POLYTECHNIC UNIVERSITY OF VALENCIA

Higher Polytechnic School of Alcoi

ASSESSMENTS OF STANDARDS AND PROCEDURES TO MEASURE EFFICIENCY AND PERFORMANCE OF PHOTOVOLTAIC AND HEAT PUMPS

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Assessments of standards and procedures to measure efficiency and performance of photovoltaic and heat pumps

by
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Supervised by: Mechanical Engineering Lecturer Dr Charles Young and Electronic Engineering Lecturer Dr Nick Timmons

I. Declaration

I declare that this project represents my own work and has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma, or other qualifications. In addition, proper reference has been made to work done by or reported by others.

II. Abstract

The proposed work investigates existing standards and procedures employed to measure the efficiency and performance of heat pumps and photovoltaic (PV) systems. Specifically, the most appropriate attributes and performance metrics for each asset type, e.g. material composition, the effect of the location, how the deterioration affects the system, how to perform system efficiency checks, identifying available standards and reviewing the latest asset management research for each asset type. This project aims to aid in developing remote measuring systems using the data collected in this project.

Keywords: Information Collection; research; collection and analysis; heat pumps; photovoltaic energy.

III. Acknowledgements

I want to thank Dr Charles Young and Dr Nick Timmons, who gave me this opportunity to work on this project.
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VII. Nomenclature

a. Abbreviations

A	Ampere
A	Area
AC	Alternating current
AM	Air mass
CdTe	Cadmium telluride
CEC	California energy commission
CIGS	Copper indium gallium selenide
CIGSe	Copper indium gallium selenide (back mirror)
cm	Centimetres
COP	Coefficient of performance
COP_e	Coefficient of performance effective
COP_r	Coefficient of performance real
CSP	Concentrated solar power
DC	Direct current
EM	Energy Mutual
EUR	European
FF	Fill factor
G	Irradiation
G_{eff}	Effective irradiance
h	Enthalpy
HIL-Si	Heterojunction intrinsic layer monocrystalline silicon
HIT	Silicon heterostructure
HP	Heat pump
I	Current
IBC-Si	Integrated back contact monocrystalline silicon
I_{sc}	Short circuit intensity
J	Jules
k	Boltzmann constant
kg	Kilograms
kW	Kilowatts
kWh	Kilowatt-hour
m	metre
mA	Milliamperes
NTP	Normal temperature and pressure
p	Pressure
PV	Photovoltaic
q_c	Heat load in the condenser
Qh	Annual heat demand
Qhe	Annual work supplied
s	Entropy
SCOP	Seasonal coefficient of performance
STC	Standard testing conditions
SR	Soiling rate
T	Temperature
v	Velocity
V	Voltage
W	Watts
w	Work

b. Greek letters

Δ	Differential
η	Efficiency

c. Subscripts

B-O	Boron and oxygen
c-Si	Crystalline silicon
J_{SC}	Short circuit current density
mono-Si	Mono-crystalline silicon
poly-Si	Poly-crystalline or multi-crystalline silicon
Tamb	Ambient temperature
t_c	Temperature in the condenser
t_o	Temperature in the refrigerator
V_{OC}	Open circuit voltage

1 Introduction

Humanity has started using fossil fuels extensively since the industrial revolution at the end of the 19th century. From that point to this day, the earth's temperature has risen 0.08°C per decade since 1880. Simultaneously, energy consumption has increased drastically since the 19th century, as shown in Figure 1. It can be seen humanity is heavily dependent on fossil fuels like oil, coal and gas. This lifestyle increases the greenhouse effect, which is how heat is maintained on Earth's surface by greenhouse gases, such as water vapour, methane, carbon dioxide, and nitrous oxides (Earth Science Communications Team, 2022). On its own, this effect is not harmful whatsoever since this is a natural process. The problem comes from the increment of greenhouse gases which humans emit into the atmosphere every day. In other to deal with this problem, governments around the world are investing and promoting alternatives to fossil fuels like solar, wind, hydropower, or biofuels.

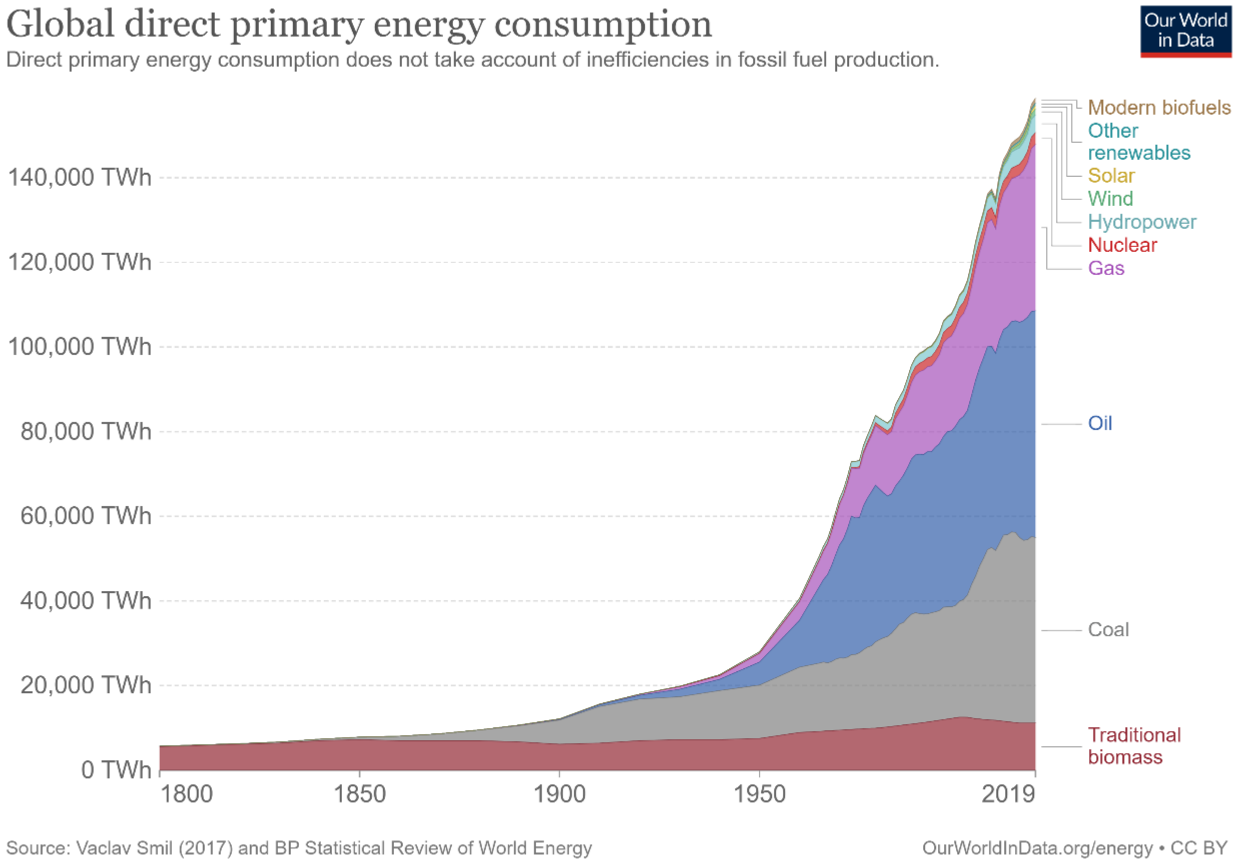


Figure 1. Global energy consumption from 1800 to 2019. (Smil, 2017)

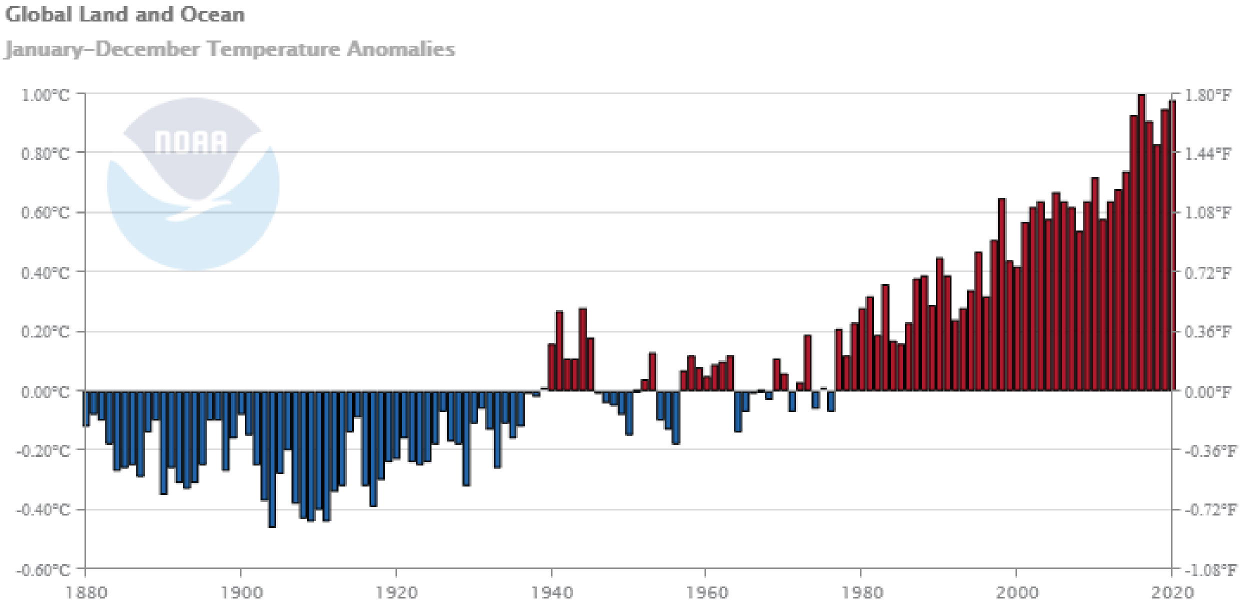


Figure 2. Yearly land and ocean temperature to the 20th-century average from 1880 to 2020. (NOAA National Centers for Environmental Information, 2020)

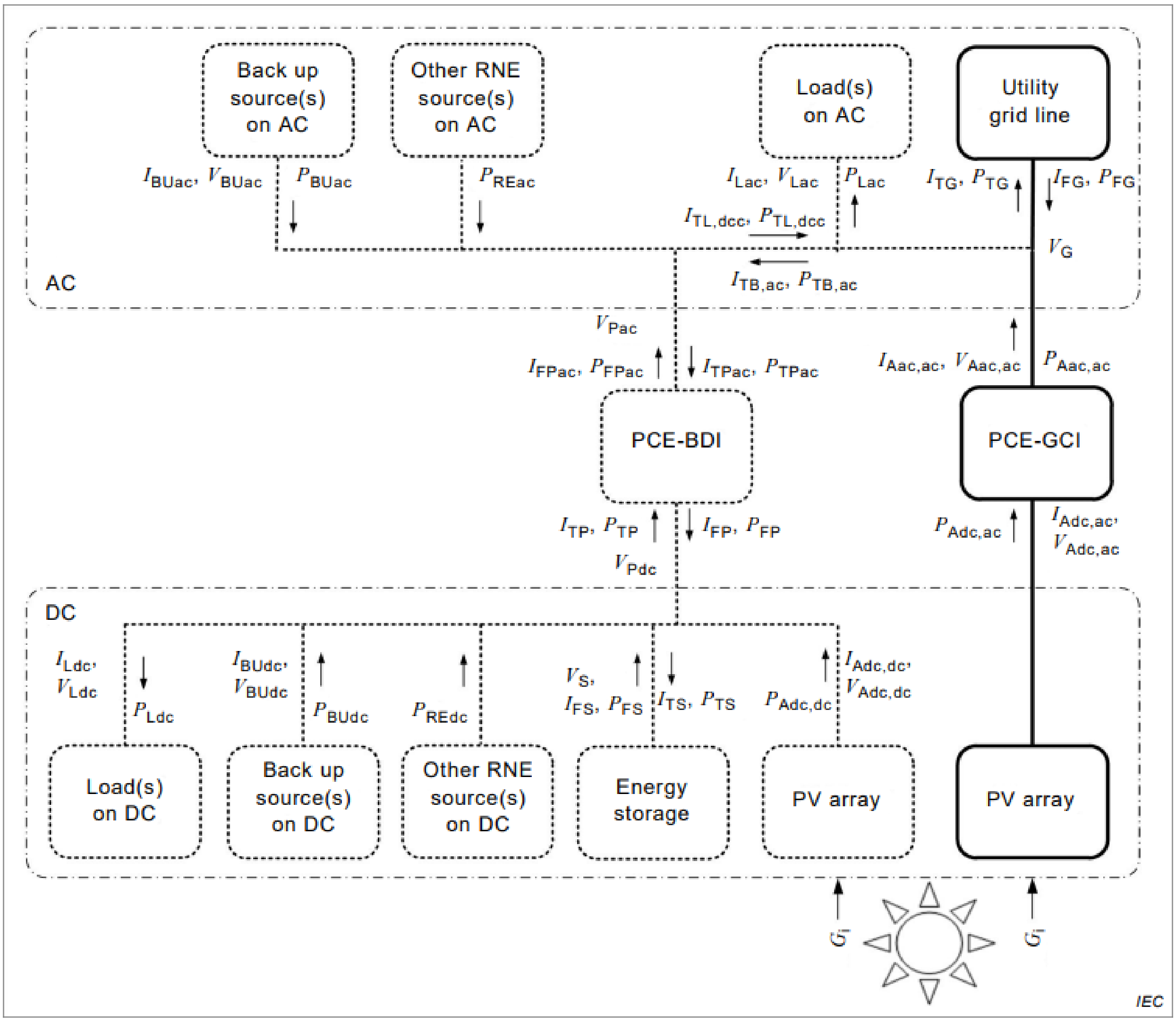
Private or community parties that want to or have renewable energy facilities might be interested in managing their assets. There is when Energy Mutual (EM) comes in. EM is a company that delivers energy infrastructure projects and operates energy assets, standardising asset management processes, sharing best practices and data, and identifying collaboration opportunities. From the repertory EM wants to develop, this project is going to be acquired two energy assets:

- Solar Photovoltaic (PV)
- Heat pump

1.1 What is solar PV?

PV is a technology that converts the energy produced by the sun in the form of irradiance into electrical energy. This technology is not the same as concentrated solar power (CSP). However, they have similarities: solar energy conversion into electrical energy (Issaadi & Issaadi, 2018). The main components of a PV installation are (more details in Appendix A):

- Solar panels
- Battery manager
- Batteries
- Inverter



Key

RNE	renewable energy
PCE	power conditioning equipment
BDI	bi-directional inverter
GCI	grid-connected inverter

Bold lines denote simple grid-connected system without local loads, energy storage, or auxiliary sources.

Figure 3. Possible elements of PV systems. (IEC 61724-1, 2017)

In a solar panel, photovoltaic cells are elements that suffer the photovoltaic effect, which is the generation of continuous voltage through the absorption of light. This effect usually is present in semiconductors explicitly designed for this purpose (UNE-206008, 2013). It implies the direct conversion of radiation into electricity when photon particles hit a cell. (Ghatak, et al., 2021)

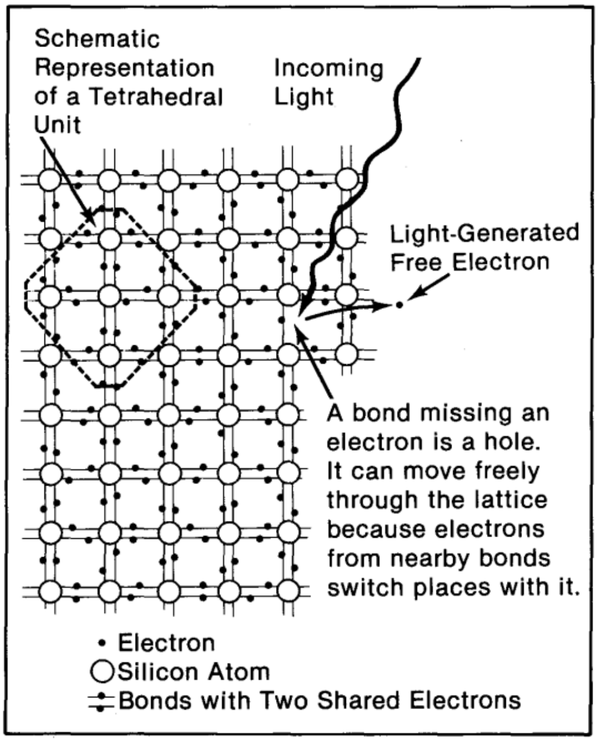


Figure 4. Light of sufficient energy can generate electron-hole pairs in silicon, both of which move for a time freely throughout the crystal. (Heresch & Zweibel, 1982)

The battery manager is also known as maximum power point tracking (MPPT), which is a device that converts DC to DC coming from the solar panels to the batteries, adapting the voltage to meet the needed voltage for charging batteries. (Victron Energy, 2022) It should be noticed that in some installations, the battery manager is included in the inverter.

The battery is the device that storages the surplus energy and releases it when the intake of electrical energy coming from the solar panels is not high enough to satisfy the necessities.

The inverter is a device whose function is to transform the energy from the solar panels in direct current to alternating current for any AC electronic device.

1.2 What is a heat pump (HP)?

A heat pump is a device whose purpose is to absorb energy from the outside (heat source) and move it through a fluid called refrigerant to the inside (heat sink) using mechanical work (Byrne & Ghoubali, 2018). There are three sources (air, water, and ground) and two possible outcomes (heating air or heating water).

