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Potential of Wall-Mounted Solar PV Panel in high-latitude areas- A case study in Swedish contexts#

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ABSTRACT

To catch up with the sustainability transition progress, the global capacity of PV system is predicted to grow dramatically in the following decades, including high-latitude regions. To effectively use the urban space resource for PV power generation in the high-latitude areas, wall-mounted PV system is becoming an attractive solution. This paper evaluates the potential of wall-mounted PV system in the high-latitude areas with a case study in Swedish contexts through a PV power generation model by considering weather conditions (including snowfall, icing and melting), orientation, and economics. The key performances are compared with rooftop fixed-tilt angle PV systems in Swedish contexts. Although the annual power generation of the wall-mounted PV system is around 5% lower under heavy snow conditions, its power generation during the snow season (from October to April) increases significantly. In general, the power generation in March almost doubled and the increase could be more than 25% in April. Therefore, wall-mounted PV system can contribute to the winter electricity supply in high-latitude areas, when the electricity price is high.

Keywords: Wall-mounted PV, High-latitude areas, Techno-economic analysis, Snow conditions

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
DNI	Direct normal irradiation
DHI	Diffuse horizontal irradiation
GHI	Global horizontal irradiation
STC	Standard test condition
LCoE	Levelized cost of electricity
SEK	Swedish Krona
Symbols	
G_{total}	Total irradiation received
ϑs	Incident angle
β	Tilt angle
al	Reflectivity of the ground
fb	Angular loss for beam radiation
fd	Angular loss for diffuse radiation
fr	Angular loss for reflection radiation
al_{dry}	Reflectivity of dry snow
al_{wet}	Reflectivity of wet snow
γ_s	Solar azimuth
γ_c	PV orientation
α_s	Solar altitude
ω	Hour angle
φ	Latitude
δ	Declination
ϑz	Solar zenith
η	Efficiency
α_T	Temperature coefficient
r_{de}	Degradation rate
yn	Lifetime
$CAPEX$	Initial costs
$OPEX$	Operational costs
r_d	Discounted rate
E_y	Annual electricity generated

1. INTRODUCTION

Energy transition was delayed due to the covid pandemic while the renewable power necessitates to be triple to catch up the targets [1]. It is predicted that by 2050, solar PV may share 25% of total electricity capacity worldwide [2]. Since the current share is around 4.5%, solar PV will continue to grow robustly [3].

It is not straightforward to implement solar PV in high-latitude regions. In high-latitude regions, due to the relatively small solar altitude angle, the PV power generation in specific land or roof area is lower than that in low-latitude regions. In addition, high-latitude regions usually suffer from heavy snow during snow seasons, and the snow cover can cause a significant reduction in PV

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power generation. The snow loss could be up to 25% for annual PV power generation in the Swedish contexts [4]. However, the electricity consumption in winter could be considerable then making a huge gap between demand and supply. In addition, the electricity price in winter is much higher thus the ultility costs could also be high. Regarding this, wall-mounted PV could be a potential solution to increase PV capacity with less extra urban space requirements. The potential benefits of Wall-mounted PV system in high-latitude areas include less snow loss, higher reflection irradiation during the now season, and no inter-row shading.

This paper evaluates the potential of wall-mounted PV system in high-latitude areas. A PV generation model is built, and a case study based on Swedish contexts is analyzed. Weather including snow conditions, PV installation orientation and economics are considered. The performance is compared with rooftop fixed-tilt angle PV systems.

