U.PORTO

MASTER
IN MANAGEMENT

The decision on overhead or underground power cables: an economic analysis of E-REDES investment projects

Ana Beatriz Lourenço Paredes

M

2022

FACULDADE DE **ECONOMIA**

U.PORTO
FACULDADE DE ECONOMIA
UNIVERSIDADE DO PORTO

THE DECISION ON OVERHEAD OR UNDERGROUND POWER CABLES: AN ECONOMIC ANALYSIS OF E-REDES INVESTMENT PROJECTS

Ana Beatriz Lourenço Paredes

Internship Report
Master in Management

Supervised by
José António Cardoso Moreira

2022

Acknowledgements

First and foremost, I would like to thank my supervisor, Professor José Moreira, for his continuous support, concern, patience and for all the meetings and emails exchanged discussing this internship report. Thank you for all your constructive advice, perspectives and unequal approaches, without which this work would not be the same.

I would also like to thank the teachers who were part of the "Teaching Team": Professors Rosário Moreira, Luísa Pinto, Belém Barbosa, and Professor João Ribeiro, for their extremely important role in the preparation and evaluation of this report.

To Engineer Marta Ferreira and Doctor Eduardo Salvador, my thanks for all the clarifications on the specifics of the subject in question, and for the corrections and suggestions made over the last six months.

Also, to thank my mother and father, for all their patience with me, for all their advice during this process, and for making me who I am today. A special thanks to my godfather for his major role in the construction of my personal and professional path and for being present in every step of the way and, in particular, for sharing his opinion and experience in this field, which greatly contributed to the development of this work.

I would also like to express my gratitude to all my friends, in particular Natércia Teixeira and Luís Miranda, for their friendship, understanding and support so that I could more easily continue with this work. I also thank my friend Cristina Gomes, for her friendship and positivity, for her continuous encouragement, for her advice, and for her text criticism.

To all, and with apologies to those not mentioned, my sincere thanks.

Abstract

Electricity can be distributed through overhead or underground systems, both depending on various factors and their impacts over the life cycle of the assets. The decision to install an overhead or underground electricity distribution network involves several factors ranging from construction and maintenance costs, reliability, and others.

This internship report emerged from an internship at the Programming and Control Department of the Directorate of Services to Northern Assets from E-REDES - Distribuição de Eletricidade, S.A, which monitors the levels of execution, outlook-trends, in order to take the necessary actions in due time.

The main purpose of this report is to answer the following research question: *Medium voltage power cables – what is the best solution for E-REDES: overhead or underground installation?*, through an analysis based on the economic and financial components of medium voltage power line investment projects, with the aim of making it a useful decision tool for the company and for its counterparts.

This report provides some practical contributions to this topic. On the one hand, it shows the decision-making factors underlying the research question and, on the other hand, enhances the understanding of the relationship between overhead and underground network costs components through their life cycle and identifies the option that can create more value.

Keywords: Electricity distribution networks, Overhead Networks, Underground Networks, Reliability, Construction and O&M Costs

JEL-Codes: D81, L23, L94, M11.

Resumo

A eletricidade pode ser distribuída através de sistemas aéreos ou subterrâneos, dependendo de vários fatores e do respetivo impacto ao longo do ciclo de vida dos bens. A decisão de instalar uma rede de distribuição de eletricidade aérea ou subterrânea envolve vários fatores que vão desde os custos de construção e manutenção, fiabilidade, entre outros.

Este relatório resulta de um estágio no Departamento de Programação e Controlo da Direção de Serviços ao Património Norte da E-REDES - Distribuição de Eletricidade, S.A, que monitoriza os níveis de execução, as tendências de perspetiva, a fim de tomar as ações necessárias em tempo útil.

O principal objetivo deste estudo é responder à seguinte questão de investigação: *Cabos elétricos de média tensão - qual é a melhor solução para E-REDES: instalação aérea ou subterrânea?*, através de uma análise baseada nas componentes económicas e financeiras de projetos de investimento em linhas elétricas de média tensão, com o objetivo de a tornar um instrumento de decisão útil para a empresa e para as suas congéneres.

Este trabalho projeto fornece alguns contributos práticos para este tópico. Por um lado, mostra os fatores de decisão subjacentes à questão da investigação e, por outro lado, melhorou a compreensão da relação entre os componentes de custos gerais e subterrâneos da rede através do seu ciclo de vida e identificou a opção que pode criar mais valor.

Palavras-chave: Redes de distribuição de eletricidade, Redes Aéreas, Redes Subterrâneas, Fiabilidade, Custos de Construção e Operação e Manutenção

JEL-Codes: D81, L23, L94, M11.

Table of contents

Index of graphs

Index of tables

1. Introduction

Electricity can be distributed through overhead or underground systems, both of which depend on various factors and on their impacts over the assets' life cycle. The decision to install/build an overhead or underground electricity distribution network involves several factors ranging from construction and maintenance costs, reliability (which is a crucial variable to provide a good quality of service to the customer), and others related to the surroundings, namely environmental, safety and aesthetic aspects that reflect the impact on ecosystems (Bumby et al., 2010).

Nowadays, this subject is of significant relevance, due to climate change and the external dimension (Fortes et al., 2019). Climate change increases the frequency and intensity of extreme events, greatly affecting the infrastructures that are exposed to them. Since overhead and underground construction have quite different levels of exposure to such events (storms, fires, among others) and to external events company non-related, it is important to take this risk into account when analysing an investment of this nature, in order to safeguard the quality of service and the future costs of the damages caused by the aforementioned events (Zamuda & Ressler, 2020).

Therefore, the quality of the service provided by the electricity distribution grids will be an increasingly critical factor, given the rising importance of the electricity sector in the economy (Panteli & Mancarella, 2015). For instance, and in accordance with Zamuda and Ressler (2020), in the United States of America, the power outages constitute a highly costly element of the extreme weather events damage. The cost of weather-related outages has increased, from 25$ billion dollars per year at the end of the 20th century to 70$ billion dollars per year in the decade of 2010.

In order to mitigate the high costs of the power outages associated with the extreme weather and external events and to increase resilience of the electricity infrastructures, Zamuda and Ressler (2020), proposed seven long-term measures, such as upgrading the distribution lines with materials that can better resist high winds, debris, wildfires, animal contact and vehicle collision; undergrounding key power lines; and carrying out maintenance activities, such as aggressive vegetation management, as presented in Chapter 3.

According to Martins et al. (2021a), and for a sample of 30 countries, there are sixteen countries (Brazil, Japan, Ireland, Greece, Latvia, USA, Hungary, Lithuania, Portugal, Czech Republic, Estonia, Bulgaria, Finland, Poland, Cyprus and Slovenia) with a percentage of underground network ranging from 0%-30%; seven countries with a percentage between 30% and 70% (Iceland, Norway, Italy, France, UK, Sweden and Austria); and seven others ranging between 70%-100% (Luxembourg, Spain, Germany, Switzerland, Denmark, Belgium and Netherlands) (Martins et al., 2021a).

Therefore, the percentage of undergrounding is quite uneven between the various countries, with some developed countries having a very low percentage, while other countries, belonging to the same economic group, are reaching a 100% undergrounding percentage (Martins et al., 2021b). In Portugal, this percentage is around 20% which is significantly lower than that of our neighbour Spain (71%), which will be better understood once the research question is answered.

This internship underlying this report took place in E-REDES-Distribuição de Eletricidade S.A. This company is responsible for the activity of construction, operation and maintenance of the electricity distribution network in Portugal, and one of the prior actions it develops is network planning which decides the meritocracy of the projects (E-REDES, 2020). To help the company improve the decision-making process concerning the construction of medium voltage overhead and underground network, this report proposes an economic and financial analysis of a set of the company's investment projects of medium voltage lines. There are several factors that influence the meritocracy of projects, ranging from the costs involved, to the reliability of the infrastructure, the future operation and maintenance costs, to the environmental impacts throughout the assets' life cycle . These factors are significantly different depending on the type of construction. Therefore, and in order to make the decision easier, one intends to perform the aforementioned analysis, in order to determine the best solution based upon it. In short, this analysis will become a useful decision tool for the company and similar companies/counterparts to know when to install overhead or underground networks.

Thus, based on the review of the available literature, one will present the context underlying the thematic of this internship report, the benefits and drawbacks associated with the overhead and underground networks, and the decision-making factors behind it; then, one will proceed to the data collection from current projects of both typologies, followed by the breakdown of costs and the identification of the factors that most influence them, in each of those projects; using an analysis based on these economic and financial components, the differences in implementation and maintenance costs of the two installation options will be highlighted. Such methodological sequence has as its main purpose to answer the following research question: *Medium voltage power cables – what is the best solution for* E-REDES*: overhead or underground installation?*

This report is divided into seven chapters, Introduction included. Chapter 2 gives a brief presentation of the company under analysis. Chapter 3 provides a review of literature on the main concepts of this topic, the costs and benefits that other studies have found to be relevant and its underlying reasons, and also the methods used by other authors to analyse similar situations. The methodology applied will be discussed in Chapter 4 of this report. In Chapter 5, the focus relies on the presentation of findings, i.e., the presentation of how the company currently decides between an underground and an overhead installation. The decision-making process used herein will be analysed in order to perform the cost-benefit analysis. A comparison between the findings and the literature review will be presented in Chapter 6, entitled Discussion. Chapter 7, the last chapter of this report, outlines the main conclusions withdrawn and presents some limitations and suggestions for future research.

2. The company and the internship

2.1. Company presentation: E-REDES – Distribuição de Eletricidade, S.A.

E-REDES is a company wholly owned by the EDP Group, responsible for the distribution of electricity in high, medium and low voltage. In order to separate the image of the national distribution network operator from that of the EDP Group, E-REDES was set up in January 2021, by regulatory imposition of ERSE- Energy Sector Regulatory Authority. The letter "E" in the name of the company stands for Energy and the word "REDES" translates the focus on an integrated management of the entire distribution network, able to ensure the reliability of the national electricity system, and also its sustainability, in order to safeguard the interests of customers, municipalities and the country as a whole.

With regard to the company's activities, E-REDES inherits all the activity of the former one, known as EDP Distribuição, which was incorporated in 2000 through the merger of the four regional distribution companies that existed in Portugal. The national distribution grid ensures the flow of energy to the various customers and receives and distributes the energy that is delivered by the various interconnected producers. The electricity distribution networks consist of high, medium, and low-voltage lines and cables, substations, and transformer stations. Substations, where high-voltage is transformed to medium-voltage; transformer stations, where medium-voltage is transformed to low-voltage; where the customers and producers are interconnected with all the voltage levels.

