WHITE PAPER
ECONOMIC CONDUCTOR SIZE OPTIMISATION IN BUILDINGS

Bruno De Wachter for ECI

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Author(s):	Bruno De Wachter
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EXECUTIVE SUMMARY

Increasing the conductor cross section of a cable reduces the energy losses. The most economic cable cross section is where the investment cost is equal to the lifetime cost of the energy losses. The basic principle of economic cable sizing is straightforward, and yet application of this principle is far from common practice.

Cable sizing is subject to regulation through national building codes, but these only take safety and aspects of functionality into account, not energy efficiency. The most economic cable cross section is often more than double the mandatory minimum.

Particularly in non-residential buildings, there is substantial potential for energy savings from upsizing cables to their economic optimum. In the context of the far-reaching decarbonisation ambition set out in the EU Green Deal, it is a regulatory opportunity that must be considered. Even more so since it comes at no cost, creates local jobs and is economically advantageous for society as a whole.

A SAVINGS OPPORTUNITY OF 30 TWH/YEAR

Approximately 8% of electrical energy generated in the EU gets lost in the network between generation and end-use, while 1.5% can be traced back to cable losses in non-residential buildings representing about 50 TWh per year (see Annex 1). By applying the principle of economic cable sizing, 60% of this, or 30 TWh/year, could be saved [2].

The opportunity to make this saving was identified in the Ecodesign Working Plan 2012-2014 and further analysed in the corresponding Preparatory Study (2013-2015) [1]. Such a savings potential is in the same order of magnitude as that of many products already subject to Ecodesign regulations. For many reasons, however, it was decided that Ecodesign was not an adequate regulatory tool to deal with the issue. As a result, the opportunity is still untapped.

This is even more regrettable given the long lifetime of electrical installations in buildings, as a result of which the inability to realise this energy savings potential will be locked-in for a long time where sub-optimal cables continue to be installed.

CALCULATING THE ECONOMIC CROSS SECTION

The international standard IEC 60287-3-2 provides a methodology for calculating the most economic cable size. It enters into a lot of detail and requires a reasonably accurate prediction of what is called the *loss load factor*, which may not always be immediately available (see chapter 'Calculating the optimised power cable size'). The standard gives no advice on how to estimate the loss load factor. Rigorously following this standard, consequently, makes calculations highly complex.

This white paper proposes a simplified formula, derived from IEC 60287-3-2, but abstracts some minor factors. For the loss load factor, the formula makes use of the typical values per sector and per type of circuit provided by the Ecodesign Economic Cable Sizing Preparatory Study. We also present two additional calculation methods for making a more precise and case-specific estimation of the loss load factor.

MAKING BUILDINGS FUTURE PROOF

Since power cables are installed to be operational for a long time, it is wise to think ahead and actively predict evolutions that might have an impact on the electrical installation. This exercise will be different for each sector. EV charging stations, PV rooftop installations, and the electrification of heating systems are among the factors to take into account in making buildings and their electrical installations *future proof*, even if it is not yet part of current building plans.

INTRODUCTION TO ECONOMIC CABLE SIZING

BASIC PRINCIPLES

Every electricity cable has a certain electrical resistance. Even though the conductor is made from highly conductive materials, such as copper, some part of the electrical energy will always be lost, dissipated as heat. Because these heat losses are distributed along the whole length of the cable, they mostly go unnoticed but, over the entire cable length and lifetime (typically 25 years), they can be significant.

This electrical resistance and the resulting energy losses are inversely proportional to the cross-sectional area of the conductor. Consequently, **increasing the cross section reduces energy losses.**

More precisely, the power losses in a single phase cable at a given moment can be calculated by:

$$P_{loss} = I^2 \times (\rho/S) \times l$$

Where:

I = current in the conductor (depending on the load)

ρ = specific electrical resistance of the conductor

S = cross section of the conductor

l = length of the cable

The lifetime energy losses E_l can be calculated by multiplying this figure by the total operational lifetime of the cable.

Of course, the conductor cross section cannot be increased endlessly. In contrast to the energy losses, the cable investment cost increases close to linear with its cross section. As a result, **the most economic cable cross section is that for which the investment cost is equal to the total lifetime cost of energy losses**, as illustrated in the following graph:

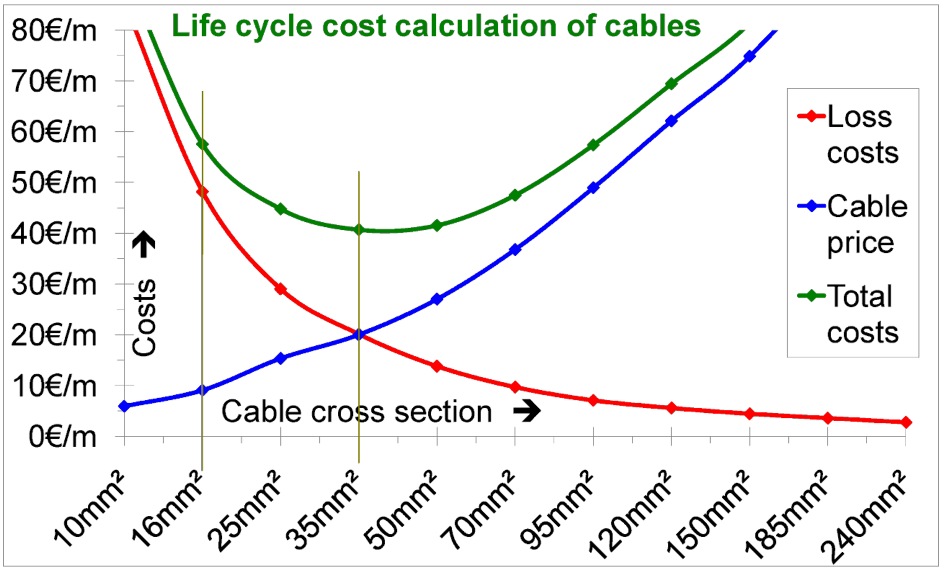

FIGURE 1 – THE CABLE COST, THE LIFE CYCLE COST OF THE ENERGY LOSSES, AND THE TOTAL LIFECYCLE COST OF A CABLE

WHY IT IS NOT COMMON PRACTICE

The basic principle of economic cable sizing is straightforward, and yet application of this principle is far from common practice. This is in spite of the obvious potential financial gain for every stakeholder – installers, cable operators and the economy as a whole.

