STUDY

COMPARING PV CABLE CURRENT CARRYING CAPACITIES AS SPECIFIED IN EN 50618 AND IEC 62930

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INTRODUCTION

The Copper Alliance assessed and compared the current carrying capacities of PV cables as specified in the European standard EN 50618, and international standard IEC 62930.

EN 50618 – *Electric cables for photovoltaic systems* – applies to low smoke, halogen-free, flexible, single-core, cross-linked insulated power cables with a cross-linked sheath, designed to be used on the direct current (DC) side of photovoltaic systems, with a nominal DC voltage up to and including 1.5 kV between conductors and between conductor and earth. The cables are suitable for use with Class II electrical equipment and are designed to operate safely at a continuous conductor temperature of maximum 90°C (normal operating conditions), with temporary peaks up to 120°C at a maximum ambient temperature of 90°C, permitted for a total maximum duration of 20,000 hours over the cable's lifetime. The expected lifetime under normal operating conditions is 25 years. The current carrying capacities listed in EN 50618 limit the conductor temperature to 120°C at an ambient temperature of 60°C.

IEC 62930 – *Electric cables for photovoltaic systems with a voltage rating of 1.5 kV DC* – applies to single-core cross-linked insulated power cables with cross-linked sheath. These cables are for use on the direct current (DC) side of photovoltaic systems, with a rated DC voltage up to and including 1.5 kV between conductors and between conductor and earth. This document covers halogen-free low smoke cables and cables that can contain halogens. The cables are suitable for use with Class II equipment as defined in IEC 61140. The cables are designed to operate safely at a continuous conductor temperature of maximum 90°C (normal operating conditions), with temporary peaks up to a conductor temperature of 120°C at a maximum ambient temperature of 90°C, permitted for a total maximum duration of 20,000 hours over the lifetime of the cable. The expected lifetime under normal operating conditions is 25 years. The current carrying capacities listed in IEC 62930 limit the conductor temperature to 90°C at an ambient temperature of 30°C.

The method adopted

The analysis is in three steps:

- Development of a model for calculating the current carrying capacity of the cables in accordance with the method described in IEC 60287-1-1 (*Electric cables – Calculation of the current rating – Part 1.1: Current rating equations (100% load factor) and calculations of losses – General*);
- Calculation of the current carrying capacity of the cables in accordance with the assumptions defined by EN 50618 and IEC 62930;
- Comparison of the results.

To be particularly cautious, the calculations were carried out for a single cable in free air. The other two installation modes included in EN 50618 and IEC 62930 – a single cable on a surface, and two loaded cables on a surface touching each other – are not specified with sufficient detail to allow for a robust calculation of current carrying capacity using the method described in IEC 60287.

Development of a model in accordance with IEC 60287

The IEC 60287 series provides a general method for calculating the current carrying capacity of power cables assuming 100% load factor. There is no reference to life expectancy in IEC 60287.

According to this standard, the current carrying capacity of DC power cables exposed to solar radiation can be calculated as follows (clause 1.4.4.2):

$$I = \sqrt[2]{\frac{\Delta\theta - \sigma \cdot D_e^* \cdot H \cdot T_4^*}{R' \cdot T_1 + nR' \cdot T_2 + nR' \cdot (T_3 + T_4^*)}}$$

EQUATION 1 – GENERAL FORMULA TO DETERMINATE THE CURRENT CARRYING CAPACITY OF A CABLE

where:

- $\Delta\theta$ is the permissible temperature rise of the conductor above the ambient temperature [K]
- σ is the solar radiation absorption coefficient of the cable surface
- D_e^* is the external diameter of the cable [m]
- H is the solar radiation intensity [W/m^2]
- T_4^* is the external thermal resistance in free air, adjusted for solar radiation [K*m/W]
- R' is the DC resistance of the conductor at maximum operating temperature [Ω*m]
- T_1 is the thermal resistance per core between conductor and sheath [K*m/W]
- n is the number of conductors in a cable
- T_2 is the thermal resistance between sheath and armour [K*m/W]
- T_3 is the thermal resistance of external serving [K*m/W]

