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36 MONTH PERFORMANCE OF 60 KWP PHOTOVOLTAIC SYSTEM IN MEXICO CITY

RENDIMIENTO POR 36 MESES DE UN SISTEMA FOTOVOLTAICO DE 60 KWP EN LA CIUDAD DE MÉXICO

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Abstract

In the Research Center (CINVESTAV), located north Mexico City was evaluated a 60 kWp photovoltaic (PV) system. The PV system energy performance ratio, so called "quality factor" is reported together with the measured solar irradiation, ambient and PV module temperatures. The performance ratio (PR), defines the overall PV system performance considering operation parameters as the produced energy, the incident solar irradiance and the total effect of system losses. The electric grid-tied PV system consists of 240 PV modules of 250 Wp each, which are connected to 5 inverters to transform three phase AC. We describe the PV system electric performance for 36 consecutive months through diverse weather conditions. The calculated average PR was 86.8% for the 36 months, even though, it had a lower PR of about 84.8% in the last 12 months due to the PV array string outages and also inverter technical troubles. The average daily energy produced by the PV system in 3 years was 260.45 kWh/day and an average accumulated energy of 95,064.25 kWh per year.

Keywords: Photovoltaic systems, energy performance, operating temperature, solar irradiance, sustainable development.

Resumen

En el CINVESTAV, ubicado al norte de la Ciudad de México, se evaluó un sistema fotovoltaico (FV) de 60 kWp. La relación de rendimiento energético del sistema fotovoltaico, denominado "factor de calidad", se reporta junto con las mediciones de irradiación solar y de temperaturas ambiente y módulos FV. La relación de rendimiento (PR) define el rendimiento general del sistema fotovoltaico considerando los parámetros de operación como la energía producida, la irradiación solar incidente y el efecto total de las pérdidas del sistema. El sistema fotovoltaico conectado a la red eléctrica tiene 240 módulos FV de 250 Wp que están conectados a 5 inversores para producir CA trifásica. Se describe el rendimiento eléctrico del sistema fotovoltaico durante 36 meses consecutivos a través de diversas condiciones climáticas. La PR promedio calculada fue del 86.8% para los 36 meses, aunque tuvo una PR menor de alrededor del 84.8% en los últimos 12 meses debido a interrupciones en el arreglo FV y también por problemas técnicos del inversor. La energía diaria promedio producida por el sistema fotovoltaico en 3 años fue de 260.45 kWh/día y una energía acumulada promedio de 95,064.25 kWh por año.

Palabras clave: Sistemas fotovoltaicos, rendimiento energético, temperatura de operación, irradiación solar, desarrollo sustentable.

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1 Introduction

In recent years, the solar photovoltaic (PV) systems are becoming one important clean-technology and alternative-energy-sources in several countries. The PV systems are safe, reliable with a low-maintenance cost without on-site pollutant emissions. Nowadays, the utility grid-connected PV systems are increasing in the world, and the underlying deployment scenario assumes 3,155 GW of cumulative installed PV capacity by 2050 (Arvizu *et al*., 2011). Although the number of grid-tied systems started growing after 2007, the off-grid installed PV capacities in Mexico were 85% in 2010. A net-metering mechanism was created in 2007 for renewable energy based systems under 500 kW capacities. It allows the users to feed into the grid part of their electricity and to receive credits in the form of kWh in return that can be used to offset their electricity bill. Since 2012, net metering is also available to multi-family housing. Each tenant will pay the difference between its individual consumption and the specific PV-generated-electricity, this difference is allocated to the electric utility company (CFE) to that tenant's utility account, according to a pre-arranged share. The PV Levelized cost of energy (LCOE) has experienced a significant decrease from 2009 to 2014, which is estimated at -18.4% compound annual growth rate, even though, for the average electricity consumer PV investment is still not competitive with grid electricity prices. The Mexican Government introduced at the end of 2013 an in-depth energy reform for the oil and gas industry, as well as the electricity sector; the reform led to extensive legislative changes in 2014 that will be finished with market rules in 2015. The reform implementation is expected to have a strong impact in the development of the PV market (CREARA 2015).

