Determining the Economic Value of Residential Rooftop Solar Photovoltaic Systems in Minneapolis Minnesota

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Abstract

Solar energy is the most accessible form of renewable energy for urban areas. Photovoltaic (PV) panels installed on a building can provide electricity that supplies that building's energy demands and add additional energy to the electrical grid. Providing an economic component to a building's potential PV output could motivate building owners to install rooftop solar photovoltaics. Using a two-part analysis, suitable roof areas of single-family residences were calculated in Minneapolis, MN and each building's potential PV output and potential financial benefits were determined. Compiling the results across the entire city, less than half of single-family residences can have their energy demands met. Of those buildings, all had a net financial benefit over the lifespan of the panels.

Introduction

As the push for renewable energy sources continues, the appeal of solar power is rising. According to Culley, Carton, Weaver, Ogley-Oliver, and Street (2011), solar energy is viewed with an 85% favorability rating in America. In addition to its favorability, solar energy is the most accessible renewable energy source for urban areas (Lukač, Žlaus, Seme, Žalik, and Štumberger, 2013). While hydropower is restricted by the area's hydrography and wind power turbines are unsafe in urban settings, solar energy generates passively with little disruption.

However, industrial-scale solar installations are ill-suited for urban environments due to the lack of space. Therefore, rooftop solar photovoltaic (PV) systems can be a possible solution for an urban area's energy demands. Rooftop PV systems are installed and managed on a building by building basis. Each building generates enough energy to meet its demands and then distributes any excess electricity onto the grid. This creates a distributed and decentralized energy grid that does not generate greenhouse gasses and improves national security (Boz, Cavert, and Brownson, 2015).

Solar energy generation is one of the sectors of renewable energy that has the most growth potential. According to the Minnesota Department of Commerce (2018), Minnesota is ranked 15th for total solar capacity, but as of 2017, it generates 1.2% of total energy with solar. This is a modest amount but three times larger than the amount the year before.

However, due to the distributed nature of rooftop PV, the decision to install panels will need to be made by the individual building owners. The inclusion of economic benefits to the building owner will likely help motivate building owners

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to install PV panels. Lee, Hong, Jeong, and Jeong (2018) illustrate this idea and state "the difference in the technical performance of the rooftop solar PV system, however, can lead to different financial returns for the rooftop solar PV adopters, which affects their decision-making."

Jakubiec and Reinhart (2013) also state "for individual building owners, implementing energy efficiency measures has become primarily a question of obtaining meaningful information regarding installation costs, potential energy savings, and payback times." Therefore, a meaningful analysis should include an economic component in order to improve implementation.

Study Area and Scope

This analysis explored the potential for rooftop solar photovoltaics in Minneapolis, Minnesota. The study area was chosen due to the large capacity for solar installation and the relatively small implementation so far (Minnesota Department of Commerce, 2018). The study area is outlined in Figure 1.

This analysis focuses on single-family residences for potential rooftops. The potential energy generated for a building is compared with the average energy demand for that building type. Single-family residences were chosen due to the lack of variability in energy demands. Commercial and industrial buildings were excluded due to the wide range of energy demands. With such a large variety of demands, a single average demand would often not accurately represent the actual demand of that building.

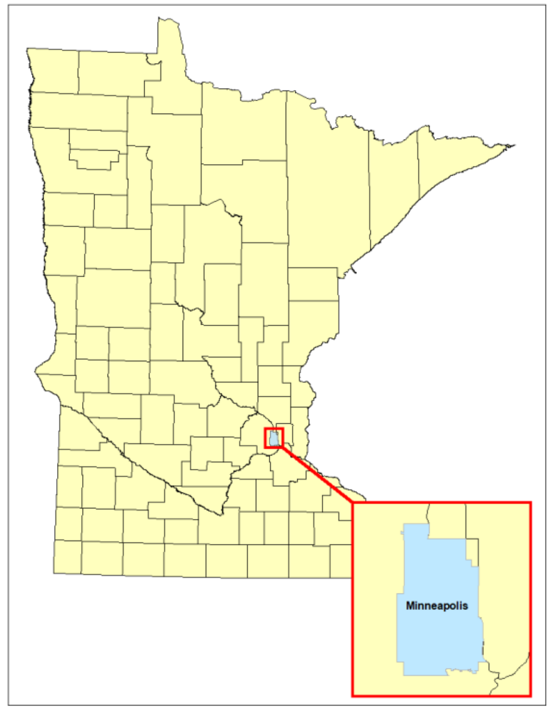

Figure 1. A map of the study area, the City of Minneapolis, in relation to the rest of Minnesota. The city boundary is seen in the map inset.