In this study, PV power cables with copper conductor and EPR insulation in accordance with IEC 62930 and EN 50618 are considered. Under these assumptions, we can consider that $T_2 = 0$, $T_3 = 0$ and n = 1, and the current carrying capacity can be determined using the following formula:

$$I = \sqrt[2]{\frac{\Delta\theta - \sigma \cdot D_e^* \cdot H \cdot T_4^*}{R' \cdot T_1 + R' \cdot T_4^*}}$$

EQUATION 2 – FORMULA USED TO DETERMINATE THE PV CABLES' CURRENT CARRYING CAPACITY.

The DC resistance per unit length of the conductor at its maximum operating temperature is given by:

$$R' = R_0[1 + \alpha_{20}(\theta - 20)]$$

where:

- R_0 is the DC resistance of the conductor at 20°C, calculated using the resistivity values given in Table 1 of IEC 60228-1-1 [Ω/m]
- α_{20} is the constant mass temperature coefficient at 20°C per kelvin (Table 1 of IEC 60228-1-1)
- θ is the maximum conductor operating temperature [°C]

The thermal resistances T_1 and T_4* can be calculated as outlined in the following paragraphs.

Thermal resistance per core between conductor and sheath (T_1)

The thermal resistance between one conductor and the sheath T_1 is given by:

$$T_1 = \frac{\rho_T}{2\pi} ln\left[1 + \frac{2t_1}{d_c}\right]$$

where:

- ρ_T is the thermal resistivity of the insulation [K*m/W]
- d_c is the conductor diameter [mm]
- t_1 is the thickness of the insulation between conductor and sheath [mm]

External thermal resistance in free air, adjusted for solar radiation (T_4^*)

External thermal resistance T4* in free air, adjusted for solar radiation, can be calculated using the following formula:

$$T_4{}^* = \frac{1}{\pi\, D_e^*\, h\, (\Delta\theta_s)^{1/4}}$$

where:

- *h* is the heat dissipation coefficient [W/m^2 (K)$^{5/4}$]
- D_e^* is the external diameter of the cable [m]
- $\Delta\theta_s$ is the excess of the cable surface temperature above the ambient temperature [K]

h is obtained from the following formula, using the values of Z, E, and d as given in Table 2 of IEC 60287-2-1 (see *Table 1 – Values for Z, E and d for black surfaces of cables in free air)*:

$$h = \frac{Z}{(D_e^*)^d} + E$$

The parameter $(\Delta\theta_s)^{1/4}$ can be obtained using the following iteration:

- Set the initial value of $(\Delta\theta_s)^{1/4} = 2$
- Calculate $(\Delta\theta_s)_{n+1}^{1/4}$ as: $(\Delta\theta_s)_{n+1}^{1/4} = \sqrt[4]{\frac{\Delta\theta - \Delta\theta_{ds}}{1 + K_A (\Delta\theta_s)_n^{1/4}}}$
- Reiterate until $(\Delta\theta_s)_{n+1}^{1/4} - (\Delta\theta_s)_{n+1}^{1/4} \leq 0{,}001$

Parameter *K_A* and factor $\Delta\theta_{ds}$, with solar radiation as a function of the temperature difference, can be calculated as:

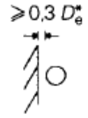
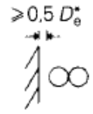
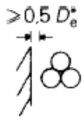
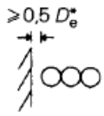
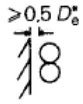
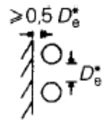
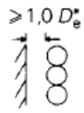
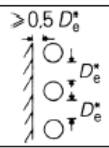
$$K_A = \pi D_e^*\, h\, T_1$$

$$\Delta\theta_{ds} = \sigma D_e^*\, H\, T_1$$

where:

- *h* is the heat dissipation coefficient [W/m^2 (K)$^{5/4}$]
- T_1 is the thermal resistance per core between conductor and sheath [K*m/W]
- *H* is the solar radiation intensity [W/m^2]
- σ is the solar radiation absorption coefficient of the cable surface
- D_e^*: is the external diameter of cable [m].

