Solar energy considerations in urban planning: The tension between solar potential and densification

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Abstract

In this paper we explore the relationship between solar potential and the built urban environment. Solar potential across the urban landscape is uneven, in part, because it is affected by the surrounding texture of the urban form. Increasingly, the integration of solar energy considerations into urban planning and design is considered a crucial step in the transition from fossil fuels toward more renewable energy sources. Given the impact of the urban form, a key challenge may be the tension between solar potential and policies that promote densification. Other studies have noted how the built environment may significantly decrease solar potential. We suggest in this paper that solar potential should be more adequately considered in pre-planning phases with emphasis on the effects of building design on solar potential. The urgency may be heightened because increasing density with taller buildings has been embraced and widely implemented as part of many cities' urban sustainability agendas. Using the City of Calgary as a case-study, we explore its solar potential. A spatial modelling tool in a GIS environment was used to assess the solar potential of the central business district and surrounding neighborhoods. The results show that Calgary's central business district has significantly lower solar potential than the surrounding neighborhoods. Importantly, current land-use regulations do not cover the potential impact of taller buildings on the area's solar potential. We suggest that there should at least be acknowledgement of this issue in urban planning practices and that solar potential should be incorporated as one variable in the urban planning process.

Keywords: GIS; solar potential; urban planning; densification

Introduction

Increasing the amount of renewable energy sources, especially from solar power, is considered a vital part of achieving sustainability goals, especially as a key part of efforts to combat global climate change (Rogelj et. al. 2018). In addition to generating significantly less greenhouse gas emissions and reducing the use of fossil fuels, increasing the energy from solar sources may also foster greater "energy security" (Proskuryakova 2018). There is evidence that advances in solar energy systems enhance the stability of electrical grids and offers greater resilience during natural disasters (Pagliaro 2019).

Solar potential is unevenly spread across the urban landscape. One factor that has been shown to have a significant impact on the solar potential of a building is the surrounding texture of the urban form. Recent studies have examined the relationship between solar potential and various aspects of the urban texture (Lobaccaro & Frontini, 2014; Cheng, et.al., 2006; Kanters & Horvat, 2012; Zhang et.al., 2019). Save the modelling by Kanters and Horvat (2012), few studies have explored the relationship between solar potential and the potential impact of changes in urban form, especially in its densification. They suggested that increased densification, especially in urban cores, could decrease solar potential by as much as 75%, primarily due to complicated overshadowing effects. Unlike their study, our case-study of Calgary, Alberta, uses an existing urban form, not a model, to quantify the reduction in solar potential resulting from increased densification.

Employing geospatial modeling within a Geographic Information System (GIS) we ascertained that Calgary’s urban core exhibits lower solar potential compared to its surrounding neighborhoods. The limits of the available techniques make it impossible to isolate the various causes of this difference such as the built form alone. Instead, we had to highlight the pattern in Calgary in which buildings in the urban core receive less solar radiation than buildings in the neighborhoods that surround it. The main cause, we suggest, is the contrasting-built forms, which is stark, where the central business district (CBD) has a much taller landscape. Building height has been shown to impact an area’s solar energy potential, largely because of how shadowing reduces the area’s solar radiation, and we suggest shadowing from taller buildings is the most plausible explanation for this difference.

In Calgary, as in other cities, this issue of building height is especially pertinent. As we note at the end of this paper, increasing densification in the areas that surround the CBD and increasing the solar potential of these areas are both central to Calgary’s urban sustainability agenda. Yet, the current land-use regulations and urban planning policies fail to account for the relationship between the built environment and urban solar potential. The findings we believe show that there is tension between policies that promote greater density from land-use intensification and the potential benefits from the more widespread adoption of solar energy.

Calgary's CBD is a small area of the city, but its built form is unique in Calgary. As a percentage of the City of Calgary – the CBD is less than 10 km^2 – while the city’s territorial jurisdiction is more than 800 km^2 – it is less than 10% Calgary’s total area. What is most important for this study is that the CBD has much taller and ridged landscape than the rest of the city. Although our results do show that the ability of the CBD to provide its own solar power has been decreased, it is important to clarify that this was not the primary objective of this research. Instead, this research aimed to explore the potential loss of solar potential in other areas should the urban form change to more resemble the landscape of the CBD. Our contention is that contrasting the two areas illuminates the issue of the relation between solar potential and the characteristics of built-up environment and may help to prevent a loss in power generation in other areas of the city where there is pressure, especially, to build taller buildings.

Background:
Urban Sustainability, Urban Solar-Power Generation, and the Urban Landscape

Cities are increasingly targeted for their vital role in achieving sustainability goals. We live in an urban age, and any solution to meeting ecological goals must involve cities, the retrofitting of existing urban fabric, and the implementation of new technologies. Since the 1980s, a suite of planning and policies, under the banner of urban sustainability, the meshing together of urban development with environmental and social goals, has been championed as necessary (Beatley, 2008). For decades, policy and design frameworks such as smart growth or new urbanism, especially in North America, have located the central problem with North American cities as urban sprawl, highlighting its negative environmental consequences and advocating for more compact, transit-oriented, and denser communities (Checker et.al, 2015). One approach to arresting sprawl is a redevelopment model, like that advocated by journalist David Owen (2010), which is to enact policies that promote more intensification of land-use and taller buildings, especially for residential uses. Although this is not the only possibility to achieving greater urban residential density without very tall buildings (it could be achieved by utilizing 4-6 storey blocks as seen in the old urban quarters in Paris, Barcelona, and Copenhagen), cities in North America have largely embraced the approach of larger and taller buildings (Keough and Ghitter, 2021; Graham 2016). More recently, urban sustainability has also come to encompass the widespread adoption of urban solar energy systems. The experience of Freiburg, Germany, is a salient and popular example because the city adopted a highly incentivized solar power development strategy that proved highly successful (Keough and Ghitter, 2021).