To manage the aforementioned assets, the company is organised into support departments (Human Resources, Management Control, among others), assets service departments (DSAN-Directorate of Services to Northern Assets; DSAS-Directorate of Services to Southern Assets; DSAT-Directorate of Services to High Voltage Assets); and the Stakeholders Management department (commercial, suppliers, municipalities, communication, among others).

DSAN oversees the service management of medium voltage and low voltage assets in the northern area, from Bragança to Castelo Branco. Its main responsibilities include: carrying out investment to develop and expand these assets; carrying out investment to connect customers or producers to the network; ensuring the permanent availability of the medium voltage/low voltage assets in the northern area, as well as their adequate state of operation through the necessary preventive and corrective maintenance actions.

In order to guarantee the fulfilment of the established objectives and to perform the support functions to the various operational units, there is the Programming and Control Department, which monitors the levels of execution and outlook-trends, in order to take the necessary actions in due time. Within the various budget items, there are two groups of accounts that are fundamental: CAPEX, capital expenditures that include: the mandatory (investment needed to connect customers), the structuring (investment needed to develop the network and improve its quality of service), and the urgent current (investment needed to ensure the operability of assets); and OPEX, which corresponds to the operational expenditures related to asset maintenance activities, and every company's objective is to reduce it.

2.2. The internship

The internship consisted in the economic and financial analysis of investment projects for the construction of overhead or underground networks, in the area of DSAN for 6 months. For this, it was necessary, in a first phase, to know the various activities of the department, which in general range from the identification of investment needs, whether of external origin, customers, producers or others, as well as the company's initiative, to the design, construction and maintenance of electricity distribution networks.

The various types of investment made by the company were also identified, from the compulsory investment, namely the investment made to connect customers or producers, the urgent current investment, investment made to recover assets in a weak situation, structuring investment made to develop the network to sustainably guarantee the supply of consumption and improve the quality of service, and the programmable current investment, which is the investment programmed to guarantee the normalisation of the network.

Following this first phase, several medium voltage network construction investment projects were analysed, always in the two options of overhead or underground construction, identifying all cost factors, verifying how these costs are calculated, which in general result from multiplying the quantities of services or materials needed to execute the project to the unit prices previously contracted with the suppliers of materials or equipment.

Moreover, it was also necessary to assess the future costs of operating and maintaining these projects throughout the life cycle of the assets. Thus, the various types of maintenance carried out on assets were identified (corrective, to repair fault situations, preventive to diagnose and maintain before the fault, whether systematic, typically inspections, or conditioned in the correction of anomalies detected during inspection actions). A special focus was made on medium voltage assets, namely on inspection actions and strips either for maintenance or to reduce fuel, identifying how they are currently paid. As these costs will last throughout the life cycle of the asset, the frequency with which maintenance actions are carried out was analysed and for non-repetitive actions, such as corrective, future costs were estimated. The techniques of investment evaluation were applied, namely the NPV to update them to the investment year and make sensitivity analyses to the variation of the main drivers of future costs. Another aspect that is of enormous importance for a regulated asset management company is knowing the criteria for classifying expenses as OPEX and CAPEX. The criteria for an intervention to be considered OPEX or CAPEX were identified, whereby if the interventions carried out lead to an increase in the useful life of the intervened assets, then the work should be CAPEX, if they do not increase it is considered OPEX.

The internship then results in the decisions to be taken by the company with regard to the analysed projects and similar future projects.

3. Literature Review

The most relevant concepts of this research are presented in this chapter. In section 3.1., a context for the overhead and underground installation subject is presented as well as definitions of relevant concepts; section 3.2., a distinction is made between the benefits and drawbacks of the two installation options (overhead and underground). In section 3.3., the decision-making factors are presented regarding whether or not to bury distribution networks and the reasons behind it. The analysis methods used by previous researchers are presented in section 3.4.

3.1. Context and concepts

Owing to increased demands and pressure from customers to improve reliability, and consequently quality of service, the system reliability subject is attracting more and more attention and is becoming one of the most important technical and economic indicators for electricity distribution companies (Bloom et al., 2006). Also, deregulation in power distribution has introduced an intense competitive business environment. These factors mean that companies have to optimally manage the performance of their distribution systems so that they can provide uninterrupted power. Therefore, the ultimate purpose of building reliability-oriented distribution systems is to reduce the frequency and duration of power outages (Agrawal et al., 2020). These power outages are costly to both residential customers and business customers since home appliances, business processes, among many other things that depend on the normal functioning of the electricity flow (Fenrick & Getachew, 2012). According to Fenrick and Getachew (2012), these outages are caused by changes in weather, such as wind and ice storms; animal contact with equipment and energised lines; vegetation, i.e., falling trees and tree limbs; lightning; vandalism, among others. According to Larsen (2016), and in the United States of America, for instance, each of these factors represents a different percentage with regard to the frequency of power interruptions. Concerning weather-related interruptions, these represent around 15% of the total power outages; the percentage of outages related with animal contact with the electrical equipment is about 11%; in what concerns the power interruptions due to falling trees or by interference from vegetation around the power lines, these represent around 24% of total interruptions; the remain factors that increase the frequency of power outages are internal to the companies, such as planned outages (4%), failures in the equipment (26%), failures due to human error (3%), and failures of unknown source (17%) (Larsen, 2016). Thus, it can be drawn the following conclusions: 50% of the factors that increase the outages' frequency in the U.S.

Power System are related with external aspects that cannot be controlled by companies, except the vegetation management, whereas the 33% constituted by the planned outages, equipment and human error can be corrected by the companies that distribute electricity. In the particular case of Portugal, the company E-REDES in the last five years has recorded around 35,250 incidents causing interruptions in the supply of energy to customers. Of these incidents, around 41% were due to extreme weather events, animal contact with the network, vehicle collisions, theft and vandalism, which are all situations external to the company (E-REDES, 2021).

Since electrical power systems are part of the indispensable infrastructure of modern society, it is essential that their ability to withstand severe weather events, the contact with animals and the surrounding vegetation, be increased (Panteli & Mancarella, 2015). Therefore, and in order to mitigate those events, resilience investments can be made (Zamuda et al., 2019). Resilience can be defined as the ability of the networks to withstand extreme events and how quickly they return to their pre-shock state (Chawla et al., 2021; Maliszewski & Perrings, 2012). There are three main categories of measures that improve the network's resilience: system hardening measures; physical changes to prevent service interruptions; and measures in order to improve recovery time (Zamuda et al., 2019). In what concerns the system hardening measures, these include selective undergrounding, vegetation management, the construction of floodwalls and the restoration of wetlands – with these measures the benefits associated are the reduction of the frequency of power outages and savings in repairing damaged electricity lines (Panteli & Mancarella, 2015). Regarding the physical changes to prevent service interruptions, these allow the electricity networks to continue deliver electricity even though there may be damages in the infrastructures. The measures to improve recovery time, as the name suggests, are measures that reduce the time lost with interruptions, such as increased labour force, the availability of standby equipment or the prediction and response to damages (Fortes et al., 2019).

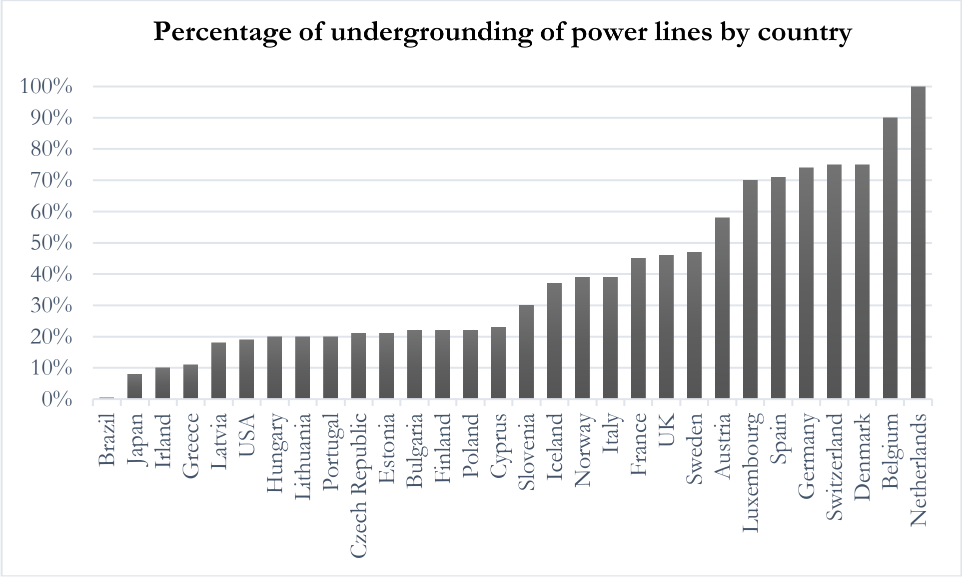
Other authors, such as Edison Electric Institute (2014) and Panteli and Mancarella (2015), also studied the development of resilience improvement measures and their implementation, but they divided the type of measures to be taken in a different way. For them, these measures are divided into short-term or long-term resilience measures. The short-term refer to the actions taken before, after and even during the extreme events, which are also called preventive and corrective measures; while the long-term measures are about the planning in order to the network to be able to support and adapt itself to future climate changes or other extreme events. The table below summarises the measures taken in both situations.

Short-term resilience measures	Long-term resilience measures
Before ▪ Estimation of the weather location and severity; ▪ Estimation of the number of repair and recovery crews possibly required following the weather event; ▪ Maintain backup components and materials, such as transmission towers.	**Operational measures** ▪ Risk assessment and management; ▪ Improve emergency and preparedness plans; ▪ Tree-trimming or vegetation management.
During ▪ Monitoring: situation awareness; ▪ Coordination with repair and recovery crews; ▪ Corrective actions: generation redispatch, re-configuration, and protection and control actions.	**Hardening measures** ▪ Undergrounding distribution and transmission lines; ▪ Upgrading poles and structures with stronger/robust materials; ▪ Elevating substations and relocating facilities to areas less prone to flooding; ▪ Re-routing transmission lines to areas less affected by weather.
After ▪ Disaster assessment; ▪ Restoration of damaged components (e.g., poles and towers); ▪ Restoration actions: reenergizing transmission lines, load restoration, resynchronization of areas).	**Smart solutions** ▪ Energy storage; ▪ Demand side management; ▪ Microgrids; ▪ Advanced visualisation and information systems.

Table 1-Short-term vs. Long-term resilience measures
Sources: Adapted from Edison Electric Institute (2014) and Panteli and Mancarella (2015)

Larsen (2016), argued that these enhancement measures need to achieve an optimum point, crossing its costs, with the associated risk and most important, its performance. Thus, the key factors that lead to the mentioned investments include the customer satisfaction, the reduction or the power to control the expenses in operations and maintenance, and also improvements on the reliability and safety levels. Nevertheless, and according to Brown (2007), some measures are considered much more expensive than the standard operational measures or the smart solutions, specifically the hardening measures.