Methods

PVWatts Model

PVWatts is a model for determining a PV system's energy output. The model was developed by the National Renewable Energy Laboratory (NREL) (2014) to calculate the output of a solar PV system. The model takes several inputs to determine its output including climate data, roof slope, roof aspect, and panel model. However, the limitation of this model for this analysis is the PVWatts model is designed for only one building at a time. In the study area of Minneapolis, there are 74,793 single-family residences according to Hennepin County, all with varying roof orientation, sizes, and surrounding features that can partially or completely block sunlight on the roof.

According to Boz *et al.* (2015), the baseline physical requirements for a PV system on a rooftop are:

- Roof slope between 0 – 60 degrees
- No shading between 9:00 am and 3:00 pm on the summer solstice
- No shading between 10:00 am and 2:00 pm on the winter solstice

Boz *et al.* (2015) also include restrictions for the roof aspect, but according to the PVWatts model, a panel outside the aspect restrictions can still generate electricity.

Even with the input restrictions, there is still a large variety in possible installation surfaces. So, for there to be an analysis of the entire city, the PVWatts system was run multiple times. Each simulation was for a unique combination of slope and aspect inputs. For each model simulation, the model was run for a single panel. This way, buildings with multiple roof orientations can combine the per panel results of the model. To limit the number of times the model needs to be run, some model inputs can be set constant on each iteration. Because all buildings in this analysis are in Minneapolis, MN, the climate data in PVWatts remained the same. The panel model for this simulation was the SunPower SPR-300E-WHT-D that is rated for 300 watts. This model was chosen because the wattage is the closest to the mean wattage for panels available on the market today. With these variables constant across all model simulations, slope and aspect were the only variables that were different in each simulation.

Because PVWatts takes slope and aspect as single values, both needed to be reclassified. However, there is one consideration with slope that needs to be accounted for. According to Singrin and Mooney (2018), flat surfaces are favorable because the installer can place the panel in the best slope and aspect. According to the PVWatts Model, the position that has the highest energy output is south facing (180 degrees) and at a 40-degree angle. Therefore, all panels installed on a flat (less than 5 degree) roof are positioned at the optimal 40 degree angle. The reclassification of slope and aspect is provided in Table 1.

Given the eight different aspect values and the six different slope values for the PVWatts model, the model was run 48 times, once for each combination of aspect and slope. After each model simulation, the resulting Annual Energy and Net Savings results were entered in a spreadsheet. This spreadsheet contained slope and aspect combinations as well as their Annual Energy and Net Savings. A sample of this spreadsheet is illustrated in Table 2.

Table 1. Reclassification table for slope and aspect. Values on the left are a range of possible roof slopes/aspects and values on the right are the single value that they are reclassed to. The single values were used as inputs in the PVWatts model. All units are in degrees.

Aspect	**Aspect (PVWatts)**	**Slope**	**Slope (PVWatts)**
0 - 22.5, 337.5 - 360	0	5 - 15	10
22.5 - 67.5	45	15 - 25	20
67.5 - 112.5	90	25 - 35	30
112.5 - 157.5	135	35 - 45, 0 - 5	40
157.5 - 202.5	180	45 - 55	50
202.5 - 247.5	225	55 - 65	60
247.5 - 292.5	270		
292.5 - 337.5	315		

GIS Data Preparation

There are three input spatial datasets from which all the needed layers were generated using the ArcGIS Spatial Analyst Toolbox. These datasets and source information are provided in Table 3. To begin, all the single-family residential buildings in the study area were selected from all building types. To do this, the building layer was spatially joined with the county parcel layer. With the parcel information from the county attributed to each building, the single-family residences were selected. Then all buildings on a lot were combined into a single multi-part building. Without this, houses and detached garages would be treated as separate properties when the results were compiled per building.

Table 2. A sample of the spreadsheet created from the PVWatts model simulations. Each row represents a different model simulation with the corresponding aspect and slope inputs.

