterion of whether energy can be directly obtained and used, energy can be classified into primary and secondary energy. Primary energy, also known as natural or primary energy(Demirel, 2012), refers to energy that exists in nature without needing to be converted from other forms of energy. Fossil fuels like coal are typical examples of primary energy. Secondary energy refers to energy that has been converted from primary energy into another form, with electricity being the most common secondary energy.

Based on the criterion of whether energy can be "renewed," primary energy can be further divided into renewable and non-renewable energy. Fossil fuels, a type of primary energy, are typical examples of non-renewable energy, as they cannot be replenished in a short period. Similarly, nuclear energy, derived from mineral resources, is non-renewable once its fuel is depleted. On the other hand, non-fossil primary energies such as hydropower, wind energy, and biomass energy are common examples of renewable energy, which most countries are currently focusing on developing.

Energy is fundamental to human survival and development. With the continuous increase in the global population, societal progress, and urbanization, the global demand for energy is enormous. Currently, the world population is nearly 7 billion, with over 50% living in urban environments, which consume 85% of energy and resources. The "2023 World Energy Yearbook" indicates that global energy consumption in 2022 reached 16.31 billion tons of oil equivalent (Mtoe), a 2% increase. Of this, oil accounted for 31.8%, natural gas for 24%, and coal for 26.8%, with these three fossil fuels making up 82.6% of the total, showing that traditional energy still dominates the global energy structure(The Energy Institute Statistical, 2023).

However, Earth's fossil fuel reserves are limited. According to the "BP Statistical Review of World Energy 2017," published in June 2018, the global oil reserve-to-production ratio was 50.2 years, natural gas was about 52.6 years, and coal was approximately 134 years, based on proven reserves and extraction rates(BP Statistical Review of World Energy, 2017). The World Health Organization predicts that by 2060, the global population will reach 10-11 billion. If by then, everyone’s energy consumption reaches the current per capita level of developed countries, the Earth's oil and natural gas reserves will be exhausted within 40 years(BP Statistical Review of World Energy, 2018).

Therefore, countries and regions worldwide have implemented policies to reduce the negative impacts of environmental pollution, focusing more on the balance between urban energy supply and demand and energy security. Reasonable planning of urban energy, considering the status and future development needs, is crucial for promoting urban development and the rational use of energy resources. To address the energy crisis and environmental pollution, transitioning from non-renewable traditional energy to safe, clean, reliable, and economical renewable energy, such as solar, wind, biomass, and geothermal energy, is imperative. Among these, wind and solar energy are the most widely used for energy production globally.

1.1.3 Energy security

1.1.3.1 Security of energy demand

The concept of energy demand security is proposed relative to the supply security of energy-consuming countries. Due to variations in geographical location, resource endowments, political systems, and economic conditions, different countries have distinct implications for energy security. Each country seeks its own interests, and the energy interests of energy-importing countries differ from those of energy-exporting countries(Yergin, 2006).

Energy-exporting countries and energy-supplying countries focus on different aspects: the former is concerned with the stability of energy demand markets and export channels, while the latter focuses on the reliability and security of import channels(Shi & Tian, 2015). Energy-importing countries seek continuous, stable, and uninterrupted supplies and aim to maintain low energy prices. In contrast, energy-exporting countries pursue demand security, ensuring that their energy production can be purchased at reasonable and profitable prices over the long term, thus providing their national finances with ample, stable, and continuous income.

1.1.3.2 Energy price security

The era of high-carbon, high-emission economies dominated by fossil fuels such as oil and coal has shaped the traditional view of energy security. This traditional perspective considers energy security primarily in terms of adequate supply and access to energy at reasonable prices. The oil crisis made Western countries aware of the power of oil when used as a global leverage, leading developed nations to place great importance on energy security (Yan & Liu, 2014).

The concept of energy price security is typically categorized as energy affordability, meaning that energy should be sold at prices that consumers can afford. Regarding oil and natural gas, energy price security refers to the fluctuations in global oil prices remaining within a reasonable and affordable range. For energy-consuming countries, lower energy prices can reduce industrial development costs and promote economic growth. Conversely, significant fluctuations in energy prices can inflict severe and potentially irreparable damage on the economies of these countries, negatively impacting domestic social and livelihood stability.

1.1.3.3 Security in Energy Use

Global warming threatens the survival of future generations, and the concept of sustainable development has gradually become a global consensus. Advances in energy technology are leading humanity from the fossil fuel era into the renewable energy era, reshaping certain aspects of energy security. The evolving and expanding implications of energy security align with Maslow's hierarchy of needs theory(Ang et al., 2015). Initially, the focus was on ensuring basic energy security to support daily life. Subsequently, higher-level demands emerged, such as "maintaining continuous and reliable supply." Once the basic security of energy supply is met, considerations of energy usage safety and the harmonious development between energy use and the environment are included in the concept of energy security.

Environmental damage caused by climate change could deteriorate to the point where society can no longer function, and extreme weather events will significantly impact energy security. If the entire inland ice sheet of Greenland melts due to global warming, global sea levels could rise by 7 meters. For countries with substantial offshore oil and gas assets, rising sea levels could necessitate the redesign or even reconstruction of energy systems(Sascha, 2008), incurring enormous economic costs. From August to September 2005, Hurricanes Katrina and Rita hit the heart of the U.S. petrochemical industry, forcing the U.S. government to shut down several energy facilities, impacting the nation's electricity and natural gas systems. Storms and floods caused by climate change also disrupt energy transportation routes, and harsh and unstable climate conditions undermine national energy security(Cruz & Krausmann, 2008).

1.1.3.4 Renewable energy and energy security

Renewable energy will reshape the global energy landscape, thereby impacting energy security. It reduces the world's dependence on fossil fuel consumption, alleviating geopolitical conflicts over energy supply and competition(H. Wang, 2013). Renewable energy is becoming a critical strategic asset in the international energy landscape, where nations vie for influence. Scholars such as Yan Shigang et al. argue that renewable and new energy sources are crucial for sustainable economic development(Yan & Liu, 2014). They are essential tools for combatting climate change and reducing emissions, and they serve as strategic resources for gaining influence and leadership in international climate governance and the future global energy landscape.

The EU has repeatedly emphasized the contribution of renewable energy to its energy security. Renewable energy helps reduce greenhouse gas emissions in the energy sector, thereby addressing climate change. Additionally, developing renewable energy can enhance the EU's energy independence, thus improving Europe's energy security. Subhash Kumar's research found that renewable energy plays a crucial role in energy security and environmental emission reduction in Southeast Asia as well(Kumar, 2016). Dong Qin points out that the EU faces energy supply security issues, as discussed by other scholars, and has experienced oil and gas disruptions due to political conflicts between Ukraine and Russia. As a result, the EU has significantly expanded its renewable energy development to improve energy security(Dong, 2012).

1.1.3.5 Climate change and energy security

Renewable energy is set to reshape the global energy landscape, subsequently impacting energy security. It reduces the world's reliance on fossil fuel consumption, alleviating geopolitical conflicts over energy supply and competition. Renewable energy is becoming a crucial strategic resource in the international energy arena, influencing the power dynamics among nations. Renewable and new energy sources are vital for sustainable economic development(Yan & Liu, 2014). They not only serve as effective tools for combating climate change and promoting energy conservation and emission reduction but also represent key strategic resources for gaining influence and leadership in international climate governance and the future global energy structure(Nyman, 2018).

1.1.4 Renewable Energy City

Renewable energy cities are harmonious settlements where cities and nature can develop in a sustainable manner and where people and nature and society can get along well, based on the principle of renewable energy and the integration of systematics, sociology, ecology and other technologies. Renewable energy city construction this initiative can not only guarantee the safety of urban energy consumption, effectively alleviate the deteriorating ecological environment, but also promote renewable energy related science and technology continue to improve and gradually mature. Renewable energy city building is a key to solving the important problems in the process of urban development.

Miguel-Angel Perea-Moreno et al. emphasized the key role of renewable energy in sustainable urban development through a global study and pointed out that China, the United States, the United Kingdom, Italy, Germany and India have been the most active in this area of research(Perea-Moreno et al., 2018). In Poland's large cities, the development of renewable energy sources is important for establishing energy security systems, and the study suggests that local governments play a key role in promoting the development of a low-carbon economy(Lewandowska et al., 2020). The development of smart green cities cannot be achieved without the combined use of a variety of renewable energy sources, which can help to reduce energy supply problems, while the study emphasizes that a wholesale shift to renewable energy sources may encounter technical and managerial challenges(Vukovic et al., 2023). Finally, Hikmet Mengüaslan's (2023) study focuses on the preparedness, capacity and strategies of European cities to achieve climate neutrality targets, particularly the role of renewable energy in high-emission sectors (e.g., buildings, transportation, waste, and industry), and the study suggests that intensified efforts, overcoming barriers, and implementation of a multi-level governance approach are needed to advance large-scale renewable energy projects (Ulpiani et al., 2023).

1.2 Research Objectives

1.2.1 Assessment of Portland’s Rooftop Solar Potential

Conduct a large-scale spatial analysis of rooftop solar potential within the City of Portland by employing open-source GIS methods. The subsequent research will yield high-resolution maps depicting solar potential. It will achieve this by calculating solar irradiance, shading effects, and rooftop orientation to identify those roofs that are best suited for PV installations.

1.2.2 Economic Feasibility and Environmental Benefits Analysis

Estimate the economic and environmental consequences of implementing solar PV systems into Portland's urban setting by determining the potential energy generation, cost-effectiveness through payback period, and quantification of the environmental benefit in terms of carbon emissions reduced against electricity derived from fossil fuel sources.

1.2.3 Develop Recommendations for Policy and Planning

Based on technical and economic evaluation, provide policy and planning recommendations that will help in the diffusion of rooftop PV systems. This covers discussions about regulatory, financial, and technical barriers, and identifies strategies to maximize solar PV deployment consistent with Portland's climate and energy goals.

1.3 Problem Statement

1.3.1 What are the optimal strategies for Portland to achieve energy self-sufficiency?

This research identifies strategies to enhance rooftop solar adoption in Portland, leveraging its energy self-sufficient future. By analyzing key factors such as rooftop characteristics, solar irradiance level, and the current policy landscape of the city, this study hopes to identify which factors are the critical drivers of Portland's capacity for widescale integration of solar.

1.3.2 How does the potential for rooftop solar affect the environment and economy?

This research quantifies the environmental benefits from rooftop solar installations through reduced carbon emissions, aligning with Portland's low-carbon objectives. It will also determine, through energy generation and payback period projections and potential cost savings for different building types and sectors, the economic viability of rooftop PV installations.

1.4 Structure of the Thesis

This book consists of seven sections, which can be divided into four main chapters. The first chapter, corresponding to the first section of the book, addresses the significance of renewable energy and the importance of photovoltaic (PV) solar systems. It also explores the relevance of integrating PV systems into urban building rooftops and provides an overview of the Geographic Information System (GIS) technologies used to assess solar energy potential.

The following chapter delves into the development of solar PV technology, current trends, and prospects. It also introduces the theoretical framework for building-integrated photovoltaics (BIPV) and examines the application of GIS technologies in renewable energy assessment.

The third chapter, covering sections three through six, focuses on the practical implementation of the discussed systems. Section three outlines the methodology, research design, data collection methods, GIS analysis, and quantitative evaluation techniques employed in the study. Section four presents a case study, wherein the methodology is applied to a specific example, and the results are visualized. Section five discusses the estimation of energy production as well as the associated economic and environmental benefits. Section six provides an in-depth analysis of relevant policies in the context of PV system implementation and adoption.

The final chapter, which constitutes the seventh section, concludes the book by summarizing the key findings of the research. It also offers recommendations to policymakers and urban planners on how to promote the adoption of rooftop solar applications, thereby encouraging the broader integration of solar energy solutions in urban environments.

CHAPTER TWO

2 Literature Review

2.1 Solar Photovoltaic Technology

2.1.1 Development of Solar Photovoltaic Technology

Solar radiation is the most crucial energy source for the Earth's atmospheric system. Of the energy that humans can collect from the Earth's surface, 99.98% comes from the sun. Solar energy can be converted into 1.77×10^{7} MW of electrical energy, which is hundreds of thousands of times the current average global energy consumption(Che, 2006). As sunlight passes through the atmosphere to reach the Earth's surface, a portion is reflected into space by the atmosphere, and another portion is absorbed by the atmosphere. Ultimately, more than 50% of the sunlight reaches the Earth's surface.

Solar photovoltaic (PV) technology generates electricity by using photons to excite electrons in a semiconductor material, producing the photovoltaic effect, which directly converts solar energy into electrical energy. In recent years, solar cell technology has advanced rapidly, with increasing conversion efficiencies. Figure 2-1show the trend in crystalline silicon conversion efficiency from 2008 to 2015, with the industrial efficiency of monocrystalline and polycrystalline cells currently reaching 19.5% and 18.3%, respectively(B. Wang, 2016).

Solar PV technology features a short construction cycle, wide adaptability, low maintenance requirements, and environmental friendliness. It has seen widespread and rapid adoption globally(Jiang, 2014). Since 2008, the annual global installed capacity of PV systems has grown rapidly, reaching a cumulative capacity of 230 GW by the end of 2015.

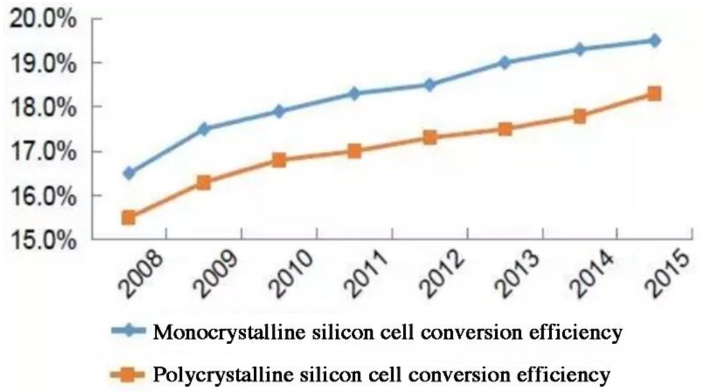

Figure 2-1 Cell conversion efficiency, 2015-2018(Source: China PV Industry 2015 Summ ary and 2016 Outlook)

2.1.2 Development Trend of Urban Scale Application of PV

Solar energy utilization encompasses three main conversion types: photovoltaic, photothermal, and photochemical. Photovoltaic (PV) conversion involves the use of solar cells to capture solar radiation and directly convert light energy into electrical energy. This study primarily focuses on PV conversion, or solar PV utilization. Solar PV systems comprise photovoltaic cells, which are specialized devices that transform solar radiation into electrical power. The fundamental unit within a PV system is the PV module, which can be classified into types such as crystalline silicon, thin-film, compound, and dye-sensitized modules.

PV systems are generally categorized into centralized and distributed configurations. Centralized PV systems capitalize on abundant and stable solar resources to construct large-scale power plants, typically situated in remote or desert regions. These plants transmit electricity over long distances to reach end-users, making them ideal for regions with vast, open spaces and consistent sunlight.

In contrast, distributed PV systems are grid-connected installations located near the point of use, directly supplying power to meet local demand. Any surplus electricity generated by distributed PV systems is fed back into the grid, making these systems highly adaptable to local needs(Hanfang Li et al., 2020). Distributed PV systems are particularly effective in urban areas, where their proximity to end-users helps reduce transmission losses.

Distributed PV systems offer additional advantages, including lower investment costs, flexible deployment, effective utilization of building surfaces, and minimal ground space requirements. These features have contributed to the rapid expansion of distributed PV systems in recent years.

Overall, distributed PV represents an innovative and promising approach to integrated energy utilization. In urban settings, it mitigates power losses associated with voltage transformation and long-distance transmission. Given the high energy demand and limited space in cities, distributed PV systems are especially suited to urban environments, where they provide localized energy supply, enhance efficiency, and effectively complement urban energy consumption patterns.

As interest in photovoltaic (PV) power generation increases, many believe that distributed PV systems, which provide electricity to local areas or nearby regions, will become the preferred method for widespread commercial PV adoption. Large-scale applications of solar PV in urban areas have been widely recognized as critical measures for reducing energy consumption, decreasing pollution, and improving the environment. This trend is expected to become the most significant method for urban solar development and an important strategy for addressing the energy crisis. Urban areas, with their relatively advanced economies and concentrated power loads, have numerous rooftops available for use. This not only preserves the buildings' functional use but also provides power supply. Additionally, building-integrated PV systems can connect at the end of the power grid without necessitating extensive upgrades to transmission lines(Xiong & Liu, 2012), making it a vital approach for developing distributed PV energy.

Distributed Generation (DG) was introduced in the United States in the Public Utility Regulatory Policies Act of 1978. Following its announcement, DG was rapidly promoted and adopted by other countries. DG is defined as small, modular power generation units ranging from a few kilowatts to several megawatts, directly configured in the distribution network or near the load, distinct from traditional centralized power generation and long-distance transmission with large, interconnected networks. DG units can operate economically, efficiently, distributivity, and reliably, with the power generated being used by the user and nearby areas, while any surplus electricity is fed into the local distribution grid. In recent years, DG has developed rapidly and has become a key technology actively promoted by many developed countries, with distributed PV generation being one of the primary method(Z'hou & Ji, 2014). Building-integrated photovoltaics (BIPV) are a crucial component of distributed PV generation. As American author Jeremy Rifkin once stated, every building in the future will become a micro-power plant, capable of collecting solar and other renewable energy on-sit(Rifkin, 2013).

Various countries and regions have provided policies and financial support to promote the development of distributed photovoltaics, specially building-integrated photovoltaics. Since 2009, the global installed capacity of distributed photovoltaics has grown rapidly, maintaining a growth rate of over 25%, with a higher proportion of installations in Europe. In countries such as Austria, Denmark, and the Netherlands, photovoltaic construction is almost entirely in distributed form, while the proportions of distributed photovoltaic installations in Germany and the US have reached 75% and 45%, respectively. Countries in Europe, North America, and Japan have conducted large-scale applications and theoretical research on photovoltaics. The Australian government plans to build seven "solar cities"; Babcock Ranch in Florida, USA, and Mecca, Saudi Arabia, plan to become cities powered entirely by solar energy(Lou, 2015). Japan has constructed the Jounishi Town photovoltaic demonstration area, installing a total of 2.13 MW of photovoltaic facilities for 553 residences. In the Netherlands, the Heerhugowaard(Figure 2-2), Alkmaar, and Langedijk regions are building a solar city with a 5 MW photovoltaic system, comprising 2,500 residences, which is one of the largest urban-scale photovoltaic projects in the world (Gaiddon et al., 2009).

Figure 2-2 The Heerhugowaard, Netherlands (Source: https://www.gebiedsontwikkeling.nu/artikelen/stad-van-de-zon-duurzame-wijk-was-zijn-tijd-ver-vooruit/)

2.2 Theories of PV and Building Integration

2.2.1 Building Integrated Photovoltaics (BIPV)

The application of photovoltaic (PV) technology in buildings can be categorized into two main types. The first type is traditional PV modules, which are additional PV modules installed on buildings. The maintenance and replacement of these PV modules do not affect the building's functionality. The second type is building-integrated PV modules, where solar cells are combined with conventional building materials, directly replacing conventional materials such as PV tiles, PV bricks, and PV glass walls. These two forms of buildings are collectively referred to as "PV buildings" or "Building-Integrated Photovoltaics" (BIPV). The term "PV building" relates to the building itself, emphasizing the presence of the PV system. In contrast, BIPV emphasizes the installation location of the PV system on the building, distinguishing it from large ground-mounted PV power plants or PV systems installed in other locations.

The term 'photovoltaic building' relates to the building itself, emphasizing the presence of the PV system. In contrast, "Building Integrated Photovoltaic" emphasizes the location of the PV system on the building, as distinct from large ground-mounted PV plants or PV systems mounted in other locations.

The concept of BIPV was first introduced in Germany in 1991 and has since been popularized in several countries emphasizes the integration of the PV system into the building, with a focus on simultaneous design and construction. The PV system becomes an important part of the building, integrating technology, functionality and aesthetics, representing the future direction of PV buildings. A study(Abojela et al., 2023) proposes an "on-demand panel" concept for flexible BIPV designs that reduces costs and enhances the aesthetic integration of PV modules. Bošnjaković et al. discuss barriers and opportunities in the BIPV market, emphasizing the need for interdisciplinary collaboration and the potential for BIPV walls to generate significant amounts of energy compared to roofs (Bosnjakovic et al., 2023). Rounis et al. focused on the standardization of BIPV/T systems to improve thermal performance and integration with buildings (Neugebohrn et al., 2022). Meanwhile, Goel conducted a comparative review of BIPV applications around the world, emphasizing the economic viability and significant power generation potential of BIPV systems in a variety of building structures(Goel et al., 2022a). These studies highlight the advances being made and the challenges facing the BIPV field, from cost reduction and design flexibility to market acceptance and interdisciplinary collaboration.

Photovoltaic buildings can be used in a wide range of residential, public and industrial buildings, integrated with roofs, facades and building components. Integration methods vary, leading to different building requirements and forms. advantages and influencing factors of BIPV.

2.2.2 Advantages of BIPV

BIPV systems integrate photovoltaic technology with architectural design, offering numerous advantages from architectural, technological, and economic perspectives.

The process of producing electricity with solar photovoltaic systems is environmentally friendly, purely green, and pollution-free. Moreover, solar energy is a renewable resource, inexhaustible and endless.

Solar photovoltaic systems are generally installed on rooftops, walls, or other unused spaces of buildings, thus not requiring additional land use.

Integrating solar photovoltaic power generation systems into buildings not only generates electricity but also provides shading, waterproofing, and lighting benefits. For integrated photovoltaics, it can also save costs on the replaced building materials and maintenance expenses. A study discusses the multifunctional nature of BIPV systems, such as providing weather protection and noise minimization, while also generating electricity, thus offering a sustainable alternative to conventional building material (Goel et al., 2022b).

In summer, when solar radiation is strong and photovoltaic modules generate relatively more electricity, it coincides with the peak electricity consumption period of buildings, where fans, air conditioners, and other cooling devices have high usage rates and power consumption. Thus, photovoltaic power generation can help balance the electricity grid. Integration of PV panels with Battery Energy Storage Systems (BESS) reduces peak demand and manages energy more efficiently, shifting peak loads to off-peak hours(Podder & Nahid-Al-Masood, 2022).

2.2.3 Challenges of BIPV

Although BIPV has promising development prospects, there are still many issues that need to be addressed. Currently, major problems exist in terms of cost, technology, efficiency, and standard systems.

