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EDITORA

METHODOLOGY FOR THE ECONOMIC SIZING OF LOW-VOLTAGE ELECTRICAL CONDUCTORS: AN INTEGRATED APPROACH TO COSTS, POWER FLOW, AND CO_2 EMISSIONS

METODOLOGIA PARA O DIMENSIONAMENTO ECONÔMICO DE CONDUTORES ELÉTRICOS DE BT: UMA ABORDAGEM INTEGRADA DE CUSTOS, FLUXO DE POTÊNCIA E EMISSÃO DE CO2

METODOLOGÍA PARA EL DIMENSIONAMIENTO ECONÓMICO DE CONDUCTORES ELÉCTRICOS DE BAJA TENSIÓN: UN ENFOQUE INTEGRADO DE COSTOS, FLUJO DE POTENCIA Y EMISIÓN DE CO_2

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ABSTRACT
This study presents a methodology for the economic sizing and techno-economic analysis of low-voltage feeder cables, integrating cost, power flow, and CO_2 emission assessments to support more efficient and sustainable conductor section selection. The proposed approach was validated through a case study analyzing the QGBT2 feeder circuit (46 kVA/220 V) installed at the School of Technology of the Amazonas State University (EST/UEA). The results indicated an economic cross-section of 226 mm², leading to the evaluation of two standardized options: 185 mm² and 240 mm². The 240 mm² cable achieved the lowest total cost (R$ 237,176.56) and an operational cost 60% lower than the 95 mm² cable currently in service, while dissipating 2.61 times less energy. Voltage drop was reduced from 2.5% to 0.97%. The economic feasibility analysis showed a payback period of 13 years and a net present value of R$ 12,995.80. The findings highlight the importance of technical and economic sizing in accordance with NBR 5410:2004 and NBR 15920:2011 standards, complemented by additional studies aimed at improving decision-making efficiency.

Keywords: Techno-Economic Analysis. Economic Conductor Sizing. Energy Efficiency. CO_2 Emission. Power Flow.

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RESUMO
Esse trabalho apresenta uma metodologia para o dimensionamento econômico e a análise técnico-econômica de cabos alimentadores de baixa tensão, integrando estudos de custo, fluxo de potência e emissões de CO_2 para apoiar decisões mais eficientes e sustentáveis na escolha da seção de condutores. A metodologia foi validada em um estudo de caso, no qual foi analisado o circuito alimentador do QGBT2 (46 kVA/220 V), instalado na Escola Superior de Tecnologia (EST/UEA). O resultado inicial indicou uma seção econômica de 226 mm², conduzindo à análise de duas seções padronizadas: 185 mm² e 240 mm². O cabo de 240 mm² apresentou o menor custo total (R$ 237.176,56) e um custo operacional 60 % inferior ao do cabo de 95 mm² (atualmente alimentador do QGBT2), além de dissipar 2,61 vezes menos energia. O desvio de tensão no cabo de 95 mm² foi de 2,5 % e de 0,97 % no cabo de 240 mm². A análise de viabilidade econômica indicou *payback* de 13 anos e valor presente líquido de R$ 12.995,80. Os resultados reforçam a importância do dimensionamento técnico e econômico, conforme as normas NBR 5410:2004 e NBR 15920:2011, bem como estudos complementares que contribuem para decisões mais assertivas.

Palavras-chave: Análise Técnico-Econômica. Dimensionamento Econômico de Condutor. Eficiência Energética. Emissão de CO_2. Fluxo de Potência.

RESUMEN
Este trabajo presenta una metodología para el dimensionamiento económico y el análisis técnico-económico de cables alimentadores de baja tensión, integrando estudios de costos, flujo de potencia y emisiones de CO_2, con el objetivo de apoyar decisiones más eficientes y sostenibles en la selección de la sección de los conductores. La metodología fue validada mediante un estudio de caso en el que se analizó el circuito alimentador del QGBT2 (46 kVA/220 V), instalado en la Escuela Superior de Tecnología (EST/UEA). El resultado inicial indicó una sección económica de 226 mm², lo que condujo al análisis de dos secciones normalizadas: 185 mm² y 240 mm². El cable de 240 mm² presentó el menor costo total (R$ 237.176,56) y un costo operativo un 60% inferior al del cable de 95 mm² (actual alimentador del QGBT2), además de disipar 2,61 veces menos energía. La caída de tensión en el cable de 95 mm² fue del 2,5%, mientras que en el cable de 240 mm² fue del 0,97%. El análisis de viabilidad económica indicó un período de recuperación de 13 años y un valor presente neto de R$ 12.995,80. Los resultados refuerzan la importancia del dimensionamiento técnico y económico conforme a las normas NBR 5410:2004 y NBR 15920:2011, así como de los estudios complementarios que contribuyen a decisiones más precisas y sostenibles.

Palabras clave: Análisis Técnico-Económico. Dimensionamiento Económico de Conductores. Eficiencia Energética. Emisión de CO_2. Flujo de Potencia.

