# IEC PAS 63446

Edition 1.0 2022-10

# PUBLICLY AVAILABLE SPECIFICATION

**Conversion method of specific absorption rate to absorbed power density for the assessment of human exposure to radio frequency electromagnetic fields from wireless devices in close proximity to the head and body – Frequency range of 6 GHz to 10 GHz**



IEC PAS 63446:2022-10(en)

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IEC PAS 63446 has been processed by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure.

| The text of this PAS is based on the following document: | This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document |
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This document contains supplemental files that are detailed in Annex D. These files can be downloaded from https://www.iec.ch/tc106/supportingdocuments.

# INTRODUCTION

This document provides the method to conservatively evaluate the area averaged electromagnetic (EM) power density entering the human body, i.e. the absorbed power density (APD), for communication devices intended to be used at a position near the human head or body, or mounted on the body, combined with other transmitters within a product, or embedded in garments. The device categories covered include but are not limited to mobile telephones, radio transmitters in personal computers, and desktop and laptop devices. The applicable frequency range is from 6 GHz to 10 GHz.

This document specifies:

- conversion of the psSAR to the psAPD (Clause 6);
- uncertainty estimation (Clause 7);
- reporting requirements (Clause 8);
- methods of validation and system check (Annex C)

The measurement and computational standards IEC/IEEE 63195-1:2022 [1][1] and IEC/IEEE 63195-2:2022 [2] for incident power density (IPD) cover the frequency range from 6 GHz to 300 GHz. Hence there is a frequency overlap from 6 GHz to 10 GHz between this document on APD and the IEC/IEEE standards addressing IPD. The committee was aware of this fact and opted for enhanced flexibility by providing methods for basic restriction metric APD in addition to reference level metric IPD.



1 Numbers in square brackets refer to the Bibliography.

# CONVERSION METHOD OF SPECIFIC ABSORPTION RATE TO ABSORBED POWER DENSITY FOR THE ASSESSMENT OF HUMAN EXPOSURE TO RADIO FREQUENCY ELECTROMAGNETIC FIELDS FROM WIRELESS DEVICES IN CLOSE PROXIMITY TO THE HEAD AND BODY – FREQUENCY RANGE OF 6 GHZ TO 10 GHZ

## 1 Scope

This document specifies a conversion method for the assessment of the peak spatial-average absorbed power density ($psAPD$) in the human head and body due to exposure to radio frequency (RF) electromagnetic fields (EMF) from wireless communication devices, with a specified conversion uncertainty. This conversion method is based on specific absorption rate (SAR) values and is specified with the objective to yield conservative and reproducible absorbed power density values of the exposure for a significant majority of the population during the use of hand-held, body-worn or any other RF transmitting communication devices that can operate in close proximity to a human head or body. This conversion method applies for devices that can feature single or multiple transmitters and/or antennas and can be operated with their radiating structure(s) at distances up to 200 mm from a human head or body.

The conversion method of this document can be employed to determine conformity with applicable absorbed power density or epithelial power density limits, such as those defined in ICNIRP guidelines 2020 [3] and IEEE Std C95.1™-2019 [4], of different types of RF transmitting communication devices being used in close proximity to the head and body. The assessment of $psAPD$ is based on the conversion of the peak spatial-average specific absorption rate (psSAR) values assessed according to applicable international standards. The applicable frequency range of the conversion method of this document is 6 GHz to 10 GHz.

NOTE Applicable international standards for the assessment of the psSAR are those accepted by the local regulatory body or specified in the CENELEC product standards. Such international standards include, e.g. IEC/IEEE 62209-1528 and IEC 62209-3 [5] for measurement methods, and IEC/IEEE 62704-1 [6] and IEC/IEEE 62704-4 [7] for computational methods. The frequency range of [5], [6] and [7] is limited up to 6 GHz. While the applicability of the methods of [5] for the frequency range of this document may need further verification, the numerical standards [6] and [7].may be applied for frequencies up to 10 GHz.

The categories of RF transmitting communication devices covered in this document include but are not limited to mobile telephones, radio transmitters in personal computers, and desktop and laptop devices or devices embedded in garments, using single or multiple transmitters and/or antennas, when operating within the frequency range indicated above.

The conversion method of this document does not apply for EMF evaluation of exposure from the devices or objects intended to be implanted in the body, such as active or passive implanted medical devices.



## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/IEEE 62209-1528:2020, *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Part 1528: Human models, instrumentation and procedures (Frequency range of 4 MHz to 10 GHz)*

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

**3.1**
**absorbed power density**
**locally absorbed power density**
*APD*
power per skin surface unit area that is absorbed in the body

Note 1 to entry: APD is determined using Formula (1) and Formula (2):

$$APD = \frac{1}{A_{av}} \iint_{A_{av}} dxdy \int_{0+}^{z_{max}} \rho(x,y,z) SAR(x,y,z) dz = PD_0 \big|_{\delta \ll z_{max}} \quad (1)$$

and

$$SAR(x,y,z) = SAR(x,y,0) e^{-2z/\delta} \quad (2)$$

where

| | |
|---|---|
| $PD_0$ | is the specific absorbed power density averaged over the area $A_{av}$ at the phantom bottom ($z$ = 0); |
| $A_{av}$ | is the averaging area; |
| $\delta$ | is the penetration depth of the tissue equivalent medium (< 6 mm), which is much smaller than the medium liquid depth $z_{max}$ at any location of the phantom; |
| $\rho(x,y,z)$ | is the mass density of the tissue equivalent medium; |
| $SAR(x,y,z)$ | is the local specific absorption rate. |

Note 2 to entry: The quantity *APD* is equivalent to the quantity $S_{ab}$ of Formula (23) of [3].

Note 3 to entry: In IEEE Std C95.1 [4] the identical metric is called epithelial power density. Identical term transmitted power density is used in some scientific publications.

Note 4 to entry: Power density is also referred to as power flux density.

Note 5 to entry: Further details can be found in Annex A and Annex B.

Note 6 to entry: Definition is valid for any surface and not limited to the flat phantom surface.

**3.2**
**incident power density**
power per unit area that impinges on the body surface

Note 1 to entry: The incident power density just outside the body surface is used to establish local exposure reference levels, which apply at frequencies above 6 GHz in some jurisdictions.

**3.3**
**spatial-average absorbed power density**
$sAPD(A_{av})$
$APD$ averaged over a surface of an averaging area $A_{av}$

Note 1 to entry: The $sAPD$ is a function of the location vector $\boldsymbol{r}$. It is defined on the evaluation surface, except for the edges where no averaging area can be constructed.

Note 2 to entry: For the frequency range from 6 GHz to 10 GHz the averaging area size specified in exposure limits is 4 cm$^2$.

**3.4**
**peak spatial-average absorbed power density**
$psAPD(A_{av})$
global maximum value of $sAPD$ (3.3) on the interface of the entire inner phantom surface and the tissue equivalent medium

Note 1 to entry: $psAPD$ is given by Formula (3):

$$psAPD = \max\{sAPD(r)\} \tag{3}$$

where $\boldsymbol{r}$ is a point on the evaluation surface as defined in IEC/IEEE 63195-1:2022 [1].

Note 3 to entry: Other local maxima (i.e. secondary peak spatial-average power density values) can exist (see 3.5).

**3.5**
**secondary peak spatial-average absorbed power density**
other local maxima of the spatial-average power density ($sAPD$) values that are smaller than the peak spatial-average power density ($psAPD$)

**3.6**
**maximized peak spatial-average absorbed power density**
$mpsAPD$
global maximum value of $psAPD$ for all combinations of phasors that represent the input signal to an antenna array

**3.7**
**Poynting vector**
$S$
vector product of the electric field strength $\boldsymbol{E}$ and the magnetic field strength $\boldsymbol{H}$ of the electromagnetic field at a given point

Note 1 to entry: The flux of the Poynting vector through a closed surface is equal to the electromagnetic power passing through this surface.

Note 2 to entry: For a periodic electromagnetic field, the time average of the Poynting vector is a vector, the direction of which, with certain reservations, can be considered as the direction of the propagation of electromagnetic energy and the magnitude can be considered as the average power flux density.

Note 3 to entry: For a sinusoidal wave of angular frequency $\omega$, the complex Poynting vector is expressed by Formula (4):

$$\boldsymbol{S} = \frac{1}{2}\boldsymbol{E} \times \boldsymbol{H}^* \tag{4}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are phasors and the asterisk denotes the complex conjugate.

Note 4 to entry: The Poynting vector has units of watt per square metre (W/m$^2$).

[SOURCE: IEC 60050-121:2019, 121-11-66, modified – excerpts combined and rearranged, Note 4 added.]

**3.8**
**averaging area**
$A_{av}$
nominal size of the area used for calculating *sAPD* (3.3)

Note 1 to entry: The shape of the averaging area is the cross section of a sphere ($r = (A_{av}/\pi)^{1/2}$) with the centre on the surface (circular in case of a planar surface) or the cross-section of a cube with side length of $(A_{av})^{1/2}$ determined according to IEC/IEEE 63195-2:2022 [2].

**3.9**
**specific absorption rate**
**SAR**
measure of the rate at which energy is absorbed per unit mass in a human body when exposed to a radio frequency electromagnetic field

Note 1 to entry: This quantity is equal to specific energy absorption rate defined in ICNIRP 2020 guidelines [3].

**3.10**
**spatial-average SAR**
*sSAR*
SAR averaged within a local region based on a specific averaging mass

Note 1 to entry: Averaging masses 1 g and 10 g of tissue in the shape of a cube are considered for example in IEC/IEEE 62209-1528:2020. In this document, 8 g of tissue in the shape of a cube is considered for determining *sAPD* over a square 4 cm$^2$ surface area of the body.

