SOLAR POWERED CITIES

A case study incorporating building use for solar mapping models of Portland, Oregon

by

Renae Boisvert

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Renae Boisvert

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by

John Withey

John Withey, Ph. D

Member of the Faculty

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Date

ABSTRACT

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Solar mapping is an essential tool to help cities meet clean energy goals. Rooftop solar is an underutilized resource in cities, but the extent to which this resource could be better utilized is not well known for most cities. This thesis examined a primarily residential area of Portland, Oregon using LiDAR imagery and the Solar Radiation tool in ArcGIS Pro. The area examined contained over 33,000 acres of rooftop space usable for power output, mostly categorized as residential (99% of the total rooftops) but with small amounts of commercial and industrial as well. For January through March of 2023, the model calculated a potential power output of 1,472,830 MWh, enough to power 589,324 homes per month. Due to the sample area being heavily residential, additional research is needed in more diversified areas.

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Introduction

Cities have two things in abundance—rooftops and energy needs. Many major cities are known for their skyline. It represents the history and culture of the city. It also shows how much dead space exists on these iconic but largely unused rooftops. These same cities are wholly dependent on external energy sources and exist in a haze of smog from the intensive use of fossil fuels by the people within. In this paper, I look at the possibility of pairing these two traits to create a cleaner future.

Solar energy is not a new concept. The quest for utilizing the sun to power machines dates as far back as 1615 when Salomon de Caus published specs for a solar powered water fountain that utilized glass lenses to heat and expand water through copper pipes (Luan et al, 2020). It took a giant leap forward in 1839 due to Edmond Becquerel's discovery of the photovoltaic effect (Luan et al., 2020). This discovery has proved to be the cornerstone of modern solar energy production and is the basis for solar panels.

The need for solar energy is on the rise. Solar panels are meeting energy needs in piecemeal patches worldwide. Clean energy technologies have increased in popularity as preferable alternatives to fossil fuels, with 194 countries having registered Nationally Determined Contributions (NDC) with the UN to actively combat climate change. According to the NDC registry, of those countries 109 have included quantified renewable energy goals (UN, 2022). Australia's total solar capacity is expected to increase from 18.6 GW in 2020 to 36 GW in 2030, while Germany has a goal of 98 GW by the same year (Sun et al., 2020). China's solar capacity has increased from 864 MW in 2010 to 174.8 GW in 2018, giving it the largest capacity for solar energy with 35% of worldwide use (Sun et al., 2020). That is an increase in the magnitude of over 200 times over eight years. As for the United States, in 2021 President Joe

Biden issued an executive order setting a goal of zero net emissions country wide by the year 2050 (Exec. Order No. 14008, 2021) which would require substantial increases in renewable energy.

This worthwhile goal is attainable but will require a seismic shift in how we think of energy production; moving away from the single source industrial toward a localized and individualized mind set. Solar is just one of the clean energy possibilities, one that shows great promise for population dense areas. Other means of clean energy production, such as wind, tidal, and geothermal, are also needed to create a sustainable energy production system. Studies are needed on all of these methods. For the purposes of this thesis, though, I will just look at solar energy production in one example of a population-dense area: a primarily residential part of Portland, Oregon. It is my hope that this methodology can be used in other areas to gain a more complete picture of the clean energy possibilities for the future.

Literature Review

Introduction

Climate change is here. Extreme weather events have become more common, as have large wildfires and increased frequency of 100-year natural disasters. We need to up our renewable energy game. Solar mapping is a means by which we can plan out greener cities that can sustain our future energy needs. Our current reliance on nonrenewable resources is unsustainable and increasingly damaging to our world. In this study, I look at the possibilities of rooftop solar panels to create self-sufficient solar powered cities that will support our needs in the coming century.

Before getting into the specifics of this case study, it is important to go over some of the base concepts that fed into it. I will start off by discussing why solar panels are important in the battle to mitigate the escalating threat of climate change, and then dive into the basics of solar mapping. Our next stop will be addressing the unused potential of urban rooftops and the qualities required to determine which rooftops are actually viable for panel placement. I will then address solar panels and the heat island effect before closing with my conclusion.

Climate Change

Climate change is a matter of scientific consensus. Global temperatures are on the rise, bringing with it changes in weather patterns, glacial melting, and a sharp increase in extreme weather events (EPA, 2023). According to the World Health Organization (WHO), climate change “threatens the essential ingredients of good health – clean air, safe drinking water, nutritious food supply and safe shelter” (WHO, 2023). Greenhouse gases are the primary cause, with carbon emissions the main culprit. This is released into the atmosphere from “burning fossil fuels, solid waste, trees, and other biological materials, and as a result of certain chemical reactions, such as cement manufacturing" (EPA, 2023). A sharp reduction in these gases is the only way to curb the trend. Clean energy, such as solar power, is an important weapon in our arsenal of climate change defeating tools.

Solar panels offer a clean and renewable source of energy, reducing reliance on fossil fuels and minimizing greenhouse gas emissions (Shahsavari and Akbari, 2018). By replacing fossil fuel-based electricity generation with solar power, significant reductions in carbon dioxide emissions can be achieved (Rabaia et al., 2021). Solar panels also contribute to the overall reduction of air pollution, since they do not emit pollutants like sulfur dioxide, nitrogen oxides, and particulate matter. Solar energy can also help to avoid the depletion of finite fossil fuel reserves, reducing the overall environmental impact associated with resource extraction and transportation. However, it is worth noting that the recycling of solar panel waste is essential for its long-term sustainability. According to Xu et al. (2018), not enough focus is being placed on recycling technologies for solar panel waste, the current cost is too high with too few facilities to process waste material. Each panel contains approximately 67.4% recyclable glass and aluminum by weight, as well as rare metals such as indium, gallium, and germanium depending on PV panel type (Xu et al., 2018).

Solar Mapping

Solar mapping has been a valuable tool in assessing the electricity generation potential of an area and has found extensive application in project planning for many years, as highlighted by Moreno et al. in 2011. The technique these researchers used leverages local climate data and incorporates topographical information to estimate the average amount of sunlight that an area receives during specific seasons or throughout the year.

When considering the utilization of rooftops as platforms for solar panels, an additional layer of complexity emerges due to the unique building topography. Variations in relative building heights and roof angles become influential factors that can significantly impact the overall efficiency of solar energy generation on these surfaces.

Solar potential is a mix of physical, geographic, and technical factors (Radosevic, 2022). Physical potential is a measure of how much solar radiation makes it to the area. Calculations for solar radiation use incoming radiation angles, atmospheric data, and the effects of shadows (Izquierdo, 2008). Geographic potential is based on where solar energy can be gathered from. The main principle behind this is to exclude all areas that are unusable, such as water features, plots that are reserved or in use, and roads (Izquierdo, 2008). Technical potential is a measure of how efficient any array will be given the solar panels used, and how they are arranged taking tilt and spacing into account (Izquierdo, 2008).

