SOLAR ENERGY AVAILABLE DEPENDING ON THE DIFFERENCE IN SLOPE AND ORIENTATION OF THE ROOFS IN CASCAVEL - PR

ENERGIA SOLAR DISPONÍVEL CONFORME A DIFERENÇA DE INCLINAÇÃO E ORIENTAÇÃO DOS TELHADOS EM CASCAVEL - PR

Michael Collin Vargas

Universidade Estadual do Oeste do Paraná, Cascavel, PR, Brasil
Mestre em Engenharia de Energia. E-mail: michaelcollin95@gmail.com
https://orcid.org/0000-0003-0166-4100

Paulo Sérgio Wolff

Universidade Estadual do Oeste do Paraná, Cascavel, PR, Brasil
Mestre em Engenharia Agrícola. E-mail: paulo.wolff@unioeste.br

Jair Antonio Cruz Siqueira

Universidade Estadual do Oeste do Paraná, Cascavel, PR, Brasil
Doutor em Agronomia. E-mail: jair.siqueira@unioeste.br
https://orcid.org/0000-0002-8140-444X

Luciene Kazue Tokura

Universidade Estadual do Oeste do Paraná, Cascavel, PR, Brasil
Pós-Doutora em Engenharia de Energia. E-mail: lucienetokura@gmail.com
https://orcid.org/0000-0001-9758-0141

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Abstract: The research aims to identify and evaluate the availability of solar energy in the four seasons of the year as a function of the different inclinations and orientations of the roofs of urban buildings in the city of Cascavel - PR, determining the variability of the solar energy incident on the surfaces studied. The work was carried out considering three types of roof coverings (ceramic, fiber cement and metal), the corresponding slope at which they should be installed and the cardinal direction. The four seasons were also taken into account to determine seasonal variations. Daily solar radiation data for Cascavel was used to determine the solar energy available on each roof according to slope and cardinal orientation. The results determined the effect of roof inclinations and orientations on the availability of solar energy incident on the roof surface, with the aim of using this energy for photovoltaic generation. The main considerations led to the conclusion that the most effective arrangement of solar panels is one that maximizes efficiency while maintaining an affordable cost. This is achieved through the most suitable installation, with a North orientation being preferable, followed by West, East and South. The choice is also influenced

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by the slope of the roof, where ceramic roofs result in greater energy generation when facing north, compared to metal or fiber cement roofs. However, for other directions, metal and fiber cement materials outperform ceramic due to the smaller reduction in productivity throughout the day.

Keywords: Photovoltaic panel. Inclination. Orientation. Available energy.

Resumo: A pesquisa objetiva-se em identificar e avaliar a disponibilidade da energia solar nas quatro estações do ano em função das diferentes inclinações e orientações dos telhados das edificações urbanas da cidade de Cascavel – PR, determinando a variabilidade da energia solar incidente sobre as superfícies estudadas. O trabalho foi realizado considerando três tipos de coberturas de telhados (cerâmica, fibrocimento e metálica), a inclinação correspondente na qual devem ser instalados e a direção cardeal. Além disso, foram consideradas as duas estações do ano para determinação das variações sazonais. Foram utilizados os dados da radiação solar diária para Cascavel para a determinação da energia solar disponível em cada telhado de acordo com a inclinação e a orientação cardeal. Como resultados fora determinado o efeito das inclinações e orientações dos telhados na disponibilidade de energia solar incidente sobre a superfície dos mesmos, com a finalidade de utilização dessa energia para a geração fotovoltaica. As principais considerações permitiram concluir que a disposição mais eficaz de painéis solares é aquela que maximiza a eficiência, mantendo um custo acessível. Isso é alcançado através da instalação mais adequada, sendo preferível a orientação para o Norte, seguida pelo Oeste, Leste e Sul. A escolha também é influenciada pela inclinação do telhado, onde telhados cerâmicos resultam em maior geração de energia quando voltados para o Norte, em comparação com telhados metálicos ou de fibrocimento. No entanto, para outras direções, os materiais metálicos e de fibrocimento superam os cerâmicos devido à menor redução na produtividade ao longo do dia.

Palavras-chave: Painel fotovoltaico. Inclinação. Orientação. Energia disponível.

Introduction

In recent years, the development of clean and green energy has been a priority in this new era, due to the increasing scarcity of fossil fuel resources. In recent decades, there has been severe environmental degradation due to rapid population growth, excessive consumerism, and industrial activities (FADDOULI et al., 2023; PAN, 2023).

Toxic materials generated and released by human activities are one of the main factors that cause significant environmental problems. In addition to toxic materials, the increasing production of greenhouse gases such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), sulfur oxides (SO_2 and SO_3), and nitrogen oxides (NOx) has become a significant threat by creating adverse effects on a planetary scale. The combustion of fossil fuels and the disposal or release of industrial waste, industrial, urban, agricultural, electronic, and plastic waste are activities with devastating environmental effects (EDWARDS, 2022).

According to Opeyemi (2022), in addition to new ecological problems, non-renewability and unequal distribution of fossil fuel resources is a challenge, as many products are manufactured with compounds derived from crude oil. According to Gani (2022), one of the main sources of CO_2 emissions is the fossil fuel energy production industry. Based on estimates provided in the "World Energy Outlook 2014" published by the International Energy Agency (IEA), from 2011 to 2035, global energy consumption will increase by a third. It is estimated that 37.2 gigatonnes of CO_2 will be released if fossil energy production capacity increases by 20%. In the "World Energy World Energy Outlook 2021" report, the goal of net-zero emissions is expected to be achieved by 2050. Reducing industries' dependence on fossil fuels and developing and widely using methods of producing renewable and clean, renewable and clean energy are crucial steps towards achieving net-zero emissions. In addition to air pollution, water pollution is also a major concern. Due to the rapid growth of industries and urbanization, significant amounts of polluting materials have been introduced into water resources.

According to Epe (2019), in Brazil, the energy situation is adverse to the global one. It should be noted that its electricity matrix is characterized by being more renewable than energy due to the participation of 65% of hydroelectric plants. In addition, wind, solar, and biomass energy represent a share of 15% of the Brazilian electricity matrix, helping to keep it, for the most part, renewable.

According to Bohn (2019), the interest in solar energy in Brazil became more attractive after Normative Resolution 482/2012 and 687/2015, decreed by the National Electric Energy Agency (ANEEL), establishing general conditions for micro and mini-generation distributed to energy distribution systems, and also created the energy compensation system. With the advent of ANEEL Resolution 687/2015 (ANEEL, 2012), the installation of systems connected to the conventional electricity grid through the credit compensation system was allowed. These systems, when used in residential consumer units, are installed on the roofs of homes.

In this context, photovoltaic solar energy stands out for its growth worldwide, as well as for its low cost, compared to other renewable sources, and also for its performance and benefits for society and the environment. In several countries around the world, the incentive for the use of this renewable source has already been applied in recent years, recently in Brazil incentives were created in this context, enabling the expansion and use of this energy source in distributed generation in the country, as well as financing systems.

In turn, the roofs have different slopes according to the type of material used for roofing. In addition, they present guidelines regarding the incidence of the sun's rays in disagreement with the recommended guidance for the installation of photovoltaic systems. In the southern hemisphere, the recommendation is to orient the photovoltaic systems to the true north and tilt them in this direction at an angle corresponding to the latitude of the site.