In the hardening measures, the undergrounding of electricity distribution lines was included. According to Larsen (2016), undergrounding is defined as the act of burying power lines in order to mitigate the consequences associated with climate change or extreme weather events, and with wildlife and vegetation contact with power lines. According to Martins et al. (2021b), most of the countries that constitute the European Union, consider the hypothesis on the implementation of underground networks. In some of these countries, this practice was adopted almost a century ago, while in others, undergrounding is proceeding at a very slow pace. By comparison, in Germany almost 80% of the networks are underground, in Greece only 10%, and in the Netherlands almost 100%, as illustrated in Graph 1 (Martins et al., 2021b). This heterogeneity is due to multiple factors, both quantitative (different economic groups) and qualitative (legislation in each country, region intrinsic characteristics).



Graph 1-Percentage of undergrounding networks by country
Source: Adapted from Martins et al. (2021)

All in all, the question – overhead or underground installation? – is posed frequently in public discussion, from electricity distribution companies, landowners, and other stakeholders. Both types of installation have their benefits and challenges and both have their field of application (Dalle, 2017). According to this author, many aspects must be taken into consideration, both with regard to the construction and installation of the lines and with regard to their life cycle, and therefore there is no simple and straightforward answer to this question. Each project is a project and must be analysed on a case-by-case basis (Dalle, 2017).

3.2. Undergrounding cables: relative benefits and drawbacks

The decision to bury or build an overhead network is a subject that has been under consideration by electricity distributors for several years and has assumed particular relevance in recent times. This section, therefore, analyses the costs and benefits in comparative terms of the two installation options.

Burying electricity lines gives companies one more tool to be able to supply electricity in more reliable ways. However, it is necessary to look at the costs and benefits associated with burying the lines when making an investment decision (Fenrick & Getachew, 2012).

3.2.1. Benefits

According to Zamuda et al. (2019), the benefits of investments in power system resilience can be divided into several categories taking into account the reliability, aesthetics, costs (construction and operations and maintenance costs), failure issues, and others.

Underground power lines have reliability benefits when compared with the overhead power lines, such as increased reliability during severe weather, fewer outages during normal weather, reduced exposure to lightning, and potentially far fewer momentary interruptions (Brown, 2007). Although the underground cables are not completely resistant to hurricanes, floods and storms, its implementation significantly reduces the impact of wind-related hurricane damages. Concerning the momentary interruptions, these last during a very short period of time, and its main causes are animals and tree branches falling on the lines, which are reduced if the cables are buried (Hall & Hall Energy Consulting, 2013). The overall advantage is the greater increase in robustness to most weather events and less exposure to wildlife.

Among all the benefits quoted about undergrounding, one of the most common is the improvement in aesthetics but they are not easily quantified (Murr, 2011). These improvements ins aesthetics appear quite often as one of the most cited reasons for undergrounding, due to the fact that it is expected to result in increasing property values and it is, sometimes, used as a strategy to increase desirability in a certain area and attract new residents, new businesses and tourism, which does not happen with the overhead networks.

In addition to this, and according to Zamuda et al. (2019), there are two more advantages in this category in relation to the overhead networks: improved relationship between the company that provides the service and its customers, because one of the factors that leads to the damage of the electric lines are the trees on the sidewalks, and when the lines are buried there is no longer the problem of interruption of service if they fall; and also, the fact that there are less structures in the sidewalks as for example, the poles that help in the distribution of electricity. In a nutshell, these are the major aesthetic benefits of undergrounding: helps with public image and strengthens the customer-company relationship (Hall & Hall Energy Consulting, 2013).

Zamuda et al. (2019) stated that there are healthy and safety benefits including fewer vehicle accidents and electrical contact injuries. Considering the vehicular pole accidents, with the undergrounding of power lines, the risk associated entirely disappears; about the electrical contact injuries, the overhead power lines recurrently burn up and fall and the conductor may still be energised, which means that contact with this conductor can lead to an injury. Thus, undergrounding is a solution to avoid this type of accident.

Lastly, there are also benefits for the companies that provide for the burying of the lines, that are often called avoided utility costs (Edison Electric Institute, 2014). Undergrounding can result in savings for the company providing the service, as for instance, lower operations and maintenance costs, costs concerning vegetation management, restoration costs derived from storms and a decrease in the lost revenue that is connected with the interruptions customers suffer (Brown, 2007). Regarding the reduced operations and maintenance costs, there is no consensus among authors on them. According to Edison Electric Institute (2014), these costs can range due to several factors such as the type of specifications, design, geographical area and others. While often the common perception is that these costs will be less expensive than the same costs incurred with overhead power lines, that is not what happens. According to Hall & Hall Energy Consulting (2013), when comparing the costs of operations and maintenance of overhead power lines and direct buried underground, these have almost the same O&M (Operation and Maintenance) cost. Nevertheless, Martins et al. (2021a), operation and maintenance costs are a benefit associated with the underground network, as there is no need to maintain the strip that is associated with the overhead network.

Regarding the vegetation management costs, this is one of the most expensive activities when the distribution systems are overhead (Edison Electric Institute, 2014). These costs depend on the height and size of the trees, the necessary equipment to execute the tree trimming and the geographic area, whether it is an urban or a rural area.

Another reason associated with the burial of the networks are the restoration costs, due to the fact that the probability of damages and interruptions of the service provided is less during the extreme weather events (Zamuda et al., 2019). Therefore, undergrounding is translated into less damage and consequently lower restorations costs. Nevertheless, and according to Edison Electric Institute (2014), the calculations of the restoration costs require information about future weather events that will have a significant impact on the reliability of the distribution power lines.

The last benefit associated with the avoided utility costs regards the lost revenue (Brown, 2007). If a company that provides the distribution of electricity is out of service because of extreme weather events, or animal collision with the networks or due to a vehicle accident, that means that it cannot sell electricity. Accordingly, if burying power lines can result in fewer outages and interruption time, then companies will lose less revenue, which is a crucial decision factor in cost-benefit analysis done for undergrounding (Murr, 2011). Furthermore, power outages constitute a high costly element, as explained in Chapter 1, and this cost has been increasing through the years, as it happens in USA, where costs went from 25$ billion dollars at the end of the 20th century to almost 300$ billion dollars in 2017, as one can see in Annexe 1. Despite this, in non-normal weather conditions and even in normal ones, if there is an equipment failure, the restoration and reconfiguration time will be longer than the time needed to complete these tasks in the overhead distribution lines (Larsen, 2016). On the European continent, for instance, extreme events cause 606 billion dollars' worth of damage, only 35% of which is covered by insurance. In Asia, only 10% of the damage ($1.280 billion) caused by these events is covered by insurance. In Africa, the percentage insured is about 5% of a total of $62 billion in damages. Only in the Americas is more than half (52%) of the damage, $2.175 billion, insured (Munich RE, n.d.).

3.2.2. Drawbacks

On the other hand, there are also drawbacks of burying distribution networks. According to Brown (2007) there are four main categories to take into account: lifetime costs, environmental problems, safety problems, and reliability and technical problems.

The greatest issue with undergrounding power lines is associated with the investment costs because these are usually more expensive to install than the overhead ones (Edison Electric Institute, 2014). These higher costs are due to the increased material costs, installation timeframes, and with the design of the projects themselves. In addition to these, O&M costs can also be higher, as explained in the previous section. This is due to the labour-intensive nature of fault location and cable repair, or the need for specialist contractors for replacement or mitigation work, or even the need for additional labour-intensive crew resources to restore power to customers when a fault occurs.

With regard to the environmental problems, Hall & Hall Energy Consulting (2013) and Zamuda et al. (2019), argued that this environmental category comprises several issues, namely, soil erosion, the disruption of ecologically-sensitive land and damage to the roots of trees. The required trenching for undergrounding can damage the trees' roots which in return can weaken and even kill trees; also, the mentioned trenching destroys the vegetation on the surface and can increase the probability of soil erosion; and electricity distribution systems often have to cross rivers, wetlands or streams, which makes the overhead systems a better solution in order to minimise the impact in that ecologically sensitive areas, while the option of undergrounding can disrupt local ecosystems.

In addition to the above-mentioned problems, there are safety problems as well (Shaw Consultants International, 2010). These are for the most part related with the operations and maintenance tasks because that is when the workers are more exposed to electric contacts, vault explosions or flash burns, which leads to the reliability problems.

According to Brown (2007), the reliability issue can generate misleading conclusions, since the perception that exists is that undergrounding overhead lines is more reliable than keeping the overhead network, which it is, in the occurrence of extreme weather events. However, if there is an equipment failure, for example, the duration of the interruptions and the duration of the system reconfiguration, there is a higher impact on customers and hence, the company-customer relationship worsens.

Regarding the interruptions duration, Larsen (2016), argued that the time needed to repair an underground fault is related to the specifics by which these systems are made of. Thus, an underground fault takes about twice as long as an overhead fault. Related to the former drawback is the impact of an outage on customers (Panteli & Mancarella, 2015). Since it is more difficult and expensive to replace underground equipment than the overhead equipment in case there is an outage, which will consequently affect the service provided to customers.

Concerning the previously mentioned extreme weather events, there is one of them that can cause severe damage to underground distribution lines (Murr, 2011). Flooding causes long interruptions because the water needs to be pumped before the restoration tasks begin, and if the equipment is not water-proof, it can cause damages to the equipment, which will further increase the repair time and affect the customers. Further on technical problems, there is the reduced flexibility issue connected with the possible upgrading and reconfiguration of the underground lines (Brown, 2007). The operational flexibility for these types of lines is more limited than for overhead lines, when it comes to extending a line or modifying it or just adding more equipment, which is particularly important in geographical areas that will be subject to new developments. In line with this, and still according to Brown (2007), there is another factor weighing on the decision to bury electricity distribution lines, which is the life expectancy of the equipment used. Considering that, overhead distribution equipment is expected to last 50 years and the underground distribution equipment is expected to last 30 years. The energy sector supports this ratio – overhead distribution equipment tolerates the wear and tear for almost 60% longer than the underground one.

The following table summarises the benefits/drawbacks of undergrounding networks compared to overhead networks, as explained above.

