Photovoltaic system design for electrical supply in a parking lot

Diseño de un sistema fotovoltaico para suministro eléctrico en un aparcamiento

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Abstract

Proposing new projects to boost photovoltaic solar energy can open opportunities to harness a free and virtually inexhaustible source like the sun, especially in countries such as Mexico where solar resources are among the most abundant on Earth's surface. In this chapter, a proposal for photovoltaic sizing was developed to supply energy to the buildings in the graduate studies area of the Instituto Tecnológico de la Laguna, located in Torreón, Coahuila. An analysis of the total estimated electrical consumption of these buildings was conducted to justify the installation of the photovoltaic system. Two proposals for photovoltaic sizing were presented, utilizing different inverter technologies. A 3D model was created using "Sketchup" to simulate the system installation. Costs and return on investment for the proposed project were also estimated. The results demonstrated that the use of central inverters was more cost-effective than the use of microinverters.

Solar parking, Photovoltaic installation, Solar energy

Resumen

Proponer nuevos proyectos que impulsen la energía solar fotovoltaica puede abrir oportunidades para aprovechar una fuente gratuita y prácticamente inagotable como el sol en países como México donde el recurso solar es uno de los mas abundantes en la superficie terrestre. Es presente trabajo presenta la propuesta de un estacionamiento fotovoltaico interconectado a la red en el Instituto Tecnológico de la Laguna que, además de generar energía eléctrica, proteja los automóviles de las intensas radiaciones que se viven en la zona. Para este trabajo se realizó un análisis del consumo eléctrico total estimado de los tres edificios para comparar la energía consumida con la energía generada. Se presentaron dos propuestas de dimensionado fotovoltaico utilizando diferentes tecnologías de inversores. Se creó un modelo en 3D utilizando el programa "Sketchup" para simular la instalación del sistema. También se estimaron los costos y el retorno de inversión del proyecto pensado para el 2023. Los resultados mostraron que el uso de inversores centrales resulta más económico que el uso de microinversores.

Estacionamiento solar, Instalación fotovoltaica, Energía fotovoltaica

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Introduction

Due to the great potential of photovoltaic generation that Mexico has due to its high levels of radiation compared to other countries, the idea of proposing new projects that enhance the presence of photovoltaic solar energy can generate a niche of opportunities for energy use with a free and relatively inexhaustible source such as the sun. In addition, taking advantage of and promoting the consumption of these technologies reduces their price, making their application and manufacture more viable in the long term.

The Instituto Tecnológico de la Laguna located in Coahuila, Mexico, houses a large number of students and professors, which results in the provision of large areas for the parking of vehicles, however there are few areas of these that contemplate shading for vehicles as a necessity. The purpose of this work was to design a parking lot that takes advantage of the area of the photovoltaic modules while producing photovoltaic electrical energy that subsidizes a small fraction of the energy consumed by the university. This work contemplates the provisions of NOM-001-SEDE-2012, especially section 690 related to photovoltaic installations.

In this work, the processes, calculations and factors to be considered for the dimensioning of a photovoltaic array designated to a specific and limited area are proposed. In the same way, the sizing process will be carried out using two different current conversion technologies (specifically central inverters and microinverters) in order to discuss their differences, advantages, disadvantages, and propose an optimal model that fits the needs and facilities of the arrangement. In the same way, several models for the arrangement of the modules of the array were analyzed and their advantages and disadvantages were discussed. Finally, an approximate estimate of the dimensions made in this chapter was made, as well as a model made in "Sketchup" to have a better perception of the real dimensions of the installation.

General concepts

In order to understand the elements that make up a photovoltaic array as well as its operation and the geographical and environmental factors that influence its performance, they will be described in this section as a theoretical framework.

Solar resource in Mexico

Mexico has great potential in terms of solar resources, so much so that UNAM (Universidad Nacional Autónoma de México) has highlighted the fact that using only 0.15% of the national territory (approximately 50 km^2) as a photovoltaic generation plant could receive enough solar radiation to meet the consumption needs of a population of 120 million inhabitants [1]. Due to the country's geographical position, it has great potential for harnessing solar radiation (Figure 1), leaving the country in a good position for the transition to the use of clean energy, specifically solar energy [1].

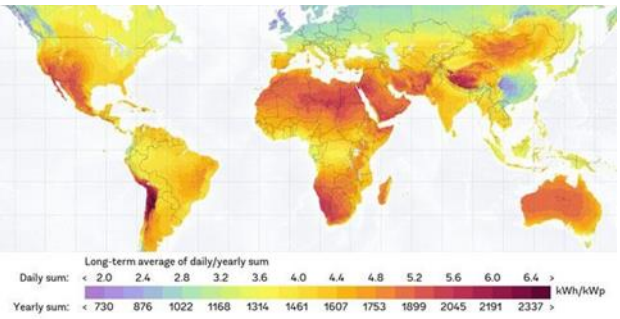


Figure 1 Global radiation map
Source: http://www.gisandbeers.com/cartografia-de-radiacion- solar-mundial/

Encouraging the use of clean energy for electricity production has become a fundamental part of the fight against climate change around the world. Photovoltaic energy, on the other hand, has a great place in Torreón, Coahuila, due to its high levels of solar radiation that it receives daily, due to the fact that it is located near the western part of the country, where a greater amount of radiation is received per square meter (Figure 2) [1]. One of the advantages of photovoltaic energy is that it does not depend on large complex infrastructures such as combined cycle plants, which allows them to be small and minimally invasive. This has made it possible to develop projects where photovoltaic energy systems, especially the modules that make them up, serve a purpose other than producing electricity [2].

Figure 2 Map of Mexico with distribution of the municipalities with the highest radiation
Source: https://solargis.com/es/maps-and-gis-data/download/mexico

Over the years, various innovative ideas have emerged to apply photovoltaic technologies, such as solar chargers for mobile devices, their implementation in aeronautics and public lighting. Among the most outstanding proposals in the field of photovoltaic solar energy is the use of space through the installation of modules with additional functions. For example, photovoltaic parking lots are a promising concept, where the modules not only generate energy, but also provide cover for cars, protecting them from solar radiation, dust, snow, rain or hail (Figure 3) [3].

This dual-functionality approach not only contributes to the generation of clean energy, but also optimizes the use of space, providing additional benefits in terms of comfort and protection. These urban implementations of solar PV demonstrate how innovation in the design and integration of renewable technologies can generate practical and sustainable solutions to everyday needs.

Figure 3 Examples of photovoltaic parking lots
Source: https://www.syscomblog.com/2023/03/que- es-un-toldo-solar-una-decision.html).

Components of photovoltaic systems

As in a human body, a photovoltaic system is made up of several individual parts that perform a separate task, but together they perform the task of transforming solar radiation into consumable electrical energy. The main element of a photovoltaic system is the solar cell, or photovoltaic cell and this is the primary component and smallest unit element of a photovoltaic module (MFV), and the set of interconnected photovoltaic modules is known as a line or "string" of modules [3] (Figure 4).