1 INTRODUCTION

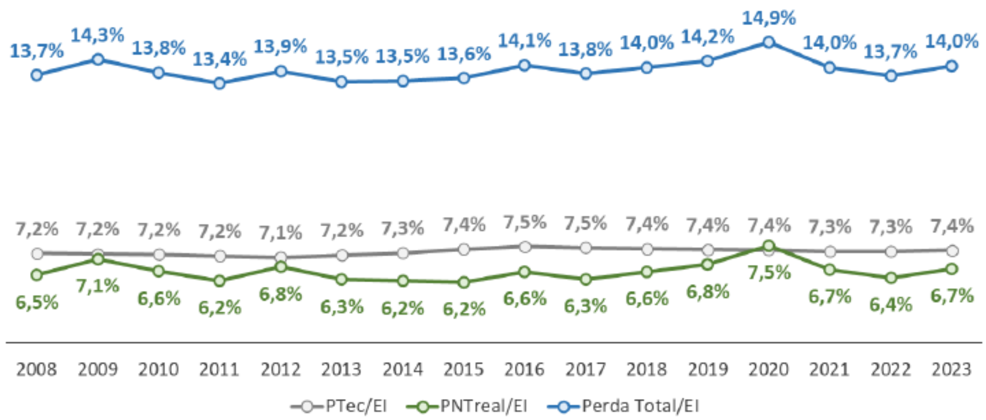
Brazil, a country of continental dimensions, with a territorial area of more than 8 million km² and a population of more than 203 million inhabitants, has high rates of energy losses in several sectors. In the specific case of electricity, losses in the distribution network correspond to the difference between the energy purchased by distributors and that actually billed to consumers, being classified into technical losses and non-technical losses.

Technical losses are mainly due to the dissipation of energy by the Joule effect in cables and conductors that carry electric currents in different lengths and cross-sections in distribution networks. In 2023, they corresponded to 7.4% of the electricity injected (EI), which is equivalent to 42 TWh. Non-technical losses, associated with energy theft, measurement fraud, equipment failures and defects, or errors in measurement systems, totaled 6.7% of EI, or approximately 38.2 TWh.

Thus, in 2023, technical and non-technical losses totaled 80.2 TWh, corresponding to 14.1% of the electricity injected into the national system. Figure 1 illustrates the historical evolution of these losses in Brazil, from 2008 to 2023 (ANEEL, 2024). Electricity losses also have a strong financial impact, directly reflecting on tariffs, since distributors pass on their costs to consumers. According to ANEEL (2024), the approximate cost of technical losses in 2023 was R$ 10.3 billion, a value calculated from the multiplication of the amounts of energy lost by the average price of energy in tariff processes, without including taxes.

Figure 1

Evolution of losses in the Brazilian electricity system



Source: ANEEL (2024).

In a study on losses in electrical networks, Barbosa and Amorim (2025) highlight the relevance of electrical losses, both technical and non-technical, as a significant challenge for energy efficiency. The authors conclude that distribution network projects planned and built according to specific norms and technical standards promote greater efficiency, system reliability and, consequently, reduce operating costs and socioeconomic impacts.

Energy efficiency comprises a set of activities and processes aimed not only at reducing energy consumption, but also at mitigating the emission of polluting gases. As Viana (2012) points out, energy efficiency is increased when a service is performed or a good is produced with a lower amount of energy in relation to the consumption previously required.

In this context, the present work aims to propose a methodology for the sizing of the economic section and for the technical-economic analysis of feeder cables of low voltage electrical circuits. The approach also includes the evaluation of carbon dioxide emissions, the study of electrical energy losses and the analysis of power flow, in order to provide more robust subsidies for the choice of the most appropriate conductor section to meet the needs of a Low Voltage Distribution Board (QGBT2).

The study was conducted at the School of Technology (EST), an academic unit linked to the University of the State of Amazonas (UEA), which houses engineering courses and has a building area composed of classrooms, course coordinators and administrative sectors, as well as laboratories, an auditorium, a sports court, a university restaurant and other facilities.

The proper sizing of the section of the electrical cables is essential to ensure the safety of people, the durability of the electrical installation and the energy efficiency of the system. According to Teixeira Júnior (2004), the correct technical dimensioning of conductors requires the consideration of several variables related to the operating and installation conditions.

Regarding the operating conditions, the author highlights the need to know the nominal voltage, the frequency of the system, the apparent power in normal and emergency regimes, the power factor, the maximum short-circuit current, the actuation time of the protection devices and the type of grounding adopted. Among the factors related to the installation conditions, the length of the circuit, the arrangement of the conductors (form of grouping), the characteristics of the installation environment, the depth (in the case of underground cables), the thermal resistivity of the ground, the average temperature of the place and the exposure to solar radiation are included.

2 METHODOLOGY

To achieve the proposed objective, an applied research was carried out with a qualitative and quantitative approach in the low voltage (LV) electrical system of the School of Technology (EST). The infrastructure analyzed includes classrooms, course coordinations, administrative sectors, laboratories, auditorium, sports court and university restaurant, among other spaces.

The methodology adopted included the sizing of the economic section and the technical-economic analysis of LV power circuit cables, complemented by CO_2 emissions calculations and power flow study, in order to provide more comprehensive subsidies for the choice of the ideal feeder cable section.

The methodological development was based on analytical methods, with the application of equations established in the NBR 15920:2011 standard and in specialized technical literature, in addition to the use of a computational tool for the modeling and analysis of the electrical system. The methodology was structured in 07 (seven) main steps:

For the development of the methodology, analytical methods were applied through equations available in the NBR 15920:2011 standard and specialized literature, as well as a computational tool for the study of the electrical network. The methodology developed was divided into 07 (seven) stages:

1. Inspection and measurements in the electrical system;
2. Design of the economic section and definition of standardized sections;
3. Cost analysis of the selected economic sections;
4. Calculation of CO2 emissions associated with feeder cables;
5. Study of the power flow of the feeder circuit;
6. Economic evaluation of alternative cable sections;
7. Integration and analysis of the results to support the decision as to the most appropriate cable section.

2.1 CASE STUDY AT THE SCHOOL OF TECHNOLOGY

The proposed methodology was applied to determine the economic section and perform the technical-economic analysis of a feeder circuit for a General LV Distribution Board, three-phase with neutral, voltages 220V/127V - QGBT2, installed in block A of the EST. The analysis is complemented by studies of CO_2 emissions and power flow. Table 1 shows values collected and measured in GBF2.