Calculating the physical potential of an area can be done with a raster map showing annual mean radiation or a radiation modeling tool that takes custom input into account (Choi et al., 2019). Raster maps for the United States are freely available from the National Solar Radiation Database (NSRDB) and are broken into annual and monthly averages. Another option is to use a more individualized approach and utilize a modeling tool that will allow you greater control over the resolution and types of data that you enter.

Geographic potential is found by looking at the map created of the area in question. GIS features assist in excluding unacceptable areas from the dataset. Polygons with land use types can be utilized to delete land reserved for other purposes, and buffers can be made to discount areas that surround bodies of water.

Technology has improved and been made freely available to facilitate the conversion to clean energy. GRASS, PVGIS, and r.sun are open-source software that were made free to encourage the use of cleaner energy sources (Pietra-Szewczyk, 2019). R.sun (a solar irradiance and irradiation model used in GRASS) can be used to find either the solar incidence angle and solar irradiance values or to estimate daily radiation sums. R.sun is open source and so can be modified to fit individual needs. Pietra-Szewczyk modified the software to account for cloud cover using the formula $Cc= 1+0.75(N/8)^{(3/4)}$, where N is the average daily cloudiness. The variable N is a rating scale. Recently machine learning AI has been utilized in determining site suitability (Sachit et al., 2022).

Huang et al. (2022) conducted a study in Aichi, Japan, that estimated rooftop solar potential by comparing solar radiation data with remote sensing data. By using the ArcGIS Solar Radiation tool, they were able to analyze solar radiation levels and identify suitable areas for solar panel installation on rooftops. Similarly, Albraheem and Alabdulkarim (2021) conducted a geospatial analysis of solar energy in Riyadh, Saudi Arabia, using the same tool. The Area Solar Radiation spatial analyst tool in ArcGIS uses algorithms to calculate solar radiation based on various parameters, such as location, date and time, topography, atmospheric conditions, and surface characteristics. It considers the position of the sun throughout the day, along with the aforementioned parameters, to provide information on solar radiation intensity, duration, and distribution over an area (ESRI, 2023).

Physical, geographic, technical, and economic potential are used to calculate solar potential of a site (Izquierdo, 2011). Sun et al. (2013) categorized land as built up, not built up, and unsuitable and also took into account the economic potential of the projects. While the physical, geographic, technical, and economic potential are important for determining solar potential, so are environmental and social factors (Choi et al., 2019). Much of the literature has concentrated purely on mapping the physical and geographical potential, but Zhang et al. completed a study in 2020 that considered impacts to the economy as well.

Urban settings

In urban environments, rooftops stand as abundant yet underutilized resources with the potential to function as power sources for cities worldwide. Ranalli et al. (2018) have highlighted the persistent issue of low adoption rates for rooftop solar panels in urban settings, despite their numerous advantages, including carbon emission reduction and cost-effective electricity generation. Peronato et al. (2018) also shed light on this underutilization, attributing it to factors such as high initial expenses, a lack of public awareness, and the complexity of installation procedures.

Santos et al. (2014) delved into the barriers hindering the deployment of solar panels on urban rooftops and identified additional challenges, such as limited rooftop space, issues related to shading, and concerns about the aesthetic impact of installations. Wegertseder et al. (2016) emphasized the role of unclear regulations and bureaucratic hurdles, which often act as deterrents to the widespread adoption of rooftop solar panels.

Furthermore, Choi et al. (2019) underscored the significance of incentivizing and raising public awareness through campaigns to promote the adoption of rooftop solar panels in urban areas. Collectively, these studies illuminate the complex landscape of challenges and opportunities surrounding the utilization of urban rooftops for sustainable energy generation.

Rooftop suitability

The suitability of a rooftop for the installation of solar panels hinges on several key factors. These critical considerations encompass roof orientation, roof tilt, shading, roof area, and structural integrity. Roof orientation, with a particular emphasis on a south-facing direction, holds paramount importance as it facilitates optimal exposure to solar radiation throughout the day, as noted by Wong et al. (2014). Equally crucial is the roof tilt angle, as it directly influences the extent of solar radiation received by the panels. The ideal tilt angle corresponds to the specific latitude of the location, as elucidated by Ko et al. (2015).

Shading emerges as yet another pivotal factor to address, given that even partial obstructions from neighboring trees or structures can significantly impede the efficiency of solar panels, as emphasized by Hong et al. (2017). The accurate modeling of shadows becomes indispensable as they evolve over the course of the day, fluctuating in both density and depth.

Additionally, the amount of available roof space assumes a pivotal role, determining the capacity for accommodating solar panels. Larger roof areas inherently provide more substantial potential for energy generation, a concept elucidated by Lee et al. in 2018. The minimum space necessary for solar panel installation is ten square meters (Lee et al., 2018).

Lastly, the structural integrity of the rooftop must not be overlooked, as it forms the foundation for ensuring the rooftop can safely bear the weight of the solar panels and accommodate their installation, a matter emphasized by Wong et al. (2014). This includes not only how the roof is supported but also the materials in its makeup. Ductal systems cannot support solar panels and are on many industrial and commercial rooftops. Skylights, while they provide decreased reliance on energy for lighting, will not support solar panel setups. In essence, a comprehensive evaluation of these multifaceted factors is essential for determining the suitability of a rooftop for solar panel installations.

Heat Island Effect

The Environmental Protection Agency defines heat islands as “zones of relative warmth created by urban air and surface temperatures that are higher than those of nearby rural areas” (2008). In plain speak smog, tarmac, and concrete absorb far more heat than forests and grasslands. The consensus of research on this topic estimates that “in the United States, the heat island effect results in daytime temperatures in urban areas about 1–7°F higher than temperatures in outlying areas and nighttime temperatures about 2–5°F higher” (EPA, 2008). This well studied phenomenon creates increasingly dangerous localized heat conditions as world temperatures rise.

Bayrakci et al. (2014) found that not only does the cloud cover and filtering effects of the weather impact solar potential, but the temperature as well. Most solar radiation is not converted into electricity, but rather into thermal energy. As the solar panels heat up, the efficiency of the cells in creating electric power, only 20% to begin with, decreases. In the southern US efficiency decreased 12%-15% from May to August, while during the winter in the northeastern US it increased 16%-20% (Bayrakci et al. 2014). The inverse effect of temperature on solar panel efficiency needs to be considered, as urban heat islands make areas inside cities warmer than surrounding areas: bad news for solar panel effectiveness. Even worse is that while the air temperature increases slightly, the surfaces experience more extreme rises in temperature.

