Performance of solar photovoltaic (PV) installations in the city of Morris

An analysis of the performance of photovoltaic systems in public and private buildings within Morris.

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A collaborative project of the city of Morris, UMN Morris, UMN Southwest Regional Sustainable Development Partnership, UMN Institute on the Environment Climate Smart Municipalities and the FH Münster University of Applied Sciences,

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1 THE CITY OF MORRIS

In this section, a concise presentation of the city, its objectives, memberships, and the average energy consumption from the year 2017 is provided.

1.1 About the City of Morris

Morris is one of five communities in Stevens County, Minnesota. As of 2020, Morris has 5,101 people living in households within the city. (Explore Census Data Population in Morris city, Steven County, Minnesota, 2023), the town is surrounded by some of the nation's richest agricultural land and agribusiness, which are important to the local economy. The town is also home of the University of Minnesota Morris (UMN Morris). There are around 1,000 students enrolled at the campus. (University of Minnesota Morris , 2023)

Morris is partnered with Saerbeck, Germany. Saerbeck is a small rural community in North-Rhine Westphalia, much like Morris. Saerbeck is a leader in renewable energy and energy efficiency and was the first winner of the prestigious European Energy Prize. Saerbeck produces over 400% of the energy they need. (Morris Model Team, 2018)

The City of Morris is involved in several projects. The most influential ones are discussed below.

1.2 Morris Model

The Morris Model (morrismodel.org) is a group of community partners working together to advance their shared sustainability aspirations. The partners include the city of Morris, UMN Morris, Stevens County, Morris Area School District, UMN West Central Research and Outreach Center (WCROC), and several other organizations.

The Morris Model focuses its work on energy conservation, clean energy, community resilience, cultural exchange, and celebration. The Morris Model partnership has also identified some big goals they are collectively working towards. In 2023, the Morris Model team won the Department of Energy's Energizing Rural Communities Prize. (Home: Morris Model , 2023)

1.3 Climate Smart Municipalities

The City of Morris is also one of five communities in Minnesota that is participating in the Climate-Smart-Municipalities program led by the University of Minnesota Institute on the Environment.

Climate-Smart Municipalities (CSM) is a multi-partner intergenerational collaboration between Minnesota and Germany, with twelve cities at its core that have decided to pursue comprehensive sustainability and climate goals that generate measurable local benefits. The central topics of these programs are sustainability, climate protection, climate adaptation, renewable energy, and energy efficiency. (About: Climate-Smart Municipalities, 2023)

1.4 Goals of the City

The three primary goals of the city are: (Morris Model Team, 2018)

1. Produce 80% of the energy consumed in the county by 2030.
2. Reduce energy consumption by 30% by 2023.
3. No landfilling of waste generated within the county by 2025.

In more detailed discussion, the city has created specific subgoals for the first goal. Most notable of these is:

- Expand solar generation to 50% of public buildings and 25% of privately-owned homes.

The present report is based on this subgoal and describes in more detail the installation and performance of solar photovoltaic systems (PV systems) installed on four public buildings.

1.5 Energy consumption 2017

Morris consumes three main sources of energy:

- Electrical energy from Otter Tail Power Company
- Natural gas from Center Point Energy
- Gasoline from various gas stations

Energy consumption in numbers

In the year 2017,

- Morris used about 76,460,000 kWh/year of electrical energy.
- 1.3 million Therms/year of natural gas in 1,487 residentials units. (1.3M Therms = 46,880,177 MWh)
- 10.8 million Therms/year of natural gas in 267 commercial and industrial accounts. (10M Therms = 293,001,111 kWh)
- 2,100,000 gallons/year of gasoline are consumed by Morris's residents yearly.

For comparison, the UMN Morris campus is 1 million square feet in size and uses about 1 million Therms of natural gas each year and between 8-9M kWh of electrical energy. A home in Morris may use about 1,000 Therms each year and 10,000 kWh of electrical energy each year.

Morris is estimated to spend $17.5 million on energy yearly. The costs are distributed as follows: (Morris Model Team, 2018)

- $8.6 million/year on electrical energy
- $3.4 million/year on natural gas
- $5.5 million/year on gasoline

2 PV System Explanation & Performance Measures

2.1.1 A brief description of the operation of a photovoltaic (PV) system

A PV system has a few main components: a solar-panel generator, blocking diode, charge controller, inverter, and a consumer that has an electrical demand, also called a load. The structure is shown in Figure 1. In short, the PV system converts sunlight into electricity. The solar generator, consisting of photovoltaic panels, demonstrated in Figure 2, generates **direct current (DC-current)**, which is directed in one direction by a blocking diode to prevent unwanted current flow. The charge controller monitors and regulates the charging process. The charge controller charges the battery with current from the modules and protects the battery from overcharging or deep discharge. The charge controller and battery are optional hardware in a PV system. The inverter, illustrated in Figure 3, converts the direct current into **alternating current (AC-current)** to supply the consumer with electrical energy. A battery can be used to store excess energy and make electricity available when needed.

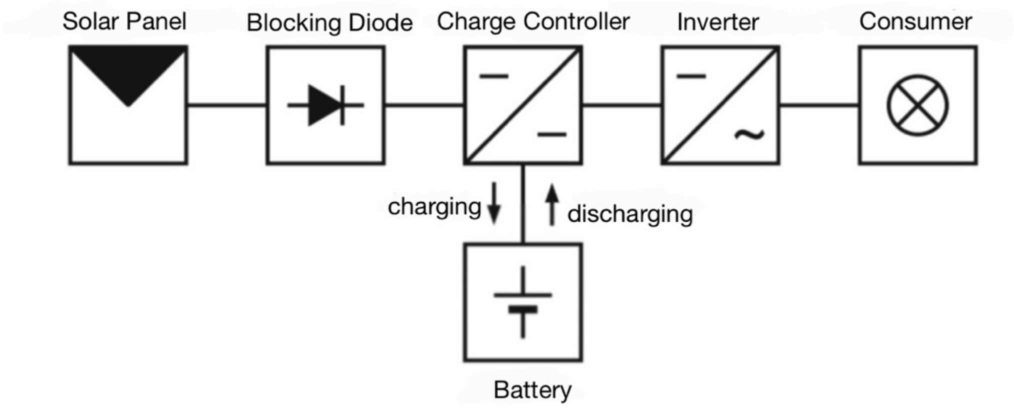

Figure 1: Circuit diagram of a photovoltaic island system *(Source: Wagner 2018)*

Figure 2: Example Picture: Solar Panel on a Roof *(Source: Luecken, 2023)*

Figure 3 shows what an inverter looks like in a PV system. This is a common inverter used in public buildings. Between 3 to 6 inverters are typically installed per PV system depending on the overall system performance.

Figure 3: Example Picture: Inverter Installation on a Wall *(Source: Luecken, 2023)*

2.2 Performance Ratio

The Performance Ratio (PR) is an independent metric for assessing the performance of solar PV systems. It measures the efficiency of energy conversion for an entire PV system.

PR is the ratio between the actual total energy of a PV system and the energy that could have been achieved on the module surface under standard test conditions.

In essence, the PR provides insights into the quality of a PV system and should not be confused with overall efficiency of the PV system. (Wagner, 2018)

$$PR = \frac{\textit{Total electricity generated by a PV system}\ [\frac{kWh}{year}]}{\textit{Total amount of solar energy hitting the panels in a year}\ \left[\frac{kWh}{year}\right]\ x\ \textit{efficiency of the modules}\ [\%]}$$

The following factors can have an influence on the PR value. (SMA Solar Technology AG, 2023)

- Environmental factors
    - Temperature of the PV panels
    - Solar radiation (the amount of sun hitting the panels) and power loss (the panels age and normally lose efficiency over time)
    - Shading or covering of PV panels (with dust, snow, etc.)
- Other factors
    - Line losses
    - Efficiency of the PV modules
    - Efficiency of the inverters

2.3 Full Load Hours

The full load hours of a PV system refer to ***the number of hours during which the system operates at its maximum capacity*** and generates its highest output of electricity. Full load hours are a key metric for assessing the system's efficiency and overall performance. It is good to know how many hours a solar PV system achieves its maximum potential during the year.

2.4 Degree of self-sufficiency

The degree of self-sufficiency of a PV system explores the following question: If all the PV-generated electrical energy connected to a building was used inside the building – then what percentage of the total electrical energy usage of the building would that be? However, since the consumption of electrical energy in a building does not always align with when solar electrical energy is produced, ***this measure is only a theoretical concept.*** Nevertheless, this measure provides insights into the effectiveness and expansion opportunities of an installed PV system. It is calculated by dividing the total PV-generated electrical energy during the year by the total electrical energy demanded by the building over the year.

3 About the installed Photovoltaic System

The following section discusses the components installed on the four Morris public buildings. Each PV system is built from components by the same manufacturers, with only the number of components varying from building to building.

3.1 Installed technology

3.1.1 Installed panels

On the roofs of each of the four public buildings**, the installed panels are made by the company Trina Solar**. Each panel is comprised of several modules and the modules are comprised of cells. The modules are available in a power range from 355 $W_{(Peak)}$ to 380 $W_{(Peak)}$ for each panel. The 132-Cell Monocrystalline module has a **maximum module efficiency of 20.6%.** (Trina Solar , 2023)

3.1.2 Installed inverters

Inverters play a crucial role in the PV system by converting the direct current (DC) generated by the PV modules or battery into the nominal alternating current (AC) that is required by the electrical loads. In residential settings, most electrical appliances operate on AC-voltage. Thus, the inverter converts DC-voltage into AC-voltage, enabling seamless integration with the household's electrical infrastructure.

For systems incorporating battery storage, it is important to install the battery storage unit before the inverters. This arrangement ensures that only DC-power, suitable for storage, is directed to the battery system, which optimizes energy storage efficiency, and enhances the overall performance of the PV system.

The installed inverters are from the company SMA. The inverter is available in different output powers from 3,000 W to 5,000 W. The maximum efficiency range is between 97.2% and 97.5%. (SMA Solar Technology AG, 2023)

3.1.3 A bit more explanation of a PV system: An Example

For the deployment of 1 kW photovoltaic (PV) system, equivalent to 1,000 Watt PV system, approximately three 355 W PV modules are requisite. Each module has a conversion of efficiency of around 21%, which means they can convert approximately 21% of the sunlight hitting the panels (also called incidental sunlight) into DC power. When the DC power is converted to AC power by the inverter, there will be an additional energy loss of approximately 3-4%.

3.2 Companies involved in the installation

3.2.1 About Blue Horizon Energy

Blue Horizon Energy is a full-service clean energy development company. Since 2009, they have helped hundreds of businesses and communities move toward a more sustainable future through clean energy. (About: Blue Horizon Energy, 2023)

In Morris, **Blue Horizon Energy took responsibility for the installation and connection of the PV systems** and all the necessary components.

3.2.2 About the Otter Tail Power Company

Otter Tail Power Company (OTP) is an electric utility with a balanced commitment to environmental, economic and community stewardship. Otter Tail Power Company serves more than a quarter of a million people in Minnesota, North Dakota, and South Dakota. OTP provided funds to help pay for the PV systems on each city building. Due this financial assistance, OTP owns the renewable energy credits – or RECs – for the solar project. (Our Companies: Otter Tail Corporation, 2023)

A bit of carbon neutrality accounting: exploring the difference between powering your building with renewables vs. getting to claim that your building is carbon neutral.

In Morris, OTP helped the city to pay for the solar installations on each building with their Public-Owned-Property (PoP) Solar program. Via the PoP program, OTP provided $1,500 per kilowatt (kW) of installed solar PV AC-nameplate capacity – up to 50% of project costs – for systems 40 kW or less in size.

For instance, upon the installation of a 40 kW AC-system, an allocation of $60,000 of financial support. In the year 2023, the prevailing cost of residential rooftop solar approximately $3 per Watt. Consequently, the total cost of an installed system is estimated to be around $120,000. In this context, the PoP Solar Program would cover the about the half of the cost of the system. It is important to know that there are new incentives in the Federal government's Inflation Reduction Act (IRA) that can cover 30% or more of the cost of solar projects.

For some projects, owing the renewable energy credits (RECs) is important. If one has the RECs, ownership of the carbon-neutral aspect of the electricity is established. A utility can engage in the sale of both electricity and RECs.

If OTP supports a project with PoP funds, then they also own the RECs, which means that the customer cannot claim they are using carbon-free electricity, only that they are using electricity generated by solar.

However, if a project is supported with IRA-funds or private funds, then the project owner can keep the RECs, and the project would be considered both carbon-neutral and powered by renewable solar. (Publicly Owned Property Solar: Otter Tail Power Company, 2023)

3.3 Prevailing conditions

3.3.1 Solar radiation

In Minnesota, the average solar radiation is 4.54 kWh/(m^2·day). Figure 4 shows the daily average irradiance over the course of the year for each month. On average 4.54 kilowatt-hours per square meter every day in Minnesota. Solar irradiance **nearly triples between January and July** in Minnesota.