Aspect	**Slope**	**Annual Energy (kWh)**	**Net Savings ($)**
0	10	277	31
0	20	238	27
0	30	203	23
0	40	173	20
0	50	147	17
0	60	126	14
45	10	288	32
45	20	260	29
45	30	233	26
45	40	210	24
45	50	192	22
45	60	177	20
…	…	…	…

Table 3. Input datasets and sources for GIS analysis.

Dataset	Data Type	Source
Lidar Elevation	Lidar point cloud	Minnesota IT Services Geospatial Information Office (MN GEO)
Building Footprint	Polygon	Hennepin County
Parcels	Polygon	Hennepin County

Next, a DSM (Digital Surface Model) and a DEM (Digital Elevation Model) was created from the LiDAR dataset. LiDAR is a point cloud file of elevations measured using light waves. LiDAR is useful in this application because it allows for very high-resolution rasters of elevation data. Without a high-resolution raster, the DSM and DEM could have a poor representation of the roof geometry (Melius, Margolis, and Ong, 2013). A LiDAR file is classified so each point is assigned a value depending on what surface the light hits. By selectively filtering out point classes, the DEM and DSM can be generated using the ArcGIS LAS Dataset to Raster tool. The DEM contains the elevation of the ground and buildings across the study area. With this layer, the slope and aspect were calculated for each surface. The DSM contains elevations of the DEM with the addition of vegetation. All types of vegetation are captured in the DSM but only trees can influence rooftop shading due to their height. The DSM is used to calculate any shading on the rooftops. Each cell in the DEM and DSM represents an area of 1.6 m^2. This is the area of a single PV panel, so each raster cell represents a single panel. Using the DEM, the slope and aspect can be calculated using ArcGIS Spatial Analyst tools. Then each can be reclassified using the same values in Table 1.

Finally, a layer is needed that depicts all areas that receive direct sunlight within the bounds set by Boz *et al*. (2015). The ArcGIS Area Solar Radiation tool was run twice with the DSM as the input raster. The first iteration of the tool was run for the Summer Solstice. The second iteration was run for the Winter Solstice. One of the outputs of this tool is a direct solar duration raster. Each cell in this raster gives the amount of time in hours the cell receives direct sunlight. The summer and winter rasters were then combined into a single raster. A sample of this output can be found in Figure 2. Then all areas that receive all 10 hours of sunlight in the bounds were selected out.

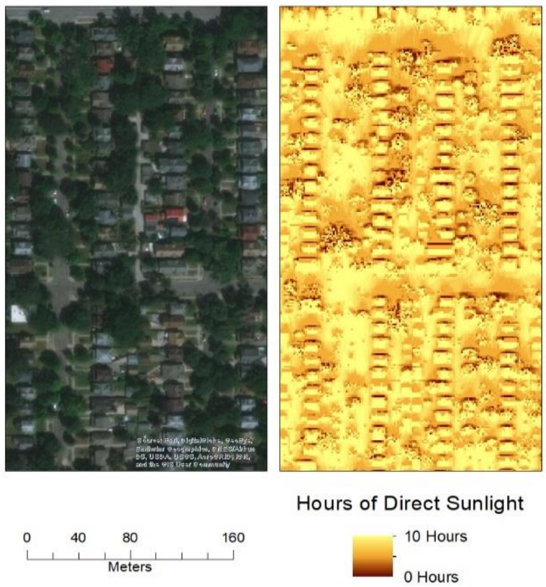

Figure 2. A sample of the solar duration raster. Each cell represents the total number of hours that that cell receives direct sunlight on the Summer Solstice and the Winter Solstice. Aerial imagery included to provide spatial context.

GIS Data Analysis

The reclassified slope and aspect GIS datasets were combined into a single raster with 48 unique values. Each value corresponded with a unique combination of slope and aspect values. With this combination raster, a one-to-one join was created with the outputs from the PVWatts simulations (Table 2). This result has the annual energy and net savings for each 1.6 m^2 surface in the study area if a panel was installed there. The combination raster was then clipped by the building polygons and then again by the direct solar raster. Finally, the raster was converted into a vector point feature in order to simplify data parsing. The result is provided in Figure 3. Each point shown in Figure 3 falls within the bounds set by Boz *et al.* (2015):

- Roof slope between 0 – 60 degrees
- No shading between 9:00 am and 3:00 pm on the summer solstice
- No shading between 10:00 am and 2:00 pm on the winter solstice