Benefits & Drawbacks	**Benefits**	Reliability improvements
		Aesthetics improvements
		Health and Safety improvements
		Avoided utility costs (O&M costs and restoration costs)
		Lost revenue
	Drawbacks	Investment costs
		Environmental problems
		Safety issues
		Increasing outages duration
		Technical problems: reduced flexibility
		Life expectancy of the equipment

Table 2-Summary of underground benefits and drawbacks in comparison with overhead

3.3. Decision-making factors: overhead or underground installation

Most of the benefits and drawbacks mentioned in section 3.2 constitute a major influence on the undertaken decision. Thus, and although the studies mentioned throughout the literature review discuss different projects in different geographic areas, the factors influencing the decision to bury power lines in many of them are common to each other. These are as follows:

- Initial Costs/Investment Costs
- Operations and maintenance costs
- Reliability indicators
- Electric load to be transferred
- Geographical area

The initial costs or investment costs can be often divided into several other costs, as some authors, such as Brown (2007) do. The first costs that are considered are the material cable costs; and the installation' costs which considers the licensing of the projects and the payment of compensations to owners in case it is required, followed by the digging of trenches for cable installation in the underground option. The operations and maintenance costs include the costs related with vegetation management (in the overhead power lines case); with network modification on overhead and buried lines, in both non-normal weather conditions and normal conditions; and with inspections (Battle et al., 2019). In addition to costs, there are also other factors that influence the decision-making process, such as the reliability indicators, namely SAIFI and SAIDI. The first one stands for System Average Interruption Frequency Index, which is translated to the average number of interruptions per customer per year. These interruptions are recorded for each customer that suffers a loss of service, then these are added and divided by the total number of clients, in order to calculate the company's average. The second one stands for System Average Interruption Duration Index, that measures on average the number of minutes of an interruption per customer during a year (Albeck Jr & Estomin, 2003; Shaw Consultants International, 2010). The last two factors (electric load to be transferred and geographical area) that influence the decision on burying or not power lines, are related with each other. Depending on the voltage to be distributed and the geographical area (rural, semi-urban, and urban), the costs will vary, thus altering the conclusions withdrawn from the projects studied. The aforementioned factors do not include the ones that cannot be quantified, such as the safety and health of the employees that install the lines and the community in general, the aesthetics improvements, and the environmental impacts, but are also important factors in deciding whether or not to bury the power lines (Kim et al., 2014). According to the previous author, these factors are taken into account in the analysis of the projects through questionnaires made to the people concerned (contractors, community, municipalities, among others).

3.4. Evaluation methods

This section contains the evaluation methods used by several studies, in different countries, regarding the decision of undergrounding power lines or not. The financial evaluation methods are the most quoted, namely, Cost-Benefit Analysis, Net Present Value, Internal Rate of Return and Payback Period.

3.4.1. Cost-Benefit Analysis

Studies such as Brown (2007) and Edison Electric Institute (2014) use this method to help with the decision of whether to bury or not distribution power lines.

Cost-Benefit Analysis is an analytical tool which lists the economic advantages and disadvantages of an investment decision (European Commission, 2015). A CBA may have several purposes. The first purpose is to assess the economic merit of a project; the second purpose is to compare competing projects; this tool can also be used to evaluate business decisions and/or to assess the wisdom of using natural resources or changing environmental conditions; and lastly, CBA is intended to examine potential future actions which main purpose is to increase social welfare (Shively & Galopin, 2013).

According to Valentin et al. (2009), a CBA can be carried out at different stages of a project (Valentin et al., 2009). Thus, there are four CBA types that are consistent with the stage a project finds itself in (Boardman et al., 2017). The first one is referred to as ex-ante CBA, which is performed before the decision to implement the project is taken. In short, this first type of CBA answers the question: would this project implementation have a positive social benefit?. The second type is designated as ex-post CBA, i.e., is done after the project has been completed. In comparative terms, the informational value of ex-post CBA is greater than the ex-ante CBA, but less direct, ending up by providing information not only about the project in question, but also about similar projects. The third one only applies to ongoing projects, which is called in-media-res CBA. The fourth and last one, compares an ex-ante CBA with an ex-post CBA or with an in-medias res CBA of the same project, which is useful to identify eventual past errors, to understand the reasons that lie behind these mistakes and to help avoid them in future projects (Boardman et al., 2017).

In what concerns the economic performance indicators contemplated by this analysis, the overall performance of a project can be measured through the Net Present Value and the Internal Rate of Return, which are going to be explained below.

3.4.2. NPV- Net Present Value

Multiple studies, such as Murr (2011), Kim et al. (2014) and Brown (2007) and others, use the Net Present Value to decide if the best solution is to bury the overhead power lines or not. This method consists of directly comparing the investment cost, which occurs in year zero, and the cash-flows generated over time updated to their present values (Soares et al., 2020). Therefore, companies should invest in projects with a positive NPV and reject those with a negative NPV (Brealey et al., 2018; Götze et al., 2008).

This method is one of the best known and most widely used methods in both theory and practice. To evaluate its usefulness compared to other methods, its computational ease, data collection requirements and, most important of all, model assumptions are considered. The NPV calculation requires: (1) forecast of the initial investment; (2) the economic life of a project; (3) forecast the cash flows generated by a given project over its economic life; (4) determine the appropriate opportunity cost of capital (k), which should reflect both the time value of money and the risk involved in a project; (5) then, use this opportunity cost of capital to discount the future cash flows of the project (the sum of the discounted cash flows is called the present value); (6) calculate the NPV by subtracting the initial investment from the present value of the cash-flows (Brealey et al., 2018). The following formula summarises the points outlined.

$$NPV = -Initial\ Investment + \sum_{t=1}^{n} \frac{Cash\ Flow_i}{(1+k_t)^t}$$

Where:

- k: discount rate that takes into consideration the opportunity cost of invested capital;
- n: investment life-cycle.

Thus, the major decision criteria is:

- If NPV>0: The project is profitable and therefore can be realized.
- If NPV<0: The project is not profitable and therefore should not be realized.
- If $NPV_A > NPV_B$: The project to be chosen is project A.

This method is the most used by similar studies since it takes into account aspects that other methods do not. For example, it is a sensible method to evaluate the meritocracy of investments, because it considers that the value of an investment is defined as the present value of the flows generated by that investment, which means that it recognizes that a dollar today is worth more than a dollar tomorrow (Brealey et al., 2018). In addition, and as noted above, it is a decision criterion as to the economic and financial viability of an investment (Soares et al., 2020).

3.4.3. IRR – Internal Rate of Return

The internal rate of return is another method used to evaluate the meritocracy of an investment, which is based on the principle of discounting cash flows. The difference with NPV is that the unknown is the discount rate, which measures the maximum return that an investment can have (Soares et al., 2020). The internal rate of return is the discount rate that leads to a NPV of zero as the following formula shows (Brealey et al., 2018; Götze et al., 2008).

$$\frac{\sum_{t=1}^{n} CF_t}{(1+TIR)^t} = Initial\ Investment$$

The decision on which investment to select based on the internal rate of return is made by comparing this with the opportunity cost of capital. In other words:

- If IRR>k: The company should accept to invest in the project;
- If IRR<k: The company should reject to invest in the project;
- If IRR=k: It is indifferent for the company to accept or not to invest in the project.

Despite being an advantageous method because it presents the result as a percentage of the return on an investment and its calculation is simple, it has some disadvantages, namely the fact that it is not informative about the useful life of an investment project; because it assumes that the cash-flows generated over the useful life are all reinvested at the same rate (IRR), which is very unlikely to happen; and it does not account for reinvestments.

3.4.4. PBP – Payback Period

The payback period is another method used by some studies mentioned in literature review, such as Murr (2011). According to Götze et al. (2008), the payback period corresponds to the period of time after which the capital invested in a project is recovered. The major assumptions, in the same line with what happens in the NPV method, to have in consideration in this method are: (1) if the payback period of a project is shorter than the designated time limit, absolute profitability is achieved; (2) an investment project is preferred if it has a shorter payback period than the alternative project - relative profitability.

The determination of the payback period involves the calculation of the Net Present Value of the project. As long as the NPV value remains negative, the payback period is not yet reached. When the NPV reaches zero or turns positive for the first time, the payback period is finally achieved (Brealey et al., 2018). Thus, the decision criteria used in the studies that considered this method to assess the decision of undergrounding is:

- $PBP_A > PBP_B$: The project to be chosen is project B (Murr, 2011).

Although the payback period can be easily calculated using NPV, it has its limitations, such as: PBP is usually defined as the comparison between the value of the investment and the sum of undiscounted cash flows; as it only takes into account the period of time needed to recover the investment, it does not consider the cash flows generated in the years following the initial investment recovery; and is not the most suitable method for dealing with investments where there is no initial investment (Soares et al., 2020).

4. Methodology and Data Collection

4.1 Methodology

The following internship report provided a deeper understanding of what factors are taken into consideration in the decision-making process and the reasons behind the installation of the aforementioned options, overhead and underground. This report aimed to understand in which cases the company should choose to install the underground or the overhead network. Therefore, addressing the following research question: *Medium voltage power cables – what is the best solution for E-REDES: overhead or underground installation?*

The first step was to decide which method was more appropriate for this internship report, having into consideration the research question and the literature review presented in Chapter 3. Since the purpose of this project is to help with the decision that is implicit in the research question, the type of research method that better suits this research question is a quantitative method (Williams, 2007) – which is corroborated by the literature, since all the methods used by other studies were quantitative.

Taking into consideration the methods mentioned in section 3.4., to analyse which solution is best for a given scenario, one had addressed the research question through an analysis based on economic and financial components, using NPV as it is the method most widely used by other studies reviewed in the literature. However, as the purpose of this method is to analyse the merits of investment projects, and in this case, the goal is to identify which option has lower costs. Which means that, for a given project, revenues will be considered the same, regardless of whether it is an overhead or underground network, since only a cost analysis will be performed (initial cost and costs to be incurred over the useful life of the assets). Therefore, as a final decision criterion, it was considered that the project that brings more costs to the company should not be chosen to the detriment of the one that presents lower costs, in terms of overhead and underground installation in each analysed project.