While solar panels are commonly recognized for absorbing heat from the sun, an intriguing discovery by Scherba et al. (2011) suggests that they can actually reduce the overall surface heat of black rooftops by approximately 11%. Moreover, when both white paint and panels are employed, the summertime heat on a black roof can be reduced by an even more significant 55% (Scherba et al. 2011). Taken together, these findings imply that solar panels have the potential to counteract a portion of the urban heat island effect, particularly on rooftops.

However, it's worth noting that some sources posit a different perspective, suggesting that solar panel farms themselves can create a localized heat island effect. Demirezen et al. (2022) conducted a study in which they observed that the air at the center of a solar power farm registered temperatures up to 6 degrees Celsius warmer than its immediate surroundings. It's essential to acknowledge that Demirezen's study was conducted in a rural setting, where the landscape transitioned from natural vegetation to dark PV cells, amplifying the heat-absorbing effect. In contrast, urban environments already feature low albedo surfaces on rooftops, with many roof tiles sporting a dark matte finish. The introduction of PV cells to these already low albedo surfaces presents the opportunity to convert solar radiation into electrical energy while potentially mitigating some of the heat-related challenges posed by urban settings.

Portland Solar Programs

Oregon has rolled out a range of solar incentives aimed at encouraging homeowners to embrace solar energy solutions. These incentives encompass a tax rebate offering homeowners the potential to receive up to $5,000 for installing a solar system, along with an additional $2,500 rebate for battery storage integration (DoE, 2023). In an effort to extend these benefits to low-income service providers, a dedicated program has been introduced, offering substantial rebates of up to $30,000 for solar system installations and an additional $15,000 for battery storage (DoE, 2023).

Furthermore, in 2021, Oregon enacted HB 2021, ushering in a new era of support for community renewable energy initiatives. This legislation allocated grant funds, with a remarkable ceiling of up to $10,000,000, to bolster such projects. It's noteworthy that the state has set aside a significant total amount of $64 million to facilitate these grants, underlining Oregon's commitment to advancing renewable energy endeavors within its communities.

Conclusion

Governments are increasingly showing a keen interest in harnessing solar energy as a sustainable power source. However, when evaluating the solar potential of a location, it's essential to consider more than just the physical capacity for solar radiation absorption. For the data to be valuable to policymakers and consumers, it must encompass various dimensions, including geographic potential, technical feasibility, economic viability, as well as the social and environmental impacts of the site.

Regarding the effect of solar panels on heat flux, sources present conflicting information, making it somewhat unclear whether they contribute to an increase or decrease in heat island effects. Nevertheless, prevailing consensus within urban areas tends to lean towards the belief that covering rooftops and other low albedo surfaces with photovoltaic (PV) cells can effectively reduce the overall heat island effect. This alignment of views underscores the potential benefits of integrating solar panels to mitigate urban heat island challenges.

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Methods

My research was conducted using ArcGIS Pro, a powerful tool for spatial analysis. I acquired shapefiles that contained data on publicly owned land parcels, building footprints, and rooftop information. By examining the overlap between the rooftops and land parcel ownership shapefile, I extracted the relevant data to create separate shapefiles for each type of building.

To assess the solar potential of the rooftops, I utilized the Solar Radiation Tool tool in ArcGIS Pro. Each of the three building type layers underwent this analysis to determine their potential incoming solar radiation. Considering the efficiency of the solar panels, I calculated the potential electricity yields for the rooftops. To obtain accurate estimations of energy output, I conducted efficiency calculations on the raw solar data.

To evaluate the significance of the rooftop energy potential, I compared the calculated energy outputs with the overall energy needs of the city. This analysis helped gauge the viability of utilizing rooftop solar energy in meeting the city's energy requirements. Additionally, I developed three suggested models to explore different scenarios. One model focused on public and government-owned buildings, while the other two incorporated commercial or residential buildings. Each model was carefully evaluated based on its ability to align with the 2050 energy goal set by the Biden Administration in 2021.

Reclassification

Accessing the wide range of GIS layers and information provided by the City of Portland through the Portland Maps website (https://www.portlandmaps.com/) expedited my research. I was able to download essential layers such as the City Boundaries and the Building Footprints, which played a crucial role in my analysis. The city boundary layer was particularly important as it allowed me to trim my raster files into more manageable sizes.

The Building Footprint layer provided comprehensive data on various aspects of the buildings, including their use, size, orientation, roof type, height, number of floors, and more. Among the available fields, I focused on BLDG_USE, which categorized the buildings based on their zoning types. However, the city's classification system included more detailed categories (such as the many different Commercial categories, *Figure 4*), which I found to be too narrow for my study.

To address this, I decided to create a more concise system for building classification. I added a new field named BDUseSimp to the database, which would serve as a simplified version of the Building Use field. To populate this field with appropriate values, I utilized the Calculate Field tool in ArcGIS Pro and wrote a Python code to reclassify the buildings into the following categories: Residential, Industrial, Institutional, Commercial, Vacant, and Other. This allowed for a more manageable comparison of the buildings based on their use types.