Following the more recent trends in urban solar energy adoption, researchers began investigating the relationship between solar potential and urban planning. Over the past two decades, extensive large-scale initiatives have sought to identify and analyze optimal practices in solar urban planning, contributing to a substantial body of knowledge. These efforts have aimed to establish a more systematic set of planning practices, fostering the effective integration of solar energy into urban landscapes, and advancing sustainable development goals. The European Union, for example, since 2009, has had a program, EU POLIS, which focused on five European cities. The program examined and identified the best practises in solar urban planning as a part of a strategy to mobilize greater solar potential in the region. Another program, TASK 51, launched in 2013 was a specific taskforce within the International Energy Agency’s Solar Heating and Cooling (IEA SHC) project. Looking at thirty-four case studies across the world, its goals were to figure out how to better support urban planners in integrating solar photovoltaics in urban areas (Lobaccaro, et.al. 2019). The TASK 51 project also highlighted several case studies showing the usefulness of conducting preliminary analysis to compare the current situation with the proposed planning alternatives regarding solar accessibility, potential, daylight, and energy generation.

A separate, more technical literature, has shown the influence of urban texture on solar potential, offering valuable insights into ways that urban density may influence solar potential and suggesting possible solutions. In particular, what the more technical literature shows is that with appropriate planning especially in the early design phases urban form could be designed to better maintain an area's solar potential. Zhang, et.al. (2019) argued that addressing specific factors in the urban form with appropriate design could increase the solar potential by up to 200%. In a case-study of Sao Paulo, Brazil, Cheng et al. (2006) found that solar potential is negatively correlated with plot ratio (i.e., the ratio of total floor area to site area). High site coverage combined with a random vertical layout, resembling those commonly found in CBD's as illustrated in Figure 1, they found, is disadvantageous because it causes overshadowing on rooftop areas resulting in a considerable proportion (30-80%) of low-level solar radiation (0-200 kWh/m^2) (Cheng, et.al., 2006).

Researchers have also explored solar access rights as a means to address diminished solar potential in urban settings, this may be especially valuable for areas experiencing increased densification. Solar access rights have not traditionally focused on the impact to active solar systems such as solar panels, rather it has been concerned with the effect on passive systems. Addressing solar access rights, however, would indirectly bring attention to active solar energy system concerns. A common method of addressing solar access rights is by using a solar envelope, which is defined as the "volumetric limits to development that will not shadow neighbours," is meant to prevent overshadowing of neighbouring buildings during critical times throughout the day (Knowles, 2003). Although solar access may be most prevalent in highly built-up areas, where the urban form was constructed and oriented without concern for solar access, implementing more appropriate frameworks during the redevelopment of neighborhoods or sites can achieve a solution for this issue. Moreover, protecting solar access has complex legal challenges. Many jurisdictions still lack statutory recognition of solar rights and in these locales, other legal mechanism must be used such as easements, restrictive covenants, or purchasing airspace above neighbouring properties (particularly, in the UK and US) (Kauffman, 2019). The lack of policy creates uncertainty, potentially, stymieing, the more widespread use of solar technologies (Krivitsky, 2010).