2. METHODOLOGY

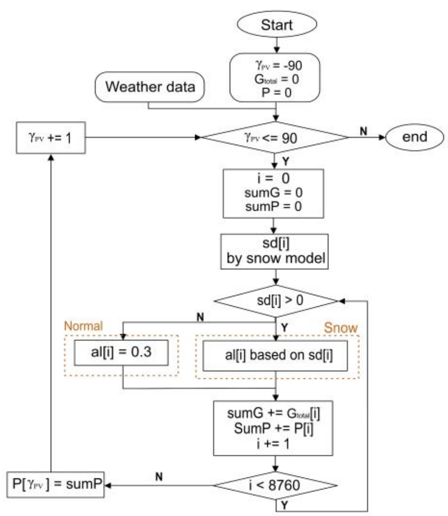

Fig. 1 Flowchart

The study begins by gathering data related to weather conditions and PV panels. These datasets are sourced from the respective databases for each category. Hourly weather data of Stockholm is collected from Swedish Meteorological and Hydrological Institute for the period 2017-2021. Subsequently, the collected data is used to estimate annual PV power generation, as illustrated in figure 1. The simulation runs several cycles by varying PV orientation from east to west with every step of 1 degree. An orientation of 0 degree refers to facing the south and positive value means rotating towards west side. For each cycle, annual power generation is estimated. For each timestep, the weather conditions are first determined mainly based on snow depth, which would influence the albedo of the surrounding ground. The snow model is based on a previous study [4]. The total global irradiation (G_{total}) is then calculated using Eq.1, considering the weather conditions [5]. The PV panel is vertically installed on the wall (tilt angle = 90), and the study does not include the shading effects of surroundings due to the limitation on data.

$$G_{total} = (1-fb)*DNI*\cos\theta_s + (1-fd)*DHI*(\frac{1+\cos\beta}{2}) + (1-fr)*al*GHI*(\frac{1-\cos\beta}{2}) \quad (1)$$

where

- *DNI* is direct normal irradiation
- ϑs is incident angle
- *β* is tilt angle
- *DHI* is diffuse horizontal irradiation
- *GHI* is global horizontal irradiation
- *al* is the reflectivity of the ground
- *fb*, *fd*, *fr* are the angular loss for beam, diffuse and reflection radiation, respectively

Snow effects are considered in this study. For normal fixed-tilt angle PV system, the processes - snowfall, snow covering and melting could all influence the operation. However, for wall-mounted PV system, the snow would not cover on the panels. The main influence comes from the albedo change on surrounding. Snow effect for wall-mounted PV system could be calculated as a function of snow depth (Eq.2 for dry snow season and Eq.3 for wet snow season) [6]. In this study, wintertime from December to February is assumed to be dry snow season, while spring and autumn are considered as wet snow seasons.

$$al_{dry} = (0.75*sd + 0.22)/(sd + 0.97) \quad (2)$$

$$al_{wet} = (0.66*sd + 0.79)/(sd + 3.66) \quad (3)$$

The incident angle is calculated based on Eq.4 [7].

$$\cos\theta_s = \cos\alpha_s \cos(\gamma_s - \gamma_c)\sin\beta + \sin\alpha_s \cos\beta \quad (4)$$

where

- γ_s is solar azimuth with respect to south,

- γ_c is PV orientation with respect to the south (positive for westwards),
- α_s is solar altitude.

Solar zenith could be calculated by Eq.5 [5].

$$\gamma_s = sign(\omega) \times \left| \arccos\left(\frac{\cos\theta_z \sin\phi - \sin\delta}{\sin\theta_z \cos\phi}\right) \right| \quad (5)$$

where

- ω is the hour angle,
- φ is the latitude,
- δ is declination,
- ϑz is solar zenith

Angular loss is also considered in this study. Three angular loss factors can be estimated with Eq.6-8 [8].

$$fb = \frac{\exp(-\cos(\frac{\theta_s}{a_r})) - \exp(-\frac{1}{a_r})}{1 - \exp(-\frac{1}{a_r})} \quad (6)$$

$$fd \cong \exp[-\frac{1}{a_r}(c_1 * (\sin\beta + \frac{\pi - \beta - \sin\beta}{1 + \cos\beta}) + c_2 * (\sin\beta + \frac{\pi - \beta - \sin\beta}{1 + \cos\beta})^2)] \quad (7)$$

$$fr \cong \exp[-\frac{1}{a_r}(c_1 * (\sin\beta + \frac{\beta - \sin\beta}{1 - \cos\beta}) + c_2 * (\sin\beta + \frac{\beta - \sin\beta}{1 - \cos\beta})^2)] \quad (8)$$