TABLE 1 – VALUES FOR Z, E, AND D FOR BLACK SURFACES OF CABLES IN FREE AIR (TABLE 2 OF IEC 60287-2-1)

No.	Installation	*Z*	*E*	*d*	Mode
Installation on non-continuous brackets, ladder supports or cleats, D_e^* not greater than 0,15 m					
1	Single cable[a]	0,21	3,94	0,60	
2	Two cables touching, horizontal	0,29	2,35	0,50	
3	Three cables in trefoil	0,96	1,25	0,20	
4	Three cables touching, horizontal	0,62	1,95	0,25	
5	Two cables touching, vertical	1,42	0,86	0,25	
6	Two cables spaced, D_e^* vertical	0,75	2,80	0,30	
7	Three cables touching, vertical	1,61	0,42	0,20	
8	Three cables spaced, D_e^* vertical	1,31	2,00	0,20	
Installation clipped direct to a vertical wall (D_e^* not greater than 0,08 m)					
9	Single cable	1,69	0,63	0,25	
10	Three cables in trefoil	0,94	0,79	0,20	

[a] Values for a “single cable” also apply to each cable of a group when they are spaced horizontally with a clearance between cables of at least 0,75 times the cable overall diameter.

CABLE CURRENT CARRYING CAPACITY: CALCULATION EXAMPLE

The input parameters to calculate the current carrying capacity of a 1.5 mm^2 cable with the formulae described above are listed in Table 2. The figures in blue are values taken from standard tables, cable manufacturer datasheets, or are otherwise known values.

TABLE 2 – CABLE AND AMBIENT CHARACTERISTICS

Cable characteristics	
Type of installation	single cable
Number of conductors in the cable	1
Insulating material	PE
Thermal resistivity of the material (ρ_T) [K*m/W]	3.5
Conductor material	Rame
$T_{conductor}$ [°C]	90
Cable cross section [mm^2]	1.5
Sigma (σ)	0.4
Ambient characteristics	
Irradiation H [W/m^2]	1000
$T_{ambient}$ [°C]	30

To calculate the thermal resistance per core between conductor and sheath (T_1), the insulation thickness and cable diameter are required. Table 3 lists the input data and the result of the calculation.

TABLE 3 – CALCULATION OF THE THERMAL RESISTANCE PER CORE BETWEEN CONDUCTOR AND SHEATH (T1)

Thermal resistance between conductor core and sheath T1	
T_1 [K*m/W]	0.35886
t_1 [mm]	0.7
dc [mm]	1.55

The external thermal resistance in free air, adjusted for solar radiation (T_4), requires the external cable diameter and parameters Z, E, and d (see Table 1 – *Values for Z, E and d for black surfaces of cables in free air*) as input values in the formulae discussed in the previous paragraph

TABLE 4 – CALCULATION OF THE EXTERNAL THERMAL RESISTANCE IN FREE AIR (T_4)

Thermal resistance between the external surface of the cable and the surrounding medium, T_4 and T_4*	
T_4 / T_4* [K*m/W]	2.70328
D*e [m]	0.00455
Doc [mm]	0
h [[K*m^2/W$^{5/4}$]	9.27996
Z	0.21
E	3.94
d	0.6
KA	0.05
Δθ [°C]	60
Δθds [K]	0.65281
Δθs$^{1/4}$ [K$^{1/4}$]	2.79004

The final step is to calculate the electrical resistance of the conductor at cable temperature.