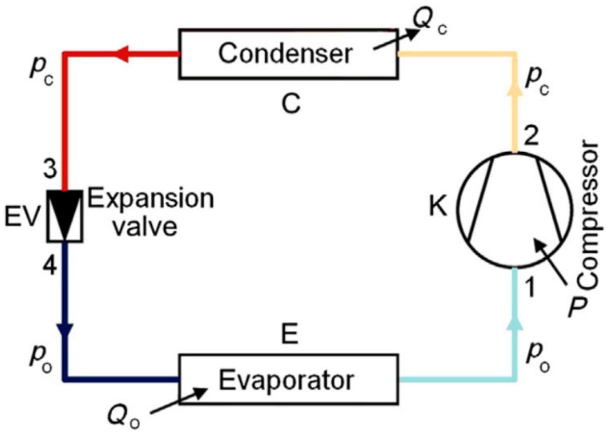


Figure 5. Schematic of a single-stage compression refrigerant system. (Sarbu & Sebarchievici, 2016)

In Figure 5 can be seen the components of a heat pump, which are:

- Compressor
- Condenser
- Expansion valve
- Evaporator

The compressor is a device that increases the refrigerant's temperature and pressure.
The condenser decreases the temperature of the refrigerant, realising heat to the inside through condensation. The expansion valve reduces the temperature and pressure of the refrigerant below the outside environment’s temperature. Finally, in the evaporator, the refrigerant absorbs heat from the cold climate and then the cycle repeats.
This project aims to extract the most appropriate attributes and performance metrics for each asset type for providing data for developing remote measuring systems by EM. Therefore, the objectives are:

- Extract installation attributes
- Extract performance metrics

2 Literature Review

Now it is known what PV and HP are in a nutshell. However, for analysing and determining the aspects that affect these assets' performance, it should be necessary to research more about this topic with the latest research papers, standards, articles, etc. Because this project focuses on two different systems, this literature review will also be divided into two parts.

2.1 PV

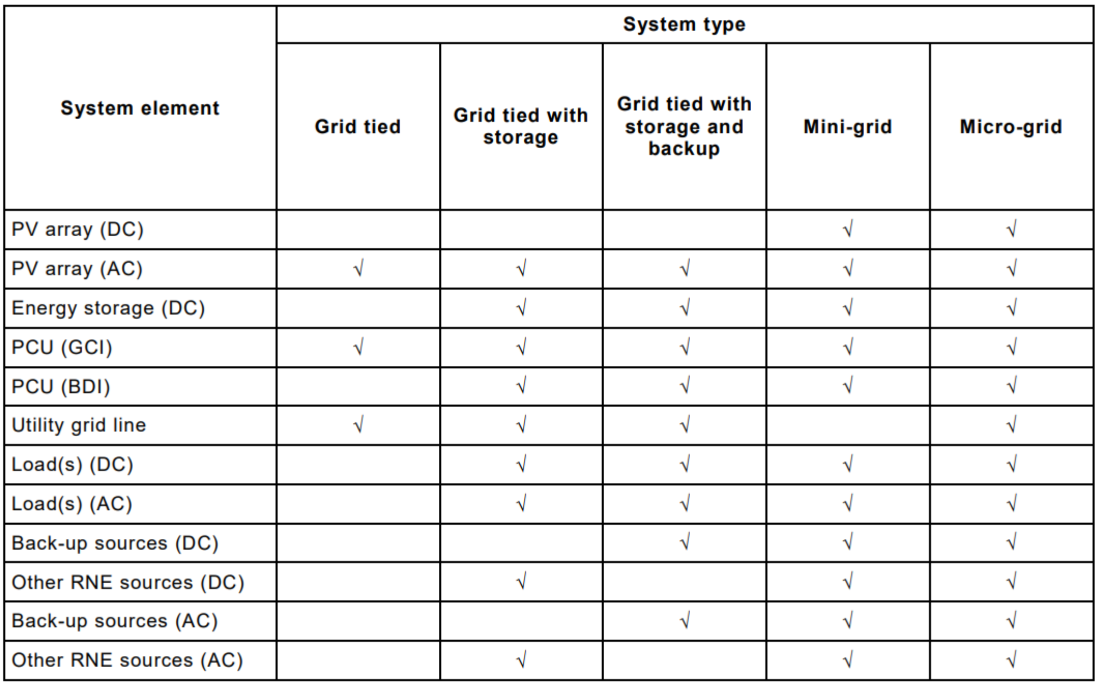
From the standard (IEC 61724-1, 2017), it can be extracted that the main components of a solar PV installation are solar panels and inverters. For that reason, in this project, these two components will be analysed.

2.1.1 Solar panel

(Green, et al., 2020) introduces the evolution of the efficiency of solar panels since 1993. Mr Green also lists the highest confirmed efficiencies measured independently by recognised test centres, for a range of photovoltaic cells. This report it is defined three subcategories within each semiconductor, which are:

- Mono-crystalline or crystalline
- Poly-crystalline or directionally solidified
- Thin films

In these subcategories, there can be found several sub-technologies apprised in Appendix A



System element	System type				
	Grid tied	Grid tied with storage	Grid tied with storage and backup	Mini-grid	Micro-grid
PV array (DC)				√	√
PV array (AC)	√	√	√	√	√
Energy storage (DC)		√	√	√	√
PCU (GCI)	√	√	√	√	√
PCU (BDI)		√	√	√	√
Utility grid line	√	√	√		√
Load(s) (DC)		√	√	√	√
Load(s) (AC)		√	√	√	√
Back-up sources (DC)			√	√	√
Other RNE sources (DC)		√		√	√
Back-up sources (AC)			√	√	√
Other RNE sources (AC)		√		√	√

Table 5. Elements of different PV systems.

Appendix B (NREL, 2022), for instance, Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), Perovskite, Silicon Heterostructure (HIT), and so on. This appendix reflects the efficiencies of several manufacturers and sub-technologies. The problem with this data is that it reflects the maximum efficiency these panels can reach. However, the efficiency customers can measure during the time might be worse due to degradation. (LONGI, 2022)

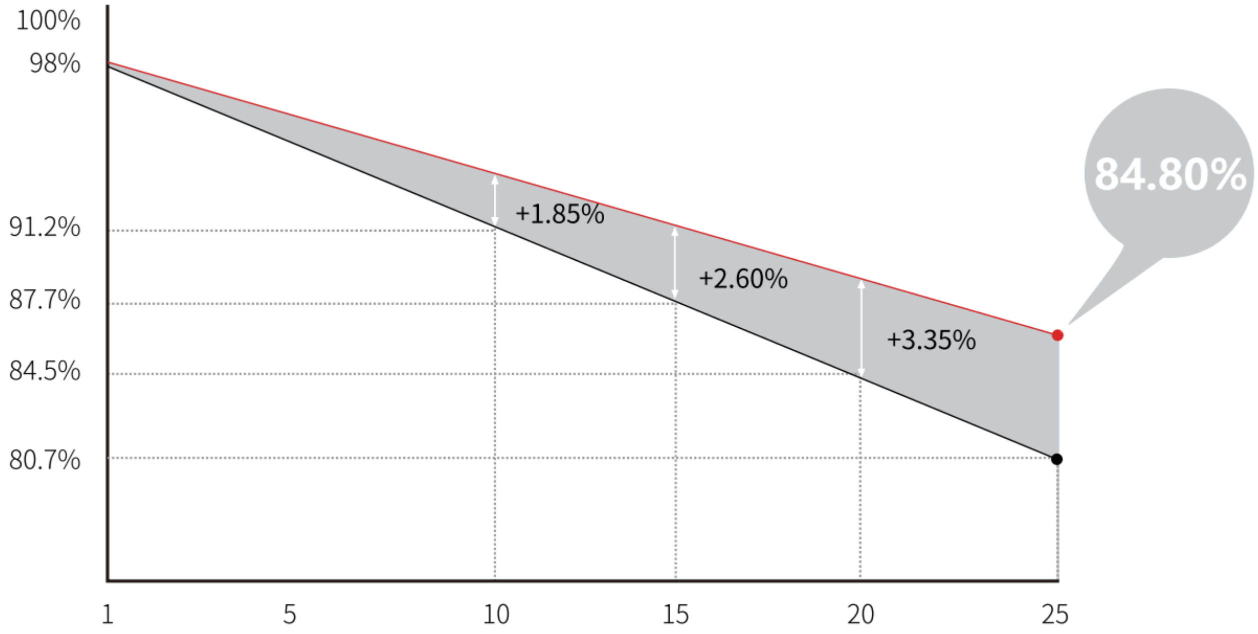


Figure 6. Liner power output warranty for 25 years. In red for the manufacturer product (LR4-60HPH) and in black for standard linear power. (LONGI, 2022)

This decreasement in power output was studied by (Hallam, et al., 2017) and noted the efficiency decreasement was correlated to the concertation of boron and oxygen (B-O) in the silicon, and the decreasement on efficiency did not happen when boron was substituted for gallium (Ga). Thus, this author concluded that it was a B-O defect causing the reduction in performance. That is why in any warranty is reflected the decreasement in performance.

Not only the decreasement in performance is relevant but also the technical limitations of a solar panel. (Heresch & Zweibel, 1982) claims there is a limitation of converting sunlight into electricity which can go up to 30% or more depending on the complexity of the cell design. Only the absorbed light can produce the photovoltaic effect, but not all electromagnetic spectrums can have this effect. Just leaving with gamma rays, x rays, ultraviolet (UV), visible light, and a part of infrared. This spectrum is reflected in (IEC 60904-3, 2019) or (ASTM G173-03, 2006) standard, which says "the terrestrial spectral irradiance distribution for use in terrestrial applications that require a standard reference spectral irradiance for hemispherical solar irradiance (consisting of both direct and diffuse components) incident on a sun-facing, 37° tilted surface or the direct normal spectral irradiance". Figure 7 from (ASTM G173-03, 2006) shows two lines, one in red and one in blue. The blue line represents the global tilt which includes diffuse and direct radiation. The red line represents the direct radiation plus circumsolar radiation.

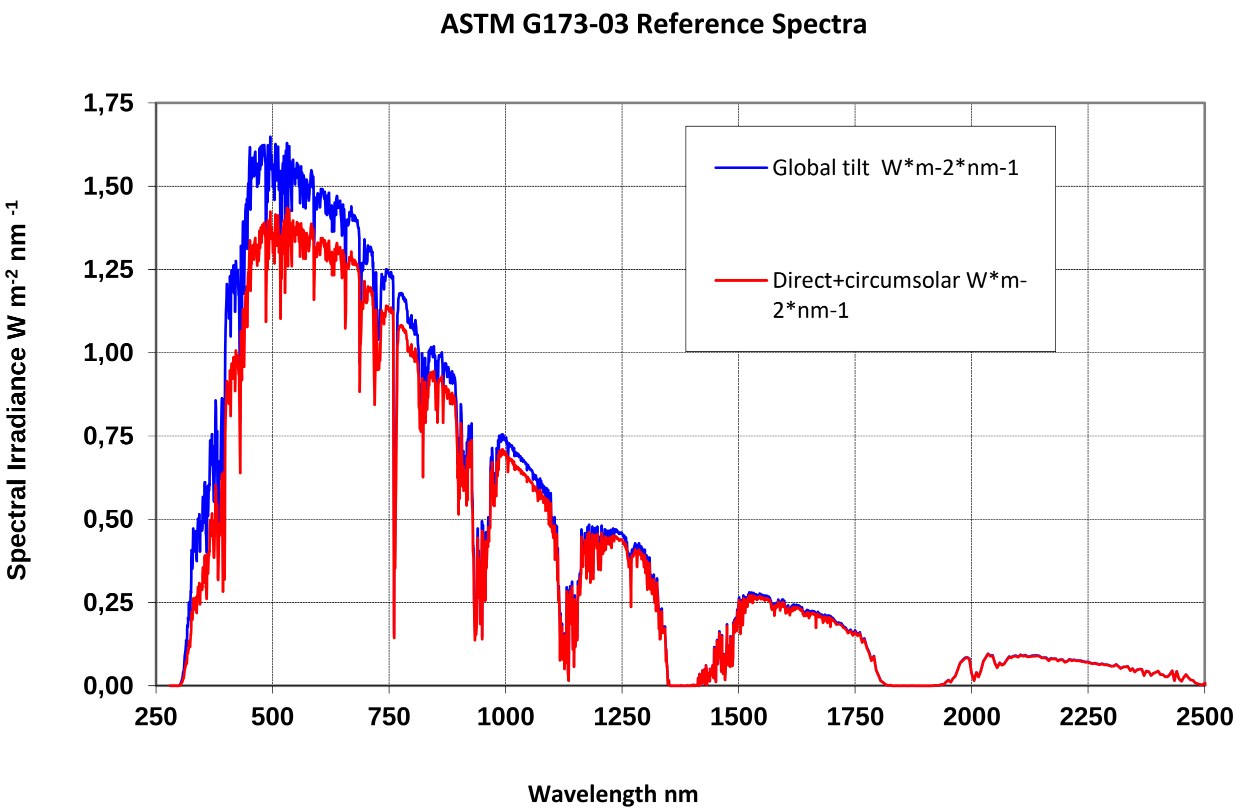


Figure 7. Reference solar spectral irradiance at AM 1.5.

AM stands for air mass which is the path length that light takes through the atmosphere. (Honsberg & Bowden, 2019) explains that “AM quantifies the reduction in power of light as it passes through the atmosphere and is absorbed by air and dust.” The Air Mass can be measured with the following equation:

$$the\ AM \approx \sqrt{1+\left(\frac{s}{h}\right)^{2}} = \frac{1}{\cos(\vartheta)+k(\vartheta)}$$

(2.1)

Where s is the shadow length, h is the object height, and ϑ is the angle between the normal and the sun. Eq.(2.1) considers the atmosphere as a flat horizontal layer, then $k(\vartheta)$is equal to 0. If the curvature of the Earth is considered, (Kasten & Young, 1989) introduce that $k(\vartheta)$ is:

$$k(\vartheta) = 0.50572 * (96.07995 - \vartheta)^{-1.6364}$$

(2.2)

In addition, (Heresch & Zweibel, 1982) show that untreated silicon reflects typically 36% of the total irradiance captured or more. For that reason, (Semenova, et al., 2014) says applying additional layers of silicon monoxide can reduce the light reflected by 10% and a second layer with a secondary material e. g. titanium dioxide can reduce the reflection as low as 3%. Moreover, (Heresch & Zweibel, 1982) added that texturing the material’s surface increases the probability of light being absorbed as shown in Figure 8.

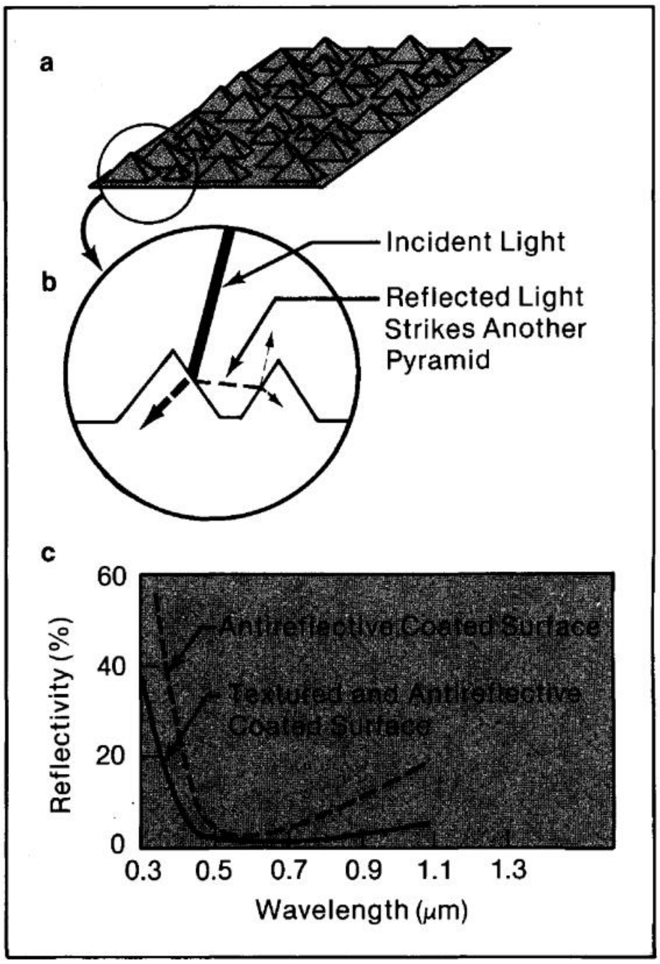


Figure 8. Texturing a cell and its effects.

Digging more into the subcategories of solar panels, from (NREL, 2018) analysis, more than 90% of PV systems use crystalline silicon cells. (Heresch & Zweibel, 1982) explains that obtaining a mono-crystalline cell is necessary to melt a single silicon cell. On the other hand, poly-crystalline is obtained after purifying silicon. The process is the following:

Purifying silicon → Poly-crystalline → Mono-crystalline

The extra step for getting mono-crystalline makes it more expensive but more efficient since it presents less or almost no defects (grain boundary) (Figure 9). Appendix B from NREL confirms mono-crystalline cells are more efficient than poly-crystalline. Finally, thin films can be made of silicon, however, there are more material based alternatives e.g. CGIS, CGISe, CdTe, Amorphous Si:H (stabilized), Perovskite, etc; and its efficiency then to be lower than the other two exposed before, however, in recent years, there are popping up prototypes with 25.6% of efficiency, from Panasonic (See Appendix B).