Finally, the annual PV power generation could be estimated with Eq.9.

$$P = \frac{P_{STC} * G_{total}}{G_{STC}} * \eta * [1 + \alpha_T * (T_c - T_{STC})] \quad (9)$$

where

- *STC* refers to the standard conditions where irradiance is set at 1000 W/m^2, and the cell temperature is 25℃.
- η is the total efficiency.
- α_T is the temperature coefficient.
- T_c is the cell temperature

The PV panels selected in this study refers to the on-stock products available in Swedish PV market. Some parameters are listed in Table 1.

Table 1. Technical parameters for PV panels [9].

Parameters	**Monofacial PV**
Type	LR5-72HTH-575M
Size	2.278×1.134 m^2
Power at STC (P_{STC})	575 Wp
Temperature coefficient (α_T)	-0.0029 ℃$^{-1}$
Nominal operating cell temperature (NOCT)	45℃
Power degradation	
First year ($r_{de,0}$)	1.5%
Other ($r_{de,1}$)	0.4%

In this study, economic performance is evaluated by levelized cost of electricity (LCoE) which is calculated by Eq.10. Some economic parameters are listed in Table 2. The unit of currency used is Swedish Krona (SEK). Some assumptions are made for economic analysis due to unknown PV size. It is assumed that two types of PV system are the same size. In addition, all electricity generated is assumed to be sold to the grid.

$$LCoE = \frac{CAPEX + \sum_{y=1}^{yn} \frac{OPEX_y}{(1 + r_d)^y}}{\sum_{y=1}^{yn} \frac{E_y(1 - r_{de,0})(1 - r_{de,1})^{y-1}}{(1 + r_d)^y}} \quad (10)$$

where:

- *CAPEX* is initial investment costs
- *OPEX* is operational and maintenance costs
- r_d is discounted rate
- r_{de} is power degradation rate
- E_y is annua electricity production

Table 2. Economic parameters for PV panels.

Parameters	**Value**
Lifetime (*yn*)	25 years
System price (*CAPEX*)	10 SEK/Wp
OPEX	64 SEK/kWp/year

The costs for wall-mounted PV system now could be much higher than fixed-tilt PV system due to installation complexity. LCoE of both types of PV system is analyzed with a sensitivity study on wall-mounted PV system price, electricity price and discounted rate. The wall-mounted

PV system price is analyzed in different levels: same price with fixed-tilt PV, 10% higher and 20% higher. The monthly electricity price in last three years are listed in Table 3 [10]. The influence of discounted rate is analyzed in two levels: high as 3.5% and low as 1.0%.

Table 3. Electricity prices in recent three years [unit: SEK/MWh]

Month	2021	2022	2023
January	490.51	1043.32	925.78
February	536.25	774.8	825.39
March	367.83	1303.3	806.2
April	336.81	892.16	686.98
May	435.02	1028.63	390.19
June	402.98	1263.09	530.55
July	590.46	866.13	376.51
August	671.14	2230.47	369.58
September	918.36	2286.33	243.22
October	647.54	806.45	330.61
November	835.18	1308.81	821.31
December	1807.44	2690.18	791.75
Average	490.51	1 378.65	589.76

3. RESULTS

Figure 2 presents the variation in annual power generation of wall-mounted PV systems with different PV orientation for 5 years. It is commonly accepted that a south-facing orientation yields the highest solar PV power generation. However, considering weather conditions, the optimal orientation could be adjusted slightly eastwards by 20-25 degrees, resulting in an approximate 2% increase in power generation.

