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Performance analysis of roof-mounted photovoltaic systems – The case of a Norwegian residential building

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Abstract

Currently, the application of solar Photovoltaic (PV) systems on energy efficient buildings such as passive house, zero energy building (ZEB) and net-positive energy building (NPEB) is becoming increasingly attractive, particularly in Europe and North America. The rooftops of residential and commercial buildings are ideal places for the installation of PV systems. The work presented in this article aims at parametric analysis of PV systems applied to a 100 m^2 flat rooftop of a Norwegian residential building in Oslo. The study shows the effect of PV module types, the modules' row spacing, and installation tilt angle on the electrical energy yield. The study also includes the economic and environmental aspects of a selected PV system.

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Keywords: Solar energy; Photovoltaic(PV); roof-mounted; NPV; greenhouse gases

1. Introduction

Buildings use a significant amount of energy for heating, ventilation, cooling, and lighting systems. Currently, nearly 40% of the total primary energy in Norway is used in the buildings sector [1]. A strong interest in the reduction of buildings' energy consumption and the improvement of their environmental performance drives researchers to look for new systems and technologies. Thus, the passive house, zero-energy building (ZEB), and net-positive-energy building (NPEB) concepts have emerged and become increasingly attractive, particularly in Europe and North America. In Europe, for example, the Energy Performance of Buildings Directives (EPBD) require that all new buildings be 'nearly zero-energy buildings' by 2020 [2].

These concepts have encouraged buildings to produce their own energy on site from renewable energy sources, such as solar energy. One interesting area of solar energy utilization for buildings is the application or integration of solar photovoltaic (PV) systems onto a building's rooftop and facade. The basic component of a photovoltaic (PV)

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system is PV cells, which convert sunlight directly into electricity with an efficiency ranging from 10-23 % [3]. The most commonly known technologies for PV cells are mono-crystalline silicon (m-si), polycrystalline silicon (P-si), cadmium-telluride (CdTe), copper-indium-diselenide (CIS), and amorphous silicon (a-Si). The PV cells are interconnected to create PV modules, which absorb direct solar radiation, diffused solar radiation, and reflected sunrays from the ground (albedo). The assembly of the PV modules called PV array.

It has become common to observe grid-connected PV systems mounted on buildings. Buildings' rooftops, particularly flat surfaces, provide a number of possibilities for the integration of PV modules [4, 5], both in the design phase of a new building or in the retrofitting stage of an existing building. As pointed out by Ceron et al [6], nearly 50% of building-integrated PV systems are based on roof installations and their performance could be affected by a number of factors, including the solar radiation availability, the tilt angle of the PV modules, the distance between the module rows, the surface temperature of the module, etc. In this study, the impacts of certain parameters that could affect the performance of PV systems mounted on the rooftop of a residential building were investigated. Moreover, economic and environmental analyses of a selected PV system were also conducted. However, since this work is a preliminary study, the entire work depends on weather data available in the PVsyst simulation tool. Moreover, the impacts of PV modules' azimuth angles, shading loss due to the surrounding elements were not investigated.

2. Methodology

In this paper, a basic parameter analysis was conducted for PV systems integrated into a Norwegian residential building's rooftop. This will help to discover how to achieve optimal energy production using the given system. For this purpose, simulations of roof-mounted PV systems were conducted using PVsyst V5.52 software [7]. The software was developed at the University of Geneva and is one of the most widely used simulation tools for analyzing the performance of PV systems. The software offers an opportunity for the preliminary or detailed design of a complete PV system, either grid-connected, stand-alone, pumping, or DC-grid. The software also has databases of weather files (global and horizontal solar radiation, ambient temperature) for various geographical locations and basic PV system components. In addition, the program provides 3D representations of buildings, PV fields and surrounding shading elements.