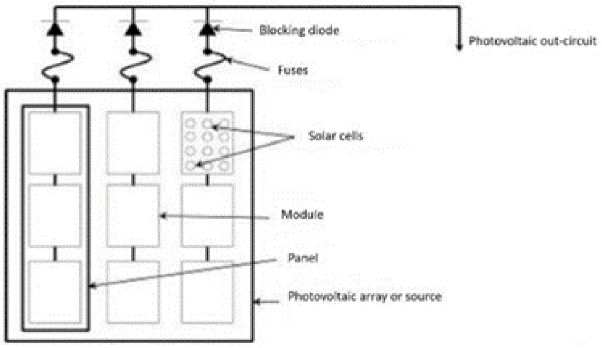


Figure 4 Component diagram of a string of photovoltaic modules
Source: NOM-001-SEDE-2012, Capitulo 690

Photovoltaic modules, on their own, cannot generate consumable electricity for homes or equipment, as the current they emit is not compatible with the conventional power grid. Therefore, it is necessary to connect the modules to a device that transforms the shape of the current signal, and this function is fulfilled by photovoltaic inverters. There are two main types of investors in the market.

The central inverter allows multiple devices to be connected simultaneously, but they are usually large and generate noise (Figure 5). Microinverters, on the other hand, are quieter, more compact, and more versatile, as they are installed close to the modules. However, they have the disadvantage of being more expensive compared to central inverters and do not support so many modules at the same time; newer models generally support no more than four modules at a time (Figure 5).

Figure 5 Example of a central inverter (left) and a micro photovoltaic inverter (right)
Source: https://www.solarwave.com.mx

Both modules and inverters are crucial elements in a photovoltaic system. Both are highly susceptible to excessive currents and surges, making it imperative to install protective devices on each component's connections. It is not only a matter of protecting them against overcurrents, but also of preventing current returns from the power grid.

In this sense, to ensure the protection of photovoltaic modules and inverters, specialized devices designed for direct current are used. These act in a similar way to a diode, unlike the protections used for alternating current (Figure 6). This comprehensive approach to protection is essential to safeguard the integrity and optimal performance of components in the PV system. [4].

Figure 6 Overcurrent protections, on the left, direct current protections, on the right, alternating current protections
Source: www.chtaixi.com and www.trupper.com

Modules in a facility.

To determine the number of solar panels needed in a photovoltaic system, it is necessary to know the energy consumption of the place in case you want to cover the consumption of a home, company or business.

However, in the case of solar parking lots or photovoltaic plants where there is no precise consumption or target production as such, but rather the aim is to take advantage of the space for the maximum possible energy production, the available area is used to determine the maximum number of panels that can be installed. In addition, the dimensions of the solar panels to be used are also taken into account, as these dimensions vary depending on the maximum power they generate. With these values, equation 1 applies:

$$Generated\,power = \#\,modules * Pmax * HSP * FGF \qquad (1)$$

Where "Pmax" is the nominal power of the module under SCT conditions, "HSP" corresponds to the peak solar hours of the region and "FGF" corresponds to the overall operating factor (this value does not have a unit of measurement since it is a quality factor and is usually taken as 0.77).

Power inverter calculation

One of the essential components for interconnected photovoltaic systems is the current inverter, this component is responsible for transforming the voltage or waveform from direct current supplied by photovoltaic modules to alternating current so that it can be accepted by the grid [3] . There are currently two types of inverter technology on the market, microinverters and central inverters.

The latter do not specify the maximum number of modules that the central inverter supports, but the maximum voltage and current that they support, so that in order to be able to size the series and parallel lines of the modules (MFV) of a photovoltaic array without damaging the inverter, equations 2 and 3 are used respectively: [6] so on with the maximum number of microinverters interconnected in the main cable.

Protections of a photovoltaic system

The components of a photovoltaic system must be protected against voltage surges, so that the equipment does not break down, as well as protection against electric shocks or lightning rods [3] ; There are also this type of protections against very high voltages on the market, such as the one in Figure 7.

These protections are commonly called ground protection systems and are very important for any electrical system as they protect from permanent damage to the equipment in the event of a current overload or short circuit that could cause a thermal and electrodynamic overload in the equipment or cause severe damage to the personnel who are handling it [7].

Figure 7 Example of Voltage Protections (SDP)

Along with current protections, voltage protections must be unified in a concentrator box or "String box" whose purpose is, as its name indicates, to concentrate all the multiple connections of an array and provide a means of safe disconnection, these boxes are usually built with fiberglass, resin or aluminum sheets and are widely used in large photovoltaic arrays and generation. An example of these can be seen in Figure 8.

$$Parallel\ MFV = Inverter\ I\ \max \qquad (2)$$

$$MFV\ Isc$$

$$Serial\ MFV = Inverter\ V\ \max \qquad (3)$$
$$MFV\ Vmax$$

Figure 8 Example of a "String box"

However, with microinverters this problem is reduced to the manufacturer's specifications, since all microinverters on the market must provide the maximum characteristics of the module to be connected (either by its maximum voltage, maximum current, power or number of cells) as well as the maximum number of modules per microinverter and

The current generated by the modules is direct in nature, which means that specially designed DC protection devices are required to protect the equipment. However, in order to protect equipment against current returns, it is essential that the protections work in a coordinated manner, acting as a shut-off valve or diode that prevents the flow of current to the module lines. Many devices, such as circuit breakers, incorporate both functions.

Additionally, to ensure the proper functioning of these devices, the protection must be calculated with a factor of 125% of the maximum current of the equipment, in accordance with NOM-001-SEDE- 2012 [3]. Consequently, when calculating equipment protection, circuit breakers are always determined by equation 4, which includes this factor mentioned above.

$$I\ de\ Proteccion = I\ \max\ del\ equipo * 1.25 \quad (4)$$

Wiring a photovoltaic system

Modules and inverters are essential in a photovoltaic system and are sensitive to overcurrents and overvoltages. Therefore, the installation of protective devices at the connections of each component is required to prevent damage. In addition to protecting against overcurrents, it is crucial to prevent current returns from the power grid. To achieve this, special protections for direct current are used in the photovoltaic modules, operating in a similar way to a diode, unlike protections for alternating current (Figure 6). This comprehensive protection approach is essential to ensure the integrity and optimal performance of the PV system, for which equation 5 is implemented.