The national building codes of EU Member States do, however, prescribe minimum conductor cross sections for a given cable load. These regulations have two basic aims:

a) **Safety**: limiting the maximum temperature rise, for reasons of fire safety and durability of the cable insulation; and
b) **Functionality**: limiting the voltage drop over the length of the cable.

National legislation does not include energy efficiency as a criterion. These mandatory cable sizing prescriptions have given rise to the general misconception that following them precisely is best practice. The notion that the regulations are only *bare minimum* requirements is often disregarded. As a result, economic cable sizing is not usually even on the installation design or energy management agendas.

In addition to this, investment in larger cable cross sections has to be made upfront and can immediately be put into figures, while savings from improved energy efficiency come only later. Calculations have to be based on estimations of future conditions, and may often be to someone else's benefit (the problem of split budgets). As a result, electrical installers and contractors have a challenging job convincing their clients of the benefits of economic cable sizing.

A SIGNIFICANT REGULATORY OPPORTUNITY

The ambition set out in the EU Green Deal in December 2019 requires all technically and economically feasible decarbonisation measures to be rolled out rigorously. Maximising the energy efficiency of electricity end use is a key element in achieving this ambition since it brings decarbonisation with a negative cost in the short term, and mitigates the need for carbon neutral generation capacity in the longer term.

An Ecodesign Preparatory Study [1] identified a substantial net energy savings potential for economic cable sizing in non-residential buildings. This could amount to as much as 30 TWh per year, making it a major opportunity comparable to the savings achieved by other energy efficiency regulatory measures.

FOCUSING ON NON-RESIDENTIAL BUILDINGS

Approximately 8% of the electrical energy generated in the EU gets lost in the network between generation and end-use. Of this 8%, around 6% represents losses in the transmission and distribution network and 2% is behind-the-meter. Of the latter, 1.5% can be attributed to non-residential buildings – around 50 TWh per year – and the remaining 0.5% to residential buildings (see Annex 1 for the origin of these figures).

In the transmission and distribution sector, cable losses are substantial due to long distances and high loading, but cables are core business, so the topic is already on the agenda (e.g. in Energy Efficiency Directive art 15.2). In the residential sector, the total losses attributed to cables is limited, as is the potential economic gain.

In non-residential buildings, however, the energy losses are substantial AND they go largely unnoticed. Choosing cable cross sections according to the lowest life cycle cost would reduce those losses by 60%. A straightforward energy savings opportunity is there for the taking, with both financial and environmental gains for every stakeholder.

ARGUMENTS FOR REGULATION

MARKET FAILURES

The Ecodesign Economic Cable Sizing Preparatory Study observed the following market failures [1, p.124], which explain why sub-optimal cables are still widely seen despite the associated economic losses:

- Electro-installers are unaware of circuit losses;
- Cable loss calculations are not conducted when designing installation;
- Life cycle costing (LCC) evaluations are not carried out because budgets for investment are split from operating expenses;
- Life cycle costing calculations are not requested in tenders.

In addition, cable efficiency is almost invariably overlooked during energy audits in buildings and industry.

THEORETICAL ENERGY SAVINGS POTENTIAL

Cable sizing according to the lowest LCC would reduce total behind-the-meter cable losses from 2.04% to 0.75% on average, corresponding to a 63% reduction [2, p.28]. Using this figure, and taking account of current electricity end use and emission intensity in the EU, the theoretical annual savings potential in non-residential buildings amounts to **32 TWh/a**, corresponding to **9.5 million tonnes CO_{2eq} /a** [3].

ENERGY SAVING POTENTIAL ACCORDING TO THE ECODESIGN PREPARATORY STUDY SCENARIO II[1]

The Ecodesign Preparatory Study [1] evaluated a scenario which comes close to the economic optimum. In this scenario, all cable cross sections in non-residential buildings must be increased by two standard sizes, except for lighting and socket circuits and distribution circuits. The energy use and GHG emissions associated with the manufacture of the additional cable material was deducted from savings made during operational lifetime. This revealed the following **net savings potential**, with savings rising gradually over the years, proportional to the renovation rate and the increasing electricity end use:

- Annual energy savings by 2025: **7.60 TWh/a**
- Annual energy savings by 2050: **28.01 TWh/a**
- Cumulative net GHG emission savings by 2050: **159 million tonnes CO_{2eq}**

ECONOMIC RATIONALE

Scenario II of the Ecodesign Preparatory Study would lead to the following economic advantages compared to business as usual, calculated for the entire EU-28:

- Annual savings in electricity costs of €483 million by 2025 ([1] Table 7-44)
- Annual savings in electricity costs of €3,727 million by 2050 ([1] Table 7-44)
- **Reduction in the total cost of ownership of the cables of €5,688 million** by 2050 ([1] table 7-24)

The payback time of upgrading *dedicated circuits* by two standard sizes (as in Scenario II) would be 2.5 years in both the service and industry sectors ([1] Table 6-27, BC4 and BC8, D2). The payback time of upgrading *distribution circuits* by one standard size (as in Scenario III) would be 7.6 years in the service sector and 12 years in the industry sector ([1] Table 6-27, BC1 and BC5, D1). These figures are still far below the typical cable lifetime of 25 years [1, p.87], and would result in reduced total cost of ownership of the cables.