Table 1. Physical and electrical characteristics of the PV module types.

	m-si	p-si	CdTe	CIS	a-si
Manufacturer	Canadian Solar Inc.	REC Scanmodule	First Solar	Wurth Solar	T-Solar
Model	CS6P - 220M	REC 220PE	FS-385	WSG 0036 E080	TS90
Maximum power output @ STC	220Wp	220 Wp	85.0 Wp	80.0 Wp	85.0 Wp
Voltage at Pmax	29.90 V	29.0 V	47.70 V	34.9 V	71.1 V
Current at Pmax	7.37 A	7.63 A	1.79 A	2.31 A	1.2 A
Temperature coefficient of max power	-0.45 %/ ºC	-0.43 %/ ºC	-0.25 %/ ºC	-0.2 %/ ºC	-0.24 %/ ºC
Module efficiency	13.68%	13.41 %	11.88 %	11.04 %	10.92 %
Open circuit voltage	36.9 V	35.9 V	61.0 V	44.0 V	93.5 V
Short circuit current	7.97 A	8.3 A	1.980	2.5 A	1.4 A
Module dimensions , Length (m) X width(m)	1.638X 0.982	1.665 X 0.991	1.2 X 0.6	1.205 X 0.605	1.3 X 1.6

The study focused in Oslo, Norway (latitude: 59.5° N and longitude: 10.4° E) whose local solar irradiation is shown in Figure 1. For the simulation, a flat rooftop with a total available surface area of 100 m^2 was selected for detailed design of PV systems. It was assumed that the PV modules faces towards south (zero azimuths). The type of PV modules and their specifications is summarized in Table 1.

The site is assumed to be located near to the weather stations, so the PVsyst's weather data files will approximate the local weather conditions well. The performances of the PV modules were evaluated mainly based on two yield indicators. The first one is normalized energy production (kWh/kWp/year), which is defined as the energy produced per year by unit of peak power for the installed PV modules. The second indicator is the annual energy production (kWh/m^2), which represents the yearly energy output from the PV system per unit area of the PV modules.

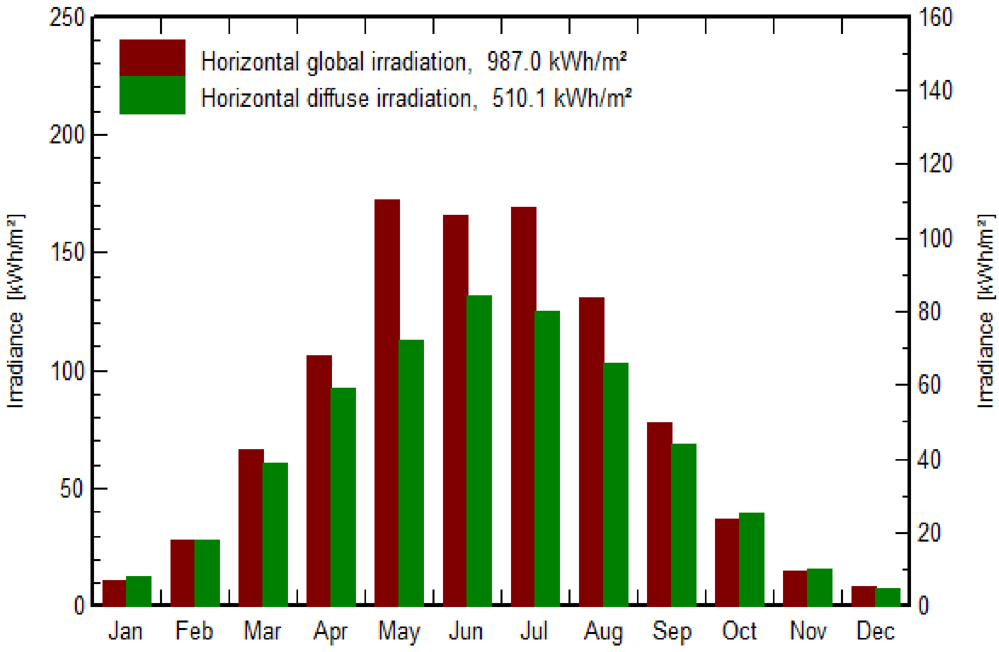

Fig. 1. Monthly solar irradiation on horizontal surface for the site in Oslo, Norway

In PVsyst, PV system losses are represented in to three categories, i.e. optical loss, PV array loss and system loss. The optical loss represents the irradiation deficiency caused by shadings on the PV array and sun's incident angle while the PV array loss encompasses losses related to modules' quality, modules' mismatch, wiring resistance loss and thermal loss. System loss is related to the operation of the inverter to convert the direct current power output from PV array to alternating current power.

