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Transitional method for PV modules, inverters, components and systems (Draft)

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Contents

Foreword

This document contains proposal for the establishment of transition methods in order to facilitate the introduction of regulations governing ECODESIGN, ECOLabel, Energy Label and GPP.

This draft has been prepared for the 2nd Stakeholder Meeting for the PV Ecodesign Preliminary Study. The final version will be available at the conclusion of the preparatory study in 2019.

1 Introduction

Following the inclusion of the photovoltaic product group in the EcoDesign Working Plan 2016-19, a preparatory study has been launched on solar photovoltaic panels and inverters, in order to assess the feasibility of proposing EcoDesign and/or Energy Labelling requirements for this product group. This will also investigate in more detail the potential for environmental improvement, including aspects relevant to the circular economy, and provide the elements needed for the identification of policy options in the subsequent impact assessment.

The EU Ecolabel (set up under Regulation EC 66/2010) aims at reducing the negative impact of products and services on the environment, health, climate and natural resources. The Regulation stipulates in Annex I a standard procedure for the development and revision of EU Ecolabel criteria, taking into account the environmental improvement potential along the life cycle of products.

Green public procurement (GPP) is defined in COM(2008)400 as a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact through their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured. The Commission plans to take action on GPP, by emphasizing circular economy aspects in any new criteria, and supporting higher uptake of GPP.

The JRC undertook a detailed study of the situation regarding standardisation for these product groups. The conclusions of this study were presented in a report

"Standards for the assessment of the environmental performance of photovoltaic modules, power conditioning components and photovoltaic systems" EUR 29247 EN

The situation for standards is varied and complex. There are over 100 relevant standards covering aspects of used materials, production, PV modules measurement and safety, power conditioning equipment, PV systems and their components and the design, construction and commissioning cycle. However, not all aspects are covered to the same degree, and where certain aspects essential to the implementation of the above measures are not covered the Commission may choose to specify transitional methods, that are implemented as regulations until suitable standards are adopted.

In the following the situation is summarised for the key areas identified in the standards report. The main chapters of this report then detail the corresponding proposals for transitional methods. The annexes provide information on the additional analyses conducted to support the proposed methods.

PV modules

This group is well covered by existing standards for materials efficiency, production, design qualification and type approval, power and energy yield. An extensive collection of operational data and correlation with laboratory testing results give confidence in building an appropriate definition of degradation effects, although an intermediate method may be required for quantifying them. The operational service life (OSL) definition is still not fully clarified; however, following the future IEC TS 62994, the IEC/TR 62635 and the guidelines in the ISO 15686 series an agreed method will be achievable. The issues of recyclability, reparability and durability should be covered by the Mandate M/543 pre-norms. PV-specific standards deriving from the horizontal ones will be necessary, although we do not foresee particular problems here.

Power Conditioning Equipment

For the PCE's the standards regarding materials and design are covered. Dedicated standards have been developed for PV inverter performance such as EN 50530, which describes the procedure for determining the "European Efficiency" that is provided in the inverter's datasheet. This parameter could be used in the transitional method for calculating a functional parameter in terms of AC power output for a nominal PV array. Regarding the definition of OSL the situation is similar to that for PV modules and again a transitional method may be required, also taking into account field data.

PV Systems

The situation for PV system reflects a combination of that for PV modules and power conditioning components, as well as factors arising from the system location and design. Aspects on PV system design are the subject of new draft norms, including the full construction cycle while the local situation can have a significant effect on the final energy (and therefore on the material balance). On-site power measurement and verification standards exist. However, there is no actual single standard for the calculation of expected energy yield of a PV system. A transitional method would be required here, based on existing monitoring standards or on the module energy-rating standards but also integrating a model to include the effects of local environment relevant to the specific geophysical position.

Degradation, Operational service lifetime and Circular economy issues.

The generic pre-norms being developed under mandate M/543 are applicable to the PV module, Power conditioning and PV system groups definition. PV-products specific standards deriving from the horizontal ones will have to be necessarily developed, coherently with the PEF guidelines developed for PV.

The degradation of PV modules, components and systems is still subject of debate and scientific investigation. No European or International standard exists at present to define the degradation of photovoltaic (PV) modules, inverters and PV systems and to give an accepted standardised procedure to evaluate it. Therefore, a transitional method that could be used to support the European legislation for PV product categories is needed until the lack of standards is solved. The approaches that were considered for the evaluation of the degradation of PV modules, inverters and PV systems include:

- Prescribed values.
- Experimental determination.
- Estimation method similar to the one in ISO 15686 series for "Buildings and construction assets".

These are not all feasible at present due to the limited amount of validated measured data for some of them. In particular the latter is considered at present premature and therefore not included in this document. Also, the available accelerated tests, which address some specific failure modes and that could be the base for the second approach, are not considered fully representing all the degradation paths that PV modules and systems could meet when installed outdoors, because several factors influence the degradation of these products.

For these reasons, the approach that is proposed as the default method among those mentioned above is the use of prescribed values, based on long-term experimental data collected on real PV modules and systems that have been mounted outdoors in the last 30-35 years. It has to be mentioned, though, that the majority of these systems have been installed only recently in a wide range of climatic conditions. Therefore, additional monitoring and data collection is needed to strengthen the values.

As a consequence, the transitional method will have to be revised once additional knowledge is available. Moreover, as the PV sector is constantly evolving and improving the existing technologies, the present document gives the possibility to the manufacturer to claim lower values than those prescribed under the condition of presenting robust and assessable measured data to support them.

In addition we present methods for Inverter Efficiency loss effects and PV System Energy yield calculation. Regarding the inverter' performance and its contribution to the final AC energy yield of the PV system, various methodologies have been analysed taking into consideration the available information commonly provided by the manufacturers and the existing standards related the energy rating of PV modules and inverter efficiency. A detailed description of the different methods evaluated is presented in Annex A of the present document.

At present, there are no available standards for the estimation of the expected AC energy yield from a PV system over its lifetime. In this document, a method is proposed taking into consideration real working conditions affecting the PV array DC energy output based on EN IEC standards, as well as the PV system degradation over its assumed service life. Additional considerations are presented so as to model all types of PV systems, including grid-connected, off-grid and BIPV systems.

Finally the topics of Dissasemblability, dissmantalability and remanufacturability are addressed.

2 Prerequisites

It is considered that component products and systems will have achieved pass or conformity to all relevant design qualification, type approval and safety tests as a pre-condition for entering the regulatory framework.

2.1 PV Modules

In case of PV Modules this would be successful completion of the harmonised standard EN IEC 61730 to conform the Low Voltage Directive (LVD) (2014/35/EU).

We propose also achievement of "pass" of the Type Approval test for PV modules and the necessity for the application of the of the module Energy Rating standard EN 61215 series and EN 61853 series respectively (Table 1) and where appropriate (specific aggressive environment).

Table 1 Requirements to be satisfied as prerequisites for modules and the standards needed for application the proposed transitional methods

Prerequisite Norm/ Standard/ Regulation	**Test Method**	**Notes**
EN 61215-1; EN 61215-1-1; EN 61215-2	Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures	Required for crystalline silicon only
EN 61215-1; EN 61215-1-2; EN 61215-2	Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures	For cadmium telluride (CdTe) only

Prerequisite Norm/ Standard/ Regulation	**Test Method**	**Notes**
EN 61215-1; EN 61215-1-3; EN 61215-2	Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements. Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-3: Special requirements for testing of thin-film amorphous silicon based photovoltaic (PV) modules. Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures.	For amorphous silicon (a-Si) only
EN 61215-1; EN 61215-1-4; EN 61215-2	Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-4: Special requirements for testing of thin-film Cu(In,Ga)(S,Se)2 based photovoltaic (PV) modules Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures	For copper indium (gallium) selenide or sulphide based PV (CI(G)Se / CI(G)S) only
EN IEC 61730-1	Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction	Mandate M/511 on Directive 2014/35/EU
EN IEC 61730-2	Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing	Mandate M/511 on Directive 2014/35/EU
IEC 61853-1	Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating	Required for transitional method – DC energy yield estimation and system AC energy yield
IEC 61853-2	Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral responsivity, incidence angle and module operating temperature measurements	Required for transitional method – DC energy yield estimation and system AC energy yield

Prerequisite Norm/ Standard/ Regulation	**Test Method**	**Notes**
EN IEC 61853-3	Photovoltaic (PV) module performance testing and energy rating - Part 3: Energy rating of PV modules	Required for transitional method – DC energy yield estimation and system AC energy yield
EN IEC 61853-4	Photovoltaic (PV) module performance testing and energy rating - Part 4: Standard reference climatic profiles	Required for transitional method – DC energy yield estimation and system AC energy yield

2.2 Inverters

We propose as a minimum prerequisite for inverters the following European safety standards should be applied. In addition the performance of the EN 50530, is required for the transitional methods application these are listed in Table 2

Table 2 Requirements to be satisfied as inverters prerequisites and standard needed for the transitional methods application