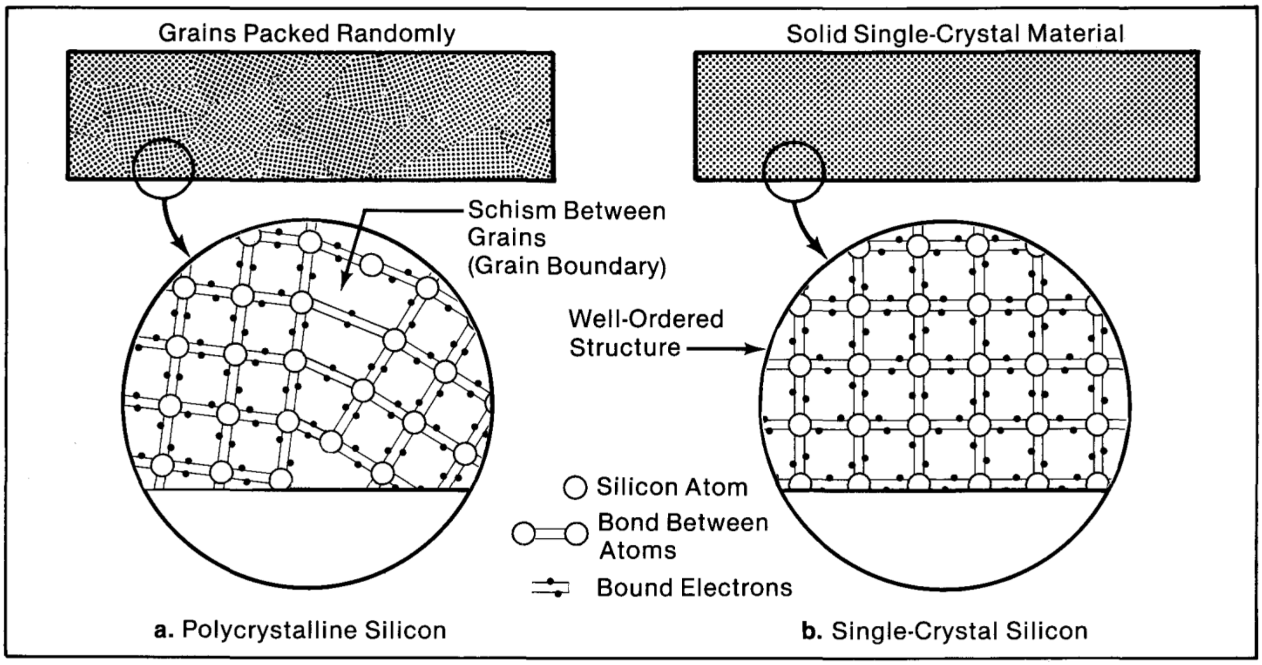


Figure 9. Microstructure of poly-crystalline silicon (a) and mono-crystalline silicon (b). (Heresch & Zweibel, 1982)

Apart from the intrinsic limitation solar panels have, there are others which do not depend on the solar panel. One of them is studied in (Reich, et al., 2009) which studies the effect of low irradiance for mono and poly-crystalline cells from different manufacturers at many light levels. From Reich article, the solar cell efficiency equation is:

$$\eta = \frac{Power\ out}{Power\ in} = \frac{Power\ out}{Irradiance * Area} = FF * Jsc * \frac{Voc}{G} \tag{2.3}$$

Where:

- Power out is the power that goes to the inverter from the solar panels. [W]
- Area is the surface of the solar panels.
- FF is the fill factor which is the ratio of maximum power. [-]
- Jsc is the short-circuit current density which can be obtained when the panel is biased to zero voltage. In [mA/cm^2]. This parameter removes the dependency on the area of the solar panel.
- Voc is the open-circuit voltage measured under standard test conditions when there is no current flowing in the circuit. In [V].
- G is the irradiance in [W/m^2].

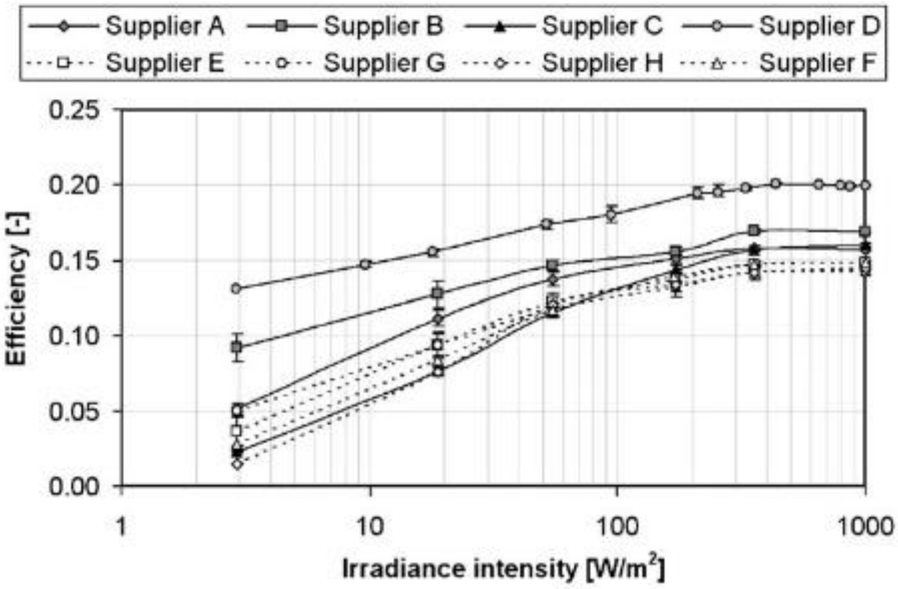


Figure 10. Measurement of efficiency for several solar cell between 3 to 1000 W/m^2. (Reich, et al., 2009)

Eq. (2.3) is going to be relevant in methodology section given that this forms part of the objective.

In order to get a general idea of how much irradiation a zone gets, (The World Bank, 2022) shows, in Appendix D, how much intensity each country around the globe gets (horizontal and global irradiation). It also includes the irradiation Ireland gets from 1994 to 2018.

Another key aspect that affects the efficiency of solar panels is temperature. (Honsberg & Bowden, 2019) says that solar panels, as other semiconductor devices, are sensitive to temperature. Moreover, the parameter that is most affected by temperature is V_{OC}, as seen in Figure 11. Unlike the short-circuit current (I_{SC}), that increases slightly. For understanding better this part, it is necessary to introduce the intensity-voltage curve or IV curve. (Honsberg & Bowden, 2019) says that the IV curve represents the possible points a solar panel can be at specific conditions (temperature, irradiance spectra, and wind). This curve in the absence of light is quite similar to a diode curve, but, when it starts to capture light, the curve shifts increasing the intensity. If this curve is compared to a diode curve it might look a little bit different, because the IV curve for solar panels is inverted (the intensity) by convention, being mainly in the first quadrant of the diagram. The point of contact between the curve and the axes are called V_{OC} and I_{SC}. From (LONGI, 2022), it can be seen the decreasement in efficiency when the temperature is risen.

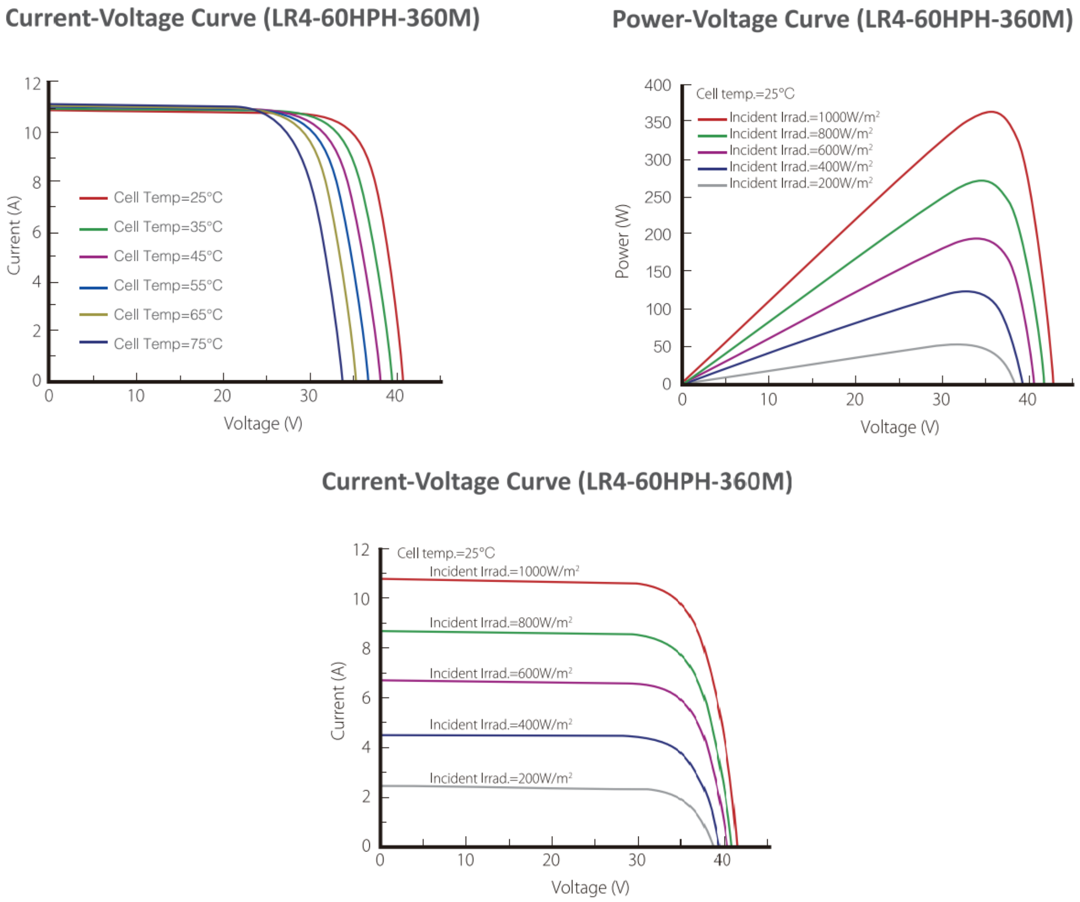


Figure 11. Intensity-voltage (I-V) curve for LR4-60HPH.

For getting values in a IV curve, the following equation may be useful:

$$I = I_L - I_0[\exp(\frac{qV}{nkT}) - 1] \tag{2.4}$$

$$I_0 = qA\frac{Dn_i^2}{LN_D} \tag{2.5}$$

$$V_{OC} = \frac{kT}{q}\ln(\frac{I_{SC}}{I_O}) \tag{2.6}$$

Where:

I_o is the dark saturation current.
I_L is the light generated current.
n is the ideality factor.
k is Boltzmann constant.
q is a constant base on the electronic charge.
A is the area of the panels.
D is a parameter depending on the silicon.
L is the minority carrier diffusion length.
N_D depends on the doping of silicon.
n_i is a constant that depends on the parameters of silicon.

T is the temperature.
(Heresch & Zweibel, 1982) adds that not only high temperatures negatively affect the efficiency, but also very low temperatures do the same.

And the last point which is going to be discussed in this project is the effect of debris on solar panels. In (Anwar Sulaiman, et al., 2014) can be found that debris like dust, water, sand, or moss on the solar panel can obstruct the light from reaching the cells, thus reducing the performance. It was found in this report that this effect can reduce up to 85% of the performance.

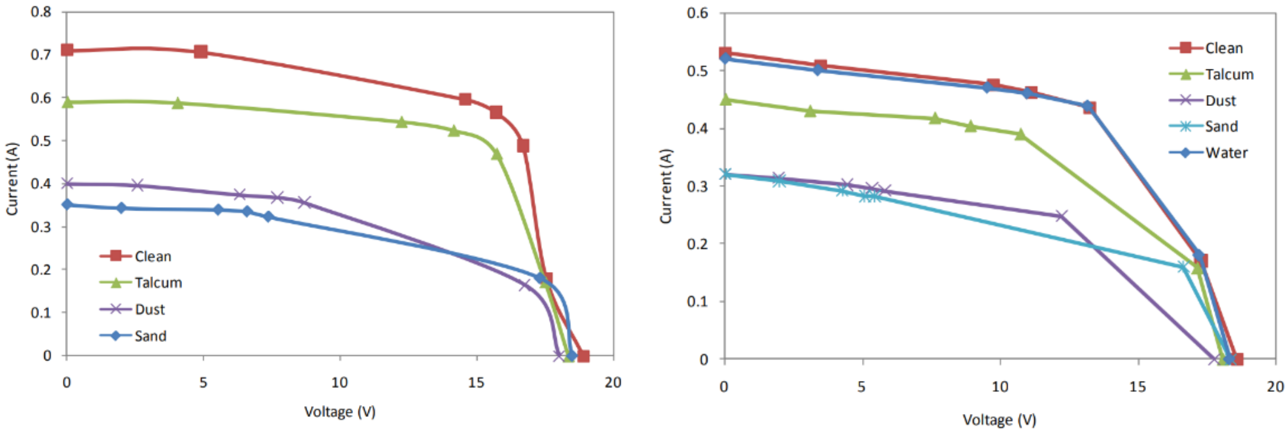


Figure 12. Variation of properties in IV curve for different type of debris at 310 W/m² (left) and 250 W/m² (right) (Anwar Sulaiman, et al., 2014)

From Figure 12, can be seen that the most harmful for the efficiency is dust and sand (between 65% and 74% of reduction for sand and dust) and the effect of water is negligible (between 0.5% and 4.3% reduction). It should be noticed that this test was only done for mono-crystalline cells. In (Martz-Oberlander, 2017) project, it is explored the effects of general debris for diferent technologies.
These are the three points (irradiance, temperature, and dust) that are going to be developed in the next point.

2.1.2 Inverter

The standard (UNE-206008, 2013) stablishes that an inverter is a device that converts DC into AC. For that reason, the efficiency of an inverter is:

$$\eta = \frac{P_{AC}}{P_{DC}} \tag{2.7}$$

Also from the same standard, there are 2 ways of measuring efficiency of inverters.

- European efficiency
- California energy commission efficiency (CEC)
- Maximum efficiency

The third one is not included in this standard but, some manufacturers, e.g. (Solis, 2019), include this efficiency for showing the peak efficiency an inverter can reach.

$$\eta_{EUR} = 0.03 * \eta_{5\%} + 0.06 * \eta_{10\%} + 0.13 * \eta_{20\%} + 0.10 * \eta_{30\%} + 0.48 * \eta_{50\%} + 0.20 * \eta_{100\%} \tag{2.8}$$

$$\eta_{CEC} = 0.03 * \eta_{5\%} + 0.06 * \eta_{10\%} + 0.13 * \eta_{20\%} + 0.10 * \eta_{30\%} + 0.48 * \eta_{50\%} + 0.20 * \eta_{100\%} \tag{2.9}$$

For measuring the partial load $\eta_{n\%}$ in Eq.(2.8) and Eq. (2.9), n is the fraction of the maximum power point of the inverter.

2.2 HP

From (Cengel & Boles, 2015), it is introduced the coefficient of performance (COP) which represents the relation between the heat load (q_c) in condenser and the work of the compressor (w).From (UNE 14825, 2019) is extracted Eq.(2.10) which represents the coefficient of performance theorical of a HP.

$$COP = \frac{q_c}{w} = \frac{h_2 - h_3}{h_2 - h_1} \tag{2.10}$$

This can also be related to (Sarbu & Sebarchievici, 2016) graphics (see Figure 13). However, in real life, there are decreasement of performance. The most noticeable is the decreasement on performance in the compressor, expressed in the following equation:

$$\eta_i = \frac{w}{w'} = \frac{h_{2''} - h_3}{h_2 - h_1} \tag{2.11}$$

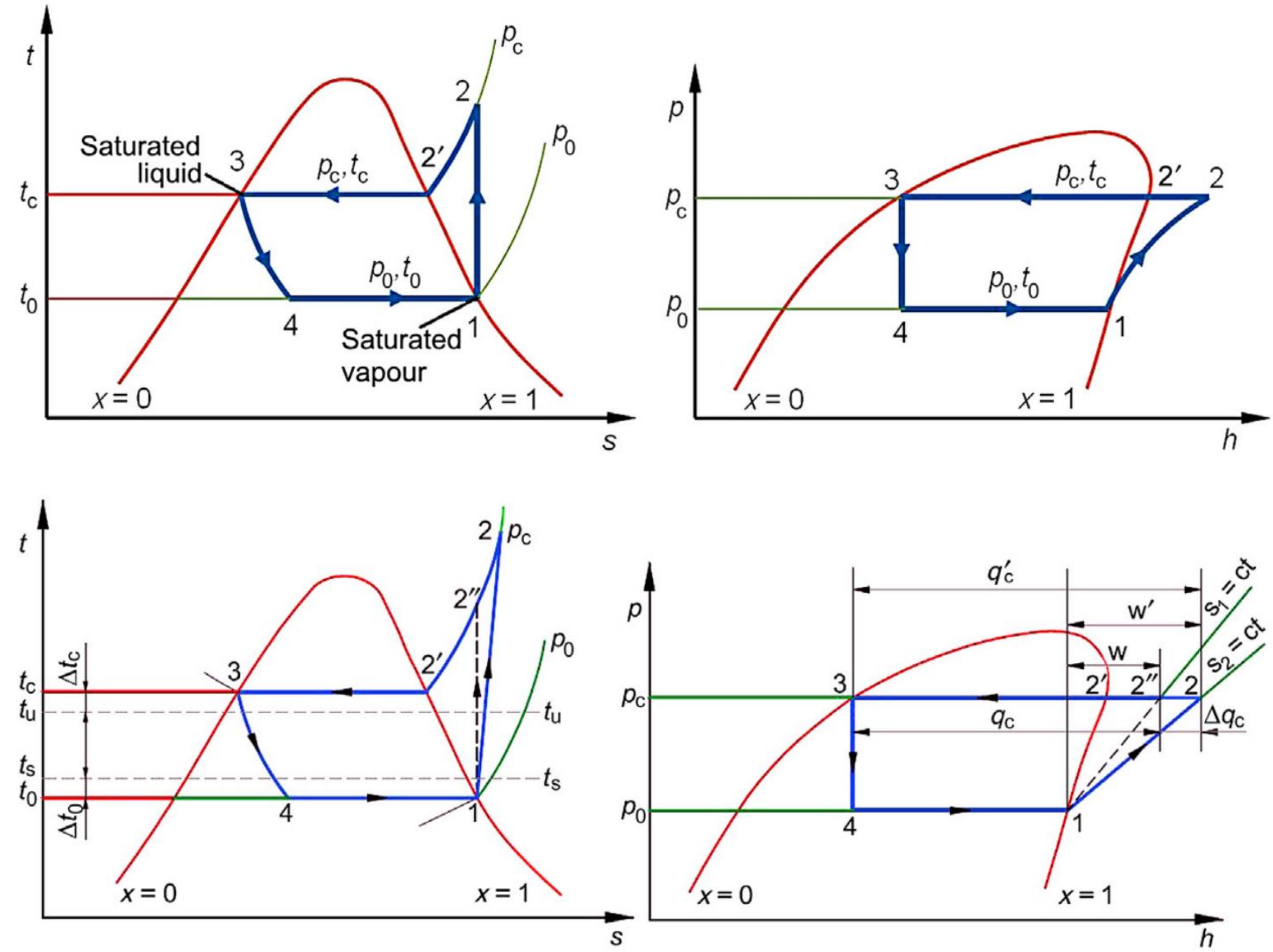


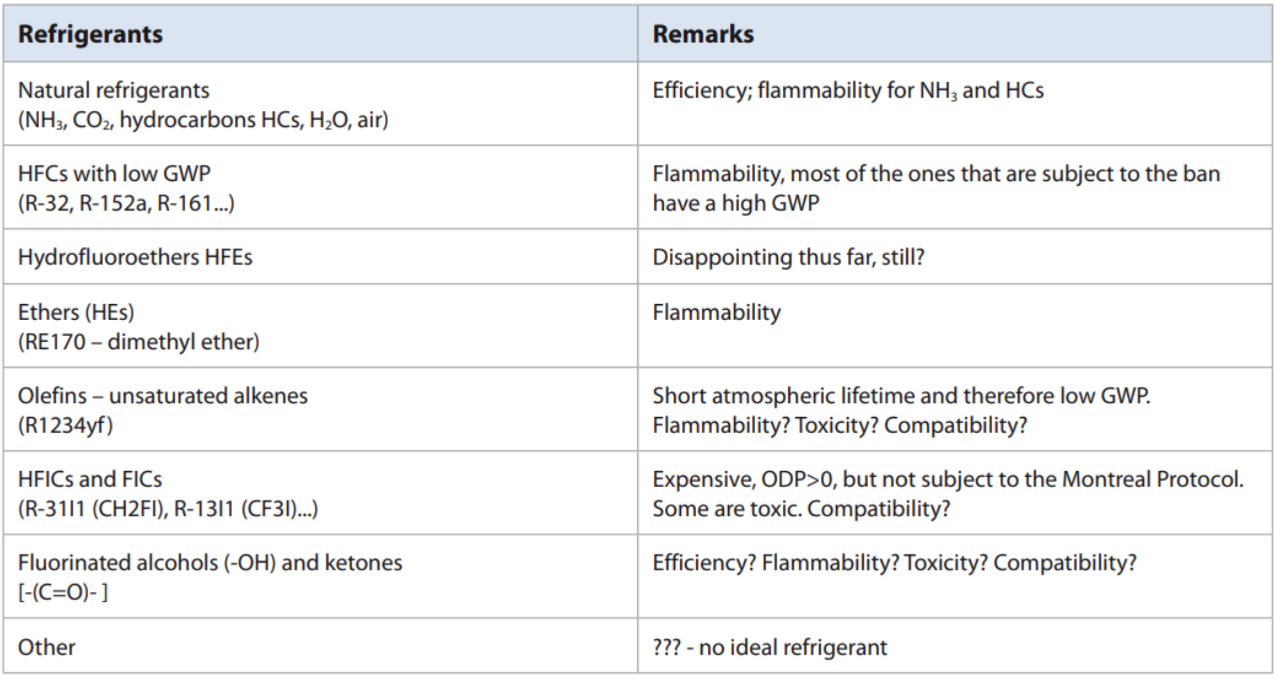
Figure 13. Temperature-entropy and pressure-enthalpy diagram for theorical (up) and real(down) cycle.

And the real COP is:

$$COPr = \frac{{q_c}'}{w'} = (COP - 1) * \eta_i + 1 \tag{2.12}$$

Where:

qc is the heat load in the condenser
w is the work in the compressor
qc’ and w’ represents the same thing but updated to the real cycle.
ƞi is the efficiency of the compressor.
It can be seen that COP is dependent on the enthalpies of refrigerant’s temperature (see Appendix G).The refrigerant is the fluid that is pumped through the circuit and its duty is to move the heat from the outside to the inside. (Pavkovic, 2013) describes and shows several refrigerants and its properties.



Refrigerants	Remarks
Natural refrigerants (NH_3, CO_2, hydrocarbons HCs, H_2O, air)	Efficiency; flammability for NH_3 and HCs
HFCs with low GWP (R-32, R-152a, R-161...)	Flammability, most of the ones that are subject to the ban have a high GWP
Hydrofluoroethers HFEs	Disappointing thus far, still?
Ethers (HEs) (RE170 – dimethyl ether)	Flammability
Olefins – unsaturated alkenes (R1234yf)	Short atmospheric lifetime and therefore low GWP. Flammability? Toxicity? Compatibility?
HFICs and FICs (R-31I1 (CH2FI), R-13I1 (CF3I)...)	Expensive, ODP>0, but not subject to the Montreal Protocol. Some are toxic. Compatibility?
Fluorinated alcohols (-OH) and ketones [-(C=O)-]	Efficiency? Flammability? Toxicity? Compatibility?
Other	??? - no ideal refrigerant

Figure 14. Refrigerant future alternatives. (Pavkovic, 2013)

(Sarbu & Sebarchievici, 2016) explains that COP gives you the performance of a specific time (t). For solving that this report introduces three ways of measuring efficiency:

- Seasonal energy efficiency ratio (SEER)
- Seasonal coefficient of performance (SCOP)
- Heating seasonal performance factor (HSPF)

This are long term measurements, energetic measurements, considering fluctuations of temperature and stand-by periods. (Sarbu & Sebarchievici, 2016)This provides more reliable efficiency over heating/cooling seasons. Moreover, at least one of this three is normally used in specifications sheet of manufacturers.

$$SCOP = \frac{Qannual\ demand}{Qannual\ energy\ consumption} = \frac{Qh}{Qhe} \tag{2.13}$$

$$Qh = Pdesign * Hhe \tag{2.14}$$

Pdesign is the power of the HP which was design for, in kW.
Hhe are the number of equivalent hours the HP is active, in h.

2.3 Synopsis

After reviewing these two systems, this project is going to focus on how to obtain the efficiency of each system, based on standards and article shown before. This project will deal with normal solar panels (not concentrator systems), and for HP, this project will address HP air to air mainly, since the majority of components and equations are the same it would be valid for others sources up to some extent.

3 Methodology

3.1 PV

DOKIO solar

Model		FSP-100M(50W*2)
Maximum Power	(Pmax)	100W±3%
Maximum Power Voltage	(Vmp)	18.00V
Maximum Power Current	(Imp)	5.56A
Open Circuit Voltage	(Voc)	22.50V
Short Circuit Current	(Isc)	5.81A
Nominal Operating Cell Temp.	(NOCT)	-45to80℃
Maximum System Voltage		DC1000V
Maximum Series Fuse		9A

For field connections,use minimum No.12 AWG copper wires insulated for a minimum 90℃

Weight	8.20Kgs
Dimension	530*660*50mm

Standard Test Conditions
AM=1.5 IRRADIANCE=1000W/m² Temp.=25℃

Figure 15. Properties of a solar panel.

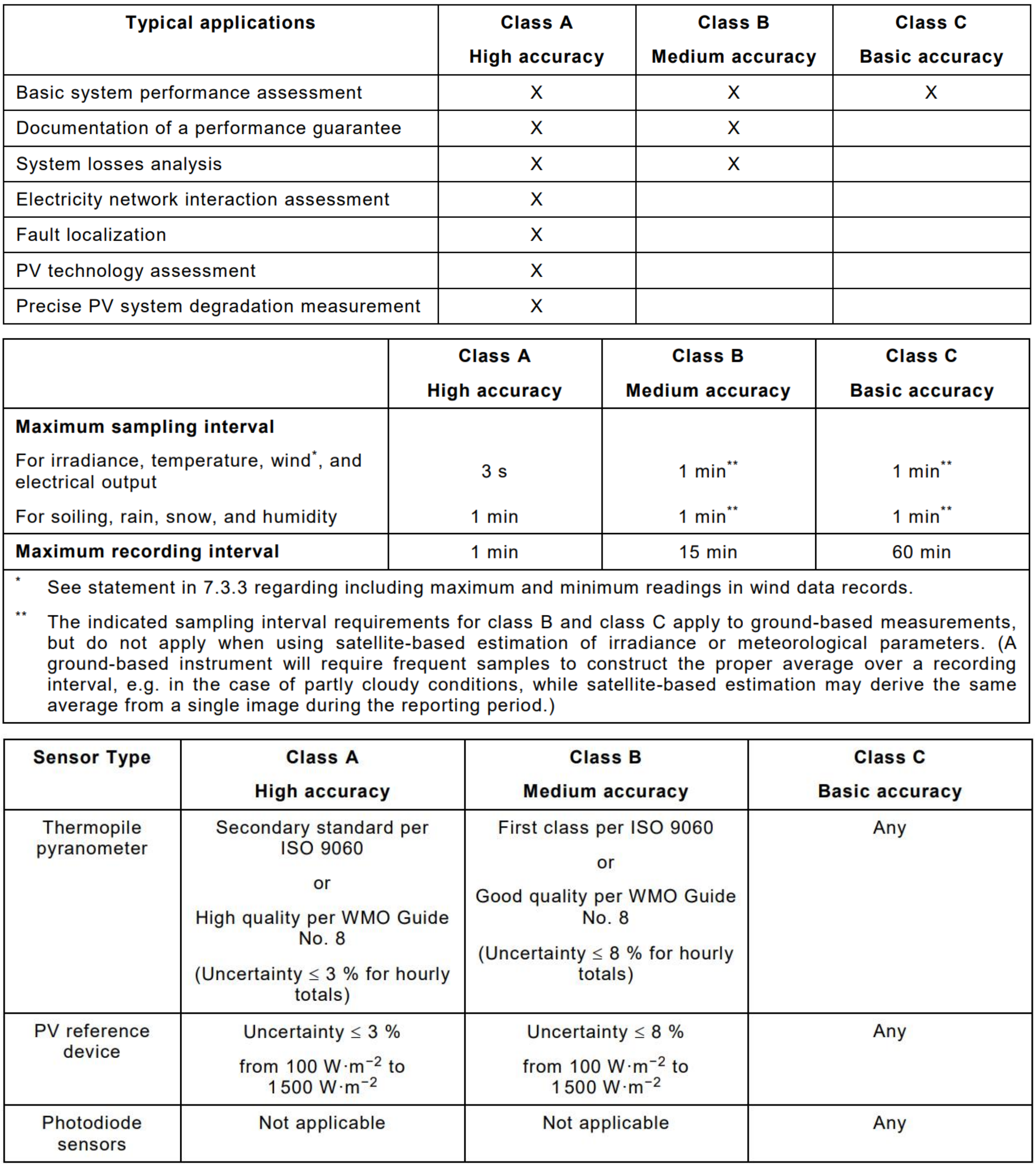
For measuring the efficiency of a solar panel first off all is necessary to see the label behind the solar panel where the Voc, Isc and the Pmax can be retrieved, this is only valid if there are under STC, otherwise, there have to be calculated with Eq.(2.3). The STC (Standard Testing Conditions) are: Irradiance 1000 W/m^2, cell temperature 25 °C and spectra at AM 1.5.

3.1.1 Irradiance sensors

Then, the irradiance can be measured with three types of sensors:

- Thermopile pyranometer
- PV reference device
- Photodiode sensor

These sensors can be categorized in three tears, A, B, or C depending on the type of application. (UNE-EN 61724-1, 2017). Each sensor must be calibrated before testing the system and any part of the system should be documented, maintenance, log of events, component changes, etc.



Typical applications	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Basic system performance assessment	X	X	X
Documentation of a performance guarantee	X	X	
System losses analysis	X	X	
Electricity network interaction assessment	X		
Fault localization	X		
PV technology assessment	X		
Precise PV system degradation measurement	X		

	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Maximum sampling interval			
For irradiance, temperature, wind*, and electrical output	3 s	1 min**	1 min**
For soiling, rain, snow, and humidity	1 min	1 min**	1 min**
Maximum recording interval	1 min	15 min	60 min

* See statement in 7.3.3 regarding including maximum and minimum readings in wind data records.

** The indicated sampling interval requirements for class B and class C apply to ground-based measurements, but do not apply when using satellite-based estimation of irradiance or meteorological parameters. (A ground-based instrument will require frequent samples to construct the proper average over a recording interval, e.g. in the case of partly cloudy conditions, while satellite-based estimation may derive the same average from a single image during the reporting period.)

Sensor Type	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Thermopile pyranometer	Secondary standard per ISO 9060 or High quality per WMO Guide No. 8 (Uncertainty ≤ 3 % for hourly totals)	First class per ISO 9060 or Good quality per WMO Guide No. 8 (Uncertainty ≤ 8 % for hourly totals)	Any
PV reference device	Uncertainty ≤ 3 % from 100 $W \cdot m^{-2}$ to 1 500 $W \cdot m^{-2}$	Uncertainty ≤ 8 % from 100 $W \cdot m^{-2}$ to 1 500 $W \cdot m^{-2}$	Any
Photodiode sensors	Not applicable	Not applicable	Any

Table 1. Monitoring system classification and suggested applications; sampling and recording interval requirements; sensor type for different requirements.

The inspection of the sensors must be done annually, for A and B class, and for C class it is per site-specific requirement. Each inspection should look for displacement or damage to external sensors, loose cables, or other potential threads. For sampling reporting or recording should be defined a specific time based on Table 1.it is strongly recommended to include a timestamp in each report, following ISO 8601. In Appendix E can be seen the minimum and the recommended number of sensor for each requirement.

Another important part is the location of the sensors. These should avoid being in a shaded position during sunrise and sunset. Secondary sensors should be placed around temporarily shaded zones to track the level of irradiance in low light. The alignment of the sensors is also contemplated by (UNE-EN 61724-1, 2017) in the following table:

Recalibrations of sensors should be done in place for minimizing the offline time of the sensors. If any sensor needs to be sent into a laboratory for recalibration, the system should contain redundant sensor for not losing tracking.

	Class A **High accuracy**	**Class B** **Medium accuracy**	**Class C** **Basic accuracy**
Tilt angle	1°	1,5°	2°
Azimuthal angle	2°	3°	4°

Item	**Class A** **High accuracy**	**Class B** **Medium accuracy**	**Class C** **Basic accuracy**
Recalibration	Once per year	Once every 2 years	As per manufacturer's requirements
Cleaning	At least once per week	Optional	
Heating to prevent accumulation of condensation and/or frozen precipitation	Required in locations where condensation and/or frozen precipitation would affect measurements on more than 7 days per year	Required in locations where condensation and/or frozen precipitation would affect measurements on more than 14 days per year	
Ventilation (for thermopile pyranometers)	Required	Optional	
Desiccant inspection and replacement (for thermopile pyranometers)	As per manufacturer's requirements	As per manufacturer's requirements	As per manufacturer's requirements

Table 2. Sensor alignment and irradiance sensor maintenance.

3.1.2 Temperature sensors

For measuring the temperature of the PV module, a sensor is attached to the back of the panel. The uncertainty of this type of sensor shall be less or equal than 2%. Its recalibration has to be every two years for class A, defined by manufacturer for class B and not necessary for class C. For measuring ambient temperature (Tamb), the sensors should be placed in solar radiation shields which allow free air movement.

3.1.3 Wind sensor

Wind's speed and direction are used for estimating the temperature of the panel. The hight of measurement is relevant since it has to be in a relevant hight for the panels and for comparing with meteorological data. Always avoiding shading the cells. Its recalibration is defined by the manufacturer for all classes.

3.1.4 Soil measurement

For measuring the soiling ration, which is the relation between a soiled panel power output and the output power of a clean panel. For that reason, a reference panel is leaved as the soiled panel, and it has to be representative for comparing with another panel which is going to be cleaned frequently, daily or twice a week for A class, and a lesser interval for class B and C. this process could be done manually or with a machine. There are two methods for measuring soiling:

- Method 1: max power reduction due to soiling
- Method 2: short-circuit current reduction due to soiling

(UNE-EN 61724-1, 2017) recommends using method 1 since it represents a more accurate power loss even if the soil is not homogeneous. The recalibration should be done each year, at least. The process is:

- Measure I_{sc} and T of the clean device.
- Measure maximum power and T for soiled panel.

- Calculate the effective irradiance (G_{eff}) from the first point.
- Calculate the expected max. power of the soiled device at G_{eff} from the previous point.
- Calculate the relation between the soiled panel max. power with the expected max. power. Soling ratio (SR).

3.1.5 Inverter efficiency measurement

All electrical measurements should be capable of running at least at 120% of the expected value when the PV system is operating at the maximum rating of the inverter operating at STC.