An additional economic advantage would be local job creation. The Ecodesign Preparatory Study assessed that economic cable sizing in non-residential buildings is expected to create jobs for electrical installers, cable manufacturers and distributors. The most significant job creation is expected to be in manual labour at electrical contractors — jobs that will always be local. [1, p.339]

RISK OF INEFFICIENT INSTALLATIONS BEING LOCKED IN

Electrical installations in non-residential buildings typically have a lifetime of 25 years [1, p.87]. Consequently, the energy savings potential will be out of reach for a long time if sub-optimal cables continue to be installed. In addition, due to the progressive electrification of energy end use as a part of the energy transition, the increase in electricity consumption is expected to lead to an increase of the energy losses from around 50 TWh/a currently to 82 TWh/a in 2050 if no action is taken [1, base case, p.334].

[1] Even closer to the economic optimum for cables in non-residential buildings would be a hybrid of Scenarios II and III of the Ecodesign Preparatory Study. In this hybrid scenario, there would be no prescribed upgrades to lighting and socket circuits, an upgrade of one standard size for the distribution circuit, and an upgrade of two standard sizes for all other circuits ("dedicated circuits") in both service and industry sectors. However, the study did not calculate the general energy, environmental and economic advantages of such a hybrid scenario. We therefore present the advantages calculated for Scenario II.

ADDITIONAL FUNCTIONAL ADVANTAGES

- **Improved power quality:** The reduction in current density, short circuit impedance and voltage drop in cables resulting from greater cross sections will have a mitigating influence on various types of power quality problems. This will result in an additional positive economic impact.

- **Improved fire safety:** Greater cross sections result in reduced heat generation and lower surface temperatures, improving fire safety, in particular during overload and short circuit conditions.

- **Higher overload capacity:** With greater conductor cross sections, cables can operate under temporary overloads without introducing a safety risk. This can be important when the electricity use of a circuit increases over the years, for example when additional appliances are introduced.

CURRENT STANDARDS OVERVIEW

There are five international standards stipulating cable cross-sectional areas (CSAs):

- **IEC 60228 – Conductors of insulated cables**: Directed at cable manufacturers. Defines how the cable CSAs should increase stepwise.

- **IEC 60364-5-52 – Selection and erection of electrical equipment – Wiring Systems**: Directed at electrical contractors and installers. Prescribes nominal CSAs for indoor LV power cables based on safety and functionality requirements. This standard is made mandatory through its adoption into national building codes. Since conformity with these codes is checked during safety inspections, they have a very high rate of adoption. This created a general misconception that following this standard is best practice, thus excluding energy loss considerations.

- **IEC 60287-3-2 – Economic optimization of power cable size**: Describes how to determine the economic CSA. The standard is very detailed and requires a reasonably accurate prediction of the loss load factor (see below), which may not always be immediately available. It claims to be a standard for all cables, but all the examples in the annexes concern utility cables. These have a less erratic load profile, making it easier to estimate the loss load factor. This is not the case for cables behind the meter. The standard's adoption rate in buildings is therefore expected to be very low.

- **IEC 62125-7 – Environmental considerations specific to electrical power and control cables – Environmental and energy cost based conductor size optimization**: Develops similar calculations as IEC 60287-3-2, but brings the cost of CO_{2eq} emissions into the equation. The calculations are based on the LCA methodology.

- **IEC 60364-8-1 – Energy efficiency of low-voltage electrical installations**: Goes much more widely and much further than just cable sizing. For cable sizing itself, it refers to standard IEC 60287-3-2, but adds a few additional considerations on the power factor and harmonic currents.

The following subchapters cover these five standards in more detail.

IEC 60228: CONDUCTORS OF INSULATED WIRES

This standard defines how the cable cross-sectional areas (CSAs) should increase stepwise according to the following values:

TABLE 1 – INTERNATIONAL STANDARD WIRE SIZES

International standard wire sizes according to IEC 60228					
0.5 mm²	0.75 mm²	1 mm²	1.5 mm²	2.5 mm²	4 mm²
6 mm²	10 mm²	16 mm²	25 mm²	35 mm²	50 mm²
70 mm²	95 mm²	120 mm²	150 mm²	185 mm²	240 mm²
300 mm²	400 mm²	500 mm²	630 mm²	800 mm²	1000 mm²
1200 mm²	1400 mm²	1600 mm²	1800 mm²	2000 mm²	2500 mm²

IEC 60364-5-52: Selection and erection of electrical systems – Wiring systems

This standard prescribes the nominal cross-sectional areas (CSAs) for indoor LV power cables based on safety requirements such as conductor temperature, short-circuit current, and earth fault current. It also describes the maximum voltage drop and how the CSA should be adapted to avoid crossing this threshold, which is important for reasons of end-use appliance functionality.

IEC 60287-3-2: Economic optimisation of power cable size

This standard defines a calculation method for economic power cable conductor sizing. It takes the initial investment cost and the anticipated cost of energy losses during the lifetime of the cable into account. It can be used for both AC and DC cables, and for all voltages.

The calculation is made for a given selection of system voltage, cable route, cable configuration and sheath bonding arrangement, abstracting maintenance costs, forced cooling costs, and time of the day energy costs.

The standard proposes two possible calculation methods:

1. Calculating the economic current range for each conductor size for given installation conditions. The upper economic current limit of one conductor size is the lower economic current limit for the next larger conductor size.