**3.11**
**peak spatial-average SAR**
*psSAR*
maximum SAR averaged within a local region based on a specific averaging mass

Note 1 to entry: Averaging masses 1 g and 10 g of tissue in the shape of a cube are considered for example in IEC/IEEE 62209-1528:2020. In this document, 8 g of tissue in the shape of a cube is considered for determining *sAPD* over a square 4 cm$^2$ surface area of the body.

**3.12**
**evaluation surface**
interface at the inner surface of the phantom shell and the tissue equivalent medium where the spatial-average power density (*sAPD*) is evaluated



# 4 Symbols and abbreviated terms

## 4.1 Physical quantities

The internationally accepted SI units are used throughout the document.

| Symbol | Quantity | Unit | Dimensions |
|---|---|---|---|
| $A_{av}$ | area | square metre | m$^2$ |
| *APD* | absorbed power density | watt per square metre | W/m$^2$ |
| $F_{APD}$ | conversion factor | kilogram per square metre | kg/m$^2$ |
| $\delta$ | penetration depth of the tissue equivalent medium | metre | m |
| $\boldsymbol{E}$ | electric field vector | volt per metre | V/m |
| $\eta$ | wave impedance of the tissue equivalent medium | ohm | Ω |
| $\varepsilon_r$ | relative permittivity (real part) | 1 | 1 |
| $\boldsymbol{H}$ | magnetic field vector | ampere per metre | A/m |
| $\boldsymbol{k}$ | wave vector | 1 per metre | 1/m |

| | | | |
|---|---|---|---|
| $k_0$ | wave number in a particular medium | 1 per metre | 1/m |
| $\lambda$ | wavelength | metre | m |
| $\lambda_0$ | wavelength in air, or free-space wavelength | metre | m |
| $\ell_c$ | edge length of SAR averaging cube | metre | m |
| *mpsAPD* | maximized peak spatial-average absorbed power density | watt per square metre | $W/m^2$ |
| $\omega$ | angular frequency | radian per second | rad/s |
| *psAPD* | peak spatial-average absorbed power density | watt per square metre | $W/m^2$ |
| *psSAR* | peak spatial-average specific absorption rate | watt per kilogram | W/kg |
| $r$ | radius | metre | m |
| $\boldsymbol{r}$ | location vector | metre | m |
| $\rho$ | mass density of the tissue equivalent medium | kilogram per cubic metre | $kg/m^3$ |
| $\boldsymbol{S}$ | Poynting vector | watt per square metre | $W/m^2$ |
| $\sigma$ | electrical conductivity | siemens per metre | S/m |
| *sAPD* | spatial-average absorbed power density | watt per square metre | $W/m^2$ |
| *SAR* | specific absorption rate | watt per kilogram | W/kg |
| *sSAR* | spatial-average specific absorption rate | watt per kilogram | W/kg |



## 4.2 Constants

| Symbol | Physical constant | Magnitude |
|---|---|---|
| $\varepsilon_0$ | permittivity in vacuum | $8{,}854 \times 10^{-12}$ F/m |
| $\mu_0$ | permeability in vacuum | $4\pi \times 10^{-7}$ H/m |

## 4.3 Abbreviations

| | |
|---|---|
| CAD | computer aided design |
| DUT | device under test |
| EMF | electromagnetic fields |
| PD | power density |
| RF | radiofrequency |
| SAM | specific anthropomorphic mannequin |
| SAT | standard ACIS text |
| TE | transverse electric |
| TM | transverse magnetic |

# 5 Application of this document

This document describes the conversion method for assessing the peak spatial-averaged absorbed power density or epithelial power density (*psAPD*) in the frequency range 6 GHz to 10 GHz. This method directly converts the measured or simulated peak spatial-averaged specific absorption rate (*psSAR*) to the *psAPD* in the head and body of the user of a DUT using psSAR values assessed according to applicable international standards. The procedures in these measurement and computational SAR standards can be applied with no modifications for supporting the conversion method in this document. The *psAPD* is converted for the averaging area specified in [3], [4], or according to *psAPD* requirements specified by national regulations. The conversion method also applies to conversion of any spatial-averaged specific absorption rate (*sSAR*) to the spatial-averaged absorbed power density (*sAPD*).

NOTE The conversion method is applicable when the SAR averaging volume includes the phantom surface. This is the case when the averaging volume is defined according to applicable SAR measurement or computational standards.

The *psAPD* is therefore evaluated with dielectric loading of the DUT taken into account, in the presence of the user represented by the phantom, where the reactive fields from the DUT can be perturbed, or electromagnetic energy can be confined between the DUT and the absorbing body [8]. The benefits are that basic restrictions are assessed while avoiding the complications in assessing the reference levels, i.e. incident power density in reactive near-field ([3]; see also 7.4.2.1 and I.2.2 of IEC/IEEE 63195-1:2022 [1]).