Parameter	**Measurement Uncertainty**		
	Class A **High accuracy**	**Class B** **Medium accuracy**	**Class C** **Basic accuracy**
Input voltage (DC)	±2,0 %	n/a	n/a
Input current (DC)	±2,0 %	n/a	n/a
Input power (DC)	±2,0 %	n/a	n/a
Output voltage (AC)	±2,0 %	±3,0 %	n/a
Output current (AC)	±2,0 %	±3,0 %	n/a
Output power (AC)	±2,0 %	±3,0 %	n/a

Parameter	**Class A** **High accuracy**	**Class B** **Medium accuracy**	**Class C** **Basic accuracy**
Active power and energy	Class 0,2 S as per IEC 62053-22	Class 0,5 S as per IEC 62053-22	Class 2 per IEC 62053-21
Power factor	Class 1 as per IEC 61557-12	Class 1 as per IEC 61557-12	n/a

Table 3. Electrical requirements for measuring parameters; AC output measurements requirements.

3.2 HP SCOP

For measuring SCOP, it is going to be followed the standard (UNE 14825, 2019). This standard has Eq. (2.13) and Eq. (2.14) as the beginning of the process. Then Q_{HE} is calculated with:

$$Q_{\mathrm{HE}} = \frac{Q_{\mathrm{H}}}{SCOP_{\mathrm{on}}} + H_{\mathrm{TO}} \times P_{\mathrm{TO}} + H_{\mathrm{SB}} \times P_{\mathrm{SB}} + H_{\mathrm{CK}} \times P_{\mathrm{CK}} + H_{\mathrm{OFF}} \times P_{\mathrm{OFF}} \tag{3.1}$$

Hnn are the number of hours that it is consider as in stan-by mode, in h.
Pnn is the power that it is considered when is in stand-by mode.
SCOPon is the coefficient of the seasonal efficiency. This can be calculated with the following equation:

$$SCOP_{\mathrm{on}} = \frac{\sum_{j=1}^{n} h_j \left[P_{\mathrm{h}}(T_j) \right]}{\sum_{j=1}^{n} h_j \left[\frac{P_{\mathrm{h}}(T_j) - elbu(T_j)}{COP_{\mathrm{bin}}(T_j)} + elbu(T_j) \right]} \tag{3.2}$$

Tj is the time interval in h
j is the number of intervals
n is the total number of intervals
Ph(Tj) is the heating load in kW
Hj is the interval of hours for Tj
COPbin (Tj) is the COP value at Tj
elbu(Tj) is required power of the supplementary heater at Tj
pl(Tj) is partial load factor
Tdesign is the reference temperature of design for heating.

$$Ph(Tj) = Pdesign * pl(Yj) = Pdesign * \frac{Tj - 16}{Tdesign - 16} \tag{3.3}$$

For calculating COP_{bin}:

$$CR = pl(T_j) \times \frac{P_{\mathrm{designh}}}{Pdh} \tag{3.4}$$

$$COP_{\mathrm{bin}} = COP_{\mathrm{d}} \times (1 - Cd \times (1 - CR)) \tag{3.5}$$

COP_d is the CP at power Pdh
Cd is the coefficient of degradation
CR is the power factor $CR \leq 1$

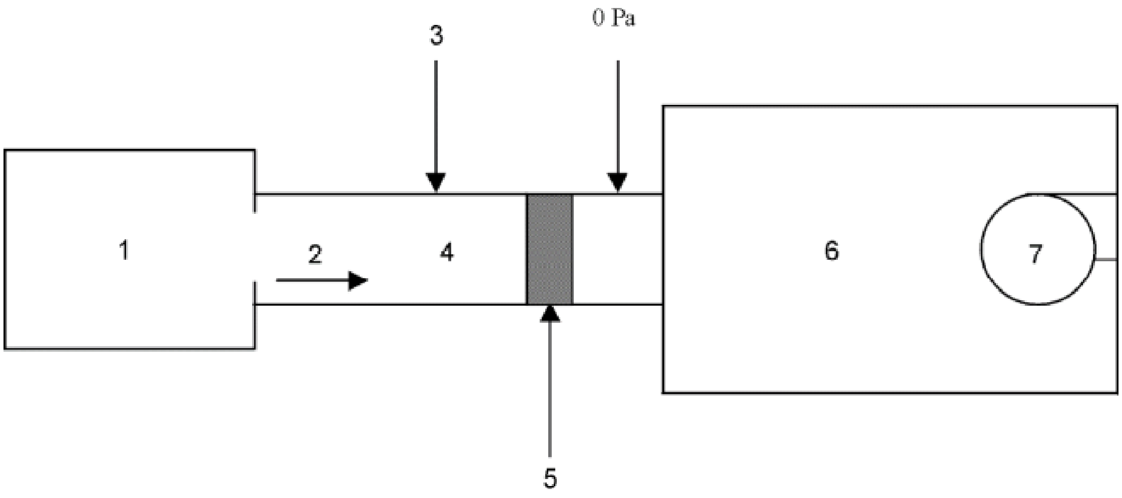


Figure 16. Test layout.

Where:
1 is the study object
2 is airflow
3 is the static pressure (external)
4 is a pipe which connects the study object with the airflow sensor and fan
5 is a gate
6 is the location of the airflow sensor
7 is a fan

The procedure measuring SCOP is the following:

First, determine Pdesign and COP_d in the maximum step of power. If this stage allows to reach the required heating load by 10% margin, it is considered that:

At T≥ Tbib, then COP is COPbin. Otherwise, COP and COPbin have to be considered as different values.

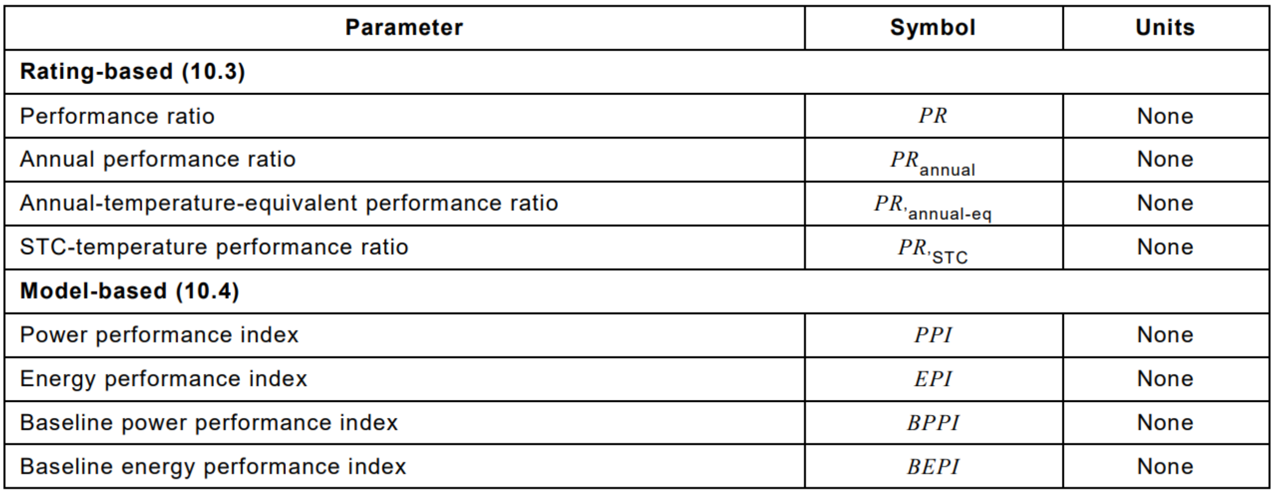
4 Results

4.1 PV

For photovoltaic systems there is a standard, (UNE-EN 61724-1, 2017),in which is clearly expressed what aspects should be taken in consideration, agreeing with other reports shown in literature review . These are:

- Irradiation as the principal factor
- Temperature
- Dust
- Wind
- Rain
- Snow
- Humidity
- Inverter
- Solar panel

Moreover, in this standard there is a section (point 8) where it sets some guidelines for doing quality checks, and in point 10 it deals with performance metric of PV.



Parameter	Symbol	Units
Rating-based (10.3)		
Performance ratio	PR	None
Annual performance ratio	PR_{annual}	None
Annual-temperature-equivalent performance ratio	$PR,_{\text{annual-eq}}$	None
STC-temperature performance ratio	$PR,_{\text{STC}}$	None
Model-based (10.4)		
Power performance index	PPI	None
Energy performance index	EPI	None
Baseline power performance index	$BPPI$	None
Baseline energy performance index	$BEPI$	None

Table 4. Performance metrics.

4.2 HP

From the standard (UNE 14825, 2019), it can be gathered that the attributes that a company must consider are the ambient temperature, the cycle temperature, the properties of the specific HP, since some parameters are dependent on the type of HP like the design power, the refrigerant that is used, and the time when the HP is working. However, (Piechurski, et al., 2017) adds that from his test compared to EN 14825, his results are different from what it should get since he claims that EN 14825 does not include the impact of defrosting.

5 Conclusion

The method for PV is optimal since it takes into account all the relevant parameters for determine the efficiency of PV. Nonetheless, it should also be into consideration the economic costs of each step. See the economic viability of cleaning frequently the panels or leaving the debris. It would be interesting to dig more into I-V curve with one diode and two diode model for evaluating the difference between these two models and how accurate is for different cell technologies, not only crystalline silicon.

In short it can be concluded, for HP, that the procedure proposed by EN 14825 is partially optimal since it contemplates key characteristics for evaluation. However, as discussed in the previous point, there are some aspects that are not evaluated or assumed as negligible that should be considered. It would be interesting to review EN 14825-2 and EN 14825-3 for getting more information related to other types of heat pumps.

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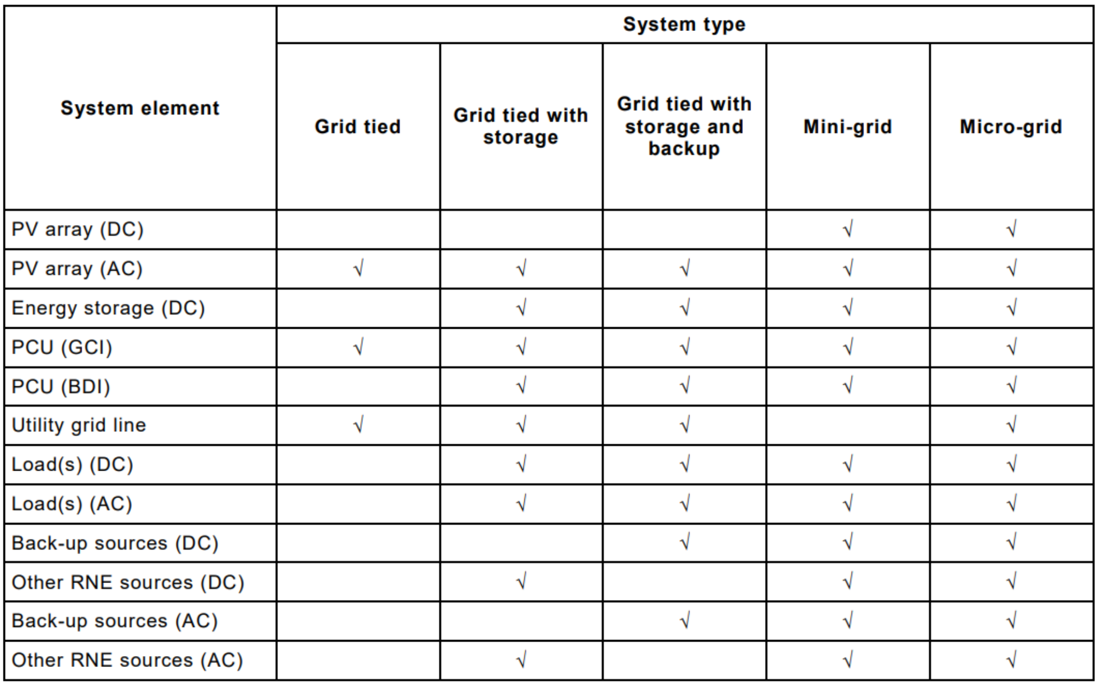
7 Appendices

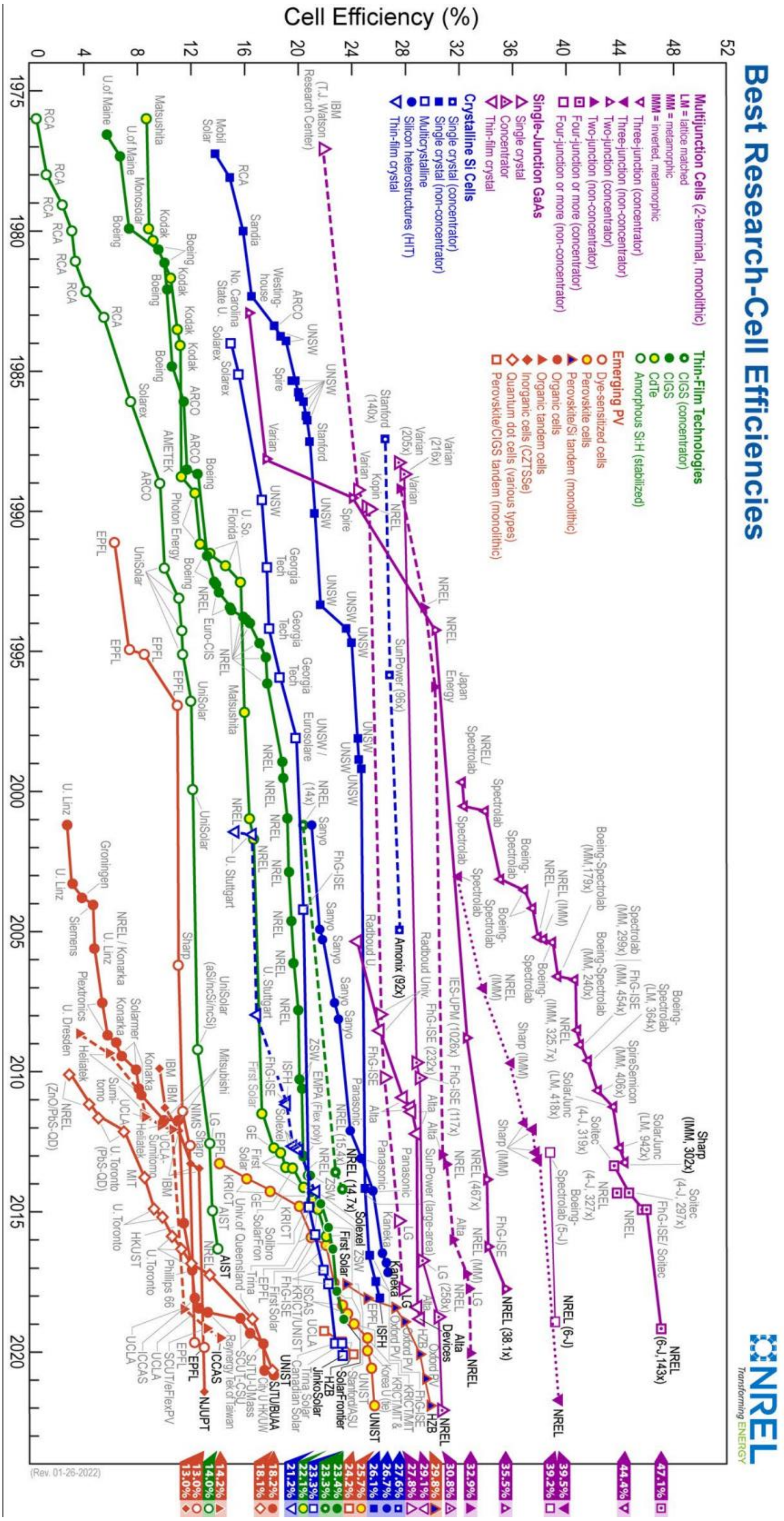
Appendix A

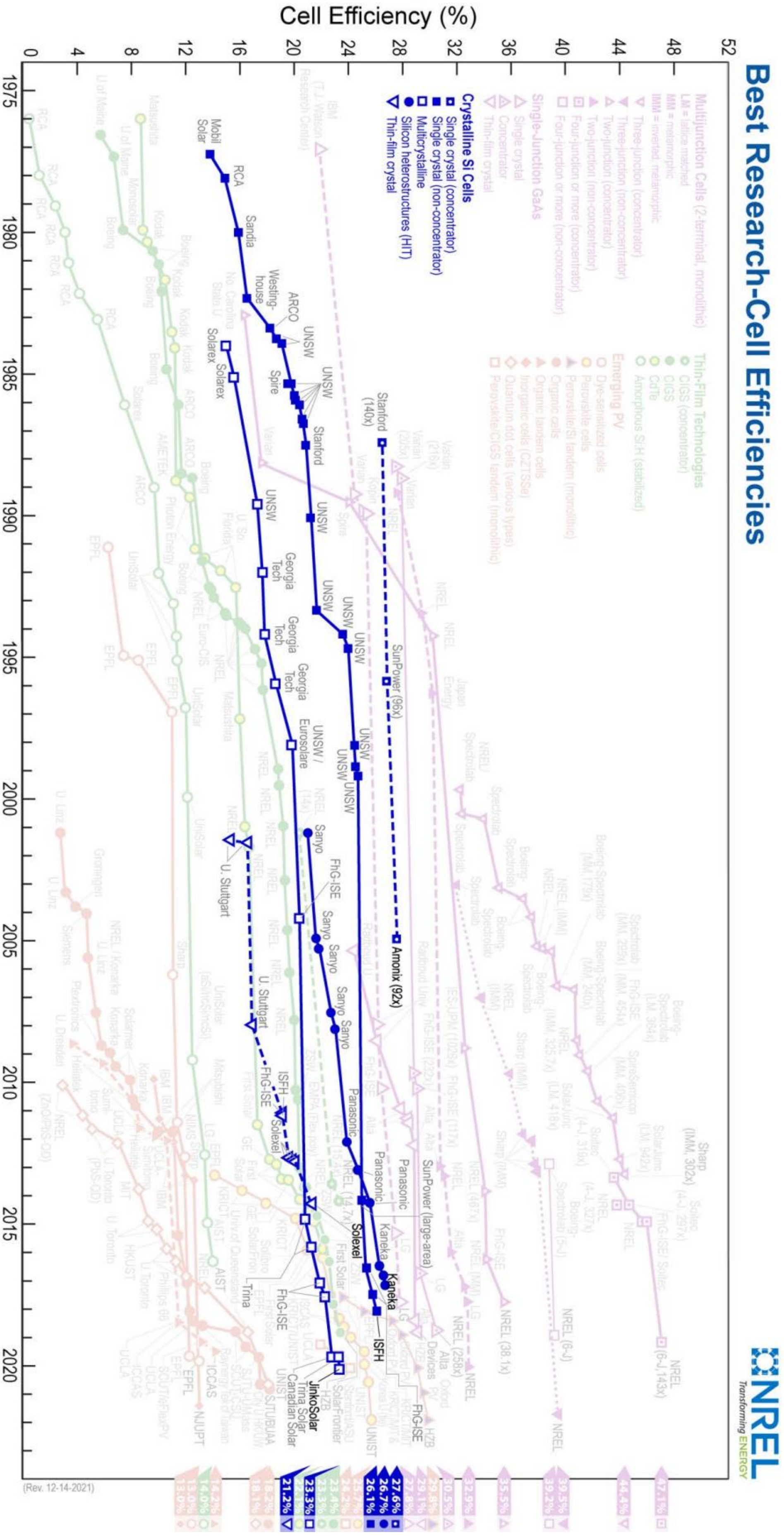


System element	System type				
	Grid tied	Grid tied with storage	Grid tied with storage and backup	Mini-grid	Micro-grid
PV array (DC)				√	√
PV array (AC)	√	√	√	√	√
Energy storage (DC)		√	√	√	√
PCU (GCI)	√	√	√	√	√
PCU (BDI)		√	√	√	√
Utility grid line	√	√	√		√
Load(s) (DC)		√	√	√	√
Load(s) (AC)		√	√	√	√
Back-up sources (DC)			√	√	√
Other RNE sources (DC)		√		√	√
Back-up sources (AC)			√	√	√
Other RNE sources (AC)		√		√	√

Table 5. Elements of different PV systems.