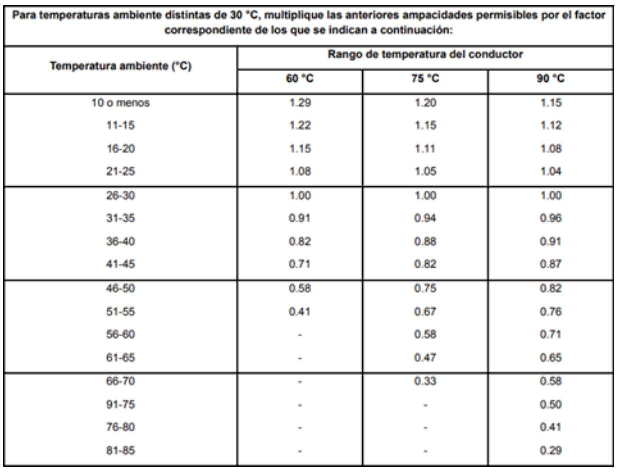
Distance above the roof to the base of the conduit (millimeters)	Temperature adder (°C)
From 0 to 13	33
More than 13 to 90	22
More than 90 to 300	17
More than 300 to 900	14

Table 1 Ambient temperature adjustments for circular pipes exposed to sunlight, extracted from NOM-001-SEDE-2012, 690 (reconstructed)
Source: [3]

Similarly, to determine the temperature factor "Ft" in regions above 30°C ambient temperature, NOM- 001-SEDE-2012 provides table 310-15 (b)(2)(a). This value can be consulted in the table in Figure 9

$$\begin{aligned}&Adjusted\ ampacity = Required\ ampacity \qquad (5)\\&Ft*Fc\end{aligned}$$

The "Fc" factor takes into account the number of wires around the conductor, but for joints with less than 5 wires, this value remains constant at "1". As for "Ft", it represents an average ambient temperature value. However, due to temperature variations in cables close to the ground, table 310-15(b)(3)(c) of NOM-001-SEDE-2012 provides additional values that are added to the ambient temperature of the area to determine the actual temperature of the cable. These values are detailed in Table 1 below.

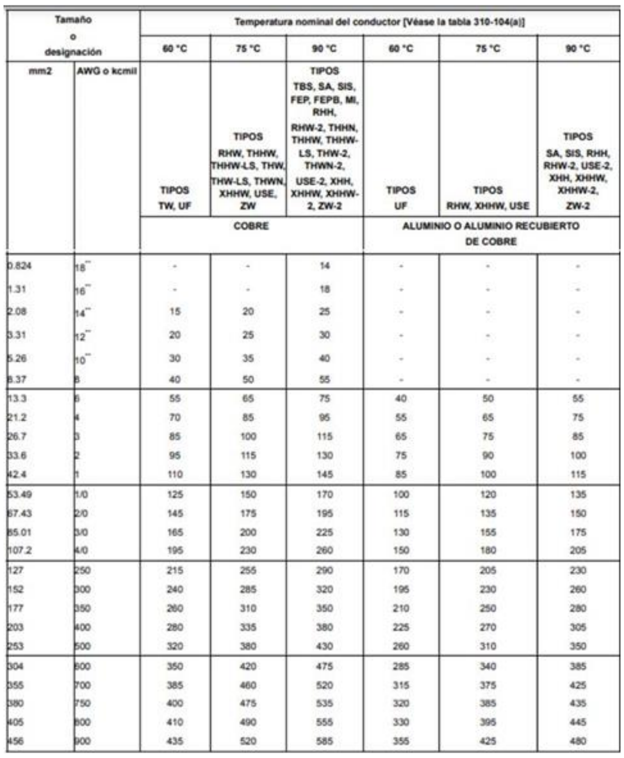


Para temperaturas ambiente distintas de 30 °C, multiplique las anteriores ampacidades permisibles por el factor correspondiente de los que se indican a continuación:			
Temperatura ambiente (°C)	Rango de temperatura del conductor		
	60 °C	75 °C	90 °C
10 o menos	1.29	1.20	1.15
11-15	1.22	1.15	1.12
16-20	1.15	1.11	1.08
21-25	1.08	1.05	1.04
26-30	1.00	1.00	1.00
31-35	0.91	0.94	0.96
36-40	0.82	0.88	0.91
41-45	0.71	0.82	0.87
46-50	0.58	0.75	0.82
51-55	0.41	0.67	0.76
56-60	-	0.58	0.71
61-65	-	0.47	0.65
66-70	-	0.33	0.58
91-75	-	-	0.50
76-80	-	-	0.41
81-85	-	-	0.29

Figure 9 Table 310-15(b)(2)(a) Correction Factors based on an ambient temperature of 30 °C, extracted from NOM-001-SEDE-2012,690
Source: [3]

It is important to note that not all cables are suitable for all applications. It is necessary to correctly size the wiring according to the different activities. Using the wrong gauge can result in overheating of the wire or unnecessary expense.

To calculate the optimal wire gauge in a photovoltaic system, the maximum ampacity of the wire must be known (using equation 6) and then refer to table 310-15 (b)(16) of NOM- 001-SEDE-2012. This table provides the different types of gauge according to their ampacity. The related information is found in the table shown in Figure 10.



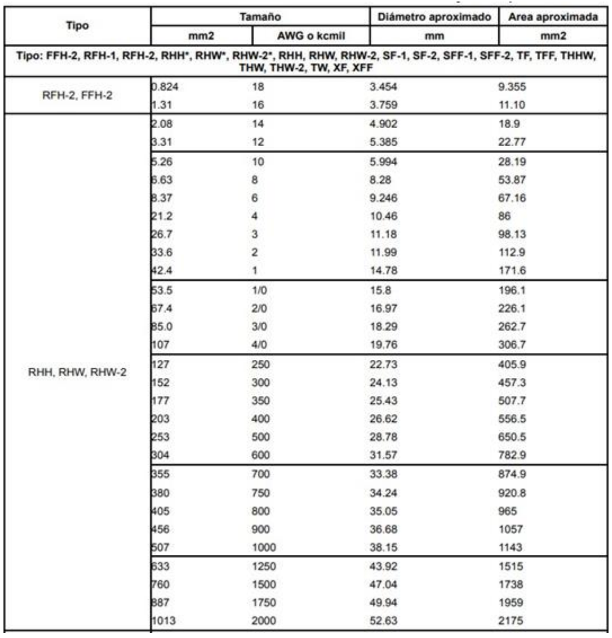
Tamaño o designación		Temperatura nominal del conductor [Véase la tabla 310-104(a)]					
		60 °C	75 °C	90 °C	60 °C	75 °C	90 °C
mm2	AWG o kcmil	TIPOS TW, UF	TIPOS RHW, THHW, THHW-LS, THW, THW-LS, THWN, XHHW, USE, ZW	TIPOS TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THHW-LS, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	TIPOS UF	TIPOS RHW, XHHW, USE	TIPOS SA, SIS, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2
		COBRE			ALUMINIO O ALUMINIO RECUBIERTO DE COBRE		
0.824	18**	-	-	14	-	-	-
1.31	16**	-	-	18	-	-	-
2.08	14**	15	20	25	-	-	-
3.31	12**	20	25	30	-	-	-
5.26	10**	30	35	40	-	-	-
8.37	8	40	50	55	-	-	-
13.3	6	55	65	75	40	50	55
21.2	4	70	85	95	55	65	75
26.7	3	85	100	115	65	75	85
33.6	2	95	115	130	75	90	100
42.4	1	110	130	145	85	100	115
53.49	1/0	125	150	170	100	120	135
67.43	2/0	145	175	195	115	135	150
85.01	3/0	165	200	225	130	155	175
107.2	4/0	195	230	260	150	180	205
127	250	215	255	290	170	205	230
152	300	240	285	320	195	230	260
177	350	260	310	350	210	250	280
203	400	280	335	380	225	270	305
253	500	320	380	430	260	310	350
304	600	350	420	475	285	340	385
355	700	385	460	520	315	375	425
380	750	400	475	535	320	385	435
405	800	410	490	555	330	395	445
456	900	435	520	585	355	425	480