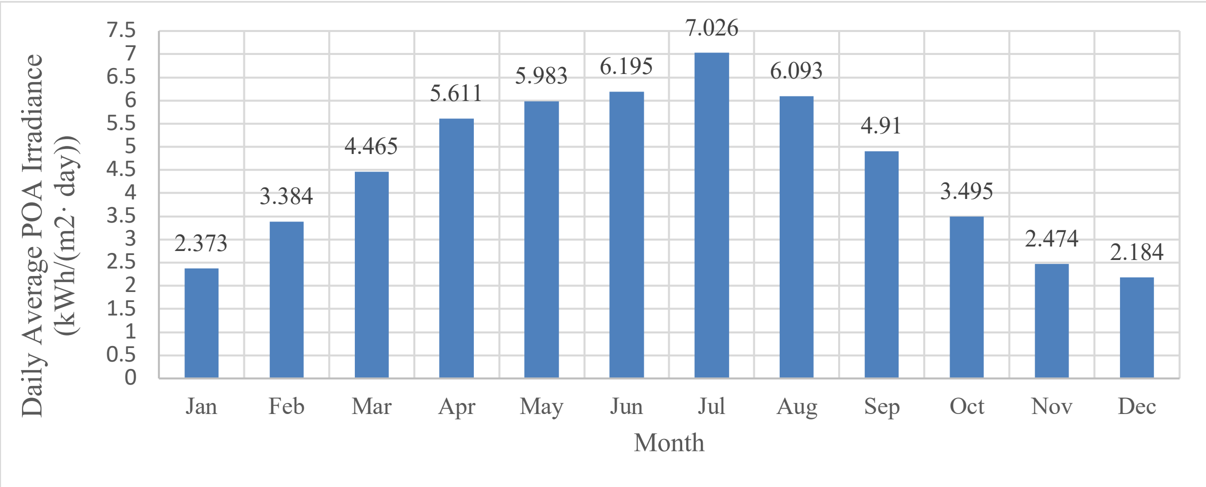

Figure 4: Daily average plane of area (POA) irradiance (kWh/(m^2·day)) over the year in Minnesota (Source: (NREL, 2023))

The average irradiation describes the average irradiation falling on the Earth's surface. **The amount of average irradiation converted into electrical or thermal energy depends on the panel efficiency and the panel area used to produce power.**

A typical panel efficiency for monocrystalline cells is between 16% and 24%. (Renewable & Sustainable Energy Reviews., 1997; 1997-2002; 2017)

3.3.2 Seasonal Limitations: Understanding the Usage Time Window of a PV system

Snow coverage of PV systems and the associated losses in energy production must also be accounted for due to the regular snowfall and accumulation in Morris. A PV system can be used to a limited extent in winter months, especially if snow is not removed. Many calculation tools do not take this into account. The losses in the snowy months can amount to 90%. Over the year, the total losses are between 1% and 12% according to a study from data obtained in Colorado and Wisconsin. (Marion , Schaefer , Chaine , & Sanchez, 2013)

4 THE FOUR PUBLIC BUILDINGS IN MORRIS WITH SOLAR PV SYSTEMS

In this section, a detailed investigation of the four public buildings is carried out. This includes a brief description of each PV system and its components. Various performance measures, including the electrical energy consumption and natural gas consumption (if available) in each building are shown in diagrams. Furthermore, a comparison between the solar-PV-generated electrical energy ***used by the building*** vs. the solar-PV-generated electrical energy ***fed into the grid*** is shown in a diagram. The theoretical electrical self-sufficiency of each building is also analyzed as a diagram.

4.1 Community Center

4.1.1 About the Building

The Community Center consumes **38,000 kWh of electrical energy** each year. The main consumer is the Heating, Ventilation and Air Conditioning (HVAC)-system. The **Community Center operates some month with over 100% self-produced electrical energy** from the PV system. Excess electrical energy is fed into the grid and the city is remunerated for every kWh that is fed into the grid. On Figure 5, the southside from the building with the solar panels is visible.

Figure 5: Picture of Community Center in Morris (Source: The City of Morris)

4.1.2 About the Photovoltaic system

The PV system is installed on a roof area of approximately 2,248 sq.ft. The 115 panels produce a DC-peak power around 41.98 kW. The outgoing AC-peak power is around 30.8 kW. Four inverters, each with a rating of 7.7 kW, work together to convert the power to AC.

4.1.3 Performance measures

Table 1 provides comprehensive performance measures of the PV system installed on the Community Center for the year 2022, including peak performance, energy consumption, energy production, overproduction fed into the grid, solar radiation over the year, degree of self-sufficiency, full-load hours, performance ratio, utilized area, and specific power. These data offer insights into the efficiency and performance of the photovoltaic system.

Table 1: Performance Measures of the PV system on the Community Center for the Year 2022 *(Source: The City of Morris, 2023)*

PERFORMANCE MEASURES		UNIT
PV SYSTEM: PEAK POWER DC	41.98	kWpeak
PV SYSTEM: PEAK POWER AC	30.8	kWpeak
EL. ENERGY CONSUMPTION 2022	49,843	kWh/yr
EL. ENERGY PRODUCTION 2022	35,822	kWh/yr
EL. ENERGY PV ENERGY USED DIRECTLY IN BUILDING 2022	16,082	kWh/yr
EL. ENERGY FROM OTHER SOURCES	33,761	kWh/yr
EL. OVER PRODUCTION 2022 → FED INTO GRID	19,740	kWh/yr
AVG. SOLAR RADIATION (YEARLY)	1649.9	kWh/(m²·yr)
DEGREE OF SELF-SUFFICENCY 2022	72%	%
PV SYSTEM: FULL-LOAD HOURS 2022	853.41	hr/yr
PV SYSTEM: PERFORMANCE RATIO 2022	50.36	%
USED AREA FOR THE PANELS	209	m²
USED AREA FOR THE PANELS	2.249	sq.ft
PV SYSTEM: SPECIFIC POWER	0.201	kWpeak/m²
PV SYSTEM: SPECIFIC POWER	0.019	kWpeak/sq.ft

4.1.4 A brief explanation of the performance measures

The **peak power DC** of a PV system is the highest DC-power output attainable by the PV modules under theoretically optimal conditions, prior to their conversion into AC.

The **peak power AC** of a PV system describes the maximum AC-power output achievable by the PV system under ideal circumstances, after the electricity is converted to AC-power by the inverters.

The **electrical energy consumption in the year** 2022 describes the electricity consumed by the building during the entire year.

Electrical energy production in 2022 describes the total amount of electricity generated by the PV system installed on the building during the entire year.

The **electrical energy from other sources** describes the total amount of electrical energy acquired from non-PV-sources, distinct from the energy produced by the PV system. **Specifically, this is power from the utility.**

Electrical overproduction refers to the surplus energy generated by the PV system that could not be utilized within the building due to insufficient demand and was consequently fed into the grid.

The **average solar radiation** characterizes the amount of kilowatt-hours per square meter received by the solar panel over the course of a year. Remember: not all this radiation can be effectively utilized by the panel; the panel efficiency describes the fraction of solar energy that can actually be converted into electrical energy.

The **degree of self-sufficiency** describes the extent to which the yearly electrical needs of a building could be theoretically fulfilled by the total electrical energy production from the PV system. The reason this measure is theoretical is because a building does not always demand power at the exact same time as when the solar panels are producing electricity.

The **full-use hours** indicate the number of hours during the year when a system operated at its maximum production.

The **performance ratio** of a PV system assesses the efficiency and overall performance of a system. It is calculated by dividing the total observed PV-generated electrical energy each year by the total amount of electrical energy the PV system ***could have theoretically produced under ideal conditions*** over a year. This measure helps make comparisons of PV systems at different locations and sizes and allows a meaningful evaluation of their effectiveness.

The **used area** describes the total surface area occupied by the installed panels of the system, expressed in square meters (m^2) or square feet (sq.ft.)

The **specific power** is calculated by dividing the peak performance DC by the used area. It yields a numerical value that allows for the assessment of a system's performance.

4.1.5 Energy consumption of the Community Center

Figure 6 shows the electrical energy consumption of the Community Center from January 2020 to February 2023, measured in kWh. The installation date of the PV system has been incorporated into the diagram. The red bars represent the electrical energy purchased from the utility. The blue bars represent the PV-generated electrical energy used by the building. Notice that electrical energy consumption is higher during the summer months compared to the winter months. This difference can be attributed to the presence of air-conditioning systems installed within the building, resulting in increased energy demand.

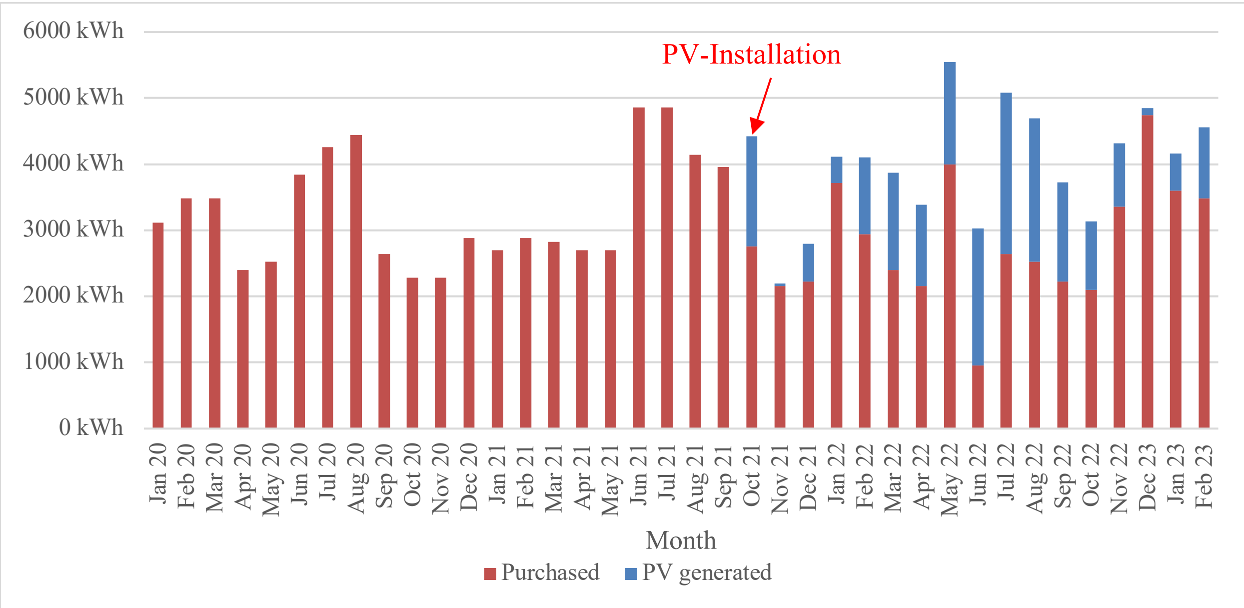

Figure 6: Electrical consumption (kWh) of the Community Center per month. From January 2020 to February 2023. *(Source: The City of Morris, 2023)*

Figure 7 compares the amount of PV-generated electrical energy consumed within the building versus the electrical energy fed into the grid, represented in percentages, in the year 2022. It can be observed that during the winter months, most of the energy is injected into the grid. This is because the main electrical consumers, the air-conditioning systems, are not operational during winter months. Additionally, in December, the building was less occupied due to the holiday season.

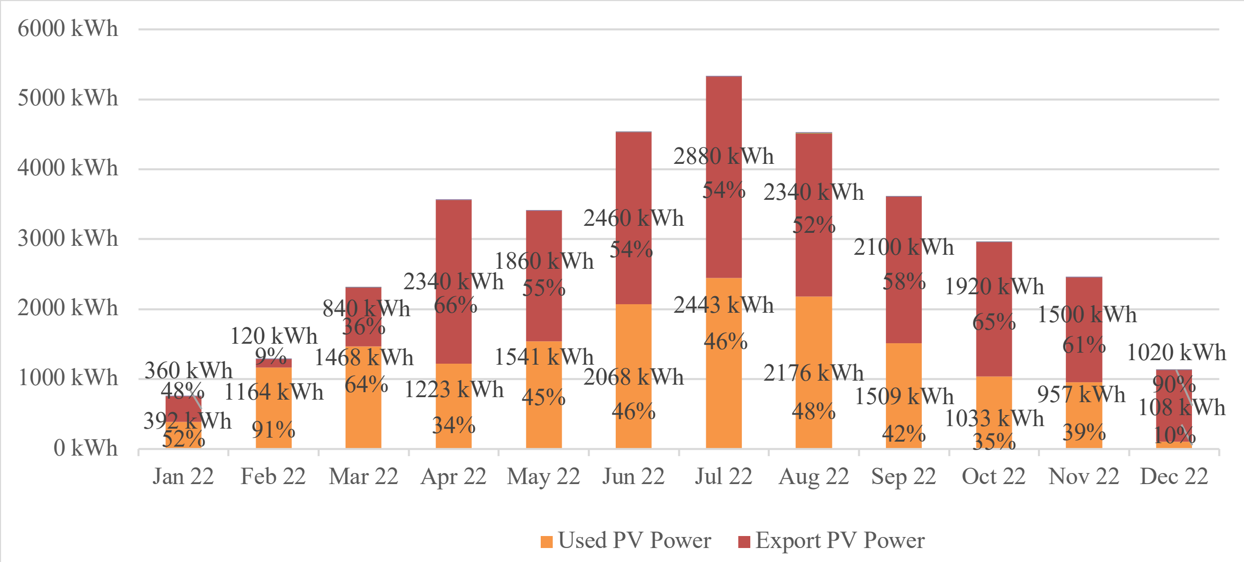

Figure 7: Analysis of PV-Generated Electrical Energy: Consumption and Export Proportions for the Community Center in 2022, in kWh and Percentage. *(Source: The City of Morris, 2023)*

Figure 8 illustrates the percentage of (theoretical) self-sufficiency in electrical energy from October 2021 to January 2023. The self-sufficiency is highest during the summer months, attributed to increased solar irradiation. In contrast, the electrical energy self-sufficiency is lowest during winter months due to snow-covered panels and reduced solar irradiation. Keep in mind that this is only a theoretical number because not all the PV-produced electrical energy can be used at the same time it is produced in the building, some of the produced electrical energy was exported to the grid. The calculation included all the total produced electrical energy. Additionally, the building was not in normal operation at its usual capacity during the months affected by the COVID-19 pandemic, which impacts the electrical self-sufficiency rate.

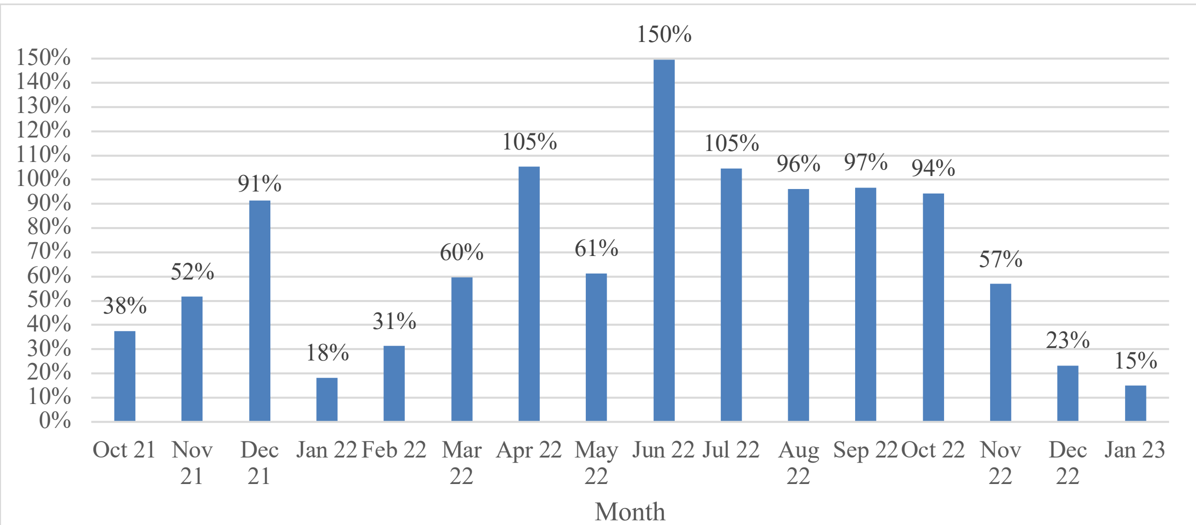

Figure 8: Electrical Self-Sufficiency of the Community Center: A Percentage Analysis Since the Installation of the PV System (from October 2021 to January 2023.) *(Source: The City of Morris, 2023)*

Figure 9 shows the natural gas consumption from January 2020 to January 2023, measured in Therms and kWh. Consumption reaches its peak during the winter months due to building heating, while in the summer months, a small portion of gas is also consumed, primarily attributed to the utilization of gas stoves.