Regarding cost, the initial expenses of Building-Integrated Photovoltaic (BIPV) systems, including materials and installation, are generally higher than those of conventional building materials. This significant upfront investment can be a barrier to adoption. However, research indicates that a cost-effective approach could help overcome this challenge(Sarkar & Sadhu, 2022). Innovations in product design and process improvements across the BIPV value chain are seen as essential strategies to reduce costs and promote wider market acceptance(Bonomo et al., 2019).

Technologically, integrating PV systems into building design requires specialized knowledge and close coordination among architects, engineers, and installers. This technical complexity can present challenges during the design and installation stages. Standardizing design practices for BIPV/T systems can simplify integration and improve efficiency through better thermal management(Rounis et al., 2021).

In terms of performance, the efficiency of BIPV systems can be affected by various factors, such as shading, orientation, and the quality of PV materials used. These variables can impact the overall energy output and performance reliability. A study addresses the issue of efficiency by proposing a new hybrid BIPV array that increases power output and reduces mismatch losses under partial shading condition(Sarkar & Sadhu, 2022). Circuit reconfiguration can alleviate the power loss caused by partial shading, and the results show that energy yield can be significantly improved by optimizing circuit connections(University of North Carolina at Charlotte et al., 2023).

Regarding durability, ensuring the long-term durability and maintainability of BIPV systems (especially under harsh environmental conditions) can be challenging. Regular maintenance and potential repairs may increase the overall lifecycle cost. In terms of market acceptance, the adoption of BIPV technology is often slow due to a lack of awareness, perceived risks, and reluctance to invest in new and unfamiliar technologies. This market hesitation can impede the growth of BIPV applications. A study (Bonomo et al., 2023) in Energy Science & Engineering proposed a new testing procedure for BIPV systems' impact resistance, addressing durability and standardization issues to ensure better market acceptance and long-term performance reliability.

2.3 GIS Techniques in Renewable Energy Assessments

2.3.1 Role of GIS in Evaluating Solar Potential

Solar photovoltaic (PV) power generation is poised to play a crucial role in shaping the future of society and transforming the global energy landscape. The large-scale development and application of solar PV systems are crucial for gradually optimizing the energy structure, conserving conventional energy, improving the ecological environment, and addressing energy shortages. Consequently, conducting solar resource assessments has become an urgent and important task.

Some scholars have conducted in-depth investigations and research on solar resources and solar planning using GIS platforms, performing visualization analysis of resource utilization potential under GIS platforms. For example, they analyze solar PV energy resources using TENSYS and 3D city models(Hofierka & Kaňuk, 2009; Choi et al., 2011), study the potential of large PV energy systems based on rooftop area distribution(Izquierdo et al., 2008), and use GIS systems to create potential maps for solar energy(Gadsden et al., 2003; Rylatt et al., 2001). They use GIS to find the optimal implementation plan for PV projects(Kucuksari et al., 2014), providing references for application. Additionally, they evaluate solar power generation using a multi-objective decision-making approach combined with GIS(Sánchez-Lozano et al., 2013), and develop solar resource maps using satellite data in GIS systems, advancing research on solar PV applications(Sørensen, 2001).

GIS plays multiple roles in assessing solar potential, including evaluating and optimizing methods for solar energy utilization on both micro and macro scales(Cui et al., 2023). For instance, GIS-based methods assess distributed and centralized PV potential at a grid scale, demonstrating their ability to handle various spatial data scales effectively. Another study showcases the use of GIS tools to support sustainable energy generation decisions, particularly assessing the suitability of different urban locations for micro solar PV systems(Cieślak & Eźlakowski, 2023). Furthermore, a study underscores the vital role of GIS in the planning and design of solar power systems in Kolkata, employing remote sensing technology to identify optimal locations for installation (Pandey & Jhajharia, 2022). Additionally, two papers published by different authors in 2023 emphasize the fine spatiotemporal resolution of 3D GIS modeling to accurately assess solar potential in urban communities, illustrating the importance of detailed spatial analysis for optimizing solar gains(Cieślak & Eźlakowski, 2023; Pandey & Jhajharia, 2022)

2.3.2 Open-Source GIS Tools and Applications in Solar PV Analysis

The Geographic Information System (GIS) is a system composed of computer hardware, software, and various methodologies (Mierzejowska & Pomykoł, 2019)

(Figure 2-3). It is closely related to cartography and geography, supporting the collection, management, processing, analysis, modeling, and display of spatial data to solve complex planning and management problems related to spatial data. Over several decades, technology has developed a complete theoretical and technical system. With continuous breakthroughs in computer technology, GIS technology is also constantly innovating and expanding its application fields.

Figure 2-3 Geographic Information System Diagram (Source:https:/www.slideshare.net/slideshow/basic-introduction-to-gis-and-gis-softwares-qgis-and-arcgis/247069975)

GIS is widely used in the assessment of renewable energy resources. By analyzing layers related to renewable energy conditions within a spatial area, GIS technology determines the quantity and suitability of renewable energy resource development in different regions. The primary methods for renewable energy resource assessment using GIS include buffer analysis and overlay analysis. GIS data structures consist of raster and vector data. In terms of spatial analysis of renewable energy resources, vector data methods are simpler and easier to operate but have limitations. They cannot handle higher-dimensional renewable energy resource expansion and often result in data redundancy. Buffer analysis, a type of proximity analysis in GIS-based renewable energy resource assessment, evaluates the distance to renewable energy targets within a specific space. A buffer is a designated width established according to the effective range of renewable energy resource influence. Overlay analysis, on the other hand, creates composite layers by repeatedly overlaying independent layers of renewable energy resources, with the resulting layers retaining the attributes of the original independent layers.

Solar energy resource assessment primarily evaluates solar energy reserves, using meteorological observation methods and surface radiation data. Solar energy utilization involves both solar thermal and photovoltaic uses. For instance, to assess photovoltaic utilization in a region, one must first understand the area's sunshine conditions over the past 30 years, including sunshine duration and surface radiation. By calculating the total surface radiation density and the ratio of energy conversion efficiency, the solar energy resource quantity in the region can be estimated. The amount of solar energy in a region does not equal the amount available for development; it depends on the land area allocated for photovoltaic fields. Using GIS, one can calculate the number of photovoltaic fields in areas with abundant climate resources that are not suitable for agricultural or industrial development, thus determining the scale of solar energy resources and accurately obtaining the amount available for development.

In comparison, this study primarily uses ArcGIS as the analysis software. The main benefits of developing a solar energy information management system with ArcGIS include: first, the technology is mature, with comprehensive reference materials, built-in help documents, and example programs, as well as abundant online resources; second, there is a rich variety of map data available, including topography, administrative boundaries, roads, and rivers.

2.4 Self-Consumption Index (SCI) and Self-Sufficiency Index (SSI)

The SCI and SSI are two fundamental parameters adopted in the energy performance assessment of RECs. According to Mussawar (Mussawar et al., 2024), , the SCI quantifies the amount of locally generated renewable energy, such as photovoltaic-generated electricity, directly being consumed by members of an REC and hence not exported to the national grid. A high SCI means that energy is put to effective local use; it is consumed more on site and enhances the energy efficiency, hence cutting costs to members. On the other hand, the Self-Sufficiency Index measures the share of the needs of a community covered by its renewable energy sources. A high SSI depicts more energy autonomy. This means that the community depends less on the energy supply from an external grid and relies more on the energy it produces within. This enhances the sustainability and resilience of the community. According to one study, the integration of non-residential prosumers enhances residential self-sufficiency by 8.2% and residential self-consumption by 4.4%, as evidenced by Veronese et al., 2024. Put together, these indices provide an overall understanding of both operational efficiency due to SCI and energy independence due to SSI of an energy community and guide efforts toward energy optimization and self-reliance(Veronese et al., 2024). Interventions related to the installation of photovoltaic panels, energy storage systems, and energy efficiency measures increase the values of both SCI and SSI.

As an example, the combinations of the case scenarios with the addition of battery storage, REC+ST, greatly improved energy performance by temporal shifting of self-consumption in order to match demands better(Mutani et al., 2021a). This will result in higher SCI and SSI values. On the other hand, seasonal variations of both demand and production limit the achievable self-sufficiency to approximately 50%, depending on higher winter demands and summer productions independent of the various interventions made..

2.5 Summary of the Chapter

2.5.1 Gaps in the current literature

Lack of fully comprehensive solar potential assessment: Though many studies have been carried out in appraising the solar potential of urban areas, most of them lack the comprehensive approach to carry out integrated high-resolution spatial data, 3D building models, and detailed climate data. Limited integration of economic and environmental impact analysis: Although the technical potential of solar PV systems has been analyzed by many works, very few wholly integrated economic feasibility and environmental impact assessments. Shading and building orientation are not adequately considered, and existing models often do not account for the dynamic effects of such factors on solar PV efficiency, which leads to situations of overestimation or underestimation of potential energy output. From regulatory and policy framework challenges. Building codes, zoning laws, and regulations for solar PV installations can be complex and are not always consistent from one region to another. There is scant research on solar PV module integration into a city's existing infrastructure, and the retrofitting of such modules onto already existing buildings could be more complex than integrating them into new construction, which often requires total refurbishment. Because of low public awareness and market acceptance, uptake usually tends to be slow, brought on by a lack of information about its benefits and perceived risks and reluctance associated with an investment in new technologies.

2.5.2 Research opportunities

This will also allow the following study to make use of high-resolution LiDAR data, DEMs, and local solar radiation data for detailed GIS-based analysis in creating an accurate map of solar potential in Portland. Perhaps just this approach may set precedence for other cities interested in optimally leveraging rooftop solar potential. The results from the GIS modeling are compared with real solar production data from existing rooftop PV installations in Portland. It is with empirical data that the model becomes fine-tuned and calibrated, hence increasing predictive accuracy, but it also increases the reliability of prediction. Advanced shading analyses available with GIS techniques have also been used to model precisely the impact of adjacent buildings and vegetation on solar irradiance. The tilt and orientation of the building are considered in the model so that the PV system layout can be adjusted appropriately to harvest maximum power output. In the sequel of this paper, I describe the regulatory environment relative to rooftop solar installations in Portland. Make clear policy recommendations on streamlining the permitting process, offering financial incentives, and community outreach to further support widescale adoption of the solar technologies. Design a model that will estimate the quantifiable potential for solar energy in terms of cost-benefit analyses and payback period. Evaluate economic viability-cost-benefit analysis-and payback period and environmental benefits-emission reductions of GHGs-particularly associated with rooftop solar photovoltaic installations. This integrated approach might allow the extraction of more actionable insights for policymakers and investors. It could also develop outreaches that deal with the specific benefit of rooftop PV systems, targeted at campaigns and education programs. Showcase success stories and case studies in Portland build trust and drive market acceptance. Ultimately, this may constitute the outcome of such a study filling these gaps in research and availing such opportunities, which can provide invaluable insights and practical solutions toward advancing the mainstream adoption and optimization of rooftop solar photovoltaic systems in Portland, Oregon. Thus, this integrated approach could serve as a model for other urban areas pursuing the same path toward sustainable energy solutions.

CHAPTER THREE

3 Methodology

3.1 Research Design

3.1.1 Overall Research Framework

3.1.1.1 Purpose of Research Design

This design of the proposed research follows a holistic approach in which it will assess the solar PV potential of a residential building rooftop in Portland, Oregon, using open-source GIS technology. As such, it represents one of the structured and formal procedures for assessing the feasibility of rooftop solar installations by incorporating data collection, spatial analysis, and energy modeling into one coherent process.

Key outputs include the identification of most suitable residential rooftops for solar PV, rating of their potential energy output, and matching data of the buildings' energy consumption. Anchored on a detailed research design, this work tends to add to the knowledge on the potentials of solar energy in urban areas while feeding data evidence into the formulation of sustainable energy policies and urban planning strategies.

A design similar in nature, by considering robust sources of data, comprehensive preprocessing steps, and the usage of advanced tools capable of spatial analysis, ensures that results are reliable and as precise as possible. This is meant to display those areas were integrating renewable energy-solar power-will be maximally in favor of regional energy self-sufficiency improvement and reduction in carbon emission, by allowing a comparative view between the generation capacities in detail.

Consequently, this research design has clear and replicable methodology that could be emulated by decision-makers, urban planners, and policy makers desirous of determining the potentials of solar PV systems in residential districts. The focus of the research is on sustainable development based on informed planning and increased adoption of renewable energy solutions that meet regional and global sustainability goals for the 21st century.

3.1.1.2 Overview of Research Steps

Data pre-processing is performed to ensure consistency and accuracy. Pre-processing involves cleaning the data for duplicates, missing values, and merging of multiple data. Also, all data layers are projected to a common coordinate reference system to enable seamless analyses in GIS. The results of data processing are integrated into a comprehensive ArcGIS geodatabase, enabling efficient data management that will support the subsequent modeling phase (Figure 3-1).

The energy modeling phase includes rooftop suitability assessment, simulating solar potential, and energy output estimations using the prepared geodatabase. To determine the most influential variables that affect the solar energy potential, the techniques used in this phase are statistical modeling techniques such as multiple linear regression and sensitivity analysis. In this respect, the proportional allocation method is applied to the city-level energy consumption data to allocate a proportion into the research area for more appropriate estimation of energy use. The SSI and SCI are also developed to quantify the amount of generated solar energy that is sufficient for local demands and on-site energy consumed. Residual analysis is carried out to assess variances between predicted energy outputs and actual values, further leading to model refinement and an improvement in accuracy. Calibration and validation of the model are key factors in the energy modeling phase, where the actual calculation of Mean Absolute Error-Mean Absolute Percentage Error is made to validate the extent at which the model has carried out its predictions. Then, residual analysis helps to explore any kind of systematic biases and informs the necessary adjustment to the model toward a more reliable one.

The last stage deals with visualization and interpretation under Results and Representation. This stage does detailed mapping using spatial visualization techniques to represent the solar potential of the rooftops in question in the study area. The output will represent in detail both SSI and SCI to represent rooftop potentials related to self-sufficiency and self-consumption, respectively. The comparative analyses, in this perspective, were made for several rooftop types-flat versus sloping roofs-on the basis of their potential and relative economic interest. It thus provides results that are important to policymakers and urban planners with regards to promoting solar technologies in urban areas.

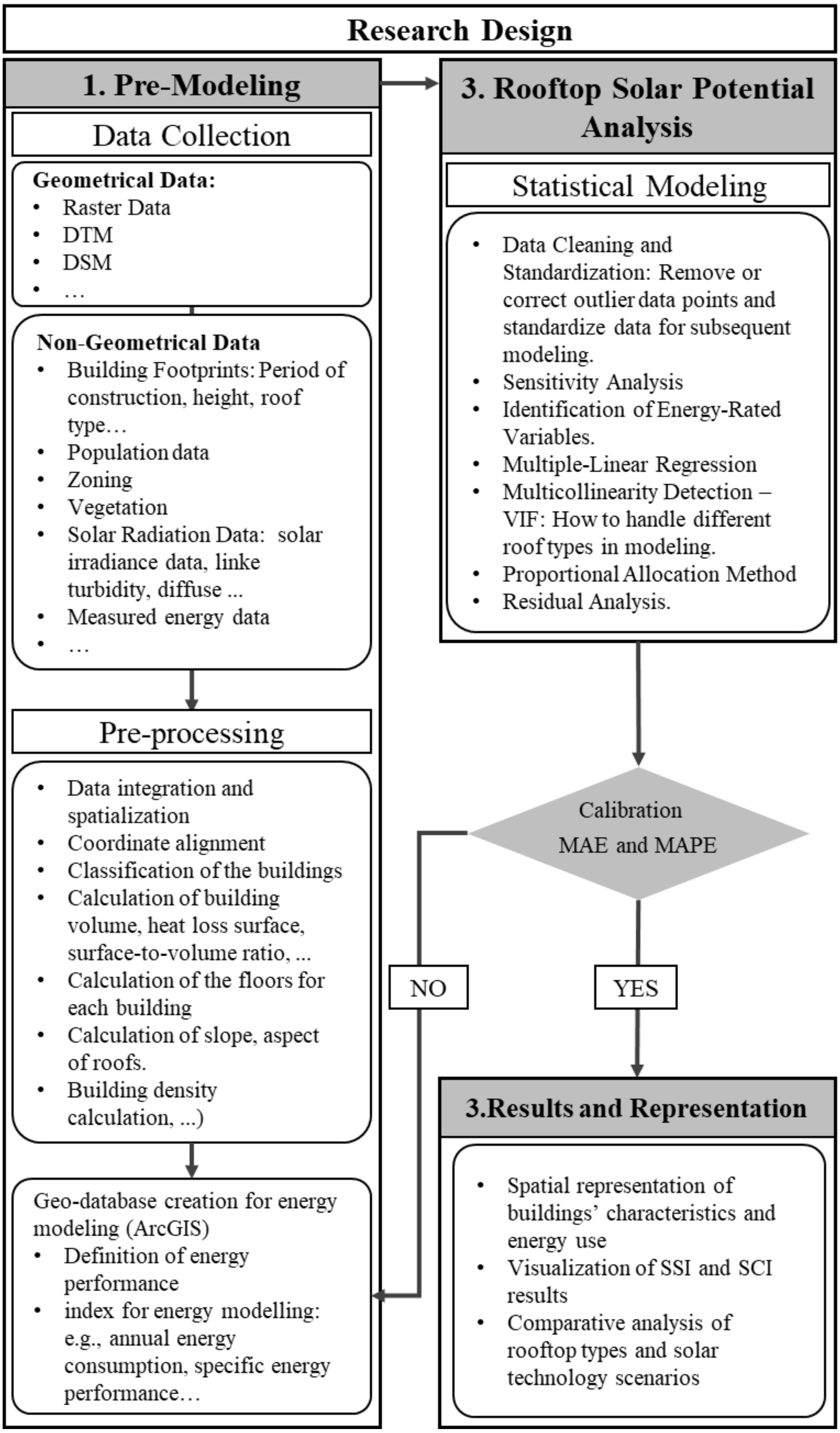

Figure 3-1 Research Design Flowchart (Source: Authorship)

3.1.2 Theoretical Basis of Research Design

3.1.2.1 Theoretical Foundation of Energy Modeling

Spatial analysis and processing of spatially referenced data are important features of urban energy modeling. Correspondingly, GIS permits an interaction of overlaying different layers-from building footprints and DSMs to solar maps-that calculate the energy potential of rooftops. This type of spatial approach enables indications of highly valued areas in terms of solar potential with high accuracy, helping to illustrate the spatial distribution of energy consumption throughout the city.

Information such as that derived from a GIS-based analysis of urban form, shading effect, and orientation forms the pre-requisite basis for arriving at a judgment on the feasibility of rooftop solar installations. Further integration of statistical and machine learning methods with GIS will enhance the accuracy in energy consumption forecasting and allow data-driven decisions for city planners.

3.1.3 Theoretical Support for Using GIS Technology

Geographic Information System (GIS) t is one of the main features of urban energy modeling due to the integral analysis and processing of spatially referenced data. Accordingly, GIS allows for the possibility of overlying different layers-from building footprints and DSMs to solar maps-to evaluate the energy potential of rooftops. Such a spatial approach enables one to precisely pinpoint highly valued areas of solar potential and helps in visualizing the spatial distribution of energy consumption across the city.

Such information from a GIS-based analysis of urban form, shading effect, and orientation serves as a prerequisite in judging the feasibility of rooftop solar installations. The integration of statistical and machine learning methods with GIS will further enhance accuracy in energy consumption forecasting and facilitate data-driven decision-making for city planners.

3.2 Data Collection and Preprocessing

3.2.1 Overview of Data Sources

3.2.1.1 Building and Energy Data

To accurately evaluate solar potential for building rooftops, comprehensive building and energy data were collected from reliable sources. The 2020 Building Footprints dataset, provided by Metro's Data Resource Center (DRC), was the primary source for building data. This dataset included crucial information such as building footprints, roof types, and building heights, which were instrumental in determining available roof areas for photovoltaic (PV) system installations and differentiating between flat and sloped structures.

Energy consumption data were sourced from the Residential Energy Consumption Survey (RECS), published by the U.S. Energy Information Administration (EIA). The RECS dataset is well regarded for its detailed insights into residential energy usage, covering essential energy end-uses like space heating, cooling, and domestic hot water. The integration of this data ensured accurate modeling of energy consumption patterns tailored to the characteristics of the study area's residential buildings.

3.2.1.2 Terrain and Climate Data

Detailed terrain data were essential for understanding the elevation and topographical features of the study area. The Digital Surface Model (DSM), sourced from the Oregon Spatial Data Library, provided comprehensive elevation data that included buildings and vegetation, enabling precise analysis of rooftop geometry and potential shading from surrounding structures. The Digital Elevation Model (DEM), acquired from Metro's DRC, was crucial for assessing foundational ground surface elevations, roof slopes, and orientations, as well as for analyzing shading impacts from nearby structures and natural features.

For climate data, NASA's Prediction of Worldwide Energy Resources (POWER) provided primary solar radiation metrics, such as global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI). These metrics were critical for modeling solar energy availability. To further refine solar radiation simulations, Linke Turbidity values were sourced from Meteonorm. These values accounted for atmospheric transparency and the attenuation effects of aerosols and water vapor, directly influencing the transmissivity of solar energy.

3.2.2 Preprocessing Steps

3.2.2.1 Data Cleaning and Integration

Data cleaning and integration are major factors in quality and consistency for the different datasets applied in analyses of solar potential. Cleaning procedures were comprehensively applied to the sets of building, terrain, and climate datasets that were collected to deal with problems related to missing values, duplicate entries, and inconsistencies in the data. Examples are the footprints of buildings, where it was checked that all relevant attributes were correctly present, such as roof type and building height. Similarly cross-validation of terrain data was performed w.r.t DSM and DEM data to remove the noise created and then the data had to match with the building data to avoid contradictory elevation values.

Data integration meant ensuring the datasets were aligned in a single and common coordinate reference system, say UTM, where seamless spatial analysis was possible. This allowed the merging of different data layers into a complete GIS database wherein thorough overlay and interaction could occur in the further course of analysis. It ascertained that in an integrated dataset, the spatial data of each building correlated with terrain and solar radiation information into a cohesive database for further processing.

3.2.2.2 Preparing Data for Analysis

Once the data were cleaned and integrated, additional processing was required to prepare it for analysis. Solar radiation data, including global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI), were preprocessed to convert raw values into formats suitable for energy modeling.