This study evaluates the electricity generated from a 60kw PV system, taking in consideration the local (Mexico City) weather conditions. The PV module temperature, wind velocity, and the solar irradiations are the main parameters for the PV system performance evaluation. The performance ratio, often called quality factor, is independent of the solar irradiation. Therefore, it is useful to compare different PV system performances. No one can totally guarantee how much electricity will generate the solar PV system because it depends mostly on the local weather conditions, as well as on the PV system's quality. However, it can be predicted and guaranteed the minimum amount of energy to be generated based on a reliable and long-term solar irradiation data. In the present work and based on 14 years of onsite solar irradiation measurements, it will be predicted the amount of energy production for the next 15 years.

2 System description

The 60 kWp PV system is shown partially in Fig. 1 consists of 240 single-crystalline silicon based PV modules with a 250 Wp each one. The detailed description of PV systems can be found elsewhere (Urbano *et al*., 2014). PV module-arrays were installed on the Institution's building on the fifth-floor roof and fixed on aluminum framed structures oriented 30° East-faced from the geographical South. The system is located at 19°30'38" North-latitude, 99°07'50" West-longitude, and the modules were installed at about the latitude angle of 20°. PV module arrays are subdivided electrically into five sections. Each section is composed of a string of 48 PV modules that consist of 12-series and 4-parall connections. For each of the five array arrangements is connected to the corresponding inverter; Fronius model IG Plus V11.4-3 DELTA with a capacity of about 11.4 kW/each. The solar irradiance was measured using a reference crystalline-silicon (c-Si) solar cell (see Annex I) installed at the top of array at the same PV module plane of array (POA) with the angle of 20 degrees from the horizontal. Also, in a site, a pyranometer Yankee Environmental Systems; Model TSP-1, was installed as a global horizontal solar irradiance measurement.

Fig. 1. Shows part of 60 kWp PV module array in CINVESTAV, Mexico City.

3 Monitoring and performance concepts

3.1 *System monitoring*

Data monitoring is one of the important requirements for diverse PV systems. It is used to track performance and comply with regulatory reporting status. Without an accurate data monitoring, the PV system performances cannot reliably be compared to the calculated generation power. Effective data monitoring not only helps to identify system performance troubles, but it also helps to resolve them (IEA-PVPS, 2017). The Fronius inverter system integrates all the monitored and logged data every 5 minutes, included solar irradiance automatically. In Annex I, it is described all of the used measurement instruments.

3.2 *General performance*

Three of the IEC standard 61724 performance parameters have used to defining the overall system performance with respect to the energy production, the solar resource and overall effect of system losses (Marion *et al*., 2005). The performance ratio (PR) or so-called Quality Factor (QF), is the ratio between actual yield (i.e. annual production of electricity delivered at AC) and the ideal yield:

$$PR = \frac{Real\ \ Yield\ \ AC}{Ideal\ \ Yield\ \ AC} \tag{1}$$

In Eq.(1) the Real Yield is the total produced electric energy by the PV system, which is monitored and logged directly using system software. The Ideal Yield is the total installed system power capacity (as is indicated on the nameplate of the PV module) multiplied by the total solar peak-hour irradiation, i.e. the total energy that should generate an ideal PV system. PR can be considered by a day, by a week, but mostly on a month basis. In the present job, we consider the values up to 36 consecutive months.

3.3 *Energy losses*

Under normal PV system operating conditions, the measured data contains deviations caused by malfunctions such as string defects, shadings, module or inverter malfunctions that influence the measured performance of a PV system. One of the unavoidable energy-loss, is due to temperature coefficient. In our case, the monocrystalline silicon solar cells, has an about -0.47%/°C. It means, about a half percentage of power loss for each degree ºC of temperature increment. It means, if the PV module has100 Watts (in its name plate), and if the operation temperature reaches 50 ºC, the temperature difference with the standard test condition is 25 ºC. So, the power loss might be of about 12% and the output power will be of about 88W, instead of 100W. Another "degradation" is through the time. Normally, the monocrystalline-Si solar cell, might degrade less than a 1% of power every year. This could be due to light and environment interaction in the surface/interface of the solar cells, which provokes slow electrical degradation (Jordan Dirk C. *et al*., 2012). Also, as potential induced degradation (PID) due to the electric field in the PV array, inducing an ion movement from the PV-module cover glass to the solar cells, (Daoren G., *et al*., 2018), etc.