Therefore, the formula of NPV provided in the section 3.4. was modified to:

$$Present\ Costs = Initial\ Investment + \sum_{t=1}^{n} \frac{Future\ Costs_i}{(1+k_t)^t}$$

In order to simplify the analysis, all the costs of each project were identified and the groups presented below were formed according to the defined criteria, by similarity to what happens in the Brown (2007) study:

- **Construction costs** – correspond to the sum of three cost factors: the cost of the materials needed to build the networks, the cost of the labour hired to build the networks, and the cost of licences and compensations;
- **Labour costs** – corresponds to the cost of the tasks required to execute the project, using the actual prices contracted through an international public tender to provide these services throughout the country, with various geographical areas of operation;
- **Material costs** – refers to the cost of acquiring equipment (poles, insulators, cables, etc.) borne by E-REDES to build the network;
- **Licence and compensation costs** – corresponds to the licensing costs with official entities, namely DGEG (Direção Geral de Energia e Geologia), Estradas de Portugal (if applicable); and compensation for loss of income paid to owners of land crossed by the network;
- **Operation and Maintenance costs** – these represent the costs of preventive and/or corrective maintenance actions that are necessary to ensure the correct operation of the infrastructure. These actions can be motivated by inspections of the equipment itself and correction of damage, whether of internal or external origin.
  In the overhead network installation option, where the surroundings are forested areas, there are costs for vegetation management, namely strip maintenance, cutting down trees so that they do not interfere with the network, and creation of the strip network system for fuel management, which consists of reducing the fuel load under the line, such as removing or reducing trees, bushes and ligneous material.
  In the underground option, there are only corrective maintenance costs since underground cables are not exposed to the surroundings as overhead cables.
  From the comparison between the two options, the operation and maintenance costs are significantly higher in the overhead option due to the vegetation management costs and due to its exposure to external actions from both current economic activities and weather phenomena.
- **Cost of energy not supplied** – The costs of energy not supplied comprise: repair costs; cost of lost revenue for energy not distributed; indirect costs of complaints;

cost of increased customer dissatisfaction; and the cost of penalties payable to customers for non-compliance with the quality of service standards defined in the Quality of Service Regulations. Given that we are talking about networks with equivalent sections in terms of transmission capacity, the level of losses is similar and therefore the differentiating benefit is related to the reliability of the infrastructure which is measured by the energy not distributed during interruptions. Thus, the underground network has a higher reliability than the overhead network due to the fact that the latter is more exposed to the external dimension, be it economic, climatic, or environmental. It was calculated the value associated with the energy not distributed. The kWh unit value used in this valuation was of 3,5€, which includes not only the cost of energy not distributed but also the negative impacts on image, reputation and others that the unavailability may cause to the company's customers. Per year, on average, it is estimated that around 0,74MWh will not be distributed by the network associated to these overhead line projects, which means that, at the price indicated above, the costs of energy not distributed over 30 years, on average, are around 28.434€ per project. The underground network has a high level of reliability, given its reliability history. It was estimated that the energy not distributed by the underground network is 10% of the energy not distributed by the overhead network.

Some other aspects necessary for cost calculation, were defined, such as:

- **Inflation rate** – in order to estimate the O&M costs and benefits throughout the assets' life cycle, which is 30 years, the inflation rate projected by the European Commission was used as a factor. According to this very same, the inflation rate will be of 1.3% in 2023 and, as from 2024 on, it is assumed that this rate will remain the same (European Commission, 2022);
- **Real price variation** – corresponds to the latest price updates, by applying the review formula, which takes into account the main cost drivers of the activities. The last variations in the prices on the service provision contracts for the construction and maintenance of the distribution network was around 1% per year;
- **Discount Rate** – in order to compare costs and benefits at the same point in time, they were discounted to the year of investment (2022), using an opportunity cost of capital of 5.86% (this is a nominal rate).[1]

---

[1] $i_{Nominal} = i_{Real} + \pi + (i_{Real} \times \pi) \Leftrightarrow i_{Nominal} = 4{,}5\% + 1{,}3\% + (4{,}5\% \times 1{,}3\%) \Leftrightarrow i_{Nominal} = 5{,}86\%$

The next section presents in detail the projects that were analysed, their characteristics, such as their location, their length, the cable section considered, the energy transportation capacity, among other things.

4.2. Investments' cases sample

In quantitative research, it is not always possible to study the entire population of interest, and so in order to obtain information about it and draw conclusions, a sample, which is a subset of the population, is used (Khalid et al., 2012). Therefore, researchers use probability and non-probability sample categories. In the case of this internship report, the type of non-probability sampling method that best suits is a judgement sample for the data collection. This type of non-probability sampling method is defined, according to Saunders et al. (2009), as the personal judgement of the researcher to select cases that, in his or her opinion, will best answer the research questions formulated and make research objectives attainable (Saunders et al., 2009). The sample of this internship report is composed of real projects, where the decision to build an overhead or underground network has not yet been taken.

The five investment projects in the medium voltage electricity distribution network are part of the Directorate of Services to Assets North (DSAN), which plans and controls all the projects to be implemented from Bragança to Castelo Branco. These investment projects present an overall investment value of 1.326.077€.

The following table shows where the projects will be implemented and their lengths in each of the installation options.

	Projects Location	**Networks length**	
Projects	**Municipality (District)**	**OH Network**	**UG Network**
Project 1	Montalegre (Vila Real)	2,5km	2,9km
Project 2	Mogadouro and Vimioso (Bragança)	3,96km	4,53km
Project 3	Torre de Moncorvo (Bragança)	2,02km	3,42km
Project 4	Freixo Espada à Cinta (Bragança)	1,8km	2,27km
Project 5	Cinfães (Viseu)	0,87km	2,2km

Table 3-Projects length and location

These projects provided by E-REDES have the same purpose: improving the quality of service and renovating and rehabilitating the assets. They all present similar energy transport capacities (435A) and therefore AA160mm (Aluminium - Steel 160) cables are used in the overhead option and FX HIOZ 240mm in the underground network, according to Solidal (2008) (Solidal-Condutores Elétricos, 2008). The reason why substantially different sections have similar load capacities is because there is one factor limiting the load capacity, which is the heating produced by the electric current in the cable, and this is released more easily in the overhead network (due to the surroundings) than underground.

Nevertheless, these projects have different characteristics, namely, the areas of implementation of the projects and, as a result, the costs of compensation to be paid to the owners of the land crossed by the network, which are significantly different. For example, if the land is agricultural or forested, construction costs differ depending on the location. In addition, the lengths of the overhead and underground networks may be significantly different, as underground networks are usually built next to roads, while overhead networks may or may not be, which means that the length of each option may be different.

In terms of construction costs, there are two cost factors that are determinant: the materials and equipment costs and the labour costs to install, since also in this segment, there are significant differences between the two options, because they do not have the same costs under these headings. In the overhead option, one of these costs has more influence on the total cost and therefore on the final decision, while in the underground network, it is the other cost that has more influence on the decision.

Finally, there are the operation and maintenance costs over the useful life of 30 years and the various factors influencing them quite differently in each option. The overhead network is much more exposed to its surroundings, which leads to increased maintenance costs for the proper functioning of the infrastructure or reduction of the fuel load to comply with legislation on forest protection and firefighting, whether external actions of an atmospheric, economic or other nature.

The projects analysis described therein was structured as follows: (1) first of all, the costs of each project and each installation option were analysed; (2) this was followed by an analysis on the length of both installation options; (3) finally, a sensitivity analysis was carried out, in which there is the variation in one variable in particular that may or may not affect the final decision.

4.3. Data Collection

In what concerns the data collection, there are two collection types: primary data, which is the data that is collected by the researcher itself; and secondary data, which is the existing data – that is generated by institutions – that can be made available for different purposes (Hox & Boeije, 2005).

In this internship report, the collected data was solely secondary data. One had to first identify the projects to be executed during the current year, and for each one of them, the two installation options were considered. For each investment project and construction typology, – overhead or underground – the costs of licensing the installation with the official entities (DGEG), the costs of compensation to owners, as well as the breakdown of construction costs in terms of labour and materials, were identified. The construction costs use the service contracts in force, which define the installation cost of each equipment, as well as the contracts for the acquisition of materials in force, in which the price of each type of equipment is defined. Based on each project and the prices defined by the contracts, the cost of labour and materials and operation and maintenance for each project and for each installation option, was determined.

In general, E-REDES' data was used since comparability must be ensured with other analyses that the company may have performed internally on similar investments.

5. Results

In this chapter, the decision between the two installation options, overhead and underground, is analysed in five E-REDES' projects. Firstly, the costs factors of each project were identified and grouped in accordance with their timeframes and category: the construction costs, which correspond to the costs incurred in the year of investment (year "zero") and the operation and maintenance costs that are borne during the 30 years of the assets' useful life. Secondly, were also identified the costs associated with the reliability of each installation option, measured through the energy not supplied due to power outages of different nature (higher reliability means less energy not distributed and vice versa). These costs are considered indirect costs because they reflect not only the cost of energy not distributed but also the costs of image, reputation, and complaints bared by the company due to less reliability of the network. Summing up, the main aim of the chapter is to present the analysis of the results obtained and understand which are the main reasons that lead to those results, so that decisions can be taken more effectively in the future.

The following table shows the decisions that were withdrawn from the projects' analysis.

		Project 1		Project 2		Project 3		Project 4		Project 5	
		OH	UG	OH	UG	OH	UG	OH	UG	OH	UG
Construction costs present values	Materials Cost	65.387	65.380	84.836	107.524	43.242	81.122	38.533	53.844	25.964	48.065
	Workforce Cost	27.378	64.447	71.290	102.084	34.588	77.018	30.821	51.120	10.821	48.516
	Licensing and Indemnities Cost	15.000	3.500	10.688	355	7.704	355	8.905	355	3.000	3.500
O&M costs present values	Strip Maintenance	1.996	N.A.	3.165	N.A.	1.613	N.A.	1.437	N.A.	693	N.A.
	Maintenance of the secondary network of fuel management strips	8.797	N.A.	13.945	N.A.	7.108	N.A.	6.334	N.A.	3.054	N.A.
	Systematic Preventive Maintenance	1.664	N.A.	2.637	N.A.	1.344	N.A.	1.198	N.A.	578	N.A.
	Corrective maintenance_OPEX	3.537	2.677	5.607	4.171	2.858	3.146	2.547	2.088	1.228	2.042
	Corrective maintenance_CAPEX	3.099	1.146	4.912	1.785	2.504	1.347	2.231	894	1.076	875
Present costs of energy not supplied		6.867	763	42.984	4.776	31.704	3.523	21.898	2.433	79.004	8.778
Total costs		133.724 €	137.913 €	240.064 €	220.694 €	132.666 €	166.512 €	113.903 €	110.736 €	125.418 €	111.776 €
Final Decision		**OH option**		**UG option**		**OH option**		**UG option**		**UG option**	

Table 4-Decisions taken from the projects analysis

Table key:

UG: Underground Network

OH: Overhead Network

N.A.: Not Applicable

Corrective/conditioned maintenance: repair of faults and/or malfunctions

Systematic preventive maintenance: networks' tri-annual inspection

5.1. Results Analysis

As previously mentioned, the costs incurred to install both options of electricity distribution network include the investment costs with the construction and installation of the networks, the costs of operating and maintaining them over 30 years, and the costs related with energy not supplied.

From the observation of table 4 above, and through the economic and financial analysis of the various projects, it was found that in projects 1 and 3, the overhead option is cheaper than the underground option, with differences in lifetime costs of 3% and 20%, respectively. With regard to projects 2, 4 and 5, the underground option is cheaper than the overhead option, with cost differences of 9%, 3% and 12%, respectively.

For projects 1 and 3, the factors determining the merit of these projects are the cost with the hired workforce, namely the costs of digging the trench to install the underground network, which represent around 36% of the total lifetime costs. In projects 2, 4 and 5, the factors contributing to the merit of the underground option are the lower operation and maintenance costs over the lifetime and the lower costs of energy not supplied.