## 6 APD conversion method by evaluation of the SAR distribution

The APD conversion is based on the SAR distribution, and it is assumed that the power on the phantom surface is dominated by modes that propagate in the phantom, that almost all energy transmitted into the body is absorbed in applicable cubic volume at surface of the phantom, and that there is no significant power leakage through the sidewalls of the cube. For conversion of the *psSAR* to the *psAPD*, the dimensions of the averaging area for the *psAPD* are identical to the surface of the *psSAR* cube at the interface of the phantom shell and the tissue equivalent medium. The accuracy of these assumptions is assessed in Clause 7. The *psSAR* shall be measured or computed according to applicable SAR measurement or computational standards, respectively for the averaging mass listed in Table 1. The *psAPD* for a given averaging area shall be converted from the *psSAR* for a given averaging mass using Formula (5), with the conversion factors $F_{\text{APD,a}}$ given in Table 1:

$$psAPD_{A\text{av}} = psSAR_{\text{avg. mass}} \times F_{\text{APD,a}} \tag{5}$$

NOTE Rationale of and the details on the $F_{\text{APD,a}}$ conversion factor derivations are provided in Annex A and [9]. The error is considered in the uncertainty budget. Different from [9], for purposes of this document Formula (5) is written as an equality rather than an approximate equality.

**Table 1 – Conversion factors for *psSAR* to *psAPD***

| ***psAPD* averaging area** [cm$^2$] | ***psSAR* averaging mass** [g] | $F_{\text{APD,a}}$ [kg/m$^2$] |
|---|---|---|
| 1 | 1 | 10 |
| 4 | 8 | 20 |



## 7 Uncertainty estimation

### 7.1 Measurement uncertainty

The evaluation of the uncertainty applies to the assessment of the *psAPD* using measurement or computational methods with the SAM and flat phantoms. The measurement uncertainty for SAR shall be evaluated according to the applicable SAR measurement standard, and the computational uncertainty for SAR shall be evaluated according to the applicable computational SAR standard. An additional uncertainty term shall be added for the uncertainty of the conversion from *psSAR* to *psAPD* (PDC) for both measurement and computational assessment. The conservative uncertainty for PDC (rectangular distribution) is provided in [9] as 13,5 % (0,55 dB). The uncertainty budget template is calculated as in Table 2.

**Table 2 – Uncertainty budget template for evaluating the uncertainty in the measured value of the $psAPD$ of a DUT or validation antenna**

| Symbol | Input quantity $X_i$ (source of unc.) | Ref. | Prob. Dist. PDF[a] | Unc. Value $a(x_i)$ | Divisor[a] $q_i$ | Std. Unc. $u(x_i) = a(x_i) / q_i$ | $c_i$ | $u_i(y) = c_i \times u(x_i)$ | $v_i$ |
|---|---|---|---|---|---|---|---|---|---|
| | ***Measurement system errors*** | | | | | | | | |
| $u(SAR)$ | SAR measurement unc. | IEC/IEEE 62209-1528 | N | | | | | | ∞ |
| *PDC* | $psSAR$ to $psAPD$ conversion unc. | Clause 7 | R | 13,5 % | √3 | 7,8 % | 1 | 7,8 % | ∞ |
| $u(psAPD)$ | **Combined unc.** | | | | | | | | |
| $u(psAPD)$ | **Expanded unc. ($k$ = 2) and effective degrees of freedom** | | | | | | | | ∞ |

[a] N stands for normal and R for rectangular probability distribution. Other probability distributions and divisors may be used if they better represent available knowledge of the quantities concerned.

### 7.2 Numerical uncertainty

The evaluation of the computational uncertainty shall consider the numerical parameters of the simulation according to 7.2 of [6] and [7], and the uncertainty of the developed DUT model according to 7.3 of [6] and [7]. For DUT models with antenna arrays, the uncertainty of the calculation of the $mpsAPD$ according to Annex C of IEC/IEEE 63195-1:2022 [1] as the final result shall be considered. As the $mpsAPD$ is calculated directly from the field components in the numerical mesh, no additional uncertainty applies.

NOTE The assessment of the numerical uncertainty according to 7.2 of [6] and [7] for frequencies up to 6 GHz and of IEC/IEEE 63195-1:2022 [1] for frequencies above 10 GHz follow the same fundamental concept: the impacts of the applied computational parameters, such as mesh resolution, convergence, etc., are quantified, and the numerical model of the DUT is validated experimentally. These methods and concepts can be applied regardless of the frequency range specified in the scopes of the respective standards. References [6] and [7] require the additional validation of the phantom model, which is also required for the evaluation of the $psSAR$ (Table 2). References [6] and [7] do not specify methods for the maximization of the exposure (i.e. for the calculation of the $mpsAPD$) for devices with antenna arrays. Antenna arrays are only considered in IEC/IEEE 63195-1:2022 [1], and optimization techniques for the calculation of the $mpsAPD$ are specified in its Annex C. While IEC/IEEE 63195-1:2022 [1] evaluates the $mpsAPD$ in free space, its optimization techniques also apply if a dielectric phantom model, such as the SAM Phantom is used. In this case, the $psSAR$ is used as parameter for maximization instead of the $psPD$.