Figure 10 Table 310-15 (b)(16), Permissible ampacities in insulated conductors, extracted from NOM-001- SEDE-2012, 690
Source: [3]

Calculation of the driver's conduit

In all photovoltaic installations, the cables are constantly exposed to solar radiation. To protect them from ultraviolet (UV) radiation and high temperatures in the environment, it is necessary to guide the cables through pipes or conduits, especially those that are exposed to weather conditions as established in the Official Mexican Standard [3].

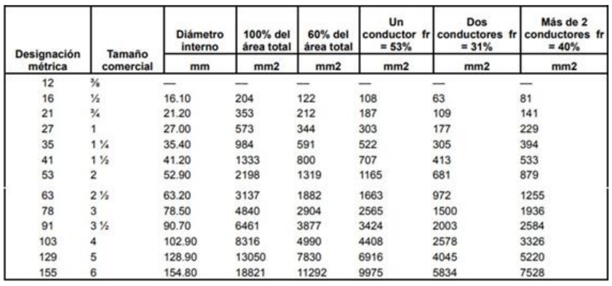
To calculate the appropriate size of the duct, there are tables available, such as Table 5 in Chapter 10 of NOM-001-SEDE-2012 [3] and the Table of "Article 344" of the same regulation. These tables are used by considering the gauge of the cable and the number of conductors to be used, allowing the area of conduit needed to be calculated. Figures 11 and 12 present the relevant data in these tables, respectively.



Tipo	Tamaño		Diámetro aproximado	Area aproximada
	mm2	AWG o kcmil	mm	mm2
Tipo: FFH-2, RFH-1, RFH-2, RHH*, RHW*, RHW-2*, RHH, RHW, RHW-2, SF-1, SF-2, SFF-1, SFF-2, TF, TFF, THHW, THW, THW-2, TW, XF, XFF				
RFH-2, FFH-2	0.824	18	3.454	9.355
	1.31	16	3.759	11.10
RHH, RHW, RHW-2	2.08	14	4.902	18.9
	3.31	12	5.385	22.77
	5.26	10	5.994	28.19
	6.63	8	8.28	53.87
	8.37	6	9.246	67.16
	21.2	4	10.46	86
	26.7	3	11.18	98.13
	33.6	2	11.99	112.9
	42.4	1	14.78	171.6
	53.5	1/0	15.8	196.1
	67.4	2/0	16.97	226.1
	85.0	3/0	18.29	262.7
	107	4/0	19.76	306.7
	127	250	22.73	405.9
	152	300	24.13	457.3
	177	350	25.43	507.7
	203	400	26.62	556.5
	253	500	28.78	650.5
	304	600	31.57	782.9
	355	700	33.38	874.9
	380	750	34.24	920.8
	405	800	35.05	965
	456	900	36.68	1057
	507	1000	38.15	1143
	633	1250	43.92	1515
	760	1500	47.04	1738
	887	1750	49.94	1959
	1013	2000	52.63	2175

Figure 11 Table 5, dimensions of conductors according to their caliber, extracted from NOM-001-SEDE-2012, 690-10

Source: [3]



Designación métrica	Tamaño comercial	Diámetro interno	100% del área total	60% del área total	Un conductor fr = 53%	Dos conductores fr = 31%	Más de 2 conductores fr = 40%
		mm	mm2	mm2	mm2	mm2	mm2
12	⅜	—	—	—	—	—	—
16	½	16.10	204	122	108	63	81
21	¾	21.20	353	212	187	109	141
27	1	27.00	573	344	303	177	229
35	1 ¼	35.40	984	591	522	305	394
41	1 ½	41.20	1333	800	707	413	533
53	2	52.90	2198	1319	1165	681	879
63	2 ½	63.20	3137	1882	1663	972	1255
78	3	78.50	4840	2904	2565	1500	1936
91	3 ½	90.70	6461	3877	3424	2003	2584
103	4	102.90	8316	4990	4408	2578	3326
129	5	128.90	13050	7830	6916	4045	5220
155	6	154.80	18821	11292	9975	5834	7528

Figure 12 Table of measurements for heavy metal conduit, extracted from NOM-001-SEDE-2012, Article 344

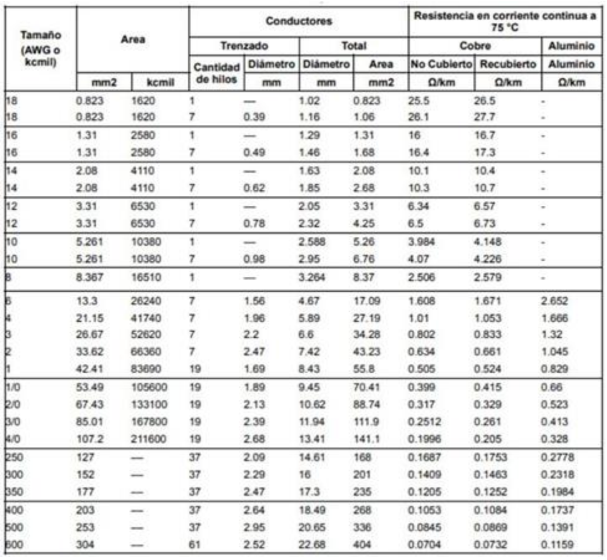
Source: [3]

Voltage Drop or Voltage

One of the problems faced by wiring is voltage drop, this is the loss of potential of a conductor caused by the resistance it possesses due to its length [8]. So, in order to calculate the voltage drop by the length of the cable of a system, the following equation 6 is used:

$$e = Z*I*L\ 10*Ef \qquad (6)$$

Where "e" is the percentage of the voltage drop, "Z" is the current resistance of the conductors in (this value is obtained from the table in Figure 13), which we can obtain from the NOM-001-SEDE-2012 specifically from table 8 Ω [15], "I" is the maximum km current flowing through the conductor in Amperes (A), "L" is the length of the cable in meters (m) and "Ef" is the voltage scheme of the system.