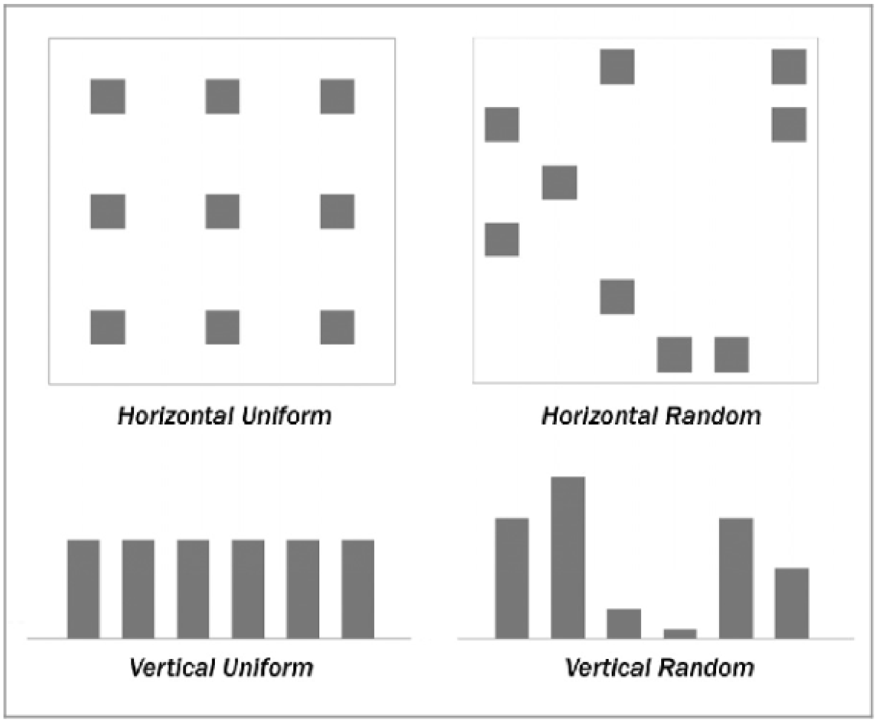


Figure 1: Horizontal and vertical urban layouts (Cheng, et.al., 2006). Both a horizontal and vertical random layout is seen in Calgary's downtown core whereas a horizontal and vertical uniform layout is more seen more in the surrounding neighborhoods.

Methods

Solar mapping allows the quantification of a city's solar energy production potential (Santos, et.al., 2014). The mapping and modeling of urban solar potential and the evaluation of specific sites, such as buildings, has been made more accurate by advances in geographic information sciences such as GIS and remote sensing (Dominguez, et.al., 2015).

In this study, three distinct sources of data were utilized to conduct a comprehensive analysis. The first dataset, acquired from Natural Resources Canada’s High-Resolution Digital Elevation Model (DEM) database, consists of a 1-meter spatial resolution Digital Surface Model (DSM) of Calgary. It is important to note that while a DSM represents the Earth's surface, including all features like buildings and vegetation, and provides heights for both terrain and objects, a DEM focuses exclusively on the bare Earth's surface. A DEM excludes objects above the ground and is typically used for applications emphasizing topography. As seen in figure 2, which compares the difference between a DEM and a DSM, given our specific interest in rooftop solar potential for this project, a DSM is considered the most appropriate choice. The DSM layer was created from the Canadian federal government's airborne Lidar data, with an aggregate nominal pulse density exceeding 2 pulses per square meter (pls/m^2) (Government of Canada, 2019). The second dataset encompasses a city-wide 3D buildings layer and building footprint layer, both sourced from the City of Calgary. These layers provide essential information about the structural landscape of the urban environment. The final data source utilized in this study is a city-wide Dissemination Block Polygon layer obtained from Statistics Canada. A dissemination block refers to a bounded area enclosed on all sides by features such as roads or rivers, providing a valuable geographical unit for our analysis.

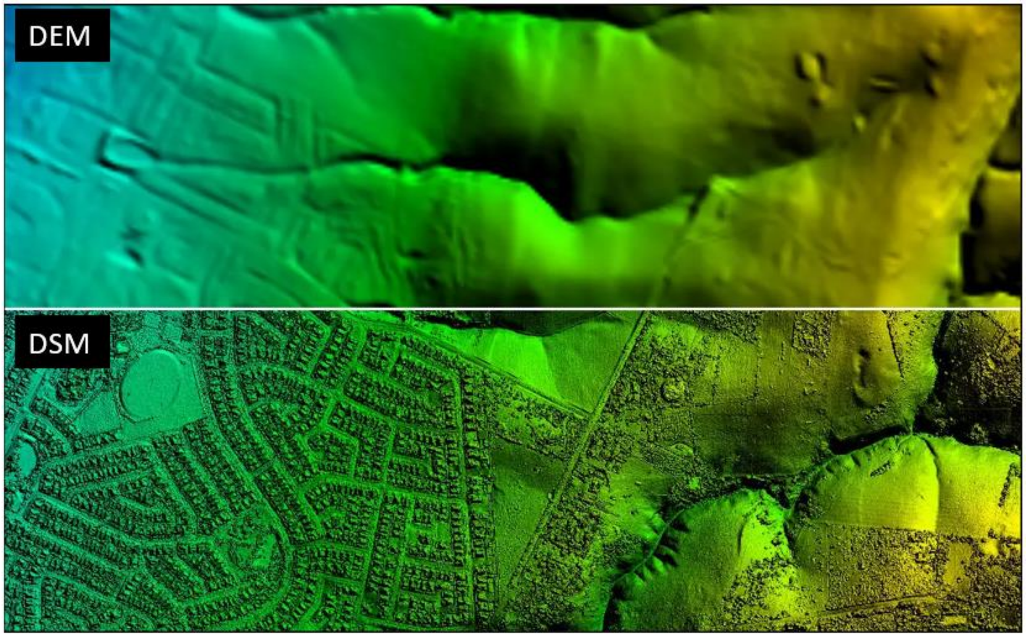
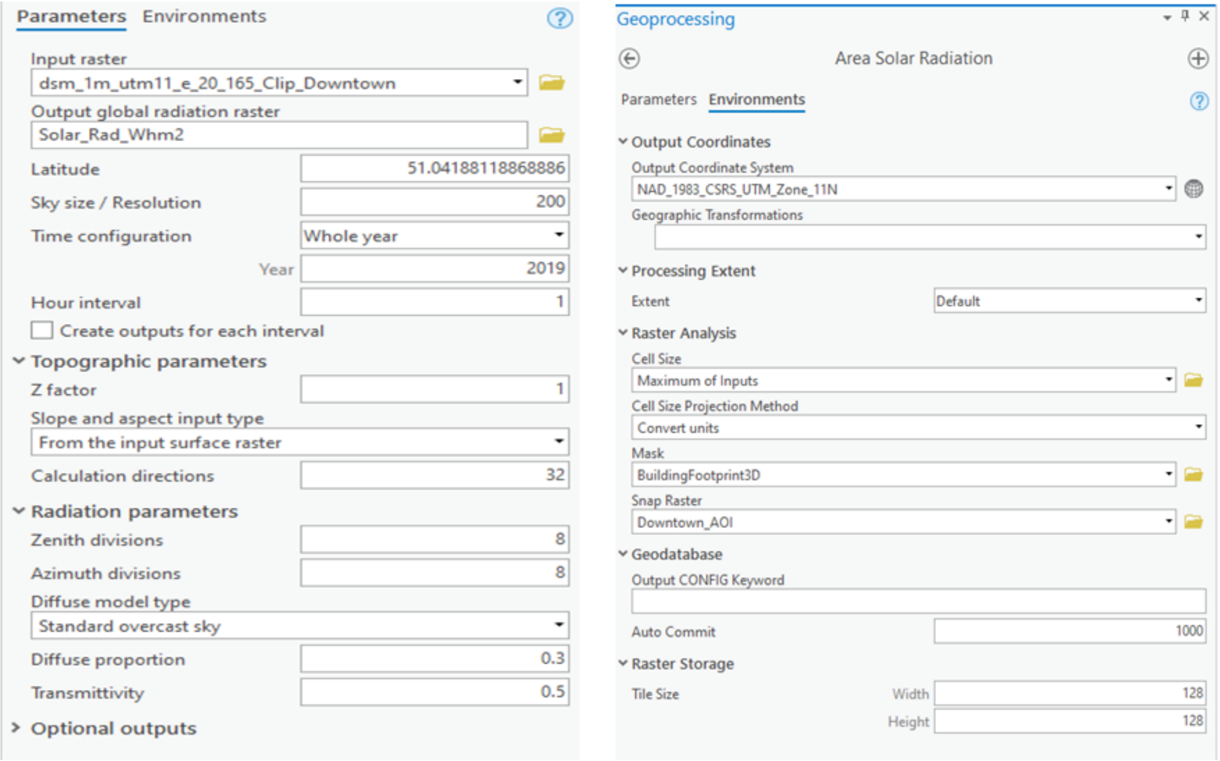