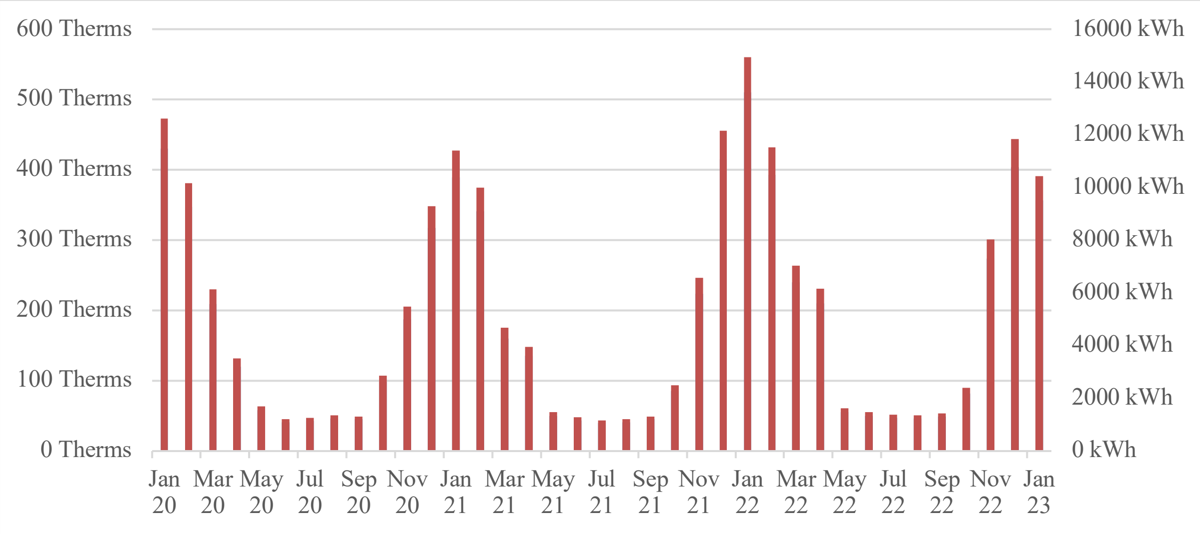

Figure 9: Natural Gas consumption of the Community Center in Therms and kWh from January 2020 to January 2023. *(Source: The City of Morris, 2023)*

Figure 10 showcases a combination of electrical consumption and natural gas consumption, with the natural gas consumption **converted into the unit of kWh (1 Therm = 29.3 kWh)**. It provides an overview of the total energy consumption of the building. The graph prominently displays the peaks in electrical demand caused by the air-conditioning system and the corresponding peaks in gas consumption resulting from heating during the winter months.

For instance, during January 2022, the building's energy consumption was 3,120 kWh of electrical energy and 430 Therms of natural gas. Considering that one Therm is equivalent to 29.3 kWh, the total energy consumption of the building can be calculated as 3,120 kWh + (430 Therms · 29.3 kWh/Therm) = 15,719 kWh. The diagram visually depicts the distribution of this total energy consumption. **Over the course of the year 2022, energy used for heating is 51% of the total energy used in the building, and electrical energy is about 49%.**

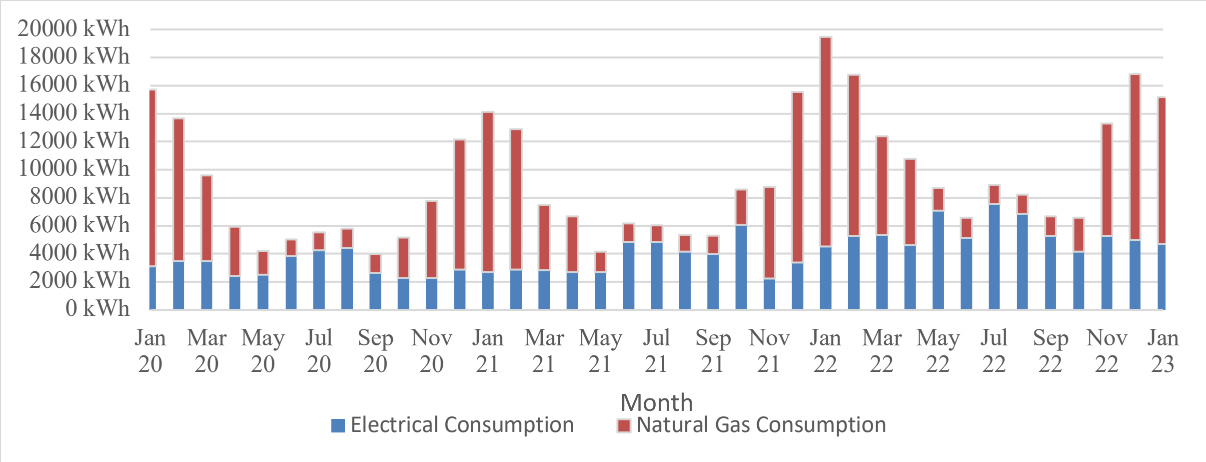

Figure 10: Total energy consumption in kWh of the Community Center. From January 2020 to January 2023 *(Source: The City of Morris, 2023)*

4.2 Library

The public library is located at 102 East Sixth Street, Morris, MN 56267. On Figure 11 the Library with the installed solar panels is visible.

Figure 11: Picture of Public Library in Morris (Source: City of Morris, 2023)

4.2.1 About the Building

The library consumes **134,000 kWh of electrical energy** each year. The main electrical load of the building is the heating system. **Both the heating and cooling systems are geothermal.** Pumps run constantly to move water from the building into wells in the ground and then back to the building.

4.2.2 About the photovoltaic system

The PV system installed on the roof is approximately 2,605 sq.ft. The 133 panels produce DC-peak power around 48.54 kW. The outgoing AC-peak power is approximately 36 kW. Six inverters with a capacity of 6.0 kW each invert the power to AC.

4.2.3 Performance measures of the library

Table 2 provides comprehensive performance measures of the PV system that is installed on the Library for the year 2022, including peak performance, energy consumption, energy production, overproduced electrical fed into the grid, solar radiation over the year, degree of self-sufficiency, full-load hours, performance ratio, utilized area, and specific power. These data offer insights into the efficiency and performance of the PV system.

Table 2: Performance Measures of the PV system on the Library for the Year 2022 *(Source: The City of Morris, 2023)*

PERFORMANCE FIGURES		UNIT
PV SYSTEM: PEAK POWER DC	48.55	kWpeak
PV SYSTEM: PEAK POWER AC	36	kWpeak
EL. ENERGY CONSUMPTION (JUNE 2022 TO JUNE 2023)	134,520	kWh/yr
EL. ENERGY PRODUCTION (JUNE 2022 TO JUNE 2023)	39,107	kWh/yr
EL. ENERGY FROM OTHER SOURCES (JUNE 2022 TO JUNE 2023)	113,520	kWh/yr
EL. OVER PRODUCTION (JUNE 2022 TO JUNE 2023) → FED INTO GRID	9,200	kWh/yr
AVG. SOLAR RADIATION (YEARLY)	1,649.9	kWh/(m^2·yr)
DEGREE OF SELF-SUFFICIENCY (FROM JUNE 2022 TO JUNE 2023)	29	%
PV SYSTEM: FULL-LOAD HOURS 2022	805.58	hr/yr
PV SYSTEM: PERFORMANCE RATIO (FROM JUNE 2022 TO JUNE 2023)	29	%
USED AREA FOR THE PANELS	242	m^2
USED AREA FOR THE PANELS	2,605	sq.ft
PV SYSTEM: SPECIFIC POWER	0.201	kWpeak/m^2
PV SYSTEM: SPECIFIC POWER	0.019	kWpeak/sq.ft

It may be useful to unpack this table. The system is sized about 48 kW DC-peak power. But the inverters won't allow more than 36 kW AC to be produced. The building consumes 134,520 kWh each year. The PV system produced nearly 39,107 kWh during a year. About 9,200 kWh were “fed into the grid” and sold to OTP. This is because all the electrical energy produced by the panels was not needed by the building during some times during the year. The library achieved a theoretical degree of self-sufficiency of about 29% from the solar panels on top of the building, which fill about 2,605 sq.ft. of the roof. Keep in mind, there are 8,760 hours in a year - and for 805.58 hours the system was producing its maximum power, which is 36 kW.

4.2.4 Energy consumption of the library

Figure 12 shows the energy consumption of the library in kWh, from January 2020 to June 2023. The installation date of the PV system was included in the diagram, which occurred during June 2022. The electrical energy purchased from the utility is shown in blue. The PV-generated electrical energy used by the building is shown in red. Clearly, electrical energy consumption is highest during winter months. This is because the geothermal heating system uses electrical energy to run pumps and motors that move the fluid between the building and ground.

For example, in June 2022, the building used 8,120 kWh of electrical energy in total. 3,040 kWh were generated by the PV system and consumed in the building, while the remaining 5,080 kWh were purchased from the from utility.

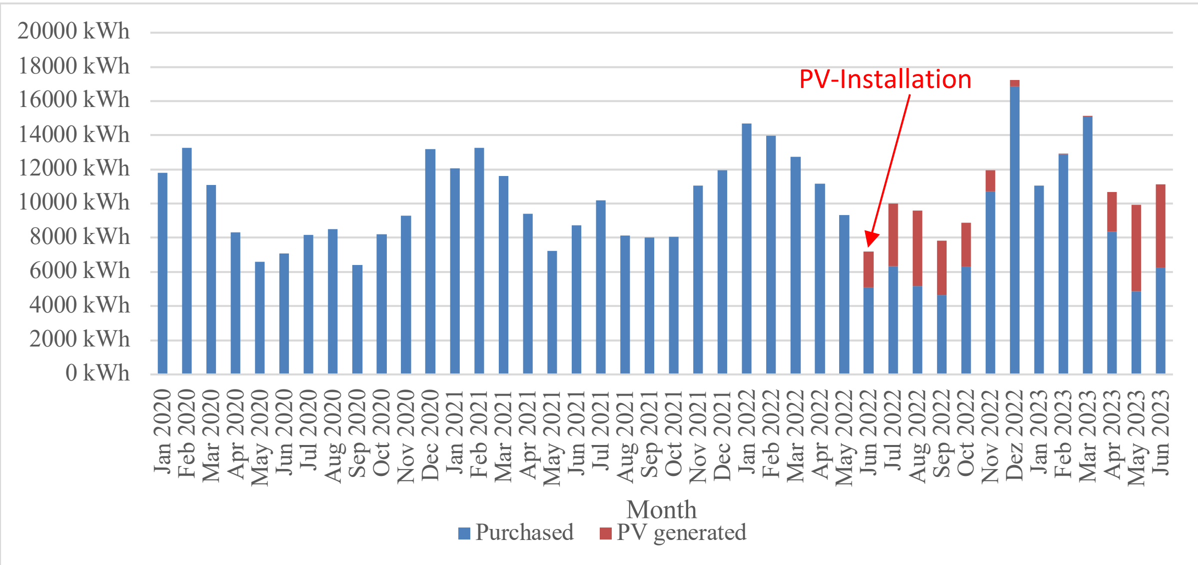

Figure 12: Electrical consumption of the Library in kWh from January 2020 to January 2023. *(Source: The City of Morris, 2023)*

Figure 13 examines the amount of PV-generated electrical energy used by the building versus the amount of PV-generated electrical energy that was fed into the grid. Notice that during winter months a very minimal amount or even no portion of energy was fed into the grid.

In June 2022, the PV system generated a total of 3,040 kWh. Out of this PV-generated amount, 2,120 kWh were directly utilized within the building, while 920 kWh remained unused and were subsequently fed into the grid. So, in June 2022, approximately 70% of the energy generated by the PV system was consumed within the building, and the remaining 30% was injected into the grid.

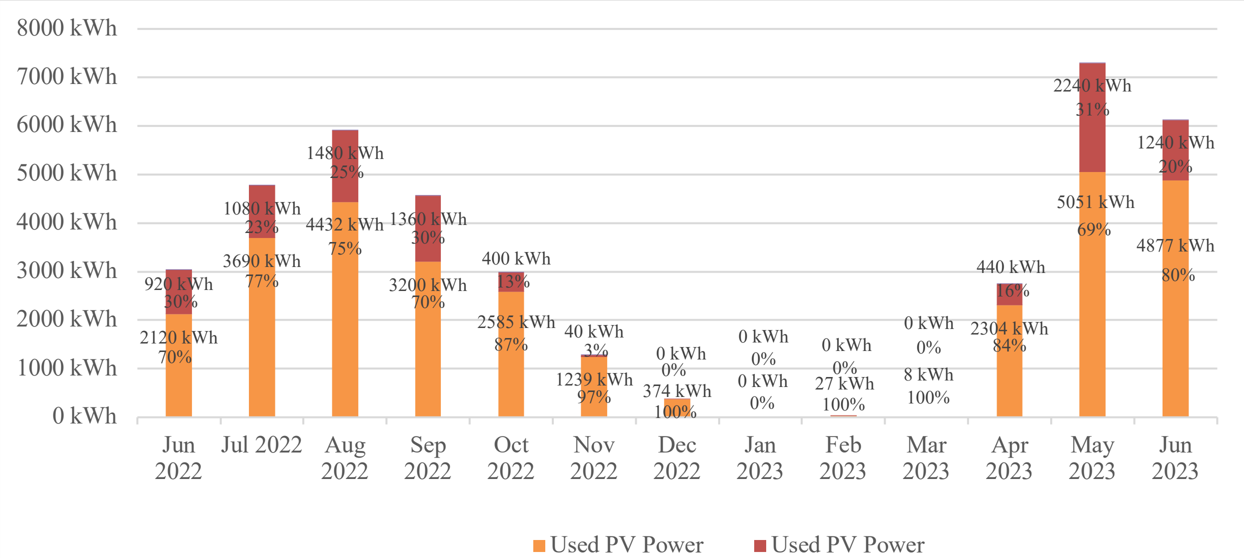

Figure 13: Analysis of PV-Generated Electrical Energy: Consumption and Export Proportions for the Library, in kWh and Percentage from June 2022 to June 2023. *(Source: The City of Morris, 2023)*

Figure 14 illustrates the percentage of self-sufficiency in electrical energy from June 2022 to June 2023. Self-sufficiency is highest during the summer months, because of increased solar irradiation. In contrast, the electrical self-sufficiency is lowest during winter months due to snow-covered panels and reduced solar irradiation. Again, it is important to note that this is only a theoretical number because all the PV-produced electrical energy is not always needed by the building at every moment the electrical energy is produced - so some of the PV-produced electrical energy was exported to the grid. The calculation included all the PV-produced electricity. Additionally, the building was not in normal operation at its usual capacity during the months affected by the COVID-19 pandemic, which impacts the electrical self-sufficiency calculation.