Relevant Norm/ Standard/ Regulation	**Specific Test Method** **Transitional method parameter**	
EN 62477-1	Safety requirements for power electronic converter systems and equipment - Part 1: General	
EN 62109-1	Safety of power converters for use in photovoltaic power systems - Part 1: General requirements	
EN 62109-2	Safety of power converters for use in photovoltaic power systems - Part 2: Particular requirements for inverters	
prEN 62109-3	Safety of power converters for use in photovoltaic power systems - Part 3: Particular requirements for electronic devices in combination with photovoltaic elements	
EN 62116	Utility-interconnected photovoltaic inverters - Test procedure of islanding prevention measures	

Relevant Norm/ Standard/ Regulation	Specific Test Method Transitional method parameter	
IEC TS 62910	Utility-interconnected photovoltaic inverters - Test procedure for low voltage ride-through measurements	
IEC 61683	Photovoltaic systems - Power conditioners - Procedure for measuring efficiency	Transitional method – AC energy yield
EN 50530	Overall efficiency of grid connected photovoltaic inverters	Transitional method – European Efficiency, AC energy yield
EN IEC 61853-4	Photovoltaic (PV) module performance testing and energy rating - Part 4: Standard reference climatic profiles	Transitional method – AC energy yield

2.3 Systems

For Systems, the standards identified as prerequisites for PV modules, PCEs would be applicable also for PV systems. Therefore Table 3 contains only the specific additional standards applicable to PV systems.

Table 3 Requirements to be satisfied as PV systems prerequisites and standard needed for the transitional methods application

Relevant Norm/ Standard/ Regulation	Specific Test Method Transitional method parameter	
IEC 62548	Photovoltaic (PV) arrays - Design requirements	
HD 60364-7-712	Low-voltage electrical installations - Part 7-712: Requirements for special installations or locations - Photovoltaic (PV) systems	
EN 62124	Photovoltaic (PV) stand-alone systems - Design verification	
IEC TS 62738	Ground-mounted photovoltaic power plants – Design guidelines and recommendations	
EN 62446-1	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection	

Relevant Norm/ Standard/ Regulation	**Specific Test Method** **Transitional method parameter**	
IEC 62446-2 (draft)	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 2: Grid connected systems – Maintenance of PV systems	
IEC TS 62446-3	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography	
EN 50583-1	Photovoltaics in buildings - Part 1: BIPV modules	
EN 50583-2	Photovoltaics in buildings - Part 2: BIPV systems	

2.4 Other system components

Other system components cables connectors are covered in Table 4

Table 4 Requirements to be satisfied as other components prerequisites and standard needed for the transitional methods application

Relevant Norm/ Standard/ Regulation	**Specific Test Method** **Transitional method parameter**	
EN 62852	Connectors for DC-application in photovoltaic systems - Safety requirements and tests	
EN 62920	Photovoltaic power generating systems - EMC requirements and test methods for power conversion equipment	
EN 61000	Electromagnetic compatibility (EMC)	
EN 61427-2	Secondary cells and batteries for renewable energy storage — General requirements and methods of test. Part 2: on-grid applications	
EN 62509	Battery charge controllers for photovoltaic systems - Performance and functioning.	
prEN 62093 ED 2 (draft)	Power conversion equipment for photovoltaic systems - Design qualification testing	
EN 50618	Electric cables for photovoltaic systems	
IEC 62930	Electric cables for photovoltaic systems with a voltage rating of 1.5 kV DC	

Relevant Norm/ Standard/ Regulation	**Specific Test Method** **Transitional method parameter**	
EN 62817	Photovoltaic systems - Design qualification of solar trackers	
IEC 63104 ED1 (draft)	Solar trackers - Safety requirements	
EN 60269-6	Low-voltage fuses - part 6: supplementary requirements for fuse-links for the protection of solar photovoltaic energy systems	
IEC 61643-31	Low-voltage surge protective devices – part 31: surge protective devices connected to the DC side of photovoltaic installations – requirements and test methods	
IEC 61643-32	Surge protective devices connected to the DC. side of photovoltaic installations - Selection and application principles	
CLC/prTS 61643-32	Low-voltage surge protective devices - Part 32: Surge protective devices connected to the DC side of photovoltaic installations - Selection and application principles	

3 Degradation and Failure Rates

For the definition and requirements given in this section some assumptions have to be made, as degradation and even more failure rates can depend on the size and on the configuration of the considered PV system. The size of the PV installations is classified (as stated in Task 2 "Market data and trend" of the Preparatory Study for Solar Photovoltaic Modules, Inverters and Systems) in terms of peak power as:

- Residential: up to 10 kW of peak power;
- Commercial: from 10 to 250 kW of peak power;
- Industrial: above 250 kW of peak power;
- Utility-scale: above 1 MW of peak power.

3.1 Definition of degradation rate

The degradation rate τ_{deg} for each PV product category is defined as the annual percentage decrease of the PV product's power output, when compared to the initial value, assuming the decrease to be constant in time and considering the same testing conditions under which the initial value was measured. If P_0 is the initial value of the power output, τ_{deg} can thus be expressed by:

$$\tau_{deg} = \left(\frac{P(t)}{P_0} - 1\right) \cdot \frac{1}{t} \qquad \text{(Eq. 1)}$$

where P is the value of the power output after an amount of years equal to t. The degradation rate τ_{deg} is therefore expressed in terms of %/year.

3.2 Failure rate

The failure rate is defined as the percentage of equal/equivalent products that stop functioning per year. Replacement of a product is considered to be due to a failure, either because of irreversible degradation or because of safety issue. For photovoltaic modules, inverters and systems this is usually reported as a linear rate per year during the operation of the system (%/year during operational life). It is accepted that the actual real failures may not follow a linear behaviour but for purposes of material estimation the linear rate is sufficiently accurate

3.3 PV modules

3.3.1 Prescribed values

The degradation rate values of PV modules shall be distinguished on the basis of the PV technology considered and according to the following list, which is supported by the most recent peer-reviewed literature and international relevant reports [1]. The following prescribed values are based on the widest possible observation of market deployed technologies, for innovative materials the degradation should be taken as that of "thin/film and heterojunction PV technologies" unless it is known to be significantly poorer or until sufficient data can be presented to justify change (see section 3.3.2) :

- Degradation rate for mono- or polycrystalline Si modules: 0.7 %/year;
- Degradation rate for all *thin-film and silicon heterojunction* PV technologies: 1 %/year.

3.3.2 Measurements

When a PV module manufacturer wishes to claim a lower value for the degradation rate compared to those given in 3.3.1, the lower claimed value shall be justified by means of robust experimental data collected from the measurement of field deployed systems.

This data should cover at least 5 (five) consecutive years.

The experimental data shall cover all the climatic profiles that are considered in the calculation of the annual energy yield of PV modules.

The data shall be collected from at least 2 (two) separate geographic locations in each climatic zone.

It should contain open rack ground-mounted, roof-mounted and building added and or building integrated systems (at least 2 of the four options must be included).

The assigned degradation rate shall be the average of all collected degradation rates from above.

The collated report on the observed degradation rates shall be made available upon request of the Authorities responsible for market surveillance for control and verification.

3.3.2.1 Guideline for the data collection

Protocols for data collection and measurement quality shall respect the guidance given in EN 61724-1 and IEC 61724 series.

3.4 Inverters

3.4.1 Prescribed values

No values are available for the degradation rate of inverters, therefore no prescribed values can be given. The inverter is assumed to be either functioning or not.

Typical failure rate is equal to 10% per year.

3.5 PV systems

3.5.1 Prescribed values

The degradation rate values of PV systems shall be distinguished on the basis of the PV technology considered and according to the following list, which is supported by the most recent peer-reviewed literature and international relevant reports [1]:

- Degradation rate for systems with mono- or polycrystalline Si modules: 0.7 %/year;
- Degradation rate for systems with *thin-film and silicon heterojunction* PV technologies: 1 %/year.

3.5.2 Measurements

When a PV System manufacturer wishes to claim a lower value for the degradation rate compared to those given in 3.5.1the lower claimed value shall be justified by means of robust experimental data collected from the measurement of field deployed systems.

This data should cover at least 5 (five) consecutive years.

The experimental data shall cover all the climatic profiles that are considered in the calculation of the annual energy yield of PV modules.

The data shall be collected from at least 2 (two) separate geographic locations in each climatic zone.

It should contain open rack ground-mounted, roof-mounted and building added and or building integrated systems (at least 2 of the four options must be included).

The assigned degradation rate shall be the average of all collected degradation rates from above.

The collated report on the observed degradation rates shall be made available to the National Authorities responsible for market surveillance for control and verification.

3.5.2.1 Guideline for the data collection

Protocols for data collection and measurement quality shall respect the guidance given in the EN 61724-1 and IEC 61724 series.

4 Operational Service Lifetime

4.1 Definition of lifetime

Technical lifetime is the total time period during which a product can technically function before it reaches a limiting state that makes it unsuitable to further operation. However, actual operational service lifetime of a product can be influenced by factors like cost/benefit analysis and maintenance.