In urban areas, tall buildings and trees can cast shadows on PV modules and reduce the energy produced by the PV array. However, in this study, it is assumed that the building is located on flat open terrain so that the surroundings will not shade its top. Thus, only the self-shading effect caused by the PV modules (Figure 2) was considered and linear shading analysis was chosen for the purpose. Moreover, the following design temperatures were used as input for the simulation:

Table 2. Design temperature for the site.

Inputs	Values
Lowest temperature for VmaxAbs limit	-20 °C
Winter operating temperature for VmppMax design	17 °C
Usual operating temperature under 1000 W/m	50 °C
Summer operating temperature for VmppMin design	70 °C

Finally, in order to determine the economic viability of the investment, a simple economic analysis was conducted for a selected PV system using a financial instrument called net present value (NPV). Moreover, the environmental performance of the selected system was also studied.

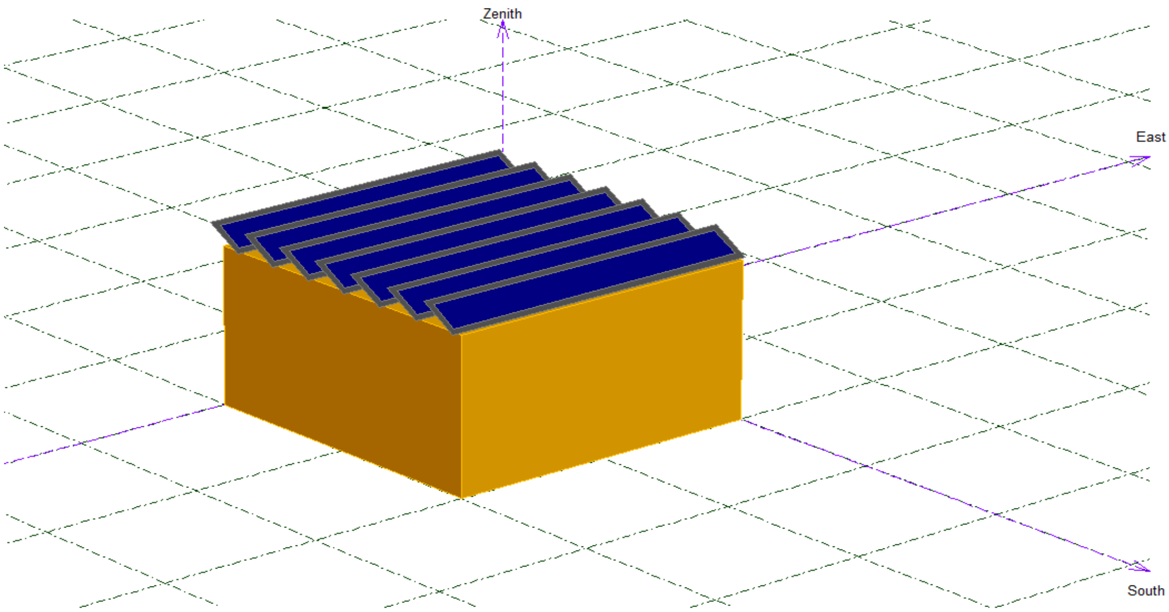

Fig. 2. 3D model for PV modules on rooftop tilted at 15 degree from the horizontal

3. Result and discussion

3.1 *Technical analysis*

In order to examine the performance of different PV cell technologies, five PV module types that differing in efficiency and size are investigated for rooftop mounting. The row spacing between the modules were varied between 0.5 m and 2.5 m while the tilt angles from the horizontal were varied from 20 to 60 degrees. As shown in Figure 3, the 0.5 m row spacing, regardless of PV types and the tilt angles, yielded low energy per module area. This is mainly due to the partial shading caused by the self-shading of PV module row over the other.