However, the variable-length of the installation options – overhead or underground – influences their merit significantly. Thus, when analysing the cost per km, it can be seen that, in all the projects, the underground option has merit over the overhead option, with cost differences over the useful life, on average, of 29%. Therefore, it is important to take this variable into account when designing the projects, and for this reason, a sensitivity analysis will be carried out to determine at what point, in terms of length, does the merit of the option become indifferent/reversed in projects 1 and 3.

5.2. Sensitivity Analysis: the networks' length

For this set of projects, a sensitivity analysis was carried out, in order to study variations in the length of the networks and observe what is the behaviour of the projects' merit. The network length variable is considered critical, since small changes in it can alter the merit of the projects. As mentioned before, the underground option is longer than the overhead option since it is built along roads. This is evident when calculating the costs per unit length of each option, where in all projects, this indicator shows that the underground option is more economical than the overhead option. The underground option presents merit for similar lengths, in all projects, as one can see in the table below.

	Project 1		Project 2		Project 3		Project 4		Project 5	
	OH	UG	OH	UG	OH	UG	OH	UG	OH	UG
Number of kilometres	2,5	2,9	3,963	4,53	2,02	3,42	1,8	2,27	0,868	2,22
Total costs per km	53.490 €	47.556 €	60.576 €	48.718 €	65.676 €	48.688 €	63.280 €	48.782 €	144.490 €	50.350 €

Table 5-Projects' number of kilometres and total costs per kilometre

In section 5.1., one concluded that in projects 1 and 3 an overhead network will be built, and since the length of the networks is a critical factor in the merits of the decision, we calculated the length of the underground network for which the merits of the decision would become indifferent.

With regard to project 1, for the lifetime costs of the underground network to equal the lifetime costs of the overhead network, the length of the former had to be 2,82km. That is, there would have to be a reduction of about 3% of the underground network compared to its current length (2,9km) to make it indifferent for the company to build either overhead or underground network.

Regarding project 3, in order for the lifetime costs of the underground network to equal the lifetime costs of the overhead network, the length of the overhead network had to be 2,73km. That is, there would have to be a reduction of about 20% in the underground network compared to its current length (3,42km) to make it indifferent for the company to build either an overhead or an underground network. In this project, the reduction in length is higher since this is the one that presents the greatest length discrepancy in the initial scenario, of about 41%.

Hence, it can be concluded that the networks' length is a critical variable that must always be analysed on a case-by-case basis, as shown above, and in which the quality of the analysis made decisively influences the merit of the installation option.

6. Discussion

The purpose of this report was to answer the following research question: *Medium voltage power cables – what is the best solution: overhead or underground installation?*, by conducting an analysis based on economic and financial components. This analysis is a useful decision tool for the company E-REDES and its counterparts to know when to install overhead or underground networks.

There are two key findings that can be drawn from the present internship report. First, in most of the projects analysed, the underground installation option presents better economic and financial indicators than the overhead option, as it presents lower operation and maintenance costs and lower costs of energy not distributed (due to its higher degree of reliability) than the overhead one. Second, it was found that the difference in lengths between the two installation options is a critical variable since it influences, as discussed in section 5.2., the merits of the decision whether or not to bury electricity distribution networks. That is to say, as underground networks have a longer network length, even if their total cost (over 30 years) is lower per kilometre, when multiplied by the number of kilometres, it always ends up being the most expensive option.

With regard to the comparison between the findings of previous research and this report, the following can be concluded:

- Investment Costs – According to Battle (2019), Kim et al. (2014), Martins et al. (2021a), among others, the greatest issue with undergrounding power lines is associated with the investment costs. These costs are higher due to the fact that they present larger installation timeframes (caused by the reduced flexibility inside the dig and the weight of the cables to be installed); the material costs are also greater than the overhead ones; and due to the design of the projects themselves.

  According to the results obtained, one can see that they are consistent with the previous literature, since all the projects present a higher investment cost in the underground installation option.

- Reliability – Past researchers, such as Agrawal et al. (2020), Brown (2007), and Fenrick and Getachew (2012), argued that by burying the networks, there will be a significant improvement in their reliability and, therefore, there will be far less failures, since that they are not exposed to extreme weather events, animal contact or vegetation, as in the case of overhead electricity distribution lines.

According to E-REDES' reliability record, the energy not distributed by underground networks, due to supply interruptions, corresponds to only 10% of the energy not distributed by the overhead network.

- O&M Costs – Some authors – such as Edison Electric Institute (2014), Zamuda et al. (2019), and Murr (2011) – have found that undergrounding can result in savings for the company providing the service, namely, lower operation and maintenance costs, vegetation management costs, restoration costs caused by storms, and a decrease in the lost revenue associated to interruptions customers service. Whereas, for example, Hall and Hall Energy Consulting, argue that these costs are almost the same in both installation options.

  The present report has shown that the overhead networks' operation and maintenance costs are, on average, about four times higher than the underground ones, which is in line with what was explained by the first aforementioned authors. This difference in O&M costs is due to the existing strip in the overhead installation option, since, and as stated above, it is necessary to maintain it, which added to the costs of conditioned and corrective maintenance, will make these costs higher in this installation option.

- Assets' life cycle – While the literature, particularly Bumby et al. (2010) and Maliszewski and Perrings (2012), claim that the life expectancy of the overhead and underground networks is 50 and 30 years, respectively. In this internship report, and according to the company, it was considered a life expectancy of 30 years for both installation options.

Thus, the present report, adds to the growing body of evidence suggesting that in most of the analysed cases, the installation option that presents less costs for the company is the underground one, due to the lower O&M costs and energy not supplied costs. However, there are two projects (project 1 and 3) which present merit for the overhead network. This is due to the fact that, in these projects, the construction costs, namely the workforce costs, are about 60% more expensive in the underground network than in the overhead one.

Therefore, it is noted that more funds are needed at the construction stage to bury networks, as shown in Table 4. However, these will have future gains in operation and maintenance and quality of service, which will create a higher value. This situation is also particularly relevant with the exposure of the overhead network to extreme events and the increase in damage caused by them due to climate change.

Furthermore, it should be noted that there were costs that could not be estimated with a high degree of reliability, such as the environmental and aesthetic repercussions costs that are often mentioned in previous studies. However, if such costs were considered, the decisions reached in section 5.1. – except for projects 1 and 3, eventually – would not change, because they would be higher for OH installation. Moreover, it should be emphasized that everything that is considered as investment, is returned through the tariff and remunerated at the rate of return for the year in which it is made, while the operating expenditure (OPEX) is not returned, with the costs being borne entirely by the company. Therefore, for a company operating electricity distribution networks, it is more advantageous to have more CAPEX and less OPEX. Which, in this particular case, does not mean building more underground networks to the detriment of overhead networks.

7. Conclusion

7.1. General conclusions

This internship report's main goal was to answer the following research question: *Medium voltage power cables – what is the best solution: overhead or underground installation?*, for the selected investment projects.

In what the literature review was concerned, and in order to answer the above question, it has been provided a context where a distinction was made between the benefits and drawbacks of the two installation options and the reasons that lead a company to decide whether to bury or not the networks, which have a lot to do with the short- and long-term perspective, due to investment costs, reliability and resilience related factors, or future costs with the maintenance, and others.

An investment project development – in this case, in the distribution of electricity – can impact positively (e.g., local or regional economic development) and/or negatively (e.g., environmental modifications) the surroundings (Drèze & Stern, 1987). Therefore, this internship report was based on an economic and financial components analysis of the various projects. The purpose of this analysis was to identify which installation option, overhead or underground, has lower costs, i.e., to provide an answer on which installation option to be implemented. Besides this, a sensitivity analysis was also carried out to find out what is the length of underground network for which the decision to bury or not bury electricity distribution networks, is indifferent, since this variable is considered a critical one.

The decision underlying the research question resulted from the analysis of the following aspects: the construction costs, the O&M lifetime costs for each option, and the costs of energy not supplied by each of them. From the results obtained, one has reached the conclusions outlined below.

In what concerns the obtained results, it was concluded that, in three of the projects analysed, the underground installation option presents a better economic and financial indicator than the overhead option, while in the other two projects (project 1 and 3) it is the overhead option that presents merit over the underground one. In addition to this, it was also found, through the sensitivity analysis carried out, that there is one variable that greatly influences the decision which is the difference in the length between the overhead and underground installation options. This is because, in the analysed projects, the length of the underground network is greater than the length of the overhead option and this difference makes the underground network significantly more expensive. Thereby, it can be concluded that this is a critical variable that must always be analysed on a case-by-case basis, and in which the quality of the analysis carried out decisively influences the merit of the option.

Thus, it was possible to verify that there was no simple and straightforward answer to the raised research question. However, it was found that there is a tendency to consider that, in the construction phase, the overhead network is cheaper than the underground network; whereas if one considers the asset useful life and the reliability difference between each option, the underground network is cheaper. The current and future prospects of increasing commodity prices, increasing operation and maintenance costs and increasing frequency and intensity of extreme events and company external events will all contribute to the increased merit of the underground option.

7.2. Limitations and Future Researches

Certain limitations of this study could be addressed in future research. For example, the study could be extended to other voltage levels and other cable sections to see if the conclusions are similar; the sample size can be increased despite the similarity of the conclusions reached in each project; this study should be regularly updated to assess whether the conclusions change or not, since there is a high level of mutability; carry out studies and analyses of what the impact of increasing the frequency and intensity of extreme events will be on overhead distribution networks and draw up scenarios of analysis of the merits of the two installation options.

Despite these limitations, the present study has enhanced one’s understanding of the relationship between overhead and underground network costs components through their life cycle and identified the option that can create more value.

References

Agrawal, P., Kanwar, N., Gupta, N., Niazi, K. R., Swarnkar, A., Meena, N. K., & Yang, J. (2020). Reliability and network performance enhancement by reconfiguring underground distribution systems. *Energies*, *13*(18), 4719.

Albeck Jr, W., & Estomin, S. (2003). *Cost benefits for overhead vs. underground utilities* [Publication](SP208B4C). http://www.roads.maryland.gov/OPR_Research/MD-03-SP208B4C-Cost-Benefits-for-Overhead-vsUndergroundUtilityStudy_Report.pdf

Battle, R., Khanna, R., & Beauger, B. (2019, 03-06-2019). *Aerial mv covered networks: Worth a new look?* International Conference on Electricty Distribution, Madrid. https://cired-repository.org/handle/20.500.12455/794

Bloom, J. A., Feinstein, C., & Morris, P. (2006). Optimal replacement of underground distribution cables. 2006 IEEE PES power systems conference and exposition (pp.389-393).IEEE.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2017). *Cost-benefit analysis: concepts and practice*. Cambridge University Press.