TABLE 5 – CALCULATION OF THE ELECTRICAL RESISTANCE OF THE CONDUCTOR AT A GIVEN CONDUCTOR TEMPERATURE, AND OF THE CABLE CURRENT CARRYING CAPACITY

Calculation of cable current carrying capacity	
R'(θ) [Ω]	0.01466
ρ' (θ) [Ω.m]	2.1984E-08
ρ20 [Ω.m]	1.7241E-08
α20 [1/°C]	0.00393
I [A]	35.03375

With this we have all the input values needed to calculate the current carrying capacity using Equation 2. The result for a 1.5 mm^2 cable can be found in the first line of Table 7.

CALCULATION RESULTS

The current carrying capacity calculated using the method set by IEC 60287-1-1, with the cable and ambient characteristics in IEC 62930 and EN 50618, is as follows.

CALCULATED CURRENT CARRYING CAPACITY OF CABLES COMPLIANT WITH IEC 62930

The current carrying capacities were calculated using the above procedure and based on assumptions listed in *Table 6*.

TABLE 6 – DATA USED TO CALCULATE THE CABLES CURRENT CARRYING CAPACITIES

Ambient temperature	From 0°C to 80°C
Conductor temperature	90°C
Insulation material	PE
Conductor material	Copper
Irradiation	1000 W/m^2
Installation mode	Single cable in free air

The results are given in Table 7.

TABLE 7 – CABLE CURRENT CARRYING CAPACITY [A] AS A FUNCTION OF CONDUCTOR CROSS SECTION AND AMBIENT TEMPERATURE ($T_{CONDUCTOR}$ MAX. = 90°C).

Cross section [mm^2]	Ambient temperature [°C]								
\	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
1.5	45.63	42.30	38.78	35.03	30.99	26.55	21.50	15.40	10.64
4	80.49	74.57	69.43	61.64	54.45	46.54	37.56	26.65	14.05
10	139.05	128.73	117.83	106.22	93.68	79.89	64.20	45.03	30.03
25	248.92	230.33	210.69	189.74	167.09	142.10	113.54	78.28	49.82
50	389.04	359.84	328.95	295.99	260.31	220.89	175.69	119.40	72.91
95	588.85	544.43	497.43	447.23	392.87	332.69	263.50	176.66	103.24
150	794.64	734.63	671.11	603.21	529.57	447.93	353.76	234.71	131.07
240	1088.97	1006.64	919.42	826.10	724.78	612.25	482.04	316.14	166.95
400	1533.33	1417.20	1294.11	1162.29	1019.01	859.60	674.59	436.99	215.84

Calculated current carrying capacity of cables compliant with EN 50618

The current carrying capacities were calculated using the above procedure and based on assumptions listed in *Table 8*.

TABLE 8 – DATA USED TO CALCULATE THE CABLES' CURRENT CARRYING CAPACITIES

Ambient temperature	From 0°C to 90°C
Conductor temperature	120°C
Insulation material	PE
Conductor material	Copper
Irradiation	1000 W/m^2
Installation mode	Single cable in free air

The results are given in *Table 9*.

TABLE 9 – CABLE CURRENT CARRYING CAPACITY [A] AS A FUNCTION OF CONDUCTOR CROSS SECTION AND AMBIENT TEMPERATURE ($T_{CONDUCTOR}$ MAX. = 120°C).

Cross section [mm^2]	**Ambient temperature [°C]**									
****	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
1.5	52.41	49.61	46.69	43.66	40.47	37.10	34.14	29.65	25.40	20.57
4	92.59	87.60	82.42	77.01	71.34	65.35	58.98	52.09	44.53	35.94
10	160.16	151.48	142.45	133.04	123.16	112.73	101.62	89.63	76.43	61,42
25	286.94	271.33	255.09	238.15	220.37	201.58	181.53	159.86	135.95	108.63
50	448.85	424.33	398.83	372.22	344.27	314.73	283.18	249.05	211.33	168.09
95	679.88	642.61	603.86	563.38	520.88	475.92	427.89	375.87	318.30	252.10
150	917.45	867.18	814.90	760.26	702.85	642.08	577.12	506.66	428.55	338.46
240	1257.33	1188.46	1116.79	1041.87	963.10	879.65	790.37	693.43	585.76	461.19
400	1770.64	1673.63	1572.63	1467.01	1355.90	1238.13	1112.02	974.93	822.42	645.41

COMPARISON OF THE RESULTS

To compare the calculated current carrying capacities with those given in IEC 62930 and EN 50618, we must use:

- the same ambient temperature as the standards (i.e., 30°C for IEC 62930 and 60°C for EN 50618), and
- the same continuous maximum conductor temperature (i.e., 90°C for IEC 62930 and 120°C for EN 50618).