Table 1

QGBT2 electrical installation data

Date: 9/7/24	**Time:** 2 p.m.	**Internal Temp. QGBT (^{o}C):** 34	**Connection/Cable Temp. (^{o}C):** 47.7

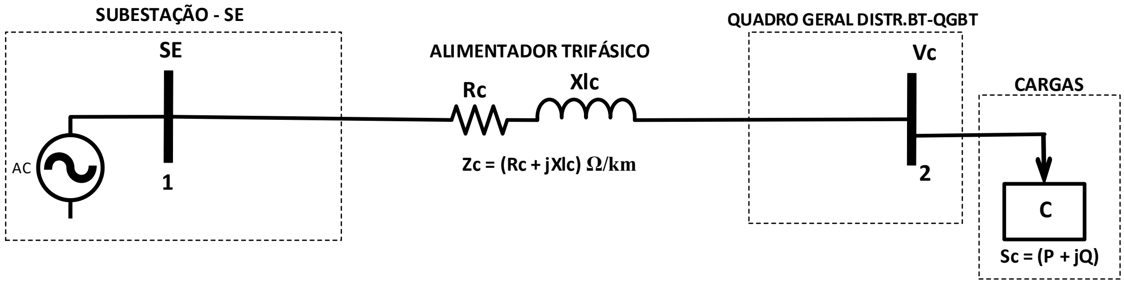
Cable Section Phase (mm2): 95	**Neutral cable section (mm2):** 95	**QGBT Load:** Block A
Current Phase A (A): 95.2	**Phase B Current (A):** 80.4	**C Phase Current (A):** 113.1
Voltage phase A (V): 125.7	**Voltage phase B (V):** 125.4	**Phase Voltage C (V):** 126.3
Phase Voltage AB(V): 222.3	**Voltage phase BC (V):** 221.6	**AC Phase Voltage (V):** 222.8
P. Active phase A (kW): 11.25	**P. Active phase B (kW):** 9.4	**Active P. C phase (kW):** 13.93
Power Factor A: 0.94	**Power factor B:** 0.93	**Power Factor C:** 0.97
Dist. SE - QGBT2 (m): 123		**General Circuit Breaker Current (A):** 600

Source: Prepared by the authors.

Figure 2 shows the single-line diagram of the electrical circuit under analysis. In addition to this, there are three other feeder systems with similar configurations, called QGBT3, QGBT4 and QGBT5. Figure 3 shows the front view of the QGBT2 frame and the power factor measurement in phase A.

Figure 2

Single-line representation of a three-phase LV feeder circuit



Source: Prepared by the authors.

Figure 3

Measurements in QGBT2

Source: Prepared by the authors.

For the application of the proposed methodology, the following case study is considered: three-phase low-voltage feeder circuit with neutral, operating at 220/127 V and 60 Hz, composed of single-core copper cables, with EPR insulation, maximum operating temperature of 90 °C and PVC cover, nominal voltage of 0.6/1 kV. The cables are installed in rigid PVC conduits, embedded in soil or masonry, at a depth of approximately 0.60 m. The installation method corresponds to 61A, with reference method D, and there are no other circuits in the feeder conduit of the QGBT2.

The circuit has a total length of 123 m, an average ambient temperature of 40 °C, a maximum design current of 120 A in the first year, and an annual growth rate of 1%. The power factor is 0.93 inductive and the allowable voltage drop in the feeder circuit is 2.5%. The electrical system operates 2,880 hours per year, considering an average energy tariff of 0.68761 R$/kWh in the first year. The annual variation in demand was disregarded, adopting an average annual adjustment of the energy tariff of 3%, without considering inflation.

For economic calculation purposes, the average unit value of the electrical cables was adopted, including installation labor and accessories, represented by A = 1.0303 R$/m·mm². The financial analysis considers a period of 30 years as the economic life of the cables and a capitalization rate of 5% per year.

Regarding the useful life of electrical cables, electrical engineer Hilton Moreno, professor and technical consultant, notes that there are no specific technical standards that establish an exact value. However, based on accelerated aging tests carried out in the laboratory, as well as the analysis of cables removed from old installations, it is estimated that, as long as the technical recommendations for design, installation, operation and maintenance are strictly followed, the useful life of the cables can vary between 20 and 30 years.

The loss of energy in the electrical cables compromises the efficiency of the electricity transmission system, requiring greater energy generation to meet the same demand. This process leads to an increase in operating costs and contributes significantly to the increase in carbon dioxide (CO2) emissions. Among the effects associated with electrical losses, the following stand out: voltage drop, degradation of the quality of energy supply, inefficient use of electricity by the final consumer, and worsening of losses with the growth of energy demand (Myat, Myint, and Phyu, 2018).

Given this scenario, the design of an electrical installation must consider not only the conventional technical criteria for the sizing of the cable section, but also economic and environmental aspects. This includes evaluating the economic sizing, which aims to optimize the total cost of the cable over its useful life, considering the expenses with electricity and the impacts of CO2 emissions (Cotrim, 2009). In addition, complementary analyses such as the calculation of CO_2 emissions in the stages of cable manufacturing and operation (Moreno, 2014), as well as the study of power flow, are essential for a more sustainable and efficient approach to electrical design (Grainger and Stevenson, 1994; Melo, 2023).

2.2 TECHNICAL AND ECONOMIC DESIGNS OF THE CONDUCTOR SECTION

The planning of the electrical installation is a fundamental step in the development of an electrical project, as it involves the collection and analysis of essential information, such as: the type of activity of the enterprise, voltage available at the site (low or medium voltage), implementation of distributed generation, external influences on the installations, architectural plans and other technical documents of the site. The proper sizing of the conductors requires a careful analysis of the installation conditions, as well as detailed knowledge of the characteristics of the load to be fed.