Figure 2: Comparison showing the difference between a DEM and a DSM (Singh, 2013). A DEM shows changes in bare ground elevation. It does not capture any features on the ground. A DSM shows the surface of the earth including features such as buildings and trees. For this research, given we are interested in rooftop solar a DSM is the appropriate choice to use in the analysis.

The study employed the ArcGIS Pro's area solar radiation tool with specific input parameters detailed in Figure 3. This tool generates an upward-looking hemispherical viewshed based on a DSM and is suitable for high spatial resolution scale analyses (Kodysh et al., 2013). The viewshed algorithm, part of the ArcGIS Pro Solar Analyst toolbox, involves three initial calculations—viewshed, sunmap, and skymap—and a final calculation that utilizes the results to estimate solar radiation values for each location on the DSM (Kodysh et al., 2013). In customizing key input parameters for the solar radiation tool, considerations such as sky size resolution, time intervals, and number of calculation directions were examined.



Input raster	dsm_1m_utm11_e_20_165_Clip_Downtown
Output global radiation raster	Solar_Rad_Whm2
Latitude	51.04188118868886
Sky size / Resolution	200
Time configuration	Whole year
Year	2019
Hour interval	1
☐ Create outputs for each interval	
Topographic parameters	
Z factor	1
Slope and aspect input type	From the input surface raster
Calculation directions	32
Radiation parameters	
Zenith divisions	8
Azimuth divisions	8
Diffuse model type	Standard overcast sky
Diffuse proportion	0.3
Transmittivity	0.5
Optional outputs	

Output Coordinates	
Output Coordinate System	NAD_1983_CSRS_UTM_Zone_11N
Geographic Transformations	
Processing Extent	
Extent	Default
Raster Analysis	
Cell Size	Maximum of Inputs
Cell Size Projection Method	Convert units
Mask	BuildingFootprint3D
Snap Raster	Downtown_AOI
Geodatabase	
Output CONFIG Keyword	
Auto Commit	1000
Raster Storage	
Tile Size Width	128
Height	128

Figure 3: Inputs for ArcGIS Pro’s “area solar radiation” tool. The input raster was a DSM collected from Natural Resources Canada. The solar potential was calculated as an average over an entire year. 32 directions were used to calculate the solar radiation input for each 1 m pixel. Diffuse proportion and transmissivity values were used to estimate average cloud coverage seen in Calgary.

The sky size, determining the resolution for viewshed, sunmap, and skymap rasters, significantly affects calculation accuracy and time (Esri, n.d.). Although increasing sky size enhances accuracy, it also extends calculation time. Typically, for entire DSMs with day intervals exceeding 14 days, a value of 200 is sufficient (Esri, n.d.). Given that this project assessed solar potential throughout an entire year, using monthly intervals, a sky size value of 200 was appropriate to balance detail and computation time.