Tamaño (AWG o kcmil)	Area		Conductores				Resistencia en corriente continua a 75 °C		
			Trenzado		Total		Cobre		Aluminio
			Cantidad de hilos	Diámetro	Diámetro	Area	No Cubierto	Recubierto	Aluminio
	mm2	kcmil		mm	mm	mm2	Ω/km	Ω/km	Ω/km
18	0.823	1620	1	—	1.02	0.823	25.5	26.5	-
18	0.823	1620	7	0.39	1.16	1.06	26.1	27.7	-
16	1.31	2580	1	—	1.29	1.31	16	16.7	-
16	1.31	2580	7	0.49	1.46	1.68	16.4	17.3	-
14	2.08	4110	1	—	1.63	2.08	10.1	10.4	-
14	2.08	4110	7	0.62	1.85	2.68	10.3	10.7	-
12	3.31	6530	1	—	2.05	3.31	6.34	6.57	-
12	3.31	6530	7	0.78	2.32	4.25	6.5	6.73	-
10	5.261	10380	1	—	2.588	5.26	3.984	4.148	-
10	5.261	10380	7	0.98	2.95	6.76	4.07	4.226	-
8	8.367	16510	1	—	3.264	8.37	2.506	2.579	-
6	13.3	26240	7	1.56	4.67	17.09	1.608	1.671	2.652
4	21.15	41740	7	1.96	5.89	27.19	1.01	1.053	1.666
3	26.67	52620	7	2.2	6.6	34.28	0.802	0.833	1.32
2	33.62	66360	7	2.47	7.42	43.23	0.634	0.661	1.045
1	42.41	83690	19	1.69	8.43	55.8	0.505	0.524	0.829
1/0	53.49	105600	19	1.89	9.45	70.41	0.399	0.415	0.66
2/0	67.43	133100	19	2.13	10.62	88.74	0.317	0.329	0.523
3/0	85.01	167800	19	2.39	11.94	111.9	0.2512	0.261	0.413
4/0	107.2	211600	19	2.68	13.41	141.1	0.1996	0.205	0.328
250	127	—	37	2.09	14.61	168	0.1687	0.1753	0.2778
300	152	—	37	2.29	16	201	0.1409	0.1463	0.2318
350	177	—	37	2.47	17.3	235	0.1205	0.1252	0.1984
400	203	—	37	2.64	18.49	268	0.1053	0.1084	0.1737
500	253	—	37	2.95	20.65	336	0.0845	0.0869	0.1391
600	304	—	61	2.52	22.68	404	0.0704	0.0732	0.1159

Figure. 13 Table 8, characteristics of conductors

Partial shading of modules can lead to system efficiency losses or overheating issues due to hot spots. Therefore, in static arrangements it is necessary to calculate the length of the shadows produced by other rows of modules that are in front of them, this is achieved by means of equation 7 [5]:

$$d = L*\sin(\beta)\ \tan(61° - |\boldsymbol{\Phi}|) \qquad (7)$$

extracted from NOM-001-SEDE-2012, 690 [3].

Calculation of Module Shadows

A photovoltaic module is a grouping of P-N doped silicon cells that harness the photovoltaic effect to produce electricity. It is also made up of other components with the purpose of protecting them from the weather and providing a higher current and voltage than would be obtained with an individual cell, when combined by series and parallel connections [5].

The efficiency of a module can be affected by different factors, such as the position it is in, the temperature, and the amount of sunlight it receives. To determine the optimal position of the module, it is recommended to install it facing the equator (southward in the Northern Hemisphere and northward in the Southern Hemisphere) and with an inclination similar to the latitude of the place where it is located. It is estimated that even with a small difference of ±5 degrees, this could cause a loss of efficiency of at least 1%. [5].

One of the main problems that arises when installing modules is the shadow coming from nearby objects or even from other rows of subsequent modules. Although photovoltaic systems are generally intended to be installed in areas that are clear of obstacles that can shade, for systems with several rows of modules, the distance between them can be a determining factor in not generating shade from each other (Figure 14).

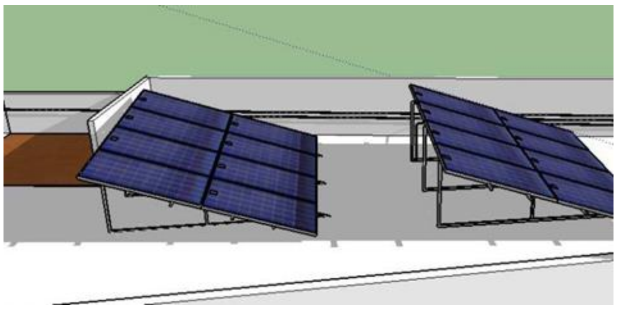


Figure 14 Example of partial shading between modules
Source: https://cceea.mx

Where "d" is the distance of the shadow cast by the module in front, "L" is the length of the module, "β" is the angle of inclination of the module, and "Φ" is the latitude of the place, as shown in Figure 15:

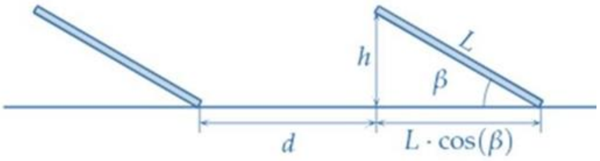


Figure 15 Exemplification diagram for shading calculation between rows of modules
Source: [5]

Methodology

Below are the calculations developed for the dimensioning of the components of the PV (photovoltaic) system with the information from the tables and figures and with the execution of the equations described in the previous section.

Module, central inverter and microinverter selection

For the photovoltaic parking, 500W modules of the JASOLAR brand were chosen, the technical sheet of the modules is below in Figure 16 framed in red.

ELECTRICAL PARAMETERS AT STC

TYPE	JAM66S30 -480/MR	JAM66S30 -485/MR	JAM66S30 -490/MR	JAM66S30 -495/MR	JAM66S30 -500/MR	JAM66S30 -505/MR
Rated Maximum Power(Pmax) [W]	480	485	490	495	500	505
Open Circuit Voltage(Voc) [V]	45,07	45,20	45,33	45,46	45,59	45,72
Maximum Power Voltage(Vmp) [V]	37,62	37,81	37,99	38,17	38,35	38,53
Short Circuit Current(Isc) [A]	13,65	13,72	13,79	13,86	13,93	14,00
Maximum Power Current(Imp) [A]	12,76	12,83	12,90	12,97	13,04	13,11
Module Efficiency [%]	20,2	20,4	20,6	20,9	21,1	21,3
Power Tolerance	0~+5W					
Temperature Coefficient of Isc(α_Isc)	+0,045%/°C					
Temperature Coefficient of Voc(β_Voc)	-0,275%/°C					
Temperature Coefficient of Pmax(γ_Pmp)	-0,350%/°C					
STC	Irradiance 1000W/m², cell temperature 25°C, AM1,5G					

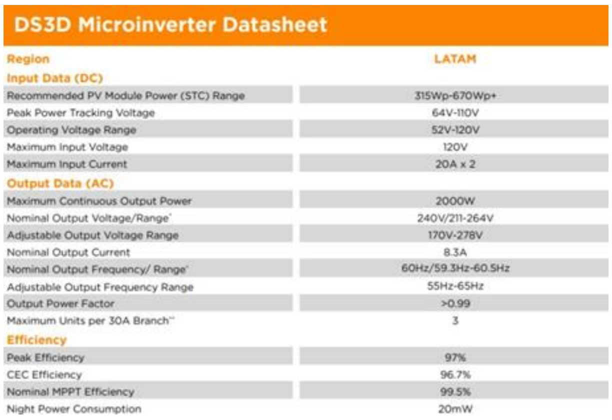
Figure 16 Technical data sheet of the JA SOLAR 500W DEEP BLUE 3.0 model demodule
Source: https://cdn.autosolar.es/pdf/datasheet-deep-blue-480-505.pdf)

For the sizing of the parking lot, both proposals from investors were made. Starting with the central inverters, four central inverters were first designated that will share the load of the entire array, given that the modules are 500W and that the array will be divided into four sections of 78 modules so the inverter must be of a power of at least 39kW. The inverter data sheet is below in Figure 17 framed.