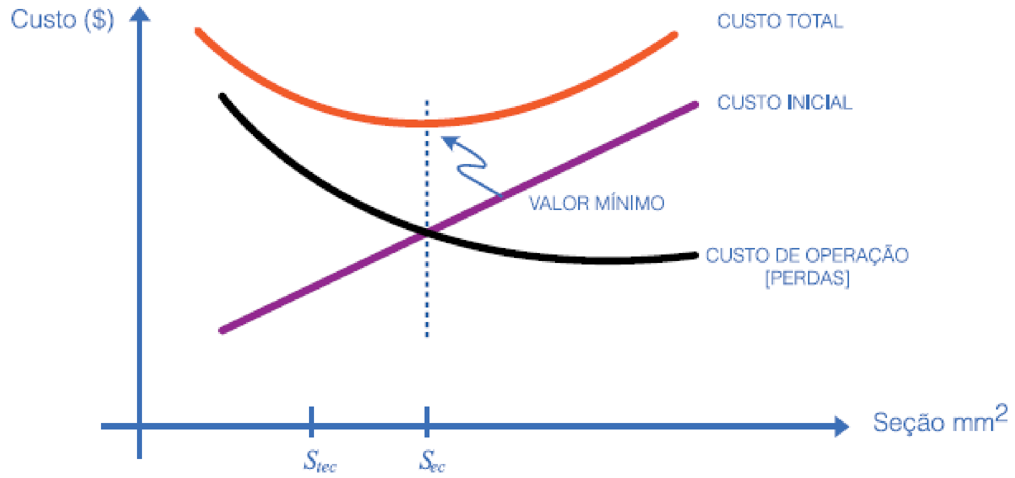
A poorly sized conductor can result in improper equipment operation, excessive heating of cables and, in more serious cases, a risk of fire (Mamede Filho, 2023). According to (ABNT, 2004), the technical section of the phase conductors of a circuit must be the normalized section that simultaneously meets the criteria of: Current conduction capacity; Overload protection; Protection against short circuits and thermal stresses; Protection against electric shocks; Voltage drop limits and minimum sections, according to NBR 5410:2004.

In addition to determining the technical section of the cable, it is equally important to calculate the economic section, which acquires relevance in the face of increasing requirements for efficiency and conservation of electrical energy. This evaluation is particularly advantageous in feeder circuits with cross-sections equal to or greater than 25 mm² (Cotrim, 2009). The guidelines for the economic sizing of conductors are defined in the NBR 15920:2011 standard (ABNT, 2011).

Figure 4 illustrates the typical curves of drivers' initial and operating costs. The point-by-point sum of these curves, for each nominal section considered, results in the total cost of the conductor over its useful life, expressed in present value. The resulting curve presents a point of minimum total cost, which corresponds to the economic section of the cable, which is defined as the one that provides the lowest aggregate cost of installation and operation throughout its economic life cycle (Moreno, 2014).

Figure 4

Initial and operational costs of cables as a function of nominal section



Source: Moreno (2014).

The total cost of an electrical cable (CT) is composed of the initial cost (CI), which includes acquisition, installation and accessories, and the cost of energy losses over its useful life (CJ), both expressed in present values, calculated by:

$C_T = C_I + C_J$ (1). According to (ABNT, 2011), the total cost can be obtained by:

$C_T = C_I + I_{max}^2 . R . l . F$ (2), being I_{max} a the load current in the first year (A); the apparent AC resistance of the conductor (Ω/m); the length of the cable (m). R l

The factor $F$is given by: $F = N_p . N_c . (T . P + D) . \frac{Q}{\left(1+\frac{i}{100}\right)}$ (3),

being N_p the number of phase conductors per circuit, the number of circuits with equivalent load, the annual operating time (h/year); the cost of energy ($/W.h); the annual change in demand ($/W.year); the capitalization rate (%); $N_c T P D i N$ the economic life of the cable (years). The coefficient considers the increase in the load over time, and is calculated by:Q

$Q = \sum_{n-1}^{N}(r^{n-1}) = \frac{1-r^N}{1-r}$ (4). The factor $r$is calculated by the expression:

$$r = \frac{\left(1+\frac{a}{100}\right)^2.(1+\frac{b}{100})}{(1+\frac{i}{100})} \quad (5),$$

in which a it represents the annual increase in the load (%) and the annual increase in the cost of energy, disregarding inflation (%). According to (ABNT, 2011), the apparent resistance of the conductor is expressed as a function of the cross-section (S) and the average operating temperature (θm) by:b

$$R(S) = \frac{\rho_{20}.B[1+\alpha_{20}.(\theta_m-20)]}{S}.10^6 \quad (6),$$

in which is the $R(S)$ resistance in alternating current (Ω/m); is the direct current resistivity of the conductor, adopting = 18.35 x 10-9$\rho_{20}\rho_{20}$ (Ω/m); is the temperature coefficient of the resistivity of the conductor at 20 °C, with value ; is the cross-sectional area of the cable (α_{20} $\alpha_{20} = 4{,}3 \text{ x } 10^{-3}\ K^{-1} S$ mm2).