## 8 Measurement and computational report

All the information needed for performing repeatable tests, calculations, measurements, computations and giving results within the required calibration and uncertainty limits shall be recorded and reported. The reporting requirement of the applicable SAR measurement standard shall be applied. In addition, the details of the conversion calculations shall be presented.

# Annex A
(informative)

## Rationale for conversion of *psSAR* into *psAPD*

The conversion of *psSAR* to *psAPD* as per Clause 6 is based on the assumption that the electromagnetic field in the cubical volume in which *psSAR* is measured is dominated by plane wave propagation (see Annex B for detailed analysis). Its penetration depth $\delta$ (3.1) is given by Formula (A.1):

$$\delta = -\frac{1}{\Im\{k_1\}} \tag{A.1}$$

where $k_1$ is the complex wave number of the tissue equivalent medium, and the notation $\Im\{\ldots\}$ denotes imaginary part of a complex number.

The *psAPD* can then be calculated from Formula (A.2) with Formula (A.3):

$$psAPD_{Aav} = psSAR_{\mathrm{avg.\,mass}} \times \left[\frac{2\rho\ell_\mathrm{c}}{\sigma\delta\left(1-\mathrm{e}^{-2\ell_\mathrm{c}/\delta}\right)} \times \Re\left(\frac{1}{\eta}\right)\right] = psSAR_{\mathrm{avg.\,mass}} \times F_{\mathrm{APD,a}} \tag{A.2}$$

with

$$F_{\mathrm{APD,a}} = \frac{2\rho\ell_\mathrm{c}}{\sigma\delta\left(1-\mathrm{e}^{-2\ell_\mathrm{c}/\delta}\right)} \times \Re\left(\frac{1}{\eta}\right) = \frac{\rho\ell_\mathrm{c}}{\left(1-\mathrm{e}^{-2\ell_\mathrm{c}/\delta}\right)} \tag{A.3}$$

where

$\rho$ is the mass density of the tissue equivalent medium;

$\ell_\mathrm{c}$ is the edge length of the SAR averaging cube;

$\eta$ is the wave impedance of the tissue equivalent medium;

$\sigma$ is the conductivity of the tissue equivalent medium;

$\delta$ is the penetration depth of the tissue equivalent medium;

and the notation $\Re\{\ldots\}$ denotes real part of a complex number. The *psSAR* in Formula (A.2) is measured in a cube with the surface area that corresponds to the surface of the averaging area of the *psAPD* (Table 1).

The uncertainty of this conversion has been determined as 13,5 % (0,55 dB) by numerical comparison of the *psAPD* of short dipole antennas evaluated directly at the inner surface of the phantom to the result obtained from the conversion of the *psSAR*. Because the fields of these antennas can be assumed to contain a large amount of reactive energy, the approach can be regarded as conservative. Details are found in [9].

# Annex B
(informative)

# Poynting vector and absorbed power density

## B.1 Introduction

The electromagnetic fields in a homogeneous space can be represented as a superposition of propagating and reactive TE-modes and TM-modes. In a lossy half space, the total absorbed power can be expressed as a function of these modes. The total absorbed power in the half space can be calculated by integrating the local electric losses, or the local absorbed power, over the entire volume of the half space.

Alternatively, the Poynting theorem can be applied to calculate the power that enters the half space. In an infinite half space, the power is absorbed entirely. The total power integrated from the electric losses and the total power that enters the half space are identical. This annex gives expressions for the total power calculated: a) by integrating the local electric losses, and b) by integrating the transmitted power using the Poynting theorem, and shows that these expressions can be transformed into one another. The presentations in this annex are similar to those of [10] and [11].



## B.2 Electric fields and magnetic fields in a lossy half space

The electric fields and magnetic fields in an electrically lossy half space, the boundary of which is normal to the $z$-axis of a Cartesian coordinate system and located at $z_0$ = 0, can be decomposed into TE-wave and TM-wave as follows as per Formula (B.1), Formula (B.2), Formula (B.3), and Formula (B.4):

$$\boldsymbol{E}^{\mathrm{TE}}(\boldsymbol{r}) = \begin{pmatrix} 0 \\ E_0^{\mathrm{TE}} \\ 0 \end{pmatrix} \exp(-\mathrm{j}\boldsymbol{k}_1 \cdot \boldsymbol{r}) \tag{B.1}$$

$$\boldsymbol{H}^{\mathrm{TE}}(\boldsymbol{r}) = \frac{1}{\omega\mu_0} \begin{pmatrix} -k_{1z} E_0^{\mathrm{TE}} \\ 0 \\ k_{1x} E_0^{\mathrm{TE}} \end{pmatrix} \exp(-\mathrm{j}\boldsymbol{k}_1 \cdot \boldsymbol{r}) \tag{B.2}$$