Figure 1 and Figure 2 compare the calculated figures with those given in IEC 62930 and EN 50618 respectively.

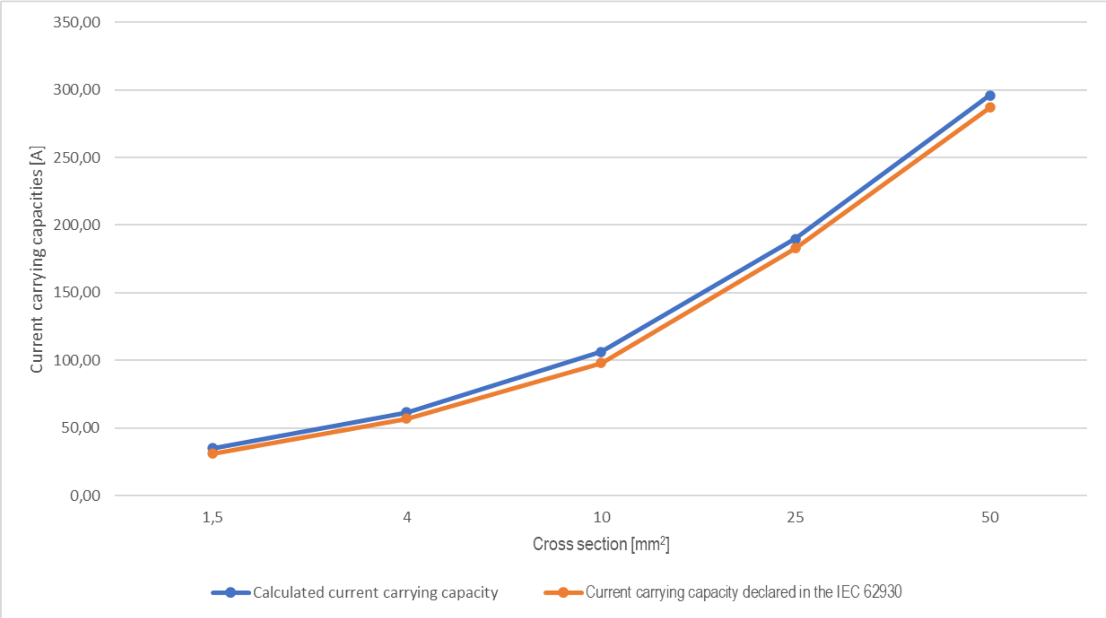


FIGURE 1 – COMPARISON OF CALCULATED CURRENT CARRYING CAPACITIES WITH THOSE GIVEN IN IEC 62930 (AMBIENT TEMPERATURE 30°C, CONTINUOUS MAXIMUM CONDUCTOR TEMPERATURE 90°C).