Table I. Different energy loss parameter in the PV system.

Different losses	Amount of losses	Loss concepts
Module	**~ 55%**	Solar cell efficiency and temperature dependence of the PV module.
Optical	**~ 6%**	Attenuation of the incoming light through shading, dirt, snow and reflection before it hits the photovoltaic solar cell. In concentrating PV systems, it also includes losses from diverse optical components.
System	**~ 12%**	Losses in the composed electrical devices including DC-AC wiring, connectors, inverters, and transformers.

Sometimes it is intuitive to think in terms of energy losses that occur at every step of the way, rather than component efficiencies. Both concepts are related as:

$$Losses = 1 - Efficiency \quad (2)$$

The both terms in Eq. (2) are expressed in percentage. Commonly, there are three major blocks of energy losses and are indicated in the Table I.

4 System general performance

The PV system has been monitored for 36 consecutive months from June 2012 to May 2015, and the measured data were logged and recorded every 5 minutes. Figure 2 shows the average month based solar irradiance detected in the plane of array (POA) through c-Si solar cell sensor. The average daily solar irradiance was 4.71kWh/m^2 for three years, with the highest solar irradiances for February to April of each year. In October 2012, as shown in Fig. 2, an outstanding irradiation has been detected. The rainy season in Mexico City normally starts from May-June and up to September-October of every year.

Figure 3 shows the PV-module day-night temperature cycle, i.e. maximum and minimum temperatures detected during 12 months of 2013. It can be seen that March registered a negative temperature value in the range of -3 ºC. The maximum temperature ranges between 58 to 68 °C, with the highest during the sunny days of June. Now, after two years of operation, in some of the PV modules started appearing the so-called "snail trails". However, it seems that this "cosmetic" effect does not perturb directly the electric performance. Recently, twenty of the affected PV modules were renewed by the manufacturer.

Figure 4 shows the monthly-based daily-average produced energy of PV system. As can be seen, for each of the considered years, February to April was the highest energy generated months. It was produced in average 310.09 kWh/day in February 2013. However, September (2013), was the worst with only 176.79 kWh/day. These differences were produced by cloudy and rainy days during September (see Fig. 2), but also due to the electric failure in one of the inverters. It must be said that due to the electric grid maintenance performed by CFE, the utility company, there was an interruption on July 24th, on August 17th and on December 1st (all in 2013). Those three days are not considered in our data.

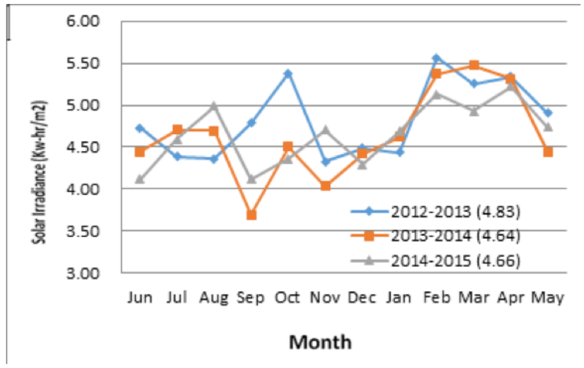

Fig. 2. Monthly average Solar irradiance measured at POA by using c-Si solar cell sensor, which is monitored by Fronius Datamanager 2.0 plug-in card through IG Plus inverter system. The irradiance units were kWh/m^2/day. The number in the parenthesis indicates the average irradiance during the measured period in peak-hours (or kWh/m^2).

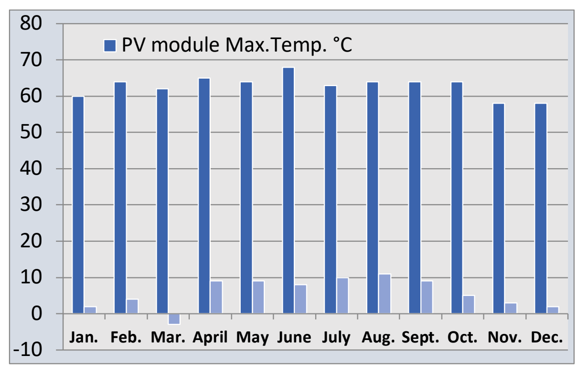

Fig. 3. Maximum and minimum PV module temperatures (in °C) during 2013.