This work hypothesizes that different inclinations and orientations for the installation of photovoltaic systems affect the capacity of electricity generation by these systems. The present study aimed to determine the solar energy available in different inclinations and orientations of roofs of urban buildings in the summer and autumn seasons. Regarding the proposed method for obtaining solar irradiance data, prototypes were used with the same inclinations as the ceramic roofs (i= 37%) and fiber cement and metal (i=18%) in the 4 cardinal directions established for the roofs, aiming at measuring the irradiance from the period of sunrise to sunset. Every 15 minutes, with averages every hour.

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Metodology

Location of the experiment and general provisions

The research work was developed in the CASA Project, at Unioeste – Cascavel Campus – Pr, longitude 53º 27' 19" W, latitude 24º 57' 21" S, and altitude of 781m. The average annual daily solar radiation is 4.80 kWh/m². day (CRESESB, 2017). The study considered three types of roof coverings (ceramic, fiber cement, and metal) and their respective slope recommendations by the NBR 15873 (2010) standard. The orientation of each roof was considered according to the four cardinal points (North, South, East, and West).

Determination of global solar irradiance data on inclinations and orientations of prototypes

For the orientation of the prototypes in which the global solar irradiances were determined, with the use of a DQL-8 compass and a theodolite, the Magnetic North was determined. Using the current magnetic declination calculated by the NOAA software (2017), with latitude and longitude input, the orientation of the prototypes about Geographic North (True North) was obtained.

Subsequently, with the aid of the theodolite, an angle of 17° was measured horizontally with vertical locking, corresponding to the value of the magnetic declination found, to the right of the Magnetic North of the site for determining the Geographic North, establishing the alignment of the North of the prototype with the Geographic North found.

The compass used was the Pocket Transit Precision Geological Compass model DQL-8, accompanied by a leather case for compass protection, available at GEOLAB (Geoprocessing Laboratory of Unioeste). By orienting it levelly, the orientation of Magnetic North was obtained.

With an angular accuracy of 2" (two seconds) and an angular reading of 1" (one second), the Orient Theodolite CDT-02 is equipped with 2 (two) electronic liquid crystal displays. It was also made available by Unioeste's GEOLAB and, with the help of the compass, the azimuth of Magnetic North was determined.

With a vertical inclination of 90° (ninety degrees) and a horizontal displacement of 0° (zero degrees), the Magnetic North is fixed on the device.

With the magnetic declination value of 17° (seventeen degrees), it rotates clockwise, fixing when this angle is at 17°, which is, in turn, the magnetic declination value. Thus, obtaining the Geographic North.

The inclination of the faces of the prototypes in each cardinal direction (North, South, East and West) was defined for the ceramic roof, according to NBR 8039. To this end, the definition of the standard that informs that the inclination of the ceramic roof must be between 32 and 40% was considered. Therefore, considering the local arrangements and the average slope at which these roofs are installed, a prototype (Figure 1) was used to represent it with the respective slope of 37% (i= 37% or 20°) in each orientation of the prototype faces, as can be seen in Figure 3.

To determine the slope of metal and fiber cement roofs, the recommendation of NBR 15930 (2010) was considered, which suggests that these types of roofs use the data contained in the manufacturers' catalogs.

Thus, we used the slope data from the Technical Guide of Fiber Cement Tiles and Roof Accessories from Brasilit (2014), which recommends that the slope for this type of roof should be greater than 5° and no more than 15° of inclination.

For metal roofs, the minimum recommended slope is 8% for roofs with a water length of no more than 20m, according to the manufacturer's catalogue Kingspan Isoeste (2017). In general, for this type of roof, the minimum possible slope is 5-8%. However, technical catalogs, such as the one by Eternit (2008), are very clear about the geometric arrangement of this roof and the inclination, and thus the slope was adopted for the ridge-type profile of 18% (i= 18% or 10°).

Therefore, realizing that the slope of the fiber cement and metal roofs are very similar, a single prototype was used to represent the slope and orientation of the two types of roofs, fixing the slope, for the purposes of the study, at 18% (i= 18% or 10°).

The prototypes were made of recyclable material and properly coated with thin film and insulated. The defined slopes of 37% for ceramic roofs and 18% for metal and fiber cement roofs were determined using an inclinometer on all sides of the prototypes and verifying the flatness of the base of the prototypes (Figures 2 and 3).

Figure 1- Prototypes with the indicated inclinations and orientations

Source: Prepared by the authors.

Figure 2- Inclinometer indicating the inclination of 18% or 10°

Source: Prepared by the authors.

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Figure 3- Inclinometer indicating the inclination of 37% or 20°

Source: Prepared by the authors.

The data of global solar irradiance incident on each surface were collected using an INSTRUTHERM MES-100 portable pyranometer. This measurement is made by placing the pyranometer on the desired face and, thus, the irradiance value arriving at that surface is read thus, with this value, the sum of the solar energy available for each orientation and inclination is performed.

The collections were made as follows: for each season, the months that compose it are subdivided into five parts, having the same interval, and within each interval, a measurement is made, both for open and cloudy skies. However, as cloudy days were the most exceptional, some measurements exceeded these ranges. This was done for a better distribution of measurements during the beginning, middle, and end of each cycle.

Thus, 40 spreadsheets were generated for the summer and fall. For each station, there are 10 spreadsheets for open days, 5 for 18% slope and 5 for 37%. The same goes for cloudy days, having 5 worksheets for each slope studied.

The measurement is made considering the beginning of sunrise and its twilight. With each measurement, the magnetic slope is corrected and this measurement takes place every 15 minutes. Generating a spreadsheet that is too large, therefore, an hourly average is made, generating better spreadsheets and thus obtaining the data from graphs and other spreadsheets that will be shown below.

Determination of the percentage of solar energy available on roofs with ceramic, fiber cement, and metal roofs

With the data of the solar energy available seasonally for each type of roof, a comparison was made between the solar energy available on the inclined plane (as recommended for each type of roof covering) with the solar energy available on the north facing with the same recommended slope. I was considering the solar energy available on the north face as corresponding to the total available energy incident on the site.

Results and discussions

From the collection of global solar irradiance data on each face of the prototypes, the Tables below were elaborated, which present, respectively, the average solar irradiance of the hourly average (W/m2) in the North, West, South, and East directions in the slope of 18%

(metal roofs and fiber cement) and 37% (ceramic roofs). The Figures show the irradiance behavior over a day of clear and cloudy skies, respectively for the four cardinal orientations and for the slopes of 18% and 37%.

Summer season

Open sky days

Regarding the face facing North, it can be seen that the highest irradiance, of 1090.26 W/m², is at 1 p.m. For West and South, the highest value, of 1048.73 W/m² and 956.60 W/m² respectively, is at 2 pm. On the other hand, for the east-facing face, the highest value, of 1031.12 W/m², is found at 12 o'clock (Table 1 and Figure 4).

Table 1- Average Solar Irradiance of the Hourly Average (W/m²) of Summer in the North, West, South and East directions in the inclination for metal and fiber cement roofs (i=18%)

Hours	North	West	On	East
07:00	9.44	9.77	9.69	11.29
08:00	53.12	41.37	46.41	67.43
09:00	350.58	228.38	303.48	409.40
10:00	686.34	475.85	586.71	733.40
11:00	910.50	706.17	777.61	939.14
12:00	1056.12	918.30	932.07	1031.12
13:00	1090.26	1046.82	922.77	961.55
14:00	1037.03	1048.73	956.60	936.65
15:00	910.43	1008.39	872.10	799.88
16:00	647.75	789.03	698.75	541.03
17:00	427.48	575.34	467.79	325.73
18:00	156.99	226.51	189.22	133.34
19:00	5.65	6.44	6.53	4.85

Source: Prepared by the authors.