4.2 Lifetime values

The lifetime value of the PV product categories are given according to the following list, which is supported by the most recent peer-reviewed literature and international relevant reports:

1. PV modules: **30 years**;
2. Inverters and electronic components: **10 years**;
3. Cabling: **30 years**;
4. PV systems: **30 years**.

NOTE: Although the lifetime of PV systems might be in principle indefinite if an appropriate maintenance is assured, it is reasonable to estimate a value close to the one given for modules with the additional inclusion of replacement of the inverter once or twice in the given lifetime of the system (at least for small installations and to be considered in LCA).

5 Transitional method – Calculation of Inverter Performance Functional Parameter for AC power output from a reference PV system

5.1 Introduction

5.1.1 Definition

The International Electrotechnical Committee's IEC TS 61836 "*Solar photovoltaic energy systems – Terms, definitions and symbols*" defines the inverter as an 'electric energy converter that changes direct electric current to single-phase or polyphase alternating currents', being 'one of a number of components that is included in the term "power conditioner"'.

In line with this definition, the main function of PV inverters is the conversion of the DC power received from the PV modules array into AC power suitable with the grid requirements or the downstream consumer. In addition to this, the inverter is also responsible of controlling the operating point of the PV array, adjusting it to its Maximum Power Point (MPP tracking) so as to maximize the power output from the PV array.

5.1.2 PV inverter types

The IEC TS 61836 identifies different types of inverters which can be classified according to their features or properties as follows:

- Power output characteristics: current control, high frequency link, voltage control inverter
- Grid interaction: grid-connected, grid-dependent, grid-interactive, non-islanding, stand-alone inverter
- PV array interaction: central, string, module integrated inverter.

As stated in the Task 1 report "*Product scope*" of the "*Preparatory study for solar photovoltaic modules, inverters and systems*" after the stakeholders' consultation, all inverters should be included in the scope of this preparatory study.

5.1.3 Functional unit

The functional unit for PV inverters is defined in Task 1 report "Preparatory study for solar photovoltaic modules, inverters and systems" of the PV preparatory study as "*1 kWh of AC power output from a reference photovoltaic system (excluding the efficiency of the inverter) under predefined climatic and installation conditions for 1 year and assuming a service life of 10 years*"

Hence, the aim of the present section is to propose a methodology to model the PV inverter performance and its contribution to the estimation of the AC power output or energy yield from a reference PV system as required in the functional unit definition.

5.2 Input data for PV inverter performance model

The proposed methodology accounts for the inverter's DC to AC conversion efficiency as we assume that the PV array connected to it always works at its maximum power point (MPP). Therefore the MPP tracking efficiency is not considered. The suggested methodology was compared to other modelling approaches as detailed in Annex A. PV inverter modelling.

The proposed methodology requires two main input data as described in the following:

5.2.1 DC energy yield

Following the EN IEC 61853 Standards series "*Photovoltaic (PV) module performance testing and energy rating*" it is possible to estimate the DC energy yield from a reference 1 kWp PV module array over a year (kWh/year). Additionally, following the inverter's functional unit definition, Part 4 of the Standards series entitled "*Standard reference climatic profiles*", contains six datasets that represent the most common climatic conditions that PV systems may encounter worldwide. Out of these six, three are considered as representative of the European climate conditions: subtropical arid, temperate continental and temperate coastal, which will be referred to in the present document as Sub, Temp and Coast respectively

Therefore, following the EN IEC 61853 we could obtain the DC energy yield from a reference 1 kWp PV array for the three European representative reference climates: EY_{DC_Sub}, EY_{DC_Temp} and EY_{DC_Coast} expressed in kWh/year per installed kWp.

The final output of the EN IEC 61853 standard is not the energy yield but the *Climate Specific Energy Rating* parameter (*CSER*) calculated according to Equation 2.

$$CSER = \frac{EY_{DC}\,(kWh/year)\ \cdot\ G_{ref}\,(W/m^2)}{P_{max}\,(W)\ \cdot\ H_p\,(kWh/m^2 \cdot year)} \qquad \text{(Eq. 2)}$$

Where *EY* is the DC energy output from the 1 kWp installed PV array, calculated on hourly basis over a year, G_{ref} is the STC irradiance (10000 Wm^{-2}), P_{max} is the maximum power of the PV module under consideration as stated in the datasheet and H_p is the yearly irradiation received by the plane of array ($kWh{\cdot}m^{-2}{\cdot}year$).

If EN IEC 61853 was to be applied by PV manufacturers, they could include in the PV module's datasheet the *CSER* value obtained for that particular PV module for the six reference climatic profiles provided in Part 4 of the Standard. Focusing on the three European reference climates, knowing the corresponding *CSER* values ($CSER_{Sub}$, $CSER_{Temp}$ and $CSER_{Coast}$) and the global irradiation at the reference climatic profiles ($H_{p,Sub}$, $H_{p,Temp}$ and $H_{p,Coast}$), the calculation of the yearly DC energy yield of a 1 kWp array of that particular PV module will be straightforward, according to Equation 3.

$$EY_{DC}\,(kWh/year) = \frac{CSER\ \cdot\ P_{max}\,(W)\ \cdot\ H_p\,(kWh/m^2 \cdot year)}{G_{ref}\,(W/m^2)} \qquad \text{(Eq. 3)}$$

The yearly in-plane irradiation depends on the climatic conditions, while the *CSER* value will depend as well on the PV module under consideration. For the three European reference climatic conditions, the H_p values are shown in Table 5.

Table 5 Yearly in-plane irradiation ($kWh/m^2{\cdot}year$) for the three proposed reference climatic conditions

Reference climatic condition	Yearly in-plane irradiation, H_p ($kWh/m^2{\cdot}year$)
Subtropical arid	2295.452
Temperate continental	1266.003
Temperate coastal	972.934

5.2.2 PV inverter efficiency

The EN 50530 "*Overall efficiency of grid connected photovoltaic inverters*" describes the procedure for calculating the Euroefficiency or European efficiency (η_{EUR}), which is an average weighted efficiency for a full year of power distribution of a middle-Europe climate. This value is always reported in the inverter's datasheet.

5.3 Inverter functional parameter estimation

The first step is the estimation of the AC energy yield (EY_{AC}) from a reference PV system over the period of a year for the different reference climatic conditions considered. The output of the EN IEC 61853 provides the DC energy yield for these climatic conditions, so their product by the European efficiency provide an estimate of the AC energy yield, as shown in Equations 4 to 6.

$$EY_{AC\_Sub}\ \text{(kWh/year per installed kWp)} = \eta_{EUR} \cdot EY_{DC\_Sub} \qquad \text{(Eq. 4)}$$

$$EY_{AC\_Temp}\ \text{(kWh/year per installed kWp)} = \eta_{EUR} \cdot EY_{DC\_Temp} \qquad \text{(Eq. 5)}$$

$$EY_{AC\_Coast}\ \text{(kWh/year per installed kWp)} = \eta_{EUR} \cdot EY_{DC\_Coast} \qquad \text{(Eq. 6)}$$

From the yearly AC energy output (EY_{AC}) obtained from 1 kWp PV array for the different reference climates, the inverter function parameter, $FP_{inverter}$, can be calculated according to Equation 7:

$$FP_{Inverter\_Climate\ N} = \frac{1\ (kWh\ of\ AC) \cdot 1\ (kWp\ PV\ array)}{EY_{AC\_Climate\ N}\ (kWh\ of\ AC/year)} \qquad \text{(Eq.7)}$$

Considering the three reference climatic datasets selected for Europe, there will be three different values for the functional parameter for every inverter, one per reference climate ($FP_{inverter\_Sub}$, $FP_{inverter\_Temp}$ and $FP_{inverter\_Coast}$).

5.4 General considerations

5.4.1 Size of the inverter and PV module array

The relative size of the inverter (AC or DC capacity) in relation to the PV module array nominal power depends on the size of the system and should be that so as to maximize the performance of both components. As stated in the Task 2 report "*Market data and trend*" of the of the "*Preparatory study for solar photovoltaic modules, inverters and systems*" in residential PV systems the size of both components is "closely related", in industrial PV systems the "inverter AC capacity may be less than the module DC power", while for utility scale systems "the inverter AC capacity will tend to be significantly less than the module DC power, with an indicative range for the ratio being 1.2 – 1.4".

In the analysis described in Annex A. PV inverter modelling, two different sizing values have been applied to quantify the impact in the functional parameter estimation: 1.25 more suitable for utility scale systems and 1.1 better suited for small PV systems.

Although it would seem reasonable to define specific sizing ratios for the same categories of PV systems as used in the Task 2 report (residential, industrial and utility scale), the results obtained show a limited impact of the sizing factor on the AC energy yield and consequently on the inverter's functional parameter value obtained for the five inverters considered in the Annex A analysis. For further information, please check Table 11 in Annex A.

5.4.2 **DC power output**

We assume in the proposed methodology, as it is considered in the EN IEC 61853 Standard series that the PV module array works at its maximum power point.