Viewshed calculations determine the angular distribution of sky obstructions for each cell in the DSM, considering shadow obstructions impacting solar potential (Fu and Rich, 1999). The viewshed is determined by searching a specified number of directions around the location of interest to ascertain the maximum angle of sky obstruction, known as the horizon angle; for the remaining unsearched directions, horizon angles are calculated using interpolation (Fu and Rich, 1999). The number of calculation directions are linked to the DSMs spatial resolution. High spatial resolution DSMs, especially with human made structures require an increased number of directions (Esri, n.d.).

Direct solar radiation calculations utilize the sunmap, displaying the sun's position at designated time intervals, and are based on the study area's latitude and time configuration (Esri, n.d.). The skymap calculates diffuse radiation, incorporating atmospheric components. Atmospheric conditions, crucial for accurate calculations, are approximated using average diffusivity and transmissivity values. Default values of 0.3 for diffusivity and 0.5 for transmissivity were used, aligning with generally clear skies in Calgary.

The standard overcast sky option was chosen to account for zenith angle variation in relation to incoming diffuse radiation flux, particularly relevant for Calgary's varying sun angles throughout the year. The choice of the standard overcast sky option is not intended to account for shadows but rather to simulate the variation in incoming diffuse radiation flux based on the zenith angle. This option specifies the type of diffuse model used. The options are standard or uniform. The uniform overcast sky option means that the amount of incoming diffuse radiation will be considered the same from all sky directions. The standard overcast sky option means that the incoming diffuse radiation flux varies with the zenith angle. At higher zenith angles, sunlight has to pass through more of the Earth's atmosphere, leading to increased scattering and reduced radiation reaching the surface. This is the correct choice given Calgary’s latitude and it does not impact the shadowing calculation.

After researching these inputs, the tool was initially run without a mask (Figure 4) and subsequently with a building footprint layer mask (Figure 5) to assess overall and building rooftop solar potential.

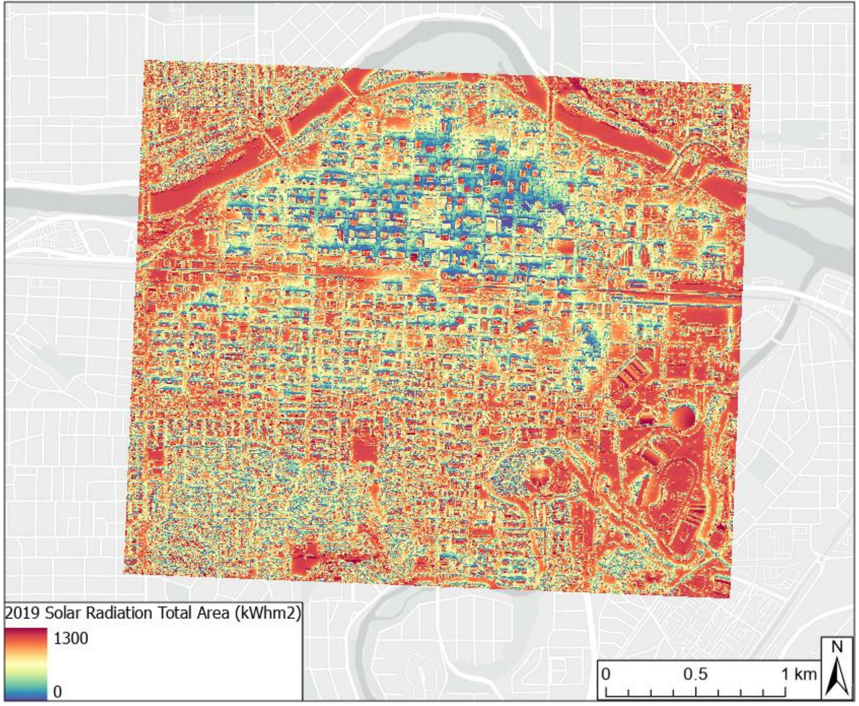


Figure 4: Calculated solar radiation from ArcGIS area solar radiation tool. Pixel size is 1 m. Areas of lower solar radiation/potential (shown by blue colours) in the downtown core are the result of overshadowing by tall buildings.