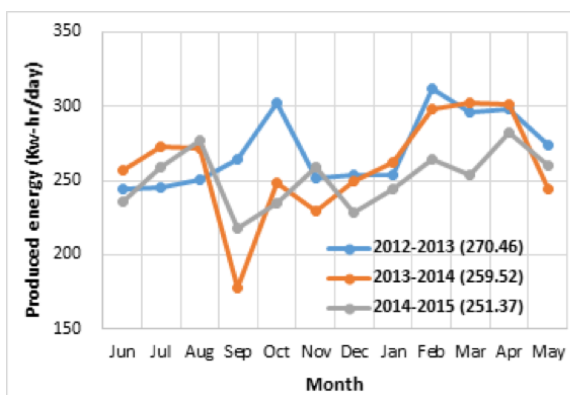

Fig. 4. Monthly-based average produced energy from the PV system. The number in the parenthesis indicates the produced daily average energy during the indicated period in kWh/day.

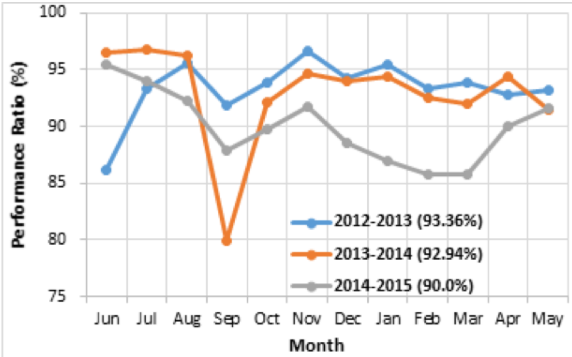

Fig. 5. Measured PR of the PV system during 36 months. The corresponding average PR for the period is indicated in the parenthesis.

Figure 5 shows the monthly-based performance ratio (PR). It is noted that the worst month was September with 79.98%, and the best was July with 96.74%, both for 2013 (in red line). On September 2013, the inverter N° 2 had a severe failure in its electronic circuit and did not contribute during 20 days for the energy transformation, which could be calculated as about 30 kWh/day of energy loss. It means, instead of 79.98%, it might have to be about 93% of PR. The system average PR for the 36 month-basis performance was 92.1%, however, the last 12 months of June 2014-May 2015, the system had a lower value of 90% because of the PV array string outages. The string outages were corrected by replacing the interrupted fuse in the string circuit that is located at the fuse-box under PV array. The daily average energy produced through 3 consecutive years was 260.45 kWh/day, and the total energy during 36 months was 285,192.6 kWh.

5 System specific performance

The purpose of monitoring PV system performance ratio (PR) is to determine whether or not the system is working as expected as to the incident solar irradiation. To do this, it requires measurement of the actual system output and its operating conditions. Solar irradiance in a plane of the array (POA) is by far the most important data, and it is the base to calculate PR. Even though, the results obtained and discussed in the previous section (with the reported average PR of more than a 90%) is not reliable as Reich *et al.*, 2012. The obtained and used 3-year-based solar irradiance was 4.71 kWh/m^2/day as an average. It was the irradiance detected by c-Si-based solar cell sensor at POA. However, we have previously reported that the average global irradiance (during 14 consecutive years 1999-2012) using global horizontal pyranometer was 5.0 kWh/m^2/day as is shown in Fig. 6 (Matsumoto *et al.*, 2014). Certainly, the differences in spectral and directional response, between pyranometers and c-Si sensors lead to intraday and seasonal fluctuations (Driesse *et al.*, 2012). For the electricity yield measurements, the inverter-integrated measurements are usually not sufficiently precise. When selecting irradiation sensor technology, generally two possibilities exist Pyranometers (thermopile sensors) and solar cell sensors. In solar cells, only crystalline-silicon (c-Si) sensors provide the required stability, with the spectral range from 400 to 1150 nm with a relatively quick response-time to the irradiance changes. However, there are some factors that influence the uncertainty of c-Si sensors as irradiance level; the angular distribution; the shift of transfer function over time; the ambient and sensor's temperatures. The c-Si reference sensors are calibrated under indoor and outdoor conditions which should comply with IEC 60904-2 and -4, respectively. On the other hand, Pyranometers are based on a thermocouple device with a wider wavelength sensibility in a range from 300 to 3,000 nm (Matsumoto *et al.*, 2014). The parameters that influence the uncertainty of pyranometers are irradiance level and spectral distribution of the solar radiation. Furthermore, irradiance change rate during the measurement; cosine effect; its tilt angle; ambient and pyranometer's dome temperature (Guerin de Montgareuil, 2004). The overall uncertainty of the instantaneous irradiance measurement based on secondary standard pyranometers is approximately 3% (Betts *et al.*, 2005; Spena *et al.*, 2009). It is reported that in an annual basis, c-Si sensors measure less irradiation than pyranometers. Also, the highest absolute difference between the signal measured by a c-Si sensor and a pyranometer is at clear sky conditions with a low diffuse/direct ratio (Glotzbach *et al.*, 2008). The annual difference between the two sensor types depends very much on the sensor and the location, but recent publications (Zehner *et al.*, 2009; Muller *et al.*, 2007) indicate that the deviation between different sensors installed in Germany varies considerably. On the average, the annual irradiation measured by c-Si sensor is 2 to 4% less than the irradiation measured by a pyranometer (Woyte *et al.*, 2013).