Regarding the faces facing North and South, it can be seen that the highest irradiance, of 1136.48 W/m² and 850.76 W/m² respectively, is at 1 p.m. To the East, the highest value, of 1069.34 W/m², is at noon. On the other hand, for the west-facing face, the highest value, of 1073.95 W/m², is found at 2 p.m. (Table 2 and Figure 5).

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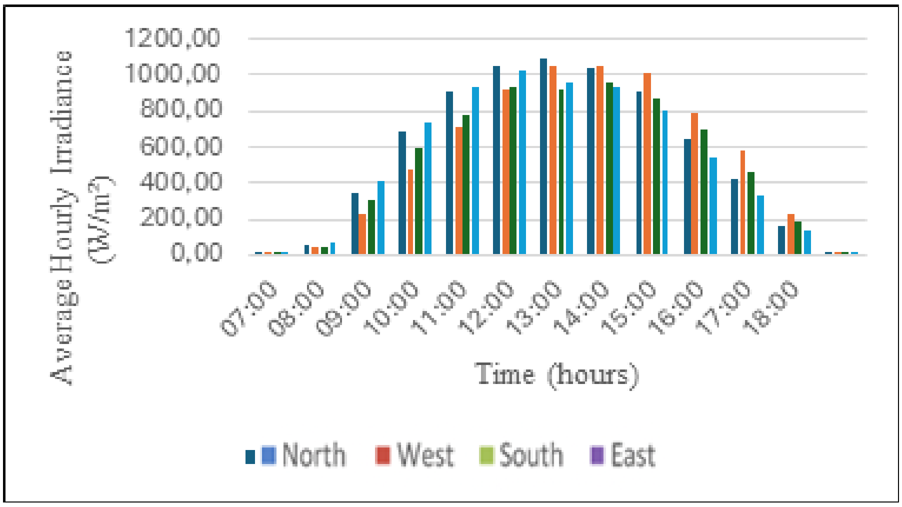
Figure 4 - Average irradiance of the hourly average for metal and asbestos cement roofs (i=18%)



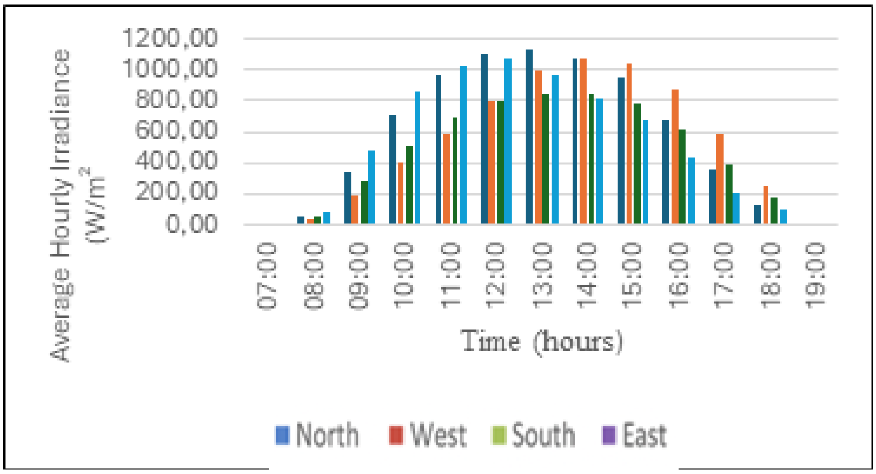
Source: Prepared by the authors.

Table 2- Average Solar Irradiance of the Hourly Average (W/m²) of Summer in the North, West, South and East directions in the inclination for ceramic roofs (i=37%)

Hours	North	West	On	East
07:00	10,80	10,06	10,27	12,10
08:00	57,31	44,78	60,34	91,35
09:00	344,93	198,03	287,53	477,45
10:00	708,72	402,78	505,09	863,36
11:00	965,28	590,28	696,28	1028,34
12:00	1100,72	803,06	799,86	1069,34
13:00	1136,48	989,70	850,76	970,50
14:00	1078,58	1073,95	839,25	813,83
15:00	954,60	1046,05	786,68	676,58
16:00	671,96	872,75	610,00	428,91
17:00	355,13	580,79	394,66	199,01
18:00	136,72	255,87	180,85	97,70
19:00	6,63	7,53	7,74	5,33

Source: Prepared by the authors.

Figure 5 - Hourly average irradiance for ceramic roofs (i=37%)



Source: Prepared by the authors.

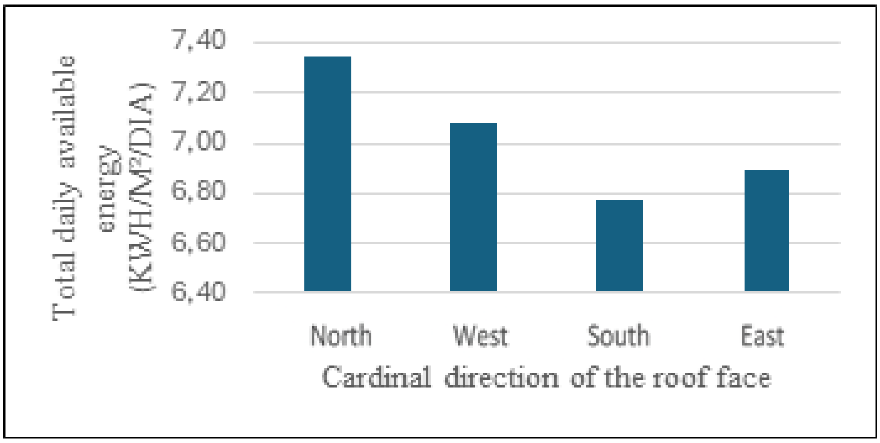
With the data from both tables, two others were constructed (Table 3 and 4), relating the Available Solar Energy (kWh/m²/day) - both for Ceramic Roofs (i=37%) and for Metal and Fiber Cement roofs (i=18%) in the North, West, South and East directions -, with the solar energy available in the ideal reference for the local latitude and longitude. Whose orientation and inclination correspond to the north face. A graph of total daily available energy was also made (Figures 6 and 7).

Table 3- Available Solar Energy (kWh/m²/day) for Metal and Fiber Cement Roofs (i=18%) in the North, West, South and East directions

Cardinal Direction	North	West	On	East
Energy (kWh/m²/day)	7,34	7,08	6,77	6,89
Percentage Of Available Energy Relative to North Face (%)	100	96,45	92,21	93,91

Source: Prepared by the authors.

Figure 6 - Total daily available energy (i=18%).



Source: Prepared by the authors.

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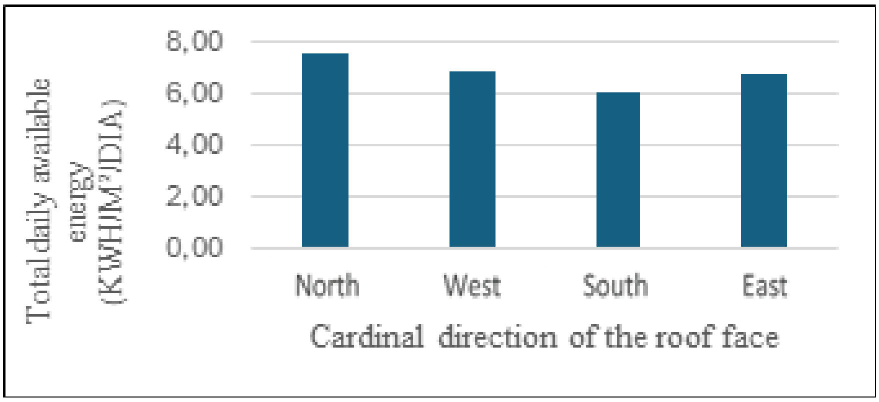
It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place would come the West with 96.45%, with East and South being the faces with the lowest energy, with 93.91% and 92.21% respectively.