The results also indicate that there is no significant energy output variation for a given PV module when the row spacing increases from 1.5 m to 2.5m, because of a negligible effect caused by the self-shading of the modules. The results also revealed that the optimal tilt angle lies between 30 and 40 degrees for the year round operation of the PV systems. Nevertheless, considering snow and dust deposition, the PV module should tend to incline 2-5 degrees more than the optimum value. Furthermore, the m-si based PV system offered the best energy yield, while the a-si PV system produce the lowest energy output, which is the direct reflection the higher efficiency of the m-si module.

Figure 4 shows the simulation results when the rooftop is covered with the five types of PV modules at zero tilt angle. The results indicates that the a-si yielded less energy per modules area and required a larger number of modules to cover the 100 m^2 roof area. This is mainly due to the lower efficiency of the a-si compared to the other PV modules.

The simulation showed that all the modules have an optical loss of 5.6 % due to sun's incidence ray loss, called incident angle modifier (IAM). However, no near shading loss was observed as all the modules are placed horizontally.

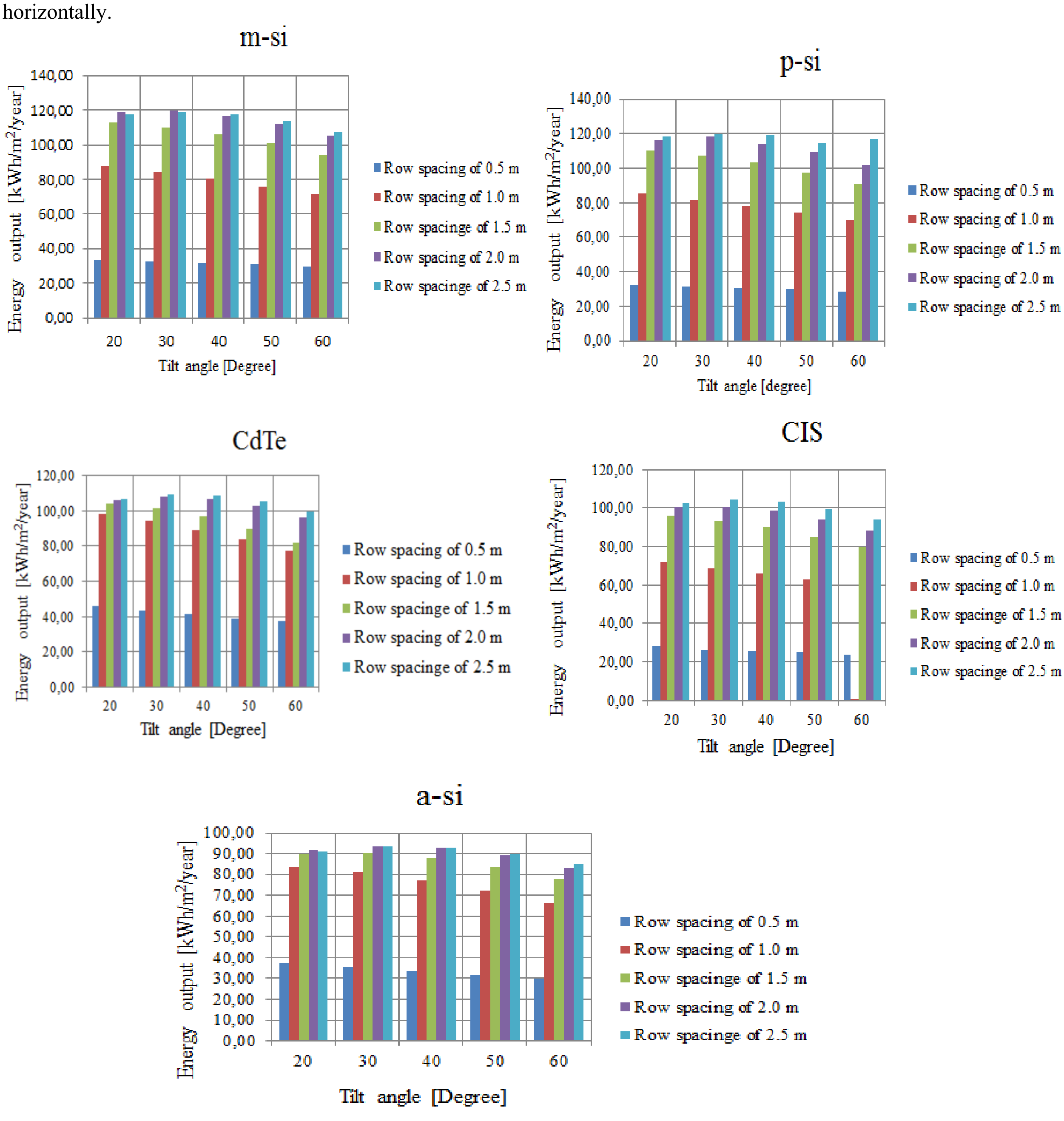

Fig. 3. The annual energy output per modules area of the PV system at different tilt angles and modules' row spacings.

Moreover, the system loss due to the operation of the inverter is nearly the same (3.7%) for all types of modules, but the maximum and minumum PV array losses of 16.2 % and 7.4 % were observed with a-si and CIS modules respectively.