Examining June 2022 again, the building's total electrical energy consumption was 7,200 kWh, while the PV system generated 3,040 kWh during the same period. Consequently, 42% of the electrical energy used by the building originated from the PV system. It is important to note that this calculation is based on the total production of the PV system, including the PV-generated electrical energy that remained unused within the building.

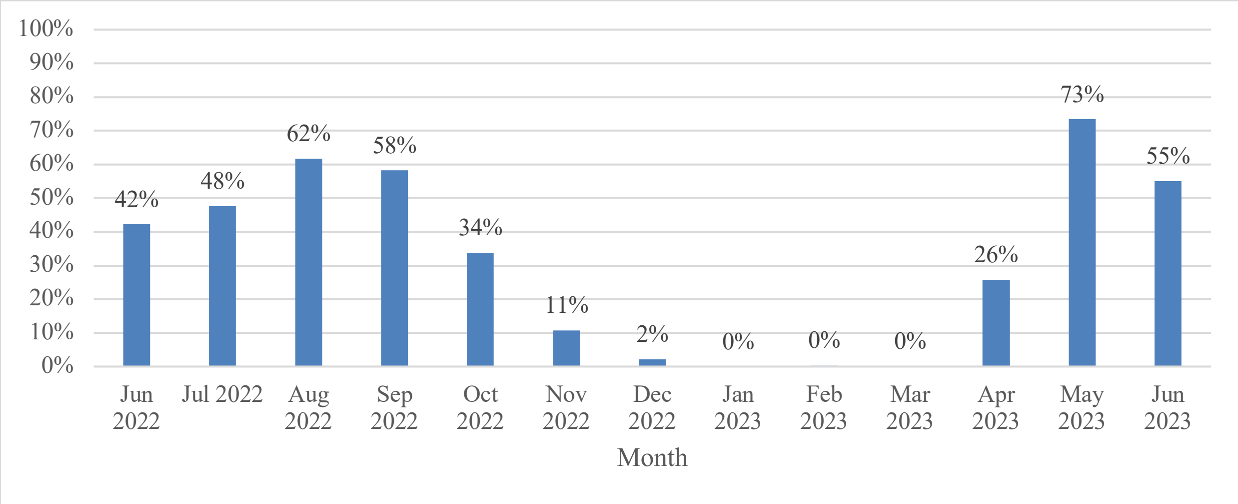

Figure 14: Electrical Self-Sufficiency of the Library: A Percentage Analysis Since the Installation of the PV System from June 2022 to June 2023. *(Source: The City of Morris, 2023)*

4.3 Municipal Liquor Store

The Morris Liquor store is a municipally owned liquor store at 14 East 5th Street. The profits from the liquor store are used by the city to provide additional resources for the store and support other operations of the city as needed. According to state statues, the city of Morris has the sole authority to sell liquor off-sale in the city. The city manager is responsible overall for the operation of the city and the liquor store, but the store is operated by the liquor store manager. (The City of Morris Minnesota, 2023). Figure 15 shows the south and west sides of the building with the installed solar panels on the roof. Some refrigeration machines are visible on the right side between the Liquor Store and the red shed.

Figure 15: Picture of the Municipal Liquor Store (Source: City of Morris)

4.3.1 About the Building

The Municipal Liquor Store consumes **98,000 kWh of electrical energy** each year. The main consumers of the building are the refrigeration systems. Refrigeration is necessary to keep store products at the desired temperature. **One interesting feature of the building is that waste heat from the chillers essentially heats the entire building.**

4.3.2 About the Photovoltaic system

The PV system installed on the roof covers approximately 1,410.5 sq.ft. The 72 panels produce a direct current DC-peak power around 26.28 kW. The outcoming alternating current AC-peak power is about 23.1 kW. Three inverters with a rating of 7.7 kW each invert the power to alternating current.

4.3.3 Performance measures

Table 3 provides comprehensive performance measures of the photovoltaic system installed on the Municipal Liquor Store for the year 2022, including peak performance, energy consumption, energy production, overproduction with grid feed-in, solar radiation over the year, degree of self-sufficiency, full-load hours, performance ratio, utilized area, and specific power. These data offer insights into the efficiency and performance of the PV system.

Table 3: Performance Measures of the PV system on the Municipal Liquor Store for the Year 2022 *(Source: The City of Morris, 2023)*

PERFORMANCE MEASURES		UNIT
PV SYSTEM: PEAK POWER DC	26.28	kWpeak
PV SYSTEM: PEAK POWER AC	23.10	kWpeak
EL. ENERGY CONSUMPTION 2022	98,557	kWh/yr
EL. ENERGY PRODUCTION 2022	28,171	kWh/yr
EL. ENERGY PV ENERGY USED DIRECTLY IN BUILDING 2022	25,226	kWh/yr
EL. ENERGY FROM OTHER SOURCES	73,331	kWh/yr
EL. OVER PRODUCTION 2022 → FED INTO GRID	2,945	kWh/yr
AVG.SOLAR RADIATION (YEARLY)	1649.9	kWh/(m^2·yr)
DEGREE OF SELF-SUFFICIENCY 2022	29%	%
PV SYSTEM: FULL-LOAD HOURS 2022	1,071.96	hr/yr
PV SYSTEM: PERFORMANCE RATIO 2022	63.25	%
USED AREA FOR THE PANELS	131.04	m^2
USED AREA FOR THE PANELS	1,410.5	sq.ft
PV SYSTEM: SPECIFIC POWER	0.2005	kWpeak/m^2
PV SYSTEM: SPECIFIC POWER	0.0186	kWpeak/sq.ft

4.3.4 Energy consumption of the Municipal Liquor Store

Figure 16 shows the energy consumption of the Municipal Liquor Store from January 2020 to February 2023, measured in kWh. The installation date of the PV system is included in the diagram. The red bars represent the electrical energy purchased from the utility. The blue bars represent the PV-generated electrical energy used by the building. We can see the electrical energy consumption is relatively higher during the summer months compared to the winter months.

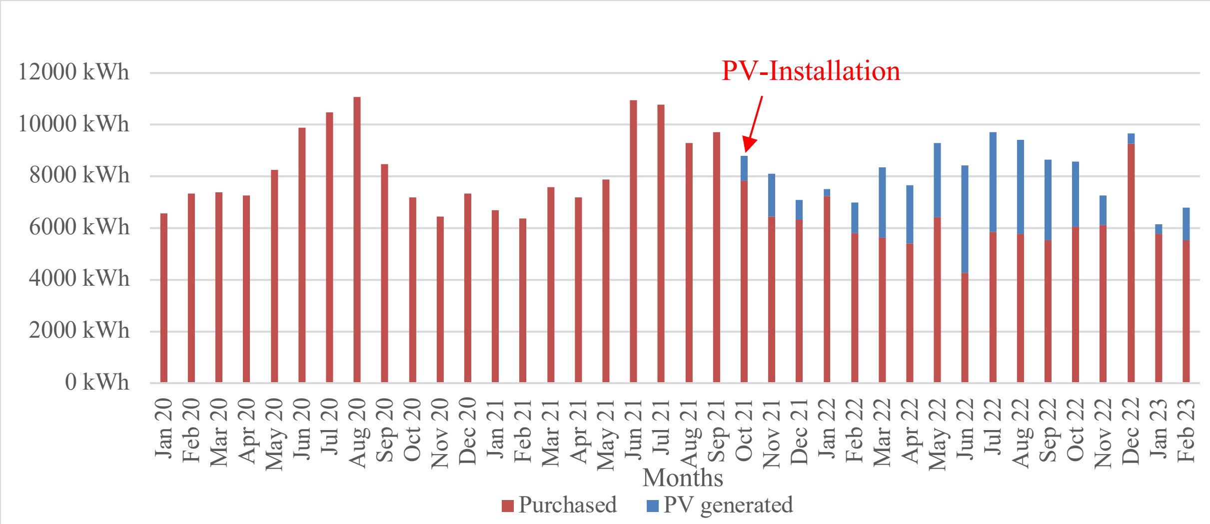

Figure 16: Electrical consumption (kWh) of Municipal Liquor Store from January 2020 to February 2023. *(Source: The City of Morris,2023)*

Figure 17 illustrates the comparison between the PV-generated electrical energy consumed within the building and the PV-generated electrical energy fed into the grid, depicted as percentages, in the year 2022. It is evident that only a very small proportion of the electricity generated on top of the building is fed into the grid. This can be attributed to the continuous operation of the refrigeration systems, even during the winter months. The electrical energy consumption of the building is significantly higher due to the presence of these refrigeration systems, particularly compared to other public buildings.

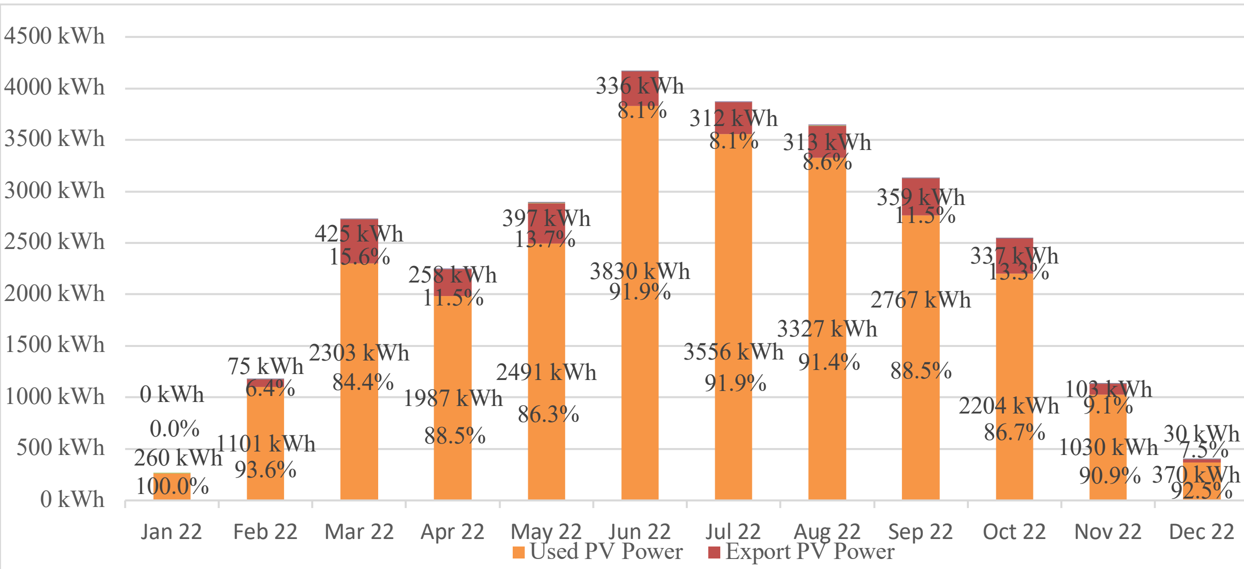

Figure 17: Analysis of PV-Generated Electrical Energy: Consumption and Export Proportions for the Liquor Store from January 2022 to December 2022, in kWh and Percentage. *(Source: The City of Morris, 2023)*

Figure 18 shows the percentage of electrical self-sufficiency from October 2021 to January 2023. Electrical self-sufficiency is highest in the summer months, which is due to increased solar radiation. In contrast, the electrical self-sufficiency is lowest in the winter months, which is due to snow-covered panels and lower solar radiation.

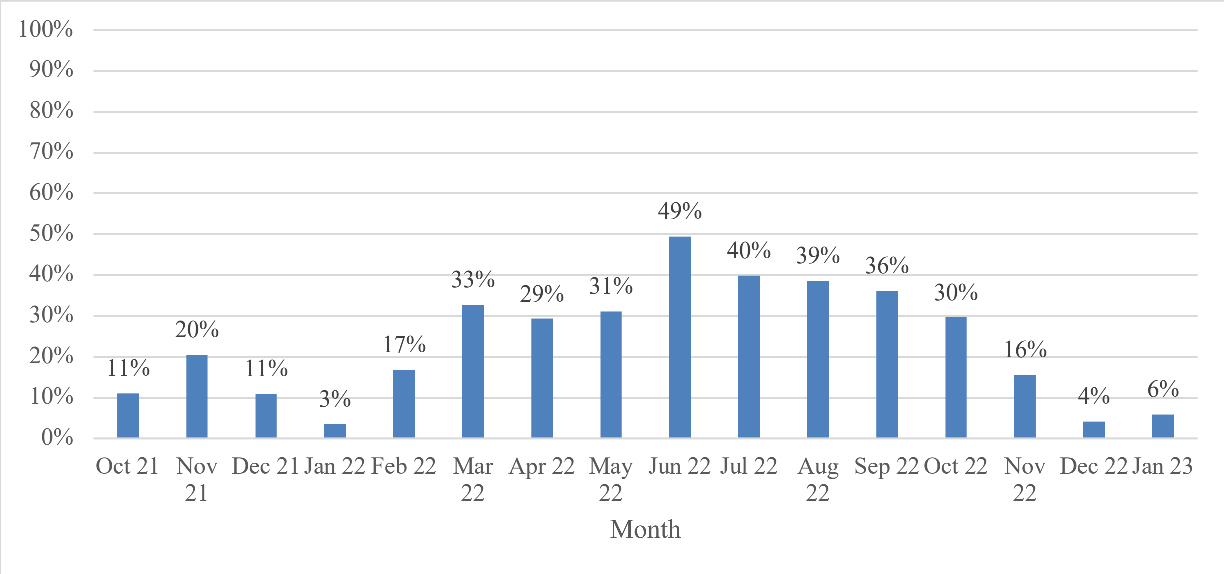

Figure 18: Electrical Self-Sufficiency of the Municipal Liquor Store: A Percentage Analysis Since the Installation of the PV System from October 2021 to January 2023. *(Source: The City of Morris, 2023)*

Figure 19 shows the natural gas consumption from January 2020 to January 2023, measured in Therms. Natural Gas consumption reaches its peak during the winter months due to building heating. The building is not heated during summer months, resulting in relatively low gas consumption. Waste heat from the refrigeration systems helps provide heat in winter but must be removed from the building with air-conditioning in the summer.