Table 4 - Available Solar Energy (kWh/m²/day) for Ceramic Roofs (i=37%) in the North, West, South and East directions

Cardinal Direction	North	West	South	East
Energy (kWh/m²/day)	7,53	6,88	6,03	6,73
Percentage Of Available Energy Relative to North Face (%)	100	91,34	80,09	89,45

Source: Prepared by the authors.

Figure 7 - Total daily available energy (i=37%).



Source: Prepared by the authors.

It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place would come the West with 91.34% and, with East and South being the faces with the lowest energy, 89.45% and 80.09% respectively.

Cloudy days

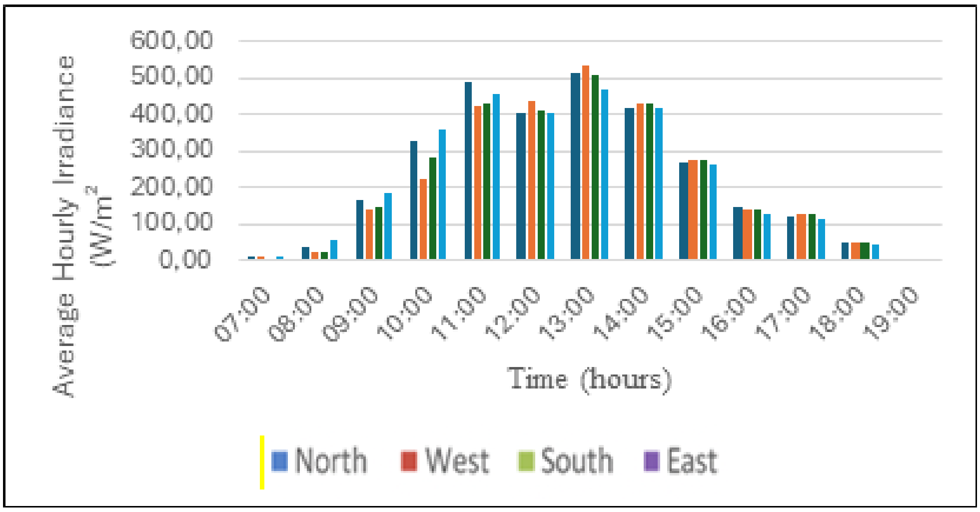
Regarding the face facing North, it can be seen that the highest irradiance, of 510.45W/m², is at 1 p.m. For the West and South, the highest value, of 534.15 W/m² and 506.88 W/m² respectively, is 1 p.m. On the other hand, for the east-facing face, the highest value, of 472,50 W/m², is found at 1 p.m. (Table 5 and Figure 8).

Table 5 - Available solar energy (kWh/m²/day) for ceramic roofs (i=37%) in the North, West, South and East directions

Hours	North	West	On	East
07:00	8,09	7,77	7,35	8,66
08:00	33,49	23,09	26,70	53,52
09:00	164,45	137,91	148,16	183,41
10:00	324,10	221,30	278,38	358,33
11:00	484,06	425,31	427,63	470,20
12:00	400,60	433,30	408,58	405,38
13:00	510,45	534,15	506,88	472,50
14:00	414,48	428,95	430,55	419,60
15:00	269,18	272,43	277,10	263,08
16:00	144,75	137,40	140,23	136,58
17:00	122,18	123,45	127,18	116,65
18:00	46,19	49,11	49,24	46,01
19:00	4,33	4,96	3,70	3,25

Source: Prepared by the authors.

Figure 8 - Average irradiance of the hourly average for metal and asbestos cement roofs (i=18%).



Source: Prepared by the authors.

Regarding the face facing North, it can be seen that the highest irradiance, of 511.89/m², is at 11 am. For the West and South, the highest value, of 500.92 W/m² and 531.80 W/m² respectively, is 1 p.m. On the other hand, for the east-facing face, the highest value, 481.39 W/m², is found at 2 p.m. (Table 6 and Figure 9).

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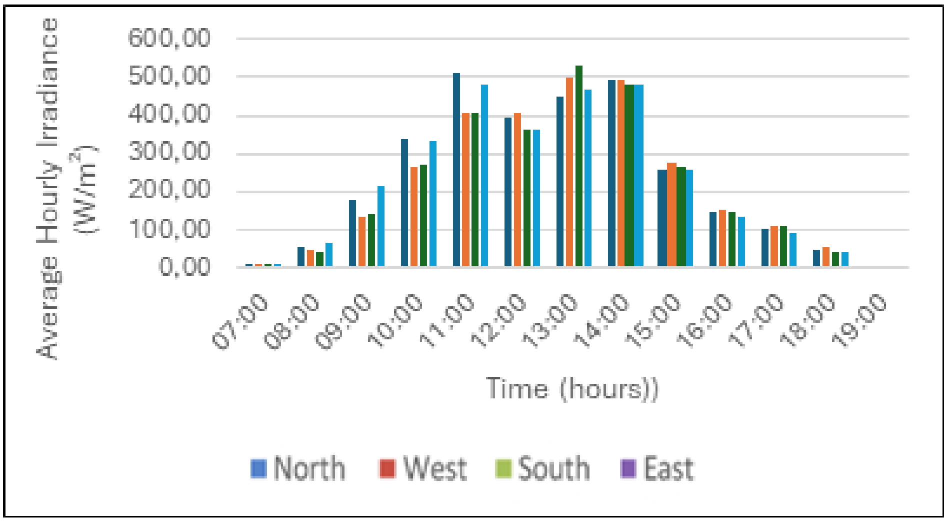
Table 6 - Average Solar Irradiance of the Hourly Average (W/m²) of Summer in the North, West, South and East directions at the inclination for ceramic roofs (i=37%)

Hours	North	West	On	East
07:00	8,47	9,87	8,32	8,75
08:00	56,14	46,31	42,64	66,01
09:00	178,01	133,63	137,94	213,10
10:00	340,28	264,60	268,10	331,28
11:00	511,89	409,03	407,30	479,93
12:00	395,90	403,60	365,68	360,46
13:00	449,67	500,92	531,80	470,38
14:00	493,68	493,56	479,71	481,39
15:00	259,05	273,55	264,13	258,35
16:00	149,08	154,33	148,78	136,78
17:00	103,35	107,83	107,58	93,98
18:00	49,60	52,28	43,65	43,86
19:00	5,27	4,25	4,97	4,23

Source: Prepared by the authors.

Figure 9 - Average hourly irradiance for ceramic roofs (i=37%).



Source: Prepared by the authors.