5.4.3 **Efficiency dependency on temperature**

As stated in the EN 50530 standard, the measurements of the inverter's efficiency required to calculate the European efficiency are to be performed at an ambient temperature of 25 °C ± 2 °C. In our model we haven't considered temperature of the inverter, which depends on its location indoors or outdoors, nor its impact on the inverter's performance. Even if the temperature effect on the efficiency was to be considered, not all manufacturers provide in the inverter's datasheet the necessary information regarding this impact so as to take it into account.

5.5 Example of the proposed methodology. Results

Following the analysis described in Annex A PV inverter modelling, the functional parameter for the different inverters considered there as part of a residential PV system for the Subtropical arid reference climatic conditions are shown in Table 6 as an example. Values are calculated following Equation 7.

Table 6 Functional parameter for the inverters used residential PV systems presented in the Annex A. PV inverter modelling**.**

Inverter	*European efficiency*	EY_{AC_Sub} (kWh of AC/year · installed kWp)	Functional parameter, $FP_{inverter\_Sub}$
1	94.5	1917.457	$5.21 \cdot 10^{-4}$
2	93.6	1899.195	$5.27 \cdot 10^{-4}$
3	93.2	1891.079	$5.29 \cdot 10^{-4}$
4	91.8	1862.672	$5.37 \cdot 10^{-4}$
5	90.9	1844.411	$5.42 \cdot 10^{-4}$

6 Transitional methods – Determination of the Energy Yield of PV systems

6.1 Introduction.

6.1.1 **Definition**

As stated in the "*Standards for the assessment of the environmental performance of photovoltaic modules, power conditioning components and photovoltaic systems*" report a photovoltaic (PV) system could be defined as a power system designed to supply usable electrical power by means of photovoltaic modules. It consists of an arrangement of several components. The PV modules, which absorb and convert sunlight into electricity, constitute the main one. Other components known collectively as Balance of System (BOS) include switches, wiring, controls, meters and Power Conversion Equipment (PCE). Out of PCEs, the inverter, which changes the electric current from direct (DC) to alternate (AC) is the main element. Other components of the PV system may include mounting structures, solar tracking system or energy storage systems, like batteries.

We assume the PV system include all the elements up the AC output part of the inverter. Therefore the AC cables which link the inverter to the grid interface or the transformer, if present, are not considered part of the PV system.

6.1.2 **PV systems types**

PV systems can be classified according to their properties or features as follows:

- Spatial arrangement: centralised, distributed
- Configuration: grid-connected, off-grid system
- End-use: residential, commercial, industrial or utility-scale

This last classification is usually related to the installed capacity of the PV system according to the following ranges as stated in the Task 2 report "*Market data and trend*" of the "*Preparatory study for solar photovoltaic modules, inverters and systems*":

- Residential: up to 10 kW
- Commercial: from 10 to 250 kW
- Industrial: above 250 kW
- Utility-scale: above 1 MW

6.1.3 **Functional unit**

The functional unit assumed for PV systems is defined in Task 1 report "Preparatory study for solar photovoltaic modules, inverters and systems" of the PV preparatory study as "*1 kWh of AC power output supplied under fixed climatic conditions for 1 year (with reference to IEC 61853-4) and assuming a service life of 30 years*".

After analysing the available international standards, it was identified the lack of an agreed methodology to estimate the performance of PV systems as prerequisite for the estimation of their functional unit. Therefore, the aim of the present section is to propose a method to model the performance of PV systems. Due to the wide range of possible configurations, such as grid connected, off-grid systems or BIPV, the proposed methodology is the concatenation of various models that account for the behaviour of the main components of PV systems: PV modules, PCE (inverter) and cables. The methodology accounts for different losses and degradation of the PV system so as to model its performance over the defined service life of 30 years of the functional unit definition.

6.2 PV systems performance model

The proposed model of the performance of a PV system is the concatenation of the performance models for its main components: PV array, inverter and cables, as well as other losses affecting the AC energy output from the PV system.

6.2.1 **PV module**

The first step in the estimation of the PV system energy yield is the estimation of the PV array DC energy yield (EY_{DC}).

The EN IEC 61853 Standard series "*Photovoltaic (PV) module performance testing and energy rating*" defines a methodology to estimate the performance of PV modules considering real working conditions defined by six datasets representative of the major climatic conditions likely to be encountered by PV installations worldwide. The estimation of the PV energy output takes into consideration various effects, like the irradiance being reflected at the module's surface and therefore not used, the spectral content of the irradiance which results in different PV technologies providing different output under the same irradiance conditions, or the temperature reached by the module that can significantly modify its performance. Taking these effects into consideration enables a more realistic estimation of the energy output of the PV modules than by just considering the power output declared by the manufacturer in the module's datasheet.

The modules are assumed to be installed in a free standing rack, facing the equator with an inclination angle of 20°. No local horizon effects or presence of obstacles are taken into account.

The calculation is based on one year of hourly values as provided in the climatic datasets. Therefore, the output of the standard is the yearly DC energy output produced by 1 kWp of the PV modules under consideration for the different reference climatic datasets in 8760 hourly values or as their yearly sum. As stated in Section 5.2.1, if PV manufacturer's provided the EN IEC 61853 output parameter, the *Climate Specific Energy Rating* for the different climatic datasets, the estimation of the yearly DC energy yield of 1 kWp system could be easily obtained. Please refer to Section 5.2.1 for more information.

6.2.2 **Power Conditioning Equipment. Inverter**

The functional unit of PV systems requires the estimation of its AC energy output, therefore a conversion from DC PV array output to AC is needed. To that aim we need to model the inverter's performance, for which the methodology described in Section 5.3 would be applied. Besides the yearly DC energy yield retrieved from the PV array (EY_{DC}, kWh/year per installed kWp), the other required input data is the European efficiency (EN 50530), η_{EUR}, provided at the inverter's datasheet.

6.2.3 **PV system losses**

There are several losses inside a PV system and for every component in particular. Unless specifically calculated, losses in cables will be accounted for as part of the general system losses, which is a generic value for the whole system, $\eta_{system\_loss.}$ It may be appropriate to define different system losses according to the size of the system, whether it is residential, commercial, industrial or utility-scale PV system.

The procedure for determining the η_{system_loss} parameter is under development.

Other factors that can reduce the estimated energy yield of the PV system such as presence of soiling, dust or partial shading are considered site specific and are not taken into account.

6.2.4 **AC energy yield**

Combining the elements described in the previous subsections, the estimation of the PV system's AC energy yield (*System* EY_{AC}) can be performed following Equation 8.

$$System\ EY_{AC}\ \text{(kWh/year per installed kWp)} = \eta_{EUR} \cdot \eta_{system\_loss}\ EY_{DC} \qquad \text{(Eq. 8)}$$

Where η_{EUR} is the European efficiency of the inverter, η_{system_loss} are the system losses and EY_{DC} is the DC energy yield from the PV array, expressed in kWh/year per installed kWp as resulted from the EN IEC 61853 methodology.

6.3 PV systems functional parameter estimation

The first step for calculating the functional parameter of any PV system is the estimation of its energy yield over its lifetime, which is considered to be 30 years as stated in the functional parameter definition.

Equation 8 provides an estimate of the PV system AC energy output over a year, which is considered to be the installation year of the system (System EY_{annual_0}). In order to estimate the energy yield over the assumed lifetime (System $EY_{AC\_lifetime}$), Equation 9 is applied.

$$System\ EY_{AC\_lifetime} = System\ EY_{annual\_0} \cdot T_{lifetime} \cdot \left(1 - \tau_{deg} \cdot \frac{T_{lifetime}}{2}\right) \qquad \text{(Eq. 9)}$$

Where $T_{lifetime}$ would be considered service life of the PV system (30 years) and τ_{deg} would be the PV system annual degradation rate, which depends mainly on the PV modules degradation rate, as the other components are mainly subjected to failure, not degradation. The degradation rate is assumed constant over the lifetime of the PV system.

Once the energy yield of 1 kWp PV system is estimated over its lifetime, it is possible to calculate the installed kWp that would be required to obtain 1 kWh of AC power as defined in the functional parameter. This could be estimated according to Equation 10, which considers an average energy yield over the PV system's lifetime (EY_{av}) of System $EY_{AC\_lifetime}$ / $T_{lifetime}$.

$$FP_{system\_Climate\_N} = \frac{1\ (kWh\ of\ AC) \cdot 1\ (kWp\ PV\ system)}{EY\ av\ (kWh\ of\ AC/year)} \qquad \text{(Eq.10)}$$

Considering the three reference climatic datasets selected for Europe, there will be three different values for the functional parameter for every system, one per reference climate (FP_{system_Sub}, FP_{system_Temp} and $FP_{system\ \_Coast}$).

6.4 General considerations

As mentioned in the introduction, there are many different types of PV systems which may have different configurations and often components. That would be the case of off-grid systems, for example.