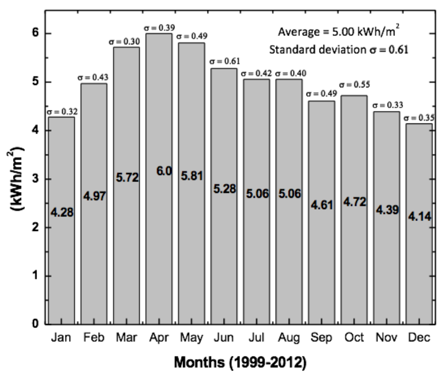

Fig. 6. Monthly averaged solar radiation from January to December during fourteen (1999-2012) consecutive years. In the figure shows the corresponding standard deviation in per month-basis also in kWh/m^2/day (Reich *et al*., 2012).

It is not the correct way to consider the horizontal global irradiance as our PV system reference because the pyranometer is not installed at POA but taking in consideration the annual average irradiance of 5.0 kWh/m^2, the calculated PR of the PV system reduces from 92.1% to 86.8%. It means around 5% less PR than that obtained by using c-Si sensor irradiance. However, the newly calculated PR of 86.8% seems more consistent and somehow more reliable than the one calculated using the c-Si sensor's as was asseverated using different experimental experiences by several authors. Now, as can be seen in Fig. 5, the obtained PR during 2014 - 2015, had a lower PR compared to previous years (2012 -2013 and 2013 - 2014). This situation has prevailed because of one of the PV module array string outage that fed the inverter N° 5. The PV array worked only at its 75% capacity for a couple of days in August, all September, some days of October and also December 2014. Furthermore, this string outage was prolonged from January to April 2015. In this sense, the lower PR can be explained during the mentioned period. However, on November 2014 its related PR also was lower than the previous years. To find out the possible cause of the resulted lower PR on November 2014, it has been done some analysis. Table II indicates the average parameters obtained from the acquired and stored data for all of the November period of 2012, 2013 and 2014. Comparing 2014 and 2012, it was possible to determine two factors: a) The obtained average wind velocity during the day-time (during the period that PV modules were operating 6:00 to 18:00 hrs) was 0.590 m/s in 2014, which is less than 0.876 m/s of 2012.

Table II. Different electric and environmental parameters and the performance ratio obtained from the PV system exclusively for November of every year; 2012, 2013 and 2014. The solar irradiation is monitored by c-Si solar cell sensor at POA.

Average in November	**2012**	**2013**	**2014**
Performance Ratio %	**96.7**	**94.7**	**91.8**
Electric Gener. kWh/day	251.4	229.2	259.3
Irradiance kWh/m2	**4.33**	**4.04**	**4.71**
Irradiance kWh/day	259.9	242.4	282.4
PV module Temp. °C	**30.5**	**33.2**	**33.2**
Ambient Temp. °C	19.2	19.5	20.8
Wind velocity m/s	**0.876**	**0.795**	**0.59**

B) The average ambient and module temperatures in 2014 were higher than that of 2012. Moreover, these temperature differences were of about 2 to 3 °C for ambient and PV module, respectively. Now, it is difficult to asseverate and confirm whether the analyzed data can explain the obtained PR's differences, and by using these averaged data-parameters, in any case, the crystalline-silicon based PV module temperature coefficient of - 0.47%/°C (Matsumoto *et al*., 2014), had the influences which lowered the generation power of about 2 to 3%. The obtained average parameters in Table II may indicate the possible reasons to explain the lower PR in 2014.