Figure 3 presents the power generation difference between the wall-mounted PV with optimal orientation and the rooftop fix-tilt PV with optimal installation angle during the period of 2017-2021. The orange bar represents the annual power generation loss due to snow effects for the fix-tilt PV system. In general, wall-mounted PV systems result in a smaller annual power generation. However, the power difference between these two types of PV systems varies significantly depending on actual weather conditions. Heavy snow can lead to significant power loss for fix-tilt PV. Wall-mounted PV can perform similarly well under heavy snow conditions with only a 3% decrease in power generation in 2017. This is because fixed-tilt PV would be covered by snow, resulting in minor power in the winter, while wall-mounted PV could be still productive in snow conditions. In high-latitude areas, such as Sweden, frequent snowfall in the spring can significantly impact PV performance. This is because the snow covers the PV panels for a long time before melting, preventing PV panels from using considerable solar irradiation in spring. Even if it is sunny afterwards, the solar PV could not be productive.

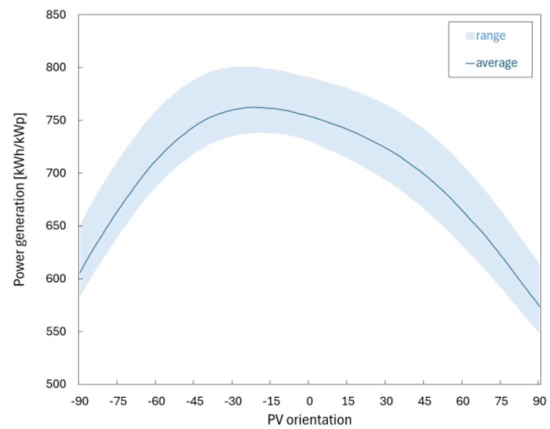

Fig. 2 Annual power generation with different orientation

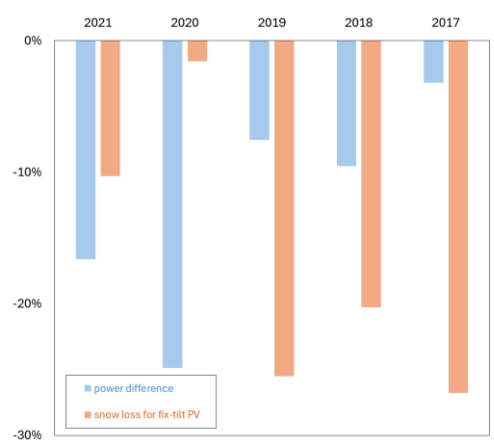

Fig. 3 Power difference compared to fix-tilt PV

Figure 4 demonstrates the monthly power generation difference between the wall-mounted PV system and the rooftop fix-tilt PV system with optimal installation angles. It is observed that the power generation of the wall-mounted PV system is significantly lower than the rooftop fix-tilt PV system during May to September when there is no snow, which accounts for the smaller annual power generation. During snow season from October to April, the wall-mounted PV system can generate considerably more power than the PV system with fixed optimal tilt angle. To be noticed that the electricity price is much higher during this period. Therefore, more cost reduction could be achieved. In addition, wall-mounted PV system exhibit less seasonal variation in power generation, which is beneficial for energy distribution planning.

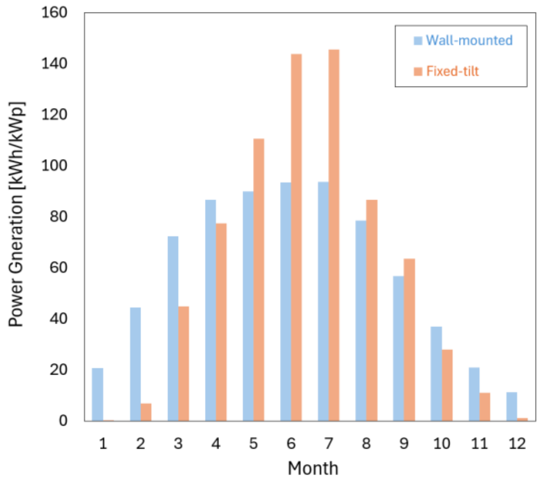

Fig. 4 Comparison of monthly average power generation

Annual benefits of two types of PV systems with different electricity prices are presented in Figure 5. When the electricity price is relatively low in summer and high in winter, such as the year 2021 and 2023, the wall-mounted systems could achieve higher annual benefits than fixed-tilt systems. In 2022, although the electricity price in winter is also high, the electricity price of May and June is quite high. Thus, fixed-tilt systems could gain more during these two months which could compensate for the loss in winter.