6.4.1 **Installation and Location Specific Energy Yield**

For systems with different module configurations (orientation and inclination) than those used in the IEC 61853 series (20° inclination and equator facing), additional procedures are needed in order to estimate the in-plane effective irradiance as input to the IEC 61853-3 methodology. Alternatively to perform more specific analysis for particular PV plants and locations, the output variables specified in the IEC module energy rating standard 61853-4 could be obtained from tools such as PVGIS.

6.4.2 **Building integrated PV systems**

For BIPV systems, in additional to the location specific factors such as orientation and inclination, the temperature reached by the modules should be accounted for. This can be done following the EN IEC 61853 methodology, but using different thermal coefficients (u_0 and u_1). At present the said standard does not define how to obtain these coefficients for BIPV modules, as its scope is based on PV modules installed on a free standing rack. A transitional method for this purpose is also under preparation.

6.4.3 **PV systems with battery storage**

Modelling the performance of PV systems with energy storage would require additional models not considered in Section 3. To be rigorous, it would be necessary to model the battery's working cycles of charge and discharge, the state of charge and the efficiency of the battery which in turn depends on other factors such as temperature, longevity, etc. In addition to this, it would be necessary to have consumption profiles which depend on the end user. For an accurate modelling of the performance it would be necessary to perform, at least, hourly calculations so as to model the flow of energy between the different components (PV array, battery, load, inverter and grid). The EN IEC 61853 standard used for modelling the DC energy yield already provides hourly values. Regarding the inverter, the method based on the European efficiency could be applied for the hourly calculations, or alternatively an hourly efficiency could be applied. This approach is described in the Annex A. PV inverter modelling as Method 2.

A simplified approach would be to apply a fixed loss factor to reflect the battery's nominal load cycle performance.

6.5 Datasets for Europe

The estimation of the functional unit of the PV system requires using fixed climatic conditions (with reference to EN IEC 61853-4. Three of the six datasets of Part 4 "*Photovoltaic (PV) module performance testing and energy rating – Part 4: Standard reference climatic profiles*" represent the weather conditions PV systems installed in Europe will most likely encounter. These are:

- Subtropical arid

- Temperate coastal

- Temperate continental

To perform more specific analysis for particular PV plants and locations, the same variables contained in the IEC standard datasets could be obtained from tools like PVGIS.

A description of the three reference climatic datasets is presented in Annex B. European reference climatic profiles.

7 Transitional Method for Dismantlability of PV Modules

The development of standards for Dismantlability of PV Modules, Dissasembilability of PV Systems and Remanufacturing of PV systems are being developed under the mandate M/543 horizontal Standards. The definition of these horizontal standards due in 2019 will facilitate the development of dedicated or transitional standards for the PV specific products.

8 Transitional Methods for Disassemblability of PV Systems

The development of standards for Dismantlability of PV Modules, Dissasembilability of PV Systems and Remanufacturing of PV systems are being developed under the mandate M/543 horizontal Standards. The definition of these horizontal standards due in 2019 will facilitate the development of dedicated or transitional standards for the PV specific products.

9 Transitional Methods for Remanufacturing of PV Systems

The development of standards for Dismantlability of PV Modules, Disassemblability of PV Systems and Remanufacturing of PV systems are being developed under the mandate M/543 horizontal standards. The definition of these horizontal standards due in 2019 will facilitate the development of dedicated or transitional standards for the PV specific products

References

[1] Jordan D and Kurtz S 2017 *The Performance of Photovoltaic (PV) Systems*: Woodhead Publishing) pp 71-101

List of abbreviations and definitions

ANNEX A. PV inverter modelling

In order to define a methodology for the estimation of the inverter's performance inside a PV system and its contribution to the final AC energy yield, we considered different options. The estimated AC energy yield is necessary for the estimation of the inverter's functional unit as described in Section 5.3.

The different methodologies analysed are based on two sets of standards. Firstly, most of the estimation procedures considered are in line with the one described in the recently published EN IEC 61853 Standard series "*Photovoltaic (PV) module performance testing and energy rating*" which defines the method for the estimation of the DC energy yield of 1 kWp PV module array over a year.

Secondly, the considered methodologies use the efficiency values measured on the inverter under consideration according to IEC 61683 and EN 50530 standards.

A1. PV inverter efficiency

There are two international standards whose scope is the quantification of the DC to AC conversion efficiency and the MPP tracking efficiency of PV inverters.

A1.1. IEC 61683

The standard IEC 61683 "*Photovoltaic systems – Power conditioners – Procedure for measuring efficiency*" whose second edition is currently under development, describes the guidelines for measuring the efficiency of power conditioners used both in stand-alone and utility-interactive PV systems. The scope of this standard does not cover maximum power tracking accuracy.

The efficiency is calculated from direct measurements of input and output power at different levels of the rated power as specified in Table A1.

Table A1. Rated power conditions under which measure the inverter efficiency. The applied testing conditions depend on the type of inverter.

Total load, % of rated VA	5	10	25	50	75	100	120
Grid-connected		✓	✓	✓	✓	✓	✓
Stand-alone	✓	✓	✓	✓	✓	✓	✓

These measurements are to be performed at three input voltages: minimum rated input voltage, the inverter's nominal voltage or the average of its rated input range and at 90% of the inverter's maximum input voltage.

Measurements are to be performed at an ambient temperature of 25 °C ± 2 °C.

The results shall be presented in tabulated or in graphical form. Most manufacturers provide the efficiency measured at one of those voltage levels in graphical form. The complete measurements in tabulated form are not normally available.

This standard also describes a weighted average energy efficiency whose weighting coefficients depend on the type of inverter. For utility-interactive inverters, the weighting coefficients are derived from the regional irradiance duration (Figure A1a), while for stand-alone ones, the coefficients are defined according to the load duration curve (Figure A1b).

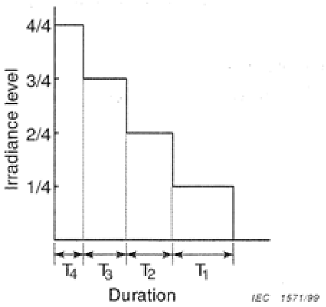

Figure A1a. Example of irradiance duration curve

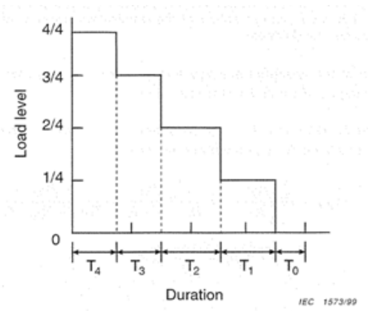

Figure A1b. Example of load duration curve

(Figures extracted from IEC 61683 standard)

A1.2. EN 50530

The EN 50530 "*Overall efficiency of grid connected photovoltaic inverters*" describes the procedure for measuring the accuracy of both static and dynamic MPP tracking. The static efficiency describes the accuracy of the inverter to regulate on the maximum power point on a given static characteristic curve of a PV generator. While the dynamic efficiency accounts for the performance of the inverter under variable irradiation intensity conditions which require the transition to different operation points.

The overall efficiency of the inverter (η_t) is calculated from the conversion efficiency obtained from the IEC 61683 (η_{conv}) and the static MPPT efficiency ($\eta_{MPPT\ stat}$), as shown in Equation A1, where P_{DC} is the actual DC power of the inverter under test, which depends on the MPP power provided by the PV generator.

$$P_{AC} = \eta_t \cdot P_{DC} = \eta_{conv} \cdot \eta_{MPPT\ stat} \cdot P_{MPP} \tag{Eq. A1}$$

The static MPPT efficiency is measured at different levels of DC rated power, similarly to IEC 61683. New measuring conditions are added regarding the IEC standard as indicated in Table A2. Differently from the IEC 61683, the scope of the EN 50530 standard only covers grid connected inverters.

Table A2. Rated power conditions under which measure the inverter static efficiency.

MPP power normalized to rated DC	5	10	20	25	30	50	75	100
Grid-connected	✓	✓	✓	✓	✓	✓	✓	✓

For the static MPPT efficiency, measurements are to be performed at AC nominal grid voltage, and shall be repeated three times at three different levels of DC voltage (maximum MPP voltage, rated DC input voltage and minimum MPP voltage).

The dynamic MPPT efficiency, which is reported separately, is determined applying a test sequence of fluctuating irradiance intensities as defined in the Annex B of the EN 50530 standard.

All measurements have to be made at the same reference ambient condition as that applied in the IEC 61683.

The results are to be documented in the measuring report.