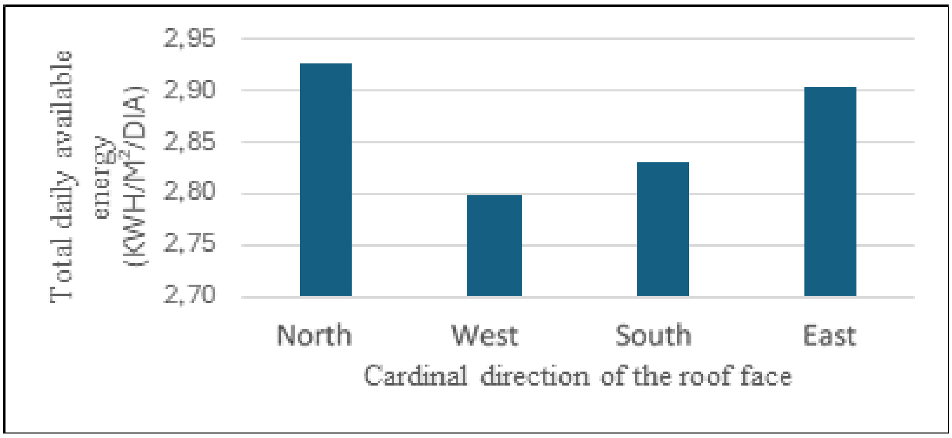
With the data from both tables, two others were constructed (Tables 7 and 8), relating the Available Solar Energy (kWh/m²/day) - both for Ceramic Roofs (i=37%), as well as for Metal and Fiber Cement roofs (i=18%) in the North, West, South and East directions -, with the solar energy available in the ideal reference for the local latitude and longitude. Whose orientation and inclination correspond to the north face. A graph of total daily available energy was also made (Figures 10 and 11).

Table 7- Available Solar Energy (kWh/m²/day) for Metal and Fiber Cement Roofs (i=18%) in the North, West, South and East directions

Cardinal Direction	North	West	On	East
Energy (kWh/m²/day)	2,93	2,80	2,83	2,94
Percentage Of Available Energy Relative to North Face (%)	100	95,65	96,76	99,26

Source: Prepared by the authors.

Figure 10 - Total daily available energy (i=18%)



Source: Prepared by the authors.

It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place would come the East with 99.26%, with the South and West being the faces with the lowest energy, with 96.76% and 95.65% respectively.

Table 8 - Available Solar Energy (kWh/m²/day) for Ceramic Roofs (i=37%) in the North, West, South and East directions

Cardinal Direction	North	West	South	East
Energy (kWh/m²/day)	3,00	2,85	2,81	2,95
Percentage Of Available Energy Relative to North Face (%)	100	95,11	93,67	98,27

Source: Prepared by the authors.

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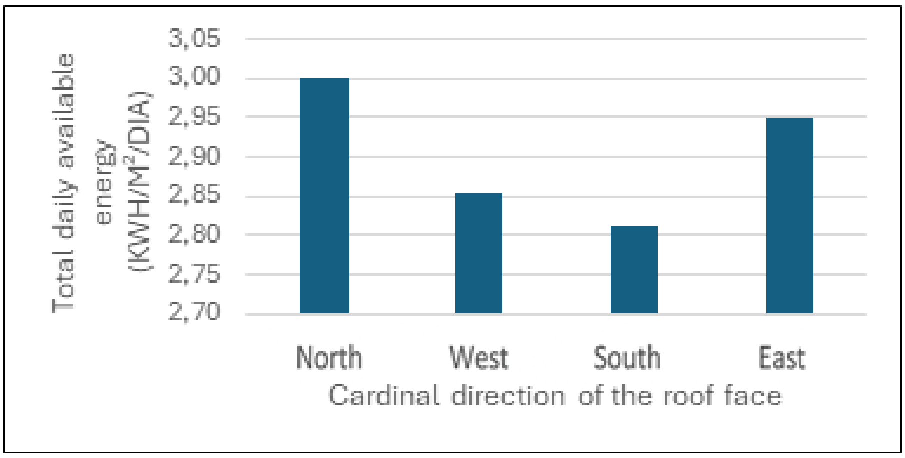
Figure 11- Total daily available energy (i=37%)



Source: Prepared by the authors.

It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place was the East with 98.27% and, with the West and South being the faces with the lowest energy, 95.11% and 93.67% respectively.

Autumn season

Days of open skies

Regarding the face facing North, it can be seen that the highest irradiance, of 493,68 W/m², is at 1 p.m. For West and South, the highest value, of 500,92W/m² and 531,80W/m² respectively, is also at 1 p.m. On the other hand, for the Eastwest-facing face, the highest value, of 481,39W/m², is found at 2 p.m. (Table 9 and Figure 12).

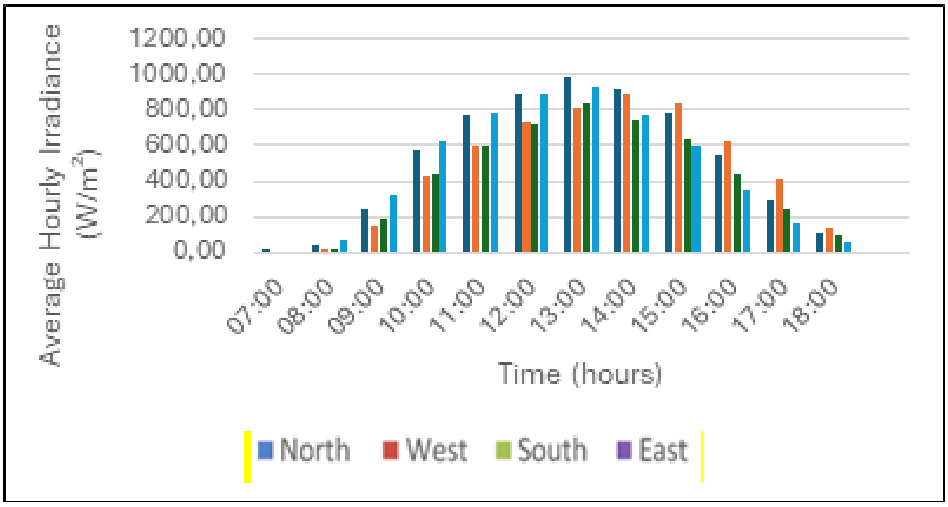
Table 9 - Average Solar Irradiance of the Hourly Average (W/m²) of Autumn in the North, West, South and East directions on the slope for metal and fiber cement roofs (i=18%)

Hours	North	West	South	East
07:00	8,47	9,87	8,32	8,75
08:00	56,14	46,31	42,64	66,01
09:00	178,01	133,63	137,94	213,10
10:00	340,28	264,60	268,10	331,28
11:00	511,89	409,03	407,30	479,93
12:00	395,90	403,60	365,68	360,46
13:00	449,67	500,92	531,80	470,38
14:00	493,68	493,56	479,71	481,39
15:00	259,05	273,55	264,13	258,35
16:00	149,08	154,33	148,78	136,78
17:00	103,35	107,83	107,58	93,98

18:00	49,60	52,28	43,65	43,86
19:00	5,27	4,25	4,97	4,23

Source: Prepared by the authors.

Figure 12 - Average irradiance of the hourly average for metal and asbestos cement roofs (i=18%).



Source: Prepared by the authors.

Regarding the faces facing North and South, it can be seen that the highest irradiance, of 1104.97 W/m² and 831.34 W/m² respectively, is at 1 p.m. To the East, the highest value, of 1043.94 W/m², is at 1 p.m. as well. On the other hand, for the west-facing face, the highest value, of 965.61 W/m², is found at 2 p.m. (Table 10 and Figure 13).

Table 10 - Average Solar Irradiance of the Hourly Average (W/m²) of Autumn in the North, West, South and East directions at the inclination for ceramic roofs (i=37%)

Hours	North	West	On	East
07:00	0,38	0,00	0,00	0,00
08:00	36,65	13,57	16,88	44,86
09:00	288,55	85,01	145,36	338,99
10:00	644,20	334,08	362,85	676,25
11:00	866,82	553,18	536,73	852,74
12:00	1066,86	766,61	713,51	978,24
13:00	1104,97	902,34	831,34	1043,94
14:00	1006,11	965,61	682,57	708,08
15:00	865,52	913,55	591,55	526,56
16:00	629,58	808,73	451,42	275,13
17:00	357,01	571,59	286,88	119,14
18:00	91,99	174,02	89,63	83,38
19:00	0,38	0,00	0,00	0,00

Source: Prepared by the authors.