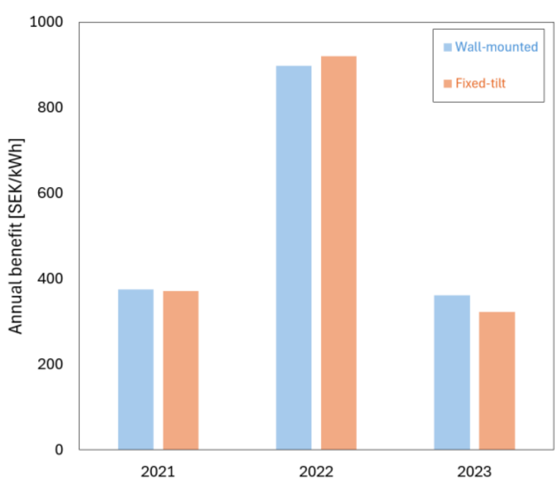

Fig. 5 Annual benefit of two types of PV system with different electricity price.

However, due to lower power generation, the LCoE of wall-mounted system is still slightly higher than fixed-tilt systems even if the system price is same (Figure 6). With system price increasing, wall-mounted systems become less competitive. The discounted rate could also influence LCoE. A lower discounted rate results in lower LCoE. With a discounted rate of 1.0%, LCoE could be around 21% lower than with a discounted rate of 3.5%. According to Figure 6, the LCoE for both types of PV systems is higher than the annual average electricity price in 2021 and 2023, which means that it could be profitable only with high electricity price. This is because the assumption is made that all the electricity is sold to the grid. Since the charge for consumption is much higher, more benefits can be achieved by self-consumption. The profitability of the system could be underestimated in this study. The current market for wall-mounted systems is relatively smaller compared to traditional systems. In the future with growing demands and technical development, the decrease of system price would increase the competitiveness.

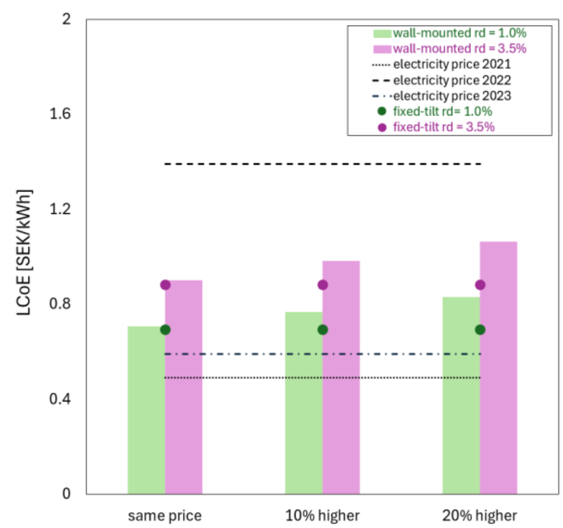

Fig. 6 Comparison of LCoE of different PV systems in different conditions.

4. CONCLUSIONS

This paper evaluates the potential of wall-mounted PV system in high-latitude areas with a case study in Swedish contexts through a PV power generation model by considering weather conditions (including snowfall, icing and melting), orientation, and economics. The key performances are compared with rooftop fixed-tilt angle PV systems in Swedish contexts. Key findings are listed below:

- Optimal orientation could be slightly eastwards by 20-25 degrees.

- The annual power generation of the wall-mounted PV system is slightly lower (<5%) than that of the rooftop fixed-tilt angle PV systems with heavy snow.
- Wall-mounted PV system has a significantly higher power generation during snow season, but lower in other seasons.
- LCoE of wall-mounted system is slightly higher than fix-tilt system, but it could still be profitable.
- Economic performance heavily relies on market conditions.

Due to data limitations, some assumptions are made for the analysis, the profitability of wall-mounted PV system may be underestimated. For future work, a case study could be involved with an actual system size.

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