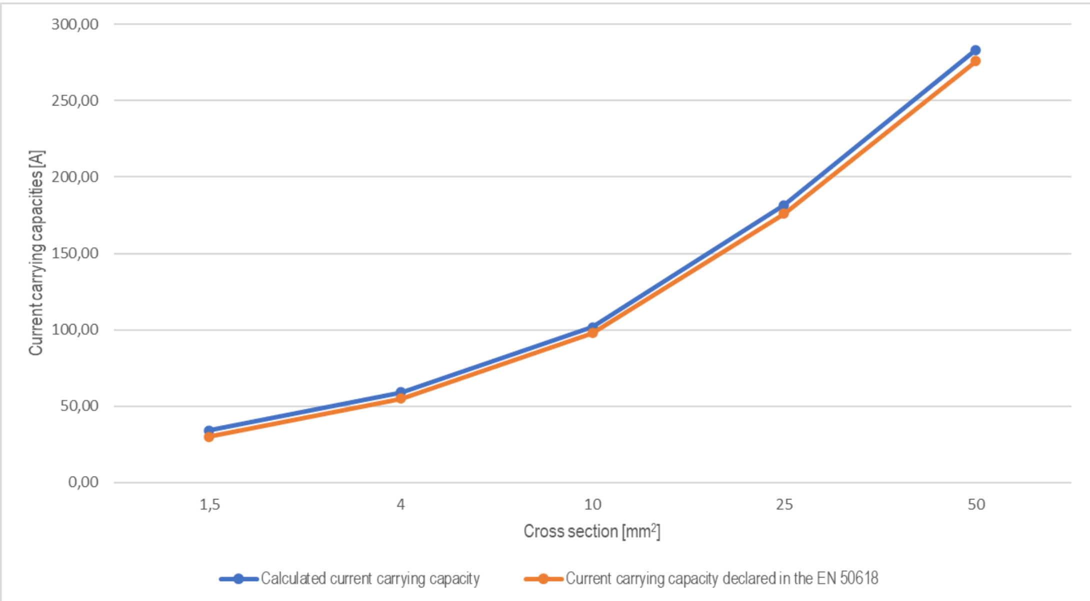


FIGURE 2 – COMPARISON OF CALCULATED CURRENT CARRYING CAPACITIES WITH THOSE GIVEN IN EN 50618 (AMBIENT TEMPERATURE 60°C, CONTINUOUS MAXIMUM CONDUCTOR TEMPERATURE 120°C).

Figure 3 merges Figure 1 and Figure 2 into a single graph. It demonstrates the calculated (following the IEC 60287-1-1 method) and standards (IEC 62930 and EN 50618) current carrying capacities for different cross sections. All figures are based on a maximum temperature rise of 60 K, which is an assumption made in both IEC 62930 and EN 50618, and is also assumed in the calculations.