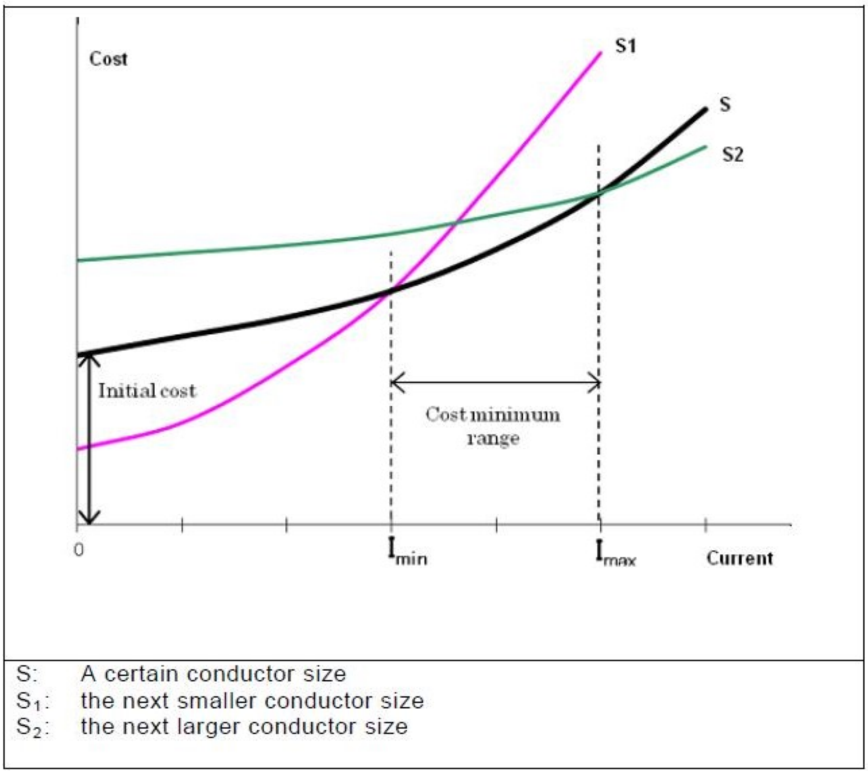

FIGURE 2 – OPTIMAL CURRENT RANGE FOR MINIMUM CABLE LIFE CYCLE COST

2. Calculating the economic conductor size for a given load (and thus current) – see Figure 1. This is unlikely to be equal to a standard size, and so the costs for the adjacent larger and smaller standard sizes are calculated, before the most economic cross-section is chosen.

Note that the costs of the actual energy losses **and** the required additional supply capacity are both considered (losses in the cable must be added to the peak power consumption of the installation).

The standard also proposes a calculation method for the charging current and the dielectric losses (= voltage-dependent losses). These losses go up as the conductor cross section increases, since greater cross section means greater cable capacitance. They consequently have an effect contrary to that of the current-dependent losses. The standard observes that these losses are only relevant to high-voltage cables.

The standard further concludes that:

- Expected LCC savings are around 50%;
- Impact of errors on financial data is minor;
- Cables with an economically optimised size usually fulfil other selection criteria, such as conductor temperature, short-circuit current, earth fault currents or voltage drop, but this should still be verified;
- "Economic cable sizing is only a part of the total economic considerations of a system and may give way to other important economic factors." This makes the standard entirely voluntary: each user can decide whether economic cable sizing is important to them;
- Environmental cable sizing "may justify a larger conductor size than that determined by economic factors alone".

A few important considerations

The standard describes how the economic cable size can be calculated with high precision. The calculations will be different for each building, and for each type of circuit within that building. It requires much input data that are not always immediately available. The major difficulty for which no solution is proposed, is the estimation of the loss load factor (load factor x load form factor). We propose some options later in the chapter 'Calculating optimal cable size'.

The standard also assumes that it is known how the load, load profile and electricity costs will evolve over cable lifetime (typically 25 years). This is disregarded in our calculation method to avoid over-complexity.

The formulae in the standard (see Annex 2) gather a few variables together into the variable F, including the loss load factor and its variation over the years, the load variation over the years, the energy cost and its variation over the years, and the discount rate. Furthermore, N_P (= the number of phases) and N_C (= the number of circuits with the same load and loss load factor) are also incorporated into F. This is curious, because these are known values and this decision precludes the possibility of creating tables with average values for F per sector and type of circuit.

IEC 62125: Environmental considerations specific to electrical power and control cables

Chapter 7 – Environmental and energy cost based Conductor Size Optimization

This chapter develops similar calculations as in IEC 60287-3-2, but brings the cost of CO_{2eq} emissions into the equation. It takes the following costs into account:

- investment cost of the cable;
- scrap value of the cable;
- cost of CO_2 emissions during manufacturing, transportation, installation and final disposal;
- cost of the Joule losses;
- cost of the CO_2 emissions related to the Joule losses.

The calculations are based on the LCA methodology which takes the emission intensity of electricity generation as an input value (kg CO_{2eq} emissions/kWh).

A few important considerations

- Contrary to IEC 60287-3-2, this standard recommends taking the scrap value of the material at end of life into account, and deduct it from the initial purchasing cost;
- An important value in the calculation is the CO_{2eq} emission cost M, to be adjusted to the national situation;
- The standard includes formulae to express the total energy and CO_{2eq} savings in the use phase compared to conventional cable sizing;
- The standard stresses that “this method is not an environmental impact evaluation, it may be used in addition to the checklist or LCA approach”, among other reasons because “the cost of CO_{2eq} emissions might not adequately reflect the environmental effect of those emissions”;
- For highly loaded cables, CO_{2eq} emissions at the use phase are overwhelmingly dominant. From experience in Japan, they typically amount to 97% of the life cycle CO_{2eq} emissions.

IEC 60364-8-1: Energy efficiency of low voltage electrical installations

This standard goes much wider and further than cable sizing. For cable sizing itself, it refers to standards IEC 60364-5-52 and IEC 60287-3-2, though it adds two points of attention:

- Consideration shall be given to power factor improvement;
- Harmonic currents should either be reduced through the installation of harmonic filters, or their effect should be reduced by increasing the CSA of conductors. A third option is to use installation methods and equipment that produce less harmonics.