Comparing the energy output of horizontal installation with the tilt angle installations, the former yields less energy due to the latitude of the location, in which the sun's position is usually low in the winter and spring. Hence, the horizontal integration of the PV module into the rooftop is not recommended for Norwegian buildings. The results from Figure 3 and 4 show that the energy yield is strongly dependent on the PV cell or module technologies and the operating conditions of the PV array, in this case, the tilt angle and row spacing.

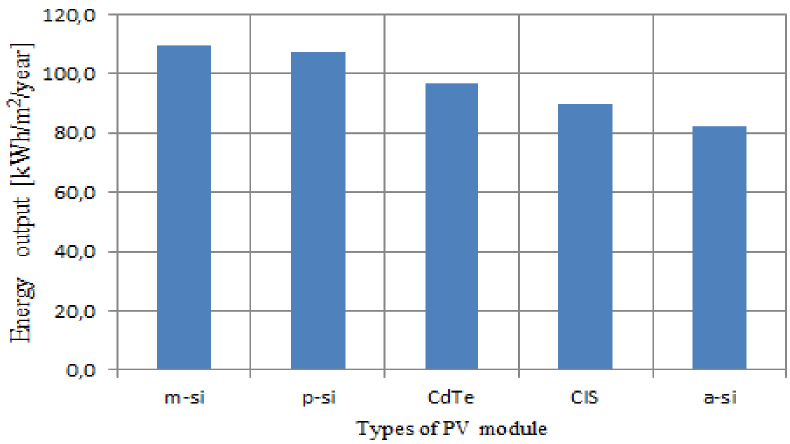

Fig. 4. The annual energy output for five PV modules at zero tilt angle.

Because the m-si PV system showed the best performance in terms of energy output per square meter of the module, it was selected for further analysis. The modules were tilted at different angles and the yearly specific energy production of the system is depicted in Figure 5. The results revealed that energy output varies with tilt angle and that the maximum energy output was achieved at a tilt of 30 degrees and a row spacing of 2.5 m. The results also revealed that row spacing has more impact than tilt angles, despite no significant difference between a row spacing of 2.0 m and 2.5 m. The effect of the tilt angle is insignificant, particularly for the 0.5 m row spacing. Interestingly, the installation with 30 degrees of tilt and 1.5 m of row spacing yields 7,492 kWh/year energy, which is sufficient to meet the annual energy demand of an efficient Norwegian residential house (100 m^2 heat floor area) whose energy demand 70 kWh per heated floor area per year.