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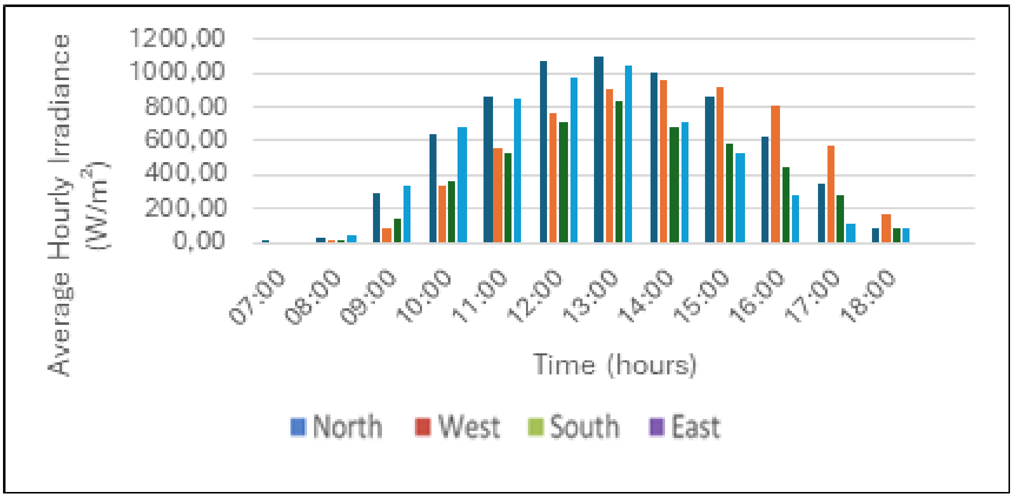
Figure 13 - Hourly average irradiance for ceramic roofs (i=37%).



Source: Prepared by the authors.

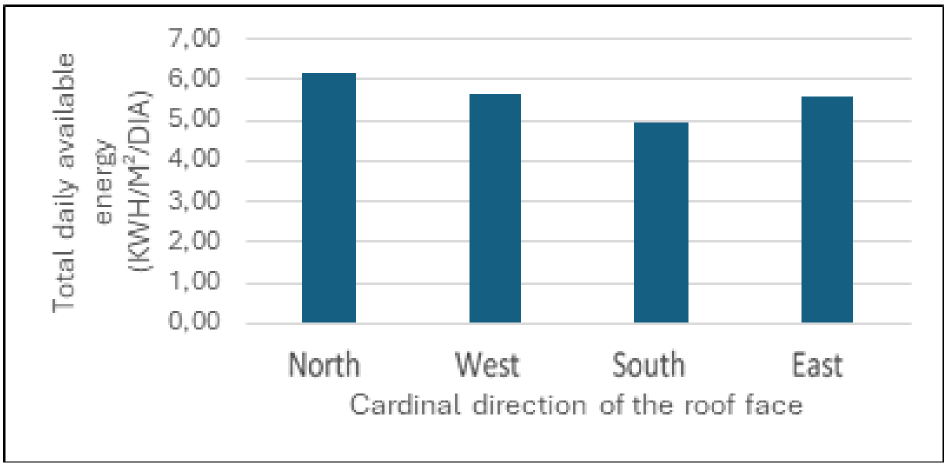
With the data from both tables, two others were constructed (Tables 11 and 12), relating the Available Solar Energy (kWh/m²/day) - both for Ceramic Roofs (i=37%) and for Metal and Fiber Cement roofs (i=18%) in the North, West, South and East directions -, with the solar energy available in the ideal reference for the local latitude and longitude. Whose orientation and inclination correspond to the north face. A graph of total daily available energy was also made (Figures 14 and 15).

Table 11- Available Solar Energy (kWh/m²/day) for Metal and Fiber Cement Roofs (i=18%) in the North, West, South, and East directions

Cardinal Direction	North	West	On	East
Energy (kWh/m²/day)	6,18	5,67	4,98	5,56
Percentage Of Available Energy Relative to North Face (%)	100	91,71	80,55	90,01

Source: Prepared by the authors.

Figure 14 - Total daily available energy (i=18%).



Source: Prepared by the authors.

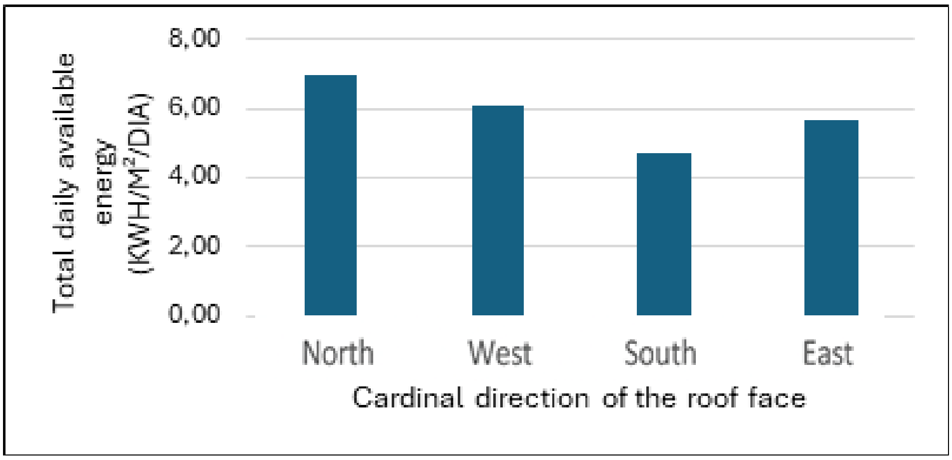
It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place was the West with 91.71%, with East and South being the faces with the lowest energy, with 90.01% and 80.55% respectively.

Table 12 - Available Solar Energy (kWh/m²/day) for Ceramic Roofs (i=37%) in the North, West, South, and East directions

Cardinal Direction	North	West	South	East
Energy (kWh/m²/day)	6,69	6,09	4,71	5,65
Percentage Of Available Energy Relative to North Face (%)	100	87,49	67,67	81,16

Source: Prepared by the authors.

Figure 15 - Total daily available energy (i=37%).



Source: Prepared by the authors.

It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place would come the West with 87.49% and, with East and South being the faces with the lowest energy, 81.16% and 67.67% respectively.

Cloudy days

Regarding the faces facing North and West, it can be seen that the highest irradiance, of 415.28 W/m² and 389.05 W/m², respectively, is at 12 o'clock. For the East and South, the highest value, of 313.71 W/m² and 328.85 W/m², respectively, is at 2 p.m. (Table 13 and Figure 17).