$$\boldsymbol{E}^{\mathrm{TM}}(\boldsymbol{r}) = \frac{1}{k_1} \begin{pmatrix} k_{1z} E_0^{\mathrm{TM}} \\ 0 \\ -k_{1x} E_0^{\mathrm{TM}} \end{pmatrix} \exp(-\mathrm{j}\boldsymbol{k}_1 \cdot \boldsymbol{r}) \tag{B.3}$$

$$\boldsymbol{H}^{\mathrm{TM}}(\boldsymbol{r}) = \frac{\omega\bar{\varepsilon}_1}{k_1} \begin{pmatrix} 0 \\ E_0^{\mathrm{TM}} \\ 0 \end{pmatrix} \exp(-\mathrm{j}\boldsymbol{k}_1 \cdot \boldsymbol{r}) \tag{B.4}$$

where

$E_0^{\mathrm{TE}}, E_0^{\mathrm{TM}}$ are the complex amplitudes of the electric field of the TE-wave and TM-wave transmitted in the lossy half space;

$\boldsymbol{r}$ is the location vector $x\boldsymbol{e}_x + y\boldsymbol{e}_y + z\boldsymbol{e}_z$ for the coordinates $x$, $y$, and $z$, with $\boldsymbol{e}_x$, $\boldsymbol{e}_y$, and $\boldsymbol{e}_z$, being the respective unit vectors;

$\omega$ is the angular frequency of the fields;

$\bar{\varepsilon}_1$ is the complex permittivity of the lossy half space per Formula (B.5);

$\mu_0$ is the permeability in vacuum;

$\boldsymbol{k}_1$ is the wave vector in the lossy half space given in Formula (B.6).

The complex permittivity of the lossy half space is per Formula (B.5):

$$\bar{\varepsilon}_1 = \varepsilon_1 - \mathrm{j}\frac{\sigma_1}{\omega} \tag{B.5}$$

where

$\varepsilon_1$ is the real part of the absolute permittivity of the lossy half space;

$\sigma_1$ is the electric conductivity of the lossy half space.

The wave vector $\boldsymbol{k}_1$ is given as the product of the normalized vector of the direction of propagation of the TE-wave or TM-wave in the lossy half space and the wave number $k_1$ of Formula (B.6):

$$k_1 = \omega\sqrt{\mu_0\bar{\varepsilon}_1} \tag{B.6}$$

In the spectral domain, the tangential components $k_{1x}$ and $k_{1y}$ of the wave vector $\boldsymbol{k}_1$ are real values and are identical in both half-spaces, so the index $i$ can be omitted. For each wave in the spectrum the coordinate system can be oriented such that $k_y$ = 0. The $z$-component of $\boldsymbol{k}_1$ is then given by Formula (B.7):

$$k_{1z} = \sqrt{\omega^2\mu_0\varepsilon_1 - k_x^2 - \mathrm{j}\omega\mu_0\sigma_1} \tag{B.7}$$

## B.3 Power density absorbed in the lossy half space

Provided that lossy half space extends in a positive $z$-direction and that its boundary is located at $z_0$ = 0, the differential dissipated power at a location $\boldsymbol{r}$ in space is per Formula (B.8):

$$dP = \frac{\sigma}{2}\left\|\boldsymbol{E}^{\mathrm{TE,TM}}(\boldsymbol{r})\right\|^2 dV \tag{B.8}$$

Integration of Formula (B.8) along the $z$-axis yields the dissipated power density $PD^{\mathrm{TE,TM}}$ for a TE-wave or TM-wave according to Formula (B.1) and Formula (B.3) in the lossy half space between its boundary and a plane located at $z_1 > z_0$, per Formula (B.9):

$$\begin{aligned} PD^{\mathrm{TE,TM}} &= \frac{\sigma_1}{2}\left\|\boldsymbol{E}^{\mathrm{TE,TM}}\right\|^2 \int_{z_0}^{z_1} \exp(-\mathrm{j}k_{1z}z)\times\exp(-\mathrm{j}k_{1z}z)^* \, dz \\ &= \frac{\sigma_1}{2}\left\|\boldsymbol{E}^{\mathrm{TE,TM}}\right\|^2 \int_{z_0}^{z_1} \exp(2\Im\{k_{1z}\}z)\, dz \end{aligned} \tag{B.9}$$

According to Formula (B.7), $\Im\{k_{1z}\}$ is negative.

$\left\|\boldsymbol{E}^{\text{TE}}\right\|^2$ and $\left\|\boldsymbol{E}^{\text{TM}}\right\|^2$ are squares of the moduli of the complex amplitudes of the electric fields of the TE-wave and TM-wave of Formula (B.1) and Formula (B.3). Therefore, Formula (B.10) gives for the TE-wave:

$$\left\|\boldsymbol{E}^{\text{TE}}\right\|^2 = \left(E^{\text{TE}}\right)^2 \tag{B.10}$$

Note that the phase angle of each complex plane wave amplitude can be assumed to be zero if regarded independently from the others. Hence, $\left(E^{\text{TE}}\right)^2$ in Formula (B.10) is written without vertical double-bars.