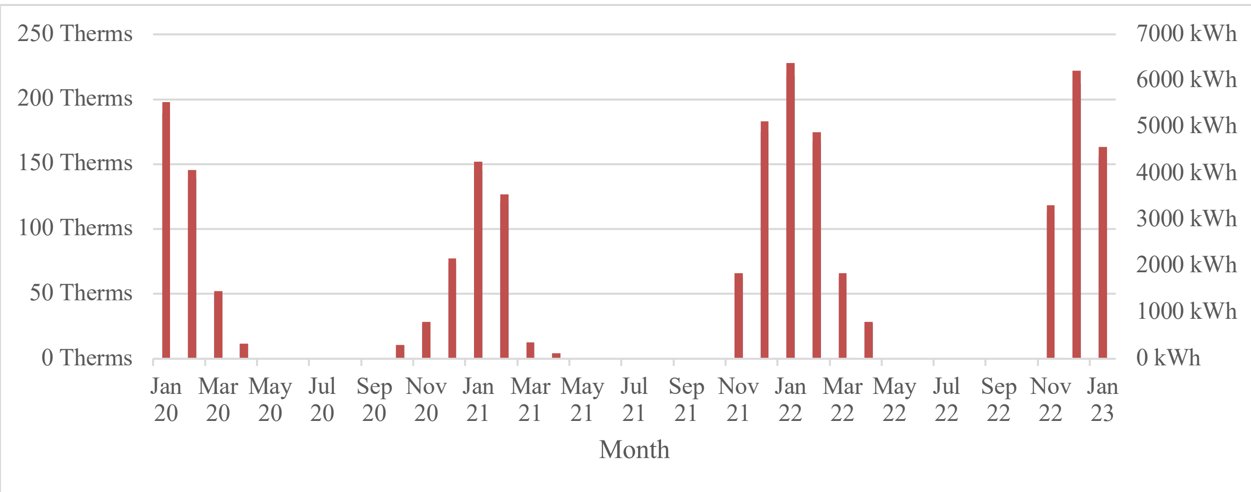

Figure 19: Natural Gas (Therms and kWh) consumption of the Liquor Store per month. From January 2020 to January 2023 *(Source: The City of Morris, 2023)*

Figure 20 shows a combination of electrical energy and natural gas consumption, with natural gas consumption converted into kWh (1 Therm = 29.3 kWh). It provides an overview of overall energy consumption in the building. The diagram also highlights a significant increase in electrical energy consumption during the summer months, which can be attributed to rising energy demand because of higher temperatures, and the increased demand put on the air-conditioning system. The comparatively low consumption of natural gas in the building is clear in this diagram. Again, this is because waste heat from the refrigeration system provides heat to the building in winter but must be removed in the summer. **Over the course of the year 2022, energy used for heating is 16% of the total energy used in the building, and electrical energy is 84%.**

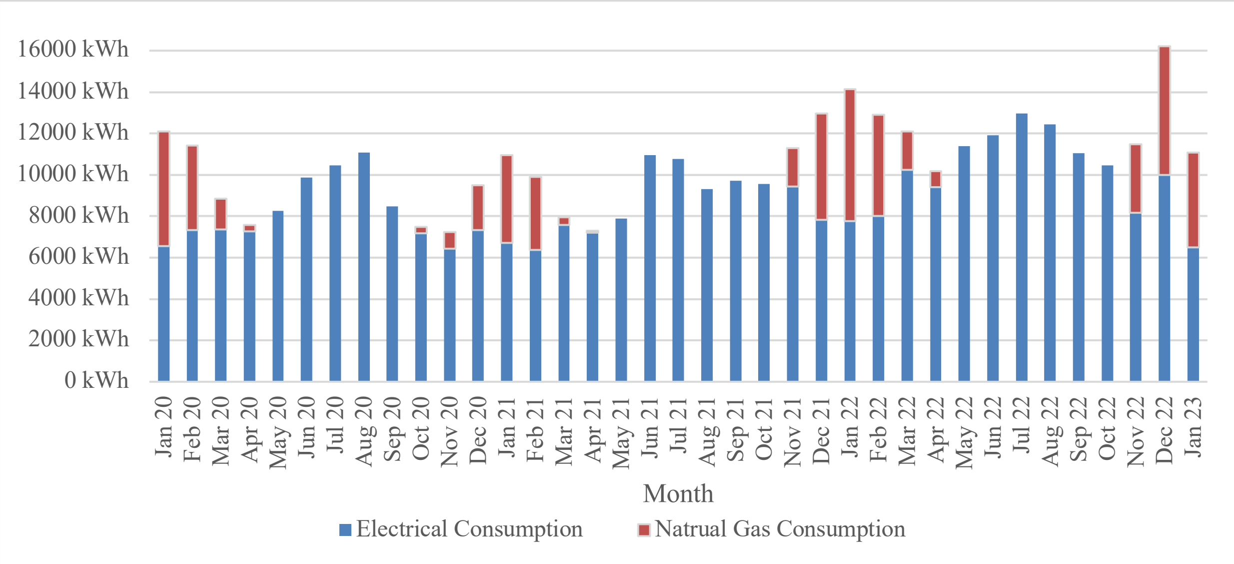

Figure 20: Total energy consumption in kWh of the Municipal Liquor Store from January 2020 to January 2023. *(Source: The City of Morris, 2023)*

4.4 City Hall

4.4.1 About the Building

City Hall consumes **17,500 kWh of electrical energy** each year. The main consumers of the building's electrical needs are the HVAC-system and a server that is in the building. City Hall operates most of the time with 100% self-produced electrical energy from the PV system. Excess electrical energy is fed into the grid. Figure 21 shows the roof from the City Hall with the installed solar panels. On the wall there are also the inverters visible. The outdoor units of the air conditioning system can also be seen on the roof.

Figure 21: Picture of the City Hall (Source: City of Morris, 2023)

4.4.2 About the Photovoltaic system

The PV system installed on the roof covers approximately 1,802 sq.ft. The 92 panels produce a DC-peak power around 33.58 kW. The outcoming AC-peak power is about 23.1 kW. Three inverters with a rating of 7.7 kW each invert the power to AC.

4.4.3 Performance measures

Table 4 provides comprehensive performance measures of the PV system installed on City Hall for the year 2022, including peak performance, energy consumption, energy production, overproduction with grid feed-in, solar radiation over the year, degree of self-sufficiency, full-load hours, performance ratio, utilized area, and specific power. These data offer insights into the efficiency and performance of the PV system.

Table 4: Performance Measures of the PV system on the City Hall for the Year 2022. *(Source: The City of Morris, 2023)*

PERFORMANCE MEASURES		UNIT
PV SYSTEM: PEAK POWER DC	33.58	kWpeak
PV SYSTEM: PEAK POWER AC	23.10	kWpeak
EL. ENERGY CONSUMPTION 2022	16,367	kWh/yr
EL. ENERGY PRODUCTION 2022	32,232	kWh/yr
EL. ENERGY PV ENERGY USED DIRECTLY IN BUILDING 2022	8,389	kWh/yr
EL. ENERGY FROM OTHER SOURCES 2022	7,978	kWh/yr
EL. OVER PRODUCTION 2022 → FED INTO GRID	23,843	kWh/yr
AVG.SOLAR RADIATION (YEARLY)	1649.9	$kWh/(m^2 \cdot yr)$
DEGREE OF SELF- SUFFICIENCY 2022	197%	%
PV SYSTEM: FULL-LOAD HOURS 2022	959.86	hr
PV SYSTEM: PERFORMANCE RATIO 2022	56.64	%
USED AREA FOR THE PANELS	167.4	m^2
USED AREA FOR THE PANELS	1,802	sq.ft
PV SYSTEM: SPECIFIC POWER	0.157	$kWpeak/m^2$
PV SYSTEM: SPECIFIC POWER	0.0146	kWpeak/sq.ft

4.4.4 Energy consumption of City Hall over several months

Figure 22 shows the energy consumption of the City Hall from January 2020 to February 2023, measured in kWh. The charts show the installation date of the PV system. The red colors represent the electrical energy used from the utility. The blue bars represent the PV-generated electrical energy used by the building. Notice that electrical energy consumption is relatively higher during the summer months compared to the winter months. This difference can be attributed to the presence of air-conditioning systems installed within the building, resulting in increased energy demand. In Figure 22, it is evident that approximately 50% of the electrical energy in generated by the PV System during the period from March 2022 to September 2022. This is due to the increased solar radiation in summer.

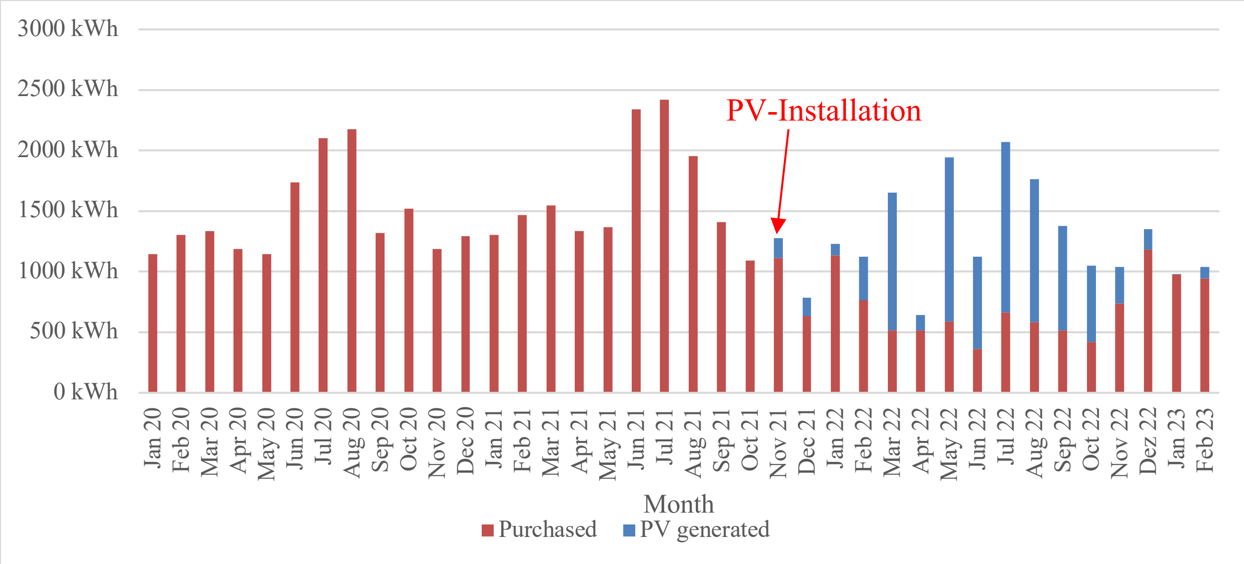

Figure 22: Electrical consumption of City Hall in kWh from January 2020 to February 2023. *(Source: The City of Morris, 2023)*

Figure 23 compares the electrical energy consumed in the building versus the energy fed into the grid, shown as a percentage, in the year 2022. A significant amount of the electrical energy generated by the PV system on the roof of City Hall is fed into the grid. From March 2022 until November 2022, 10 months, about 70% of the electrical energy produced by the PV system is fed into the grid and not used in the building.

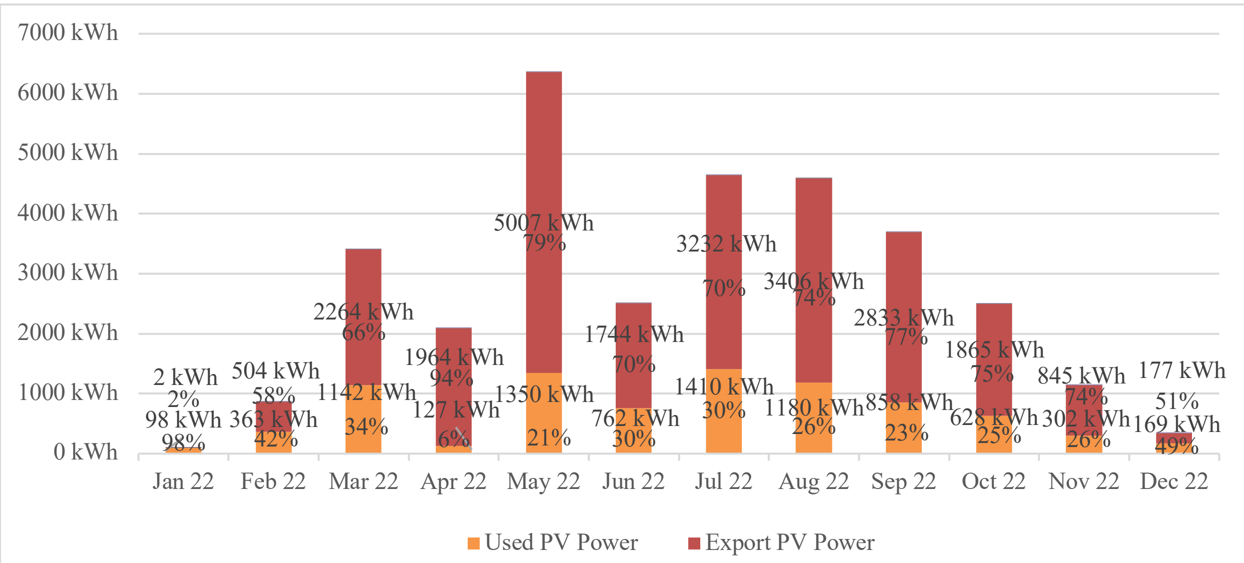

Figure 23: Analysis of PV-Generated Electrical Energy: Consumption and Export Proportions for City Hall in 2022, in kWh and Percentage. *(Source: The City of Morris, 2023)*

Figure 24 shows the percentage of electrical self-sufficiency from November 2021 to January 2023. The electrical energy self-sufficiency is highest in summer months, as expected, due to higher solar irradiation on the panels. Summer is sunny in Minnesota. In contrast, self-sufficiency in electrical energy is lowest during the winter months, primarily due to snow-covered panels and reduced solar irradiation. City Hall uses much less electrical energy than the other public buildings. For 8 months, March 2022 to October 2022, the building is more than 80% self-sufficient. The city of Morris has a big goal to produce about the same amount of PV-generated electrical energy they would purchase from the utility. This building reflects progress towards that goal. In this dataset, the city did not clear snow from the PV panels on the roof.