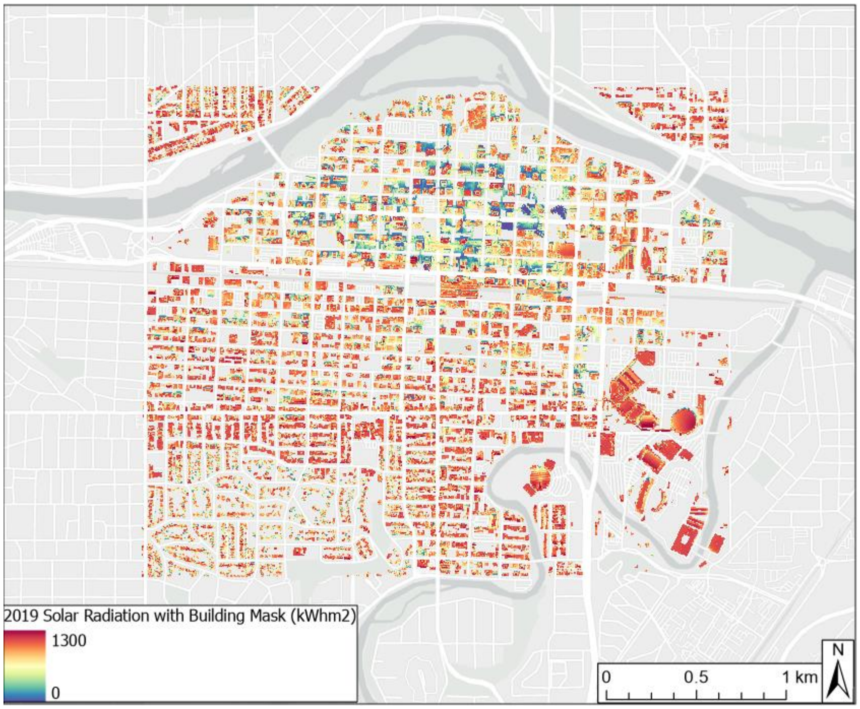


Figure 5: Calculated solar radiation from ArcGIS area solar radiation tool. Showing only rooftop results. Pixel size is 1 m. Areas of lower solar radiation/potential (shown by blue colours) in the downtown core are the result of overshadowing by tall buildings.

For this study, area density and its solar potential were joined. Building volume, cubic size of a building, was chosen as a reasonable proxy for density. It was calculated using the buildings footprint layer and the following equation.

((rooftop elevation (z) – ground elevation (z)) * shape area)

Equation 1: Calculation for above ground building volume, used to quantify density.

After calculating each buildings volume, a spatial join was performed that linked the dissemination block polygons and the buildings layer, then these building volumes were dissolved into each dissemination block (Figure 6). To calculate the mean solar potential for each dissemination block, a zonal statistics tool was used and joined to the building volume for each dissemination block. From there the data was exported into a table and building density was recalculated as the sum of the volume of all buildings for each dissemination block. For the analysis only a sub-set, comprising a spatial coherent area which included Calgary's CBD and adjacent areas to the south (as shown on Figure 6), of the dissemination blocks was used.

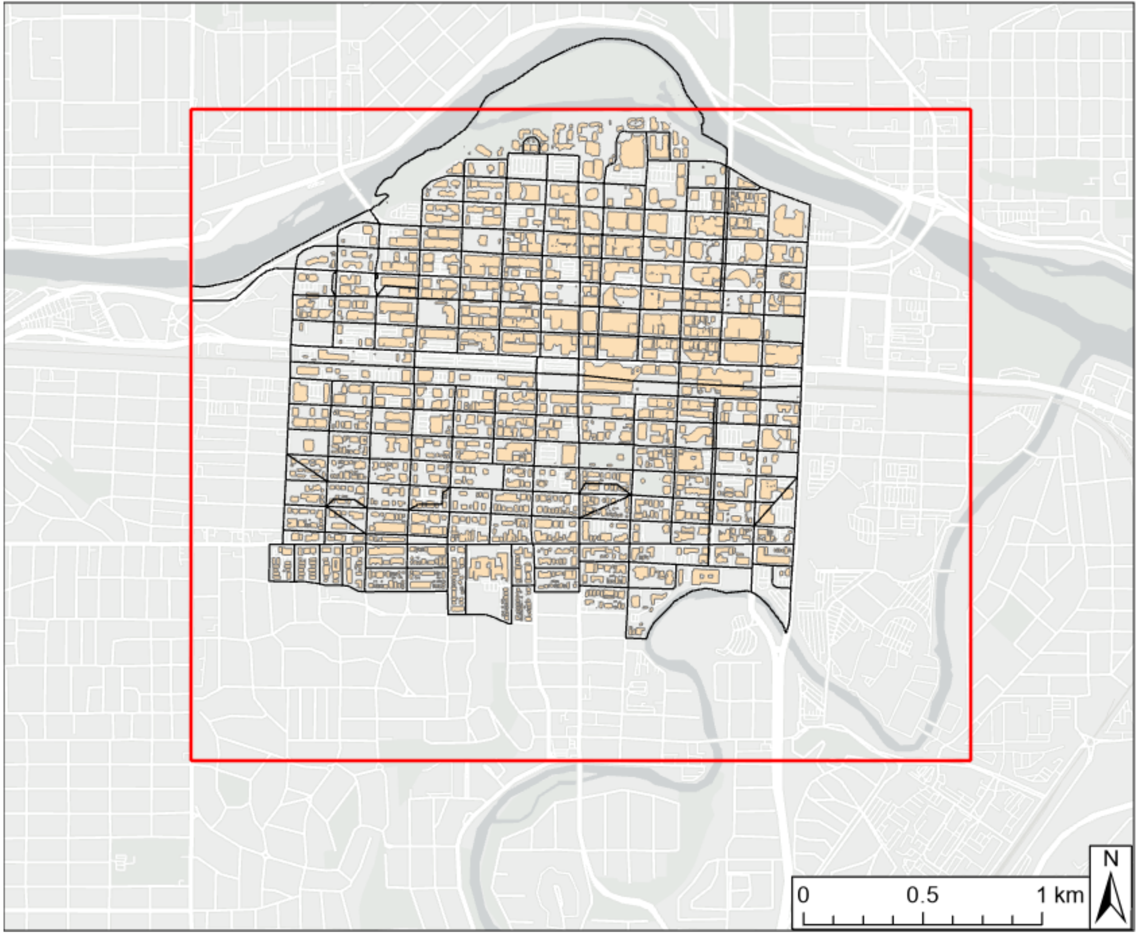


Figure 6: Dissemination blocks (black outlines) and building polygons (yellow blocks) included in correlation analysis. Excludes areas to the east as they comprise of light industrial and stampede ground areas. Excludes areas south of the elbow river comprising of green spaces and parks. Over 200 blocks included.