The factor is determined by: where B $B = (1 + y_p + y_s).(1 + \lambda_1 + \lambda_2)$ (7),y_p and represent the proximity and skin effects, respectively; $y_s\lambda_1$ and correspond to losses in coverage and frame. According to Moreno (2010), these factors can be neglected in low voltage (≤ 1 kV) and medium voltage (≤ 36.2 kV) cables. The average operating temperature of the conductor (°C) is calculated, according to NBR 15920, by:λ_2

$$\theta_m = \frac{(\theta-\theta_a)}{3} + \theta_a \quad (8),$$

the maximum nominal temperature being according to the type of cable; is the average ambient temperature and factor 3 is of empirical origin. $\theta\theta_a$The optimal economic cross-section of the conductor, (mmS_{ec}2), is obtained by the expression:

$$S_{ec} = 1000\left[\frac{I_{max}^2.F.\rho_{20}.B.[1+\alpha_{20}(\theta_m-20)]}{A}\right]^{0,5} \quad (9),$$

in which $A$is the average cost of the cost of cable and installation accessories ($/m.mm2).

According to NBR 15920, the calculated section hardly coincides with a standardized nominal section. Thus, the cost should be evaluated for the adjacent standardized sections, choosing the one with the lowest total cost.

2.3 ENVIRONMENTAL ANALYSIS OF ELECTRICAL CABLES

During the life of a cable, CO_2 emissions occur mainly due to electrical energy losses. The emissions associated with the manufacturing and disposal phases are relatively small. Thus, there is an environmental gain when the emissions avoided during operation exceed those generated in the manufacture of the driver.

Considering the use of the economic section, the total reduction of CO_2 emissions, (kg·CO_2), according to Moreno (2014), can be calculated by the expression: Z_1

$$Z_1 = N.\left[N_p.N_c.I^2.(R_1 - R_2).10^{-3}.T.l.K_1\right] \quad (10),$$

being the period of economic life of the corporal; NN_p the number of phase conductors per circuit, the number of circuits; the charge current (A); the resistance of the conductor with technical section (Ω/km), according to equation (6); the resistance of the conductor with economic cross-section (Ω/km), obtained by equation (6); the annual operating time (h/year); the length of the cable (m); and the CO_2 emission factor in energy generation, adopting kg·CO_2/kWh (Moreno, 2014). $N_c I\ R_1\ R_2\ T\ l\ K_1\ K_1 = 0{,}081$

However, the use of conductors with an economical section leads to an increase in CO2 emissions during manufacturing, as larger sections require more material and energy in the production process. The main increase in emissions is associated with the production of copper, which represents the most carbon-intensive stage. The annual increase in CO_2 emissions, resulting from the use of larger sections, can be estimated by (Moreno, 2014):

$$Z_2 = N_p.N_c.[(W_2 - W_1).l.K_2] \quad (11),$$

in which is the annual increase in CO_2 emissions (kg·CO_2); and are the weights of the conductors of the technical and economic sections, respectively $Z_2\ W_1 W_2$(kg/km); l is the length of the cable (km); and is the CO_2 emission factor in the production of the cable, adopting kg·CO_2/kg· Cu (Moreno, 2014). Table 18 by Moreno (2014) presents the approximate weights of copper cables (kg/km), used to calculate and . The final amount of CO $K_2\ K_2 = 4{,}09 W_1 W_2 2$ emissions is obtained by:

$ECO_2 = Z_1 - Z_2$ (12).

When , the reductions in CO2 emissions$Z_1 - Z_2 > 0$ resulting from the use of cables with an economical section, over their service life, outweigh the additional emissions generated in manufacturing. In this case, the choice of a conductor with a larger section represents an environmental gain.

2.4 FINANCIAL ANALYSIS OF ELECTRICAL CONDUCTORS

The ability to analyze, evaluate, and decide on an investment is a fundamental premise, both for individuals and companies. Such decisions must be based on appropriate analysis techniques, given their importance in the competitive business environment. Examples of strategic dilemmas that require such an analysis include (Moreira *et al*., 2021): whether or not to participate in an auction for the purchase and sale of energy; opt for self-generation of energy or invest the resource in investment funds; invest in one's own generation or acquire it from third parties; investing or not in an energy efficiency project; acquiring a new piece of equipment or machinery *versus* its full recovery.

Taking as an example the financial analysis of a project in the area of electricity, it is necessary to consider variables such as: initial investment costs, project and installation costs, cost of electricity generated, useful life of systems/equipment, and operation and maintenance costs. In this work, the financial analysis will be conducted using the investment valuation methods: simple *payback*, discounted *payback* and net present value.

Simple *Payback* (PBS) is an initial indicator of liquidity and allows the calculation of the time required for the cash flow generated to recover the initial investment, but it does not consider the value of money in time, since the values of the accumulated flows are taken by their face (or nominal) value up to the point of equivalence with the investment made (Moreira et al., 2021). The PBS calculation is given by:

$$I_0 = FC_1 + FC_2 + \cdots + FC_n \quad (13),$$

being the initial investment; positive cash flows and is the number of periods (days, months, years). In the case of equal cash flows, PBS can be determined by:$I_0 FC_1, FC_{2,} FC_n n$

$$PBS = \frac{I_0}{FC} \quad (14).$$

Discounted *Payback* (PBD) is similar to PBS, but incorporates the time value of money, allowing you to determine the payback period by adjusting cash flows by a discounted rate. PBD is obtained by:

$$I_0 = \frac{FC_1}{(1+i)^1} + \frac{FC_2}{(1+i)^2} + \cdots + \frac{FC_n}{(1+i)^n} \quad (15),$$

the $i$discount rate being (i%/100). Adjusted cash flow is obtained by calculating its present value (), expressed by:VP_{FC}

$$VP_{FC} = \frac{FC}{(1+i)^n} \quad (16).$$

Net Present Value (NPV) is a technique that is widely used in investment analysis, in which future cash flows are brought to present value through a discount rate, considering the time value of money. This method is generally recognized as the most appropriate for assessing the economic viability of investment projects.