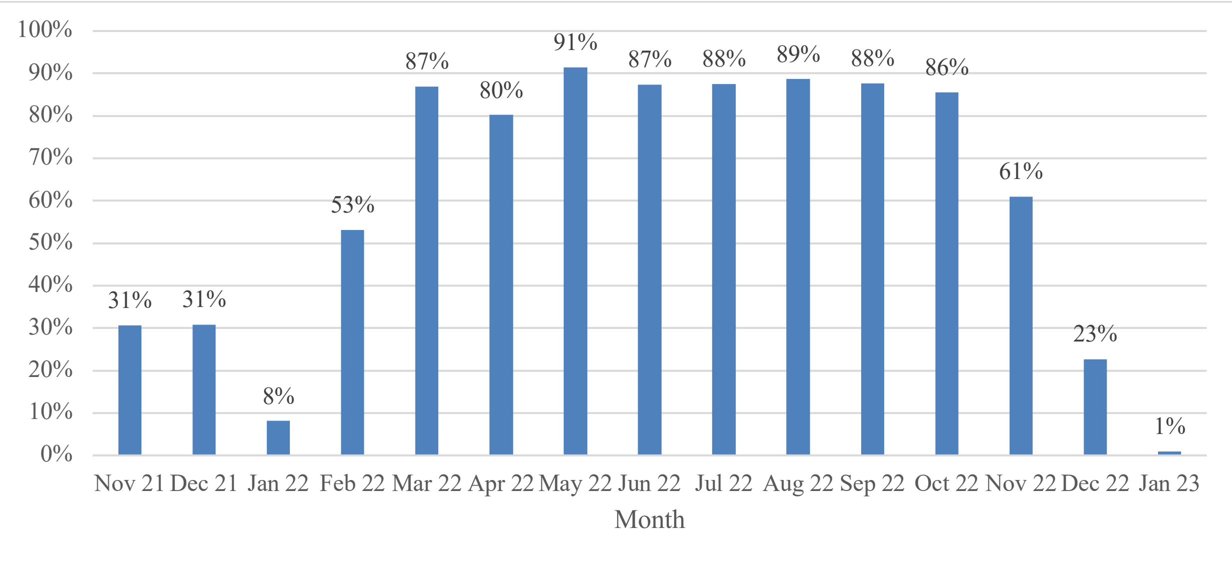

Figure 24: Electrical Self-Sufficiency of the City Hall: A Percentage Analysis Since the Installation of the PV System from November 2021 to January 2023. *(Source: The City of Morris, 2023)*

Figure 25 illustrates the natural gas consumption from January 2020 to January 2023, measured in Therms. Consumption reaches its peak during the winter months due to building heating. In contrast, no natural gas is consumed during the summer.

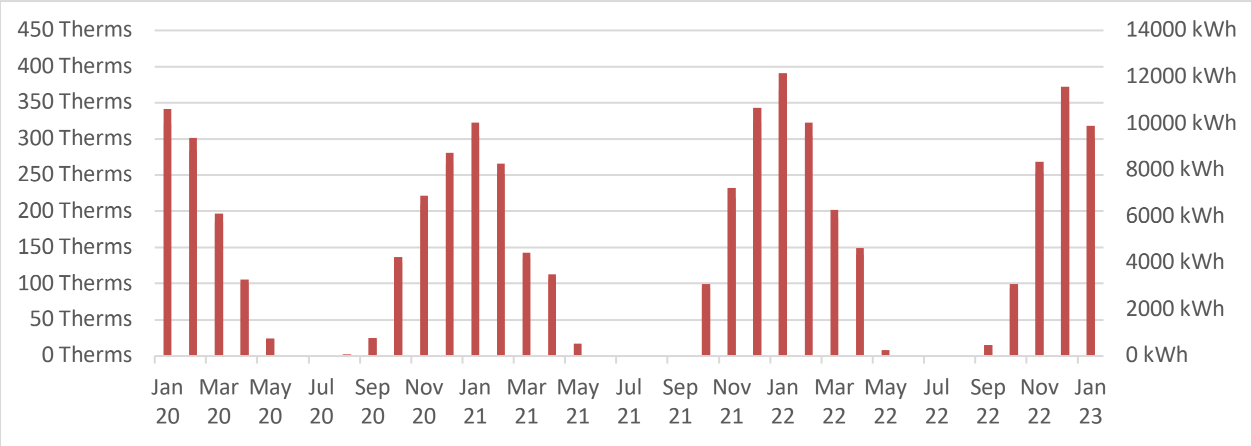

Figure 25: Natural gas consumption of the City Hall in Therms from January 2020 to January 2023. *(Source: The City of Morris, 2023)*

For comparison, Figure 26 shows the natural gas usage from a home in Morris from about August 2022 to August 2023. The home uses about 250 Therms (7,325 kWh) in January 2023, nearly the same about as City Hall in January 2023, which used a bit over 300 Therms (8,790 kWh). Over the year, the home used about 1,000 Therms (29,300 kWh), an average of about 100 Therms (2,930 kWh) per month. Average temperatures affect the natural gas demanded by the household: December (25.4°F; -3.7°C), January (16.0°F; -8.9°C), February (17.1°F; -8.3°C), March (21.2 °F; -6.0°C), and April (25.7 °F; -3.5°C).

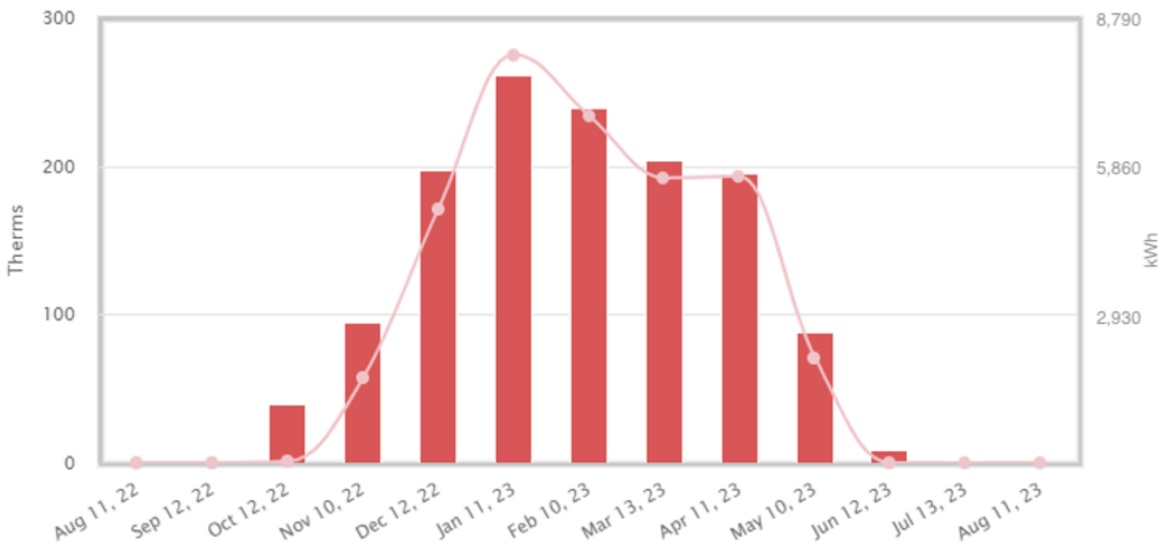

Figure 26: Screenshot of an example natural gas usage from a household in Morris. *(Source: Private Houseowner in Morris, 2023)*

Figure 27 depicts a combination of electrical energy and natural gas consumption, with the natural gas consumption converted into kWh (1 Therm = 29.3 kWh). It provides an overview of the overall energy consumption of the building. The diagram clearly illustrates the increased natural gas consumption during the winter months. It is important to realize that heating dominates the energy usage in Minnesota. Over the course of the year 2022, **energy used for heating is 77% of the total energy** used in the building, **and electrical energy is only 23%.** City Hall is also a candidate for an air-source heat pump cooling and heating.

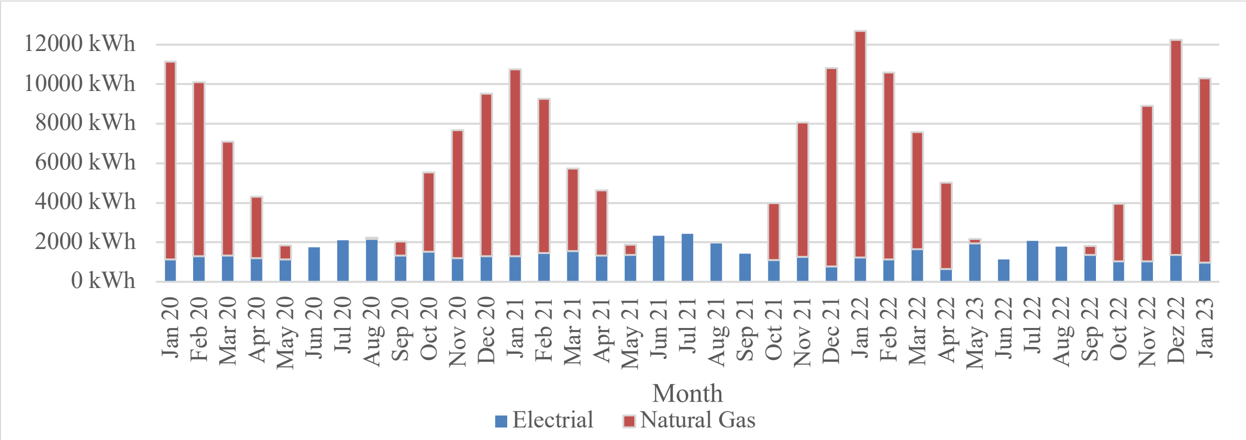

Figure 27: Total energy consumption in kWh of the City Hall from January 2020 to January 2023. *(Source: The City of Morris, 2023)*

4.5 Self-sufficiency of all public facilities

This section explores the total self-sufficiency of the public buildings in the city of Morris, presenting consumption numbers and charts to provide a comprehensive understanding of their energy independence.

The **public facilities in the city of Morris consumed 475,728 kWh** in 2022. About **99,405 kWh were produced by solar PV** on the four public buildings. In 2022, the **degree of self-sufficiency is nearly 21%.**

Table 5 shows the exact production and consumption of the seven public buildings.

Table 5: Electrical Consumption and Production from all public buildings in Morris in the year 2022. *(Source: The City of Morris 2023)*

NAME	CONSUMPTION	UNIT	PRODUCTION	UNIT
AIRPORT	114,092	kWh/yr	No installed PV	kWh/yr
PUBLIC AIRPORT	27,549	kWh/yr	No installed PV	kWh/yr
FIREHALL	32,000	kWh/yr	No installed PV	kWh/yr
LIBRARY	137,320	kWh/yr	22,920	kWh/yr
CITY HALL	16,367	kWh/yr	32,232	kWh/yr
LIQUOR STORE	98,557	kWh/yr	28,171	kWh/yr
COMMUNITY CENTER	49,843	kWh/yr	16,082	kWh/yr
TOTAL	**475,728**	**kWh/yr**	**99,405**	**kWh /yr**

Figure 28 shows the split of electrical energy between **purchased** electrical energy from external sources (Otter Tail Power Company) versus the energy **sustainably generated by the PV systems** during the analyzed period. It provides a visual representation of the relationship between the energy purchased from conventional sources, represented in electrical energy consumption, and the proportion of energy sustainably generated on-site by the PV system.

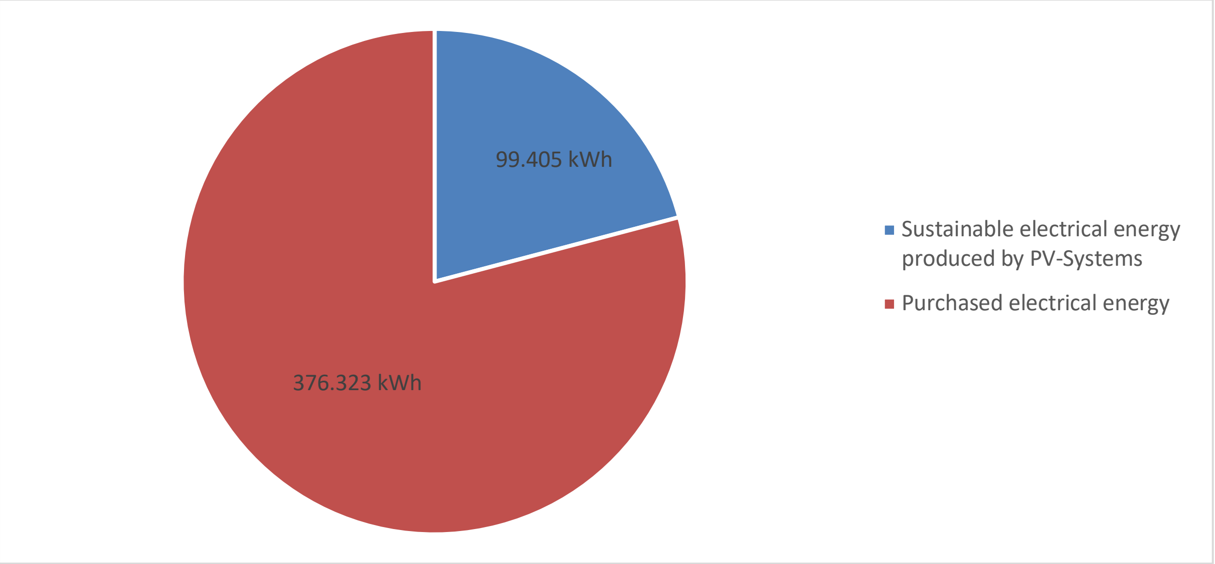

Figure 28: Electrical Energy in all Public Buildings in 2022: Distribution of PV-generated electrical energy and Purchased Energy. *(Source: The City of Morris, 2023)*

Figure 29 provides a further breakdown of the energy consumption distribution among the respective public buildings for the year 2022.