Given the non-linearity observed in the dataset, as illustrated in Figure 7, Spearman's rank correlation coefficient was employed. Spearman's rank correlation analysis was chosen as it does not assume a linear relationship between the variables. This analysis provided a quantitative measure of the relationship between solar potential and building density.

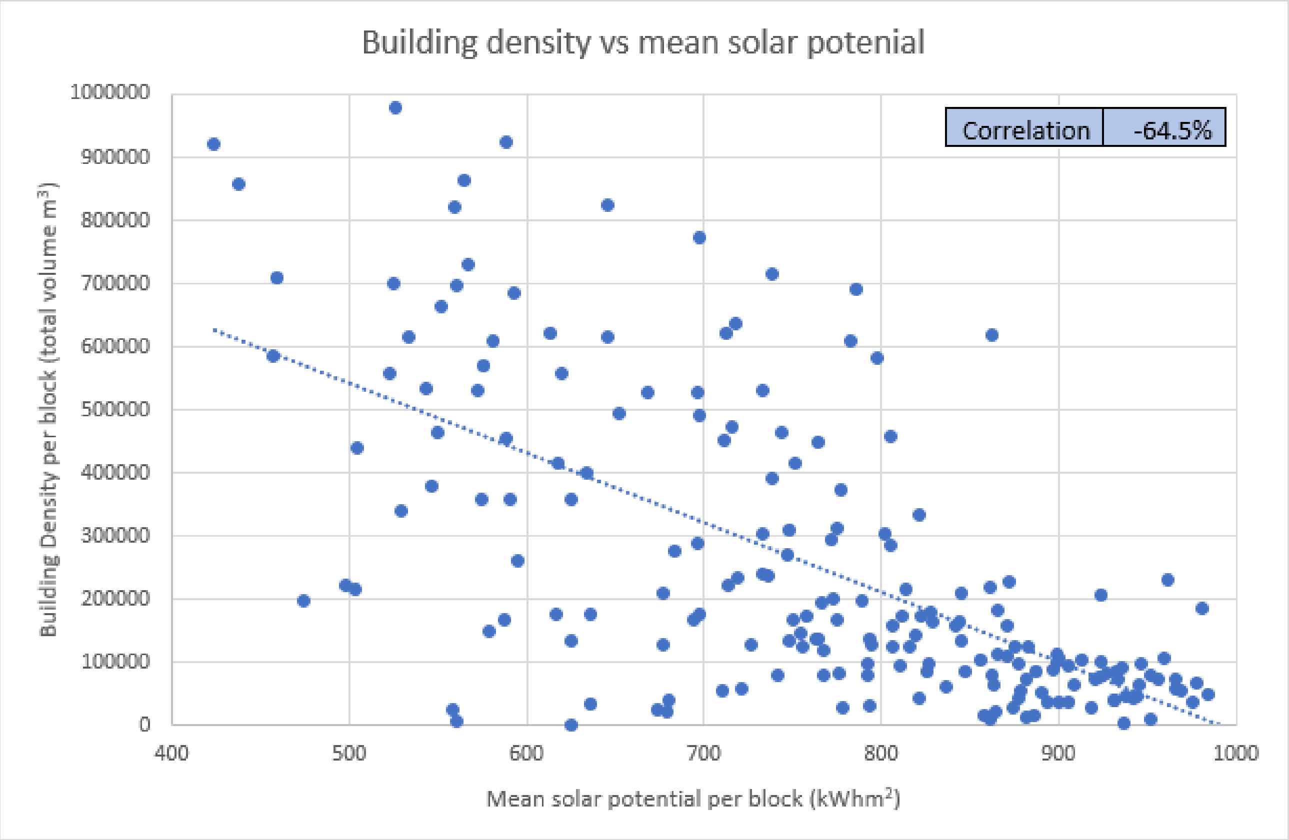


Figure 7: Building Density vs mean solar potential. Excludes 10 outliers with extremely high building density and varying solar potential. Includes a line of best fit. The Spearman's rank correlation coefficient is -64.5%, indicating a strong negative correlation between the two variables.

An examination of Calgary's urban planning regulations was also conducted to see if it contained information which addressed solar potential, strategies to increase densification, and measures to address the potential tension between solar potential and densification. In particular, Calgary's municipal development plan was consulted. It is the core planning document, updated in 2020, which shapes the city's long-term planning priorities. Further, a search for policy and regulations regarding solar access rights was conducted.

Results

Figures 3 and 4 show the calculated solar potential for the study area and shows starkly that Calgary's CBD has significantly lower solar potential (cold colours) than its surrounding neighbourhoods (hot colours). To provide a more precise assessment, the average solar potential for buildings in the downtown commercial core was determined and juxtaposed with the average solar potential for buildings in the surrounding areas. Notably, the downtown core demonstrated an average solar potential 33.5% lower than that of the surrounding regions.