Figure.17. Huawei SUN2000-40KTL-M3 central inverter data sheet (Source: https://solar-distribution.bayware.mx/fileadmin/Solar_ Distribution_ MX/04_ Products/03_ Media/Huawei/SUN2000-30-36- 40KTL-M3_MX.pdf)

Knowing then that the nominal power of the inverter is adequate, equations three and four were used to determine the maximum number of modules that are tolerated in parallel and in series. In this way, it is possible to know if the arrangement of the modules is supported by the inverter.

In the case of microinverters, it is only necessary to look for a microinverter that tolerates the largest number of modules while supporting the combined power of the connected modules. In this case, the data sheet of the microinverter used can be found in Figure 19.



DS3D Microinverter Datasheet

Region	LATAM
Input Data (DC)	
Recommended PV Module Power (STC) Range	315Wp-670Wp+
Peak Power Tracking Voltage	64V-110V
Operating Voltage Range	52V-120V
Maximum Input Voltage	120V
Maximum Input Current	20A x 2
Output Data (AC)	
Maximum Continuous Output Power	2000W
Nominal Output Voltage/Range*	240V/211-264V
Adjustable Output Voltage Range	170V-278V
Nominal Output Current	8.3A
Nominal Output Frequency/ Range*	60Hz/59.3Hz-60.5Hz
Adjustable Output Frequency Range	55Hz-65Hz
Output Power Factor	>0.99
Maximum Units per 30A Branch**	3
Efficiency	
Peak Efficiency	97%
CEC Efficiency	96.7%
Nominal MPPT Efficiency	99.5%
Night Power Consumption	20mW

Figure 19 Technical data sheet of the Apsystems DS3D model microinverter
Source:
https://drive.google.com/file/d/19I1kDBYEud1W1L5uPc8pU0OfWM14VcAc/view?pli=1

The data sheet indicates that the maximum number of modules that each microinverter accepts is four, while the maximum number of interconnected microinverters that it accepts is 3. Therefore, to know the number of microinverters needed, it is enough to divide the number of modules of the array (312 modules) by the maximum number of modules per microinverter (4) giving a total of 78 microinverters, however, since the microinverter resists up to three of these interconnected, to know the main lines of the entire array it is enough to make a simple division:

$\# \; total \; MFV$

$Serial \; MFV = 1{,}100 \; V = 28.68 \sim 28 \; modelos$

$Total \; strings \; = \; MFV \; per \; inverter \; * \; Max \; conected \; inverters \; 312 \; 38.35 \; V \; 40 \; A$

$Parallel \; MFV = 13.03 = 3.07 \sim 3 \; modules$

$Total \; inverter == 26 \; strings$
$4 * 3$

These 26 branches will be the ones that carry the energy of the entire system, Figure 20 shows a connection diagram of this option.

With the results obtained, it can be concluded that each section should be of no less than three strings in parallel of 28 modules each. So dividing the space of proposal b into four sections yields a connection diagram like the example below (Figure 18).

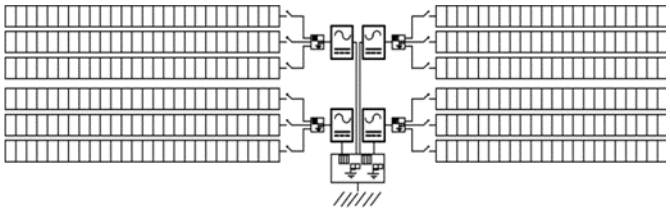


Figure 18 Diagram of connection of the components of the array with central inverters

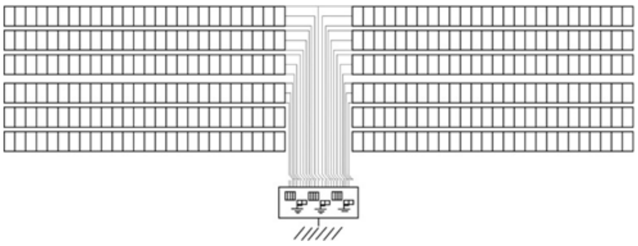


Figure 20 Diagram of connections of the components of the array with microinverters

Calculation of protections

For the system with central inverters, the main protections must first be identified, a direct current protection for the modules at the end of each string of each annex, a direct current protection for the total set of modules in parallel of each annex along with a voltage protection and finally, an alternating current protection for all central inverters together as well as a voltage protection. To better understand this list, Figure 21 shows a diagram with the connection of the protections.

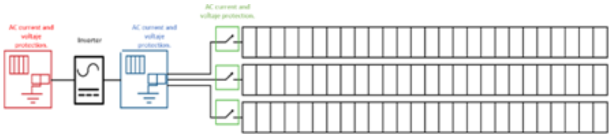


Figure 21 Central inverter protection diagram

To calculate the protection of each string, the indication of the NOM-001-SEDE-2012 is followed, which indicates that for the protection equipment, the maximum current of the equipment must be dimensioned by the protection factor of 125%, so that to know the current of the protective equipment that is planned to be used, this factor must be multiplied by the short-circuit current of the module (this value can be consulted in the data sheet of the Figure 19)

$I \; de \; proteccion = Isc \; del \; modulo * 1.25$

$I \; de \; proteccion = 13.93 \; A * 1.25 = 17.41 \; A$

The same NOM-001-SEDE-2012 specifically in chapter 2, Article 240, Section 6 where the different values that we find for 50 safety switches are indicated, being the list (in amperes)15, 16, 20, 25, 30, 32, 35, 40, 45, 50, 60, 63, 70, 80, 90, 100, 110,125, etc. Therefore, all current switches and protections will be jumped to the immediately higher value as the case may be, that is, for this case, 20 A switches were contemplated and as the diagram marks these must be for direct current. For the second protection (blue color) the same protections are used as in the previous case, because the current remains the same, and in the same way one is installed for each string of modules.