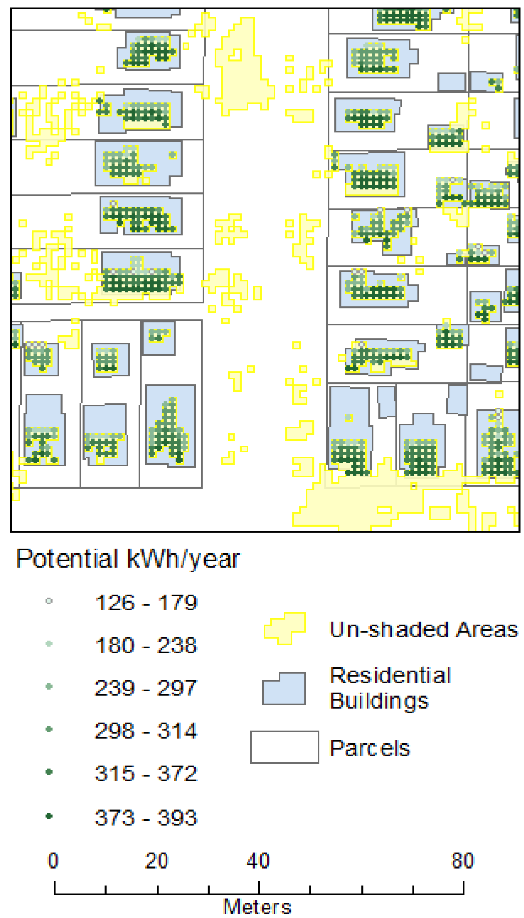

Figure 3. Suitable roof areas for PV installations. Each point represents the potential location for a single panel and contains the potential energy generated at that point. Buildings, parcels, and un-shaded areas added to provide context.

Financial Analysis

The GIS analysis determined areas suitable for a solar panel, and the PVWatts analysis determined the expected output of each panel. The outputs were in a per panel format and needed to be compiled per building. To do this, a Python script was created that iterated through each building and determined:

- Can the building have its electrical demands met by solar panels?
- What is the minimum number of panels needed?
- What is the optimal configuration financially?
- What is the maximum output given the building's capacity?

The benchmark for if a building can have its electrical demands met is if a panel configuration can produce 9,432 kWh in a year. This number is the average annual electricity demand for a residential building in Minnesota according to the United States Energy Information Administration (EIA) (2019).

The PVWatts model also provides a method for determining the final cost for a system. This financial model provides costs on a per watt basis. For this analysis, all panels installed would be rated to 300 watts. This is about average for currently available panels on the market. Because all the panels are rated at the same wattage, the model was adjusted to have costs based per panel installed. There are two financial incentives that factor into the final cost of the system according to the Database of State Incentives for Renewables and Efficiency (DSIRE) (2019). First, the state of Minnesota has a sales tax exemption for solar energy systems. Second, the Federal government offers a tax credit to cover the installation costs. The amount credited would be 26% of installation costs as of January 2020. Table 4 shows a full cost breakdown.

To determine the optimal configuration, a metric for value was determined. For this analysis, the payback period was used. The payback period is how long it would take to pay off a system installation using the reduction in electricity bills. For example, if a system costs $15,000 to install but the owner saves $1,000 per year on their electricity bill, then the system will have paid for itself in 15 years.

Table 4. A cost breakdown for a single PV system adapted from PVWatts. Costs are represented on a per-panel basis.

Financial Component	**Cost per panel installed**	**Costs for a 24-panel system**
Panel Cost	$204.00	$4,896.00
Inverter Cost	$57.00	$1,368.00
Equipment Cost	$108.00	$2,592.00
Labor Cost	$90.00	$2,160.00
Installer Overhead	$300.00	$7,200.00
Permitting Costs	$30.00	$720.00
Total Costs	$789.00	$18,936.00
Federal Tax Credit *26% of Total Cost*	$205.14	$4,923.00
Final Cost *Total Cost - Tax Credit*	**$586.86**	**$14,013.00**

According to Qiu, Kahn, and Xing (2019), if the payback period is too long, it can deter installations. According to SunPower (2019), the lifespan of the panels used in this analysis is 25 years. If the payback period is longer than the lifespan of the panels, then the PV system would have a negative value. The optimal configuration would determine if a homeowner adds an additional panel to their system, does that panel's savings offset its costs. If the panel can lower the payback period, then its benefits outweigh the panel's cost.