The EN 50530 standard defines two weighted efficiencies: the Euroefficiency or European efficiency (Equation A2) whose weighting coefficients account for a full year of power distribution of a middle-Europe climate, and the CEC efficiency (California Energy Commission) defined for locations with higher radiation profiles and whose weighting factors consider, for example, less likely that the inverter would work at its maximum efficiency (η 100%) as shown in Equation A3.

$$\text{European efficiency} = 0.03 \cdot \eta\,5\% + 0.06 \cdot \eta\,10\% + 0.13 \cdot \eta\,20\% + 0.1 \cdot \eta\,30\% + 0.48 \cdot \eta\,50\% + 0.2 \cdot \eta\,100\% \qquad \text{(Eq. A2)}$$

$$\text{CEC Efficiency} = 0.04 \cdot \eta\,10\% + 0.05 \cdot \eta\,20\% + 0.12 \cdot \eta\,30\% + 0.21 \cdot \eta\,50\% + 0.53 \cdot \eta\,75\% + 0.05 \cdot \eta\,100\% \qquad \text{(Eq. A3)}$$

Manufacturers provide the European efficiency at the inverter's datasheet, along with the maximum efficiency.

A2. Considered estimation methodologies

Taking into account the commonly available data regarding the inverter's efficiency and the inverter's functional unit definition linked to the AC energy output from a reference PV system over one year considering reference climatic conditions, we defined different models for the estimation of the inverter's AC energy output.

A2.1. Method 1: European efficiency

Considering that the European efficiency is present at all inverter's datasheet, the first proposed methodology uses this value to estimate the AC energy output from a reference PV system.

Following the EN IEC 61853 methodology it is possible to estimate the yearly DC energy output retrieved from a 1 kWp PV module array, expressed in kWh/year per installed kWp. Using the datasets included in Part 4 of the said Standard series that represent European conditions (Subtropical coastal, Temperate continental and Temperate coastal), the DC energy output value could be calculated for these predefined reference climatic conditions (EY_{DC_Sub}, EY_{DC_Temp} and EY_{DC_Coast} (kWh/year per installed kWp).

Using these two inputs, a very simple estimation of the yearly AC energy output could be obtained by multiplying the DC energy output derived from the EN IEC 61853 methodology (kWh/year per installed kWp) by the European efficiency (η_{EUR}) of the inverter under consideration (Equation A4). The result would be expressed in kWh/year as well, but of AC energy.

$$EY_{AC\_Climate}\ \text{(kWh/year per kWp)} = \eta_{EUR} \cdot EY_{DC\_Climate}\ \text{(kWh/year per kWp)} \qquad \text{(Eq. A4)}$$

A2.2. Climate Zone Methods

As part of the proposed approach for determining PV system performance in the scope of the Ecodesign preparatory study, it is proposed to refer to three distinct climatic zones. These are defined in the EN IEC 61853 Part 4, which provides a series of 8760 hourly values of the relevant environmental parameters, and the procedure for calculating the corresponding DC energy output (kWh).

In opposition to the first methodology that uses the inverter's European efficiency value for the calculations at all climatic zones, the other proposed methodologies apply different efficiency values depending on the working conditions of the inverter under the various climatic conditions. The efficiency values are obtained from linear interpolation on the efficiency values measured following IEC 61683 and EN 50530 standards at different rated power (5%, 10%, 20%, 25%, etc.) and are used to calculate the energy output accordingly for the three climate reference datasets.

The yearly DC energy output (kWh/year) obtained with the models described in the EN IEC 61853 and used in Method 1, is in fact the sum of the 8760 hourly values in a year of DC energy output (kWh) estimated for every reference climatic dataset. Considering these hourly values, it is possible to define for every hour the working condition of the inverter regarding its rated power and with these calculate the corresponding efficiency for every hour.

Depending on how the climate specific inverter efficiencies are treated, we have considered three new methods.

A2.2.1. Method 2: hourly efficiency

Using as input the hourly values of DC energy output and inverter efficiency, their product would provide an estimate the AC energy output for every hour. Their sum will be a more realistic estimate of the yearly AC energy output (Equation A5) compared to using the single European efficiency value.

$$EY_{AC}\ \text{(kWh/year per kWp)} = \sum_{h=1}^{8760} \eta_h \cdot EY_{DC}\ \text{(kWh/year per kWp)} \qquad \text{(Eq. A5)}$$

Where η_h would be the inverter's efficiency for hour *h* obtained by interpolation of the efficiency values derived from IEC 61683 and EN 50530 standards, which range between 6 and 8 values. The working conditions of the inverter at every hour, required to perform the interpolation, is defined by the ratio of the DC power received from the PV array and the inverter's nominal power.

In opposition to the European efficiency value which is always provided in the inverter's datasheet, these efficiency values measured at different rated power working conditions (IEC 61683 and EN 50530) are not always available in the inverter's datasheet. And when they are, they are normally provided in graphical format as an efficiency curve which makes it more difficult to estimate the hourly efficiency values. If the rated efficiency values are provided in tabulated form (following Table A1 and A2 structure) or defined from the efficiency curve, we propose a simple linear interpolation to calculate the η_h values.

In case the DC power delivered from the PV array is higher than the recommended maximum power for the inverter, we assume the inverter continues working at its maximum power during that period (clipping).

A2.2.2. Method 3: weighted efficiency based on in-plane irradiance

The weighted annual conversion inverter efficiency, internationally adopted as Euroefficiency or European efficiency in the EN 50530 standard was originally defined by Hotopp in the 1990s [A1.1, A1.2]. It was defined based on averaged hourly irradiance data measured for a single reference year at the location of Trier in Germany. The weighting factors shown in Equation A2 (0.03, 0.06, 0.13, etc.) were obtained by analysing the distribution of irradiance levels over the considered year, normalized to the STC irradiance (1000 Wm^{-2}). The authors found that, for example, the number of hours during the period of a year that the received irradiance is 50% of the STC one represented 20% of the time.

Considering the in-plane irradiance hourly values provided in the reference climatic datasets of EN IEC 61853-4, it would be possible to define new weighting factors for the three reference climatic datasets following Hotopp's procedure based on irradiance values ($f_{\_I5}$, $f_{\_I10}$, $f_{\_I20}$, etc.) and with those obtain an average weighted inverter efficiency adjusted to the reference irradiance yearly profiles, following Equation A6.

$$\begin{aligned}\eta_{\mathit{Irrad\ climate}} = {} & f_{\_I5} \cdot \eta\ 5\% \ + \ f_{\_I10} \cdot \eta\ 10\% \ + \ f_{\_I20} \cdot \eta\ 20\% \ + \ f_{\_I30} \cdot \eta\ 30\% \ + \\ & f_{\_I50} \cdot \eta\ 50\% \ + \ f_{\_I100} \cdot \eta\ 100\% \end{aligned} \qquad \text{(Eq. A6)}$$

Following Hotopp methodology, the weighted factors ($f_{\_I5}$, $f_{\_I10}$, $f_{\_I20}$, *etc.*) are calculated from the number of hours when the received irradiance is between the following ranges:

$f_{\_I5}$ is defined counting the hours the in-plane irradiance divided by the STC irradiance is between the interval (0% to 7.5%) over a year. Similarly,

$f_{\_I10}$ considers the range [7.5% to 15%)

$f_{\_I20}$ considers the range [15% to 25%)

$f_{\_I30}$ considers the range [25% to 40%)

$f_{\_I50}$ considers the range [40% to 75%)

$f_{\_I100}$ considers the range ≥ 75%

The estimation of the yearly AC energy output is then obtained by multiplying the DC energy output derived from the EN IEC 61853 methodology (kWh/year per kWp installed) by the climate specific aggregate efficiency of the inverter under consideration for a particular reference climate ($\eta_{Irrad\_climate}$) as shown in Equation A7:

$$EY_{AC\_climate}\ \text{(kWh/year per kWp)} = \eta_{Irrad\_climate} \cdot EY_{DC\_climate}\ \text{(kWh/year per kWp)} \qquad \text{(Eq. A7)}$$

Where $\eta_{Irrad\_climate}$ would be the inverter's weighted efficiency obtained considering the hourly in-plane irradiance values of the reference climatic conditions under consideration, and $EY_{DC\_climate}$ would be the DC energy output from a reference 1 kWp PV array under the same climatic conditions. This latter value is common with Method 1, but instead of using the European efficiency, this third Method applies an efficiency adjusted to the irradiance profiles of every climatic condition ($\eta_{Irrad\_climate}$·).

A2.2.3. Method 4: weighted efficiency based on rated power

In Method 3 the weighting factors ($f_{\_I5}$, $f_{\_I10}$, $f_{\_I20}$ *etc.*) are calculated based on the irradiance profile at the different reference climatic profiles, while the efficiency values (η 5%, η 10%, η 20%, *etc.*) are measured according to IEC 61683 and EN 50530 standards submitting the inverter to different rated power. Since not all the received irradiance is effectively transformed to DC energy by the PV module array, Method 4 proposed here would define the weighting factors considering the number of hours the inverter works at different working conditions (received DC power), which are better related to the conditions in which the inverter's efficiency are measured.