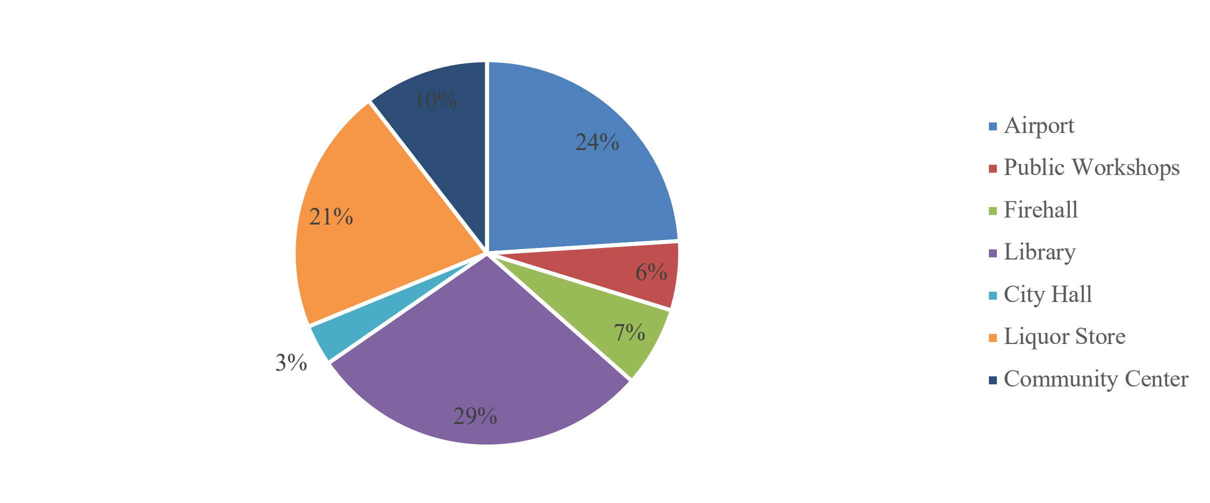

Figure 29: Electrical Consumption of Buildings in 2022: Distribution of Consumption Across Respective Buildings. *(Source: The City of Morris, 2023)*

This calculation did not include the freshwater treatment and the wastewater treatment plants. The reason for this omission is their classification as industrial facilities rather than public buildings. To ensure a comprehensive presentation of the data, a thorough documentation and listing of the energy consumption of these facilities has been conducted. Additionally, a calculation of the self-sufficiency of all public buildings has been included, considering the two industrial plants mentioned above.

Table 6: Energy Consumption: Wastewater Treatment Plant and Freshwater Treatment Plant in 2022 *(Source: The City of Morris, 2023)*

NAME	CONSUMPTION	UNIT	PRODUCTION	UNIT
WASTEWATER TREATMENT PLANT	848,332	kWh/yr	No installed PV	kWh/yr
FRESHWATER TREATMENT PLANT	124,113	kWh/yr	No installed PV	kWh/yr

If these two plants with their electrical consumption were included in the self-sufficiency calculation – then the total self-sufficiency of all public buildings including the plants would be 6.81%. It is clear that that the freshwater treatment plant with 848,332 kW is the largest energy consumer in the city of Morris. The Morris freshwater treatment plant was recently built to reduce chloride contamination in the Pomme de Terre river from household water softeners in Morris.

4.6 Exploring Battery Storage at the Community Center

The possibility of a battery storage system at the Community Center was explored as a case study. It is the only building that is occasionally operating at a self-sufficiency of over 100%. By analyzing production and consumption data, expanding the capacity of the photovoltaic system would make more sense than deploying a battery storage system at this time.

The graph in Figure 30 shows that currently there is not always enough PV-generated energy to meet the energy demand. Therefore, an energy storage system becomes relevant only in an emergency outage. Consequently, increasing the system's capacity is a more meaningful approach.

For instance, at 1:00 PM, the PV system produces around 10.33 kW, while the building consumes approximately 12.23 kW at the same moment. This means that 10.33 kW of the required 12.23 kW is produced by the system. So, at 1:00 PM, 84.5% of the electrical energy demanded by the building was generated by the PV system installed on the building.

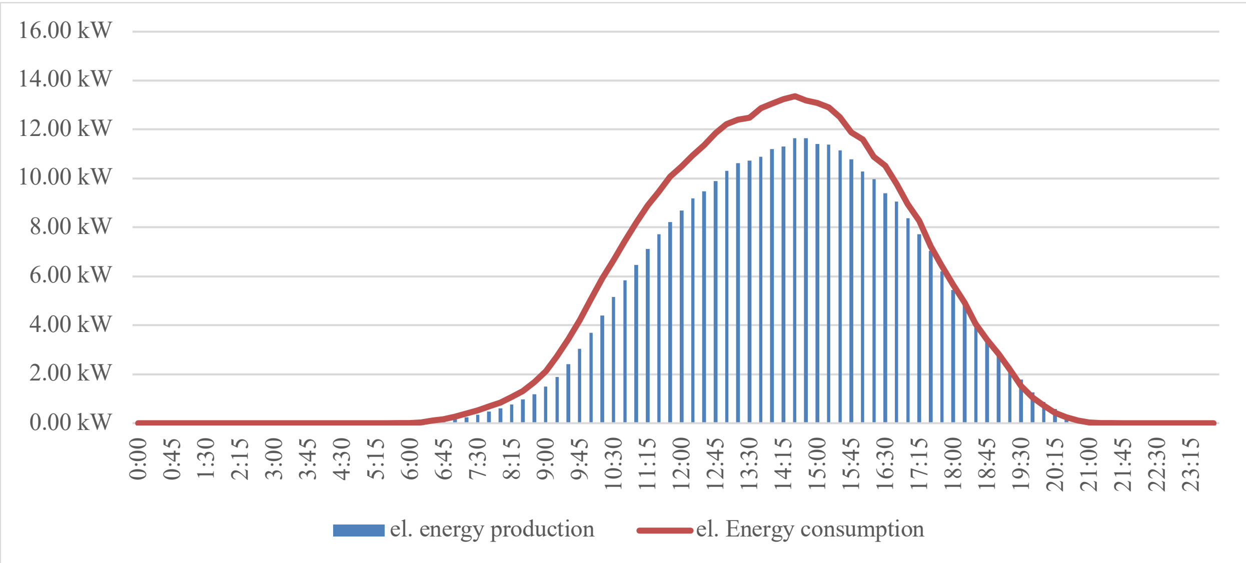

Figure 30: Comparison of Daily Energy Consumption and Production: Annual Average Analysis. *(Source: The City of Morris, 2023*)

5 PV SYSTEMS ON PRIVATE HOUSEHOLDS

This section takes a closer look at two PV systems on two private households. Performance measures are listed and an interview with the respective homeowner is conducted to describe the motivation, expectations, and the problems of the private PV installations.

5.1 Example household 1

5.1.1 Installed System

The installed PV system is on a roof area of approximately 297 sq.ft. The 15 panels produce a DC-peak power around 6 kW. The annual production amounts to 6,040 kWh/yr. An interesting aspect of this installation is that every panel has its own micro-inverter. The system works with no DC-strings. Micro-inverters from the company Enphase are used. The system is installed on the south side of the house. On Figure 31 the roof with the 15 panels is visible.

Figure 31: Example Household 1 *(Source: Luecken, 2023)*

5.1.2 Performance measures

Table 7 provides an overview of various performance measures of the PV system, including peak performance, energy consumption in 2022, energy production in 2022, solar radiation over the year, degree of self-sufficiency in 2022, full load hours of the PV system in 2022, performance ratio of the PV system and the specific power. Table 7 shows the performance measures.

Table 7: Performance Measures of the example household 1 *(Source: Private Houseowner in Morris, 2023)*

PERFORMANCE MEASURES		UNIT
PV SYSTEM: PEAK PERFORMANCE	6	kWpeak
EL. ENERGY CONSUMPTION 2022	10,906	kWh/yr
EL. ENERGY PRODUCTION 2022	6,040	kWh/yr
SOLAR RADIATION OVER THE YEAR	1,649.9	kWh/(m^2·yr)
DEGREE OF SELF-SUFFICENCY 2022	55.38	%
PV SYSTEM: FULL-LOAD HOURS 2022	1007	hr/yr
PV SYSTEM: PERFORMANCE RATIO 2022	66.72	%
USED AREA	27.6	m^2
USED AREA	297	sq.ft
PV SYSTEM: SPECIFIC POWER	217.39	Wpeak/m^2
PV SYSTEM: SPECIFIC POWER	20.2	Wpeak/sq.ft

5.1.3 Interview Houseowner 1: Photovoltaic Installation on Private Houses:

Interviewer: What was the reason why decided to install a PV system on your private house?

Houseowner 1: I work in the renewable energy industry, so I am familiar with the technology and I wanted to reduce my carbon footprint. Also, I have always been independently-minded so the idea of providing my own energy is appealing to me.

Interviewer: How has the performance of the PV system met your expectations?

Houseowner 1: The system has performed well, meeting the projections provided by the contractor.

Interviewer: How has the PV system impacted your energy bill and overall electricity consumption?

Houseowner 1: The array has provided about 75% of my electricity usage.

Interviewer: Did you experience any challenges or difficulties with permitting or regulatory processes during the installation of the PV system?

Houseowner 1: No. City permitting and interconnection with Otter Tail Power were both easy and quick.

Interviewer: How has the maintenance and upkeep of the PV system been, and have there been any unexpected cost or issues?

Houseowner 1: There has been no maintenance yet (almost 2 years) except removing snow from the panels in winter. No extra costs either.

Interviewer: Based on your experience, would you consider installing a PV system on your house again in the future?

Houseowner 1: Absolutely.

Interviewer: Would you recommend a private PV installation to other homeowners?

Houseowner 1: Absolutely.

Interviewer: What advice or tips would you give to other homeowners considering the installation of a PV system on their houses?

Houseowner 1: Get a couple bids from different contractors and use the Clean Energy Resource Teams website to educate yourself about solar and find local certified solar contactors. If you might need a new roof in less than 10 years, I recommend doing that before putting solar on the roof.

5.2 Example household 2

5.2.1 Installed System

The PV system is installed on a roof area of approximately 238 sq.ft. The 12 panels produce a DC- peak power of around 4.8 kW. The annual production amounts to 3,527 kWh/yr. The interesting part about that is that every panel has its own micro-inverter. The system works with no DC-strings. Micro-inverters are from the company Enphase. The system is installed on the south side. On Figure 31 shows the 12 panels installed on a garage roof.

Figure 32: Example Household 2 *(Source: Luecken, 2023)*

5.2.2 Performance measures

Table 8 provides an overview of various performance measures of the photovoltaic system, including peak performance, energy consumption in 2022, energy production in 2022, solar radiation over the year, degree of self-sufficiency in 2022, full-load hours of the PV system in 2022, performance ratio of the PV system and the specific power.

Table 8: Performance Measures of the example household 2 *(Source: Private Houseowner in Morris, 2023)*

PERFORMANCE MEASURES		UNIT
PV SYSTEM: PEAK PERFORMANCE	4.8	kWpeak
EL. ENERGY CONSUMPTION 2022	2,033	kWh/yr
EL. ENERGY PRODUCTION 2022	3,527	kWh/yr
SOLAR RADIATION OVER THE YEAR	1,649.5	kWh/(m^2·yr)
DEGREE OF SELF-SUFFICENCY 2022	173.51	%
PV SYSTEM: FULL-LOAD HOURS 2022	735	hr/yr
PV SYSTEM: PERFORMANCE RATIO 2022	48.65	%
USED AREA	22.11	m^2
USED AREA	238	sq.ft
PV SYSTEM: SPECIFIC POWER	217.1	Wpeak/m^2
PV SYSTEM: SPECIFIC POWER	20.17	Wpeak/sq.ft

5.2.3 Interview Houseowner 2: Photovoltaic Installation on Private Houses:

Interviewer: What was the reason why you decided to install a PV system on your private house?

Houseowner 2: The fact that many city dwellers were interested in it also aroused my interest. Through webinars I built up a rough understanding of the technology. The sustainability aspect was the deciding factor for me. I wanted to invest my money in sustainability. I found a PV system to be good alternative investment for a green renewable energy fund.

Interviewer: How has the performance of the PV system met your expectations?

Houseowner 2: The first year was somewhat worse than expected. However, this is due to the shadows cast by the trees and the snow in winter. I decided not to reforest the trees. The next year I removed the snow from the modules with a big shovel. The performance in the next year was significantly higher.

Interviewer: Did you experience any challenges or difficulties with permitting or regulatory processes during the installation of the PV system?

Houseowner 2: It takes some time until all inspections are completed. You also must stay on the ball yourself and make new appointments for the inspections. Connection to the grid also takes time. Also, the time needed for the paperwork should not be neglected. But everything is manageable.

Interviewer: How has the maintenance and upkeep of the PV system been, and have there been any unexpected cost or issues?

Houseowner 2: The snow in winter. But a suitable scoop with a long handle you get the PV system free of snow again.

Interviewer: Based on your experience, would you consider installing a PV system on your house again in the future?

Houseowner 2: Yes, in any case! I am also thinking about integrating a battery into the system. To be able to use the energy later in the day. The idea came to me last spring when the storm completely knocked out the grid.

Interviewer: Would you recommend a private PV installation to other homeowners?

Household 2: Yes! I have also already recommended it to others.

Interviewer: What advice or tips would you give to other homeowners considering the installation of a PV system on their houses?

Houseowner 2:

- If you don't have much experience, you should work with a good installer. It is also an advantage to know someone who knows a bit about the technology. But it is not necessary.
- You should be prepared for the snow.
- I have found great joy in tracking the data. It's really fun to see how much you are producing and consuming. The webinars from the installer have helped a lot in understanding PV systems and energy consumption.

6 Comparison of Solar radiation with Germany

The city of Morris is partnered with a German sister-city, the city is called Saerbeck. Morris has established a strong connection to Germany via the Climate-Smart Municipalities program. Saerbeck is in North Rhine-Westphalia (NRW) – and the two cities have had a climate-protection agreement and technical partnership since 2009. The primary objective of Saerbeck is to achieve energy self-sufficiency by generating more energy from renewable sources than it consumes by the year 2030. The achievability of this goal appears promising.