According to Nascimento (2010), the NPV method consists of determining the current value of the inputs (VAE) and the current value of the outputs (VAS), applying the discount rate, and adding both values algebraically. When the NPV is positive, the investment is considered viable for the adopted rate; if it is negative, the investment is unfeasible; and, in the event that the NPV is null, the decision depends on the investor's discretion. NPV can be calculated by the following expression:

$$VPL = -I_0 + \frac{FC_1}{(1+i)^1} + \frac{FC_2}{(1+i)^2} + \cdots + \frac{FC_n}{(1+i)^n} \quad (17).$$

3 RESULTS AND DISCUSSION

3.1 ECONOMIC SIZING AND COST ANALYSIS OF FEEDER CABLE

The costs of cables, installation and accessories are presented in Table 2, with the average unit value obtained being equal to A = 1.0303 R$/m·mm². In (7) the auxiliary parameter B was considered equal to 1.00, disregarding the skin effects, proximity, losses in the roof and in the frame (Moreno, 2016). Applying (9) an initial economic cross-section of $\boldsymbol{S_{ec}}$ = 226 mm2 was obtained. Since this value does not correspond to a standardized section, two adjacent commercial sections were selected: one immediately below ($\boldsymbol{S_{ec1}}$= 185 mm2) and one above ($\boldsymbol{S_{ec2}}$= 240 mm2).

Table 3 presents the data and results obtained in the stage of economic sizing of the feeder cable, as well as the corresponding costs, including the 95 mm² cable of QGBT2, adopted as a technical reference section. The total costs were calculated considering four similar QGBT feeders. Thus, based on the global cost results, it is concluded that the most suitable economic section for the QGBT2 feeder cable is S_e **= 240 mm2**.

Table 2

Cable, Installation and Accessory Costs

	STARTUP COST			
Section (mm2)	**Cable (R$/m)**	**Inst./Aces. (R$/m)**	**Total (R$/m)**	**Variable A (R$/m.mm2)**
25	27,33	21,00	48,33	
35	32,45	22,89	55,34	0,7010
50	45,45	25,18	70,63	1,0193
70	63,30	27,95	91,25	1,0310
95	86,06	31,30	117,36	1,0446
120	110,52	35,37	145,89	1,1412
150	137,24	40,32	177,56	1,0557
185	169,00	46,37	215,37	1,0802
240	209,81	53,79	263,60	0,8769
300	278,49	62,94	341,43	1,2971
400	372,80	74,27	447,07	1,0564
			Average	**1,0303**

Source: Prepared by the authors.

Table 3

Data and results obtained - economic and costs section

DATA		
Project current year 1 – **I** (A): 120.00	Circuit length – (m): 123.00l	Economic life – **N** (years): 30,00
Copper Resistivity -ρ20 (Ω/m): 18.35x10-9	Copper temperature coefficient - (α_{20}K-1): 4.3x10-3	Capitalization rate – **i** (%): 5,00
Growth Rate – **A** (%): 1.00	Energy Boost Ratio - **b** (%): 3.00	Operation time circuit – **T** (h): 2.880,00
Annual variation in demand – **D** (R$/kW.year): 0.00	Average energy tariff – **P** (R$/kWh): 0.68761	Average installed cable price - **A** (R$/m.mm2): 1.0303
Circuit Quantity - **Nc**: 1	Circuit Phase Quantity - **Np**: 3	Oper. temp. Cond. - θcond (oC): 90
Mean ambient temperature - **θamb** (oC): 40	Technical Section - (mmS_{tec}^{2}): 95	Price of 95 mm2 cable and installation (R$/m): 117.36

Price of 185 mm2 cable and installation (R$/m): 215.37	Price of 240 mm2 cable and installation (R$/m): 263.60	
	FINDINGS	
Conductive Medium Temperature - **θm** (oC)(8): 57	Auxiliary variable **r** (5): 1,0007	Auxiliary variable **Q** (4): 30,2931
Auxiliary variable **B** (7):1.00	Auxiliary variable **F** (3): 171.3993	Economic Section - (mmS_{ec}^{2}): 226
Economy Section 1 - (mmS_{ec1}^{2}): 185	Economy Section 2 - (mmS_{ec2}^{2}): 240	Resistance R(S)185 - (Ω/m) (6): 1.15 x 10-4RS_{ec1}
Resistance R(S) 240 - (Ω/m) (6): 8.85 x 10-5RS_{ec2}	Resistance R(S)95 - (Ω/m) (6): 2.24 x 10-4RS_{tec}	
Initial cost cable 185 mm2 - (R$): CI_{ec1}105,963.28	Initial cost cable 240 mm2 - (R$): CI_{ec2}129.692,24	Initial cost of cable 95 mm2 - (R$): CI_{tec}57,742.37
Operating cost 185 mm2 - (R$): CJ_{ec1}139,439.11	Operating cost 240 mm2 - (R$): CJ_{ec2}107,484.32	Operating cost 95 mm2 - (R$): CJ_{tec}271,539.33
Total cost cable 185 mm2 - : CT_{ec1} (R$)245.402,39	Total cost of cable 240 mm2 - (R$) CT_{ec2} 237,176.56	Total cost cable 95 mm2 - : CT_{tec}(R$)329.281,69

Source: Prepared by the authors.

3.2 ENVIRONMENTAL ANALYSIS OF QGBT FEEDER CABLES

In the environmental analysis, both the selected economic section and the existing technical section of the QGBT feeder were considered, with the aim of calculating the final amount of CO_2 emissions over the life of the cables. Assuming N = 30 years and applying (10), a total emission reduction of Z_1= 4,045.33 kg·CO_2 per circuit was obtained during the period considered. Thus, for four feeder circuits, the total emission reduction is Z_{1T}= 16,181.34 kg·CO_2.