The scatterplot of density (building volume) and mean solar potential, represented in Figure 7, clearly depicts a negative correlation between these two variables and the spearman's rank correlation coefficient of -64.5% further confirms this. In correlation analysis the sign of the coefficient indicates the direction of the relationship. A positive coefficient suggests a positive monotonic relationship (as one variable increases, the other tends to increase). A negative coefficient suggests a negative monotonic relationship (as one variable increases, the other tends to decrease). The magnitude (absolute value) of the Spearman's rank correlation coefficient indicates the strength of the relationship. A coefficient close to 1 (positive or negative) suggests a strong monotonic relationship. A coefficient close to 0 suggests a weak or no monotonic relationship. In this case, the calculated coefficient of -0.645 shows a moderately strong negative correlation.

The potential impact on solar panel installations is evident and, potentially troubling because, in practical terms, lower overall solar potential decreases the number of suitable rooftops. Several factors are used to determine suitability for solar panels such as the amount of incident solar radiation, facing direction, individual building energy usage, roof size, and slope. In this study a general analysis of suitable rooftops was conducted using a minimum amount of incident solar radiation criteria generally accepted to be >800 kWh/m^2 (Bujarkiewicz et. al. 2018).

Discussion

ArcGIS Pro's area solar radiation tool has been shown to be accurate and robust, specifically by Giannelli et.al. (2022), who compared six different solar radiation modelling tools and real-world weather data, showing that ArcGIS only had a 0.2% difference, and a root mean square error of 0.91, when compared with yearly weather station data. However, despite its strengths, the tool has limitations that may impact the accuracy of solar maps. One notable limitation is its reliance on an internal radiation model, preventing users from providing their own weather data files, thus potentially reducing accuracy (Giannelli, et.al., 2022).

Another potential limitation of using this tool is that it does not include reflected radiation in the calculations. This does not have a large effect as reflected radiation is considered to be only a small proportion of the total radiation. However, reflected radiation can be affected by different surface conditions such as snow cover or different building material types. While this was not explored in this research it may be an interesting future direction of study to consider the impact of building materials on solar potential.

In Calgary, we found the denser urban core has significantly lower solar potential than the less densely developed surrounding areas. Despite that we show this, we are not able to isolate the various causes of the difference. We suggest that the main cause of reduced solar potential is due to overshadowing of suitable rooftops by tall buildings.

The negative correlation identified between solar potential and urban densification may have important ramifications for Calgary as solar energy generation becomes more common and a key part of how Calgary meets its carbon reduction targets. A key recommendation emerging from this research is to formally acknowledge the tension between densification and solar potential in urban policy. An increased awareness of the tension between the adoption of a large-scale urban solar network and increasing urban density would allow for sounder objectives to be developed that would not undermine either. Our recommendation here is supported by recent literature, which shows that solar power has become a more important element of urban sustainability and that appropriate planning, especially in the early design phases, could better maintain the solar potential of areas in a city. Failure to incorporate solar potential in urban planning policies, may impact the solar potential across entire urbanized areas and it appears this could be minimized. This is an unforeseen missed opportunity that will be much more manageable and inexpensive to address in the pre-planning phase.

The problem is especially evident when examining the City of Calgary's municipal development plan, updated in 2020. Outlining a myriad of goals and objectives, the plan put a great deal of emphasis on the urgency of increasing density in Calgary's existing urbanized areas as a way to arrest sprawl and increase municipal housing supply (City of Calgary, 2020). While the plan does not specify what types of building will help accomplish this goal, the trends in redevelopment in Calgary have been to permit more high-rise buildings. Although the plan briefly mentions solar considerations, these are limited to maximizing passive solar gain through street design and building orientation, ensuring solar penetration throughout a block, and reducing shadowing to public sidewalks on the North side of streets. The plan does not mention the suitability of solar panels and active solar potential, and therefore, does not envision the potential impact of a densification strategy that prioritizes taller buildings. The results of this study suggest that addressing this potentially significant and costly omission is crucial to maximize the goals of densification and solar production in future developments. Further, as of 2021, in Alberta, there is no legal acknowledgement of solar access rights (Kauffman, 2021). This lack of policy creates uncertainty, potentially, stymieing, the more widespread use of solar technologies (Krivitsky, 2010).

The omission of active solar in the plan is especially surprising in Calgary. The City of Calgary has made significant commitments to maintaining high solar coverage in other contexts - specifically, preventing shadowing of pathways along the Bow River pathways to preserve the sunlight and warmth in and along pedestrian corridors. The results of this policy on solar potential are seen in Figure 4. Applying this approach more broadly would encourage better design of buildings that could maximize their solar potential and increase the desired building density more effectively.

Conclusion

In conclusion, a forward-thinking approach to urban planning should incorporate solar potential considerations from the design phase. The study recommends modeling solar potential under various design scenarios to ensure the consideration of trade-offs early in the design process when implementing changes is less costly. This proactive approach would prevent the wasteful loss of the city's urban solar potential and foster a balance between the goals of densification and solar production. Acknowledging and addressing the tension between these objectives in urban policy is crucial for sustainable and effective city planning. The study underscores the importance of adopting a comprehensive approach that takes solar potential into account, fostering the design of buildings that not only maximize solar efficiency but also align with the objectives of achieving desired building density.

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