Results

Of the 74,793 single-family residences in

Minneapolis, 32,211 or 43.1% of them can have their annual electricity demands met by rooftop solar PV. 56.9% of buildings could not meet their annual electricity demands. Of the buildings that did not meet their demands, 14,108, or 18.9% of total buildings, were completely unsuitable and were unable to install a single panel within the model parameters. This is likely due to shading, as 13,701 buildings do not have any area that receives direct sunlight within this model's parameters.

As for the buildings that can generate electricity but are unable to meet the required output, a breakdown of how much more they would have needed is provided in Figure 4.

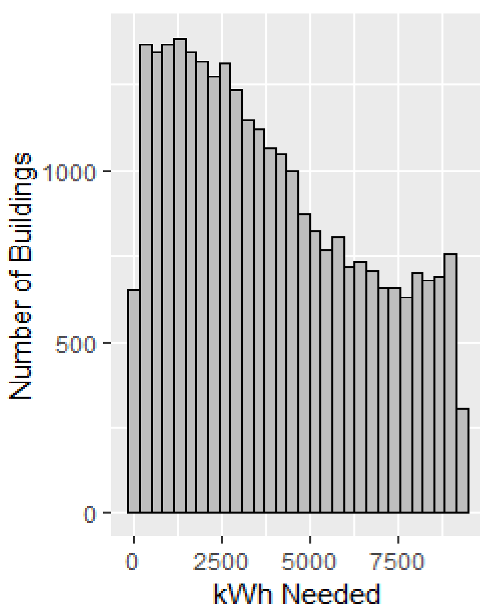

Figure 4. Distribution of buildings that do not meet their annual requirement with how many more kWhs are needed to meet that requirement. Buildings that cannot generate any electricity are excluded.

For buildings that do meet the energy requirement, the minimum number of panels needed ranges from 24 to 34 panels with a median of 26. The overall distribution of panels needed is right-skewed and the distribution of the number of panels needed can be found in Figure 5. For these same buildings, the minimum installation cost was $14,012 and the maximum was $19,851 with a mean cost of $15,534.

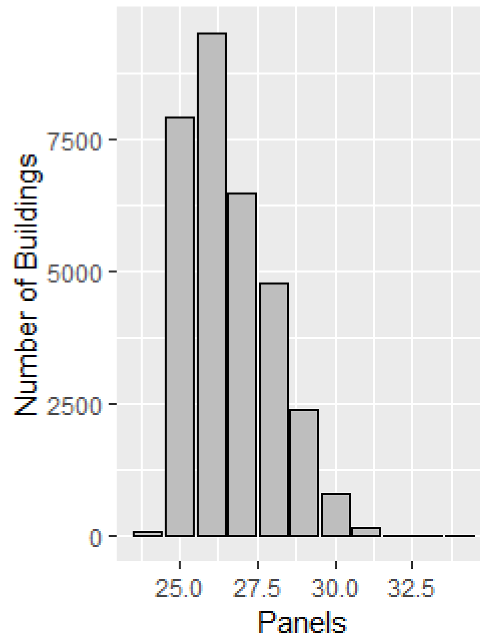

Figure 5. Distribution of buildings that meet their energy requirement with the minimum number of panels.

Finally, when evaluating the payback period, the minimum period was 13.4 years, the maximum was 18.9 years, and the mean was 14.7 years. Distribution of the payback period shows another right-skewed distribution where a majority of buildings require about 15 years of a payback period. The number of buildings gradually decreases as the payback period increases (Figure 6). According to PVWatts, the average lifespan of a PV panel is 25 years; all of the PV systems would recoup their costs in the lifespan of the system. While the financial analysis tried to find the optimal number of panels, there was not a single case in which the optimal number of panels was more than the minimum number of panels needed.

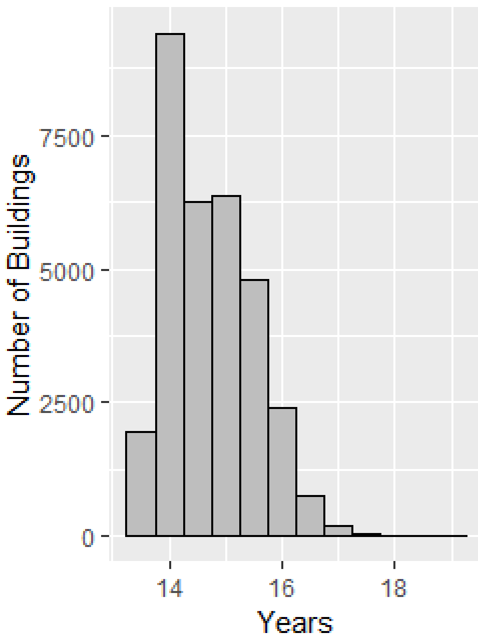

Figure 6. Distribution of payback periods for buildings that can meet their annual energy demands with solar PV.