Using identity for two complex numbers $a$ and $b$ of Formula (B.11):

$$\left|\frac{a}{b}\right| = \frac{|a|}{|b|} \tag{B.11}$$

$\left\|\boldsymbol{E}^{\text{TM}}\right\|^2$ can be written as in Formula (B.12):

$$\left\|\boldsymbol{E}^{\text{TM}}\right\|^2 = \frac{k_{1x}^2 + \left|k_{1z}^2\right|}{\left|k_1^2\right|}\left(E^{\text{TM}}\right)^2 \tag{B.12}$$

The dissipated power density can be regarded as the difference of the power density that enters the half space at $z_0$ and leaves it at $z_1$.

For $z_0$ = 0 and $z_1$ approaching $\infty$, the total absorbed power density for the TE-wave and TM-wave in the lossy half space according to Formula (B.9) can be written as in Formula (B.13) and Formula (B.14).

$$PD_{\text{total}}^{\text{TE}} = -\frac{\sigma_1}{4\Im\{k_{1z}\}}\left(E^{\text{TE}}\right)^2 \tag{B.13}$$

$$PD_{\text{total}}^{\text{TM}} = -\frac{\sigma_1}{4\Im\{k_{1z}\}}\frac{k_{1x}^2 + \left|k_{1z}^2\right|}{\left|k_1^2\right|}\left(E^{\text{TM}}\right)^2 \tag{B.14}$$

## B.4 Power transmitted by the Poynting vector of the TE-waves

Inserting the $y$-component of Formula (B.1) and the $x$-component of Formula (B.2) into the definition of the Poynting vector of 3.7, the real part of the $z$-component of the Poynting vector of the TE-waves at $z_0$ = 0 can be written as in Formula (B.15):

$$\Re\left\{S_{z0}^{\text{TE}}\right\} = -\frac{1}{2}\Re\left\{E_0^{\text{TE}}\cdot\left(\frac{-k_{1z}}{\omega\mu_0}E_0^{\text{TE}}\right)^*\right\} = \frac{1}{2\omega\mu_0}\left(E_0^{\text{TE}}\right)^2\Re\{k_{1z}\} \tag{B.15}$$

Using the identity of Formula (B.16) for the real numbers $x$ and $y$ [13]

$$\sqrt{x+\mathrm{j}y}=\sqrt{\frac{\sqrt{x^2+y^2}+x}{2}}\pm\mathrm{j}\sqrt{\frac{\sqrt{x^2+y^2}-x}{2}} \quad \text{(B.16)}$$

and applying Formula (B.17):

$$\Re\left\{\sqrt{x+\mathrm{j}y}\right\}\cdot\Im\left\{\sqrt{x+\mathrm{j}y}\right\}=\pm\frac{1}{2}\sqrt{\sqrt{x^2+y^2}+x}\cdot\sqrt{\sqrt{x^2+y^2}-x}=\pm\frac{1}{2}y \quad \text{(B.17)}$$

on Formula (B.7) yields Formula (B.18):

$$\Re\{k_{1z}\}\cdot\Im\{k_{1z}\}=\pm\frac{1}{2}\omega\mu_0\sigma_1 \quad \text{(B.18)}$$

Expanding the result of Formula (B.15) by $\Im\{k_{1z}\}$ and inserting the result of Formula (B.18) with its negative sign yields Formula (B.19):

$$\Re\left\{S_{z0}^{\mathrm{TE}}\right\}=\frac{1}{2\omega\mu_0}\left(E_0^{\mathrm{TE}}\right)^2\frac{\Re\{k_{1z}\}\cdot\Im\{k_{1z}\}}{\Im\{k_{1z}\}}=\frac{\sigma_1}{4\Im\{k_{1z}\}}\left(E_0^{\mathrm{TE}}\right)^2 \quad \text{(B.19)}$$

which is identical to the expression obtained for $PD_{\mathrm{total}}^{\mathrm{TE}}$ in Formula (B.13).

## B.5 Power transmitted by the Poynting vector of the TM-waves

Inserting the $x$-component of Formula (B.3) and the $y$-component of Formula (B.4) into the definition of the Poynting vector of 3.7, the real part of the $z$-component of the Poynting vector of the TM-waves at $z_0$ = 0 can be written as Formula (B.20):

$$\Re\left\{S_{z0}^{\mathrm{TM}}\right\}=-\frac{1}{2}\Re\left\{\frac{k_{1z}}{k_1}E_0^{\mathrm{TM}}\cdot\left(\frac{\omega\bar{\varepsilon}_1}{k_1}E_0^{\mathrm{TM}}\right)^*\right\}=\frac{1}{2|k_1|^2}\left(E_0^{\mathrm{TM}}\right)^2\Re\{k_{1z}(\omega\varepsilon_1+\mathrm{j}\sigma_1)\} \quad \text{(B.20)}$$

Factoring out $\Re\{k_{1z}\}$ from $\Re\{k_{1z}(\omega\varepsilon_1-\mathrm{j}\sigma_1)\}$, expanding the last summand in the real part of the resulting expression by $-\Im\{k_{1z}\}$, and applying Formula (B.18) yields Formula (B.21):

$$\Re\left\{S_{z0}^{\mathrm{TM}}\right\}=\frac{1}{2|k_1|^2}\left(E_0^{\mathrm{TM}}\right)^2\Re\{k_{1z}\}\left(\omega\varepsilon_1+2\frac{\left[\Im\{k_{1z}\}\right]^2}{\omega\mu_0}\right) \quad \text{(B.21)}$$

Note that the sign of Formula (B.18) is chosen such that Formula (B.21) is always positive.