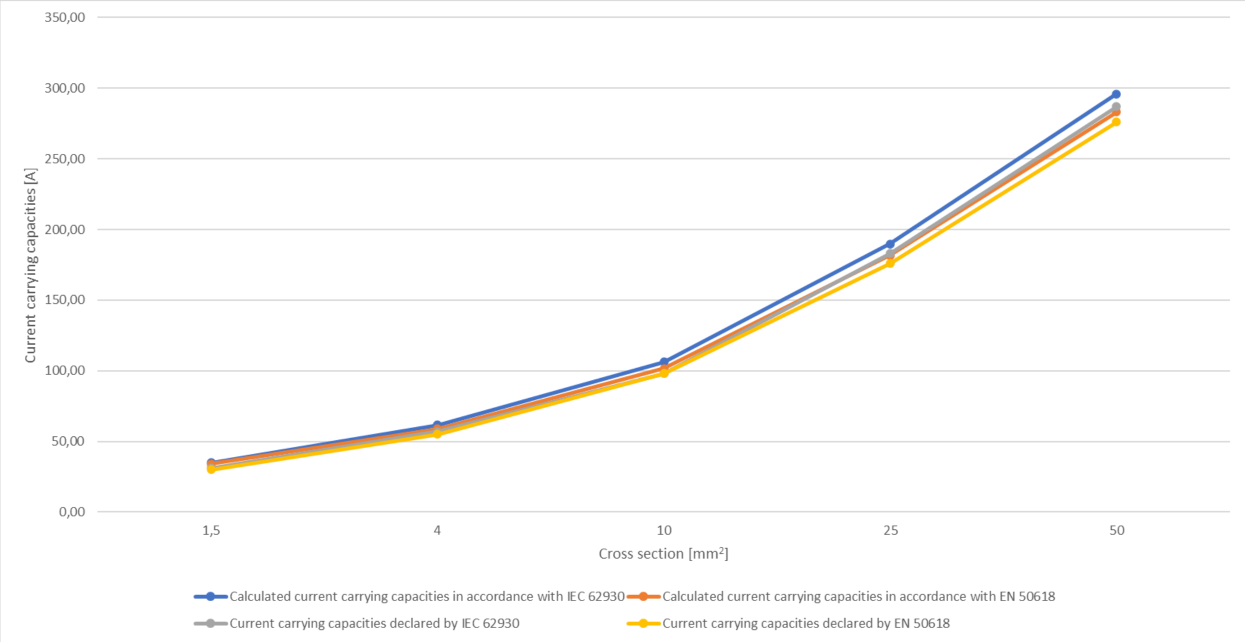


FIGURE 3 – COMPARISON BETWEEN THE CURRENT CARRYING CAPACITIES CALCULATED AS DESCRIBED IN IEC 60287-1-1 AND THOSE GIVEN BY IEC 62930 AND EN 50618. ALL FIGURES ASSUME THE SAME TEMPERATURE RISE OF 60 K.

DISCUSSION

RESULTS OF THE COMPARISON

The above analysis reveals that the perceived inconsistency between the current carrying capacities given in IEC 62930 and those given in EN 50618 does not actually exist. However, each standard presents its calculations in a different way, which could be misleading at first, and make comparison less straightforward:

- The current carrying capacities listed in IEC 62930 correspond to a maximum conductor temperature of 90°C at an ambient temperature of 30°C;
- The current carrying capacities listed in EN 50618 Table A.3, correspond to a maximum conductor temperature of 120°C at an ambient temperature of 60°C.

A meaningful comparison of current carrying capacities can only be made if the same temperature rise is considered, which is the case in our comparison.

Note that:

- A maximum conductor temperature of 120°C is higher than the allowed maximum conductor temperature for continuous operation, defined in both standards as 90°C.
- Both standards allow cables to be operated at a maximum conductor temperature of 120°C for a limited time of 20,000 hours over the lifetime of the cable.
- Ambient temperatures, and consequently also conductor temperatures, are subject to significant daily and seasonal variations. Consequently, the maximum temperature will be reached for a limited time only. Over a 25-year period, 20,000 hours corresponds, for example, to 5 hours a day for 5 months per year.

LIFE EXPECTANCY

The difference between conductor temperature and ambient temperature influences the heat exchange mechanism, but the major influencing parameter for life expectancy is conductor temperature. The life expectancy of a cable at normal operating conditions, allowing for a maximum conductor temperature of 90°C and with the current carrying capacities listed in IEC 62930, is 25 years. For every time a higher conductor temperature is reached, the lifetime of the cable will slightly diminish.

According to the Arrhenius law, cable lifetime is halved for every +10°C increase in conductor temperature — assuming continuous operation at this temperature. This means that the life expectancy of a cable operated continuously at 120°C will be just 3.12 years or 27,375 hours.

AMBIENT TEMPERATURE

The ambient temperature of the cable must be estimated carefully. Indeed, keeping the difference between the conductor temperature and the ambient temperature constant, a higher ambient temperature will result in a higher conductor temperature, and consequently a reduction in cable lifetime. Correction factors for the current carrying capacity can be used if the ambient temperature is estimated to be higher than the one given in the standard.

If the cable ambient temperature is unknown, and a given service life is to be guaranteed, oversizing the conductor cross section may be advisable.

There is more on ambient temperature in the European Copper Institute whitepaper "PV string cable temperature correction — How to obtain the ambient temperature?".

CONCLUSIONS

From the above analysis, it can be concluded that:

- cable current carrying capacities can only be usefully compared when the same temperature rise is considered;
- cable current carrying capacities given in both product standards (IEC 62930 and EN 50618) are consistent with those obtained when applying the general calculation method defined in IEC 60287-1-1;
- cable current carrying capacities given in both product standards (IEC 62930 and EN 50618) are essentially identical if the same temperature rise is considered (60 K).