To understand the proportion of diffuse radiation relative to the total global solar radiation, the following ratio was calculated:

$$\textit{Diffuse-to-Global Radiation Ratio (D/G)} = \frac{DHI}{GHI}$$

This ratio provides insights into the distribution and quality of solar radiation, which is essential for accurately modeling solar energy potential.

The transmissivity($\boldsymbol{\tau}$) of solar radiation was calculated using:

$$\tau = \frac{GHI}{E_0 \cdot cos(\theta_z)}$$

where:
E_0 represents the extraterrestrial solar irradiance,
θ_z is the solar zenith angle.

This step involved resampling and interpolating the solar radiation data to match the spatial resolution of the building dataset, ensuring consistency across the data layers.

Energy consumption data sourced from the RECS dataset were scaled and matched to local building characteristics using a proportional allocation method. The allocation formula used was:

$$E_{buildings} = E_{total} \cdot \left(\frac{A_{buildings \cdot F_{year}}}{\sum(A_{all\ buildings \cdot F_{year}})}\right)$$

where:
$E_{\text{buildings}}$ is the estimated energy consumption for an individual building,
E_{total} is the total energy consumption for the study region,
$A_{\text{buildings}}$ is the total floor area of the specific building,
F_{year} is the building year factor that accounts for energy efficiency variations based on the construction period,
$\sum(A_{all\ buildings \cdot F_{year}})$ is the sum of all floor areas weighted by their respective year factors.

The final prepared dataset was optimized for use in GIS analysis and modeling, ensuring a robust foundation for evaluating the potential of rooftop PV systems and comparing solar energy generation with energy consumption. This comprehensive dataset allowed for detailed assessments tailored to the study area's specific conditions, providing meaningful insights into solar energy potential and energy usage.

3.3 ArcGIS Analysis Method

3.3.1 Overview of Radiation Analysis Techniques

This sub-section provides a comprehensive overview of the techniques used for radiation analysis, focusing on how solar irradiance and potential shading were assessed in the study area using ArcGIS. The specific flowchart is shown in the Figure 3-2.

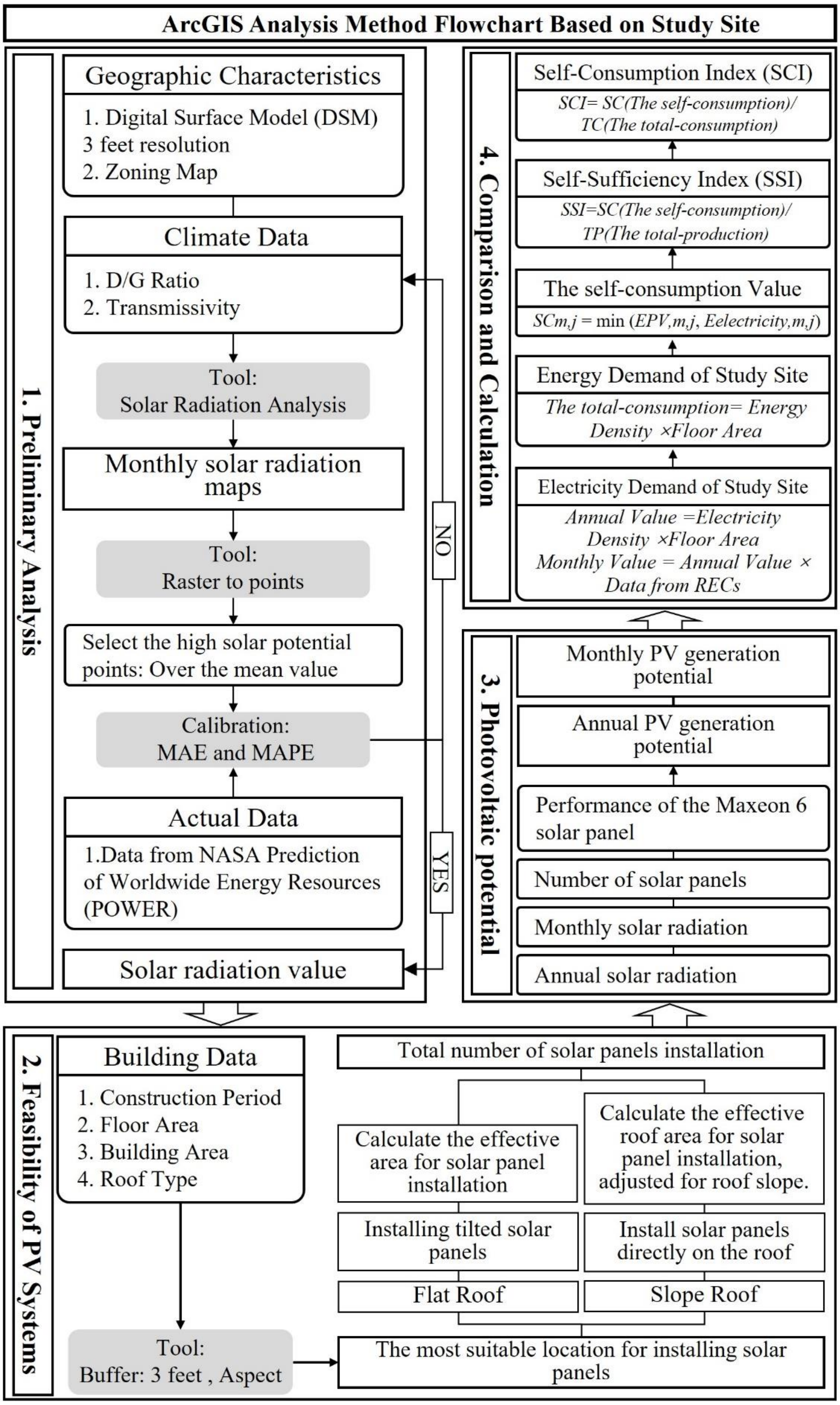

Figure 3-2 ArcGIS Analysis Method (Source: Authorship)

3.3.1.1 Selected ArcGIS Tools

The work carried out solar radiation analysis, rooftop suitability assessment for the installation of PV using the comprehensive suite of ArcGIS tools. Major ArcGIS tools adopted for this work include

Solar Radiation Tool, which then went on to be used for the calculation of direct, diffuse, and global solar radiation across the study area. This becomes a very important tool since it's meant to provide very vital data on yearly solar exposure on building rooftops, acting as a platform for understanding the energy yields that are possible.

The Raster to Points Tool allowed the annual solar radiation raster outputs to be converted into point data. By selecting points where the annual solar radiation was above the median, one can develop a best practice in identifying the optimal installation locations of PVs in such a way that the analysis focuses on those with high solar potential.

The Buffer Tool was important in determining the most suitable rooftop where a solar panel can be installed. With the use of this buffer, zones around high-radiation points are created and attain areas satisfying the criteria of receiving the best sunlight exposure and accessibility by reducing further focus to only promising parts of the roofs.

Roof orientation was calculated by Aspect Tool, considering the important variable in the capture of solar energy. In many ways, it gives the direction faced by each rooftop-a very major determinant for how well the surface could harness solar energy and detect the most viable location within the city for PV installation.

Summation of the potential solar radiation data was done for each individual building footprint using the Zonal Statistics Tool. This was so that comparisons of solar potential among varied rooftops and tracts could be made to support an extensive suitability evaluation of those for the deployment of solar panels.

The integration of these ArcGIS tools provided a robust framework for carrying out in-depth analysis on rooftop solar potential. An approach like that has allowed the identification of the best places in terms of installation by considering some critical criteria: radiation exposure, roof orientation, and slope.

3.3.1.2 Parameter Selection and Alignment

Some key parameters were selected, and their alignment was carried out with due care to ensure the robustness and accuracy of the analysis. In this respect, the time resolution was one such aspect where either monthly or annual values of solar radiation were selected, depending upon the focus of the study. The decision on this was quite pivotal in capturing the seasonal and long-term solar potential correctly.

Other important factors included the establishment of the study area's geographical boundary in ArcGIS. To this effect, the boundaries of this study are clearly demarcated to encapsulate all necessary urban structures and topographies that might have a bearing on solar potential analysis. This was meant to ensure that the area under consideration was comprehensive and relevant to the research objectives.

The alignment was done in detail, to be consistent across various datasets of different nature, such as building footprints, terrain models, DSM and DEM, and solar radiation data. That means all these datasets had to refer to one common coordinate reference system, which is important for the correct spatial overlay and further analysis. The transformation of coordinate systems or projection changes were performed if needed to achieve proper data alignment. Each step was important to ensure that spatial data interacted well within a GIS environment for coherent, precise analysis of rooftop solar potential.

3.3.2 Model Validation Method

3.3.2.1 Data Validation Methods

Validation of the ArcGIS model was, therefore, an important step in this analysis toward the robustness and reliability of the outputs. It hence included comprehensive validation of data input and error analysis techniques to ensure that the model is accurate and credible.

Various means have been implemented in assessing correctness regarding the solar potentials model as a means of performance benchmarking against standards recognized.

i. Cross-validation with external datasets: The data retrieved from the model were again cross-checked with data from recognized and established external sources, such as PVGIS and NASA's POWER database. It was done with a view to cross-checking whether the ArcGIS model solar radiation estimates are at par with credible datasets, hence setting the benchmark of accuracy against which confidence can be built on the model.

ii. Statistical Measures: Other than the quantification of the prediction errors, model performance was assessed in terms of the following common statistical metrics:

$$\textit{MAE (Mean Absolute Error)} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i|$$

MAE measured the average magnitude of the errors between observed values(y_i) and predicted values($\hat{y}_i$), offering a straightforward assessment of the overall prediction accuracy without considering error direction.

$$\textit{MAPE (Mean Absolute Percentage Error)} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100$$

MAPE provided an average error as a percentage, allowing for a scale-independent evaluation of the model's performance. This metric was particularly valuable for interpreting the relative magnitude of errors across varying scales of data.

i. These statistical measures collectively provided a nuanced understanding of the model’s predictive capability. While MAE and MAPE focused on the average accuracy of predictions.

3.3.2.2 Error Analysis of Results

Error analysis has been conducted to understand model result discrepancies and enhance their accuracy. This includes the identification of likely error sources, such as terrain irregularities, assumptions made about atmospheric data, and limitations of the DSM data, which should help indicate where improvements need to be made. Residual analysis looks at the differences between observed and predicted values and recognizes over- or underestimation patterns. Sensitivity analysis involves changing the input parameters such as Linke turbidity and solar zenith angle to test the sensitivity of results. This helps in identifying those parameters that greatly affect the results. From this, model calibration can be instituted for better results in terms of accuracy and reliability.

3.4 Quantitative Assessment Methods

3.4.1 Solar Potential of Different Roof Types Analysis

3.4.1.1 Calculating PV for Flat Roofs

For this analysis, Maxeon 6 solar panels were selected due to their superior efficiency and performance characteristics. The use of Maxeon 6 panels, with their integrated microinverters and robust construction, ensures reliable performance under varied weather conditions, making them ideal for residential sloped roofs in Portland. Their 40-year warranty further reinforces their long-term suitability for PV projects.

These panels provide a power output range of 420 to 445 W and an efficiency rate of up to 23%, making them highly suitable for sloped roof applications. To accurately estimate the photovoltaic (PV) potential of flat rooftops, a comprehensive step-by-step methodology was followed.

i. Selection of Suitable Rooftop Areas: The analysis began with using GIS tools to identify flat rooftop areas appropriate for PV installation. The Raster to Points Tool was used to convert annual solar radiation raster data into discrete points, isolating those with values exceeding the median solar radiation to identify optimal panel placement locations. After determining these high-radiation points, the total usable rooftop area was calculated in ArcGIS by measuring the areas of the identified raster cells.

ii. Panel Installation Angle: Given that Portland's latitude is approximately 45.5°, a 45° tilt is close to optimal, ensuring consistent performance throughout the year. For maximum energy production in winter, a steeper tilt can enhance exposure to the low-angle winter sun. However, a 45° tilt also allows for strong solar capture during summer months when the sun is higher, balancing energy generation over the year.

iii. Row Spacing Calculation: To prevent shading between rows of panels on flat roofs, it is necessary to calculate the required spacing (z) between each row, based on the tilt angle (α) and the solar altitude angle (β) on December 21st. The spacing formula used is:

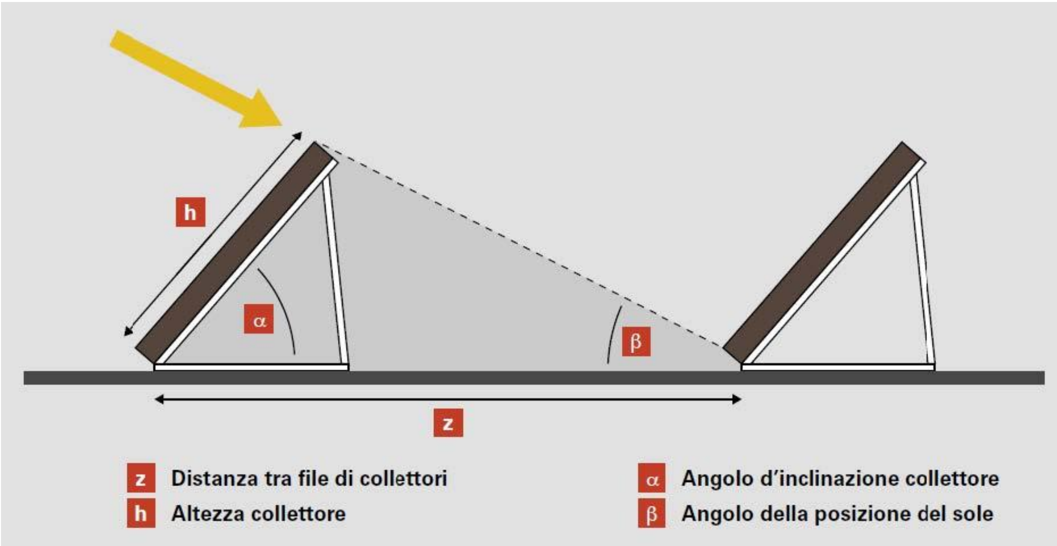

Figure 3-3 Flat roof installation (Source: Viessmann manuale solare completo)

$$\frac{z}{h} = \frac{sin(180° - (\boldsymbol{\alpha}+\boldsymbol{\beta}))}{sin\boldsymbol{\beta}}$$

where:

z is the distance between rows of panels,

h is the height of the tilted panel, calculated as $H = Panel\ length \times sin(\theta)$,

α is the tilt angle 45°,

β is the solar altitude angle on December 21st (approximately 21° for Portland).

For a panel length of 1.872 m:

$$H = 1.872 \times \sin(45^{\circ}) \approx 1.32m$$

With β as the solar altitude angle on the winter solstice, the distance z between rows can be calculated to ensure minimal shading. Assuming a representative value for β, the row spacing is approximately 3.05 m.

iv. Effective Panel Area Calculation: To determine the effective area occupied by each panel, including necessary row spacing, the following formula is applied:

$$\textit{Effective area per panel} = (\textit{Panel length} + \textit{Row spacing}) \times \textit{Panel width}$$

Substituting the panel length of 1.872 m, row spacing of 3.05 m, and panel width of 1.032 m:

$$\textit{Effective area per panel} = (1.872+3.05) \times 1.032 \approx 5.11\ m^2$$

This calculated area considers both the physical size of the panel and the spacing required to prevent shading, ensuring continuous sunlight exposure for optimal energy production.

v. Calculation of Panel Numbers: The number of panels that could be installed was determined using the calculated usable rooftop area and the known dimensions of the Maxeon 6 solar panels. The dimensions of Maxeon 6 panels were approximately 1.048 m × 1.838 m (width × length), allowing for precise calculations of panel layout and quantity. The total number of PV panels that could be installed on the rooftop was calculated using the following formula:

$$N_{panels} = \frac{Usable\ roof\ area}{Effective\ Panel\ Area}$$

where:

Usable Roof Area is the total rooftop area available for PV installation after considering obstructions and clearance requirements,

Effective Panel Area represents the sum of the panel's physical area and the spacing needed between panels to prevent shading.

vi. Energy Potential Calculation: The total energy potential (E) for the PV system was calculated based on the number of solar panels that could be installed on the available rooftop area. Using the previously determined number of Maxeon 6 panels and their individual power output, each panel has a power output of 420–445 W depending on the model, the annual energy output was estimated with the following formula:

$$E_{flat} = N_{panels} \times P \times G_{total} \times PR$$

where:
E_{flat} is the actual annual energy generation (kWh/year) of slope roofs,
N_{panels} is the number of panels on flat roofs,
P is the power output of each Maxeon 6 panel (420–445 W, depending on the model),
G_{total} is the annual average solar radiation(kWh/m²/year) received on flat roofs,
PR is the performance ratio, set at 0.8 to account for typical system losses.

3.4.1.2 Calculating PV Sloped Roofs

The typical roof slope for residential homes in Portland, Oregon, averages around a 6/12 pitch, which corresponds to a roof angle of approximately 26.57 degrees. This moderate slope is common for residential homes as it balances aesthetics, functionality, and water drainage effectively, especially in a climate like Portland's, which receives significant rainfall.

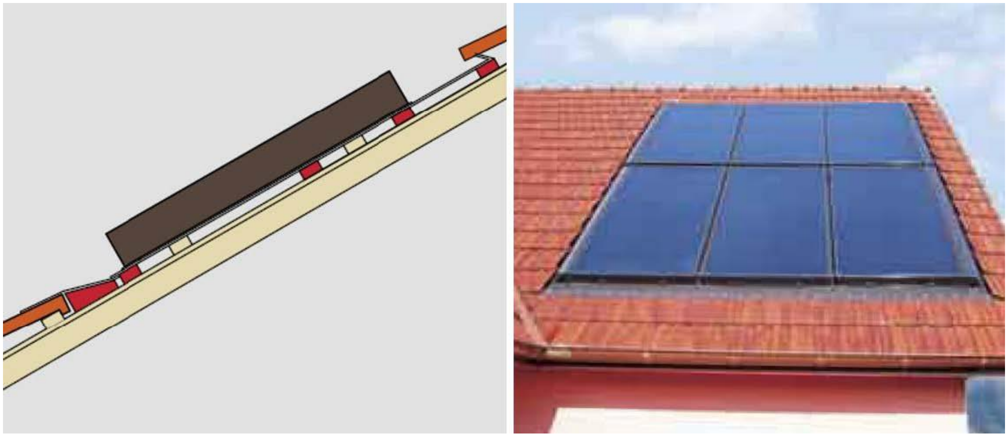

Figure 3-4 Installation method of photovoltaic panels on slope roof (Source: Viessma nn manuale solare completo)

The following analytical procedures were applied:

i. Solar Radiation Data Collection: The Solar Radiation tool in ArcGIS was employed to collect data on direct, diffuse, and global solar radiation over the study area. This data served as a foundation for estimating annual energy yields and understanding solar exposure on sloped surfaces.

ii. Aspects Analysis: The Aspect tool was used to assess the orientation of rooftops. Due to Portland's geographic location in the northern hemisphere, roof orientations facing east to west (67.5° to 292.5°) were selected as optimal for maximizing solar energy capture. This choice reflects the city's latitude and typical solar path, where these orientations can harness the highest levels of solar exposure throughout the year.

iii. Raster-to-Point Conversion for High-Radiation Zones: The Raster to Points tool converted the solar radiation raster data into point data. Points where annual radiation exceeded the median value were selected, allowing for the identification of high-potential areas for PV installation.

iv. Roof Suitability Assessment Using Buffer Tool: The Buffer tool was applied to create zones around the high-radiation points, delineating roof sections that met criteria for solar exposure and accessibility, and focusing on feasible installation areas. Finally, the roof areas (A_{total}) suitable for installing photovoltaic panels are comprehensively determined. The actual area available for PV panel installation was calculated by adjusting for the slope using the following formula:

$$A_{actual} = \frac{A_{total}}{cos\,(\theta\,)}$$

where:
A_{actual} is the effective area available for PV installation,
A_{total} is the total roof area (m²),
cos (θ) is the roof slope angle (26.57°).

v. Calculation of PV Potential:

The number of solar panels that can be installed is calculated as:

$$N_{panels} = \frac{A_{actual}}{A_{panel}}$$

where:

N_{panels} is the number of panels on slope roofs,

A_{panel} is the area of a single solar panel (m²).

To estimate the PV power potential on sloped roofs, the following formula was applied:

$$E_{slope} = N_{panels} \times P \times G_{total} \times PR$$

where:

E_{slope} is the actual annual energy generation (kWh/year) of flat roofs,

N_{panels} is the number of panels on slope roofs,

P is the power output of each Maxeon 6 panel (420–445 W, depending on the model),

G_{total} is the annual average solar radiation received (kWh/m²/year) on slope roofs,

PR is the performance ratio, set at 0.8 to account for typical system losses.

3.4.2 Comprehensive Analysis of Consumption Data

3.4.2.1 Energy Consumption Model

The study will calculate the energy consumption factor, taking into consideration already existing data on energy consumption in combination with building age and floor area. These will then be applied to the study site, estimating energy use of the buildings in that area by floor area and age.

By analyzing the relationship from existing energy consumption data, identifying the energy consumption factors caused by building age and floor area. The formula is expressed below:

$$E_{consumption,i} = f(Age_i, Area_i)$$

where:

$E_{consumption,i}$ is the annual energy consumption for building i (in kWh),
Age_i is the construction age of building i,
$Area_i$ is the building area of i (in m²),
f is a function representing the calculation of energy consumption factors, derived through regression or modeling based on existing data.

Using the calculated energy consumption factors and known building area and age, the total energy consumption for the study area can be estimated:

$$E_{total,site} = \sum_{i=1}^{n} E_{consumption,i}$$

where:
$E_{total,site}$ is the total annual energy consumption for the study site (in kWh),
n is the number of buildings in the study area.

3.4.2.2 Consumption Data Comparison

A comprehensive understanding of how photovoltaic (PV) systems contribute to meeting electricity demands in the study area's sub-regions requires detailed monthly comparisons of energy production and consumption. This analysis helps identify the extent to which local PV generation aligns with monthly electricity needs and highlights opportunities for optimizing self-consumption.

To assess self-consumption monthly, the following formula is used:

$$SC_{m,j} = \min\left(E_{PV,m,j}, E_{electricity,m,j}\right)$$

where:
$SC_{m,j}$ is the actual energy consumed on-site from the PV system for sub-region j during month m (in kWh),
$E_{PV,m,j}$ is the total energy generated by the PV system for sub-region j during month m (in kWh),
$E_{electricity,m,j}$ is the total electricity demand of sub-region j during month m (in kWh).