The following elements in the standard are not strictly about cable sizing, but describe methods that allow power cables to contribute to the energy efficiency of the electrical installation:

- The Barycenter method: to install the transformer and switchboard at a location based on a relative weighting of the energy consumption of the loads, so that the distance to a load of high energy consumption is less than the one to a load of low energy consumption. This method improves the energy performance of the installation and also reduces the installation cost by reducing the cable lengths.

- Criteria for the design of the meshes in the electrical installation. Apart from technical criteria based on external parameters or control functions, the following criteria should also be taken into account:
    - Group loads in a mesh that require a common energy consumption measurement;
    - Group loads in a mesh with a similar time of utilisation so that they can be put on and off together (if there is a price variability for electricity consumption according to the time of the day);
    - Group loads in a mesh with a high energy inertia; they can more easily participate in load shedding.

Calculating optimal power cable size

Non-residential buildings

The load and loss load factor in industry and tertiary sector buildings is generally medium to high. As a result, when cable cross sections are sized according to their minimum life cycle cost, they will in most cases also fulfil the other requirements (e.g. temperature and voltage drop).

Standard IEC 60287-3-2 provides a calculation methodology for economic cable sizing, but rigorously following this standard makes calculations highly complex. The standard also fails to explain how to come to the loss load factor µ, which is the product of the load factor and the load form factor.

We propose a formula derived from formula 13 on p.13 of IEC 60287-3-2, but abstracting the following factors to avoid the procedure becoming over-complex:

- Grid connection capacity cost D. We take only the energy cost of the losses into account, not the minor cost of the increase in required grid connection capacity caused by the losses. So, D = 0.
- The evolution over time of the load, the load factor and the cost of electricity. We assume these variables are constant over the operational lifetime of the cable. Therefore, Q = N.
- The charging current and dielectric losses, because they are only relevant for high voltage cables.

This results in the following approach:

To minimize the LCC of all cables, the maximum current allowed in a cable with cross section S should be given by:

$$I_{\max S}\,[kA] = K_S\ x\ \sqrt{\frac{(C_{S+1} - C_S)\ (1+i)}{N_p\ x\ T\ x\ N}}$$

Where:

- C_S = cost of a cable with cross section S (€/m)
- C_{S+1} = cost of a cable with a cross section of one standard size up (S+1)
- N_P = number of phases in the circuit
- T = electricity tariff (€/kWh)
- N = estimated operational lifetime (in years) – 25 years would be a good guess if this is not known
- i = discount rate (value between 0 and 1). In 2015, the weighted average discount rate in the private sector in the EU was 0.057 (or 5.7%) [4]

And

$$K_S[\sqrt{km/\Omega}] = \sqrt{\frac{1}{\mu\ x\ 8760\ x\ (R_S - R_{S+1})}}$$

Where:

- µ = loss load factor
- R_S = resistance of a cable with cross section S in (Ω/km)

If the rated current of the circuit exceeds this value, the cable CSA should go one standard size up (S+1).

The resistance values for a copper conductor with a given standard cross section are as follows:

TABLE 2 – CONDUCTOR ELECTRICAL RESISTANCES FOR STANDARD CROSS-SECTIONAL AREAS

Conductor cross-sectional area (mm^2)	Conductor resistance for PVC and XLPE cable in milliohm per metre (mΩ/m)			
	PVC cable at max. conductor operating temperature of 70°C		XLPE cable at max. conductor operating temperature of 90°C	
	Enclosed in conduit/trunking	Clipped direct or on tray, touching	Enclosed in conduit/trunking	Clipped direct or on tray, touching
1.5	14.5	14.5	15.5	15.5
2.5	9	9	9.5	9.5
4	5.5	5.5	6	6
6	3.65	3.65	3.95	3.95
10	2.2	2.2	2.35	2.35
16	1.4	1.4	1.45	1.45
25	0.9	0.875	0.925	0.925
35	0.65	0.625	0.675	0.675
50	0.475	0.465	0.5	0.495
70	0.325	0.315	0.35	0.34
95	0.245	0.235	0.255	0.245
120	0.195	0.185	0.205	0.195
150	0.155	0.15	0.165	0.16
185	0.125	0.12	0.135	0.13
240	0.0975	0.0925	0.105	0.1
300	0.08	0.075	0.0875	0.08
400	0.065	0.06	0.07	0.065
500	0.055	0.049	0.06	0.0525
630	0.047	0.0405	0.05	0.043
800	-	0.034	-	0.036
1000	-	0.0295	-	0.0315

The loss load factor is the most complicated element in the calculation. It can never be an exact value, as it depends on the future load pattern of the cable. In addition, an estimation of the average future loading of the cable in a *load factor* α_c will not be sufficient, as the losses increase with the square of the current. For the calculation to be precise, the root mean square (RMS) of the current should be calculated. Put simply, the current values at 15-minute intervals (so, 35,040 per year) must be squared, the squares added together and the root derived from the total. As a result, not only the average value of the loading has an influence, but also the form of the load pattern. This effect can be summarised in a second correction factor, called the *load form factor* K_f. The *loss load factor* is then the product of the *load factor* and the *load form factor*.