The adoption of the 240 mm² section, however, implies an increase in CO_2 emissions during the manufacturing process, due to the greater amount of material used. This increment is calculated by (11). Based on Table 18 by Moreno (2014), we have W_1 = 853 kg/km for the 95 mm² cable and W_2 = 2,170.00 kg/km for the 240 mm² cable, resulting in Z_2 = 1,987.63 kg·CO_2 per circuit. Considering four feeders, a total of additional emissions of Z_{2T} = 7,950.52 kg·CO_2 is obtained.

The final assessment of carbon emissions was obtained by applying (12), resulting in a net emissions reduction of 2,057.70 kg·CO_2 per circuit. Considering the four feeders, the total amount avoided over the operational life of the cables is 8,230.82 kg·CO_2. The $ECO_2 =$

ECO_{2T} =**average annual emission reduction of 274.36 kg·CO_2 can be expressed in terms of environmental financial gain.**

Adopting the carbon price of US$ 37.52 per ton of CO_2 equivalent (tCO_2e), according to data from the Bioeconomy Observatory of the Getúlio Vargas Foundation (FGV), the annual economic benefit corresponds to US$ 10.29. Considering the exchange rate of 1 USD = R$ 5.57 (Central Bank of Brazil, 07/22/2025), an estimated annual gain of R$ 57.34 is obtained.

3.3 ANALYSIS OF TECHNICAL LOSSES IN QGBT2 FEEDER CABLES

In addition to the analysis of the unit, operating and total costs, which make it possible to choose the economic section of the feeder cables of QGBT2, a power flow study was carried out with the objective of determining technical losses associated with the selected cables, such as power and active energy dissipated, drop and the voltage profile in QGBT2. For the calculation of the dissipated power and active energy, only the resistive components of the 95 mm², 185 mm² and 240 mm² feeder cables were considered, in addition to other parameters of the power flow study, whose values are presented in Table 4.

Table 4

Data and results obtained from technical losses

	DATA	
Current year 1 – I (A): 120,00	Stretch length – (m): 123.00l	Bar Tension 1 – SEB1 – V1 (V): 220.00
Resistance R(S) cable 185 mm2 (Ω/m): 1.15x10-4	Resistance R(S) cable 240 mm2 (Ω/m): 8.85x10-5	Resistance R(S) cable 95 mm2 (Ω/m): 2.24x10-4
Base power – Sb (MVA): 100.00	Base voltage – Vb (kV): 0.22	Operating time – T (h): 2,880.00
Circuit Quantity - Nc: 1	Circuit Phase Quantity - Np: 3	Voltage drop adopted stretch – ΔV= 2.5 %
	FINDINGS	
Lost cable power 240 mm2 – Pla240 (kW): 0.48	Annual energy lost cable 240 mm2 – EPla240 (kWh): 1,379.30	Lost cable power 185mm2 – Pla185 (kW): 0.63
Annual energy lost cable 185 mm2 (kWh): 1,802.97	Lost power feeder 95 mm2 (kW): 1.25	Lost energy cable 95 mm2 (kWh): 3,600.78
Voltage at QGBT with 240mm2 – V2 cable (pu): 0.9903	Voltage at QGBT with 240mm2 – V2 (V) cable: 217.87	Voltage deviation on QGBT with 240 mm2 cable – ΔV (%): 0.97

Tension bar 2 – cable 185 mm2 QGBT – V2 (pu): 0.9874	Tension bar 2 – cable 185 mm2 QGBT – V2 (V): 217.23	Voltage deviation on QGBT with 185 mm2 cable – ΔV (%): 1.26
Voltage bar 2 – cable 95 mm2 QGBT – V2 (pu): 0.9751	Voltage bar 2 – cable 95 mm2 QGBT – V2 (V): 214.52	QGBT voltage deviation with 95 mm2 cable – ΔV (%): 2.49

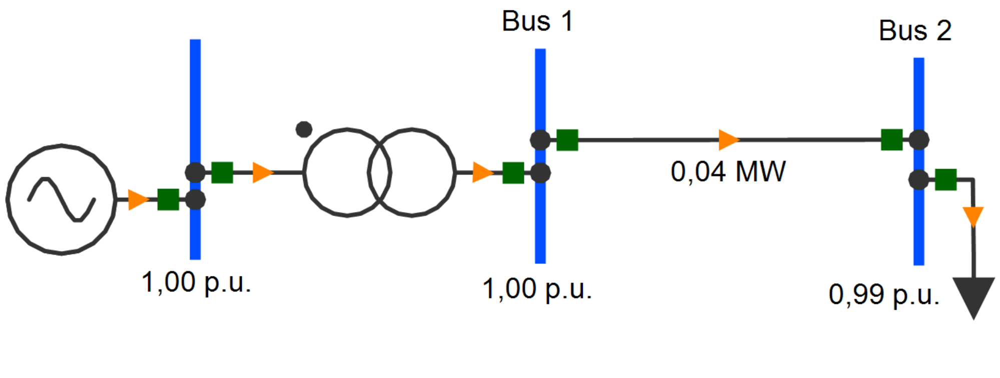
Source: Prepared by the authors.

According to the results presented in Table 4, considering four identical feeders for the QGBTs, the active energy losses in 30 years total 108.02 MWh with 95 mm² cables and 41.4 MWh with 240 mm² cables, that is, the energy dissipated with the smallest section is 2.61 times higher. Figure 5 shows the power flow scheme between the substation (bar 1) and QGBT2 (bar 2), with the respective voltage values in p.u.