Brealey, R. A., Myers, S. C., Allen, F., & Mohanty, P. (2018). *Principles of corporate finance, 12/e* (Vol. 12). McGraw-Hill Education.

Brown, R. (2007). Undergrounding assessment phase 1 final report: Literature review and analysis of electric distribution overhead to underground conversion. *Quanta Technol., Florida, FL, USA, Tech. Rep.*

Bumby, S., Druzhinina, E., Feraldi, R., Werthmann, D., Geyer, R., & Sahl, J. (2010). Life cycle assessment of overhead and underground primary power distribution. *Environmental science & technology*, *44*(14), 5587-5593.

Chawla, K., Bajpai, P., & Das, R. (2021). Decision support tool for enabling resiliency in an underground power distribution system. *International Journal of Electrical Power & Energy Systems*, *133*, 1-11.

Dalle, B. (2017). History of Overhead Lines in Cigré. In *Overhead Lines* (pp. 19-25). Springer.

Drèze, J., & Stern, N. (1987). The theory of cost-benefit analysis. In *Handbook of public economics* (Vol. 2, pp. 909-989). Elsevier.

E-REDES. (2020). *E-REDES relatório & contas 2020*. https://www.e-redes.pt/sites/eredes/files/202105/RC%20EREDES%202020%20PT%20Online%5B1%5D.pdf

E-REDES. (2021). *Relatório de qualidade de serviço 2021*. https://www.e-redes.pt/sites/eredes/files/202105/Relat%C3%B3rio%20da%20Qualidade%20de%20Servi%C3%A7o%202020%20E-REDES.pdf

Edison Electric Institute. (2014). *Before and after the storm: A compilation of recent studies, programs, and policies related to storm hardening and resiliency [Press Release]*. Retrieved 10th November from https://slidelegend.com/before-and-after-the-storm-update-march-2014-edison-electric-_59bc98d31723dd78e8249228.html

European Commission. (2015). *Guide to cost-benefit analysis of investment projects [Press Release]*. Retrieved 1st December from http://ec.europa.eu/regional_policy/index_en.cfm

European Commission. (2022). *European Economic Forecast [Press Release]*. Retrieved 29th April from https://ec.europa.eu/info/publications/economic-and-financial-affairs-publications_en

Fenrick, S. A., & Getachew, L. (2012). Cost and reliability comparisons of underground and overhead power lines. *Utilities Policy*, *20*(1), 31-37.

Fortes, P., Simões, S. G., Gouveia, J. P., & Seixas, J. (2019). Electricity, the silver bullet for the deep decarbonisation of the energy system? Cost-effectiveness analysis for Portugal. *Applied Energy*, *237*, 292-303. https://doi.org/10.1016/j.apenergy.2018.12.067

Götze, U., Northcott, D., & Schuster, P. (2008). *Investment appraisal methods and models* (S.-V. B. Heidelberg, Ed.). https://doi.org/10.1007/978-3-540-39969-8

Hall, K. L., & Hall Energy Consulting, I. (2013). *An updated study on the undergrounding of overhead power lines [Press Release]*.Retrieved 30th November from https://eei.org/issuesandpolicy/electricreliability/undergrounding/Documents/UndergroundReport.pdf

Hox, J. J., & Boeije, H. R. (2005). Data collection, primary vs. secondary. *Encyclopedia of Social Measurement*, *1*, 593-599.

Khalid, K., Abdullah, H. H., & Kumar M, D. (2012). Get along with quantitative research process. *International Journal of Research in Management*, *2*(2), 15-29.

Kim, J.-H., Kim, J.-Y., Cho, J.-T., Song, I.-K., Kweon, B.-M., Chung, I.-Y., & Choi, J.-H. (2014). Comparison between Underground Cable and Overhead Line for a Low-Voltage Direct Current Distribution Network Serving Communication Repeater. *Energies*, *7*(3), 1656-1672. https://doi.org/10.3390/en7031656

Larsen, P. H. (2016). *Severe weather, power outages, and a decision to improve electric utility reliability* [Doctoral, Stanford University]. Retrieved 22nd November from http://purl.stanford.edu/sc466vy9575

Maliszewski, P. J., & Perrings, C. (2012). Factors in the resilience of electrical power distribution infrastructures. *Applied Geography*, *32*(2), 668-679.

Martins, B. d. A., Arango, L., & Kubota, L. C. (2021a). *Análise sobre o enterramento de infraestrutura de redes dos setores de distribuição de energia e telecomunicações* http://repositorio.ipea.gov.br/bitstream/11058/11058/3/publicacao_preliminar_analise_sobre_o_enterramento_de_infraestrutura_de_redes.pdf

Martins, B. d. A., Arango, L., & Kubota, L. C. (2021b). *Análise sobre o enterramento de infraestrutura de redes dos setores de distribuição de energia e telecomunicações [Press Release]*

Munich RE. (n.d.). *Extreme weather risks*. Retrieved 20th December from https://www.munichre.com/en/risks/extreme-weather.html

Murr, M. (2011). *Burying ovehead power lines update*.

Panteli, M., & Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, *127*, 259-270. https://doi.org/10.1016/j.epsr.2015.06.012

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*. Pearson education.

Shaw Consultants International, I. (2010). *Study of the feasibility and reliability of undergrounding electric distribution lines in the district of columbia* (1026). M. D. o. E. Resources.

Shively, G., & Galopin, M. (2013). An overview of benefit-cost analysis. *Accessed online at http://www. agecon. purdue. edu/staff/shively/COURSES/AGEC406/reviews/bca. htm.*

Soares, M. I., Moreira, J. A. C., Pinho, C., & Couto, J. (2020). *Decisões de Investimento: Análise Financeira de Projetos (4ª edição, revista e corrigida)* (Sílabo, Ed. 4 ed.).

[Record #59 is using a reference type undefined in this output style.]

Valentin, M., Marius, P., Andrei, P., & Delia, G. (2009). Methodological Approaches in Realizing and Applying Cost Benefit Analysis for the Investment Projects. *Journal of Annals of the University of Oradea. Economic Science*, *2*(1), 156-162.

Williams, C. (2007). Research Methods. *Journal of Business & Economic Research 5*, 65-72.

Zamuda, C. D., Larsen, P. H., Collins, M. T., Bieler, S., Schellenberg, J., & Hees, S. (2019). Monetization methods for evaluating investments in electricity system resilience to extreme weather and climate change. *The Electricity Journal*, *32*(9), 1-7. https://doi.org/10.1016/j.tej.2019.106641

Zamuda, C. D., & Ressler, A. (2020). Federal adaptation and mitigation programs supporting Community investment in electricity resilience to extreme weather. *The Electricity Journal*, *33*(8), 1-11. https://doi.org/10.1016/j.tej.2020.106825

Annexes

Annexe 1- United States Billion-Dollar Disaster Events 1980-2019

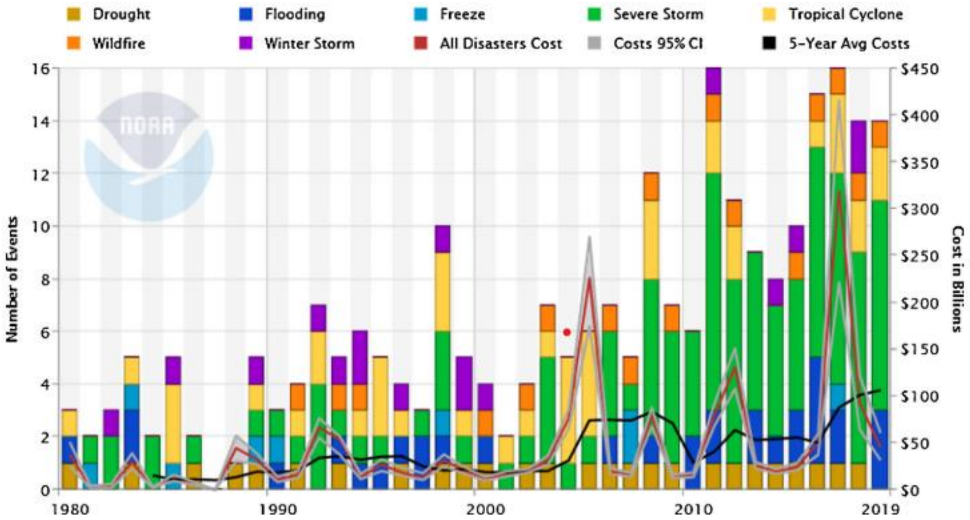


Fig. 1. Billion-dollar climate- and weather-related disaster event types, by year (CPI-adjusted). Source: NOAA 2020.

Annexe 2-Project 1: Overhead breakdown of costs

Investment	**Materials (km)**	**Price per unit**	**Quantity**	**Total**
	Poles	3.500,00 €	15	52.500,00 €
	Frame for electric pole	250,00 €	15	3.750,00 €
	Isoladores cadeia	152,34 €	15	2.285,10 €
	Insulators	215,10 €	15	3.226,50 €
	Cable AA 160 mm (meters)	1.450,00 €	2,5	3.625,00 €
	Total			**65.387 €**
	Workforce (km)	**Price per unit**	**Quantity**	**Total**
	Pit opening	182,00 €	15	2.730,00 €
	Assembly of the frame	1.367,00 €	15	20.505,00 €
	Colocação cadeias	112,20 €	15	1.683,00 €
	Cable placement	983,95 €	2,5	2.459,88 €
	Total			**27.378 €**
Other Costs	**Licensing and indemnities**			15.000,00 €
	Total			**15.000 €**
O&M Costs during 30 Years	**Operating Cost (km)**	**Price per unit**	**km**	**Total**
	Strip maintenance (year)	798,59	2,5	1.996,49 €
	RSFGC maintenance (year)	3.518,75	2,5	8.796,88 €
	Systematic preventive maintenance (every 3 years)	665,49	2,5	1.663,71 €
	Corrective maintenance (year) OPEX	1.414,77	2,5	3.536,93 €
	Corrective maintenance (year) CAPEX	1.239,43	2,5	3.098,56 €
	Total			**19.093 €**
Costs of energy not supplied				**6.867 €**
Total costs				**133.724 €**
Total costs per km				**53.490 €**