Loss load factor = load factor(α_c*) x load form factor (*K_f*)*

In the Ecodesign Economic Cable Sizing Preparatory Study published by VITO [1], typical loss load factors per sector and per type of circuit were calculated. For each case, three values were calculated, corresponding to low loading, medium loading and high loading. The result is summarised in the table below:

TABLE 3 – LOSS LOAD FACTORS PER SECTOR AND TYPE OF CIRCUIT (FOR LOW, MEDIUM AND HIGH LOADING)

		Lighting circuit			Socket-outlet circuit			Dedicated circuit			Distribution circuit		
		Low	Ref	High	Low	Ref	High	Low	Ref	High	Low	Ref	High
Residential sector	Kf	3.12	2.11	1.67	4.38	1.74	1.34	4.61	3.99	3.12	1.24	1.14	1.08
	αc	0.01	0.05	0.10	0.00	0.04	0.10	0.01	0.02	0.05	0.01	0.06	0.22
	Kf . αc	0.03	0.11	0.17	0.01	0.06	0.13	0.02	0.08	0.14	0.02	0.07	0.23
Services sector	Kf	1.50	1.27	1.16	1.50	1.27	1.16	1.37	1.21	1.13	1.37	1.21	1.13
	αc	0.07	0.24	0.41	0.04	0.15	0.24	0.14	0.41	0.54	0.14	0.41	0.54
	Kf . αc	0.11	0.31	0.48	0.06	0.19	0.27	0.20	0.49	0.61	0.20	0.49	0.61
Industry sector	Kf	1.11	1.06	1.03	1.11	1.06	1.03	1.03	1.01	1.00	1.05	1.02	1.01
	αc	0.12	0.34	0.54	0.06	0.27	0.46	0.23	0.61	0.76	0.22	0.57	0.72
	Kf . αc	0.13	0.36	0.55	0.06	0.29	0.47	0.24	0.61	0.76	0.23	0.58	0.72
αc correction factor		0.5	1	1	0.5	1	1	0.5	1	1	0.5	1	1

These values can be used in the formula above to determine the most economic cross section.

Estimating the loss load factor with greater precision – Method 1

The Ecodesign Economic Cable Sizing Preparatory Study [1] used an approximate method to determine the *load factor α_c*. It is calculated by splitting the operating time into two periods: period 1 with a high load P1 (e.g. during daytime) and period 2 with a low load P2 (e.g. at night). It is defined as:

$$\alpha_c = \frac{(period\ 1 + (P2/P1)\ x\ period\ 2)}{period\ 1 + period\ 2}\ x\ use\ factor$$

Where the *use factor* = the ratio of the design load (expected load at moments of maximum use) and the rated maximum load of the circuit (defined by the fuse or circuit breaker). These values can often be estimated, providing a way to obtain the load factor specific to the case under investigation.

This is more difficult for the load form factor, which is defined as the RMS value of the load divided by the average load: $K_f = P_{rms} / P_{avg}$. If historical data are available, with values every 15 minutes for an entire year, for the circuit under consideration or similar circuit, the RMS value of the load can be calculated. If not, the procedure will have to rely on tables of typical load form factors such as the one above.

Estimating the loss load factor with greater precision – Method 2

A similar, but slightly different, method to the one above was developed by Stefan Fassbinder in the ECI Application Note: *Energy Efficiency of Low Voltage Building Wire* from 2017 [5]. It uses the following formula for the loss load factor:

$$I_{load\ loss} = \sqrt{\frac{I_{min} x I_{\max\ rated}}{F_P}}\ x\ F_F$$

Where:

- I_{min} = the value obtained by dividing the expected annual energy consumption of the installation by 8760 h/a and spread evenly over all circuits according to their current-carrying capacity
- $I_{max\ rated}$ = maximum rated current in the circuit, defined by the fuse or circuit breaker
- F_P = peak factor = $I_{Z\_mean} / I_{max\ rated}$
- F_F = form factor

Estimating the economic cable cross section with no additional calculations

The Ecodesign Economic Cable Sizing Preparatory Study [1] proposes four scenarios for upsizing non-residential building cables without the need to make any calculations additional to those required to comply with the existing building codes. Scenarios II and III come close to the economic optimum. Integrating these two scenarios leads to the following recommendations:

- No upsizing of cables for lighting and socket circuits
- One standard size up for feeder cables (S+1)
- Two standard sizes up for all other circuits (S+2)

Verifying the other criteria

In addition to economic cable sizing, the following criteria should still be verified according to IEC 60364-5-52:

- Maximum temperature
- Earth fault current and short circuit current
- Voltage drop

In some cases, voltage drop might be the decisive factor and require a cross section greater than the economic optimum.

Taking harmonic currents into account

Harmonic currents should be taken into account in the cable sizing calculations where relevant, as stipulated in IEC 60643-8-1.

RESIDENTIAL BUILDINGS

In residential buildings, loss load factors are low, and the energy losses will not, in most cases, be the decisive factor in sizing cable cross sections. Limiting the voltage drop is what mostly determines the minimum cross section in residential buildings. If the voltage drop standards are rigorously followed, safety and life cycle costing requirements will be fulfilled in almost every case. The maximum voltage drop values are summarised in Table G52.1 of standard IEC 60364-5-52:

TABLE 4 – MAXIMUM VOLTAGE DROP ACCORDING TO IEC 60364-5-52

C	Lighting circuits	Other uses
Low voltage installations supplied directly from a public low voltage distribution system	3%	5%
Low voltage installation supplied from private LV supply	6%	8%

When the cable is longer than 100 m (e.g. a feeder cable), the permitted voltage drop limits can be increased by 0.005% per metre above 100 m, with a maximum addition of 0.5% in total. In the special case of a circuit feeding a motor (e.g. a heat pump compressor system), the voltage drop in starting conditions should not exceed 15% [6].

FUTURE-PROOF BUILDINGS

PLANNING 25 YEARS AHEAD

Power cables are installed to be operational for a long time, typically 25 years. It is therefore wise to think ahead and actively predict evolutions that could have an influence on the electrical system. This exercise will be different for each sector. The following are general considerations to be taken into account in making a building *future-proof*.

HOW WILL THE LOAD EVOLVE?

The cable sizing formula in IEC 60287-3-2 includes an estimation of the increase in load and loss load factor over the service time of the cable. We proposed to leave this factor out of the calculation for reasons of simplicity, but that does not mean that it should not be considered.