Applying the imaginary part of the right-hand side of Formula (B.16) on Formula (B.7) yields Formula (B.22):

$$\left[\Im\{k_{1z}\}\right]^2=\frac{1}{2}\left[\sqrt{\left(\omega^2\mu_0\varepsilon_1-k_x^2\right)^2+\left(\omega\mu_0\sigma_1\right)^2}-\omega^2\mu_0\varepsilon_1+k_x^2\right] \quad \text{(B.22)}$$

After splitting up the term $2\left[\Im\{k_{1z}\}\right]^2/\omega\mu_0$ of Formula (B.21) into two equal summands and replacing the numerator of one of them by Formula (B.22), Formula (B.21) can be rearranged as Formula (B.23):

$$\Re\left\{S_{z0}^{\mathrm{TM}}\right\} = \frac{1}{2|k_1|^2}\left(E_0^{\mathrm{TM}}\right)^2 \frac{\Re\{k_{1z}\}}{\omega\mu_0}\times\left[\left[\Im\{k_{1z}\}\right]^2 + \frac{1}{2}\sqrt{\left(\omega^2\mu_0\varepsilon_1 - k_x^2\right)^2 + \left(\omega\mu_0\sigma_1\right)^2} + \omega^2\mu_0\varepsilon_1 + k_x^2\right] \tag{B.23}$$

Subtracting $k_x^2$ from the expression in the inner brackets and adding it again as a separate term yields Formula (B.24):

$$\Re\left\{S_{z0}^{\mathrm{TM}}\right\} = \frac{1}{2|k_1|^2}\left(E_0^{\mathrm{TM}}\right)^2 \frac{\Re\{k_{1z}\}}{\omega\mu_0}\times\left[\left[\Im\{k_{1z}\}\right]^2 + k_x^2 + \frac{1}{2}\sqrt{\left(\omega^2\mu_0\varepsilon_1 - k_x^2\right)^2 + \left(\omega\mu_0\sigma_1\right)^2} + \omega^2\mu_0\varepsilon_1 - k_x^2\right] \tag{B.24}$$

Applying the real part of the right hand side of Formula (B.16) on Formula (B.7) shows that the last term in the brackets corresponds to $\left[\Re\{k_{1z}\}\right]^2$, and Formula (B.24) can be rewritten as Formula (B.25):

$$\Re\left\{S_{z0}^{\mathrm{TM}}\right\} = \frac{1}{2|k_1|^2}\left(E_0^{\mathrm{TM}}\right)^2 \frac{\Re\{k_{1z}\}}{\omega\mu_0}\times\left[\left[\Re\{k_{1z}\}\right]^2 + \left[\Im\{k_{1z}\}\right]^2 + k_x^2\right] \tag{B.25}$$

The first two summands in the braces can be replaced by $\left|k_{1z}^2\right|$. Expanding the resulting expression by $-\Im\{k_{1z}\}$ and applying Formula (B.18) with negative sign yields Formula (B.26):

$$\Re\left\{S_{z0}^{\mathrm{TM}}\right\} = -\frac{\sigma_1}{4\Im\{k_{1z}\}}\frac{k_x^2 + \left|k_{1z}^2\right|}{\left|k_1^2\right|}\left(E^{\mathrm{TM}}\right)^2 \tag{B.26}$$

which is identical to the result of Formula (B.14).

## B.6 Summary

The comparison of Formula (B.13) and Formula (B.14) to Formula (B.19) and Formula (B.26) shows that the total absorbed power density for both TE-waves and TM-waves is transmitted entirely by the real parts of the $z$-components of their Poynting vectors.

It should be noted that the tangential components of the Poynting vector of a TM-wave, according to Formula (B.3) and Formula (B.4), also have nonzero real parts. These components do not contribute to the absorbed power because the tangential components of the wave vector are assumed to be real (Clause B.2). The tangential components of the Poynting vector are therefore not attenuated as they propagate parallel to the interface of the lossy half space, and no energy is dissipated.

The results of this annex are derived for the Poynting vector of the electric fields and magnetic fields that are transmitted into a lossy medium. They do not apply to the specifications of the $sPD$ and $psPD$ described in IEC/IEEE 63195-1:2022 [1] and IEC/IEEE 63195-2:2022 [2] because those refer to the Poynting vector of the incident electric fields and magnetic fields.