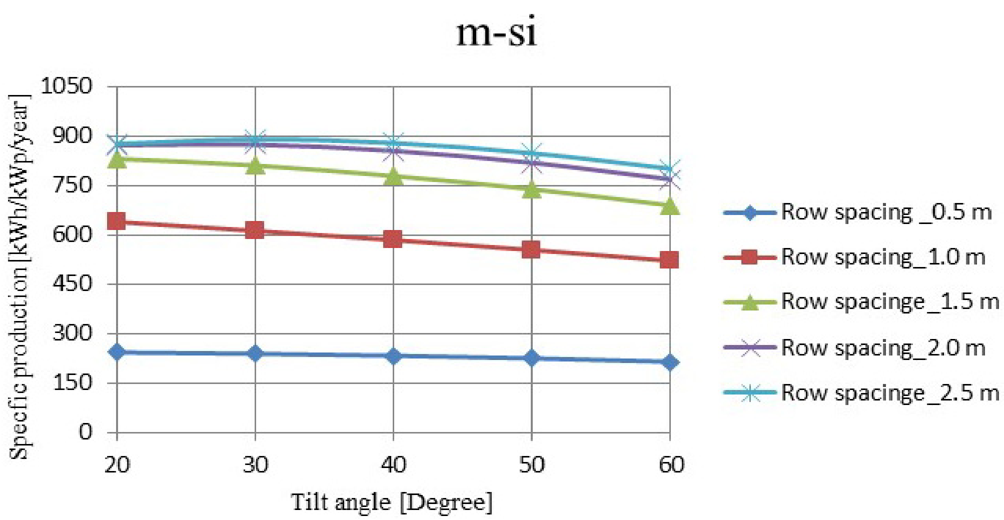

Fig. 5. Performance ratio of the m-si PV module at various tilt angles and row spacing.

Self-shading due to the PVmodule is a single shading factor that is considered in this study, i.e. the effects of surrounding buildings and trees are not included. Self-shading for the m-si module at various row spaces is shown in Table 3. The shading factor for diffuse is 1 for the modules at zero tilt angle regardless of the row spacing which represents. However, for other tilt angles, the shading factor increases as the modules' row spacing increases, which cause the modules to operate at partial load. The shading factor for diffuse represent the overall sky directions seen by the plane of the PV array and it is mainly affected by the geometry of the PV system. Shading factor of one represent the PV arrays fully seen the sun while shading factor zero represents the array is blocked to view the sun. Furthermore, for a given row spacing, the shading factor for diffuse decreases as the tilt angle of the module increases and thus results in a reduction of solar irradiation on the PV array, which has a substantial impacts on energy produced from the system. These effects are reflected in Figure 5

Table 3. Shading factor for diffuse of the m-si module at various tilt angles and with different row spacing.

Tilt angle	Distance between modules' row				
	0.5	1.0	1.5	2.0	2.5
0	1	1	1	1	1
20	0.342	0.757	0.927	0.966	0.979
30	0.329	0.710	0.878	0.935	0.960
40	0.328	0.670	0.833	0.903	0.936
50	0.327	0.636	0.794	0.872	0.912
60	0.321	0.607	0.761	0.844	0.889

As depicted in table 4, a simulation was also conducted to investigate the various losses of the m-si module while it was tilted at different angles. Change in optical losses due to self-shading of modules and incident angle modifier (IAM) was observed while no significant losses were observed due to the other factors. The more tilted the PV module, the more shading losses for the given row spacing and consequently a reduced in energy production.

Table 4. Percentage of losses for m-si module at row spacing of 1.5 m and various tilt angle.