To create a real future-proof building, smart estimations about the evolution of the electrical load patterns are required. Efforts to reduce energy consumption could reduce the load, but many emerging applications work on electricity, which will lead to an increase in the load. A rise in the ambient temperature caused by climate change will increase the need for forced cooling and, in turn, the load on the associated electrical circuits.

EV CHARGING STATIONS

The electric vehicle (EV) is here to stay. The number of EVs has increased steeply in recent years and this evolution is expected to continue in the years ahead, particularly following the EU commitment to decarbonise the economy. The increasing number of EVs leads to the urgent need for EV charging points, and non-residential buildings can play an important role in providing them. In principle, EVs can be charged from a conventional socket, but this is very slow and involves the risk of the installation overheating, which could ultimately cause a fire. Dedicated EV charging points are specifically designed to achieve optimum charging in the shortest possible time and with adequate safety. Future-proof non-residential building projects should include them in their design.

For more details on this subject, see Application Note *Multiple EV Charging Stations* [7].

PV ON THE ROOF

The past ten years have seen exponential growth in PV rooftop installations in Europe, and this trend is predicted to continue for years to come, especially on the rooftops of non-residential buildings.

PV installations require a dedicated approach to cable sizing. For example, DC cables connecting PV panels with junction boxes and inverters often experience unusual thermal conditions. Rooftops have a high solar exposure, resulting in a higher ambient temperature than the average temperature of the surroundings. A black rooftop surface and a lack of ventilation beneath the PV panels can further contribute to increasing the ambient temperature on hot summer days. This should be taken into account when determining the cables' conductor cross sections .

For more details on this subject, see Application Note *Determining the Conductor Cross Section of DC Cables in PV Installations* [upcoming].

CASE STUDIES

CASE STUDY 1 - INDUSTRY

A secondary substation in a major industrial plant in Japan serves 126 kW of equipment: a blower, a pump and four air conditioners [11].

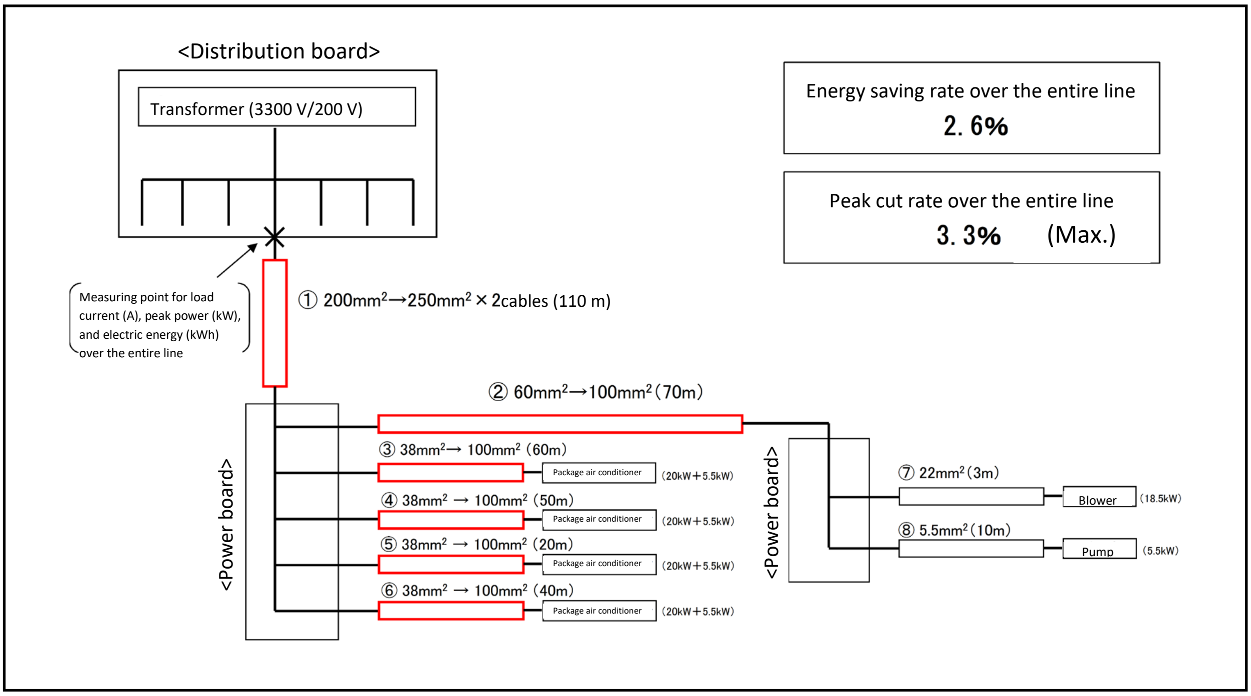

FIGURE 3 – ELECTRICAL SCHEME OF A SUBSTATION AND ITS CIRCUITS IN A MAJOR INDUSTRIAL PLANT IN JAPAN

For six cables, the economic cable size is calculated:

- **Cable 1:** 110-m cable from distribution board to power board, load loss factor 0.65
- **Cable 2:** 70-m cable feeding the blower and pump, loss load factor 0.8
- **Cables 3, 4, 5 and 6:** 60-m cables feeding the air conditioners, load loss factor 0.65

The plant is operated 300 days per year. The power factor is 0.8.

After calculating the most economic cable sizes, the following upgrades were put in place:

TABLE 5: CABLE CROSS SECTIONS BEFORE AND AFTER UPSIZING

	Old cable sizes	After cable upsizing to economic optimum
Cable 1	1 x 200 m^2	2 x 250 m^2
Cable 2	1 x 60 m^2	1 x 100 m^2
Cables 3 to 6	1 x 38 m^2	1 x 100 m^2

The energy savings after renovation were 2.6% of the end use consumption. The energy consumption peak was reduced by 3.3%.