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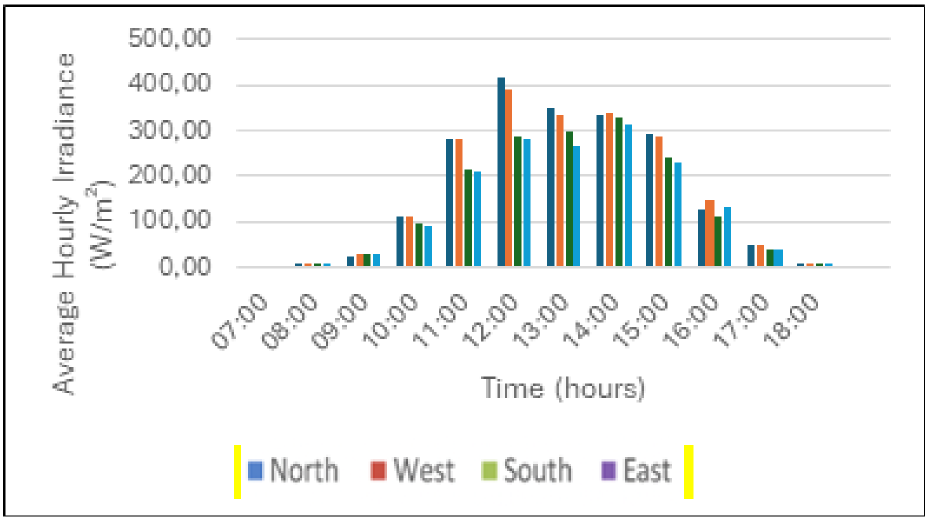
Table 13- Mean Solar Irradiance of the Hourly Average (W/m²) of Autumn in the North, West, South and East directions on the slope for metal and fiber cement roofs (i=18%)

Hours	North	West	On	East
07:00	0,00	0,00	0,00	0,00
08:00	8,81	7,96	7,77	7,93
09:00	26,34	28,05	27,75	31,18
10:00	110,24	110,84	98,95	91,79
11:00	279,80	281,29	213,74	207,80
12:00	415,28	389,05	284,87	284,11
13:00	351,13	333,28	295,42	264,31
14:00	331,88	336,38	328,85	313,71
15:00	291,61	284,89	241,87	232,26
16:00	129,10	148,49	113,44	133,26
17:00	50,52	52,09	42,02	41,84
18:00	11,21	10,79	11,42	11,17
19:00	0,00	0,00	0,00	0,00

Source: Prepared by the authors.

Figure 17- Average irradiance of the hourly average for metal and asbestos cement roofs (i=18%).



Source: Prepared by the authors.

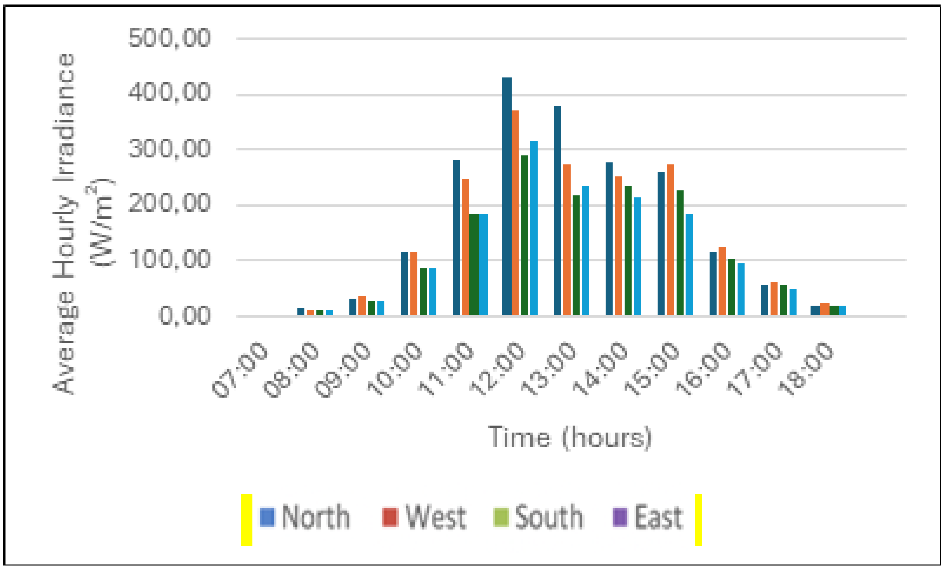
Regarding the faces facing North and South, it can be seen that the highest irradiance, of 432.11 W/m² and 290.65 W/m² respectively, is at 12 o'clock. For the East and South, the highest values are 316.40 W/m² and 290.65, respectively, also at 14 hours (Table 14 and Figure 18).

Table 14- Average Solar Irradiance of the Hourly Average (W/m²) of Autumn in the North, West, South and East directions at the inclination for ceramic roofs (i=37%).

Hours	North	West	On	East
07:00	0,00	0,00	0,00	0,00
08:00	13,69	11,68	11,32	11,65
09:00	33,20	35,48	29,11	29,13
10:00	115,09	115,12	85,91	85,68
11:00	280,46	246,26	182,82	184,76
12:00	432,11	370,17	290,65	316,40
13:00	381,59	272,39	219,21	233,71
14:00	276,49	253,58	233,74	214,83
15:00	262,76	274,04	228,08	184,36
16:00	118,30	126,99	103,12	94,06
17:00	56,32	63,51	58,79	47,61
18:00	19,79	23,34	17,95	18,98
19:00	0,00	0,00	0,00	0,00

Source: Prepared by the authors.

Figure 18- Hourly average irradiance for ceramic roofs (i=37%).



Source: Prepared by the authors.

With the data from both tables, two others were constructed (Tables 15 and 16), relating the Available Solar Energy (kWh/m²/day) - both for Ceramic Roofs (i=37%) and for Metal and Fiber Cement roofs (i=18%) in the North, West, South and East directions -, with the solar energy available in the ideal reference for the local latitude and longitude. Whose orientation

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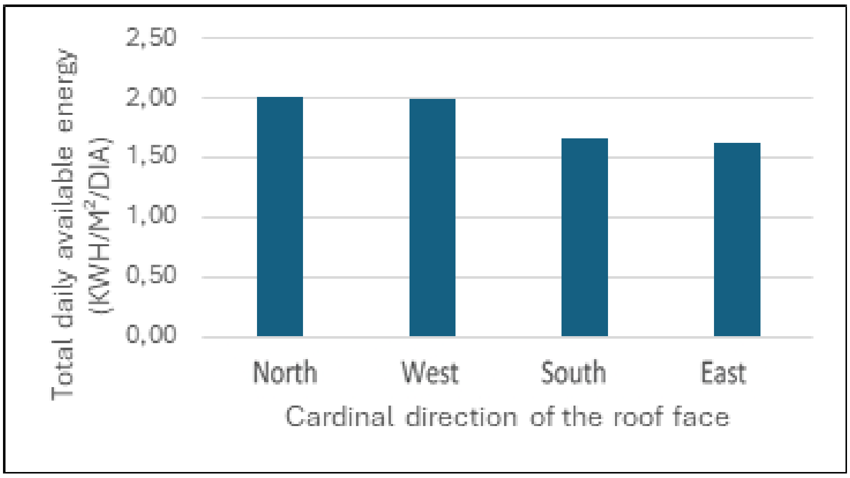
and inclination correspond to the north face. A graph of total daily available energy was also made (Figures 19 and 20).

Table 15- Available Solar Energy (kWh/m²/day) for Metal and Fiber Cement Roofs (i=18%) in the North, West, South and East directions.

Cardinal Direction	North	West	On	East
Energy (kWh/m²/day)	2,01	1,98	1,67	1,62
Percentage Of Available Energy Relative to North Face (%)	100	98,86	83,06	80,73

Source: Prepared by the authors.

Figure 19- Total daily available energy (i=18%).



Source: Prepared by the authors.