Figures 6 and 7 illustrate the tension profiles on the power bars for the 240 mm² and 95 mm² cables, respectively. Based on the power and active energy losses, as well as the observed voltage profiles and deviations, it is concluded that the 240 mm² section is the most suitable for powering the QGBTs.

Figure 5

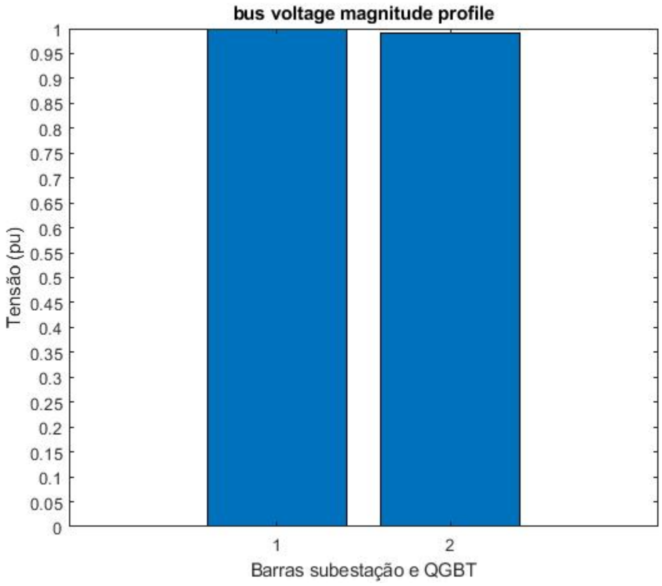
Power flow between substation and QGBT2



Source: Prepared by the authors.

Figure 6

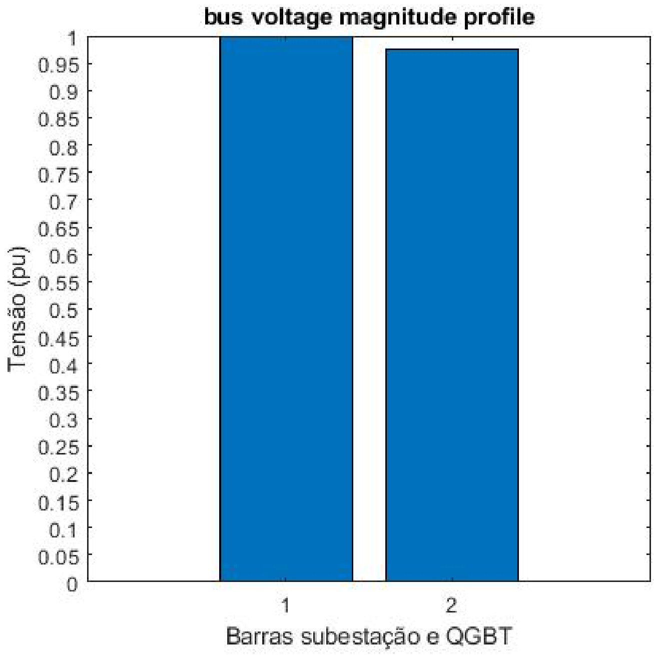
Voltage profile on QGBT2 with 240 mm2 cable



Source: Prepared by the authors.

Figure 7

Voltage profile on QGBT2 with 95 mm2 cable



Source: Prepared by the authors.

3.4 TECHNICAL AND ECONOMIC EVALUATION OF QGBT FEEDER CABLES

The technical and economic evaluation of the work was carried out based on economic data and the cost results presented in Table 4 and on the environmental analysis. Table 5 details the results of the initial and operational costs, considering the cables dimensioned by the technical and economic criteria, and Table 6 presents the results obtained from the calculation of the return time, using the PBS, PBD and NPV methods.

Table 5

Financial analysis of the cables resulting from the technical and economic criteria

Design Criteria	Nominal Section (mm2)	Initial cost – CI (R$)	ECO/tec ratio (%)	Operating cost – CJ (R$)	ECO/tec ratio (%)	Total cost – CT (R$)	ECO/tec ratio (%)
Economical	240	129.692,24	225	107.484,32	40	237.176,56	72
Technician	95	57.742,37	100	271.539,33	100	329.281,69	100
QGBT quantity	4	Investment (R$)		71.949,87	Total Savings (R$)		164.055,01
Annual Earnings (R$)	5.468,50	Annual CO2 gain (R$)		57,34	Total annual earnings (R$)		5.525,84

Source: Prepared by the authors.

Table 6

Payback time

Capitalization rate - i (%)	5,00	Economic life - N (years)	30
Payback time (years)	13,02	Payback time – discounted *payback* (years)	21,58
Net present value – NPV (R$)	12.995,80		

Source: Prepared by the authors.

4 CONCLUSION

In this work, a methodology was presented for the sizing of the economic section of feeder conductors at low voltage, integrating the technical, economic and environmental analyses, in addition to the power flow. The effectiveness of the methodology was proven in a real case study for the economic dimensioning of the QGBT2 feeder cable, installed at the School of Technology of UEA.

The technical sizing of feeder cables is a widely employed practice in electrical projects. However, the results obtained in the case study demonstrate the relevance of making economic sizing also common, ensuring better technical performance and greater energy efficiency of the facilities.

In the financial analysis carried out, it was found, for example, that the total cost of the

95 mm² cable is approximately 1.4 times higher than that of the 240 mm² cable, and that the annual energy losses are reduced from 3,600.78 kWh to 1,379.30 kWh, representing a saving of 62%.

In this context, it is concluded that the proposed methodology allowed the efficient integration of technical, economic and environmental analyses, indicating that the most appropriate nominal section of the feeder cables of each QGBT is 240 mm².

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