This quantifies the portion of PV-generated electricity that is directly utilized by the sub-region each month. If the PV energy production meets or surpasses the electricity demand for that month, all produced energy is consumed, maximizing self-consumption.

To evaluate the overall self-consumption over the year, the monthly values are aggregated:

$$SC_{annual,j} = \sum_{m-1}^{12} SC_{m,j}$$

where:
$SC_{annual,j}$ is the total self-consumption for sub-region j over the course of the year (in kWh).

This total reflects the cumulative amount of PV energy utilized on-site across the year, serving as a key metric for understanding the local consumption of renewable energy within the sub-region.

Calculating the total electricity consumption for each sub-region is essential to understanding overall energy needs:

$$TC_j = \sum_{m-1}^{12} E_{electricity,m,j}$$

where:
TC_j is the total annual electricity consumption for sub-region j (in kWh).

This total consumption figure provides a baseline for comparison with both the self-consumption and total PV energy production, facilitating a comprehensive energy balance assessment.

With the calculated annual self-consumption, total-consumption, and total-production data, it is possible to derive two critical indices: the Self-Consumption Index (SCI) and the Self-Sufficiency Index (SSI).

$$SCI_J = \frac{SC_{annual,j}}{E_{PV,annual,j}}$$

where:

SCI_J is the self-consumption index for sub-region j, indicating the fraction of the total PV energy produced that is directly consumed on-site.

A higher value of SCI is indicative of a greater utilization of locally generated renewable energy, therefore an efficient on-site energy system. SCI can be one of the most important indices to find out the role of integration of PV systems into energy management practices. It highlights how much of the energy generated is retained and used within the sub-region versus how much might be exported to the grid.

$$SSI_J = \frac{SC_{annual,j}}{TC_j}$$

where:

SSI_J measures the degree to which the annual electricity demand of sub-region j is met by the self-*consumed* PV energy. An SSI value approaching or exceeding 1 indicates that a substantial portion, if not all, of the region's electricity needs is satisfied through locally produced PV energy.

SSI is critical for evaluating the independence of the sub-region from external energy sources. It reflects the potential for energy autonomy and supports strategic decisions aimed at enhancing energy resilience and sustainability. These analyses provide a multi-faceted view of energy performance, allowing stakeholders to understand how effectively PV systems contribute to meeting local energy needs.

4 Case Study: Portland: Oregon

4.1 Geographic and Climatic Characteristics

4.1.1 Major Geographic Features

Figure 4-1 Portland and Study Site Geographic Map (Source: USGS)

Portland (Figure 4-1), Oregon, it shows a range in topography that has a great impact on solar energy possibilities and further urban development. The city is situated within Willamette Valley, bounded to the east by the Cascade Range and to the west by the Tualatin Mountains. With such varied topography, ranging from riverfront areas to hilly neighborhoods, solar exposure is affected by shading and changing sunlight angles.

The Willamette River runs right through the city and tends to mold Portland's physical landscape, while affecting local microclimates and hence cloud cover and solar radiation. Additionally, highly extended urban tree canopy and nearby forested areas contribute to shading, potentially reducing direct solar access for residential and commercial buildings. This vegetation supports cooler temperatures, which are beneficial for PV system efficiency since panels perform better at lower temperatures.

The urban design of Portland is a grid-pattern street system with clear zones of residence, commercial, and industrial areas. Characteristic setting, inclusive of high-rise downtown buildings and single-family suburban homes, affects the way sunlight reaches rooftops and the available space for possible PV installations. In areas with taller buildings, partial shading of adjacent structures could occur which would give rise to solar potential.

4.1.2 Climate Analysis

4.1.2.1 Influence of Seasonal Variations

The climate of Portland is a mild oceanic climate: mild, wet winters and warm, dry summers. This gives way to large seasonal variations in solar irradiance because of cloud cover and precipitation patterns. On average, Portland gets about 2,400 hours of sunshine per year with peak solar potential during the summer months.

It can be noticed that during summer, from June to September, there is longer daylight and less cloud cover to ensure that the sun's rays strike with maximum exposure, giving higher energy output from PV systems. Longer days mean solar panels generate energy for extended periods. Overall power production increases. On the other hand, the most critical months of the year, winter, are the months of November, December, January, and February, due to lower sun angles, reduced daylight, and frequent cloud cover. All these factors reduce the availability of solar radiation, hence the expectations of PV systems in those months in terms of energy output are lowered.

These are seasonal variations that need to be understood in order to assess the solar potential and plan the installation of PV systems accordingly to maximize production from them in peak seasons with recognition of a decrease during winter.

4.1.2.2 Impact of Climatic Conditions on Power Generation Efficiency

These climatic features affect not only the availability of sunshine in the region but also the performance and reliability of solar panels throughout the year. The critical factors determining the efficiency of solar power generation include temperature, cloud cover, and precipitation.

Generally, mild summer temperatures in Portland, Oregon support sustained energy production in solar panels, since cooler conditions avoid excessively high temperatures that raise cell resistance and reduce efficiency. Quite fortunate for that fact, since extreme temperatures degrade performance, which is of less concern with the Portland weather climate. Their efficiencies, like the Maxeon 6, which undergo performance testing at temperatures upwards of 60°C, meet Portland's general weather conditions quite well(Maxeon Solar Technologies., 2023; Viessmann Werke GmbH & Co. KG, 2009).

However, cloud cover, which is prevalent in fall and winter, reduces the amount of direct solar radiation and necessitates reliance on diffuse radiation, leading to lower power output. Advanced PV systems, like the Maxeon 6 panels, are designed to perform well in low-light conditions, which helps mitigate this limitation(Maxeon Solar Technologies., 2023). Moreover, precipitation, although it limits solar exposure during rainfall, serves as a natural cleaning agent for the panels. This helps maintain their efficiency by removing dust and debris.

4.2 Data Collection and Processing Overview

4.2.1 Overview of Collected Data

This study draws from several data sources, including meteorological information, geospatial data, and building characteristics. These data sets, each different, are merged in a strategic manner to allow for appropriate analysis that can reflect the true solar potential of the area under study.

While this is going on, meteorological data, geospatial datasets of various sources, and building-specific information put together a full understanding of solar potential. For example, meteorological data provides the critical parameters required to drive the model's energy production simulations-solar irradiance, temperature, and wind velocity-while geospatial data allows for the spatial mapping and analysis of this information, building characteristic data enables correct modeling of energy use patterns. High-resolution spatial data and current meteorological records are considered important features to represent the real variations and nuances that define the solar potential. A scrutiny of each data set on the basis of the criteria mentioned above was considered necessary for carrying out the analysis on a sound basis of reliable and credible data. The biases or discrepancies in analysis are also minimal in this way.

Sometimes, processing and analyses of raw data require heavy use of data processing and sophisticated analysis tools. Complex datasets in performing spatial analysis, mapping building footprints, and including elevation data are transformed into usable formats with GIS software. Energy consumption can be modeled with statistical software. This level of processing turns disparate datasets into consistent formats that will allow cross-referencing and coherent analysis.

While this study presents a wide-ranging approach, it recognizes that some of the challenges likely to be faced in acquiring and processing data include access limitation and different levels of quality in various data sources. There are instances when interpolation and validation methods at appropriate levels are considered to develop incomplete data series or to check for inconsistencies in data series. These methods thus help overcome such problems, although they may be of limited value in their positive contributions to the final analysis and are recognized when interpreting the results.

The study follows data licensing agreements and ethical best practices on the use of data, and therefore uses each dataset in correspondence with the license it has and attributes providers accordingly. This commitment to transparent practices in the use of data or information is in correspondence with the best practice of academic integrity.

The clear distinctions in the role of each dataset permit an in-depth solar assessment. Meteorological data are used in calculating solar irradiance and energy production potential for a range of climatic conditions. Geospatial data allow for precise mapping of rooftops' orientation and elevation, crucial for the optimal placement of photovoltaic panels. Building characteristic data allows for a comparison between estimated energy production and actual demand.

Table 4-1 Data Sources (Source: Authorship)

Input Data	**Source**	**License**	**Download Link**
Typology: Solar Radiation Data			
Global Horizontal Irradiance (GHI)	NASA Prediction of Worldwide Energy Resources (POWER)	Public Domain	POWER
Diffuse Horizontal Irradiance (DHI)			
Global Horizontal Irradiance (GHI)	PVGIS (Photovoltaic Geographical Information System)	CC BY 4.0	PVGIS
Typology: Climate Data			
Linke Turbidity Factor	Meteonorm	Proprietary (Meteotest License)	Meteonorm
Humidity, Wind Speed, Temperature	NOAA (The National Solar Radiation Database)	Public Domain	NOAA
Typology: Geospatial Data			
DSM - 3feet resolution	Oregon Spatial Data Library	Public Domain (DOGAMI)	LiDAR DSM
DEM - 10m resolution			Oregon Spatial Data Library

Input Data	Source	License	Download Link
Portland Boundaries	Metro's Data Resource Center (DRC)	Public Domain	DRC
Building Footprints	Metro Regional Land Information System (RLIS)	Public Domain	RLIS Building Footprints
Typology: Photovoltaic Specifications			
Performance metrics of Maxeon 6 AC panels	Maxeon Solar Technologies	©2023 Maxeon Solar Technologies	
Typology: Energy Consumption Data			
Electricity usage, Total energy consumption	Residential Energy Consumption Survey (RECS)	Public Domain	RECS
Typology: Topographical Data			
Elevation and terrain data	United States Geological Survey (USGS)	Public Domain	USGS Elevation and terrain
Typology: Socio-Economic Data			
Population density	Metro Regional Land Information System (RLIS)	Public Domain	RLIS Population density
Income levels	U.S. Census Bureau	Public Domain	Income levels
Zoning Code	Metro Regional Land Information System (RLIS)	Public Domain	RLIS Zoning Code
Typology: Vegetation			
Land use/cover statistics	Metro Regional Land Information System (RLIS)	Open Data	RLIS Land Use
Typology: Past Energy Production and Projections Data			
Energy Projections Data	U.S. Energy Information Administration (EIA)	Public Domain	EIA Energy Projection

Input Data	Source	License	Download Link
Past Energy Demand Data	U.S. Energy Information Administration (EIA)	Public Domain	EIA Energy Demand
Typology: Policy and Regulatory Data			
Renewable energy incentives and zoning laws	Government publications	Public Domain	Incentives and Zoning

4.2.2 Data Processing and Integration

After data collection from various data sets, these data are processed and integrated in order to analyze the potential of solar energy. This section covers the methodology of the calculation for key metrics from the collected data and how such processed data are integrated in this study.

Transmissivity Calculation and Solar Radiation Metrics: Transmissivity is an indicator of the transparency of the atmosphere to solar radiation. It is calculated using meteorological data, including solar irradiance, temperature, and humidity. The data are processed about hourly, daily, and seasonal variations of transmissivity. In this study, for simplification monthly, transmissivity metrics are calculated to understand how the atmospheric condition influences solar energy potential. Table 4-2 shows the meteorological data considered.

Table 4-2Results of the monthly solar metric calculations (Source: Authorship)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Transmissivity (T)	0.28	0.47	0.51	0.53	0.47	0.50	0.60	0.66	0.51	0.53	0.38	0.39
D/G	0.69	0.39	0.43	0.38	0.49	0.46	0.30	0.23	0.38	0.35	0.51	0.47
Turbidity	2.73	2.68	2.76	2.98	3.13	2.88	2.75	2.84	2.75	2.77	2.67	2.76

The data highlights seasonal variations in atmospheric conditions affecting solar radiation. Transmissivity is lowest in winter (e.g., January at 0.28) and highest in summer (e.g., August at 0.66), indicating clearer skies and higher solar energy potential in the summer months, while winter months face more atmospheric attenuation due to cloud cover and humidity. The D/G ratio, representing diffuse to global solar radiation, is higher in summer (e.g., July at 0.30), reflecting clearer skies and more direct sunlight. In contrast, it decreases during winter (e.g., February at 0.39), signifying increased diffuse radiation from cloudier conditions.

Turbidity, measuring atmospheric aerosols, peaks in late spring (e.g., May at 3.13) and is lowest in December (2.67), indicating varying levels of particulate matter that affect solar transmission.

Data processing should involve considering seasonal fluctuations in solar radiation and climate variables, to ensure the authenticity of the analysis. This is a matching of temporal resolution in meteorological data with geospatial layers in such a way that the study simulates changes in solar energy potential throughout different times of the year. Therefore, such data may be processed for cloud cover, atmospheric pressure, and other climatic conditions specific to the production of solar energy.

These validation checks were performed by using the historical data of solar energy and energy consumption. Cross-referencing the data against simulation results helps confirm that the processing method is sound and allows for identification of discrepancies that may need adjustment.

The last step of data processing involves collation of all the calculated and derived variables in one dataset for comprehensive analysis. This would enable a detailed assessment of self-consumption and self-sufficiency indices by comparing the potential production of solar energy with the actual energy use patterns in the study area.

4.3 ArcGIS Analysis

4.3.1 Preliminary Analysis

The preliminary analysis involves preparing digital surface models (DSM) and zoning maps to understand the structural and geographic characteristics of the study area. These maps provide foundational data on building heights, roof orientations, and other landscape features essential for accurate solar radiation simulation.

Characteristics of buildings in the study area, totally 11,381, are summarized in Table 4-3. Building type, use, number of units, stories, construction year, floor area, and roof type are summarized herein. House type dominates the study area, whereas less than a quarter of the structures in the study area are apartment buildings.

This distribution suggests that the data focuses on residential buildings, which are bound to differ in energy use when compared to commercial or industrial buildings. Many buildings were constructed before 1950, indicating the strong prevalence of older structures. This factor is important for solar feasibility assessments since old buildings may require structural upgrades to support solar installations effectively. Only a small minority of the buildings had flat roofs, while most of the buildings had pitched roofs. Pitched roofs can limit the orientation of the panels, while for flat roofs, the change of orientation for solar panels is rather easy to adjust.

Table 4-3 Building Characteristics Summary of study site (Source: DRC)

Attribute	**Category**	**Count**
Building Type	House	11296
	Apartment	85
Building Use	Single family	11296
	Multi family	85
Number of Unit(s)	One unit	11309
	Two or more over units	72
Stories	One story	6839
	Two stories	4432
	Three stories	107
	Four or more over stories	3
Year Made Range	Before 1950	9858
	1950-1959	644
	1960-1969	60
	1970-1979	160
	1980-1989	74
	1990-1999	183
	2000-2009	222
	2010-2015	400
	After 2016	5
Floor Area	< 93 m^2 (1000 ft^2)	179
	93 $m^2$to 186 m^2 (1000 ft^2 to 1999 ft^2)	7233
	186 $m^2$to 279 m2(2000 ft2 to 2999 ft^2)	2023
	> 279 m^2 (3000 ft^2)	336
Roof Type	Flat	290

Attribute	Category	Count
	Pitched	11091

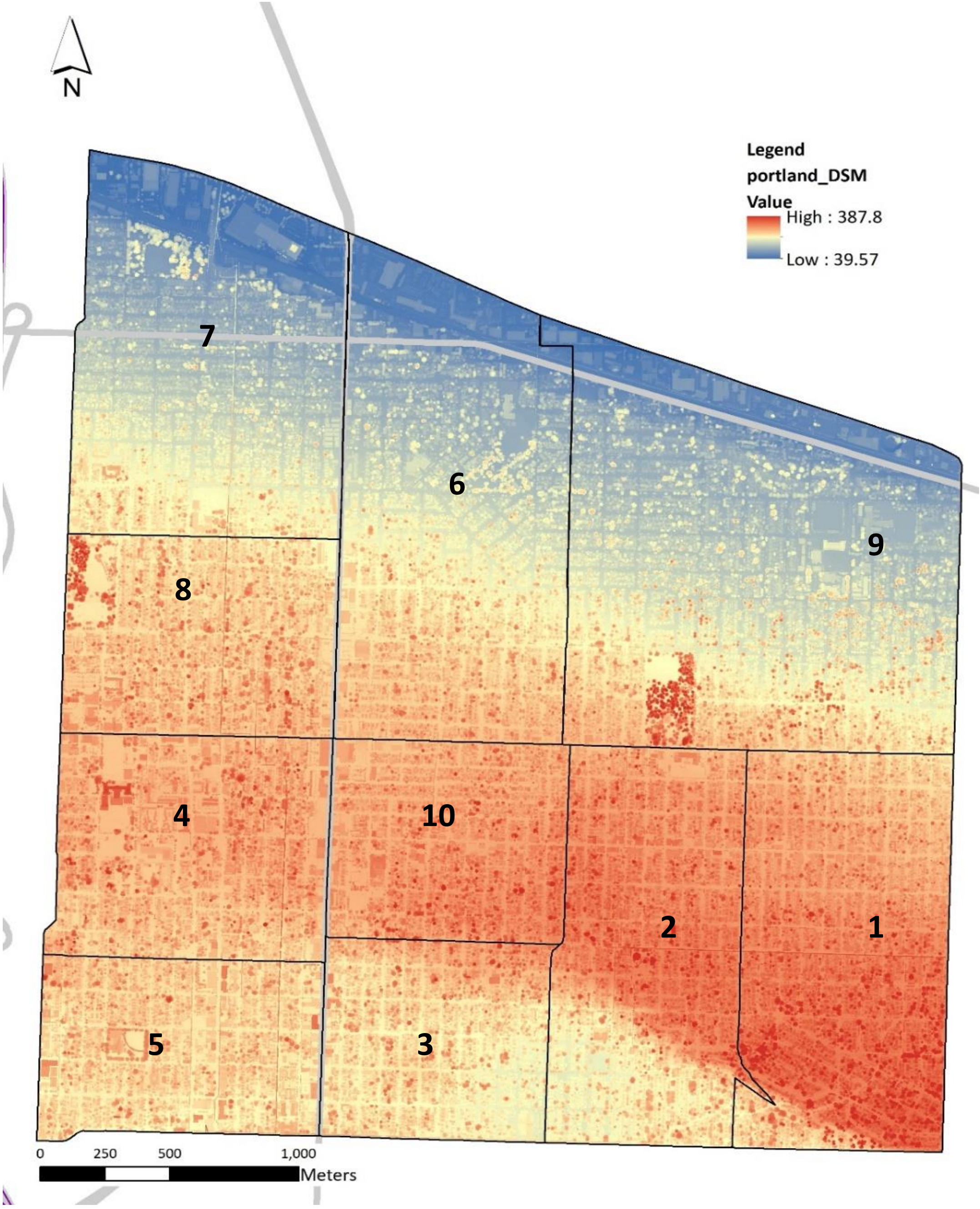

Figure 4-2 Digital Surface Model (DSM) Maps (Source: Oregon Spatial Data Librar
y)

Figure 4-2 illustrates the DSM of the study area, representing the height and contour variations across buildings and land surfaces, as it helps account for shadow effects from surrounding structures.

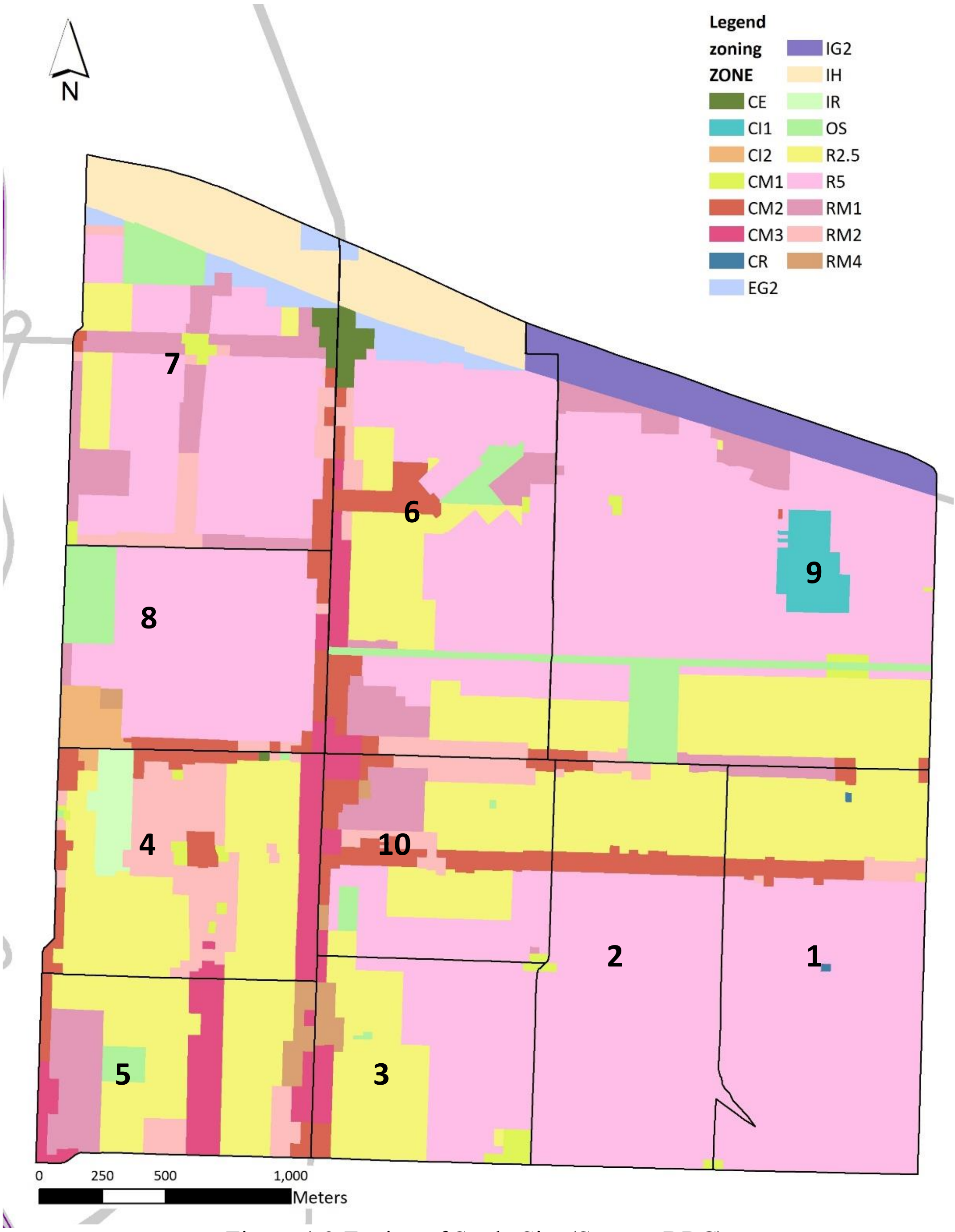

Figure 4-3 Zoning of Study Site (Source: DRC)

Figure 4-3 The zoning map categorizes the study area into distinct land use zones, such as residential (e.g., R2.5, R5), commercial (e.g., CM1, CM2), and industrial zones (e.g., IG2, IH). Zoning significantly influences solar potential, as different zones contain buildings with varying heights, orientations, and rooftop sizes. For instance, commercial zones with taller buildings may cast shadows on adjacent residential zones, thereby reducing the solar exposure for those areas. This zoning analysis supports targeted PV system deployment by identifying areas with optimal sunlight access and larger rooftop spaces.