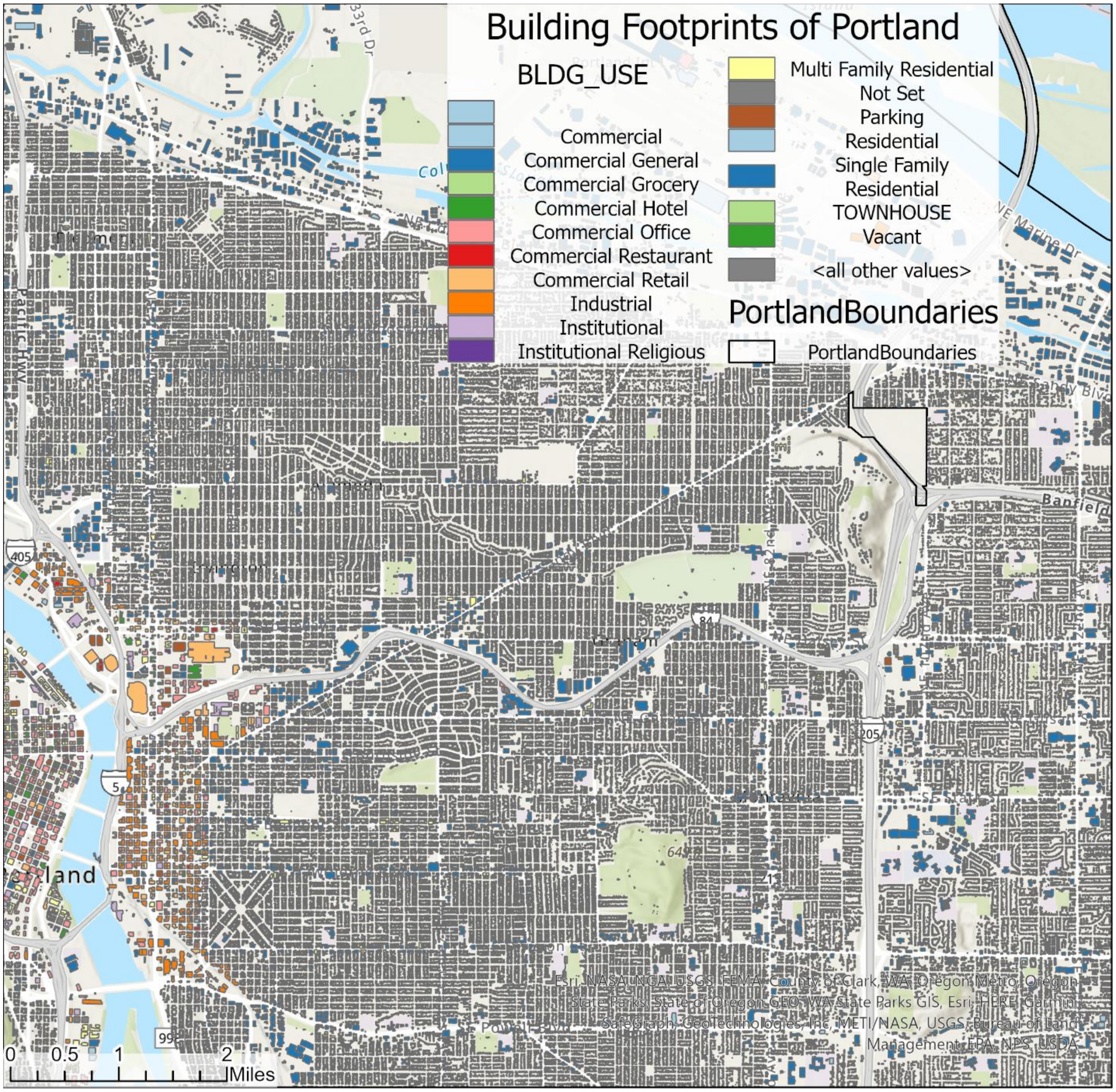

Figure 4. Building Use Types before simplification. The building use category needed to be simplified for ease of analysis. It was reconfigured into Residential, Commercial, Industrial, and Institutional categories. Source: City of Portland (https://www.portlandmaps.com/)

Lidar

I obtained lidar imagery from the DOGAMI web site (Oregon Department of Geology and Mineral Industries; https://www.oregongeology.org/gis/). I deduced which quadrangles were located within Portland by comparing a map of Portland to the map on their website. I determined that Portland contained e4-7, d4-6, and f4 quadrangles. Once the correct quads were identified, I clicked on the respective links to download the GIS packets, each of which was approximately 10GB in size (see study area mapped in

Figure 5).

I used the “Highest Hit” shapefile, which was located within the 2014 dataset of each zip file. LiDAR stands for light detection and return and basically measures the distance objects are from a plane flying overhead. Light is shot out of the plane, and it's timed how long it takes for it to be reflected off the surfaces and come back to the plane. The time produces a 3D image of the canopy below the plane. Highest hit refers to the first series of reflections to make it back to the plane, these are from openly exposed surfaces of buildings, treetops, and other features. Light can also travel between cracks between leaves and other surfaces and reflect to the plane in subsequent returns that can be used to create bare earth models to determine the topography of an area. I used the highest hit shapefile as I needed a 3D imprint of the buildings, trees, and any other features that could cast shadows throughout the winter months.