	Tilt angle [degree]				
Losses	20	30	40	50	60
Near shading loss	8.8	14.4	19	22.5	25.3
IAM loss	3.6	3.3	3.2	3.2	3.5
Irradiation loss	5.2	5.2	5.4	5.7	6.0
Module temperature loss	2.8	2.8	2.7	2.5	2.1
Module quality loss	1.2	1.2	1.2	1.2	1.2
Module mismatch loss	4.2	4.2	4.3	4.3	4.3
Ohmic wiring loss	0.7	0.7	0.7	0.7	0.7
Inverter operation loss	7.9	8.0	8.0	8.3	8.5

The simulation results in Figure 6 revealed that the m-si module's yearly average performance ratio, which relates the actual and the theoretical energy output of the PV system, was found to be 67.2%, which is in the normally expected range of between 60 % and 80 % [7]. Factors such as shading, modules' surface temperature and intensity of the solar radiation and components performance may contribute to the loss of the performance.

The monthly average performance ratio reaches its maximum value of about 0.72 in May and its minimum value of 0.32 in December. In the months from March to September, the performance ratio is in the recommended range, which could be attributed to the high levels of solar radiation at the site, as shown in Figure 1. Furthermore, the high temperature coefficient of the m-si may also contribute to the loss related to the high surface temperature of the PV module during the summer.

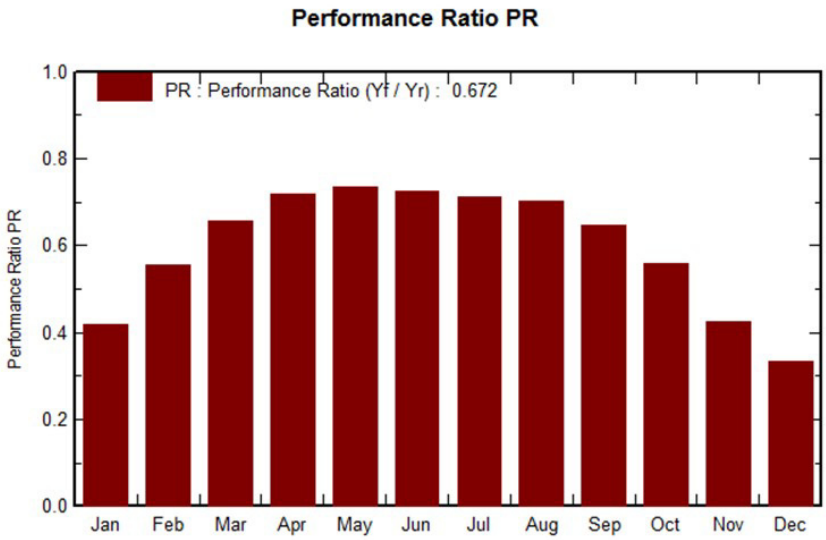

Fig.6. Performance ratio of the m-si PV modules at row spacing of 1.5 meter and tilt angle of 30 degree.

The solar reflection from surfaces of the ground, called albedo, varies seasonally (e.g., snow in the winter and trees in the summer). The default value for the PVsyst simulation is 0.2 for all months of the year. A simulation was conducted for m-si PV module (row spacing of 1.5 m) by varying the albedo of the ground from 0.2 to 0.6, and the results are shown in Table 5. The energy output is not significantly influenced by albedo for low tilt angles. The influence of the albedo was observed when the modules are tilted to steeper angles, for example 60 degree, which is near the winter optimum tilt angle. Hence, the tilt angles of the modules could be considered to increase to absorb more reflected irradiance from the earth's surface. The results also signify that the effects of albedo should be clearly considered during the integration of PV modules into facades (90 degree tilt).

Table 5. Effect of Albedo on the m-si PV system on the energy output [kWh/year].