Appendix B


Best Research-Cell Efficiencies
Cell Efficiency (%)
0
4
8
12
16
20
24
28
32
36
40
44
48
52
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Perovskite/CIGS tandem (monolithic)
47.1%
44.4%
39.5%
39.2%
35.5%
32.9%
30.8%
29.8%
29.1%
27.8%
27.6%
26.7%
26.1%
25.7%
24.2%
23.4%
23.3%
23.3%
22.1%
21.2%
18.2%
18.1%
14.2%
14.0%
13.0%
13.0%
NREL Transforming ENERGY
(Rev. 01-26-2022)


Best Research-Cell Efficiencies
NREL Transforming ENERGY
Cell Efficiency (%)
0
4
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44
48
52
1975
1980
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2020
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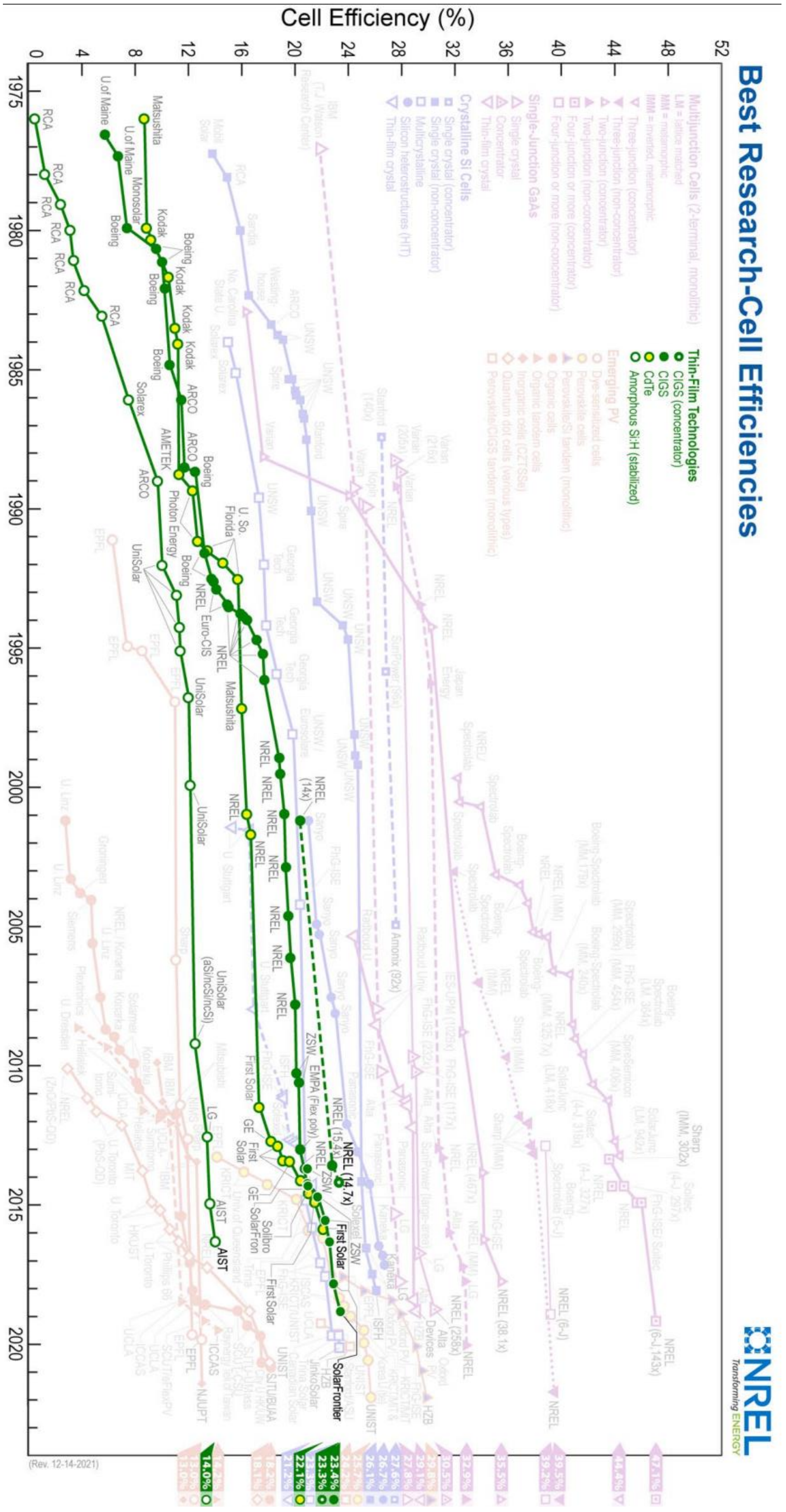
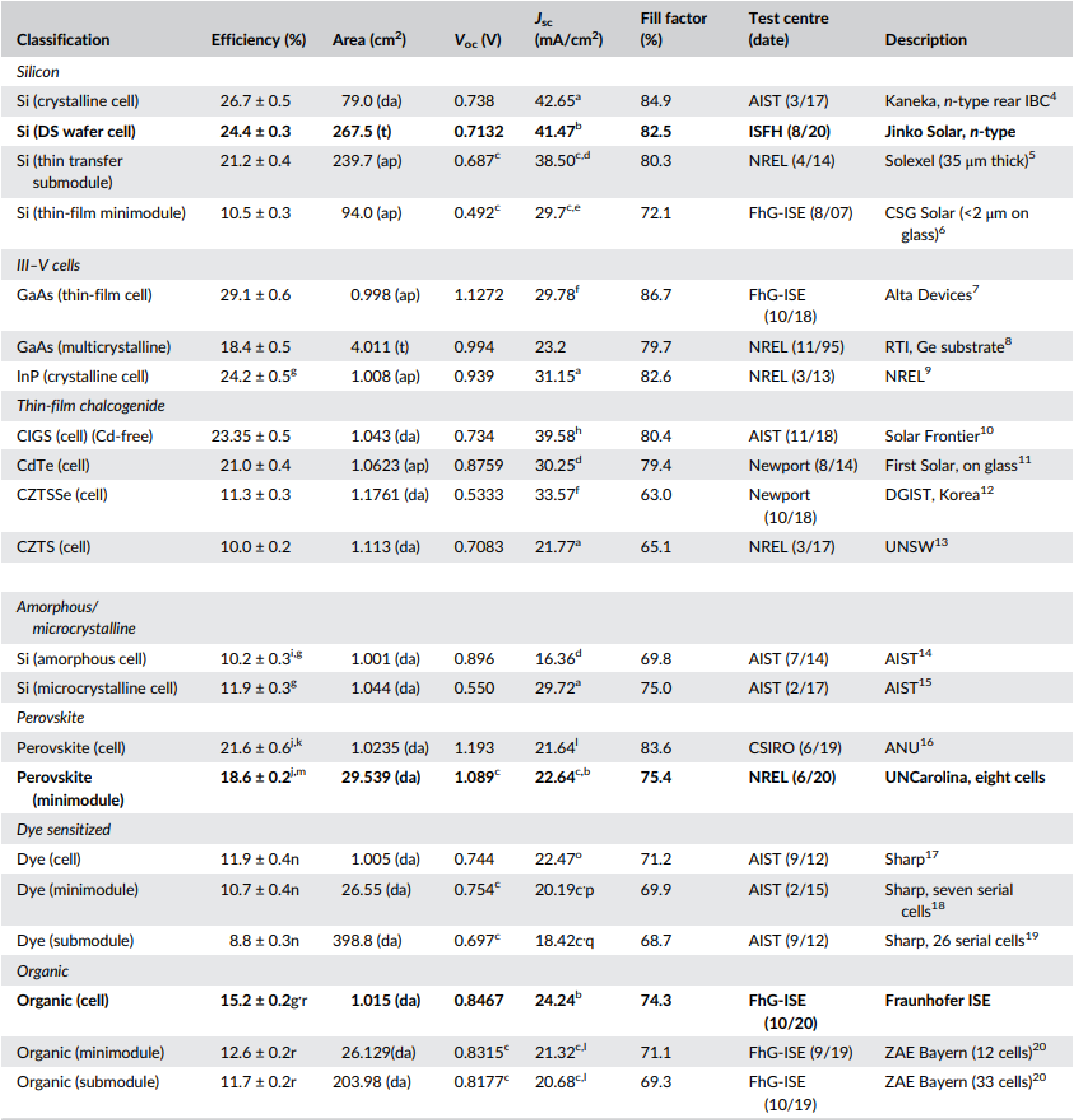
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
Emerging PV
47.1%
44.4%
39.5%
39.2%
35.5%
32.9%
29.1%
27.6%
26.7%
26.1%
23.3%
21.2%
(Rev. 12-14-2021)


Best Research-Cell Efficiencies
Cell Efficiency (%)
0
4
8
12
16
20
24
28
32
36
40
44
48
52
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Perovskite/CIGS tandem (monolithic)
RCA
Matsushita
U.of Maine
Monosolar
Kodak
Boeing
ARCO
Solarex
AMETEK
Photon Energy
U. So. Florida
UniSolar
NREL
Euro-CIS
NREL (14x)
NREL (15.4x)
NREL (14.7x)
ZSW
EMPA (Flex poly)
First Solar
GE
Solibro
Solar Frontier
LG
AIST
UniSolar (aSi/ncSi/ncSi)
23.4%
23.3%
22.1%
14.0%
(Rev. 12-14-2021)
NREL
Transforming ENERGY

Appendix C



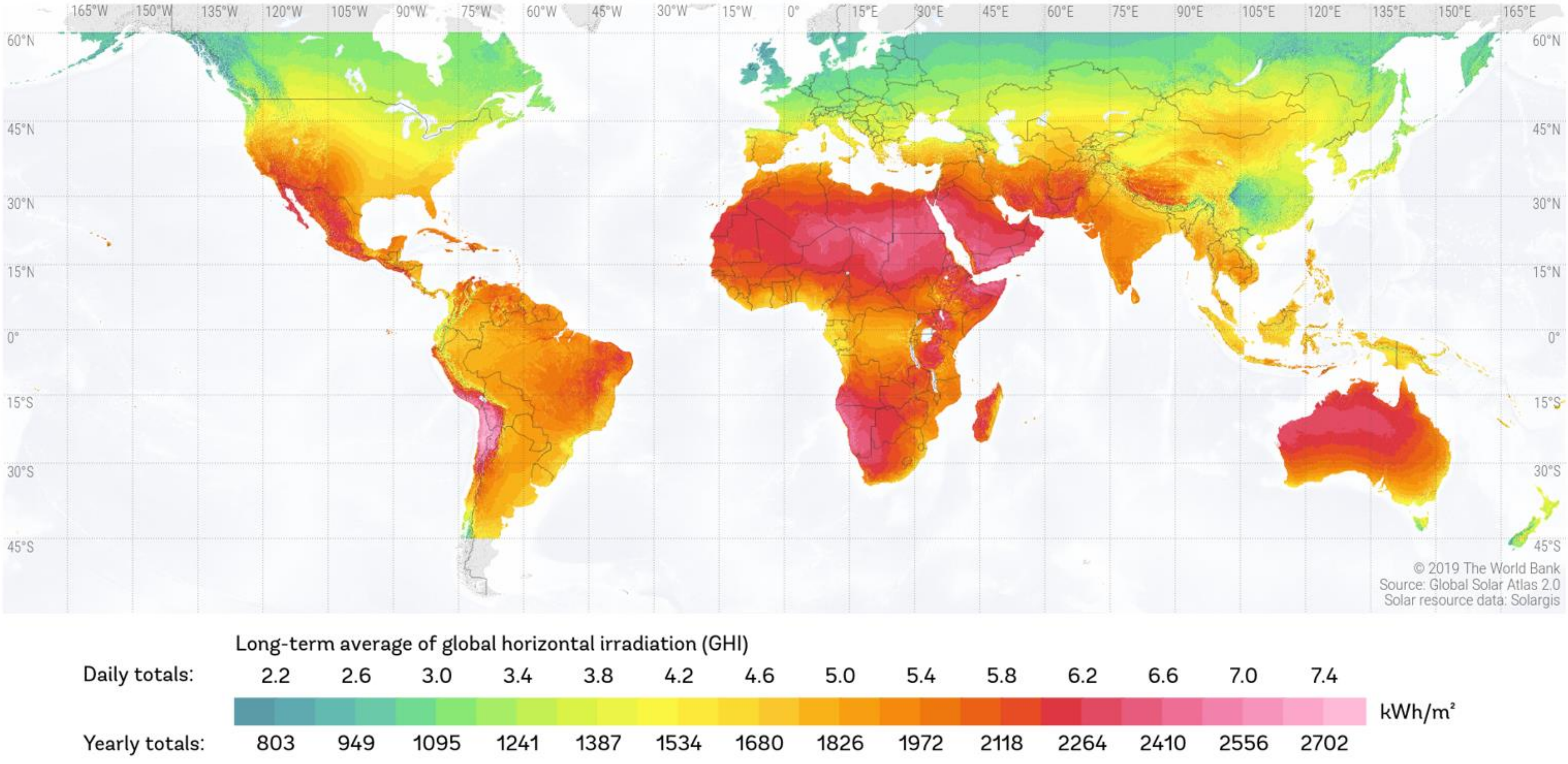
Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	26.7 ± 0.5	79.0 (da)	0.738	42.65^{a}	84.9	AIST (3/17)	Kaneka, *n*-type rear IBC[4]
Si (DS wafer cell)	**24.4 ± 0.3**	**267.5 (t)**	**0.7132**	**41.47^{b}**	**82.5**	**ISFH (8/20)**	**Jinko Solar, *n*-type**
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687^{c}	38.50^{c,d}	80.3	NREL (4/14)	Solexel (35 μm thick)[5]
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492^{c}	29.7^{c,e}	72.1	FhG-ISE (8/07)	CSG Solar (<2 μm on glass)[6]
III–V cells							
GaAs (thin-film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78^{f}	86.7	FhG-ISE (10/18)	Alta Devices[7]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[8]
InP (crystalline cell)	24.2 ± 0.5^{g}	1.008 (ap)	0.939	31.15^{a}	82.6	NREL (3/13)	NREL[9]
Thin-film chalcogenide							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	0.734	39.58^{h}	80.4	AIST (11/18)	Solar Frontier[10]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25^{d}	79.4	Newport (8/14)	First Solar, on glass[11]
CZTSSe (cell)	11.3 ± 0.3	1.1761 (da)	0.5333	33.57^{f}	63.0	Newport (10/18)	DGIST, Korea[12]
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77^{a}	65.1	NREL (3/17)	UNSW[13]
Amorphous/ microcrystalline							
Si (amorphous cell)	10.2 ± 0.3^{i,g}	1.001 (da)	0.896	16.36^{d}	69.8	AIST (7/14)	AIST[14]
Si (microcrystalline cell)	11.9 ± 0.3^{g}	1.044 (da)	0.550	29.72^{a}	75.0	AIST (2/17)	AIST[15]
Perovskite							
Perovskite (cell)	21.6 ± 0.6^{j,k}	1.0235 (da)	1.193	21.64^{l}	83.6	CSIRO (6/19)	ANU[16]
Perovskite (minimodule)	**18.6 ± 0.2^{i,m}**	**29.539 (da)**	**1.089^{c}**	**22.64^{c,b}**	**75.4**	**NREL (6/20)**	**UNCarolina, eight cells**
Dye sensitized							
Dye (cell)	11.9 ± 0.4n	1.005 (da)	0.744	22.47^{o}	71.2	AIST (9/12)	Sharp[17]
Dye (minimodule)	10.7 ± 0.4n	26.55 (da)	0.754^{c}	20.19c·p	69.9	AIST (2/15)	Sharp, seven serial cells[18]
Dye (submodule)	8.8 ± 0.3n	398.8 (da)	0.697^{c}	18.42c·q	68.7	AIST (9/12)	Sharp, 26 serial cells[19]
Organic							
Organic (cell)	**15.2 ± 0.2g·r**	**1.015 (da)**	**0.8467**	**24.24^{b}**	**74.3**	**FhG-ISE (10/20)**	**Fraunhofer ISE**
Organic (minimodule)	12.6 ± 0.2r	26.129(da)	0.8315^{c}	21.32^{c,l}	71.1	FhG-ISE (9/19)	ZAE Bayern (12 cells)[20]
Organic (submodule)	11.7 ± 0.2r	203.98 (da)	0.8177^{c}	20.68^{c,l}	69.3	FhG-ISE (10/19)	ZAE Bayern (33 cells)[20]