Calculated using a discount rate of 4%, the base case had a NPV of 90,739,000 yen. Economic cable sizing reduced the NPV to 86,536,000 yen. This means an NPV reduction of 4,203,000 yen or -4.6%.

The investment had a payback time of 8.1 years.

See [11, p 25 – 27] for the detailed calculations.

CASE STUDY 2 – SMALL OFFICE LIGHTING CIRCUIT [2 AND 8]

A small office has a low voltage supply from the public distribution network and just one level of internal power distribution. The circuit under study supplies fluorescent lamps through a one phase 50-m XPLE cable. It has a maximum load current of 6.4 A and a power factor of 0.92. It should consequently have a current carrying capacity of 6.4 A / 0.92 = 6.96 A.

Assuming an electricity tariff of €0.194/kWh [2, p. 8]

In the base case, the circuit's cable has a conductor cross section of 2.5 mm^2, which falls within mandatory safety standards. We will now verify whether this also falls within the economic cable sizing standard IEC 60287-3-2.

We first calculate K_s

$$K_S[\sqrt{km/\Omega}] = \sqrt{\frac{1}{\mu\, x\; 8760\; x\; (R_S - R_{S+1})}}$$

In Table 3 we find that μ for a lighting circuit in the services sector is 0.31 on average.

Table 4 provides us with the conductor resistance values: $R_S - R_{S+1} = R_{2.5} - R_4 = 9.5\ \Omega/km - 6\ \Omega/km = 3.5\ \Omega/km$

So, $K_S = 0.0103\ \sqrt{km/\Omega}$

From this we can calculate $I_{max\ S}$:

$$I_{\max\ S}\ [kA] = K_S\ x\ \sqrt{\frac{(C_{S+1} - C_S)\ (1+i)}{N_p\ x\ T\ x\ N}}$$

Where: i = 0.057

$C_{S+1} - C_S$ = (€153.00 – €115.82)/50 m = €0.74/m [2, p.31 and 32]

$N_p = 1$

T = €0.194/kWh

N = 25 years

Which gives I_{max} = 4 .14 A

This is not sufficient for the required economic current carrying capacity of 6.96 A.

We make the same calculation for **one-size-up (S+1)**. The new values are:

$R_{S+1} - R_{S+2} = R_4 - R_6 = 6\ \Omega/km - 3.95\ \Omega/km = 2.05\ \Omega/km$ (Table 4)

$C_{S+2} - C_{S+1}$ = (€201.85 – €153.00)/50 m = €0.98/m [2, p. 32 and 33]

So K_{S+1} = 0.0134 $\sqrt{km/\Omega}$

Which gives I_{max} = 6.19 A

This value is still lower than the required 6.96 A, but only marginally so. Going **two sizes up** (S + 2 = 6 mm^2) will certainly suffice.

[2] calculated the ten-year total cost of ownership of this cable to be €1,439.44 for the base case [2, p.31] and €319.61 for the S+2 cable [2, p.33]. By choosing for the economic cable size for this cable, the company has gained €1,119.83 over the first ten years of the cable lifetime. It will continue to save money with every additional year it remains in service.

ANNEX 1: ESTIMATION OF LOSSES

Net electricity generation in the EU in 2017 was 3,100 TWh/a [9].

Total distribution and transmission loss in the EU in 2017 was 185 TWh/a [10, p. 158].

Energy losses from behind-the-meter networks are 2.04% [2, p.28] or 64 TWh/a.

Of these losses, roughly 20% (13 TWh/a) are residential and 80% (51 TWh/a) are non-residential [11, p. 28].

The latter figure corresponds with the figure of total cable losses in non-residential buildings given in the Ecodesign Preparatory Study [1, p. 343] (50 TWh/a).

ANNEX 2: FORMULAE IN THE IEC 60287-3-2 STANDARD

The following are the economic cable sizing formulae in standard IEC 60287-3-2:

Coefficient F

$$F\,[\frac{€}{W}] = N_p\ x\ N_c\ x\ (T\ x\ P + D)\ x\ \frac{Q}{(1 +\ i/100)}$$

Where:

- N_P = number of phase conductors per circuit
- N_C = number of circuits carrying the same type and value of load
- T = loss load factor, calculated back to operating time at maximum Joule losses [h/year]
- P = cost of one watt-hour at relevant voltage level [€/Wh]
- D = grid connection capacity demand charge each year [€/(W x year)]
- i = discount rate [%]

And

$$Q = \frac{1 - r^N}{1 - r}$$

Where:

- N = operational lifetime of the cable

And

$$r = \frac{(1 +\ a/100)^2\ x\ (1 +\ b/100)\ x\ (1 +\ c/100)}{(1 +\ i/100)}$$

Where:

- a = increase in load per year [%]
- b = increase in the cost of energy per year, not including the effect of inflation [%]
- c = increase in the loss load factor per year [%]

Then the total life cycle cost CT to be minimized is given by:

$$CT = CI + I_{max}^2 \, x \, R_L \, x \, L \, x \, F$$

Where:

- CI = installed cost of the cable [€]
- I_{max} = maximum rated current of the connection [A]
- R_L = ac resistance per unit of length [Ω/m]
- L = cable length [L]

The maximum current for a certain cross section in order to minimize the life cycle cost is given by:

$$I_{max} = \sqrt{\frac{CI_2 - CI}{F \, x \, L \, x \, (R_L - R_{L2})}}$$

Where:

- CI = installed cost of the cable [€]
- R_L = ac resistance per unit of length [Ω/m]
- CI_2 = installed cost of a cable of one standard size greater than the one under consideration [€]
- R_{L2} = ac resistance per unit of length of a cable one standard size greater than the one under consideration [Ω/m]
- L = cable length [L]

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