	Albedo Values		
Angle [degree]	0.2	0.4	0.6
20	7676	7684	7691
30	7492	7508	7525
40	7199	7231	7262
50	6827	6877	6927
60	6377	6451	6526

3.2 Economic analysis

The net present value (NPV) method was used to perform the economic analysis, considering the current specific cost of a complete PV system: 20,000 NOK/kWp. The current incentive given by the Norwegian government for solar electricity production at residential houses amounting to 10,000 NOK and 1250 NOK per kWp. It was also assumed that the m-si module would operate for 30 years and its efficiency decreases linearly by 0.8 % each year in the 30 years of operation. Moreover, the selling price of electricity to the grid is assumed to be equal to the current purchasing cost, 0.38 NOK/kWh. At 5% interest rate, the NPV of the system is about -96619 NOK, which indicates that the application of the PV onto the Norwegian residential building is at present, not economically attractive. If the rooftop installation designed to covers only the energy consumption of electric equipment in a given house, the NPV becomes -28078 NOK. However, the recent years market development and rapid drop of pricing is a good indication for a better future of building integrated PV systems.

3.3 Environmental performance

A lifecycle assessment of the m-si PV module was performed in order to evaluate the environmental performance of the PV module. CO_2 emissions and cumulative energy demand (CED) were evaluated for 1m^2 of PV panel, m-si, at plant/RER/IU data from Ecoinvent v2.2 database [9]. For a PV lifetime of 30 years, values of 194 kg CO_2eq/m^2 and 3740 MJ/m^2 CED were obtained.

The energy payback time (EPBT) expresses the number of years the system takes to recover the initial energy consumption involved in its creation via its own energy production. The annual electricity generation calculated using the PVSyst was converted to primary energy using a conversion factor of 0.35 [10]. EPBT is calculated in accordance with International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) Task 12 guidelines [11] using Equation 1.

$$\text{EPBT (year)} = \frac{\text{Total primary energy } [MJ/m^2]}{\text{Annual energy generation expressed as primary energy } [MJ/m^2/y]} \quad (1)$$

The CO_2 emission rate is a useful index for determining how effective a PV system is in terms of global warming. Since minimizing global warming is a frequently mentioned reason for governments to stimulate the use of PV-systems, the CO_2 emission per kWh of PV electricity was calculated according to Equation 2.

$$CO_2 \text{ emission } (gCO_2eq/kWh) = \frac{\text{Total } CO_2 \text{ emission during life } [gCO_2 \text{ eq}]}{\text{Annual energy generation } \left[\frac{kWh}{y}\right] * \text{life time}[y]} \quad (2)$$

The results in Table 6 show that the EPBT will take between 3 and 4 years to recover the embodied energy of the selected m-si PV module. In 30 years of operation, this PV module will emit a maximum of 69 gCO_2 per kWh if the modules are tilted at 60 degree and a minimum of 57. 3 gCO_2 per kWh if the tilt angle is 20 degree. In 30 years of operation, this PV module will emit a maximum of 69 gCO_2 eq / kWh, which is lower than the current Norwegian ZEB CO_2 eq factor for electricity of 132 gCO_2 eq/kWh [12].

Table 6. CO_2 eq emission and EPBT from m-si PV module with 1.5 m row spacing and different tilt angle installation.

Tilt angle[degree]	Energy yield [$kWh/m^2/year$]	CO_2 emission [g CO_2/kWh]	EPBT [year]
0	109	59,1	3,3
20	113	57,3	3,2
30	110	58,7	3,3
40	106	61,1	3,4
50	100	64,4	3,6
60	94	69,0	3,9

4. Conclusions

In this study, the performances of grid-connected PV systems, for a residential building in Oslo with a 100 m^2 flat rooftop, were investigated using PVsysts. The site location has average solar radiation of 987 kWh/m^2 on a horizontal surface. The study showed that PV modules' row spacing in the array and their tilt angles should not be neglected when designing grid-connected PV systems for rooftop. Moreover, with the current price of electricity and the low level of financial support from the government, grid-connected PV systems are not financially profitable, particularly if we consider the fact that the PV system would cover the residential building's annual energy demands. From an environmental point of view, the m-si PV module would emit a maximum of 69 g CO_2/kWh in its 30 years of operation, with an energy payback time of 3.9 years.

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