Table 4-4 Zoning Description (Source: DRC)

Category	Zoning Code	Description
Residential Areas	R2.5, R5	Suitable for single-family homes and small residential buildings, ideal for assessing solar PV potential.
	RM1, RM2, RM4	Multi-family residential zones, suitable for apartment buildings and complexes with larger roof areas.
Commercial Areas	CE	Commercial employment zones, supporting various commercial buildings that can accommodate large PV systems.
	CI1, CI2	Commercial industrial zones, which include commercial buildings with large roofs suitable for solar PV assessment.
	CM1, CM2, CM3	Commercial mixed-use zones supporting residential, commercial, and sometimes industrial uses, ideal for diverse PV deployment.
	CR	Commercial residential zones that support both residential and commercial buildings, suitable for PV system installations.
Industrial Areas	EG2	General employment zones with large buildings and extensive roof space suitable for PV installations.
	IG2, IH, IR	Industrial zones with large, flat roofs and minimal shading, making them ideal for extensive PV installations.
Open Space Areas	OS	Open space areas that primarily include parks and recreational areas; facilities within these areas may be assessed for PV potential.

4.3.2 Simulation and Validation of Radiation Data

The Solar Radiation tool in ArcGIS was used to estimate solar radiation on building rooftops by accounting for solar angles, building orientations, and shading effects from nearby structures. The simulated radiation values were then validated against actual solar data from NASA to ensure reliability (Table 4-5).

Table 4-5 ArcGIS Simulation and Actual Data Compering (Source: NASA)

Month	ArcGIS Simulation Value (kWh/m2)	ArcGIS Simulation Value Over Mean Value (kWh/m2)	Actual Data (kWh/m2)	Absolute Error (kWh/m²)
Jan	0.29	0.32	0.93	0.61
Feb	1.24	1.39	2.31	0.92
Mar	2.97	3.23	3.61	0.38
Apr	4.51	4.81	4.96	0.15
May	5.66	5.92	5.14	0.78
Jun	6.41	6.66	5.79	0.87
Jul	6.47	6.78	6.70	0.08
Aug	5.78	6.16	6.41	0.25
Sep	3.15	3.42	3.93	0.51
Oct	1.82	2.04	2.89	0.85
Nov	0.48	0.54	1.38	0.84
Dec	0.27	0.31	1.13	0.82
Annual	39.04	41.56	45.18	

The average absolute error between ArcGIS-simulated data and actual NASA data is about 0.588 kWh/m². This reflects generally quite reliable but somewhat conservative estimation from the ArcGIS model that, in most cases, tends to keep the estimations quite conservative, especially in the low-solar months. The Moving Average Percentage Error of this comparison stood at about 27.51%, which states the percentage error difference in the average prediction error between simulated and actual data. This error percentage flags some areas of possible calibration, especially in those months where the ArcGIS model provides lower estimates for solar radiation.

Figure 4-4 Annual Solar Radiation Simulation on Building Roofs (Source: ArcGIS Simulation, Unit: kWh/m^2/year)

4.3.3 Feasibility of PV Systems

After the radiation analysis, we assessed the installations of PV systems regarding feasibility according to solar exposure and available space on rooftops, recognizing which rooftops have more potential with respect to the generation of solar energy, according to seasonal and geographic variability in solar radiation.

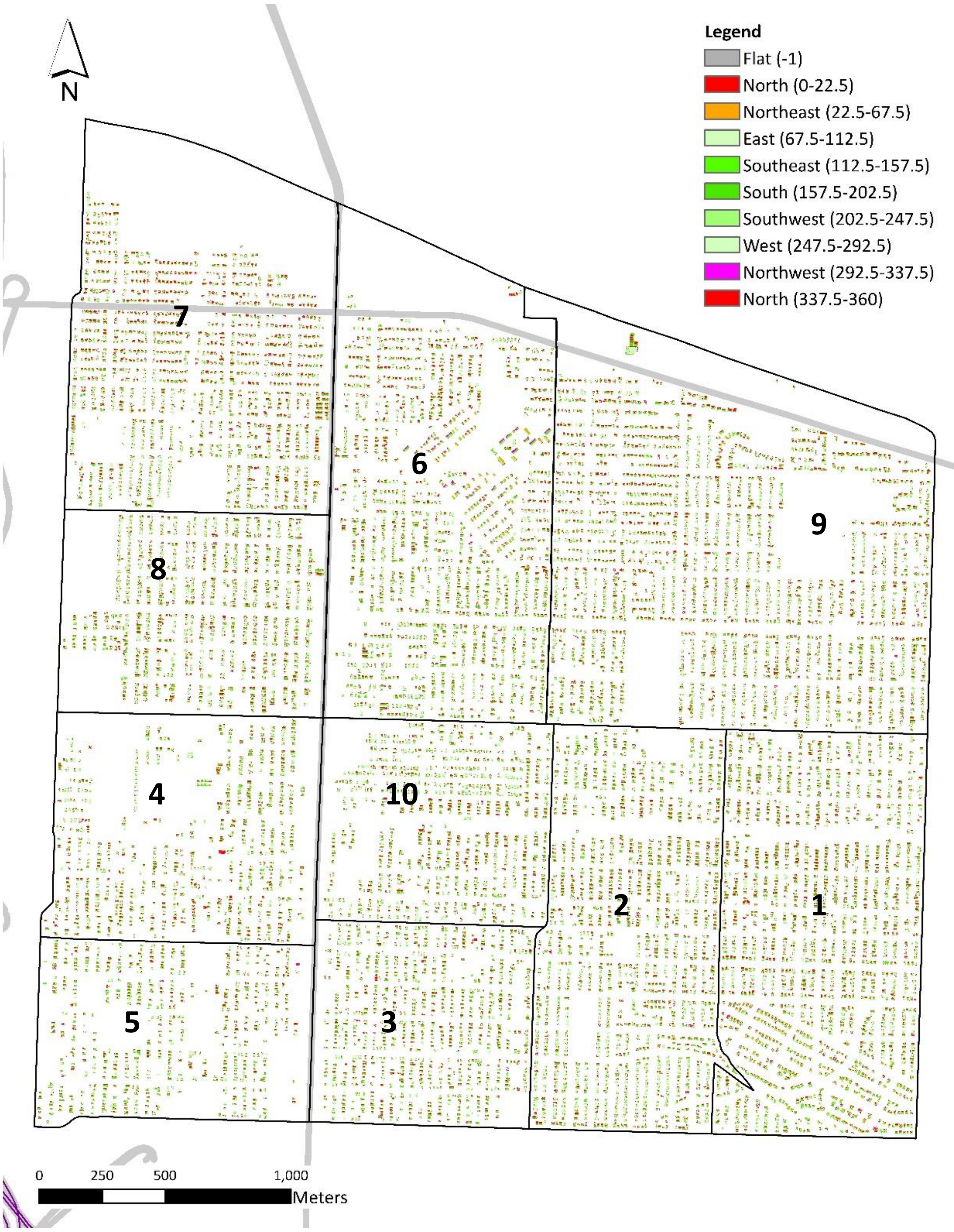

Figure 4-5 Aspect of Roofs (Source: ArcGIS Simulation)

Figure 4-5 categorizes rooftop orientations throughout the study area. The roofs with south-facing orientations generally show greater suitability for PV systems because of higher solar exposures, especially at northern latitudes.

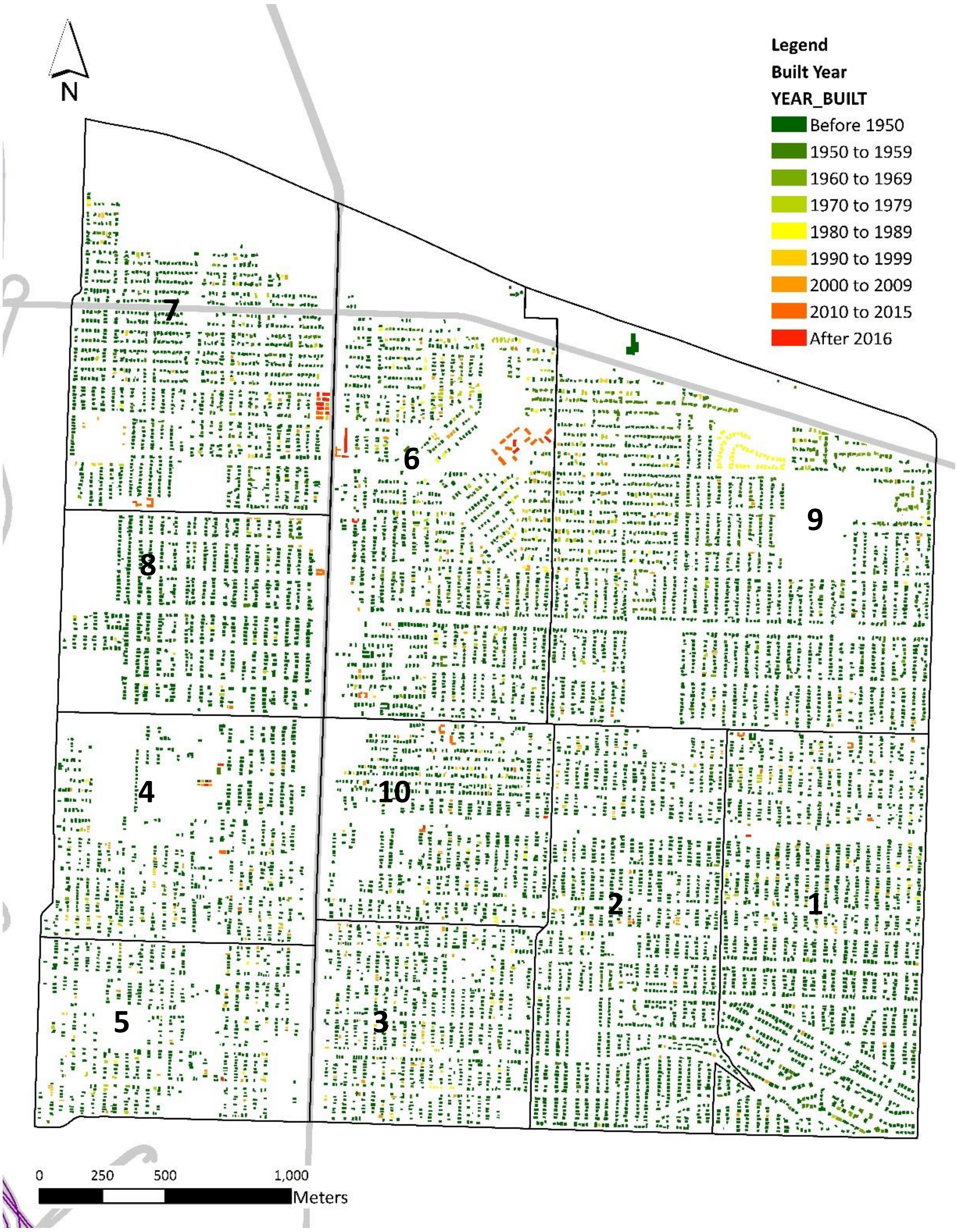

Figure 4-6 Building Construction Period (Source: DRC)

Figure 4-6 gives the distribution of periods of building construction, which determines indirectly the strength or suitability of rooftops for PV installations. For instance, the suitability of older buildings could be preceded with structural assessments regarding additional loads.

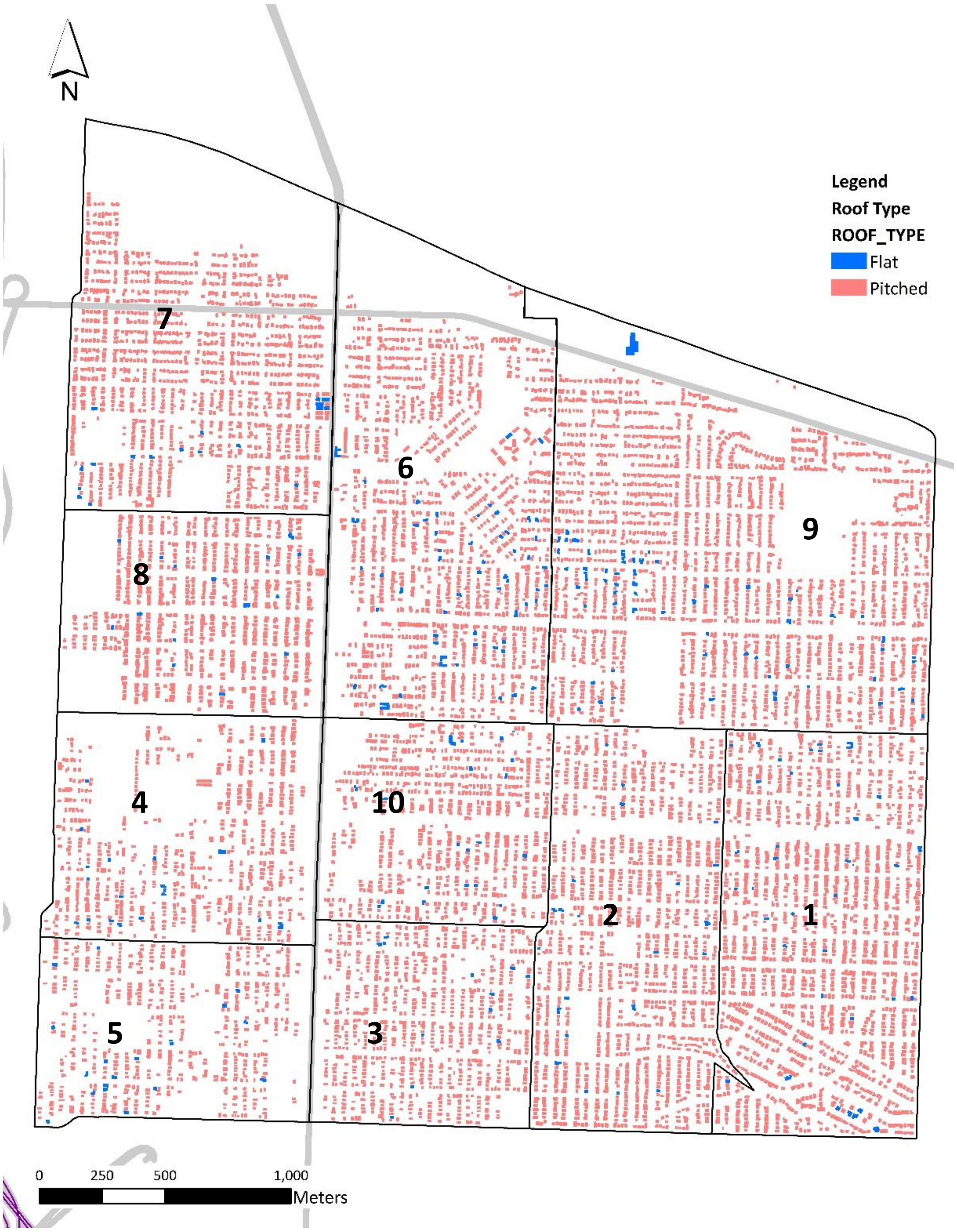

Figure 4-7 Building Roof Type (Source: DRC)

Figure 4-7 shows flat roofs differ from the pitched roof, each has its unique considerations for PV installations. Flat roofs allow for flexibility in panel orientation and spacing, while for pitched roofs, to increase sunlight exposure, an angle adjustment is made with accuracy.

Figure 4-8 provides a suitability map indicating rooftops with high potential for PV installations. This visual analysis helps pinpoint optimal locations for PV systems, enhancing the accuracy of energy generation projections.

And Table 4-6 shows an estimate of the photovoltaic panels that can fit on each tract within the study area. The estimations were calculated using a GIS analysis of rooftop availability and solar exposure throughout each individual tract. The difference in numbers reflects the fluctuation in available roof space, building density, and orientation of rooftops that contribute to the total capacity of PV installations.

The highest potential can be observed in Tract 1, which has 22,973 panels, and is likely due to larger general rooftop areas or a more optimal orientation of the roofs. Tract 9 comes second with 26,315 panels and again has very favorable building characteristics for solar installations. Tract 4 has a capacity for only 6,961 panels installed, whereas Tract 5 has a total capacity for only 6,482 panels. That would possibly indicate smaller buildings, small or awkwardly oriented roof areas, or orientation issues that make the application of solar panels difficult.

Table 4-6 Number of Panels (Source: ArcGIS Calculation)

Tract	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of panels	22,973	19,615	9343	9,410	6,961	19,869	16,482	12,926	26,315	9,853

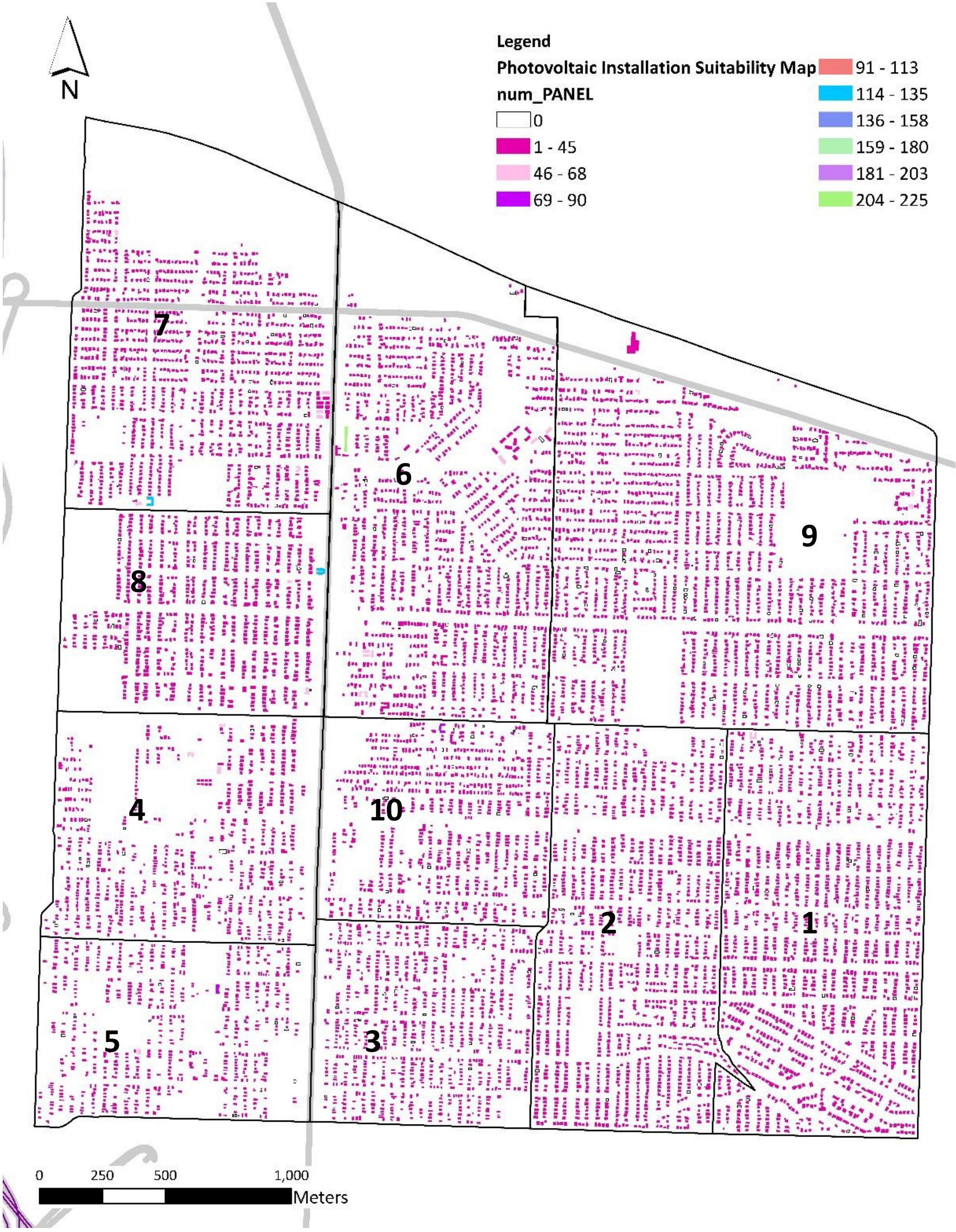

Figure 4-8 Photovoltaic Installation Suitability Map (Source: ArcGIS Calculation)

4.3.4 Solar Energy Generation Potential

In this section, we evaluate the potentials of photovoltaic solar energy generation within the study area using data obtained from ArcGIS simulation. The latter communicates the potential PV generation for every single tract against its relevant electricity demand.

Table 4-7 Photovoltaic Power Generation Potential of Study Site (Source: ArcGIS Calcul ation, Unit: 10^3kWh/m^2)

No.	1	2	3	4	5	6	7	8	9	10
Jan	342.80	1,382.59	3,477.67	5,044.71	6,466.70	7,058.47	7,401.49	6,679.43	3,566.30	2,175.43
Feb	291.64	1,173.51	2,958.87	4,299.09	5,519.09	6,026.42	6,316.46	5,693.24	3,034.78	1,846.76
Mar	139.88	565.62	1,419.76	2,057.07	2,633.35	2,873.19	3,013.66	2,723.17	1,455.69	889.83
Apr	140.99	570.27	1,430.11	2,069.65	2,648.83	2,889.68	3,030.86	2,739.36	1,465.82	897.05
May	104.03	419.54	1,056.08	1,532.07	1,964.96	2,144.95	2,248.55	2,028.24	1,082.91	660.18
Jun	295.62	1,194.14	3,003.67	4,356.14	5,583.76	6,095.00	6,391.12	5,768.07	3,079.81	1,879.25
Jul	244.76	990.32	2,490.82	3,611.06	4,628.02	5,052.01	5,298.03	4,781.74	2,553.74	1,558.93
Aug	191.85	771.87	1,946.81	2,828.40	3,632.60	3,967.60	4,158.08	3,745.19	1,996.77	1,214.79
Sep	391.98	1,587.86	3,985.45	5,773.85	7,391.06	8,064.99	8,461.75	7,646.70	4,086.03	2,498.45
Oct	146.87	592.44	1,490.32	2,161.54	2,770.98	3,024.19	3,170.81	2,861.62	1,528.16	932.25
Nov	342.80	1,382.59	3,477.67	5,044.71	6,466.70	7,058.47	7,401.49	6,679.43	3,566.30	2,175.43
Dec	291.64	1,173.51	2,958.87	4,299.09	5,519.09	6,026.42	6,316.46	5,693.24	3,034.78	1,846.76

Table 4-7 is a summary of the monthly PV generation potential for each tract in the study area. The values of these are in 10^3 kWh/m² and depict the total amount of energy generated per month per square meter of PV panel. The portion in the table represents that trend of variability due to the seasonality of solar irradiance; as such, generation peaks in summer-for example, June and July-and records low generation during winter-for example, December and January. Indeed, this is a seasonal pattern one would expect to see, since sunlight availability varies.