Figure 17. Confirmed single-junction terrestrial cell and submodule efficiency measured under STC. (Green, et al., 2020)

Appendix D

SOLAR RESOURCE MAP

GLOBAL HORIZONTAL IRRADIATION



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Source: Global Solar Atlas 2.0
Solar resource data: Solargis

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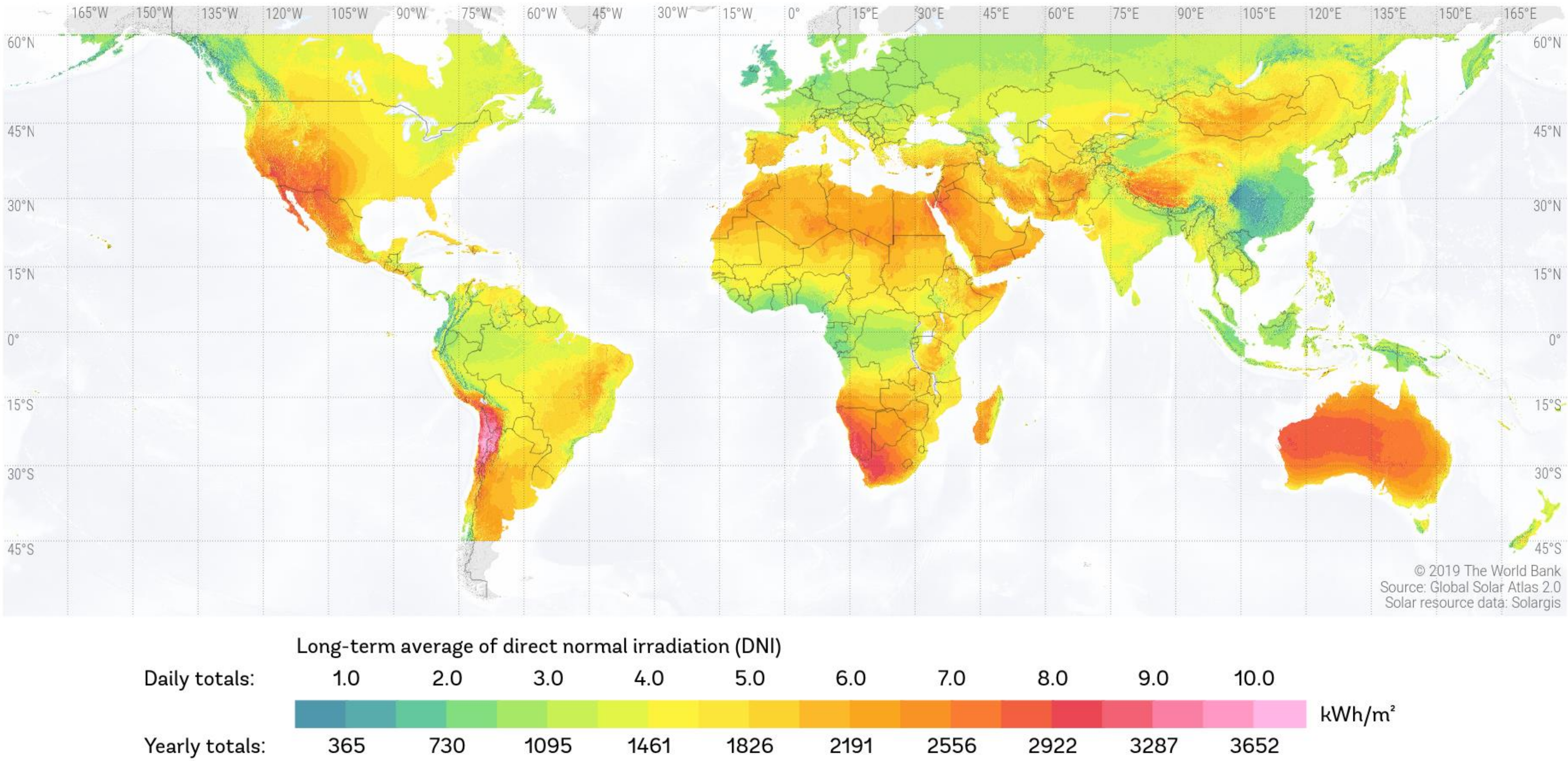
SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION

WORLD BANK GROUP ESMAP SOLARGIS



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Solar resource data: Solargis

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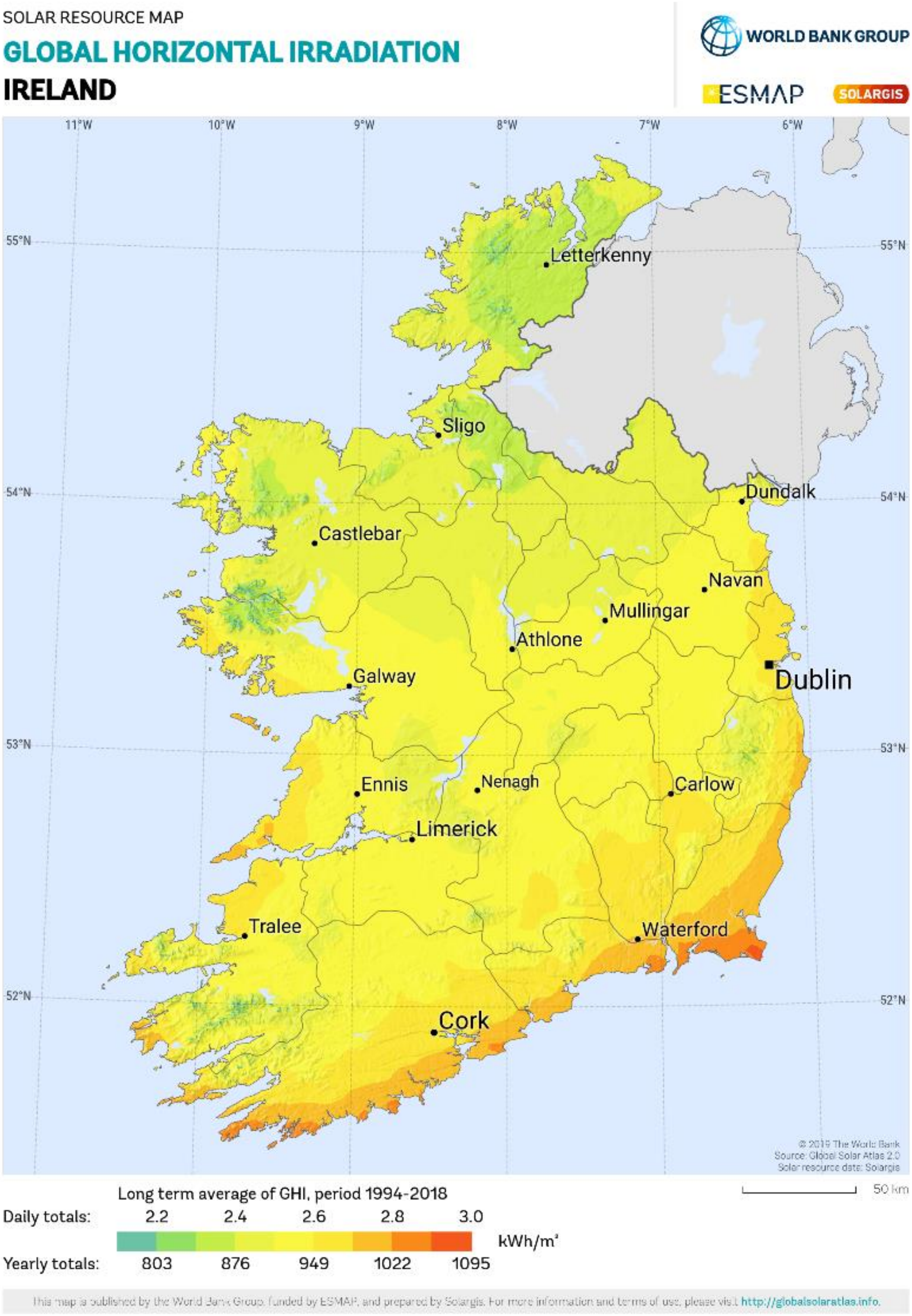
SOLAR RESOURCE MAP
GLOBAL HORIZONTAL IRRADIATION
IRELAND
WORLD BANK GROUP
ESMAP
SOLARGIS
11°W
10°W
9°W
8°W
7°W
6°W
55°N
54°N
53°N
52°N
Letterkenny
Sligo
Dundalk
Castlebar
Navan
Mullingar
Athlone
Dublin
Galway
Ennis
Nenagh
Carlow
Limerick
Tralee
Waterford
Cork
© 2019 The World Bank
Source: Global Solar Atlas 2.0
Solar resource data: Solargis
50 km
Long term average of GHI, period 1994-2018
Daily totals:
2.2
2.4
2.6
2.8
3.0
kWh/m²
Yearly totals:
803
876
949
1022
1095
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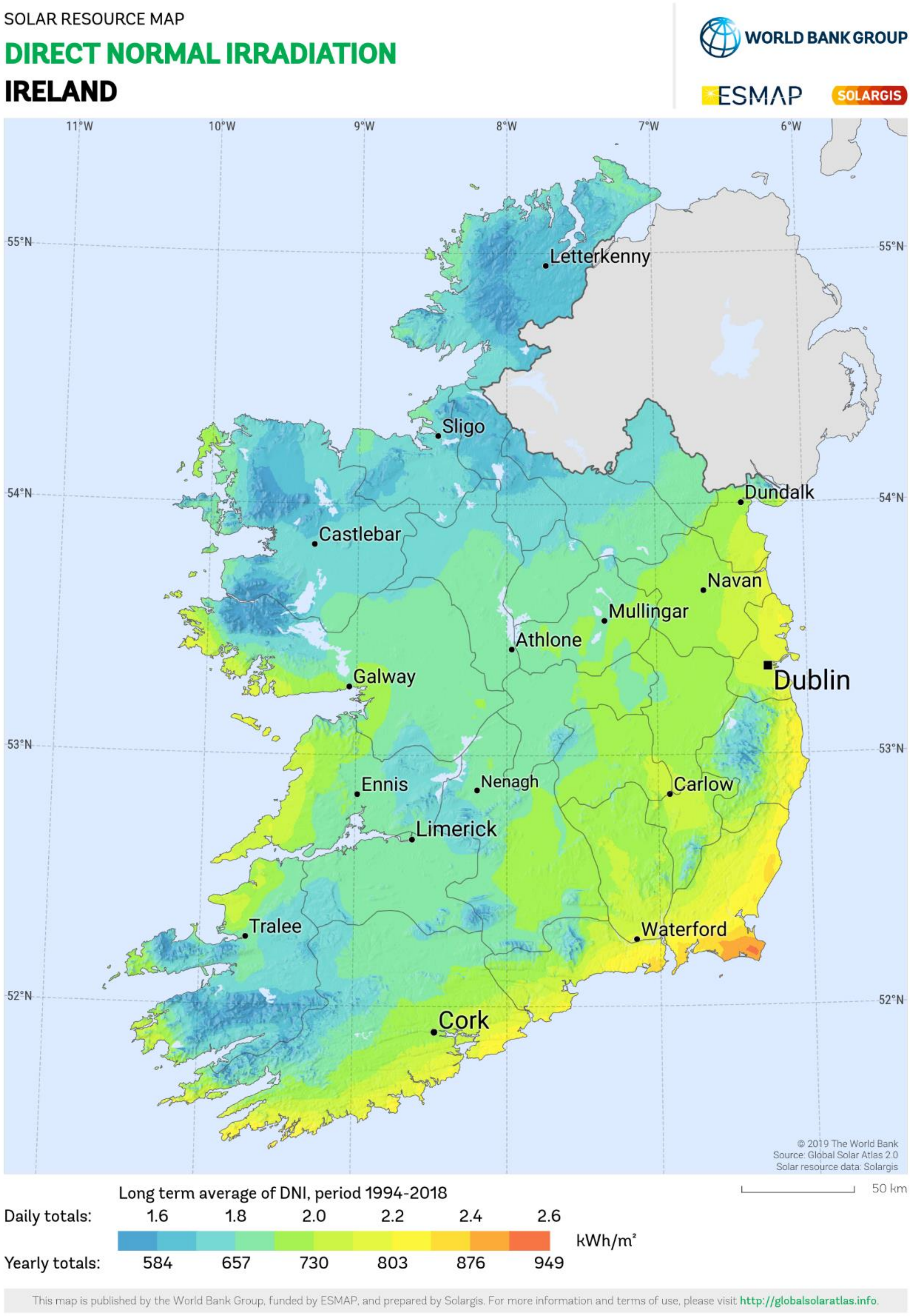
SOLAR RESOURCE MAP
DIRECT NORMAL IRRADIATION
IRELAND
WORLD BANK GROUP
ESMAP
SOLARGIS
11°W
10°W
9°W
8°W
7°W
6°W
55°N
54°N
53°N
52°N
Letterkenny
Sligo
Dundalk
Castlebar
Navan
Mullingar
Athlone
Dublin
Galway
Ennis
Nenagh
Carlow
Limerick
Tralee
Waterford
Cork
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Source: Global Solar Atlas 2.0
Solar resource data: Solargis
50 km
Long term average of DNI, period 1994-2018
Daily totals: 1.6 1.8 2.0 2.2 2.4 2.6
kWh/m²
Yearly totals: 584 657 730 803 876 949
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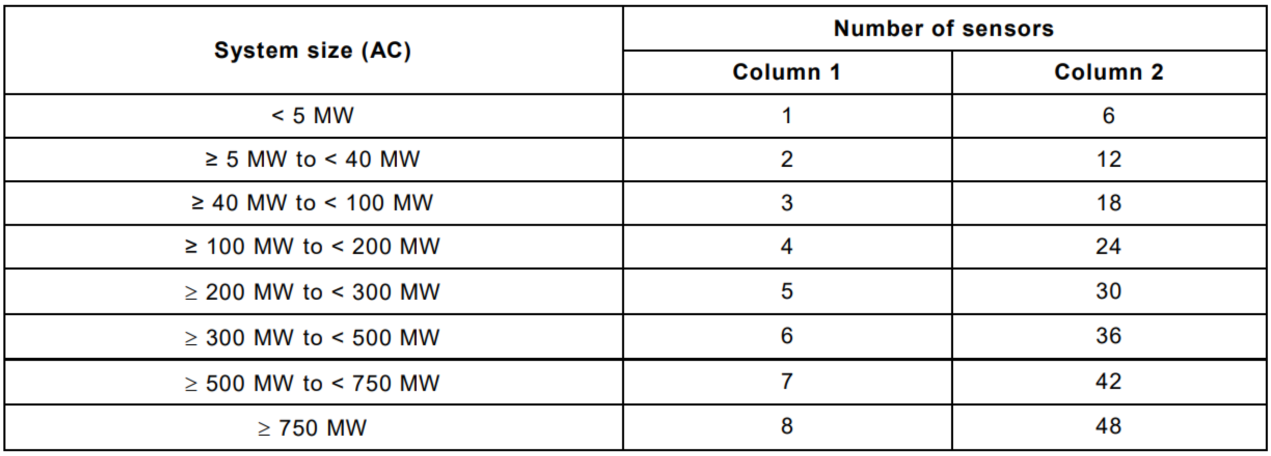
Appendix E

Parameter	Symbol	Units	Monitoring purpose	Required?			Number of sensors
				Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy	
Irradiance (see 7.3)							
In-plane irradiance (POA)	G_i	W·m^{-2}	Solar resource	√	√ or E	√ or E	Table 4 column 1
Global horizontal irradiance	GHI	W·m^{-2}	Solar resource, connection to historical and satellite data	√	√ or E		Table 4 column 1
Direct normal irradiance	DNI	W·m^{-2}	Solar resource, concentrator	√ for CPV	√ or E for CPV		Table 4 column 1
Diffuse irradiance	G_d	W·m^{-2}		√ for CPV with < 20× concentration	√ or E for CPV with < 20× concentration		Table 4 column 1
Circumsolar ratio	CSR						
Environmental factors (see 7.3)							
PV module temperature	T_{mod}	°C	Determining temperature-related losses	√	√ or E		Table 4 column 2
Ambient air temperature	T_{amb}	°C	Connection to historical data, plus estimation of PV temperatures	√	√ or E	√ or E	Table 4 column 1
Wind speed		m·s^{-1}	Estimation of PV temperatures	√	√ or E		Table 4 column 1
Wind direction		degrees		√			Table 4 column 1
Soiling ratio	SR		Determining soiling-related losses	√ if soiling losses expected to be >2 %			Table 4 column 1
Rainfall		cm	Estimation of soiling losses	√	√ or E		Table 4 column 1
Snow			Estimation of snow-related losses				

Parameter	Symbol	Units	Monitoring purpose	Required?			Number of sensors
				Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy	
Humidity			Estimation of spectral variations				
Tracker system (see 7.4)							
Error in dual-axis tracker primary angle	$\Delta\phi_1$	degrees	Tracker system fault detection, dual-axis	√ for CPV with >20× concentration			Table 4 column 1
Error in dual-axis tracker secondary angle	$\Delta\phi_2$	degrees		√ for CPV with > 20× concentration			Table 4 column 1
Single-axis tracker tilt angle	ϕ_T	degrees	Tracker system fault detection, single-axis	√ for single-axis tracker			Table 4 column 1
Electrical output (see 7.5 and 7.6)							
Array voltage (DC)	V_A	V	Energy output, diagnostics and fault localization	√			At each inverter (optionally at each combiner box or each string)
Array current (DC)	I_A	A		√			
Array power (DC)	P_A	kW		√			
Output voltage (AC)	V_{out}	V	Energy output	√	√		At each inverter and at system level
Output current (AC)	I_{out}	A		√	√		
Output power (AC)	P_{out}	kW		√	√	√	
Output energy	E_{out}	kWh		√	√	√	
Output power factor	λ		Utility request compliance	√	√		At each inverter and at system level
Reduced load demand			Determine utility or load request compliance and impact on PV system performance	If applicable	If applicable		At system level
System output power factor request	λ_{req}			If applicable	If applicable		At system level

Table 6. Requirements for monitoring.