Discussion

These results are largely positive in terms of solar adoption in Minneapolis. Of the 43% of residences that can meet their energy demands, all of them would have long-term economic benefits within the lifespan of the system. However, one issue with this is that for the homeowner to experience any of the economic benefits, they must own the property for the extent of their payback period. This can pose an issue to more transient residents.

If every residence that can meet their energy demands installed a PV system, then all these buildings combined can produce 309,700 MWh annually. This is equivalent to 11.5% of the annual output of the Allen S. King plant in Oak Park Heights, MN according to Xcel Energy (2019). The King Plant is one of largest coal-fired power plants in the state and is currently slated for retirement in 2028. This solar implementation also means that 302,220 tons of carbon is not released into the atmosphere due to coal emissions.

Sources for Error

One source of potential error in this project is the simplification of energy production and usage into annual amounts. The PVWatts model evaluates PV production on an energy produced per month basis and then sums the monthly amounts into an annual amount. The energy demand statistic from EIA is an average for an entire year. Like with all averages, the single average number does not provide any clarity for the entire range of values. Both PV production and energy demand fluctuate throughout the entire day. Kovač, Stegnar, Al-Mansour, Merše, and Pečjak (2019) state how solar panels can exceed the instantaneous demand during most periods of sunlight but produce nothing during nighttime. However, electricity is still needed by the home's occupants when the solar panels are not producing. One way to alleviate this disparity is with a battery storage system. When the solar panels are overproducing, the battery stores the excess electricity and disperses it when the panels are no longer producing. In this analysis, the cost of a battery storage system would increase the payback period in every simulation. However, if this analysis was able to look at the daily production and demands of a PV system, the benefits of a battery backup system could become more pronounced.

The largest limiting factor for a suitable roof location was shading. Only areas that received all 10 hours of direct sunlight in the parameters from Boz *et al.* (2015) were considered suitable. However, if those parameters were adjusted to include only areas that receive 9.5 hours of direct sunlight, the suitable roof area increases by 27.4%. These areas are still able to produce electricity however at a lower amount. Considering Figure 4 and the number of buildings that did not meet the energy threshold, the inclusion of more less-efficient panels might put some buildings over the threshold.

Consideration for Future Analysis

This analysis was performed using a single model of PV panel, the SunPower SPR-300E-WHT-D. This panel is rated for 300 watts which is about average for panels available at this time. However, there is a big range in panels varying in price and efficiency. An additional parameter to include in a future analysis would be to run the same analysis with different models of PV panels. Buildings with less suitable areas for an installation could benefit from more efficient panels. These more efficient panels would be able to generate the same amount of energy with less space. But that would come at a higher panel cost. Also, buildings with more suitable areas could install less efficient panels instead. This set-up would require more panels to meet demand but would come at a lower per panel cost.

When it comes to system costs, the cheapest system that can meet annual energy demands costs a projected $14,012. For some homeowners, this financial cost could be covered using a loan. Further analysis could incorporate loan interest in the financial model. Finally, the financial model that was used to calculate payback years assumes that electricity prices do not change. The inclusion of future electricity rate forecasting could be incorporated into a future analysis.

This project was focused on Minneapolis, Minnesota for residential rooftop PV installations, but the analysis could be expanded to other locations. Different regions of Minnesota can have similar energy demands but have slightly different climates. A future analysis could study which regions have the biggest potential for PV installations. The scope could also be broadened even further across the country. With a wide variety of climates and energy demands, future analyses can determine where in the country has the biggest economic potential for rooftop solar.

Conclusions

Rooftop solar PV can be economically viable in Minneapolis. For buildings that can meet their energy demands, all the systems had a long-term economic benefit over the lifespan of the panels. The potential benefits for homeowners would hopefully increase the number of installations in Minneapolis, therefore increasing the share of energy generated from renewable sources and utilizing Minnesota’s solar capacity.

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