As an example, Tract 6 illustrates the highest generation in each month, with generation peaking at 6,391,122 kWh in June. This would be due to good orientations of roofs, more surface areas, or reduced obstruction to maximize exposure to the sun. In contrast, tracts like Tract 3 yield smaller values for generations and represent either roof space that is limited in size or, conversely, one that has the interference of shading from other buildings or trees.

Figure 4-10 This map shows the annual PV generation potential by tract for the study area. The color ramp shows light yellow to dark red, representing the magnitude of the potential solar energy production in kWh/m² per year. Darker areas are higher in solar generation potential while lighter areas are lower.

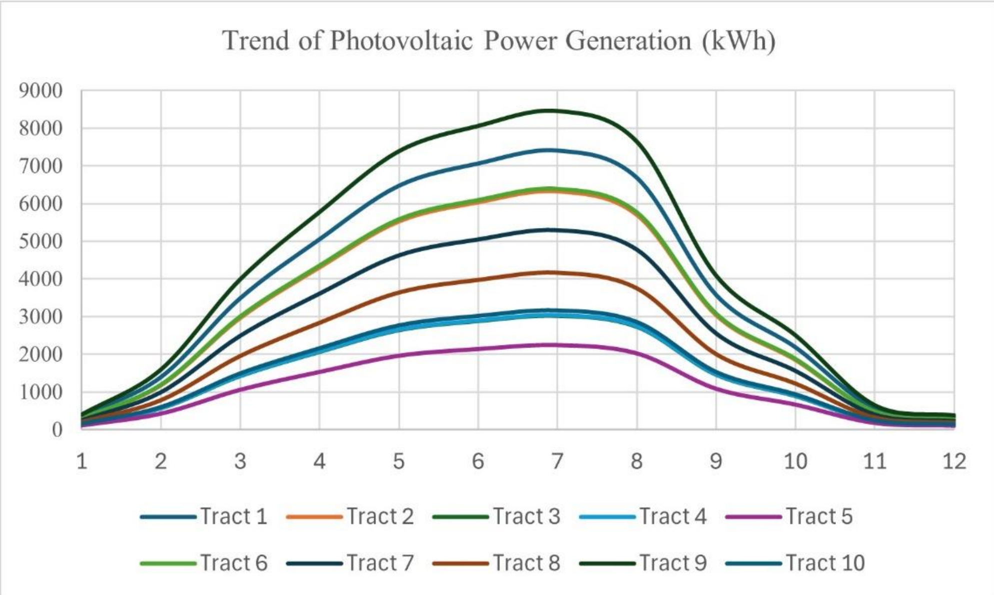

Figure 4-9 Trend of Photovoltaic Power Generation of Study Site (Source: Authorship)

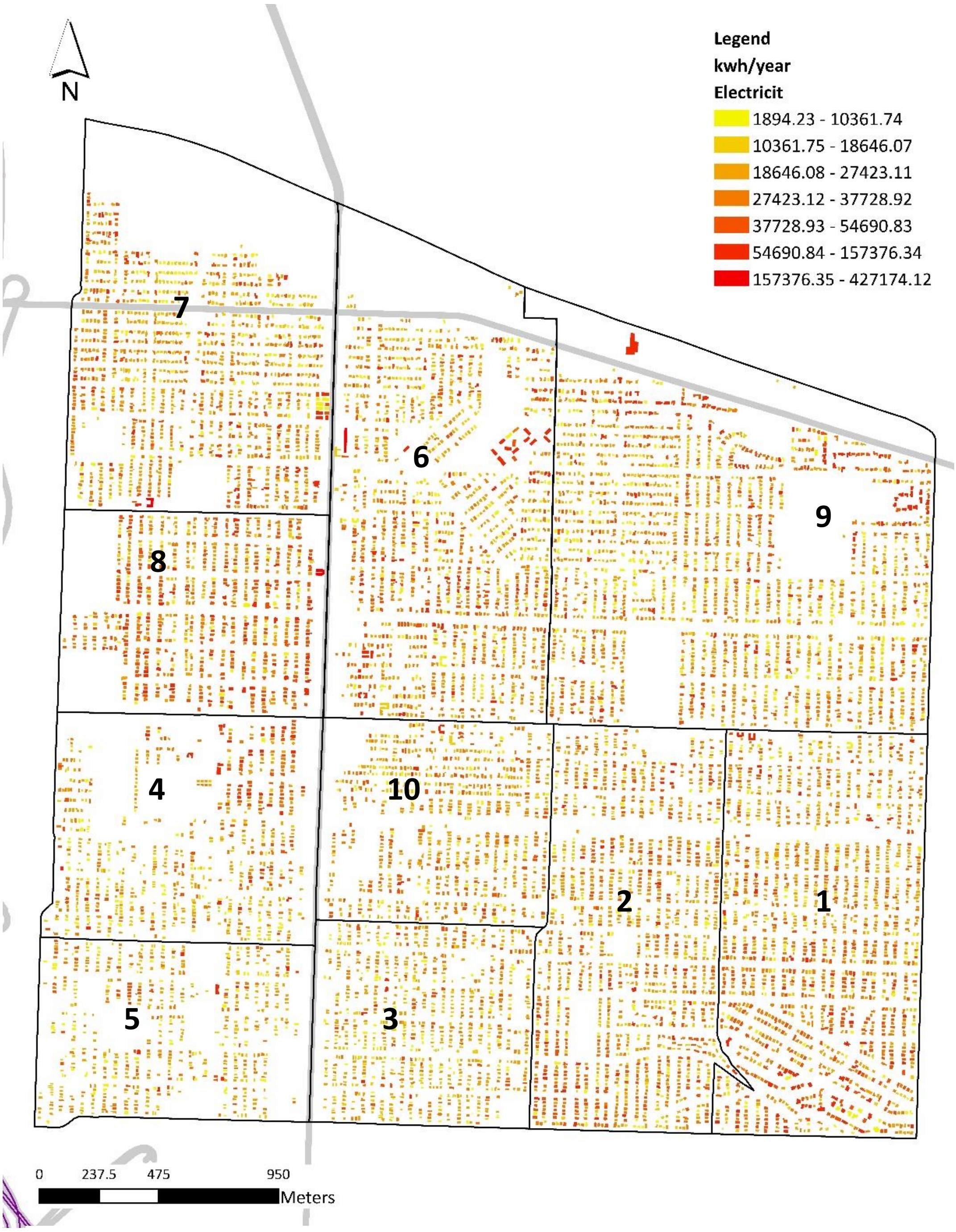

Figure 4-10 Photovoltaic potential of Study Site (Source: ArcGIS Calculation, Unit: k Wh/m^2/year)

4.4 Electricity Consumption Analysis

This project is based on the data from the Residential Energy Consumption Survey, RECS, for 196 housing units within Oregon. The purpose is to analyze the relationship of residential building characteristics - building type, number of stories, construction year, floor area - with respect to electricity consumption. The selected variables initially were Unit Type, Stories, Year Made Range, Floor Area, and Electricity Consumption (Table 4-8).

Table 4-8 Incorporates data from 191 housing units of Oregon (Source: RECs)

Variable	**Variable ranges**	**Percentage**
Building Type	1-Single, detached	66.02%
	2-Single, attached	8.90%
	3-Apartment (2-4 units)	3.14%
	4-Apartment (over 5 units)	20.94%
Year Made Range	1-before 1950	13.61%
	2-1950-1959	10.47%
	3-1960-1969	12.57%
	4-1970-1979	17.80%
	5-1980-1989	9.95%
	6-1990-1999	15.18%
	7-2000-2009	12.57%
	8-2010-2015	4.19%
	9-after 2016	3.66%
Floor Area	=< 93 m^2 (1000 ft^2)	26.18%
	93 $m^2$to 186 m^2 (1000 ft^2 to 1999 ft^2)	45.03%
	186 $m^2$to 279 m2(2000 ft2 to 2999 ft^2)	21.47%
	> 279 m^2 (3000 ft^2)	7.33%
Electricity Consumption	42.01-184101.84 (kWh)	100%

4.4.1.1 Electricity Consumption Model

This research re-classified and re-calculated building types in the original data set to better represent the actual conditions of the study area. The single, detached and Single, attached were combined into one category named Type 1 (Single Family) that represents single-family residences. Similarly, Apartment (2-4 units) and Apartment (over 5 units) were combined as Type 2 (Multi Family) that represents multi-family residences. This reclassification is more representative of the building attribute distribution in the study area.

The unit area electricity consumption, in kWh/m², was then computed for every household surveyed in 2020. The overall process was done in two steps:

i. Household annual electricity consumption in kWh was divided by the building area in m² to compute the per unit area values for each household.

ii. Grouping these values according to the construction year of the buildings and calculating the average for each group yields the average electricity consumption per unit area for different construction periods.

The results are put together in Table 4-9, showing the results of average electricity use by unit area for Type 1 and Type 2 buildings when categorized by construction period.

Table 4-9 Average Electricity Consumption (kWh/m^2) Across Various Building Types and Construction Period (Source: Authorship)

Construction Period	Type 1	Type 2
Before 1950	71.65	60.51
1950 to 1959	70.70	53.58
1960 to 1969	87.95	96.38
1970 to 1979	85.58	76.14
1980 to 1989	72.27	108.15
1990 to 1999	63.77	84.46
2000 to 2009	63.66	61.81
2010 to 2015	57.33	76.52

2016 to 2020	39.59	68.17

From deeper analysis (Figure 4-11) in the impact that can be generated by construction year, for example, all those constructed before 1960 demonstrate higher usage; again, Type 2 mostly has the lowest per unit-area electricity consumptions compared with Type 1. Probably that is explained by shared walls in the design of multifamily buildings: less heat release, whereas concentrated electricity consumption per unit area may reduce energy use. However, this trend was reversed in the period of 1980-1989 when Type 2's per-unit area electricity consumption surpassed that of Type 1. This might reflect a fact that, during the period, there is more use of electrical appliances in the multi-family houses, such as the popularity of electric household appliances or the change of the requirements of indoor space configuration.

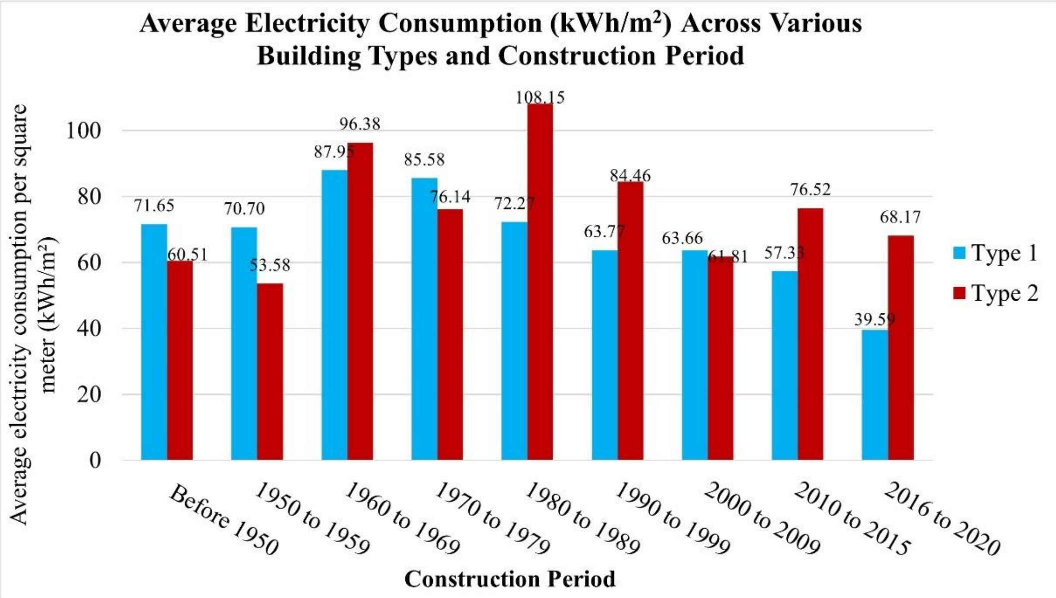

Figure 4-11 Average Electricity Consumption (kWh/m^2) Across Various Building Types a nd Construction Period (Source: Authorship)

After 2000, both types began to see a significant drop in per-unit area electricity consumption. It might be a function of the general improvement in the technological development of building insulation material, window designs, and optimization of building structure. In addition, there are also green building policy promotions; local and federal policy developments implementing energy-efficient and sustainability standards step by step in building designs. In addition, a wide dissemination of energy-efficient appliances, LED lighting systems, and new power management technologies supported this decline.

4.4.1.2 Electricity Consumption Calculation

The electricity consumption model is based on building type and construction period. This model calculates the annual electricity consumption of each building by multiplying the unit area power consumption (kWh/m²) by the building floor area (m²). The calculations are performed on the ArcGIS platform. Upon completion, the total power consumption for each study area is presented in Table 4-10. The results indicate that the total annual electricity consumption across the 10 study areas is 122,468,398.12 kWh, with significant variations observed between the different study areas.

Table 4-10 Total Electricity Consumption of Study Case

Tract No.	Electricity Consumption (kWh/year)
1	19,532,264.68
2	15,715,465.69
3	8,057,072.49
4	7,802,235.27
5	6,101,458.67
6	13,956,575.39
7	12,489,115.47
8	9,550,973.52
9	21,702,352.58
10	7,560,884.37
Annual	122,468,398.12

This method for calculating and aggregating electricity consumption based on buildings not only quantifies regional energy demand but also provides essential insights for identifying high-energy-consuming buildings and developing regional energy-saving strategies. For instance, for areas with higher consumption, such as Tract 9 and Tract 1, further analysis of building characteristics and electricity usage patterns can be conducted to implement targeted energy-saving measures and technologies.

4.4.1.3 Monthly Electricity Consumption Analysis

This section characterizes monthly electricity consumption patterns both for the state of Oregon and the study area to reveal seasonal and spatial variations in energy demand.

State-Level Monthly Consumption in Oregon Table 4-11 Oregon Residential Electricity Consumption by Month, 2020 The peak demand is in December (2,387.26 million kWh, 11% of the annual) due to winter heating, and the lowest demand is in June when both heating and cooling demands are at the lowest (520.94 million kWh, 6.89%).

Table 4-11 Residential Electricity Consumption Statistics for Oregon in 2020 (Source: U. S. Energy Information Administration)

Month	**Electricity Consumption of Residential (Unit: million kilowatt-hours)**	
Jan	1,989	10.13%
Feb	1,797	9.16%
Mar	1,813	9.24%
Apr	1,478	7.53%
May	1,368	6.97%
Jun	1,353	6.89%
Jul	1,574	8.02%
Aug	1,570	8.00%
Sep	1,349	6.87%
Oct	1,406	7.16%
Nov	1,772	9.03%
Dec	2,159	11.00%
Annual	19,628	100.00%

Table 4-12 and Figure 4-12 present the tracts in the study area and their respective monthly electricity consumption. The monthly estimates of consumption by tracts are direct calculations from the monthly percent of consumption in the state, hence patterns like the trend for the state show December is the peak demand month and June and July the lowest months. Tract 9 and Tract 10 have a higher energy use constantly due either to building size or to the number of occupants.

Table 4-12 Monthly Electricity Consumption of Study Site (Source: Authorship, Unit: 10^3 kWh)

No.	1	2	3	4	5	6	7	8	9	10
Jan	1,978.62	1,591.98	816.18	790.37	618.08	1,413.80	1,265.15	967.51	2,198.45	765.92
Feb	1,789.16	1,439.54	738.03	714.68	558.89	1,278.42	1,144.00	874.87	1,987.94	692.58
Mar	1,804.78	1,452.11	744.47	720.93	563.77	1,289.59	1,153.99	882.51	2,005.30	698.63
Apr	1,470.78	1,183.37	606.70	587.51	459.44	1,050.93	940.43	719.19	1,634.19	569.33
May	1,361.40	1,095.37	561.58	543.82	425.27	972.77	870.49	665.70	1,512.65	526.99
Jun	1,345.77	1,082.80	555.13	537.57	420.39	961.61	860.50	658.06	1,495.29	520.94
Jul	1,566.49	1,260.38	646.18	625.74	489.34	1,119.32	1,001.63	765.99	1,740.53	606.38
Aug	1,562.58	1,257.24	644.57	624.18	488.12	1,116.53	999.13	764.08	1,736.19	604.87
Sep	1,341.87	1,079.65	553.52	536.01	419.17	958.82	858.00	656.15	1,490.95	519.43
Oct	1,398.51	1,125.23	576.89	558.64	436.86	999.29	894.22	683.85	1,553.89	541.36
Nov	1,763.76	1,419.11	727.55	704.54	550.96	1,260.28	1,127.77	862.45	1,959.72	682.75
Dec	2,148.55	1,728.70	886.28	858.25	671.16	1,535.22	1,373.80	1,050.61	2,387.26	831.70

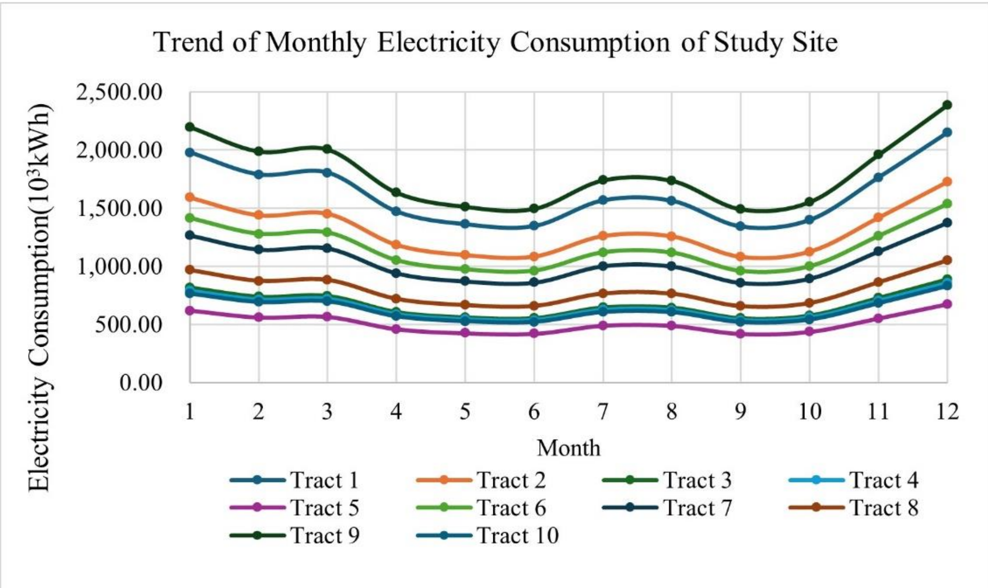

Figure 4-12 Trend of Monthly Electricity Consumption of Study Site (Source: Authorship)

4.5 Solar Energy Generation Potential and Comparison with Electricity Consumption

This section is supposed to provide a broad perspective of the levels of possible solar energy generation across the study area in contrast to the local consumption for electricity.

Table 4-13 shows self-consumption on a per-month basis by tract. Self-consumption represents the solar energy consumed within the place. The values of SC are higher in winter periods due to demand, which in this case are the months of December and January. Among the tracts, Tracts 1, 2, and 9 represent the highest self-consumption, reflecting a higher dependency on solar energy.

Table 4-13 Monthly Self-Consumption (SC) Value of Study Site (Source: Authorship, Unit: 10^3KWh)

No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Jan	342.80	1,382.59	1,804.78	1,470.78	1,361.40	1,345.77	1,566.49	1,562.58	1,341.87	1,398.51
Feb	291.64	1,173.51	1,452.11	1,183.37	1,095.37	1,082.80	1,260.38	1,257.24	1,079.65	1,125.23
Mar	139.88	565.62	744.47	606.70	561.58	555.13	646.18	644.57	553.52	576.89
Apr	140.99	570.27	720.93	587.51	543.82	537.57	625.74	624.18	536.01	558.64
May	104.03	419.54	563.77	459.44	425.27	420.39	489.34	488.12	419.17	436.86
Jun	295.62	1,194.14	1,289.59	1,050.93	972.77	961.61	1,119.32	1,116.53	958.82	999.29
Jul	244.76	990.32	1,153.99	940.43	870.49	860.50	1,001.63	999.13	858.00	894.22
Aug	191.85	771.87	882.51	719.19	665.70	658.06	765.99	764.08	656.15	683.85
Sep	391.98	1,587.86	2,005.30	1,634.19	1,512.65	1,495.29	1,740.53	1,736.19	1,490.95	1,553.89
Oct	146.87	592.44	698.63	569.33	526.99	520.94	606.38	604.87	519.43	541.36
Nov	342.80	1,382.59	1,804.78	1,470.78	1,361.40	1,345.77	1,566.49	1,562.58	1,341.87	1,398.51
Dec	291.64	1,173.51	1,452.11	1,183.37	1,095.37	1,082.80	1,260.38	1,257.24	1,079.65	1,125.23

Table 4-14 presents the results of the Solar Sufficiency Index and the Solar Consumption Index for each tract. SSI, this represents a proportion of total consumption that is met by solar. Note that tracts 6 have a high value in this metric, reflecting great self-sufficiency.

SCI, this is the measure of what proportion of on-site generated solar is consumed on-site. Note that Tract 1, Tract and Tract 5 have been consuming the energy generated from the generation of solar energy very efficiently.