Annexe 3-Project 1: Underground breakdown of costs

Investment	**Materials (m)**	**Price per unit**	**m**	**Total**
	TT Underground cable	22,05 €	2899,8	63.940,59 €
	Cable terminations	32,59 €	3	97,77 €
	Amov. Terminations	53,00 €	3	159,00 €
	15 KV junction	56,30 €	21	1.182,30 €
	Total			**130.759 €**
	Workforce (m)	**Price per unit**	**m**	**Total**
	Cable threading	4,37 €	2899,8	12.672,13 €
	Executing Terminations	36,53 €	6	219,18 €
	CX Union	46,96 €	21,00	986,16 €
	Trench opening and capping	17,96 €	2774,32	49.826,79 €
	Sidewalk Replacement CUB/BLOC/BET (m2)	14,85 €	50	742,50 €
	Total			**64.447 €**
Other Costs	**Licensing and indemnities**			3.500,00 €
	Total			**3.500,00 €**
O&M Costs during 30 Years	**Operating Cost (m)**	**Price per unit**	**m**	**Total**
	Conditioned and Corrective maintenance (year) OPEX	923,11 €	2,8998	2.676,84 €
	Corrective maintenance (year) CAPEX	395,27 €	2,8998	1.146,20 €
	Total			**3.823 €**
Costs of energy not supplied				**763 €**
Total costs				**203.292 €**
Total costs per km				**47.556 €**

Annexe 4- Project 2: Overhead breakdown of costs

Investment	**Materials (km)**	**Price per unit**	**Quantity**	**Total**
	Poles, Insulators, cables and wire frames	17.521,00 €	3,96	69.435,72 €
	Avifauna	3.886,00 €	3,96	15.400,22 €
	Total			**84.836 €**
	Workforce (km)	**Price per unit**	**Quantity**	**Total**
	Installation of poles, cables, insulators and wire frames	13,76 €	3.963,00	54.522,95 €
	Avifauna installation	3,37 €	3.963,00	13.335,50 €
	TET workforce and generators	3.431,96 €	1,00	3.431,96 €
	Total			**71.290 €**
Other Costs	**Licensing and compensation**			10.686,66 €
	Total			**10.687 €**
O&M Costs during 30 years	**Operating Cost (km)**	**Price per unit**	**Quantity**	**Total**
	Strip maintenance (year)	798,59 €	3,96	3.164,83 €
	RSFGC maintenance (year)	3.518,75 €	3,96	13.944,81 €
	Systematic preventive maintenance (every 3 years)	665,49 €	3,96	2.637,32 €
	Corrective maintenance (year) OPEX	1.414,77 €	3,96	5.606,74 €
	Corrective maintenance (year) CAPEX	1.239,43 €	3,96	4.911,84 €
	Total			**30.266 €**
Costs of energy not supplied				**42.984 €**
Total costs				**240.063 €**
Total costs per km				**60.576 €**

Annexe 5- Project 2: Underground breakdown of costs

Investment	**Materials (m)**	**Price per unit**	**Quantity**	**Total**
	All-terrain underground cable	22,82 €	4.533,00	103.443,06 €
	Cables terminations/joints	0,90 €	4.533,00	4.079,70 €
	Total			**107.523 €**
	Workforce (m)	**Price per unit**	**Quantity**	**Total**
	Cable and terminations placement	22,52 €	4533,00	102.083,16 €
	Total			**102.083 €**
Other Costs	**Licensing and compensation**			355,00 €
	Total			**355 €**
O&M Costs during 30 years	**Operating Cost (km)**	**Price per unit**	**Quantity**	**Total**
	Corrective maintenance (year) OPEX	920,65 €	4,53	4.173,29 €
	Corrective maintenance (year) CAPEX	393,95 €	4,53	1.785,78 €
	Total			**5.959 €**
Costs of energy not supplied				**4.776 €**
Total costs				**220.696 €**
Total costs per km				**48.719 €**

Annexe 6- Project 3: Overhead breakdown of costs

Investment	**Materiais (km)**	**Price per unit**	**Quantity**	**Total**
	Poles, cables and insullators	17.521,00 €	2,02	35.392,42 €
	Avifauna	3.886,00 €	2,02	7.849,72 €
	Total			**43.242 €**
	Mão de Obra (km)	**Price per unit**	**Quantity**	**Total**
	Installation of poles, cables and insullators	13.758,00 €	2,02	27.791,16 €
	Avifauna installation	3.365,00 €	2,02	6.797,30 €
	Total			**34.588 €**
Other Costs	**Licensing and compensation**			7.705,00 €
	Total			**7.705 €**
O&M Costs during 30 years	**Operating costs (km)**	**Price per unit**	**Quantity**	**Total**
	Strip maintenance (year)	798,59 €	2,02	1.613,16 €
	RSFGC maintenance (year)	3.518,75 €	2,02	7.107,88 €
	Systematic preventive maintenance (every 3 years)	665,49 €	2,02	1.344,28 €
	Corrective maintenance (year)_OPEX	1.414,77 €	2,02	2.857,84 €
	Corrective maintenance (year)_CAPEX	1.239,43 €	2,02	2.503,64 €
	Total			**15.427 €**
Costs of energy not supplied				**31.704 €**
Total costs				**132.666 €**
Total costs per km				**65.676 €**

Annexe 7- Project 3: Underground breakdown of costs

Investment	**Materials (km)**	**Price per unit**	**Quantity**	**Total**
	All-terrain underground cables	22.820,00 €	3,42	78.044,40 €
	Cable terminations	900,00 €	3,42	3.078,00 €
	Total			**81.122 €**
	Workforce (m)	**Price per unit**	**Quantity**	**Total**
	Cable installation and dig openning	22,52 €	3420	77.018,40 €
	Total			**77.018 €**
Other Costs	**Licensing and compensation**			355,00 €
	Total			**355 €**
O&M Costs during 30 years	**Custo Operação (km)**	**Price per unit**	**Quantity**	**Total**
	Corrective Maintenance (year)_OPEX	919,99 €	3,42	3.146,36 €
	Corrective Maintenance (year)_CAPEX	393,95 €	3,42	1.347,31 €
	Total			**4.494 €**
Costs of energy not supplied				**3.523 €**
Total costs				**166.512 €**
Total costs per km				**48.688 €**

Annexe 8- Project 4: Overhead breakdown of costs

Investment	**Materials (km)**	**Price per unit**	**Quantity**	**Total**
	Poles, cables, and insullators	17.521,00 €	1,8	31.537,80 €
	Avifauna	3.886,00 €	1,8	6.994,80 €
	Total			**38.533 €**
	Workforce (km)	**Price per unit**	**Quantity**	**Total**
	Installation of poles, cables and insullators	13.758,00 €	1,8	24.764,40 €
	Avifauna installation	3.365,00 €	1,8	6.057,00 €
	Total			**30.821 €**
Other Costs	**Licensing and compensation**			**8.905,00 €**
	Total			**8.905 €**
O&M Costs during 30 years	**Operation costs (km)**	**Price per unit**	**Quantity**	**Total**
	Strip maintenace (year)	798,59 €	1,8	1.437,47 €
	RSFGC maintenance (year)	3.518,75 €	1,8	6.333,75 €
	Systematic preventive maintenance (every 3 years)	665,49 €	1,8	1.197,87 €
	Corrective maintenance (year) OPEX	1.414,77 €	1,8	2.546,59 €
	Corrective maintenance (year) CAPEX	1.239,43 €	1,8	2.230,97 €
	Total			**13.747 €**
Costs of energy not supplied				**21.898 €**
Total costs				**113.904 €**
Total costs per km				**63.280 €**

Annexe 9- Project 4: Underground breakdown of costs

Investment	**Materials (km)**	**Price per unit**	**Quantity**	**Total**
	All-terrain underground cables	22.820,00 €	2,27	51.801,40 €
	Cable terminations	900,00 €	2,27	2.043,00 €
	Total			**53.844 €**
	Workforce (km)	**Price per unit**	**Quantity**	**Total**
	Cable installation and dig openning	22.520,00 €	2,27	51.120,40 €
	Total			**51.120 €**
Other Costs	**Licensing and compensation**			355,00 €
	Total			**355 €**
O&M Costs	**Operating Costs (km)**	**Price per unit**	**Quantity**	**Total**
	Corrective maintenance (year)_OPEX	920,65 €	2,27	2.089,87 €
	Corrective Maintenance (year)_CAPEX	393,95 €	2,27	894,27 €
	Total			**2.984 €**
Costs of energy not supplied				**2.433 €**
Total costs				**110.737 €**
Total costs per km				**48.783 €**

Annexe 15- Project 5: Overhead breakdown of costs

Investment	**Materials (m)**	**Price per unit**	**Quantity**	**Total**
	Poles	3.500,00 €	6	21.000,00 €
	Pole frames	250,00 €	6	1.500,00 €
	Chain insulators	152,34 €	6	914,04 €
	Insullators	215,10 €	6	1.290,60 €
	AA 90 mm cable	1,45 €	868	1.258,60 €
	Total			**25.963 €**
	Workforce (m)	**Price per unit**	**Quantity**	**Total**
	Dig openning	182,00 €	6	1.092,00 €
	Frame assembly	1.367,00 €	6	8.202,00 €
	Placing chains	112,20 €	6	673,20 €
	Cable installation	0,98 €	868	854,07 €
	Total			**10.821 €**
Other Costs	**Licensing and compensation**			**3.000,00 €**
	Total			**3.000 €**
O&M Costs during 30 years	**Operating costs (m)**	**Price per unit**	**Quantity**	**Total**
	Strip maintenance (year)	798,59 €	0,868	693,18 €
	RSFGC maintenance (year)	3.518,75 €	0,868	3.054,28 €
	Systematic preventive maintenance (every 3 years)	665,49 €	0,868	577,64 €
	Corrective maintenance (year)_OPEX	1.414,77 €	0,868	1.228,02 €
	Corrective maintenance (year)_CAPEX	1.239,43 €	0,868	1.075,82 €
	Total			**6.629 €**
Costs of energy not supplied				**79.004 €**
Total costs				**125.417 €**
Total costs per km				**144.490 €**

Annexe 16- Project 5: Underground breakdown of costs

Investment	**Materials (m)**	**Price per unit**	**Quantity**	**Total**
	All-terrain underground cables	22,05 €	2125	46.856,25 €
	Cable terminations	32,59 €	6	195,54 €
	15 KV joints	56,30 €	18	1.013,40 €
	Total			**48.065 €**
	Workforce (m)	**Price per unit**	**Quantity**	**Total**
	Cable threading	4,37 €	2125	9.286,25 €
	Implementation terminations	36,53 €	6	219,18 €
	Implementation CX Union	18,00 €	46,96	845,28 €
	Digging and covering of ditch	2.125,00 €	17,96	38.165,00 €
	Total			**48.516 €**
Other Costs	**Licensing and compensation**			**3.500,00 €**
	Total			**3.500 €**
O&M Costs during 30 years	**Operating costs (km)**	**Price per unit**	**Quantity**	**Total**
	Corrective maintenance (year)_OPEX	920,65 €	2,22	2.043,83 €
	Corrective maintenance (year)_CAPEX	393,95 €	2,22	874,57 €
	Total			**2.918 €**
Costs of energy not supplied				**8.778 €**
Total costs				**111.777 €**
Total costs per km				**50.350 €**