From the hourly irradiance values of the reference climatic datasets, the DC energy output from a reference PV module array can be estimated. With these it is possible to define the inverter's working conditions and knowing the frequency distribution of these working conditions over a year, it is possible to define the percentage of hours within a year that the inverter works at different power levels. From these a single aggregate efficiency parameter, similar to the European efficiency, can be calculated. The new weighted average efficiencies for each of the three climate reference zones are calculated as shown in Equation A8.

$$\eta_{Rated\ Power\_climate} = f_{\_RP5} \cdot \eta\,5\% + f_{\_RP10} \cdot \eta\,10\% + f_{\_RP20} \cdot \eta\,20\% + f_{\_RP30} \cdot \eta\,30\% + f_{\_RP50} \cdot \eta\,50\% + f_{\_RP100} \cdot \eta\,100\% \qquad \text{(Eq. A8)}$$

In order to apply this fourth methodology, we could maintain the rated power levels used in the European efficiency calculation, as shown in Equation A2 (5%, 10%. 20%, 30%, 50% and 100%) or define different ones like those used in the CEC efficiency. In addition to this, the method on how to quantify the hours during which the inverter works at these discrete levels has to be defined. In this regard, we propose using the levels and ranges considered in the European efficiency definition, which are also applied in Method 3 described above. Therefore, it is necessary to quantify the hours assigned to each level (5%, 10%. 20%, 30%, 50% and 100%) considering the same intervals as defined in Method 3 but linked to the rated power received by the inverter from the PV array. For example, the weighting factor $f_{\_RP5}$ would be the number of hours during the year, for a particular reference climatic region, that the DC power provided to the inverter by the PV array is between 0% and 7.5% of its rated power.

Similarly to Equation A7, the estimation of the yearly AC energy output is then obtained by multiplying the DC energy output derived from the EN IEC 61853 methodology (kWh/year per installed kWp) by the climate specific aggregate efficiency obtained considering the rated power provided to the inverter under consideration (Equation A9).

$$EY_{AC\_climate}\ (\text{kWh/year} \cdot \text{kWp}) = \eta_{Rated\ Power\_climate} \cdot EY_{DC\_climate}\ (\text{kWh/year} \cdot \text{kWp}) \qquad \text{(Eq. A9)}$$

Where $\eta_{Rated\ Power\_\ climate}$ would be the inverter's weighted efficiency for the reference climatic conditions under consideration defined using the rated power to which the inverter is submitted every hour.

A3. Results

A3.1. Input data

- From the EN IEC 61853-4 reference climatic datasets representative of the European climatic conditions, we have used the hourly in-plane irradiance values (required in Method 3).
- Following the procedure described in EN IEC 61853-3, we calculated, for every climate, the hourly DC energy output from 1 kWp PV array of crystalline silicon modules. These are assumed mounted in a free standing rack, with an inclination angle of 20° and facing the equator. The yearly sum of the hourly DC energy output at every climatic condition is the yearly energy yield EY_{DC_Sub}, EY_{DC_Temp} and EY_{DC_Coast} (kWh/year per installed kWp) used in Methods 1, 3 and 4. The hourly DC energy yield values are also needed for Methods 2 and 4.
- We considered five different inverters whose characteristics are presented in Table A3

In order to optimize the PV array-Inverter pair, for every inverter, due to their different nominal power, a different size of PV array needs to be applied so as to maintain the sizing ratio between the two elements. We have used two different size ratios, 1.25 and 1.1 to consider two different PV systems sizes, utility scale and residential respectively. The installed PV array peak power in every case is defined in Table A3.

Table A3. AC nominal power (W) and European efficiency of the five considered inverters, and the installed PV array peak power applied to every inverter for two different PV system sizes.

Inverter	AC nominal power, $P_{ac,r}$ (W)	η_{EUR}	Installed PV array (kWp) (size ratio 1.1)	Installed PV array (kWp) (size ratio 1.25)
1	1500	94.5	1.65	1.875
2	2750	93.6	3.025	3.4375
3	2300	93.2	2.53	2.875
4	1550	91.8	1.705	1.9375
5	1200	90.9	1.32	1.5

As a result, for every inverter there are two PV systems, one per size ratio. Considering 1.1 for residential systems, we name system R1 the system composed of the inverter 1 connected to the PV array with an installed power of 1.65, system R2 is the system composed of the inverter 2 connected to the PV array with an installed power of 3.025, etc.

When the size ratio applied is 1.25 better suited for utility scale systems, these will be denoted system 1, system 2, etc.

A3.2. Results for a residential PV system (size ratio 1.1)

Table A4 contains the yearly DC energy output from the PV array connected to every inverter and the estimated AC energy yield delivered from the inverter (System R), considering the four methods described in Section A2, for the Subtropical arid reference climate.

Table A4. Yearly DC energy output from the PV array of the five different PV systems, and their AC energy output estimated by the four methodologies (kWh/year).

Subtropical arid	Syst R1	Syst R2	Syst R3	Syst R4	Syst R5
EY_{DC_Sub} (kWh/year)	3347.94	6137.89	5133.51	3459.54	2678.35
Method 1. EY_{AC_Sub} (kWh/year)	3163.80	5745.06	4784.43	3175.86	2434.62
Method 2. EY_{AC_Sub} (kWh/year)	3193.99	5769.90	4800.11	3186.83	2434.40
Method 3. EY_{AC_Sub} (kWh/year)	3165.50	5729.08	4769.91	3159.93	2420.58
Method 4. EY_{AC_Sub} (kWh/year)	3159.31	5715.76	4759.36	3150.83	2414.63

In order to compare the performance of the inverter in the different systems, the results are normalised to the installed PV peak power, so as to reference all energy yield estimation to 1 kWp of installed peak power, as required by the inverter's functional unit definition. Results are shown in Table A5.

Table A5. Yearly DC energy output from the PV array at the five different PV systems, and AC energy output estimated by the four methodologies normalized to 1 kWp PV array (kWh/year per installed kWp). Subtropical arid reference climate.

Subtropical arid	Syst R1	Syst R2	Syst R3	Syst R4	Syst R5
EY_{DC_Sub} (kWh/year·kWp)	2029.05	2029.05	2029.05	2029.05	2029.05
Method 1. EY_{AC_Sub} (kWh/year·kWp)	1917.46	1899.20	1891.08	1862.67	1844.41
Method 2. EY_{AC_Sub} (kWh/year·kWp)	1935.75	1907.41	1897.28	1869.11	1844.24
Method 3. EY_{AC_Sub} (kWh/year·kWp)	1918.48	1893.91	1885.34	1853.33	1833.77
Method 4. EY_{AC_Sub} (kWh/year·kWp)	1914.74	1889.51	1881.17	1848.00	1829.26

Considering the results from Method 1 as reference values, Table A6 shows the difference, in percentage, between the AC energy yield estimated by Method 1 and the other 3.

Table A6. Difference (%) in the AC energy output from Methods 2 to 4 with regard to Method 1 estimates. Subtropical arid reference climate.

Subtropical arid	Syst R1	Syst R2	Syst R3	Syst R4	Syst R5

Method 1. EY_{AC_Sub} (kWh/year·kWp)	1917.46	1899.20	1891.08	1862.67	1844.41
Method 2. Vs. Method 1 (%)	0.954	0.432	0.328	0.346	-0.009
Method 3. Vs. Method 1 (%)	0.053	-0.278	-0.303	-0.501	-0.577
Method 4. Vs. Method 1 (%)	-0.142	-0.510	-0.524	-0.788	-0.821

The difference in all cases is below 1%. While Method 2 tends to overestimate the Method 1 results, both Methods 3 and 4 tend to underestimate.

Differences between Method 1 results and the other three methods tend to increase in the other two reference climatic datasets, as shown in Tables A7 and A8 that contain respectively the differences obtained in the Temperate continental and Temperate coastal climates.

Table A7. Difference (%) in the AC energy output from Methods 2 to 4 with regard to Method 1 estimates. Temperate continental reference climate.

Temperate continental	Syst R1	Syst R2	Syst R3	Syst R4	Syst R5
Method 1. EY_{AC_Temp} (kWh/year·kWp)	1114.13	1103.52	1098.80	1082.23	1071.69
Method 2. Vs. Method 1 (%)	0.460	0.267	0.233	0.215	0.067
Method 3. Vs. Method 1 (%)	-1.214	-1.128	-1.017	-1.472	-1.169
Method 4. Vs. Method 1 (%)	-1.243	-1.246	-1.140	-1.630	-1.336

Table A8. Difference (%) in the AC energy output from Methods 2 to 4 with regard to Method 1 estimates. Temperate coastal reference climate.

Temperate coastal	Syst R1	Syst R2	Syst R3	Syst R4	Syst R5
Method 1. EY_{AC_Coast} (kWh/year·kWp)	896.50	896.50	896.50	896.50	896.50
Method 2. Vs. Method 1 (%)	-0.061	-0.055	-0.041	-0.105	-0.088
Method 3. Vs. Method 1 (%)	-0.967	-0.867	-0.778	-1.103	-0.870
Method 4. Vs. Method 1 (%)	-0.993	-0.934	-0.847	-1.187	-0.951

Methods 3 and 4 calculate a new average weighted efficiency for every reference climate which compare to the European efficiency of the five inverters are shown in Table A9.