The international partnership between Morris and Saerbeck prompts an exploration between the climate differences between Germany and Minnesota. Specifically, this analysis will focus on the comparison of average solar radiation and the average PV full load hours given the focus of this report on PV systems.

6.1 Differences in solar radiation

Solar radiation differs significantly between Minnesota and Germany, due to their geographical and climatic differences. These factors influence the amount of sunlight that falls on these regions and have implications for the utilization and efficiency of solar energy in both areas. In the diagram, the difference in solar radiation between the two countries is observable.

Figure 33 clearly shows Minnesota experiences greater radiation over the year than Germany. The values show the monthly average solar radiation measured at the Earth's surface. Germany is located further north, and is further away from the equator, which means that the solar irradiation angle is flatter. This means that the solar rays are distributed over a larger area and provide less direct energy.

In the average month of July, the Earth's surface in Germany experiences solar radiation of approximately 5.7 kWh per square meter per day. In the state of Minnesota, this value is slightly higher, averaging around 7 kWh per square meter per day. PV panels used for harnessing solar energy demonstrate a conversion efficiency about 15-20%, enabling them to convert a portion of the received irradiation into usable electrical energy.

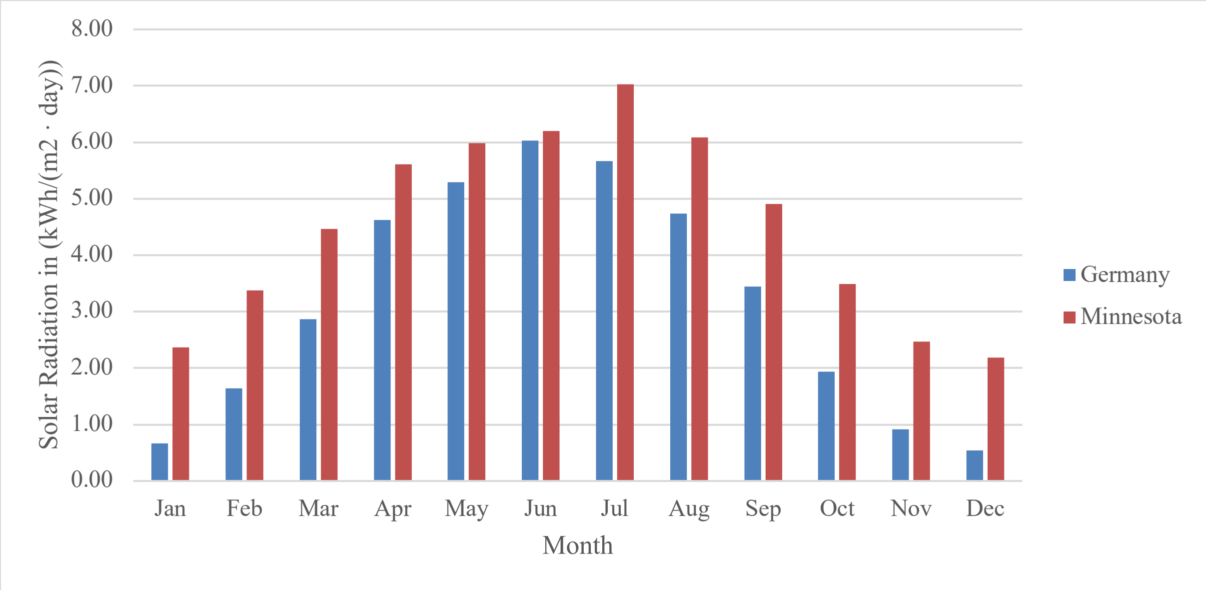

Figure 33: Average solar radiation (kWh/(m^2·day)) across individual months. Source MN: (NREL, 2023). Source Germany: (DWD, 2023)

6.2 Differences in the Full Load Hours

There are also difference in the Full Load Hours between Germany and Minnesota installed PV Systems. In Germany the average PV System works between the years 2012 to 2018 on an annual average 959.86 hr/yr under their nameplated power (Te Hessen, Herbort, & Rumpler, 12/2019)

In Minnesota the average PV systems worked in the recent years 1303,5 hr/yr under their nameplate power after estimation by PVWatts Calculator. (NREL, 2023).

Parameter configuration for the PVWatts model involved the utilization of default settings for key input parameters (module type, azimuth, DC/AC size ratio, and inverter efficiency), including accumulated system losses of 14.08% (based on soling, shading, wiring, connections, etc.). It is important to highlight that the parameter for age and snow are not considered in the analysis.

Figure 34 clearly underlines the differences in the Full Load Hours in a bar chart.

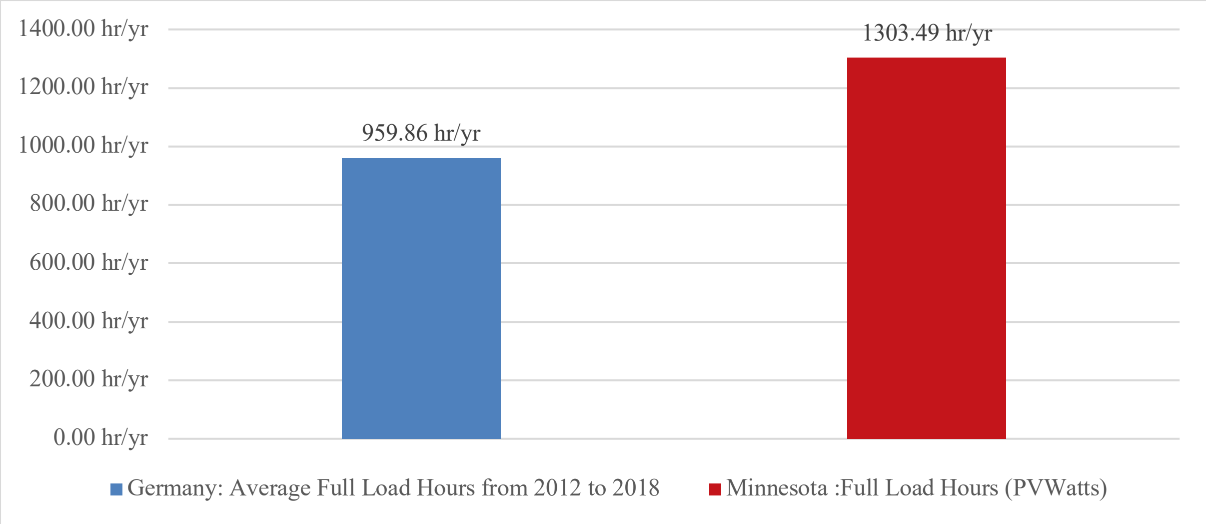

Figure 34: Comparison of the Full Load Hours (hr/yr) between Germany and Minnesota: Source Ger:(Te Heesen et al., 2019) Source MN: (NREL, 2023)

The reason why Minnesota PV system work with more Full Load Hours is that Minnesota receives more Solar radiation than Germany (see chapter 6.1). So, the System is able to produce more solar energy. Notable is that these are only theoretical numbers, the snow coverage is not taking account into this calculation.

7 CONCLUSION AND RECOMMENDATIONS

In this report, the performance of installed solar PV systems on public and private buildings in the City of Morris is examined, with particular focus on performance metrics. The presentation of the average performance metrics achievable under perfect conditions illustrates the existing potential for improvement and identifies the targets that should be pursued.

7.1 Snow Removal for increasing the Full Load Hours

The previous data has clearly shown that energy production in the winter months is significantly affected by the accumulation of snow. This seasonal challenge has a direct impact on the efficiency, overall performance and annual hours of use solar installations. In this context, it is crucial to develop and implement effective snow removal measures to maximize annual full-load hours and thus optimize energy yield. The following are simple brief but clear recommendations.

7.1.1 Regular Monitoring

Keep an eye on the energy production during the winter months. Use the already installed software to read out the energy production and compare it to previous days. If the energy production is significantly reduced, a inspection on the roof should be carried out.

7.1.2 Snow Removal as Needed

In case of heavy snow accumulation and the resulting reduction in performance, it is advisable to remove the snow from the PV modules using a soft broom or specialized snow removal tools. Care must be taken to ensure that the PV modules are not damaged in the process. It is essential to clear all modules, not just a portion of them. If the risk is too great, refrain from climbing the roof, if possible, hire specialized company with the necessary safety equipment. The own safety should always be the number one priority in this process.

7.2 Vehicle to Home (V2H) Option

The City of Morris is thinking about the connection of one or two electric plug-in hybrid cars to the Community Center as an electrical energy storage. This way, they can use them in emergencies, like power outages. The Community Center need on an average day in the year 2022 around 136 kWh/day.

Considering the use of larger SUV´s, such as the Ford-150 Lightning, could prove beneficial. These vehicles could serve dual purpose by powering the Community Center when needed and performing other applications when not in use. The Ford F-150 Lightning, particularly in its “Extended-Range Battery” variant, boasts a substantial battery size, around 131 kWh of usable energy, providing sufficient power to run a the Community Center for approximately one day. (F-150 Lightning Tech Specs, 2023)

To facilitate this bi-directional energy flow, a specialized vehicle charger and software is essential. (Ford Intelligent Backup Power, 2023)

In case of emergencies where power is unavailable, it would be prudent to develop a plan that prioritizes essential application within the building. To power the buildings with car battery for an extended period.

7.3 Installation of a PV system on unused roof area

The City of Morris Fire department building offers a large, usable roof area for installation purpose as the roof was recently renovated. The total area is approximately 695 m^2.

For this potential calculation, the "Sunny Design" software from the company SMA Solar Technology is utilized for the design of the PV system. The screenshots in Figure 35 illustrate how a potentials and realistic installation on the roof of the Morris Fire Hall might appear.

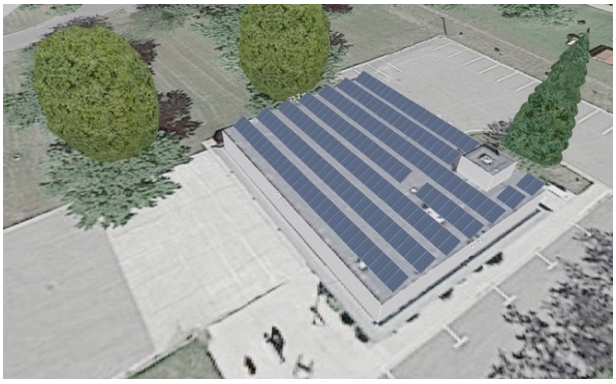

Figure 35: Example installation. (Source SMA Solar Technology AG)

The software calculated that 182 solar modules can fit on the roof. Each module is expected to produce approximately 300 W peak power.

The Software calculated the following performance measures (shown in Table 9) for the system on the Morris Fire Hall. (SMA Solar Technology AG, 2023)

Table 9: Performance Metrics for the Fire Department (Source: (SMA Solar Technology AG, 2023))

PERFORMANCE MEASURES		UNIT
PEAK POWER	54.60	kWpeak
MAX. DC POWER (COS Φ = 1)	51.00	kW
MAX. AC ACTIVE POWER (COS Φ = 1)	50.00	kW
TOTAL NUMBER OF PV MODULES	182	pcs

When the system will operate with the same number of full use hours as the City Hall, the PV system on the Morris Fire Hall would yield the following in one year.

Estimate the annual energy production of the PV system involved utilizing the formula:

$$Expected\ yield\ (kWh) = Peak\ Power\ \times\ Full\ Load\ Hours$$

Insert the given values:

$$Expected\ yield\ (kWh) = 54.60\ kW\ \times\ 960\ hr = 52{,}416\ kWh$$

If the system were to operate for the same number of full use hours as City Hall did in 2022, it would produce 52,416 kWh per year. **This would increase the total self-sufficiency of all public facilities from 21% to maximum of 32%. It is important to mention that the calculation the software does not take into account the real possibilities and conditions. Therefore, the yield will be lower in the practice.**

8 SUMMARY

This report examines the impact of PV systems on public and private buildings within the city of Morris.

The data collected and analyzed show that the implementation of PV systems on city buildings has positively impacted the clean energy production of the city. The installation of these PV systems on buildings has significantly contributed to the production of renewable energy, thereby reducing reliance on external energy sources and to some extent, fossil-fuel-based electricity.

According to the analyzed data, it can be clearly observed that the four different public buildings have different total energy usage profiles over the year and differ in their electrical consumption patterns.

The report examines the factors that lead to significant differences in the performance indicators. A significant influencing factor is the use of air-conditioning in the buildings, especially during periods of increased solar radiation. During these periods, a considerable amount of electrical energy is consumed, but this can be effectively covered by the installation of a photovoltaic system.

Implementation of an electrical energy storage/battery system should only be considered when the buildings reach a higher level of self-sufficiency. This can be achieved by expanding the PV system or by reducing the electrical consumption in the building itself. The latter should be carefully reviewed, especially when purchasing new large electrical loads such as air-conditioning, refrigeration, HVAC systems or heat pumps. When selecting such equipment, attention should be paid to the electricity demands.

Examining the installation of PV System on public buildings and their impact on the energy independence of the city, it becomes evident that this decision represents a positive and effective measure. In the context of the building analyzed for this report, the dependence on other electrical sources (utility power) was reduced by approximately 30%. This conclusion is drawn from a quantitative evaluation and assessment of the energy production and consumption of individual buildings.

To increase the self-sufficiency rate, the city may consider installation of additional PV systems on unused roof areas of public buildings, for example, the Fire Hall.

The city may also want to explore energy storage options to improve the resilience of some buildings during storm/emergency events. Energy storage systems provide the capability to store excess energy and make it available during periods of low or no solar irradiation. This ensures continuous energy supply and enhances independence from external power sources. There are now vehicles with very large batteries that could be integrated into a building's electrical system for use during emergencies.

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9.2 List of Figures

9.3 List of Tables

9.4 List of Abbreviations

AC	Alternating Current
Avg.	Average
CSM	Climate Smart Municipalities
DC	Direct Current
El	Electrical
HVAC	Heating, Ventilation, and Air Conditioning
Hr	Hours
IRA	Inflation Reduction Act
kW	Kilowatt
kWh	Kilowatt Hour
OTP	Ottertail Power Company
POP	Public Owned Property
POA	Plane of Area
PR	Performance Ratio
PV	Photovoltaic
REC	Renewable Energy Credits
Sq.ft	Square feet
UMN	University of Minnesota
V2H	Vehicle to Home
WCROC	West Central Research and Outreach Center
Yr	Year