Table 4-14 Value of SSI and SCI of different Tracts (Source: Authorship, Unit: 10^3kWh/year)

Tract No.	SC (Self-Consumption)	TC (Total-Consumption)	TP (Total Production)	SSI	SCI
1	14,460.23	19,532.26	44,478.26	0.74	0.33
2	11,749.92	15,715.47	37,908.50	0.75	0.31
3	5,955.91	8,057.07	18,132.61	0.74	0.33
4	5,810.02	7,802.24	18,246.97	0.74	0.32
5	4,493.68	6,101.46	13,509.26	0.74	0.33
6	10,720.27	13,956.58	38,408.24	0.77	0.28
7	9,444.13	12,489.12	31,840.09	0.76	0.30
8	7,251.61	9,550.97	24,946.32	0.76	0.29
9	16,161.84	21,702.35	50,901.14	0.74	0.32
10	5,705.24	7,560.88	19,057.15	0.75	0.30

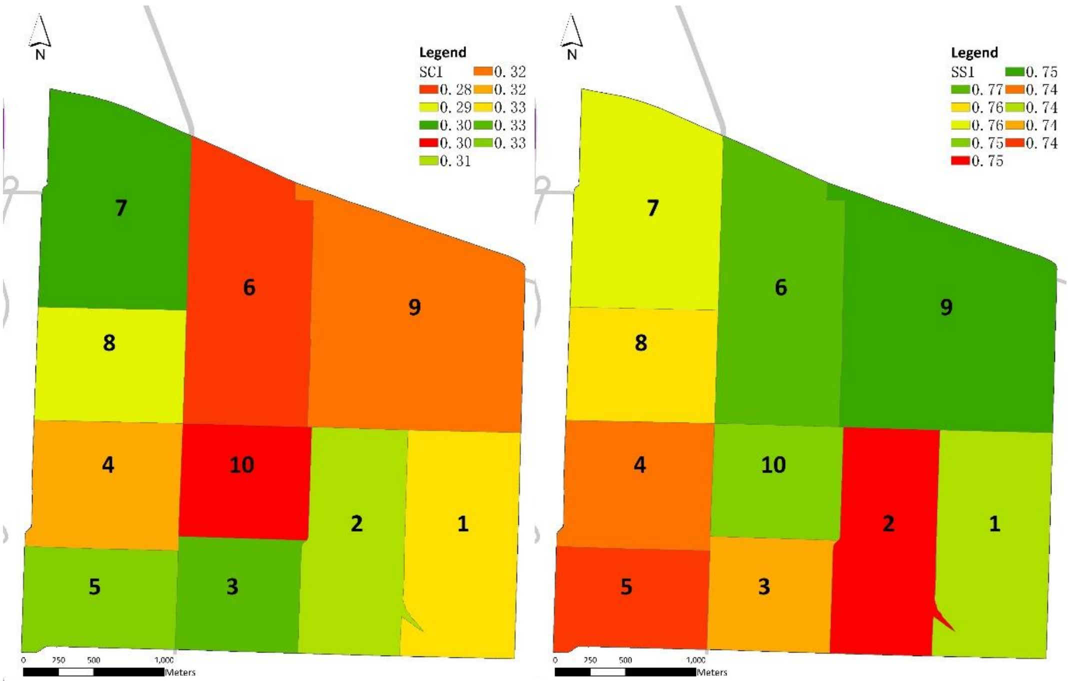

Figure 4-13 Results of SSI and SCI of Study Site (Source: Authorship)

Figure 4-13 shows SSI and SCI by tracts, Tract 10 exhibits the lowest values for both SCI (Self-Consumption Index) and SSI (Self-Sufficiency Index), reflecting a deficiency in energy utilization and self-sufficiency. On the one hand, although a portion of the distributed generation in this area is used for self-consumption, the total electricity generated still falls short of meeting the overall demand, resulting in a low SSI. On the other hand, a significant proportion of the generated electricity is likely exported to the grid rather than being consumed locally, which further contributes to the decline in SCI.

In contrast, Tract 6 demonstrates the highest SSI, with a relatively high SCI as well, indicating a strong capacity for distributed generation that largely meets local electricity demand. However, there remains room for further optimization in the direct utilization of self-generated power, and increasing the local consumption proportion could lead to more efficient use of distributed generation resources.

Additionally, Tract 5 and Tract 3 show relatively high SCI values, suggesting that a large proportion of their distributed generation is directly utilized to meet local electricity demand. However, the SSI values in these regions do not reach the highest levels, indicating that while the distributed generation capacity can adequately serve local needs, the total generation is still insufficient to fully meet the overall electricity demand of the region.

5 Results and Discussion

5.1 Solar PV Potential and SSI&SCI Analysis

Photovoltaic systems integrated into building rooftops have been analyzed using open-source GIS tools for detailed spatial analysis of their solar energy potential within different urban zones in Portland, Oregon. This paper discusses the optimum location for the installation of PV, examines the potential energy output, and quantifies the extent to which these installations would be able to serve the local energy demand. The performance of the various PV systems is evaluated in terms of self-sufficiency index and self-consumption index, demonstrating their independent capability in energy and efficiency, respectively.

5.1.1 Solar PV Potential and Electricity Demand Comparison

Using ArcGIS-based simulations, the above study estimated the monthly PV generation potential zone by zone and compared it to the corresponding energy demand. As may be seen from Table 4-7 and Table 4-12 the results of energy demand as well as PV generation show seasonal variations.

The summer months, with peak PV generation, correspond to the time when Portland receives more sunlight and increased solar radiation in most zones. During this period, the surplus that might be expected due to lower residential energy demand could be stored or sold back to the grid.

Whereas PV generation takes place on a minute scale during the winter months of December to February, energy demand is usually higher. This seasonality in supply versus demand points to a complementary solution in the form of either energy storage or grid connectivity for the PV systems in Portland to ensure continuity of energy throughout the year.

The GIS analysis also provides substantial variability in PV potential throughout the urban landscape of Portland, ranging from approximately 1,894 to 427,174 kWh/year depending on location. High-potential zones, as illustrated by dark red, have large, unobstructed rooftops optimized for solar exposure-a hallmark for ideal large-scale PV installations. In contrast, areas of lower potential, as indicated by yellow zones, are limited by factors such as shading, smaller roof areas, or less optimal orientations.

High-potential zones could therefore form the critical elements in Portland's energy strategy, by being able to generate significant surplus energy that could be stored for later use or fed back to the grid to maximize both energy independence and economic return.

5.1.2 Self-Sufficiency Index (SSI) and Self-Consumption Index (SCI) Results

To assess the potential of rooftop PV systems to supply the local demand, SSI and SCI were calculated for each tract. These indices are given in Table 4-14 and are defined as the following:

The SSI is defined as the ratio of self-consumed energy to total energy consumption. The larger the SSI, the more energy-independent a building would be, although more of the energy requirements in that building would be met with the PV system.

Self-Consumption Index is the ratio of self-consumed energy over total PV generation. A higher SCI, therefore, indicates better efficiency in the utilization of the PV since more of the generated energy is being used directly on-site instead of being exported to the grid.

The resulting SSI values for all tracts range from 0.74 to 0.77, while the rooftop PV installations could meet, on average, approximately 74% to 77% of the local energy demand. Fairly high values of SSI confirm the fact that solar energy has very good potential to reduce significantly the dependency on external sources of power in the considered areas.

Indeed, the range of SCI values is from 0.28 to 0.33, which states that 28-33% of the total generation is self-consumed on-site, whereas the rest is either stored or fed back to the grid. This relatively lower value of SCI may indicate further benefits by enhancing on-site energy storage capabilities or expanding self-consumption by installing additional infrastructure, such as electric vehicle charging points.

5.1.3 Implications and Strategic Recommendations for Solar Energy Optimization

The PV potential in Portland underscores significant opportunities for advancing renewable energy self-reliance. However, enhancing SSI and SCI values is essential for maximizing PV system effectiveness. Drawing insights from Milan's urban energy model(Mutani et al., 2023) and the Villar Pellice energy community(Mutani et al., 2021b), several strategies are recommended.

One is Implement Energy Storage Systems, by incorporating energy storage, surplus energy generated during high-output months can be stored for use during low-generation periods. Villar Pellice's REC demonstrated that adding storage to PV systems improved SCI by enabling energy use when production exceeded demand.

Second is the Demand-Side Management Programs, encouraging consumption of PV-generated power during peak generation hours (e.g., through dynamic electricity pricing or automated load management) could elevate self-consumption rates. Milan's model emphasizes the role of such management tools in enhancing on-site energy utilization within urban settings.

Third is Expanding Renewable Energy Communities (REC), forming RECs, as demonstrated in Villar Pellice, facilitates collaborative energy usage among residential, commercial, and municipal buildings, enabling the sharing of renewable energy resources. This model could allow Portland's neighborhoods to achieve higher SSI values through collective energy sharing and optimized resource allocation.

5.2 Economic and Environmental Benefits

5.2.1 Economic Analysis of PV System Investment

To assess the financial viability of the PV systems, we consider the cost of Maxeon 6 solar panels as the baseline. Generally, the price of Maxeon 6 panels ranges from $1.1 to $1.4 per watt. For instance, a standard 445-watt Maxeon 6 panel typically costs between $490 and $620 per panel, depending on factors such as purchase volume, supplier, market demand, and whether installation services are included. This variability can significantly influence the overall system cost and payback period.

Factoring in a 30% investment tax credit (ITC), which reduces the initial cost by a substantial margin, the adjusted installation cost is estimated at $1,400 to $2,100 per kilowatt. Using the 2020 U.S. residential electricity price of $0.1315 per kilowatt-hour (kWh), we calculate each zone's annual generation, revenue from self-consumed electricity, revenue from surplus energy sales, and overall payback period.

Table 5-1 Payback Period (Source: Authorship)

Tract	Installation Cost (Million USD Min)	Installation Cost (Million USD Max)	Total Annual Revenue (Million USD)	Payback Period (Min Years)	Payback Period (Max Years)
1	$7.88	$9.97	$6.07	1.30	1.64
2	$6.73	$8.51	$5.43	1.24	1.57
3	$3.20	$4.05	$2.46	1.30	1.65
4	$3.23	$4.08	$2.57	1.26	1.59
5	$2.39	$3.02	$1.80	1.33	1.68
6	$6.82	$8.62	$6.21	1.10	1.39
7	$5.65	$7.15	$4.84	1.17	1.48
8	$4.43	$5.61	$3.80	1.17	1.48
9	$9.03	$11.42	$7.30	1.24	1.56
10	$3.38	$4.28	$2.84	1.19	1.51

The payback periods range from 1.10 to 1.68 years, demonstrating the economic attractiveness of the PV systems. The additional revenue generated from surplus electricity sales further enhances the financial returns.

5.2.2 Environmental Impact Analysis

Beyond financial benefits, PV systems offer substantial environmental impact by reducing greenhouse gas emissions. Assuming 0.5 kg of CO_2 reduction per kWh of clean energy generated, each zone's annual CO_2 reduction is as Table 5-2 shows.

Table 5-2 Carbon Emission Reduction (Source: Authorship)

Tract No.	**Annual Generation (kWh)**	**Annual CO_2 Reduction (tons)**
1	44,478,256.45	22,239.13
2	37,908,495.15	18,954.25
3	18,132,605.66	9,066.30
4	18,246,966.40	9,123.48
5	13,509,257.33	6,754.63
6	38,408,242.62	19,204.12
7	31,840,094.69	15,920.05
8	24,946,316.44	12,473.16
9	50,901,140.26	25,450.57
10	19,057,151.03	9,528.58
Total	297,428,526.03	148,714.27

The PV system across all zones collectively reduces approximately 148,714 tons of CO_2 annually. This substantial reduction underlines the PV system's role in mitigating climate change and advancing urban sustainability.

The analysis confirms that PV systems provide substantial economic returns alongside significant environmental benefits. The favorable payback periods, combined with the notable carbon reduction, position PV systems as a high-impact investment supporting clean energy and carbon neutrality goals within urban settings.

5.3 Contribution Towards Portland's Energy and Climate Targets

5.3.1 Short-Term Goals (by 2025)

In the short term, Portland's goal is to address the urgent need for decarbonizing its electricity supply while promoting energy equity and justice.

5.3.1.1 Electricity Decarbonization

Portland is working towards achieving its goal of using 100% renewable electricity citywide by 2025. This is crucial for phasing out fossil fuels like coal and natural gas and transitioning to clean energy sources such as solar and wind. One important aspect of this transition is increasing community-based renewable energy projects, including community-owned solar projects, to ensure fair distribution of clean energy resources(PCEF Climate Investment Plan Council, 2023).

5.3.1.2 Carbon Emission Reduction

Portland aims to reduce its carbon emissions by 50% compared to 1990 levels. This target, to be achieved by 2030, will require significant investments in energy-efficient technologies and retrofitting existing buildings, including both residential and commercial properties(Bureau of Planning and Sustainability, 2022; PCEF Climate Investment Plan Council, 2023).

5.3.1.3 Energy Efficiency in Buildings

Electrification of buildings and improvement in the field of energy efficiency are also in the calendar. The plan is supposed to retrofit residential and multifamily buildings, especially in under-resourced communities, for better energy efficiency and resiliency related to climate change(Bureau of Planning and Sustainability, 2022).

5.3.2 Medium-Term Goals (by 2030)

By 2030, Portland aspires to reach a series of ambitious goals on further decarbonization of its energy system and building a more resilient infrastructure, centered around clean energy.

5.3.2.1 Achieving 100% Renewable Electricity

By 2030, the city intends to meet all its electricity needs from renewable energy. This will be driven by a combination of utility-scale renewable energy sources and decentralized projects such as community solar(Bureau of Planning and Sustainability, 2022; PCEF Climate Investment Plan Council, 2023).

5.3.2.2 Transportation Decarbonization

Another core focus is the reduction of carbon emissions from transportation. The strategy includes increasing investments in electric vehicle (EV) infrastructure and incentivizing the adoption of EVs. Portland plans to introduce more bike-friendly policies and enhance public transport systems to reduce reliance on fossil fuel-powered vehicles(PCEF Climate Investment Plan Council, 2023).

5.3.2.3 Energy Justice in Action

The Portland Clean Energy Community Benefits Fund (PCEF) plays a crucial role in this transition. This initiative focuses on funding clean energy projects that are led by and benefit historically marginalized communities. The PCEF provides direct investments in energy-efficient housing and workforce development programs for the clean energy sector(Bureau of Planning and Sustainability, 2024; PCEF Climate Investment Plan Council, 2023).

5.3.3 Long-Term Goals (by 2050)

Portland's long-term vision is aligned with the city's commitment to achieving net-zero emissions by 2050. The clean energy targets set for this timeline aim to completely transition the city away from fossil fuels and ensure a sustainable, resilient energy future.

5.3.3.1 Net-Zero Carbon Emissions

By 2050, Portland aims to achieve net-zero greenhouse gas emissions. This requires a full transition to renewable energy across all sectors, including electricity, transportation, and industrial processes(Bureau of Planning and Sustainability, 2024; PCEF Climate Investment Plan Council, 2023).

5.3.3.2 Scaling Renewable Energy Infrastructure

By 2050, Portland intends for at least 10% of its total energy needs to be met by community-owned renewable energy projects. This ensures that energy production is decentralized, and more equitable, and supports local job creation and economic resilience(PCEF Climate Investment Plan Council, 2023).

5.3.3.3 Full Electrification of the Transportation System

The city envisions a transportation system that runs entirely on electricity, powered by renewable energy. Portland’s strategy includes expanding the EV infrastructure and electrifying the city’s public transportation system to reduce emissions from traditional fossil-fuel-powered vehicles(PCEF Climate Investment Plan Council, 2023).

5.3.3.4 Community Resilience

The city plans to integrate climate adaptation measures, such as urban green infrastructure, to protect vulnerable populations from the impacts of climate change. This includes investing in energy-efficient housing and renewable energy installations for low-income and climate-sensitive communities(Bureau of Planning and Sustainability, 2024; PCEF Climate Investment Plan Council, 2023).

5.3.4 Conclusion

Portland's comprehensive approach to shifting towards a sustainable renewable-energy-powered future agrees in principle with its short-, medium-, and long-term energy and climate goals. Indeed, a vast rooftop PV potential analyzed via GIS-based simulation work shows the capability of local PV installations to highly offset energy demand. According to the SSI and SCI analyses, rooftop PV systems seem to have ample potential to supply a great deal of Portland's energy needs while enhancing its energy self-sufficiency. However, the benefits will need appropriate on-site energy consumption optimization by storage solutions and demand-side management.

The ambitious goals of the city-100% renewable electricity in 2030 and net-zero emissions in 2050-are informed through policy actions, such as the Portland Clean Energy Community Benefits Fund and Oregon's Renewable Portfolio Standard. These have facilitated equitable access to renewable energy, incentivized community solar projects, and equitably shared benefits arising from the clean energy transition among all communities, especially those that have been historically marginalized.

With its proactive role in integrating PV systems, supported by strong policy frameworks, Portland stands to act as a model pertaining to urban resilience and sustainability. In making strategic investment in renewable energy infrastructure, furthering community-based energy solutions, and remaining committed to environmental justice, Portland is taking a course that will enable it to reach carbon neutrality and institute a resilient, clean energy-based economy.

6 Policies and Regulations Discussion

6.1 Development of Energy Efficiency Policies and Regulations

6.1.1 Renewable Portfolio Standard (RPS)

A significant policy of Oregon in promoting the development of clean energy involves its RPS, or Renewable Portfolio Standard. The RPS will reduce Oregon's dependence on fossil fuels by increasing the growth of clean energy through mandating electricity providers to gradually increase the share of renewable energy in their mix of electricity. In 2007, the standard was enacted into law, requiring at least a starting goal of 25% of the state's electricity from renewable sources by 2025. With burgeoning demand for clean energy and mounting pressure on the dire need to act on climate change, the state government had raised the ante even more with the passage of the "Coal to Clean Energy Act", SB 1547, in 2016. At least 50% of the electricity by 2040 should come from renewable energy sources(Oregon Department of Energy, 2018).

Solar energy has been identified as a qualified renewable energy generation resource under the RPS policy framework and thus has received extensive support. It is not only a policy framework for promoting the construction of large-scale solar power stations, but also encouraging the development of small-scale, distributed solar systems. These distributed solar systems installed by families, companies, and communities enjoy policy incentives such as the net metering mechanism. The latter point is accomplished by net metering, whereby excess solar electricity is sold back into the grid to provide a financial return. The mechanism lowers the economic barrier of installing solar systems and greatly encourages broader adoption of it(Oregon Department of Energy, 2022).

Oregon's RPS policy also invests attention in developing community solar projects. Fundamentally, community solar projects share the output produced by a large facility among several houses and businesses that correspond particularly to needs where on-site installations are impossible for users. This model not only allows more residents to benefit from solar energy but also promotes distributed flexibility of the energy system and social equity in ensuring more people can be engaged in and benefiting from the transition to clean energy(Oregon Department of Energy, 2022).

6.1.2 Net Metering

Oregon's net metering policy dates to 1999, when the state legislature passed a bill that compelled utility companies to institute a system of net metering with the intention of encouraging the development of scattered renewable energy. This policy has focused on monetary incentives for those customers who install a small-scale renewable energy system like solar power that feeds excess electricity into the grid and is paid for by utility companies.

As the cost of solar technology continued to decline and public interest in sources of clean energy increased, Oregon continually updated its net metering policy to meet emerging market demand. For example, early net metering policies applied only to relatively small, distributed energy systems, but eventually the policy was expanded to include larger commercial- and industrial-scale solar systems. This policy also increased its scope from targeting a home-based user to a more commercial user base, which further increased the rate of adoption of solar technologies.

After 2010, Oregon revised the current net metering policy variously, with the view to further encouraging individuals and businesses in installing solar systems. Net metering allowed users not only to reduce their electricity cost but also to earn extra money by selling excess power. This was therefore a well-thought-out policy design in enhancing the economic viability of solar power, hence spreading the installed solar systems.

In 2016, Oregon passed the milestone Coal to Clean Energy Act (SB 1547) that raised the state's Renewable Portfolio Standard while strengthening several clean energy incentive policies, including net metering. It aimed to phase out coal-fired power by 2040 and strongly encouraged distributed solar generation, making a legal guarantee for the further development of net metering.

Through 2020 and 2022, net metering policies continued to be supported and bolstered. As the number of solar installations grew, Oregon's net metering policy has become one of the foundational policies supporting small-scale solar in the state. The passage of House Bill 2021 in 2022 set a target of achieving 100% clean electricity by 2040, further providing long-term and robust policy for net metering(Oregon Department of Energy, 2022).

Great as the strides have been that the policy on net metering has made in the advancement of the dispersion of solar power, the continuous growth in distributed energy systems creates new challenges for Oregon in the areas of ensuring stability within the grid and the fair distribution of various costs and benefits accrued to the net metering policy, and will be major points of consideration in any future revisions of the policy.

6.1.3 Incentives for solar installations

The Residential Energy Tax Credit has been among the longest-standing solar incentive programs in Oregon since 1977. In the program, residential users who installed solar systems could receive tax credits and offset part of the installation costs.(Oregon Department of Energy, 2022). It has expired, but it did a great deal during the formative stages of residential installations. Oregon also offers several other financial incentives to reduce the cost of solar projects. Many local municipalities grant tax benefits or grants to enhance the local solar installation. The incentive policy related to the solar system varies based on geographic region, and accordingly, the users can avail themselves of different kinds of help based on location.

Apart from state-level incentives, there is also a federal incentive called the Solar Investment Tax Credit available to solar users in Oregon. According to this incentive policy, users are entitled to a tax credit for a portion of their solar installation costs incurred at 26% in 2020, hence reducing investment costs. This federal incentive, put together with the state-level incentives, makes solar systems much more economically viable(Oregon Department of Energy, 2022).

6.1.4 Energy Trust of Oregon Support

In 1999, the state of Oregon passed Senate Bill 1149, which provided the platform for financing energy efficiency and renewable energy. The bill required investor-owned utilities-like Portland General Electric and Pacific Power-to charge a 3% public purpose charge on all their revenues to finance energy efficiency and renewable energy projects(Oregon Department of Energy, 2018). In 2002, the OPUC named the Energy Trust of Oregon as the lead administrator of the public purpose funds, responsible for guiding how those funds would be spent. The mission of the Energy Trust is to help residents and businesses save energy and reduce carbon emissions by providing money for energy efficiency and renewable energy projects.

In 2007, Oregon passed Senate Bill 838, which extended the public purpose charge through 2025 and allowed utilities to collect additional money through rate increases to spur energy efficiency projects. The change provided more long-term stability for the operations of the Energy Trust. In the same period, Energy Trust expanded the project portfolio to include energy-saving retrofits for large commercial and industrial users, as well as enhanced energy efficiency programs for the low-income households. It began a set of grant programs for solar and wind projects, among others, which have driven rapid growth in renewable energy capacity throughout the state.