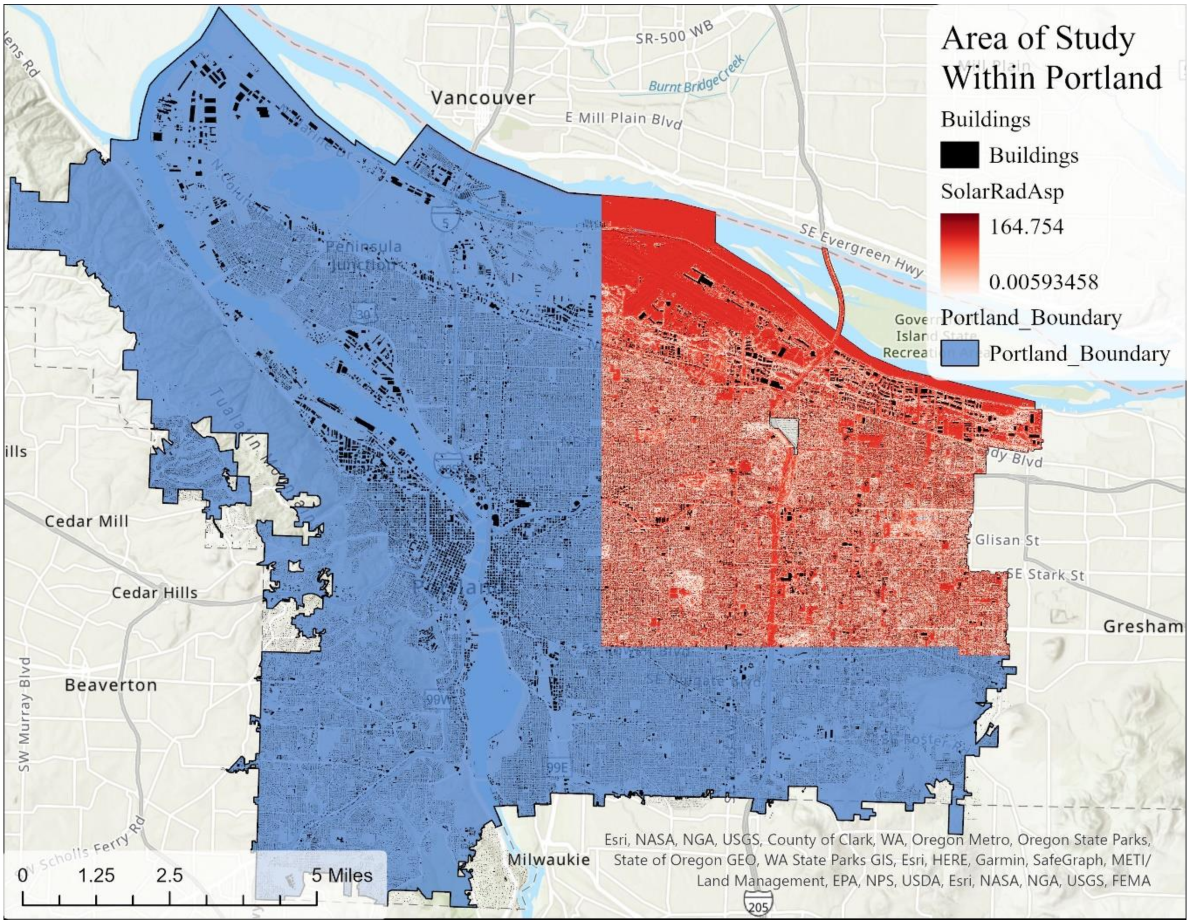

Figure 5. Selected Area of Study Within Portland. Portland is shaded in blue with the building footprints shown in black. The red gradient is a representation of the incoming solar radiation I modeled using the solar radiation tool within the selected study area. Dark red represents the highest levels of solar radiation and that color fades away into the background as the value lowers. Source: City of Portland (https://www.portlandmaps.com/)

Solar Radiation Tool

To initiate the analysis process, I added the appropriate LiDAR raster from each quad folder to the map. I then proceeded to clip the raster files to the City of Portland boundary, ensuring that the data was focused solely on the desired area of analysis. This step was essential in reducing processing time and narrowing down the dataset.

Using the Area Solar Radiation tool in the Spatial Analyst extension, I conducted calculations to determine the incoming solar radiation within the defined area. The accuracy of the results heavily relies on the inputs provided, such as the length of time, location, dispersion rate, and sun tracking. Considering that winter months typically have lower solar radiation levels, I chose to study the period from January through March, so as to estimate a level of solar radiation as a ‘minimum’ or more conservative estimate. The variables that I adjusted in the tool were the dates for the model, January 1- March 22nd, 2023 (Julian Day 81), which represents the end of winter.

Narrowing Down the Field

To enhance the realism of the analysis, I included parameters that excluded sub-optimal rooftops from consideration. For example, I excluded north-facing roofs from consideration due to their lesser solar exposure at this latitude. For a corresponding southern hemisphere region, the same would be done for south facing rooftops. This decision allows us to concentrate solely on rooftops with substantial solar potential for a more focused evaluation.

I carried out further filtration using attribute selection techniques in the “Acceptable Rooftop” layer of my GIS analysis, specifically implementing a minimum area threshold of 30 square meters for each rooftop. Subsequently, the rooftops meeting this specified criterion were extracted and compiled into the “ChosenRooftops” layer. As the name implies, the “ChosenRooftops” layer is composed of rooftops that have been identified as suitable for a comprehensive assessment of their solar energy potential.

Calculations

The Area Solar Radiation tool provides radiation values in Wh/m^2, which is the standard unit for solar radiation. However, for enhanced user-friendliness and alignment with common energy measurements, I converted the units to kWh/m2 using the Raster Calculator tool and dividing the Area Solar Radiation layer by one thousand. The base unit for the radiation value is watt-hour per meter squared. Changing the base power unit of watt to kilowatt puts the power into more accessible amounts.

Utilizing the Zonal Statistics tool, I processed all the raster pixels, generating a comprehensive table that included various statistics such as mean, area, count, and other relevant information for each of the building types. The raster pixels each contained a calculated amount of incoming radiation over the 81-day time period. That information was ground buy each building footprint within the buildingFootprint shapefile and sorted by the building type.

Finding Power Potential

Finally, to estimate the power potential of the rooftops, I multiplied the mean raster radiation values by the area, installation performance ratio and solar panel efficiency. For the region of Oregon, the solar panel efficiency was estimated to be 0.15, while the performance ratio was estimated to be 86% (Feldman et al., 2022). By performing these calculations, I obtained an estimation of the potential energy output for each building type, contributing to the evaluation of their viability in meeting the energy needs of the city.

Results

The model conducted an analysis of a substantial rooftop area, totaling 136,059,246 square meters, equivalent to over 33,000 acres. For the months spanning January through March, it was determined that a significant potential power generation of 1,472,830 megawatt-hours (MWh) could be harnessed if solar panels were installed across all available rooftop surfaces within this designated zone.

Within this zone, residential buildings occupy a substantial portion, comprising 128,483,268 square meters, representing 99.2% of the total rooftop area, as indicated in Table 5. Correspondingly, these residential buildings hold the potential for generating 1,387,466.688 MWh of power, which accounts for approximately 99.1% of the total potential power output within the zone.

In addition to residential buildings, the zone also encompasses commercial properties, encompassing a rooftop area of 529,785 square meters. These commercial properties have the potential to contribute 6,413 MWh of power to the overall output.

Furthermore, industrial properties in the designated zone occupy 424,730 square meters of rooftop space, with an associated potential power output of 5,252 MWh. This breakdown illustrates the distribution of rooftop areas and their respective contributions to the overall potential power output within the analyzed section.

Zonal Statistics Tool

Table 1, referred to as the Zonal statistics table, provides comprehensive data regarding the solar radiation levels associated with buildings within the chosen quadrants in Portland. To generate this table, the "suitableBuildings" raster was employed, following a cleaning process to ensure it represented rooftops deemed suitable for solar applications. The zonal statistic tool operated using the "suitableBuildings" raster, which had been filtered using the building footprint shapefile. This specific configuration enabled the tool to conduct a statistical analysis of solar radiation intensity as documented within the raster file.

Within the table, several key attributes hold significance. Specifically, the "count" value within the table serves as a representation of the number of cells associated with each building type contained within the specified sample area. This count metric provides essential information about the distribution and prevalence of various building types within the analyzed region.

Furthermore, another crucial parameter within the table is the mean (average solar radiation), measured in kilowatt-hours per square meter (kWh/m^2), received by a particular building type. This mean value is instrumental in conjunction with the building area data, as it aids in calculating the potential power output achievable from the rooftops.

Table 1. Zonal Statistics Table showing cells counts, areas, and statistics for incoming solar radiation received by building type.