For the third protection (red), the same pattern was followed with the difference that now instead of using the short-circuit current of the module, the maximum input current obtained from the sheet in Figure 21 was used. In addition, since the protection

Figure 22 On the left, DC protection switch (20 A), on the right, AC protection switch (50 A)

For the option with microinverters, the protection of the components is reduced and simpler, because the microinverter is installed so close to the modules, it does not need protection for each module. Only one protection for each main branch of the array (26 branches), and to select a circuit breaker the same procedure dictated by NOM-001-SEDE-2012 is used and the maximum output current of the inverter (obtained from Figure 24) is multiplied by the number of microinverters per branch at 125%:

$I\ de\ proteccion = Imax\ out * inverters\ per\ string * 1.25$

$Proteccion\ current = 24\ A * 3 * 1.25 = 90\ A$

Wiring calculation

For the system with central inverters it was taken into account that the cables of the array will go as close as possible to the ground, in table 1 we obtain that the temperature factor is 33°C, this factor is added to the average ambient temperature of the area, which is 22.1°C, giving a total temperature of 55.1°C. Using this value, table 6.1 was consulted to obtain the temperature factor of the conductor in a range of 75°C, which is 0.67. Since the factor Fc is replaced by "1" and the current is the maximum output of the inverter (Table 3) multiplied by the number of central inverters, applying equation 5 is the following: 63.8 $A * 4$ is inverter, direct current protections are no longer contemplated but alternating current protections and

$Adjusted\ ampacity\ required = 0.67 * 1 = 380\ A$

The corresponding procedure was carried out. Figure 22 below shows examples of switches that can be installed in the array (these protections will go inside a concentrator box with a general disconnect switch):

$I\ de\ proteccion = Isc\ del\ inversor * 1.25$

$I\ de\ proteccion = 40\ A * 1.25 = 50\ A$

Since it is a three-phase system, i.e. with three current-carrying lines, this ampacity is divided into three, giving a total of 127 A each. With this ampacity, the table in Figure 12 was consulted to find the gauge of the cable, being a 2/0 gauge, with a designation AWG of copper at a temperature range of 75°C.

For the calculation of the voltage drop, using the value of the 2/0 gauge corresponding to this dimensioning, it was obtained that the resistance offered by the cable was 0.261 Ω/km from the table in Figure 13. Finally, a cable distance of 65 meters was figured out and equation 6 was applied:

$0.261\ \Omega * 190\ A * 65\ mts$

$Tension\ fall = \quad km \quad = 0.73\% < 3\%\ 10 * 440v$

As can be seen from the above result, the voltage drop does not exceed the limit established by the NOM of 3%, so the corresponding calculations and values obtained are acceptable.

Finally, for the option with microinverters, as with the central inverters section, table 1 indicated together with the average ambient temperature of the place that the temperature adder value is 55.1°C. Consulting the temperature value with the table in Figure 12, the temperature factor of the conductor was extracted in a range of 75°C, which was 0.67. Equation 6 was implemented to determine the adjusted required ampacity using the output current of each branch as the inverter current value, multiplied by the number of microinverters:

column of "two or more conductors" for the exact cross-sectional area for the conduit, it was determined that the 35-gauge conduit () is the most suitable. 4

Finally, for the proposal with microinverters: each cable is 800 gauge, when consulted in the table in Figure 15 a total area result of 405 mm2 is obtained for each 800 gauge cable. Because it is a two-phase system (three wires), due to the maximum voltage output of the inverter (240V), the total wiring area is $1215mm^2$. From the table in Figure 16 it is concluded that a 53 gauge (2") conduit is needed.

Module distribution and shading calculation

For the dimensioning of the parking lot of the technological institute of the lagoon, a space was considered behind the postgraduate study area with dimensions of 18 meters wide by 53 meters long with a latitude of 25° (Figure 23). And 500W modules of the JA SOLAR brand were contemplated, measuring approximately one meter wide by two meters long.

$Adjusted\ ampacity\ required = 24.9\ A * 26$
$0.67 * 1 = 966\ A$

As in the previous case, the load must be divided into two cable lines (because microinverters have a two- phase voltage output). In this way, each line of cable will have an amperage of 483 A. Thus, using the table in Figure 13 it is obtained that each of the cables must be of 800 gauge.

With the gauge of the cable and using the table in Figure 14, the resistance of theconductor was obtained, which is 0.0544, and the $\Omega\ km$ voltage drop of the cables was calculated, using the ampacity calculated previously and the distance of the cable speculated, applying equation 6 as follows:

$0.0544\ \Omega * 483\ A * 65\ mts$

$Tension\ fall = k\text{m} = 0.77\% < 3\%\ 10 * 220v$

The voltage drop does not exceed the established limit of 3%, therefore, it does not present significant losses.

Conduit calculation

Table 5 located in chapter 10 of the NOM (Figure 15) was used to calculate the Conduit of the option with central inverters, where the diameters in millimeters of each wire gauge are shown, and the 3/0 gauge belonging to the array was located, resulting in an area of 98.13 mm2 for each wire. Since it is a three- phase system (four wires) the total area is 392.52 mm2. By looking at the table in Figure 16, in the

Figure 23 Photograph of the parking lot area
Source: Google Maps

For this space, three options were contemplated for the arrangement of the modules and their 3D models were made using the Sketchup tool, option a: contemplates a single plate of modules that covers the entire extension of the parking area (Figure 24). Option b divides the parking area into two three-module-tall sections at the edge of the parking lot (Figure 25). Finally, option c divides the parking area into three sections of two modules high each (Figure 26) taking into account a standard PV module measurement of one meter wide by two meters long.

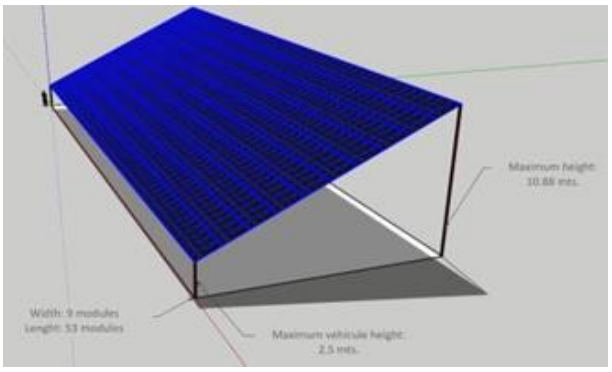


Figure 24 Proposal "a"

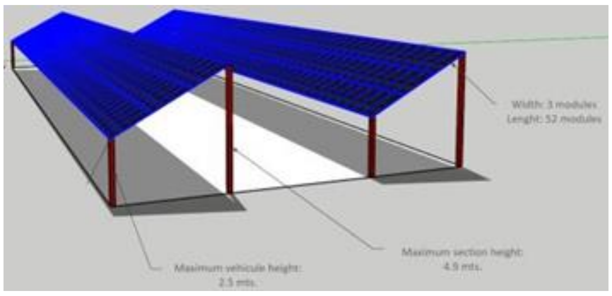


Figure 25 Proposal "b"

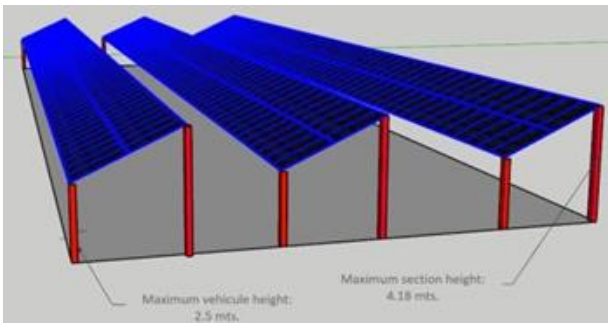


Figure 26 Proposal "c"

Analyzing the advantages and disadvantages of each arrangement, it was decided to use option b since it is the one that best adapts to the predetermined way of parking cars and is the one that best preserves the distances between cars, having a total of 312 modules distributed in two sections of three modules wide by 52 modules long. Thus, the distance between the two corresponding rows was calculated based on the diagram in Figure 27.