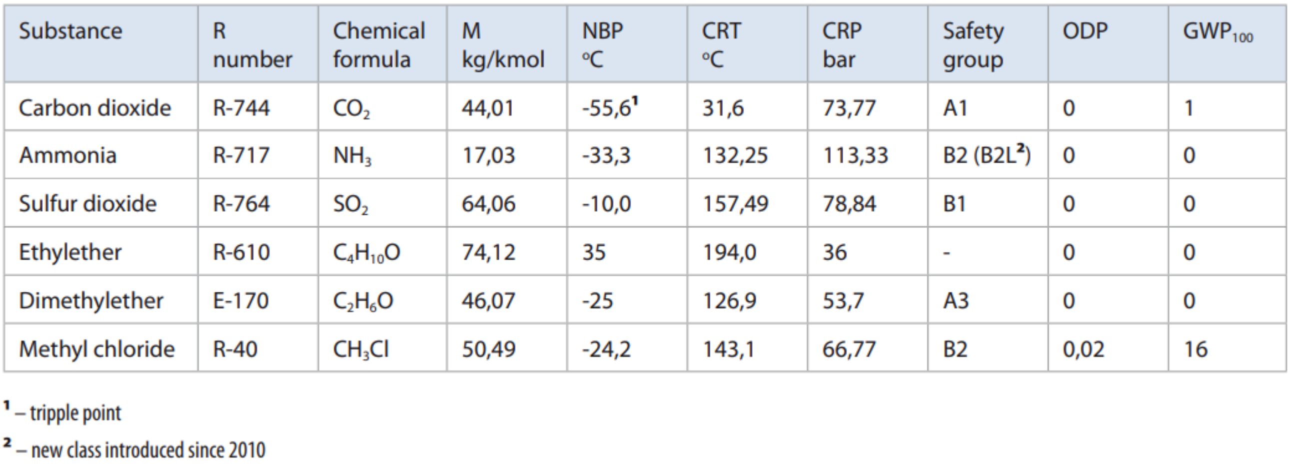
System size (AC)	Number of sensors	
	Column 1	Column 2
< 5 MW	1	6
≥ 5 MW to < 40 MW	2	12
≥ 40 MW to < 100 MW	3	18
≥ 100 MW to < 200 MW	4	24
≥ 200 MW to < 300 MW	5	30
≥ 300 MW to < 500 MW	6	36
≥ 500 MW to < 750 MW	7	42
≥ 750 MW	8	48

Table 7. Relation between system size and number of sensors (this is also known as Table 4 by the Table above).

✓ means a required parameter to measure on site. The symbol "E" indicates that might be estimated based on regional or local meteorological or satellite data, instead of measuring on site.

Appendix F

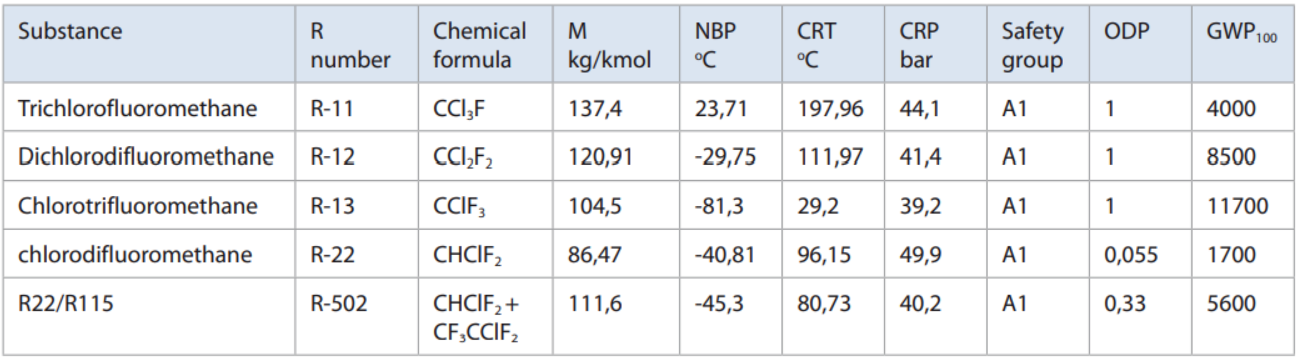
(Pavkovic, 2013) Properties of several refrigerants.



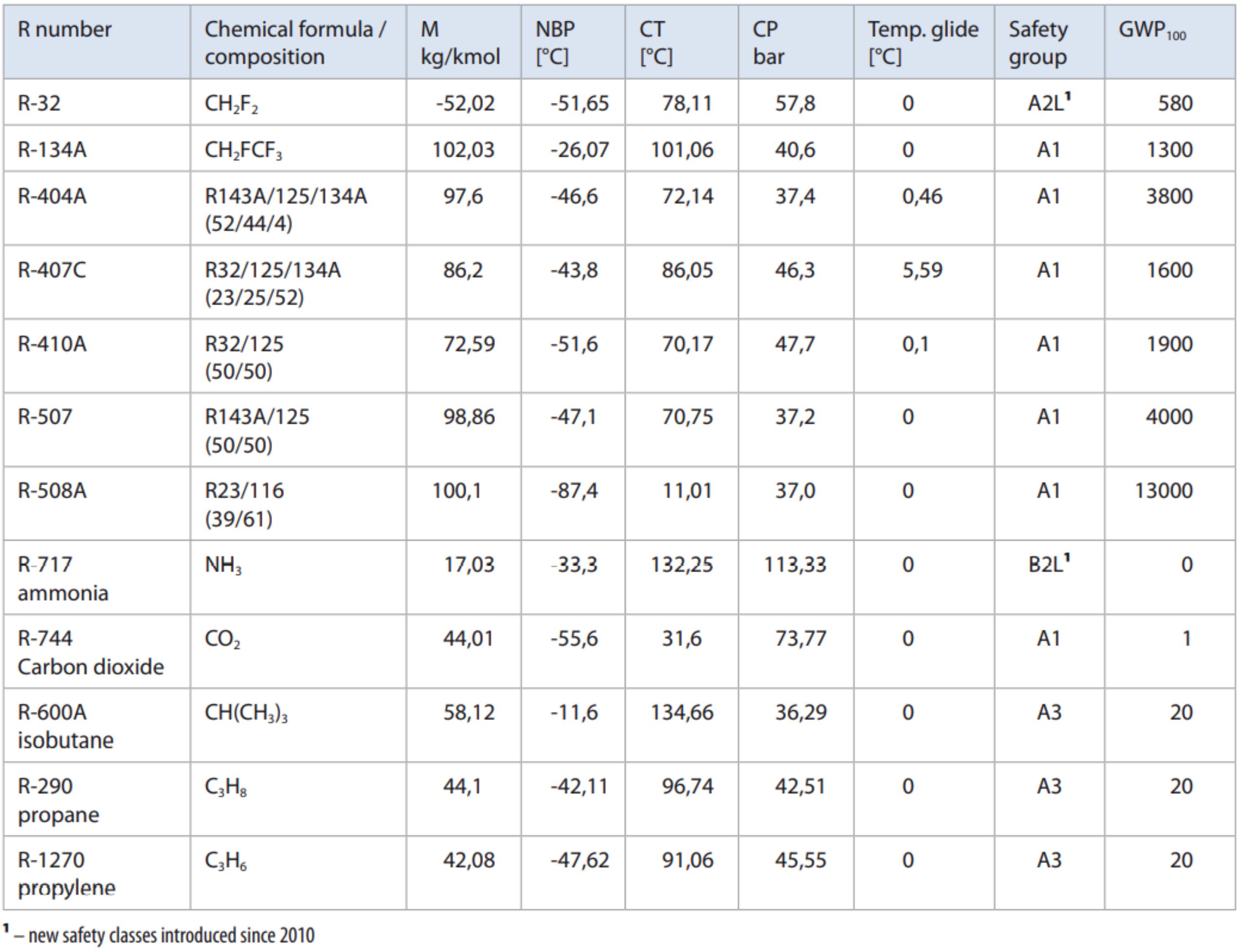
Substance	R number	Chemical formula	M kg/kmol	NBP °C	CRT °C	CRP bar	Safety group	ODP	GWP_{100}
Carbon dioxide	R-744	CO_2	44,01	-55,6[1]	31,6	73,77	A1	0	1
Ammonia	R-717	NH_3	17,03	-33,3	132,25	113,33	B2 (B2L[2])	0	0
Sulfur dioxide	R-764	SO_2	64,06	-10,0	157,49	78,84	B1	0	0
Ethylether	R-610	$C_4H_{10}O$	74,12	35	194,0	36	-	0	0
Dimethylether	E-170	C_2H_6O	46,07	-25	126,9	53,7	A3	0	0
Methyl chloride	R-40	CH_3Cl	50,49	-24,2	143,1	66,77	B2	0,02	16

[1] – tripple point

[2] – new class introduced since 2010



Substance	R number	Chemical formula	M kg/kmol	NBP °C	CRT °C	CRP bar	Safety group	ODP	GWP_{100}
Trichlorofluoromethane	R-11	CCl_3F	137,4	23,71	197,96	44,1	A1	1	4000
Dichlorodifluoromethane	R-12	CCl_2F_2	120,91	-29,75	111,97	41,4	A1	1	8500
Chlorotrifluoromethane	R-13	$CClF_3$	104,5	-81,3	29,2	39,2	A1	1	11700
chlorodifluoromethane	R-22	$CHClF_2$	86,47	-40,81	96,15	49,9	A1	0,055	1700
R22/R115	R-502	$CHClF_2+$ CF_3CClF_2	111,6	-45,3	80,73	40,2	A1	0,33	5600



R number	Chemical formula / composition	M kg/kmol	NBP [°C]	CT [°C]	CP bar	Temp. glide [°C]	Safety group	GWP_{100}
R-32	CH_2F_2	-52,02	-51,65	78,11	57,8	0	A2L[1]	580
R-134A	CH_2FCF_3	102,03	-26,07	101,06	40,6	0	A1	1300
R-404A	R143A/125/134A (52/44/4)	97,6	-46,6	72,14	37,4	0,46	A1	3800
R-407C	R32/125/134A (23/25/52)	86,2	-43,8	86,05	46,3	5,59	A1	1600
R-410A	R32/125 (50/50)	72,59	-51,6	70,17	47,7	0,1	A1	1900
R-507	R143A/125 (50/50)	98,86	-47,1	70,75	37,2	0	A1	4000
R-508A	R23/116 (39/61)	100,1	-87,4	11,01	37,0	0	A1	13000
R-717 ammonia	NH_3	17,03	-33,3	132,25	113,33	0	B2L[1]	0
R-744 Carbon dioxide	CO_2	44,01	-55,6	31,6	73,77	0	A1	1
R-600A isobutane	$CH(CH_3)_3$	58,12	-11,6	134,66	36,29	0	A3	20
R-290 propane	C_3H_8	44,1	-42,11	96,74	42,51	0	A3	20
R-1270 propylene	C_3H_6	42,08	-47,62	91,06	45,55	0	A3	20

[1] – new safety classes introduced since 2010

Appendix G

Temp [°C]	Pressure	Volume [m^3/kg]		Density [kg/m^3]		Enthalpy [kJ/kg]			Entropy [kJ/(kg)(K)]	
	kPa (abs)	Liquid v_f	Vapor v_g	Liquid $1/v_f$	Vapor $1/v_g$	Liquid h_f	Latent h_{fg}	Vapor h_g	Liquid s_f	Vapor s_g
22	608.49	0.0008	0.0338	1217.0	29.549	230.4	180.7	411.0	1.1060	1.7182
23	627.25	0.0008	0.0328	1213.3	30.462	231.8	179.8	411.6	1.1107	1.7178
24	646.44	0.0008	0.0318	1209.6	31.399	233.2	178.9	412.1	1.1155	1.7175
25	666.06	0.0008	0.0309	1205.9	32.359	234.6	178.0	412.6	1.1202	1.7171
26	686.13	0.0008	0.0300	1202.1	33.344	236.1	177.0	413.1	1.1250	1.7168
27	706.66	0.0008	0.0291	1198.3	34.354	237.5	176.1	413.6	1.1297	1.7165
28	727.64	0.0008	0.0283	1194.4	35.389	238.9	175.2	414.1	1.1345	1.7161
29	749.04	0.0008	0.0274	1190.6	36.451	240.4	174.2	414.6	1.1392	1.7158
30	771.02	0.0008	0.0266	1186.7	37.540	241.8	173.3	415.1	1.1439	1.7155
31	793.43	0.0008	0.0259	1182.8	38.657	243.3	172.3	415.6	1.1487	1.7151
32	816.28	0.0008	0.0251	1178.8	39.802	244.8	171.3	416.1	1.1534	1.7148
33	839.66	0.0009	0.0244	1174.9	40.975	246.2	170.3	416.6	1.1581	1.7145
34	863.53	0.0009	0.0237	1170.8	42.179	247.7	169.3	417.0	1.1628	1.7142
35	887.91	0.0009	0.0230	1166.8	43.413	249.2	168.3	417.5	1.1676	1.7138
36	912.80	0.0009	0.0224	1162.7	44.679	250.6	167.3	418.0	1.1723	1.7135
37	938.20	0.0009	0.0218	1158.6	45.977	252.1	166.3	418.4	1.1770	1.7132
38	964.14	0.0009	0.0211	1154.5	47.308	253.6	165.3	418.9	1.1817	1.7129
39	990.60	0.0009	0.0205	1150.3	48.672	255.1	164.2	419.3	1.1864	1.7125
40	1017.61	0.0009	0.0200	1146.1	50.072	256.6	163.2	419.8	1.1912	1.7122
41	1045.16	0.0009	0.0194	1141.9	51.508	258.1	162.1	420.2	1.1959	1.7119
42	1073.26	0.0009	0.0189	1137.6	52.980	259.6	161.0	420.6	1.2006	1.7115
43	1101.93	0.0009	0.0184	1133.3	54.490	261.1	159.9	421.1	1.2053	1.7112
44	1131.16	0.0009	0.0178	1128.9	56.040	262.7	158.8	421.5	1.2101	1.7108
45	1161.01	0.0009	0.0174	1124.5	57.630	264.2	157.7	421.9	1.2148	1.7105
46	1191.41	0.0009	0.0169	1120.0	59.261	265.7	156.6	422.3	1.2195	1.7101
47	1222.41	0.0009	0.0164	1115.6	60.934	267.3	155.4	422.7	1.2242	1.7097
48	1253.95	0.0009	0.0160	1111.0	62.652	268.8	154.3	423.1	1.2290	1.7093
49	1286.17	0.0009	0.0155	1106.4	64.415	270.4	153.1	423.5	1.2337	1.709
50	1319.00	0.0009	0.0151	1101.8	66.225	271.9	151.9	423.8	1.2384	1.7086
51	1352.44	0.0009	0.0147	1097.1	68.084	273.5	150.7	424.2	1.2432	1.7082
52	1386.52	0.0009	0.0143	1092.4	69.992	275.1	149.5	424.6	1.2479	1.7077
53	1421.23	0.0009	0.0139	1087.6	71.952	276.6	148.3	424.9	1.2527	1.7073
54	1456.58	0.0009	0.0135	1082.8	73.966	278.2	147.0	425.3	1.2574	1.7069
55	1492.59	0.0009	0.0132	1077.9	76.035	279.8	145.8	425.6	1.2622	1.7064
56	1529.26	0.0009	0.0128	1072.9	78.162	281.4	144.5	425.9	1.2670	1.7059
57	1566.61	0.0009	0.0124	1067.9	80.348	283.0	143.2	426.2	1.2717	1.7055
58	1604.63	0.0009	0.0121	1062.8	82.596	284.6	141.9	426.5	1.2765	1.705
59	1643.35	0.0009	0.0118	1057.7	84.908	286.3	140.5	426.8	1.2813	1.7044
60	1682.76	0.0010	0.0115	1052.5	87.287	287.9	139.2	427.1	1.2861	1.7039
61	1722.88	0.0010	0.0111	1047.2	89.735	289.5	137.8	427.4	1.2909	1.7033
62	1763.72	0.0010	0.0108	1041.8	92.255	291.2	136.4	427.6	1.2957	1.7028
63	1805.28	0.0010	0.0105	1036.4	94.851	292.9	135.0	427.9	1.3006	1.7021
64	1847.47	0.0010	0.0103	1030.9	97.526	294.5	133.6	428.1	1.3054	1.7015

Table 8. Freon 134a (R-134a) thermodynamics properties.