Simplified Building Use	Zone Code	Count	Area	Minimum	Maximum	Range	Mean	STD	Sum	Median	PCT90
Residential	1	14989362	134901921	0.001	161.7	161.7	83.8	33.5	1256060341	91.0	125.0
Industrial	2	49382	444430	0.203	155.1	154.9	96.1	21.6	4745288	102.4	106.5
Commercial	3	58866	529785	0.017	160.2	160.1	93.8	25.1	5523983	101.4	114.1
Other	4	17424	156813	1.611	159.3	157.7	89.1	27.3	1551951	94.5	119.8

Looking Deeper into Building Types

The calculated power estimates, both the total power in MWh and the amount adjusted for this region of Oregon (Feldman et al. 2022) are presented for the different building classifications in Tables 2-5. Different building types appear to have different potential for rooftop solar, as we examine the mean and median values for each building type in Tables 2-3. In the simplified classification, the mean solar radiation for residential buildings stands at 83.8 kWh/m^2, whereas industrial buildings have a higher mean of 96.1 kWh/m^2, and commercial buildings fall in between with a mean of 93.8 kWh/m^2 (Table 3) This data underscores that, on average, industrial buildings have the highest potential for rooftop power generation. However, as noted previously the study area is predominantly residential (Tables 4-5).

Additionally, when considering the median values in Table 3, the disparities are similarly notable. The median solar radiation for residential buildings is 91.0 kWh/m^2, whereas industrial buildings have a higher median of 102.4 kWh/m^2, and commercial buildings closely follow with a median of 101.4 kWh/m^2. The residential category also has a standard deviation of 33.5 when compared to other building types. Industrial buildings have a standard deviation of 21.6, while commercial buildings have a slightly lower standard deviation of 25.1. This divergence in standard deviations highlights a significant disparity in the potential power generation among these building categories, with residential buildings showing the greatest variation in the amount of power they could potentially produce from their rooftops.

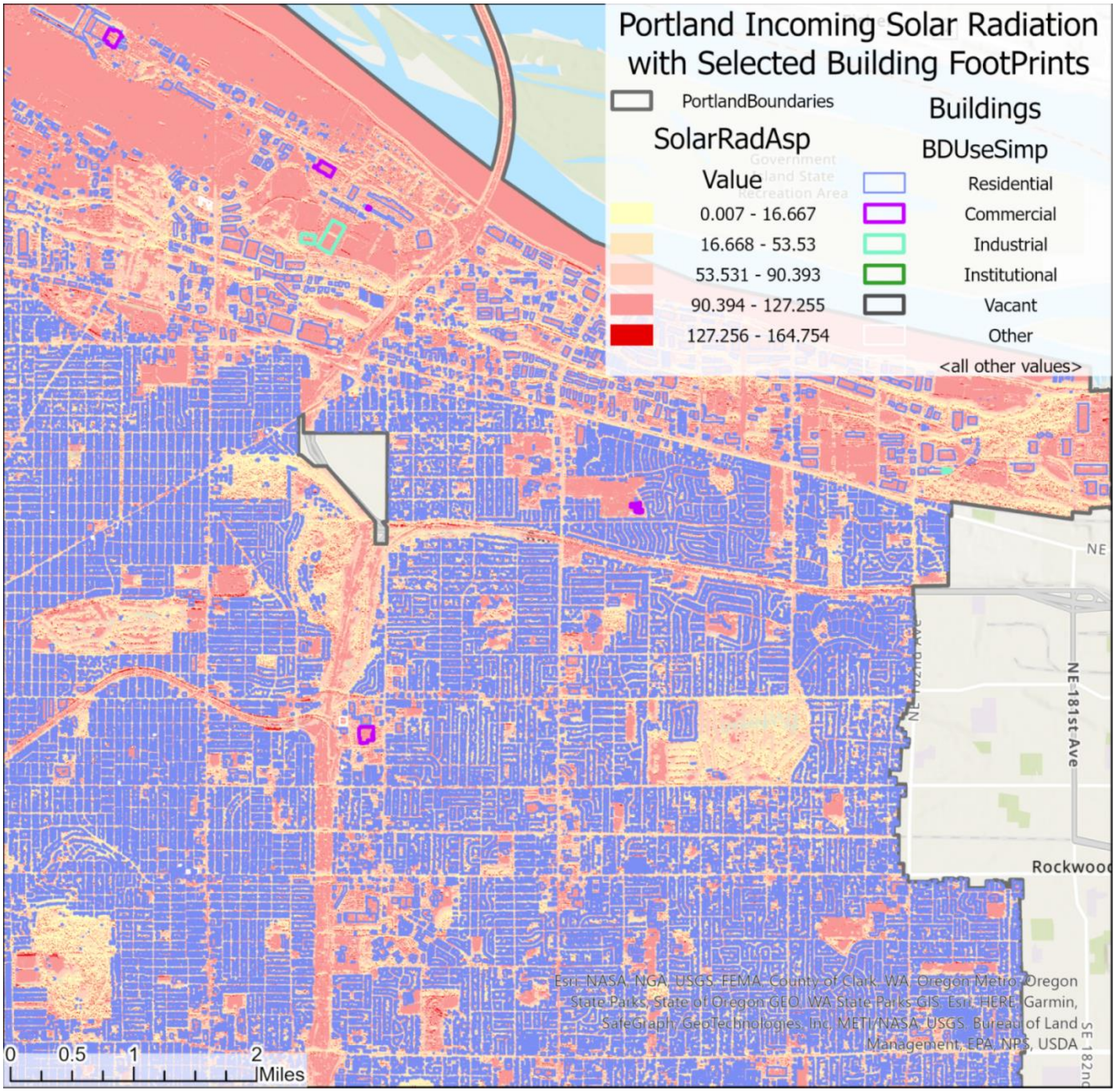

Figure 6. Map of Portland showing calculated solar radiation. The periwinkle color represents the outline or residential buildings. As you can see the map is overwhelmingly residential. Incoming solar radiation is a spectrum from red to cream, with the majority of the space coral. Source: City of Portland (https://www.portlandmaps.com/)

Figure 7. Map of accumulated winter rooftop radiation within a neighborhood setting. The residential buildings have a tendency to be more diverse in accumulated solar radiation totals than industrial or commercial buildings.