Table A9. New average weighted efficiency values obtained by Methods 3 and 4, for the five considered inverters at the three climatic regions.

		Method 3. In-plane irradiance based			Method 4. DC rated power based		
Inverter	η_{EUR}	η_{Irrad_Sub}	η_{Irrad_Temp}	η_{Irrad_Coast}	η_{RP_Sub}	η_{RP_Temp}	η_{RP_Coast}
1	94.5	94.6	93.4	92.4	94.4	93.3	92.4
2	93.6	93.3	92.5	91.8	93.1	92.4	91.6
3	93.2	92.9	92.3	91.6	92.7	92.1	91.4
4	91.8	91.3	90.4	89.5	91.1	90.3	89.3
5	90.9	90.4	89.8	89.1	90.2	89.7	88.9

A3.3. Results for utility scale PV systems (size ratio 1.25)

The same calculations have been performed for the five inverters connected to different PV arrays whose size is defined by the size ratio 1.25.

Results follow the same trend as those observed for the residential PV system (size ratio 1.1), so we only present here the percentage difference between the results obtained from Method 1 and the other three for the Subtropical arid climatic region. (Table A10).

Table A10. Difference (%) in the AC energy output from Methods 2 to 4 with regard to Method 1 estimates for utility scale PV systems. Subtropical arid reference climate.

Subtropical arid	System 1	System 2	System 3	System 4	System 5
Method 1. EY_{AC_Sub} (kWh/year·kWp)	1917.46	1899.20	1891.08	1862.67	1844.41
Method 2. Vs. Method 1 (%)	1.086	0.352	0.217	0.192	-0.244
Method 3. Vs. Method 1 (%)	0.053	-0.278	-0.303	-0.501	-0.577
Method 4. Vs. Method 1 (%)	0.088	-0.362	-0.402	-0.636	-0.756

A3.4. Selected methodology

Considering the different results, especially between Method 1, which uses readily available data such as the European efficiency and Method 2, which may be considered the most accurate methodology for doing hourly calculations, we propose applying Method 1 for the estimation of the inverter performance. Method 2 requires data that is not always provided by the inverter's manufacturer and needs to perform more complex calculations than Method 1.

Methods 3 and 4, although provide similar results to the other two, still require a further step in the calculations to obtain the new average weighted efficiency. And as it is the case of Method 2, they require further input data that it is not always available.

On the contrary, Method 1 uses the European efficiency and the yearly DC energy output from the PV array calculated according to the EN IEC 61853 standard series methodology. If in the future PV manufacturers included in the module's datasheet the *Climate Specific Energy Rating* values derived from their PV module at the different reference climatic regions, the yearly DC energy yield could be easily calculated from the said *CSER* values, as explained in Section 5.2.1, Equation 3.

Regarding the effect of the sizing factor of the combination PV array-Inverter on the AC energy yield of 1 kWp PV array when using the 1.1 ratio or the 1.25 sizing ratio is very similar. In fact, the results from Methods 1 and 3 are independent on the sizing ratio, since the DC/AC conversion factor is independent of the working conditions of the inverters. Method 1 applies the European efficiency, while Method 3 uses a weighted average efficiency which depends only on the irradiance profile. On the contrary, Methods 2 and 4 account for the hourly working conditions of the inverter, so the sizing ratio has an effect on the AC output. However, as shown in Table A11, the difference is very low.

Table A11. Difference (%) between the AC energy output from 1 kWp PV array estimated with Method 2 considering a sizing ratio of 1.1 and 1.25, for the five different inverters at the three European reference climates.

	Inverter 1	Inverter 2	Inverter 3	Inverter 4	Inverter 5
Subtropical arid	-0.131	0.080	0.110	0.153	0.235
Temperate continental	-0.189	-0.017	0.014	0.022	0.114
Temperate coastal	0.261	-0.143	-0.111	-0.149	-0.057

Since the AC energy yield is used in the transitional parameter calculation, the sizing ratio will also have a limited impact on its value.

References

[A1.1] R. Hotopp; „Private Photovoltaik-Stromerzeugungsanlagen im Netzparallelbetrieb‟, 2. Auflage, RWE Energie AG, Essen, 1991.

[A1.2] Auf den Spuren von „Euro-Eta‟, Photon, Juni 2004, S. 62 – 65

ANNEX B. European reference climatic profiles

The EN IEC 61853-4 "*Photovoltaic (PV) module performance testing and energy rating – Part 4: Standard reference climatic profiles*" describes the standards reference climatic profiles used for calculating energy rating. Six climatic profiles are used to define the climatic conditions that PV systems will most likely by subjected to when installed worldwide. Out of these six, three are considered representative of the European climatic conditions:

- Subtropical arid
- Temperate continental
- Temperate coastal

The climatic datasets included in Part 4 contain hourly values over one full year, listed as days one through 365, of the following parameters:

- Year
- Month
- Day
- Hour (local solar time)
- Ambient temperature (T_{amb}, °C)
- Wind speed at module height (v, m/s)
- Sun elevation (°)
- Sun incidence angle (to the normal of module) (°)
- Global horizontal irradiance (Gh, W/m^2)
- Direct horizontal irradiance (Bh, W/m^2)
- Global in-plane irradiance (G, W/m^2)
- Direct in-plane irradiance (B, W/m^2)
- Spectrally resolved global in-plane irradiance (W/m^2) integrated for a set of discrete bands ($G(\lambda)$,W/m^2)

Modules are assumed to be installed in a fixed open-rack, facing the equator with an inclination angle of 20°.

Figure B1 shows the geographical distribution of the EN IEC 61853-4 reference climatic profiles assumed representative of the European weather conditions.

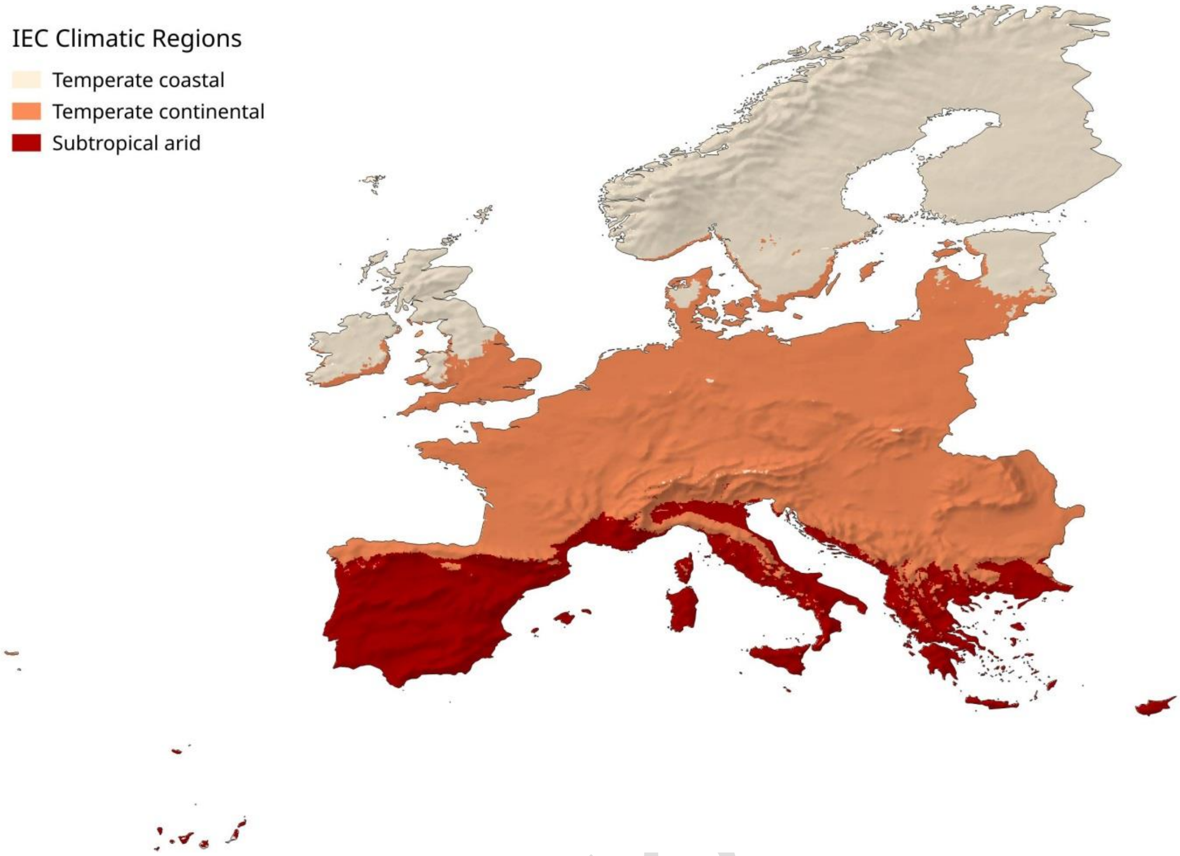

Figure 1B. Geographical distribution of the EN IEC 61853 climatic profiles representative of the European climatic conditions

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