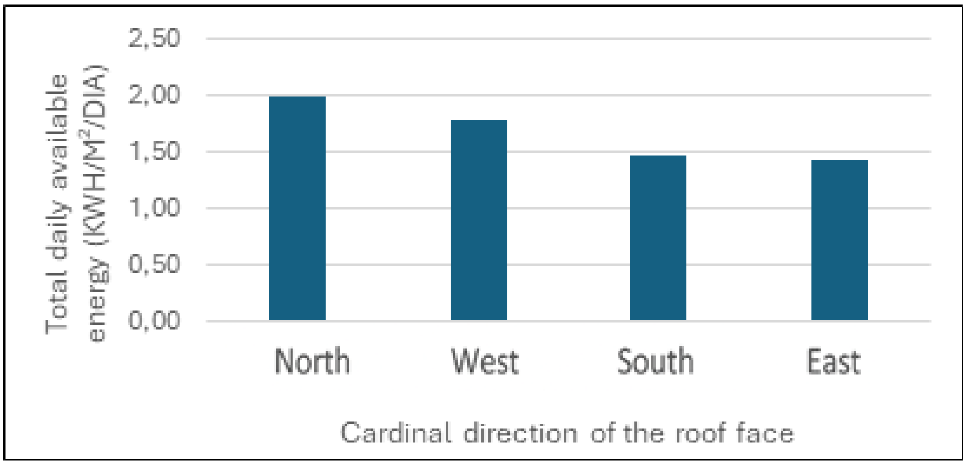
It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place would come the West with 98.86%, with the South and East being the faces with the lowest energy, with 83.06% and 80.73% respectively.

Table 16- Available Solar Energy (kWh/m²/day) for Ceramic Roofs (i=37%) In the North, West, South and East directions.

Cardinal Direction	North	West	South	East
Energy (kWh/m²/day)	1,99	1,79	1,46	1,42
Percentage Of Available Energy Relative to North Face (%)	100	90,09	73,41	71,42

Source: Prepared by the authors.

Figure 20- Total daily available energy (i=18%).



Source: Prepared by the authors.

It can be seen that the total energy available is higher for the face facing the North with 100% use (ideal). In second place would come the West with 90.09% and, with the South and East being the faces with the lowest energy, 73.41% and 71.42% respectively.

Monteiro Júnior (2016) analyzed the performance of photovoltaic systems with different angles of inclination and azimuth located in Palmas – Tocantins -, using simulators in ideal operating conditions of SFCR projects. Their results show that, in general, there is a range of varieties of inclinations and azimuth orientations in which the photovoltaic system has maximum annual energy losses of the order of 2% in relation to the energy obtained by a system with an inclination equal to latitude and azimuth 0 (orientation with geographic north). For the condition of installation on east- or west-facing roofs and typical slopes between 10° and 15°, the annual electricity production shows a reduction of 2%. The results of the simulations showed that in the east orientation the annual production was 1.2% higher when compared to the west orientation. The worst condition of annual energy production occurs when the photovoltaic array is oriented to the south and with an inclination of around 30°, with annual energy losses of around 17.75%.

The results obtained from the experiment are reconciled with those of Monteiro Júnior (2016) in the aspect that yes, there are inclinations and orientations that give losses of the order of 2%, however they are not predominant. Roofs with a 10° or 18% slope show reductions of more than 2%, ranging from 3 to 10% approximately for days of open skies and from 1 to 20% approximately for days of cloudy skies. In agreement, the worst annual energy condition occurs when the arrangement is oriented to the south, however differing from the inclination, which for the results obtained, for an inclination of 20° (37%), there are reductions ranging from 20 to 32%, greater than those found by Monteiro Júnior (2016).

The data presented here have coefficients of variation in a range between 10 and 20%, which according to the Classification according to Ferreira, F.V. (1991), Experimental Statistics Applied to Agronomy, classifies with respect to the accuracy of the process that a range between 15% and 20% has a good accuracy, having an average coefficient of variation.

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Sizing of a PV system and pricing system

As explained above, it can be seen that there are several percentage variations in relation to the maximum amount of ideal energy capture. The irradiance that reaches the north face is greater for ceramic roofs - for both seasons - however the losses to the other directions are also greater for this type of roof. Thus, all orientations, except for the North, had a better use for metal roofs (i=18%). For a 500kWh/month On Grid Solar Generation System, there are several efficiencies in capturing this energy along all slopes and orientations studied here for the city of Cascavel - PR. Tables 17 and 18 show below the values that will be captured:

Table 17- Really usable power of a 500kWh/month On Grid Solar Generation System in the summer season.

Summer	Inclination	North	West	On	East
Open	18%	500	482,25	461,05	469,55
Open	37%	500	456,70	400,45	447,25
Cloudy Sky	18%	500	478,25	483,80	496,30
Cloudy Sky	37%	500	475,55	468,35	491,35

Source: Prepared by the authors.

Table 18- Usable power of a 500kWh/month On Grid Solar Generation System in the autumn season.

Autumn	Inclination	North	West	On	East
Open	18%	500	458,55	402,75	450,05
Open	37%	500	437,45	338,35	405,80
Cloudy Sky	18%	500	494,30	415,30	403,65
Cloudy Sky	37%	500	450,45	367,05	357,10

Source: Prepared by the authors.

A 500kWh/month On Grid Solar Generation System, according to the average prices offered in the Free Market, is around R$ 17,599.00. Therefore, it is possible to estimate the total cost of this investment considering its allocation dependent on the type of roof, its orientation and inclination. Thus, having to discount its efficiency (in case the orientation is not the North) and if in case of need of 100% of this capture of 500kWh/month, having to buy one of higher power due to the losses generated from its poor application. For most cases, a 600kWh/month generator would solve the problem at a cost of R$ 23,199.00, on the same website surveyed (Mercado Libre). An increase of R$ 5,600.00 in the budget just for the improper and inefficient allocation of the photovoltaic panel.

Considerations

The hourly mean irradiance in the open air, measured over time, resembles a polynomial function of the 2nd degree (quadratic) with concavity downwards. For cloudy days, the graph is unstable, totally variable and conditional to the weather interferences of the day.

Considering the solar energy available for the North face as ideal (100%), an available energy was obtained for each orientation and inclination and thus compared them with the ideal one, obtaining a percentage of utilization.

For metal and asbestos cement roofs (i=18%) there was a better use of solar energy for the west side and, worse, for the south. For ceramic roofs (i=37%), the same result was obtained. However, although the uptake for the North face in the ceramic roofs is always higher, for the other orientations the same does not occur considering that the metal and fiber cement roofs have less losses and, accordingly, more efficiency than the ceramic ones for the rest of the slopes (West, South and East).

Therefore, comparing the two types of roofs with their respective slopes and orientations, it is preliminarily seen that the solar energy available daily to the north face of ceramic roofs is, in relation to that of metal roofs and fiber cements, between 2 and 8% higher.

However, for the West, South and East faces, the energy available daily for metal and asbestos cement roofs is higher than that of ceramic roofs. That is, with the exception of the installation in the North, which despite being ideal may not be feasible or reconcilable depending on the building, metal and fiber cement roofs provide a greater use of solar energy in relation to ceramic roofs due exclusively to their inclination, with the orientations, in descending order of use: West, East and South.

Compared to the data from Monteiro Júnior (2016), there is a major variable in question that, at first, is immeasurable: geographic location. This is of fundamental importance to consider the data, because for the same experiment different results can be obtained according to its location, with different climate, temperature, atmosphere and environments that will reproduce different results.

Thus, it can be concluded that the best photovoltaic arrangement is the one in which you can have a better use at a low cost-benefit. And this is due to the most usable form of its installation which, as seen, is best when facing the North followed by the West, East and South. This still depends on the slope of your roof, which for ceramic roofs north-facing photovoltaic panels produce more energy than metal or fiber cement. However, for the other orientations, metal and fiber cement stand out over ceramics because they have less reduction in productivity throughout the day.

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