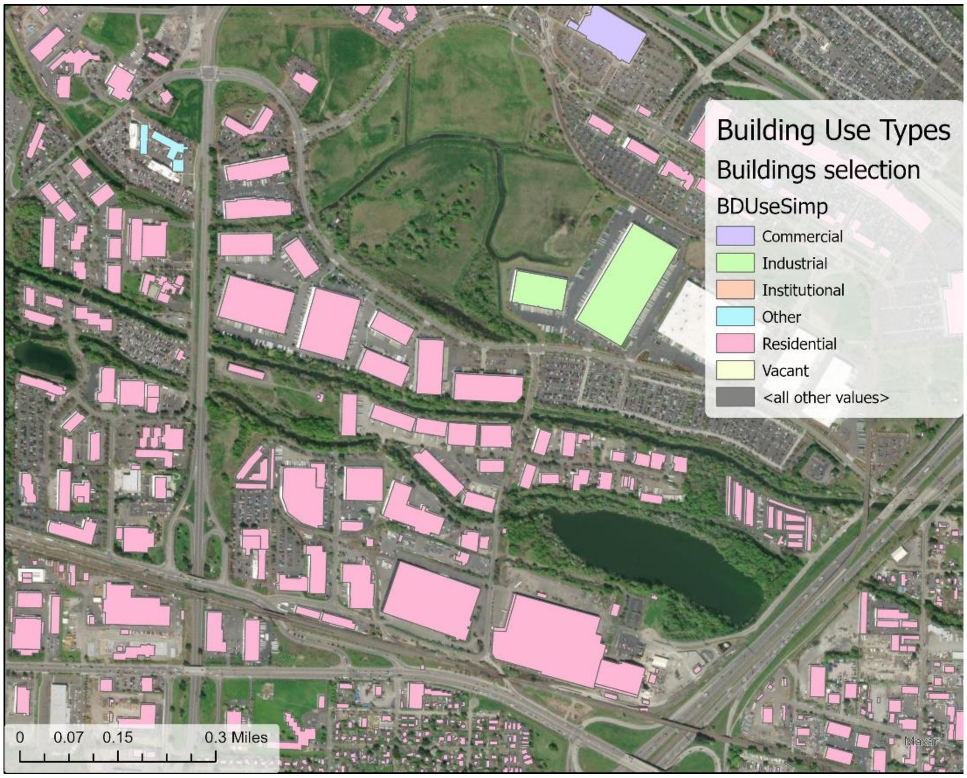

Figure 8. Map building use types within a neighborhood setting. Source: City of Portland (https://www.portlandmaps.com/)

Table 2. Expanded Building Type Solar Power Calculations. The last column (OR Adj) reflects the performance adjustment for Oregon suggested by Feldman et al. (2022). The total power calculated comes from a mean value which is 0.06% different than the simplified classification (Table 3).

Solar Radiation Table – Buildings Expanded

Building Use	***Area (m^2)***	***Mean (kWh/m^2)***	***STD (kWh/m^2)***	***SUM (kWh/m^2)***	***MEDIAN kWh/m^2)***	***Power (MWh)***	***OR Adj (MWh)***
Residential Condominiums	1994248	84.08	34.12	18631625	88.92	25152	21631
Unlabeled	48001199	92.49	27.49	493303193	100.37	665948	572715
Apartment Complex	7291107	85.47	33.24	69241198	91.52	93474	80388
Duplex	2303258	80.31	35.45	20552154	84.55	27745	23861
Multiplex	504396	79.10	35.26	4433129	83.88	5985	5147
Not Set	170448	84.74	31.55	1604978	89.69	2167	1863
Dormitories	70613	87.08	34.86	683242	90.21	922	793
Townhouse	5958	73.96	24.82	48963	80.12	66	57
House	70046524	79.05	35.44	615243860	82.80	830565	714286
Garage	5635441	70.22	37.22	43971103	71.03	59360	51050
Commercial Building	18882	96.76	26.43	203005	97.44	274	235
Building	19701	101.37	15.11	221894	104.90	300	258
Tool Shed	225	70.96	30.45	1774	79.09	2.4	2.1
Condo Tower	44198	81.72	32.80	401309	97.62	542	466
Commercial/ Retail	6831	89.06	33.64	67600	96.66	91	78
Total:						**1712593**	**1472830**

Table 3. Simplified Building Type Solar Power Calculations. The last column (OR Adj) reflects the performance adjustment for Oregon suggested by Feldman et al. (2022). The total power calculated comes from a mean value which is 0.06% different than the expanded classification (Table 2).

Solar Radiation Table – Buildings Simplified

Building Use	***Area*** ***(m^2)***	***Mean*** ***(kWh/m^2)***	***STD*** ***(kWh/m^2)***	***SUM*** ***(kWh/m^2)***	***MEDIAN*** ***(kWh/m^2)***	***Power*** ***(MWh)***	***OR Adj*** ***(MWh)***
Residential	134901921	83.80	33.53	1256060341	91.01	1695652	1458261
Industrial	444430	96.09	21.60	4745288	102.42	6406	5509
Commercial	529785	93.84	25.10	5523983	101.41	7457	6413
Other	156813	89.07	27.29	1551951	94.49	2095	1802
Total						**1711610**	**1471985**

Table 4. Percentages of power and area for buildings, simplified. Over 99% of the rooftop area was residential in nature.

Buildings Simplified - Percentages

Building Use	***OR Adj (MWh)***	***% of Total***	***% of Area***
Residential	1458261	99.07	99.17
Industrial	5509	0.37	0.33
Commercial	6413	0.44	0.39
Other	1802	0.12	0.12

Table 5. Percentages of power and area for buildings, expanded. House rooftops make up over half of the total area.

Buildings Expanded – Percentages

Building Use	***OR Adj (MWh)***	***% of Total***	***% of Area***
Residential Condominiums	216301	1.47	1.47
Unlabeled	572715	38.89	35.27
Apartment Complex	80388	5.46	5.36
Duplex	23861	1.62	1.69
Multiplex	5147	0.35	0.37
Not Set	1863	0.13	0.13
Dormitories	793	0.05	0.05
Townhouse	57	0.00	0.00
House	714286	48.50	51.46
Garage	51050	3.47	4.14
Commercial Building	236	0.02	0.01
Building	258	0.02	0.01
Tool Shed	2.1	0.00	0.00
Condo Tower	466	0.03	0.03
Commercial/ Retail	78	0.01	0.01

Discussion

Calculated Power Output

If we covered the rooftops of the study area with solar panels (including the exclusions noted in the Methods), the modeled output alone has the potential to supply power to a staggering 589,324 homes every month. This represents a significant leap towards sustainable energy solutions, displaying the capacity of solar energy to meet the electricity needs of a substantial portion of the population.

It's worth noting that this model is projected to provide an essential contribution to solar power generation even during the winter months. During this period, the projected power generation is sufficient to cover 6.9% of Portland General Electric's (PGE) annual energy delivery, which encompasses a vast network of 51 cities across Oregon. These figures are rooted in PGE's 2022 statistics for Oregon, which reported an energy deliverable of 21,231,000 megawatt-hours (MWh) and an average annual consumption of 9,991 kilowatt-hours (kWh) per consumer.

This convergence of factors, from the solar potential of rooftops to the seasonal variation in solar radiation, underscores the viability of solar energy as a substantial contributor to Oregon's energy mix. It not only represents an opportunity for clean and sustainable power generation but also aligns with broader efforts to reduce carbon emissions and foster a more environmentally conscious energy landscape.