Since 2010, as the cost of solar technology was coming down and the demand from the public for clean energy went up, more support for the Energy Trust solar projects resulted in the building of several solar power facilities in the state. In 2015, Energy Trust developed a new long-term strategic plan and committed to saving 240 average megawatts (aMW) of electricity and 2.4 trillion BTUs of natural gas by 2019. These included targets to promote efficient products and technologies through market transformation programs in support of wider business and consumer adoption of energy efficiency more broadly. Energy Trust engaged in market transformation with the Northwest Energy Efficiency Alliance to support high-efficiency products-like LED lighting and efficient appliances-so that energy efficiency is the mainstream choice in the market.

By 2020, the Energy Trust continued to increase the scale of its projects, which then reported significant improvements in energy efficiency for low-income households, community solar projects, and energy storage technologies(Oregon Department of Energy, 2022). The same period saw the Trust working closely with Oregon's utilities to support large-scale renewable energy projects and ongoing participation of the trust in Oregon's clean energy transition. In 2022, the Trust continued investing in community solar projects, energy efficiency retrofits, and energy storage technologies supporting the State's goal of 100% clean electricity by 2040(Oregon Department of Energy, 2022).

6.1.5 Community Solar Programs

Community Solar Programs are an important tool for promoting equity and accessibility in clean energy, particularly for residents or businesses that are unable to install solar equipment themselves, such as renters, low-income households, and commercial airports. These programs provide opportunities to participate in renewable energy projects. Participants in community solar programs typically receive utility bill credits or reductions based on the amount of electricity they purchase. Oregon’s community solar projects have made significant progress and are supported by subsidy policies, especially under the framework of the "Fourth Round Agreement 2021," which has furthered regulatory support and promotion of these initiatives.

In Oregon, community solar programs have received financial and regulatory backing. Notably, the 2021 Financial Act explicitly mentioned community solar projects, providing them with both financial and policy support. This legislation facilitated the expansion of community solar programs by offering funding and technical support(Oregon Department of Energy, 2022). The act particularly focused on marginalized communities, such as low-income households, minority communities, and rural areas. Community solar programs ensure equitable participation in clean energy projects by offering these groups prioritized access and additional financial incentives(Oregon Department of Energy, 2022).

Community solar projects in Oregon have creatively expanded circles of clean energy access through novel models and supportive policy. Access to clean energy has been expanded in Oregon to low-income and rural communities. It is funded equally by financial resources and technological innovation; community solar programs have made it possible under the "2021 Phase One Plan" that more residents and small businesses get to take part in the transition toward clean energy. This is an important model not only in terms of Oregon's contribution to climate and renewable energy goals but generally, through the valuable lessons it will be able to share with other states and regions.

6.1.6 House Bill 2021

For instance, in 2021 alone, Oregon enacted the House Bill 2021, which required major utilities companies in the state to deliver 100% clean electricity by 2040. This legislation provides the necessary regulatory support for continued growth in renewable energy resources, such as solar energy, and points out with due specificity how this transition can occur to a carbon-free electricity system.

House Bill 2021 requires each of Oregon's major electricity providers - including Portland General Electric and Pacific Power - to deliver 100 percent carbon-free electricity by 2040. Utilities would need to use all carbon-free resources, which include solar, wind, hydropower, and storage, for all their electricity in that year. The bill sets up a phased set of carbon reduction targets to ensure the state is on track to meet that goal. As such, for instance, electricity suppliers must cut their carbon emissions by 2030 by 80%, by 2035 by 90%, and finally zero carbon emissions by 2040. This stringent timeline creates reliable, long-term market demand for renewable energy sources such as solar power.

The bill identifies solar energy as one of the central sources that will fulfill the carbon-free electricity goal, hence pushing development even harder. Solar energy will be very crucial in the carbon-free electricity mix in Oregon through the facilitation of building both distributed solar and large-scale photovoltaic projects across the state. This bill encourages solar integration with storage technologies that, by allowing the system to take up variable solar electricity supplies into the grid through battery storage facilities, further facilitate flexibility and reliability in the power system. The variability associated with renewable energy sources, such as solar, is mitigated by storage support, hence making it possible for solar power to supply energy demands, especially at peak periods or periods of low radiation. The bill also does grid modernization, especially in the adoption of smart grid technologies, through the encouragement it gives for wide solar energy utilization. Smart grids enhance efficiency in energy management, hence ensuring that distributed solar systems are integrated into the power network more effectively for reduced energy losses and increased overall energy efficiency.

Competitive grants, low-interest loans, and tax credits to decrease the cost of project development and installation are financial incentives for solar projects under this bill. The bill has a unique provision for community solar programs and special incentives for low-income households. In addition, it introduces long-term incentives on monetary benefits for the installation of solar panels, energy storage devices, and all other related infrastructures. It ensures equal participation in solar projects by rural, minority, and low-income communities through the creation of special financial incentives and technical support that will facilitate equity in the distribution of solar energy throughout the state.

The bill is inextricably linked with Oregon's RPS, further solidifying RPS goals to provide for the continued growth of renewable energy resources, such as solar. RPS mandates utilities to increase the percentage of renewable energy in their electricity mix over time, and solar becomes an unequivocally supported qualifying source of renewable energy. The combination of House Bill 2021 and RPS not only supports the development of solar projects legally but also pulls for the same through market demand.

This bill supports the development and adoption of novel technologies in the solar energy industry. Supported technologies under this policy include photovoltaic integration with energy storage and synergistic development between electric vehicles and solar power. By supporting technological innovation, the bill ensures that in its development, solar energy will keep pace with state-of-the-art energy technologies, hence positioning it better to satisfy future energy needs.

6.2 Policy Recommendations

6.2.1 Enhancing Solar Adoption

Oregon's Renewable Portfolio Standard (RPS) and House Bill 2021 provide a strong foundation, additional measures can enhance their impact:

i. Increased Financial Incentives: Expanding subsidies, grants, and low-interest loan programs for residential and commercial PV systems, particularly in underserved communities, can lower the financial barrier to solar adoption. Additionally, offering enhanced incentives for integrating energy storage with solar installations will increase self-consumption and grid resilience.

ii. Targeted Support for Low-Income Households: Expanding the Portland Clean Energy Community Benefits Fund (PCEF) to provide more direct funding for PV installations in low-income neighborhoods will promote energy equity. This can be achieved by offering higher subsidies or tax credits for solar projects in economically disadvantaged areas.

iii. Long-Term Incentive Stability: Guaranteeing long-term incentives for solar energy projects, such as the federal Solar Investment Tax Credit (ITC), and introducing state-level incentives would create a stable investment environment. Such stability can encourage more residents and businesses to invest in PV systems, knowing they have sustained financial support.

6.2.2 Streamlining Permitting Processes

Permits and regulations regarding solar PV create a bottleneck in the realization of the same; simplification of such will minimize the time frames of the projects while reducing costs to allow speedier deployment of renewable energy.

i. Simplified Permitting: Implement a simplified permitting process for small-scale and residential solar installations with standardized online applications, pre-defined approval criteria, and the ability to expedite projects that meet basic safety and technical standards.

ii. One-Stop Solar Service Centers: Establish "one-stop" solar service centers or e-access points whereby an applicant could have a single point of contact to receive all necessary permits and information, which include zoning guidance, building codes, and environmental regulation, thereby reducing the administrative burden.

iii. Priority Review Policy in High-Potential Areas: Municipalities should prioritize - through a GIS-based analysis - areas identified as having high solar generation potential for priority review of permits. As a result of this, the city can shift resources where solar PV installations are performing the best by expediting the review process in these areas.

6.2.3 Community Engagement

It involves active community participation, which is very vital in the overall support for solar initiatives, the resolution of concerns about accessibility, environmental impacts, and the equity of resource distribution.

iii. Educational Programs and Public Awareness Campaigns: Public education campaigns about the incentives, advantages of solar energy, and how installations could be done. This may include partnerships with local organizations like the Energy Trust of Oregon to increase outreach and disseminate valid information about the benefits and resources related to solar photovoltaic for the community.

iv. Community Solar Projects and Renewable Energy Communities: Increase support for community solar projects and RECs by allowing renters, low-income households, and those with unsuitable rooftops to participate in the Portland renewable energy goals. It can democratize access to clean energy by allowing for shared ownership models and subscription-based access to community solar.

v. Public Feedback Mechanisms: A Forum to be set up, and regular town hall meetings are felt very necessary for the public to provide their input on solar policies. Remember, while shaping policy adjustments, the concerns and suggestions of the community need to be kept in mind. This would further enhance transparency and build community trust in the city's renewable energy actions.

6.3 Global Perspectives on Renewable Energy

6.3.1 Insights from Italy

The Italian government, in line with the underlined importance of policy support for the dissemination of renewable energy resources according to the Portland study, has actively promoted the adoption of residential photovoltaic systems through policy initiatives such as the "Superbonus" program(De Gasperis et al., 2024). The Superbonds, introduced in 2020, is a tax incentive policy that provides for a 110% tax deduction of eligible renovation-related expenses. In other words, the program makes it possible for homeowners to upgrade their properties with no out-of-pocket costs. It is mainly aimed at improving energy efficiency: installing solar PV systems, enhancing building insulation, and replacing traditional heating with greener alternatives.

Milan is a large city in northern Italy, like Portland in terms of its building density, while still being a highly endowed area in terms of solar energy. Thus, it is an environment comparable to the case study of Portland in implementing renewable energy technologies. Both cities have the same ambition: to further renewable energy transition in highly urbanized areas, high-resolution rooftop analysis on GIS technology being a leading way to reach this ambition.

6.3.2 Insights from China

Although China leads the world in solar photovoltaic installed capacity and has articulated a clear objective in the 14th Five-Year Plan to further expand the capacity of wind and solar power generation, there are still some technical and policy challenges to the further dissemination of PV in cities(Hepburn et al., 2021). Precise resource assessment is a critical issue due to the limited and complicated structure of rooftop space in high-density urban settings. In fact, the research conducted in Portland can be applied to these high-density cities using open-source GIS technology and provides possible solutions for evaluating rooftop suitability accurately in cities like Shanghai and Guangzhou in China. This technology will not only contribute to attaining the target of the 14th Five-Year Plan reaching a 20% share of non-fossil energy within the energy mix-but also contribute much to raising urban energy self-sufficiency and self-consumption rates. In promoting this technology, China could further accelerate distributed PV systems efficiently, build a solid foundation for the work of achieving peak carbon emissions and carbon neutrality, and make strong support for the green transformation of the energy structure.

CHAPTER FOUR

7 Conclusion

7.1 Major Outcomes and Practical Applications of the Study

7.1.1 Summary of Photovoltaic Potential Assessment Results

Researchers have found substantial potential for solar photovoltaic generation on urban rooftops in Portland. Using Geographic Information System (GIS) techniques, the study systematically assessed each rooftop's potential to support solar generators based on buildings structural characteristics, their orientation towards the sun, and the extent to which they are shaded. The findings revealed that with the installation of PV systems on the rooftops of urban areas, a high percentage of energy requirements within residential areas would be effectively and efficiently addressed.

Furthermore, these types of results put forward areas in the city that are truly favored by optimal sunlight, thus signaling that urban PV systems can play a significant role in saving local electricity consumption, particularly at peak periods of sunlight availability.

It points, on the one hand, to the tremendous potential for solar technologies to integrate into the urban infrastructure to make significant local and overall contributions to enhancing energy resilience and sustainability goals.

7.1.2 Contributions to Existing Literature

This thus forms a very valuable addition to the quickly growing literature on renewable urban energy potentials. It represents one of the first comprehensive case studies using free and open-source GIS technology in analyzing PV systems' potential at a very high spatial resolution. In so doing, this provides a far more detailed insight into PV capacity, which would be lost in larger, lower-resolution studies. Thus, with GIS, the study can identify the solar potential at each building, hence offering an exact assessment of how urban areas can tap into solar energy.

The study further integrates, at the level of the single building, other factors such as roof size, orientation, and shading to analyze the feasibility of rooftop PV systems. This kind of integration is quite important in that it lets each single building consider peculiarities in context. Instead of using general models or assumptions, the study quantifies two crucial indicators: the Self-Sufficiency Index (SSI) and the Self-Consumption Index (SCI). These indices give a closer reality to how far a building can supply its needs with solar energy it generates and consumes, thus making the results more applicable in the real urban situation.

The study thereby bridges the theoretical model of solar energy potential with practical applications, hence being a meaningful insight into real feasibility regarding rooftop PV systems in cities. It will point to the opportunity for the adoption of renewable energy in urban areas, and the challenge of integrating solar technology with present infrastructure. The study, therefore, fills a fundamental niche in the literature by providing more realization of the practical feasibility of solar energy in urban settings where space and energy demand are usually limited compared to rural areas.

The findings from this study will help provide the basis for future research and policy on the integration of renewable energy into cities. The research goes further, bringing in more detail and a data-based approach to understanding solar potentials that enables a next level of exploration of how the integration of renewable energy technologies within infrastructure can be better achieved by urban areas. This research contributes to an overall aim of achieving sustainable transition in urban energy systems and contributes to overcoming major global challenges related to climate change and sustainability of energy.

7.1.3 Practical Applications and Significance of Findings

7.1.3.1 Applications in Policymaking

These findings provide actionable data to local policymakers to make informed decisions on the support of photovoltaic technology. This is crucial information as it provides an indication of tangible benefits, such as the amount of energy that could be saved and correspondingly reduced carbon emissions. The study provides a concrete illustration of the ways in which rooftop PV systems can effectively serve these outcomes, which forms a very sound basis for policy development.

The findings of this study shall be informed by evidence-based insights that may represent a milestone in policy formulation towards increasing the adoption of solar energy in urban areas. This shall in turn provide information for policymakers on what precisely they need to do to facilitate rooftop PV system installations across cities so that such installations may be duly integrated into existing infrastructures.

Further, the inclusions of SSI and SCI metrics only add to the point of having policies that are cut to size. Such measures give a more detailed sense of where solar technologies work best. They help policymakers zero in on high-potential areas, securing interventions in districts where interventions in solar adoption can lead to maximum environmental and economic gains.

7.1.3.2 Implications for Urban Planning

This study, from an urbanist point of view, underlines the urgent need to incorporate solar potential studies into the process of zoning and building regulations. Based on the methodology using GIS, this paper presents a widely applicable framework for identifying areas with the highest suitability for PV installations. This will help the urban planners to screen out those regions that have the highest solar energy potential, therefore developing renewable energy solutions effectively across the urban landscape. Outputs of this approach could provide valuable input to develop energy-efficient urban design and directly contribute to Portland's overall sustainability goals.

7.2 Policy Contributions and Recommendations

7.2.1 Policy Recommendations

In this respect, the present study underlines, from an urbanist point of view, the urgent need to include the study of solar potential within the process of zoning and building regulations. This paper, in fact, presents a widely applicable framework for identifying areas of the highest suitability for PV installations based on a methodology using GIS. This would help the urban planners to filter out the regions possessing the highest solar energy potential and, hence, develop renewable energy solutions effectively within the urban landscape. The outputs of this approach would provide important input on developing energy-efficient urban design and directly contributing to Portland's overall sustainability goals.

7.2.1.1 Promoting Photovoltaic Technology

Incentives such as financing, raising public awareness, and supportive regulatory mechanisms will promote photovoltaic technology. Government subsidies, tax credits, and rebates can defray part of the high upfront installation costs and help make PV installations more economical for home and business installations. Additional incentives can be performance-based on energy produced and self-consumed. Public enlightenment on the economic and environmental advantages of PV technology will also be very vital to widespread adoption, considering that oftentimes, awareness is one of the barriers to adoption.

7.2.1.2 Streamlining Permitting and Approval Processes

One of the main barriers to PV diffusion results from lengthy and cumbersome permitting and approval processes for rooftop installations. Ideally, such processes would be standardized with shorter wait times, making the application process for PV installation friendlier to consumers. A policy with faster approvals, reduced fees, and reduced complexities in inspection protocols would remove administrative barriers and encourage investment in solar technologies by property owners. These steps also tend to make the market for PV technology more predictable and efficient.

7.2.2 Implications for Urban Energy Policy

7.2.2.1 Insights from Self-Sufficiency Analysis

The Self-Sufficiency Index (SSI) will bring valued insight into the potential of the urban setting to supply its own energy needs via PV systems. It follows, then, that setting urban policies with SSI targets will nurture panoramic city-wide ambitions of energy independence and resilience. By basing metrics on SSI, policymakers can determine those areas of high potential where investment should be concentrated, before developing a focused policy that maximizes renewable energy contributions while minimizing reliance on non-renewable sources.

7.2.2.2 Potential Challenges in Implementation

This might demonstrate great potential for urban PV adoption; its wider implementation is constrained by a host of factors such as limited rooftop space, high upfront costs, and seasonal variability in generation. It will require integrated solutions-developing affordable energy storage options to balance supply and demand, public funding for initial investments, and policies able to adapt to seasonal differences in energy generation-to make these issues tractable. Besides that, any potential grid integration-related issues should be managed to ensure that the heightened rate of PV adoption does not destabilize existing power infrastructures.

7.3 Future Research Directions

7.3.1 Data Refinement and Expanded Applications

7.3.1.1 Improving Data Collection Accuracy

Still, we recommend that researchers move forward write improved quality basic research on groundwater overextraction contributing to the University local value-added solar potential assessments. At present, there is a wide body of work based on generic data sources that cannot capture the fine resolution needed for accurate modeling. Improvements in these techniques allow for better spatial resolution data, which should permit more precise and better validated long-term solar energy evaluations. It is essential for assessing solar energy deployment options, since the power generation of solar systems highly relies on resources in a residential area unit.

An opportunity for improvement can be the implementation of high-resolution data sources (e.g., Light Detection and Ranging-LiDAR). LiDAR can provide detailed topographical information needed to accurately model solar potential by locating shading caused by surrounding terrain/building. LiDAR data could be used by researchers to build more accurate models of solar energy availability and inform optimization for PV placement. Also, LiDAR could help address how geography and land use may affect solar resource potential.

In addition, better consumption statistics could be incorporated into solar potential assessments, for less ideal locations and a more holistic picture of energy need. Consumption data is important because it allows researchers to match solar energy production with real consumption trends, thereby optimizing the balance of supply and demand. That would make solar energy systems more resilient and ensure that the produced electricity is used in a sustainable and efficient way to cover the local demand. Reliable consumption data would also make it easier to accommodate energy storage and grid integration, making solar a dependable source of energy for consumers.

7.3.1.2 Expanding to Different Building Types

This paper focuses on residential buildings, since in most urban areas, the number of these types of buildings is high enough to be taken into consideration for PV systems integration. In practice, residential buildings offer one of the nearest opportunities to rooftop solar in almost any area since they are usually quite easy to access and numerous in terms of available rooftops. However, full consideration should be given to the fact that other building types-as, for instance, commercial and industrial ones-can also give very noteworthy possibilities of siting PV systems.

Commercial buildings can serve as a good example, with most having larger roofs and very often the possibility of more flexible usage of space; hence, they are very suitable for solar installations. Such buildings can also benefit from economies of scale since their greater energy needs and available roof space enable larger installations of photovoltaic systems. Likewise, industrial structures may provide wide expanses to host rooftop solar panels, probably allowing them to achieve high energy savings and contribution toward sustainability in industry sectors. Specific characteristics of the various buildings in the commercial and industrial sectors could then be studied in detail to find out which ones would provide the best feasibility for the installation of PV systems.

7.3.2 Broader Geographic Applications

7.3.2.1 Extending to Diverse Climate Zones

Every climate zone is distinguished by special sunlight, temperature fluctuation, and seasonal variations, all factors highly influencing the performance of a photovoltaic system. Applying the same method to cities with different climates may thus provide a wider understanding of how differently the PV systems perform. This may further allow a comparison of the effectiveness of PV technology at different levels of solar radiation in cities and arrive at the right design and installation strategies for each type of climate.

Besides, Cities in cooler climates would receive lower sunlight during winter months, and at the same time, cities in the hottest regions face issues concerning heat management of the solar panels. Understanding regional challenges can help the crafting of solutions to maximize PV efficiency and find a way to defeat local barriers. Such a comparative study would yield information on factors like the impact that humidity, cloud, and pollution have on PV performance.

7.3.2.2 Adapting to Other Urban Environments

The wide application of the model in cities with varied urban layouts and architectural features should provide useful information on the flexibility and scalability of the model. Comparing different analyses done in the wide range of cities will enable researchers to propose standardized frameworks when assessing the rooftop photovoltaic potential. Such frameworks would provide easy ways of assessing, developing, and disseminating appropriate renewable energy technologies to suit unique city characteristics, thereby easing the implementation of such technologies. This will not only contribute to the general applicability of the model but also open ways for integrating sustainable energy practices within a wider array of urban settings, thereby enhancing the diffusion of renewable energy solutions across cities with different physical and infrastructural characteristics.

7.3.3 Integration of Emerging Technologies

7.3.3.1 Incorporating Advanced Photovoltaic Technologies

A further step in research is encouraged in this direction to explore the possibilities of new PV technologies, like bifacial solar panels and transparent photovoltaic materials, since such development can substantially increase rooftop PV systems in efficiency and flexibility. Integration of these relatively newer technologies could be done within existing models and frameworks to reveal newer ways for maximum energy production. The investigation into the application of advanced PV technologies will be most relevant in densely populated urban areas where traditional PV installations are normally at a disadvantage about available space. This may help in establishing better solutions to maximize the energy that can be generated from areas with limited roof space or complicated architectural features.

7.3.3.2 Exploring Additional Renewable Energy Sources

Besides solar, integration of all other renewable resources, such as wind and small-scale hydro, will help to extraordinarily improve robustness and self-reliance in city energy systems. In such a manner, diversified energy use increases lesser dependence on one source of energy, hence enhancing stability and sustainability in the power infrastructure. Future studies may consider the viability and advantage of hybrid renewable energy systems combining more than one energy source. Such systems are likely to guarantee more reliable, steadier, and more sustainable energy supplies compared to single-source systems, hence urban energy needs throughout the year. This may form one of the fundamental steps towards the fulfillment of urban sustainability objectives by obviating, among others, the challenges of climate change and ensuring urban energy security. Further, hybrid system development might unravel invaluable insights into energy generation optimization, distribution, and consumption in growing urban dynamics.

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