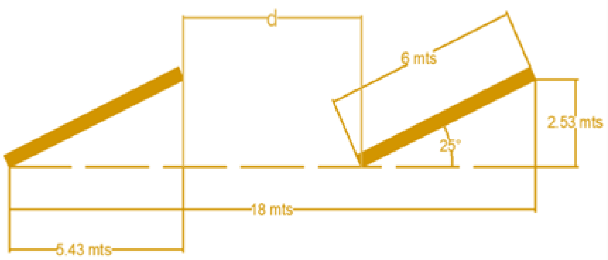


Figure 27 Distance diagram of proposal b

When applying equation 7 taking into account a modulus of 1 meter wide by two meters long, the distance of the longest shadow is as follows:

Table 2 below shows the estimated costs for the photovoltaic array with central inverters. Table 3 shows the estimated cost of the components of the photovoltaic array with microinverters; The costs of both tables were reflected taking into account the prices that manufacturers advertise on their platforms, as well as the shipping costs of some of these.

system element	units	unit prices (MNX)	total price
Modulo JASOLAR 500W	312	4,700.00	1,466,400.00
Inversor central Huaweii	4	33,200.00	132,800.00
Noark 20A thermomagnetic switch	12	186.61	2,239.32
Concentrator Boxes (Modules & Inverters)	5	500.00	2,500.00
Chtaixi 20A Protection Switch	24	238.00	5,712.00
Wolfgang SDP Overvoltage Protections	10	245.00	2,450.00
High Voltage Disconnect Switches	5	405.00	2,025.00
AWG calibre 3/0 (mts)	195	229.00	44,655.00
Cable AWG calibre 10 (mts)	104	380.00	39,520.00
1 1/4 (MTS) Conduit	65	335.00	21,775.00
Total price			1,720,076.32

Table 2 Costs for sizing with central inverters.

$$d = L * \sin(\beta)\tan(61° - |\Phi|$$

From the table above we can see that 85% of the installation costs would be only for the purchase of the modules since it is one of the most expensive

$$d = 6mts * \sin(25°)\tan(67° - |25.53°|) = 2.86\,m$$

components along with the central inverters and their overwhelming quantity. The cable also results in a significant expense, making up approximately 5% of being that the shade reaches a maximum length of 2.86 meters, that the horizontal distance of each section is 5.43 meters and that the width of the parking space is 18 meters, that leaves a margin of distances of between 2.86 meters to 4.28 meters of distance, enough space to perform displacement maneuvers for the accommodation of vehicles and it is verified that the shadows do not interpose each other.

Results

the total dimensioning. Costs could be reduced by installing a substation close to the facility. Without taking into account the labor and structures of the modules, the total cost of the arrangement could amount to approximately two million Mexican pesos.

SYSTEM ELEMENT	UNITS	UNIT PRICE S (MNX)	TOTAL PRICE
Modulo JASOLAR 500W	312	4,700.00	1,466,400.00
DS3D Micro Inverter	78	9,799.00	764,322.00
Concentrator Boxes (Modules & Inverters)	1	500.00	500.00
Chtaixi 20A Protection Switch	24	238.00	5,712.00
LT1-40 Overvoltage Protections	2	245.00	490.00
High Voltage Disconnect Switches	1	405.00	405.00
Cable AWG calibre 800 (mts)	195	309.00	60,255.00
Cable AWG calibre 10 (mts)	104	380.00	39,520.00
2" Conduit (mts)	40	275.00	11,000.00
Total price			2,348,604.00

Table 3 Costs for sizing with microinverters

As can be seen in the tables, the cost of sizing using central inverters can be up to 27% cheaper, that is, around 628 thousand pesos cheaper than with the installation of microinverters.

This is due to the fact that there are multiple inverter parts installed, which in the middle of 2023 are not entirely cheap compared to other technologies such as central inverters. One of the main advantages of using microinverters is the fact that the number of concentrator boxes is reduced and that the wiring system is more compact overall. However, due to the very nature of microinverters, they increase the costs of the cable to be used, as well as its quantity and also that of the conduit. Figure 30 shows in detail the final arrangement of the complete array performed in Sketchup.

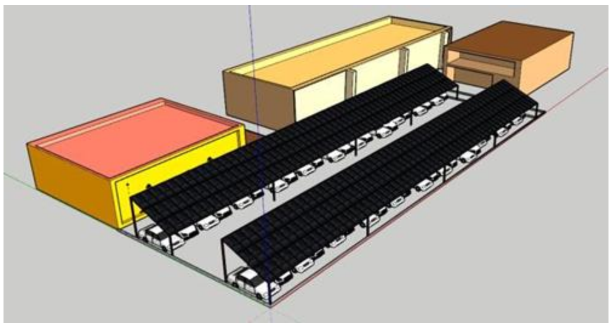


Figure 28 Aerial view in perspective 3/4 of the arrangement

As can be seen in the Figure, the number of vehicles is very close to the number shown in Figure 17, and thanks to the software it was verified that there is no shading factor that alters the efficiency of the parking.

Conclusions

In this chapter, a hypothetical analysis was carried out with the aim of sizing a photovoltaic system that could cover the needs of parking in the area of postgraduate studies of the Technological Institute of La Laguna. An exhaustive list of various inverter and module configurations was made, evaluating their respective advantages and disadvantages. A solution using central inverters was proposed, as well as another using microinverters, also considering the associated costs.

After careful analysis, it was concluded that choosing central inverters instead of microinverters for current conversion could reduce production costs by 27%. In addition, this option would allow a three-phase connection, simplifying the sizing of the conductive medium and achieving a more efficient connection between the modules.

The dimensioned photovoltaic system has a generation capacity of 750 kW per day, with an approximate cost of two million Mexican pesos. To support this choice, the surrounding buildings' electricity consumption was estimated at 739 kW per day, indicating that the proposed sizing would be able to fully meet the energy needs of the graduate area.

Acknowledgments

CONAHCYT for grants, TecNM projects and PRODE.

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