Roofing Structure

It's important to note that this modeling approach has its limitations. Specifically, the model doesn't consider roofing structures. While LiDAR imagery can provide a 3D representation that includes the layout of the rooftops and how shadows interact across them, the program isn’t able to detect and automatically discount structures such as ducts as unsuitable for solar panel installation. Additionally, the program doesn't factor in various aspects such as roofing materials, roof strength, skylights, or any other elements beyond the 3D imprint of the rooftop and the amount of sunlight it receives over time.

The responsibility for including information about these structural factors that might impede solar panel installation lies with the surveyors collecting data on the buildings. They would need to document any relevant details that could affect the ability to support the weight of solar panels and related infrastructure.

In the future, it might be worthwhile to explore how machine learning and advanced computer vision techniques could be harnessed to automatically identify duct structures and other rooftop features that might pose challenges to solar panel placement. This would not only streamline the assessment process but also enhance the accuracy and efficiency of rooftop solar potential assessments, ultimately facilitating the expansion of sustainable energy solutions.

Building Types

A significant challenge emerges in my research since a staggering ninety-nine percent of the buildings within the dataset fall into the residential category as represented in Figure 6. This presents a notable obstacle as my primary objective revolves around constructing models that compare solar output across different building types. Notably, the residential buildings exhibit distinct differences compared to their commercial and industrial counterparts. The maps

Figure 7 and

Figure 8 show how residential rooftops have less uniformity in their solar radiation levels, displaying rooftops that contain a larger portion of mixed yellows, oranges, and reds. They display a higher standard deviation while featuring lower mean and median values.

However, the data within my sample for these commercial and industrial buildings is relatively limited, making it imprudent to draw any definitive conclusions at this point.

Nonetheless, it is intriguing to observe such pronounced disparities among these building types, suggesting the need for further investigation into the distinctions between commercial and industrial rooftop solar in contrast to residential installations. This underscores the importance of prioritizing initiatives and programs tailored towards buildings that can maximize the utilization of solar investment funds effectively.

Processing Advice

When creating a solar map for a city, it's essential to optimize the data analysis process. One key recommendation is to focus the data analysis specifically on the rooftops rather than covering the entire area. This targeted approach can provide more accurate and actionable information for solar energy planning within urban environments. To achieve this, consider narrowing down the raster dataset used for analyzing incoming solar radiation to the building footprints instead of what I did. By isolating and working with these specific building structures, you can cut processing time.

Simply clip the quadrangle raster files to match the parameters of the building footprints file. Once you have these clipped raster files, you can then run them through the solar radiation model. This focused approach ensures that the analysis is directly relevant to the buildings and rooftops within the city, streamlining the processing time. As you can see in my study, I had only clipped my raster files to the City of Portland boundaries and therefore created a solar radiation model that included all surfaces within my area of Portland, including roads, fields, and other areas that are of no use for my study (Figure 6. This calculation used up much time and processing power on the part of my computer system, one quadrangle took nearly two weeks of dedicated system use, when the system didn’t crash.

Key recommendation number two, make sure the raster data you use is in the correct format. My initial efforts to utilize the solar radiation tool encountered setbacks, primarily due to my attempt to work with LiDAR data acquired from the city of Portland, which was provided in TIFF format. Raster datasets can be shared in geoTiff format, with additional geographical data layered in. Unfortunately, when attempting to process this extensive dataset, the solar radiation tool failed to initiate, and ArcGIS Pro consistently indicated that the raster file was too large for clipping. After spending a couple weeks going back and forth with the city and professors, I decided to use LiDAR acquired from the DOGAMI website instead. The LiDAR from this website contained the completed raster dataset, with the GRD files and other accessories needed for ArcGIS Proto be able to manipulate the raster data.

What’s Holding Up the Works

Solar mapping has been a well-established practice for many years (Moreno et al., 2011), and given the pressing demand for clean energy, one might wonder why our cities are not already covered in solar panels. What's causing the delay? The answer to this question can be broken down into two main factors. First, there are legitimate financial and environmental considerations that have restrained the rapid adoption of solar rooftops. These factors play a role in the slow growth of solar panel installations. Secondly, there are ongoing initiatives and programs in various regions aimed at promoting and expanding the utilization of solar panels. These programs represent a positive step forward in encouraging broader solar panel adoption.

Solar panels come with a significant cost, and their durability is not indefinite. In the state of Oregon, the installation of a 6kW solar panel system typically carries an average price tag of $18,780, and for those considering a 10kW system, the cost averages around $31,300 (Aggarwal, 2023). It's noteworthy that the expected lifespan of these panels is approximately 30 years, after which their power generation capability experiences a significant decline (Komoto et al., 2018). This is a large monetary barrier in installing solar rooftop installations as it takes the majority of the solar panel’s lifetime to recoup that investment. Tax incentives offered from state and federal government sources help with that cost barrier. Current incentives offer up to $7500 for a complete residential rooftop solar setup that includes a battery (DoE, 2023). While that makes a small system less extravagant at $11280, that price point is still far out of reach for many people, especially for an investment that won’t pay off for over a decade.

Solar panels have a dual nature, being both environmentally beneficial and posing certain challenges. I've previously highlighted their environmental advantages, particularly in reducing our dependence on fossil fuels. However, a significant concern lies in the insufficient availability of recycling facilities for these panels.

Solar panels consist of several components, including a junction box, battery, backboard, ethylene-vinyl acetate (EVA), aluminum frame, silica gel, and tempered glass (Xu et al., 2018). Within these panels, the batteries contain valuable metals like cadmium, selenium, tellurium, gallium, and molybdenum. It's crucial to consider saving these resources. Additionally, the glass, which constitutes 54.7% of the panel's weight, and the aluminum, contributing 12.7%, are materials that should also be conserved (Xu et al., 2018). Balancing the benefits of solar energy with the responsible management of its components is key to ensuring a sustainable future.

Conclusion

The method described holds great potential for replication in cities around the world as a means of enhancing city planning and harnessing clean energy from underutilized rooftop spaces. It offers a promising avenue for cities to make more efficient use of their resources and reduce their environmental footprint. Even cities located in regions with climates characterized by months of drizzle can benefit from this approach, as it has the capability to generate sufficient power to sustain a portion of their population, thereby contributing to energy sustainability and reducing dependence on fossil fuels.

However, to maximize the effectiveness of this method in estimating power generation, further research is essential. One promising avenue for improvement involves integrating machine learning techniques to identify duct systems and other features such as skylights on rooftops. This addition would enhance the accuracy of power estimates and enable cities to make more informed decisions regarding energy generation and distribution. By continuously refining and expanding the capabilities of this approach, cities can take significant strides towards a greener and more sustainable future.

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