The predicted total energy produced for the next 15 years was about 1,425,964 kWh without considering PV module degradation and considering 5 kWh/m^2 of average irradiation. However, if we consider the factor of 1% degradation per year in the generated power, after 15 years the system will generate about 1,311,887 kWh, or 87,459 kWh as an average in the year. Being this average annual generation 92% of what we calculated without degradation. Finally, the predicted system power generation after 15 years will be only around 81,755 kWh/year, or 86% of the actual generation power.

Conclusions

The performance of a grid-connected 60 kWp photovoltaic system at the north of Mexico City was evaluated and monitored from June 2012 to May 2015. The seasonal variations of the produced energy were analyzed and interpreted during 36 consecutive months. Despite the failure of the inverter and some of the PV-array string outages, the system worked acceptably with 91.2% of performance ratio. However, the average PR was reduced to 86.8% when the c-Si solar cell sensor was substituted as the irradiance reference with a horizontal pyranometer. The obtained lower PR seems to be more consistent by the analyzed system technology. At this respect, the authors have been working in some middle results (Matsumoto *et al.*, 2017) but in the next paper will be reported the PR of the same PV system, from June 2016 to recent days using the pyranometer at the PV module plane of array.

We believe that one of the major influences of the PV electric generation performance was the PV module operating temperature. The direct solar irradiance increases PV module temperature but having a higher wind speed reduces it notoriously. Some of the system troubles were briefly discussed including the PV array string outages. Undoubtedly, the correct solar irradiance detection is one of the most important keys for a reliable PV system´s PR evaluation.

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Nomenclature

W	watt. It is a unit of power defined as a derived unit of 1 joule per second (J/s)
Wp	watt-peak. It represents the maximum energy that can produce a solar panel (1 kWp = 1000 Wp).
kWh	kilowatt hour. It is a composite unit of energy equivalent to one kilowatt (1 kW) of power sustained for one hour.
nm	nanometre. It is a unit of length in the metric system, equal to one billionth (short scale) of a metre (0.000000001 m).

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Appendix I. Used instruments for the environmental condition measurements and its technical data.

General data acquisition and management; Fronius Datamanager 2.0 plug-in card http://exelsolar.com/Documentos/ManualesUsuario/Productos/DM-WLAM-GalSymPrim_ManualUsuario.pdf

Solar irradiation sensor: Spektron 210.

Sensor type	Monocrystalline cell (13 mm / 33 mm)
Measuring range	0 – 1500 W/m^2
Sensor accuracy	± 5 % (annual mean)
Outlet approx.	75 mV at 1000 W/m^2
Calibration	Sun Simulator Solar Const. 1200 with ref. sensor calibrated by the ISE
Dimensions	118 mm x 50 mm x 44 mm

http://www.tritec-energy.com/common/pdf/tritec/Spektron-210_en.pdf

Thermocouple: GHM Messtechnik GmbH.

Technology	Pt1000, NiCr-Ni (type K) thermocouple
Mounting	Threaded
Temperature	Min.: -200 °C (-328 °F), Max.: 1,000 °C (1,832 °F)
Other characteristics	with cable, 3-wire, rugged

Wind speed: Fronius IG wind speed sensor p/n.

Sensor	Cup Anemometer
Output signal	Rectangle: Low ≤ 0.5V / High ≥ 4.5 V
Calibration factor	5.22 Hz = 1 km/h;18.79 Hz = 1 m/s
Threshold	2.5 m/s wind speed
Resolution	1 m/s; 1 km/h
Accuracy	±5 % at wind speed ≥ 5 m/s
Degree of protection	IP 54
Ambient temperature	-20°C to +60°C
Dimensions	85 x 93 x 115 mm
Cable resistant	2 m CU-cable, ferrules, UV-
Max. cable length	30 m (distance: Sensor Card/Box – sensor)